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REPORT

PHASE III

LUBRICANT SELECTION MANUAL

To

GEORGE C. MARSHALL SPACE FLIGHT CENTER

MARSHALL SPACE FLIGHT CENTER, AL

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to

NASA Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

November 22, 1991

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INTRODUCTION

Future spacecraft must be designed to operate for v ry long time periods in space. For example, a target goal for the Space Station is 30 years of operation. Although the actual life may be significantly less than this optimistic goal, the life will certainly be a critical issue in design. The bearings on primary components such as the alpha and beta joints must obviously be designed and lubricated with the objective of optimum performance life. In addition to these joints, there will be numerous other tribological (rubbing or rolling) interfaces that will be required to function for the life of the spacecraft.

A major key to adequate performance of tribological interface is proper lubrication. Lubricants can be divided into two basic classes: solid films and liquids. Both types have been used extensively in space applications. Both have advantages and disadvantages that must be carefully considered in their selection.

The purpose of this document is to summarize selection criteria for liquid and solid lubricants applied to long-life spacecraft.

SOLID FILM LUBRICATION

Basic Consideratons[1]

There is no single ideal lubricant for all applications. Every lubricant has advantages and disadvantages which must be carefully considered so that the next important requirements of a given application are satisfied. The following lists provide some of the important advantages and disadvantages to consider in selecting a solid lubricant in preference to a liquid or grease lubricant.

Advantages of Solid Lubricants

1. Do not collect grit.
2. Can be used under extremely high load conditions.
3. Excellent storage stability.
4. LOX and oxygen compatible (inorganically bonded films).
5. Suitable for use over wide temperature range.
6. Resistant to the effects of nuclear and gamma radiation.
7. No disposal problem.
8. Friction coefficient decreases with increasing load.
9. In some applications solid films will provide lubrication for the life of the parts.

Disadvantages of Solid Lubricants

1. Limited amount of lubricant available.
2. Friction coefficient higher than with hydrodynamic lubrication.
3. Provisions for the effective removal of wear debris must be provided.
4. Considerations must be given to removing heat from contact zone of bearings and gears.
5. More expensive (costly relubrication).
6. Contamination must be avoided during coating processes and assembly of parts.
7. Elevated temperature cure cycle of some solid films will damage the mechanical properties of some materials.

Selection of Solid Lubricants

Solid lubricants provide capabilities unavailable with liquid lubricants, but they are not a universal lubricant. The requirements of some applications prevent their use entirely. Also, there is no single solid lubricant that will meet all of the requirements. Therefore, the selection of the basic class of lubricant (solid or liquid) and the specific lubricant must consider the needs of the particular application and the requirements of the system of which the application is a part.

The obvious advantages of solid films are that they add virtually no weight to the system and create virtually no problems due to outgassing. The primary disadvantages of solid films are that they have limited life and are very difficult to replenish.

Several types of solid lubricants are discussed by Martin[2]. Solid film lubricants are described in Table 1 and solid film compacts are described in Table 2. The four basic solid film lubricants that have traditionally been given the most attention and used most extensively are:

- Graphite,
- Polytetrafluoroethylene (PTFE),

TABLE 1. SOLID LUBRICANTS

Lubricant	Temp. Range (°F)	Comments
Molybdenum Disulfide, MoS_2	-400 to 1500 (3,4)	Most commonly used solid film. (3) Low and steady torque. (5) Wear life and friction improved by many additives such as Sb_2O_3 or graphite. (6)(7)(8)
Tungsten Disulfide, WS_2	-400 to 1500 (3)	Similar to MoS_2, but higher friction. (3)
Polytetrafluoroethylene, PTFE	-100 to 550 (3)	Low friction. Has a moderate load carrying capacity which decreases at higher temperature. (3) Good chemical resistance. (10)
Graphite	unstable in a vacuum (3)	High friction and wear in a vacuum. (3) Effective only in the presence of moisture unless impregnated with ductile metal or polymer. (10) Structure, purity and particle size strongly effect its lubricity. (11)
Silver Film	-200 to 900 (10)	Exhibits high temperature resistance, but not as effective at cryogenic temperatures. Excellent chemical and radiation resistance. (10)
Lead Film	temperature independent torque (10) -55 to 230 (10)	Ion-plating shows better adhesion than vacuum evaporation or electroplating. (12)(13)(14) Debris is generated from the cage matrix when used in rolling element bearing. (13) If the raceway is lead plated torque is steady over the long term. (14) Lead film found to be a combination of lead and lead oxide, PbO. Longer life of the film attributed to the lubricating properties of PbO. (12) Friction at very low temperatures high for pure sliding. (10)

TABLE 1. SOLID LUBRICANTS (CONTINUED)

Lubricant	Temp. Range (°F)	Comments
Lead Sulfide, PbS, and Lead Oxide, PbO films		High load capacity. Used primarily as an additive. PbO has higher temperature compatibility than PbS. (3)
TUFRAM coating	-450 to 600 (15)	Porous anodic film with a solid lubricant. Coating on Al and aluminum alloys with hardness comparable to case hardened steel. Thickness of 0.01 to 0.13 mm. (16) Friction coefficient of 0.05 (static < dynamic). Excellent corrosion and chemical resistance. (15)
NEDOX coating	-350 to 500 (16)	Nickel alloy with an infusion of PTFE used on ferrous materials and copper alloys. Coating thickness of 0.005 to 0.08 mm. (16) Better wear and abrasion resistance than case hardened steel or hard chrome plate. Friction coefficient of 0.05 (static < dynamic). Excellent resistance to most chemicals and corrosion. (15)
Cesium oxythiomolybdate silicate, Cs_2MoOS_3 (17)	Wide temp. range, (tested -65 to 1200)	Used on ceramic bearings with super alloy separator. Proved worthy of further testing.
Cesium oxythiotungstenate, Cs_2WOS_3 (17)	Wide temp. range, (tested -65 to 1200)	Used on ceramic bearings with super alloy separator. Performance depends upon interaction between lubricant and the substrate. A viable and novel lubricant.

TABLE 2. SOLID LUBRICANT COMPACTS

Material	Comments
Molybdenum disulfide and antimony-trioxide, MoS_2/Sb_2O_3	A synergistic relationship exits between MoS_2 and Sb_2O_3. Lower wear and friction result from the combination. Softening of the oxide occurs at the asperity flash temperatures allowing the molybdenum disulfide to obtain a tribologically preferential orientation. (7)(8)
Molybdenum disulfide and molybdenum-trioxide, MoS_2/MoO_3	Similar to MoS_2/Sb_2O_3 compact. (7)(9)
Molybdenum disulfide with antimony-thioantimonate, $MoS_2/Sb(SbS_4)$ or $MoS_2/Sb(SbS_4)$/graphite.	$Sb(SbS_4)$ exhibits no lubricating properties alone. Lubricating properties of MoS_2 and graphite improved by combination with $Sb(SbS_4)$. (6)
MoS_2/B_2O_3	Near the softening temp of the oxide friction increases and wear decreases. At lower temperatures the oxide acts abrasively. At higher temperatures (oxide near liquid) there is greater loss of MoS_2 and therefore an increased wear rate. (18)
Polytetrafluoroethylene (PTFE) reinforced with glass fiber and MoS_2	An effective "all around" cage material for ball bearings. (19) Excellent for low to moderate temperature use. Good smearing of PTFE at higher temperatures reducing wear. The glass fiber reinforcement enables the polymer to withstand arduous conditions. Relatively large glass fibers (10μm) wear flatten and reinforce the worn surface. Thin and brittle fibers (1μm) fragment and become mobile abrasive particles. (20)

TABLE 2. SOLID LUBRICANT COMPACTS (CONTINUED)

Material	Comments
Bronze filled PTFE compacts	For use in cage in ball bearings. Has lower wear rate than PTFE but not as abrasive as glass-filled PTFE. (21)
Sintered Cages, solid lubricants in a columbium-tantalum (Nb-Ta) matrix. (3)	MoS_2 and silver are used as lubricants. Long wear life at high temperatures and loads. Compositions containing MoS_2 can withstand 1500°F. Can have compressive strength of 150,000 psi. Are brittle and require care when machining.
Silicate and glass binders.	Are not reactive with atomic oxygen, the major constituent in low Earth orbit environment. (22)
Carbon/graphite fibers with high temperature additives. (20)	A 3-D carbon fiber weave reinforced, acetylene-terminated polymide self-lubricating composite, fortified with powdered Ga/In/WSe_2 and dibasic ammonium phosphate, $(NH_4)_2HPO_4$ as a solid lubricant. Formed a tough transfer film and protected metallic surfaces from wear. A high temperature analog to glass reinforced composite containing MoS_2.

TABLE 3. SOLID LUBRICANT DEPOSITION AND COATING TECHNIQUES

Lubricant	Technique	Comments
Solid Lubricant Films	rf diode sputtering	Temperature range of 70-200°C, growth rate of 25-35 nm/min. (25)
	dc triode sputtering	Temperature range of 130-175°C, growth rate of 60 nm/min. (25)
	rf magnetron sputtering	Temperature range of 24-70°C, growth rate of 40-60 nm/min. (25)
	burnished films	Tumbling in a ball mill, rubbing with chamois, leather or wire brush are applied methods of burnishing. Difficult to achieve consistent results. Acceptable for simple single operation devices. (24)
Transfer Films	Transfer of lubricating film (usually from retainer material) to mating material.	Thickness of transferred film can be dependent on operation speed. Creates large amounts of wear debris. (24)
TUFRAM Process	Process converts Al surface to aluminum-oxide ceramic and then electrochemically infuses porous surface with an interlocked layer of fluorocarbon for self-lubricating and corrosion resistant properties. (15)(16)	
NEDOX Process	Surfaces electroplated with hard, porous cobalt-nickel or other alloy and then infused with a low friction fluorocarbon and/or dry lubricants and heat treated to assure lubricant bonding. (15)(16)	
Hard Face Coatings	chemical vapor deposition	Gaseous carriers bring coating material to the substrate surface. The substrate must usually be heated to high temperatures (500°C). Some materials deposited by this technique include refractory metal carbides, borides and nitrides. (23)
Soft Metal Films	ion-plating	Coating is brought to the surface in a flux of argon ions that penetrate the surface of the negatively charged substrate. A graded or diffuse interface between coating and substrate provides good adhesion. (25) Ion-plating shows better adhesion and less wear debris (steadier torque) than electroplated or vacuum evaporated films. (12)(13) Optimum film thickness of 0.5 μm. (14)
	electroplating	
	vacuum evaporation	

- Molybdenum disulfide (MoS_2), and
- Lead films.

Lead films although not used as extensively as other lubricants appear to offer promise for long time applications. Table 3 lists typical methods for applying solid films. Solid film lubrication schemes can be characterized as:

- Deposited coating (lubricated for life).
- Transfer film coatings (usually used in ball bearings where coating is transferred from ball retainer to ball to race).
- Powder feed system. Powder feed systems are currently being explored for use in high temperature applications.

Application of Solid Lubricants

Sliding Contact

Solid film lubricants have been used extensively in various space programs, as described in Table 4. It must be emphasized that non-replenishible solid films have a limited wear life which for long term applications (such as Space Station) can become a major factor.

Bartz, Holinski, and Xu[6] indicate that there exists optimum concentrations for MoS_2 doped with materials such as graphite and antimony compounds to yield longer wear life than attainable with single components. A comparison of wear lives as obtained in rub block experiments is given in Table 5, and the friction coefficients are presented in Table 6. Table 7 shows the test conditions. Wear lives of 100,000 cycles are possible with this approach, which should be adequate for many components of Space Station.

TABLE 4. SPACE APPLICATIONS OF SOLID LUBRICANTS

Lubricant	Application
Lead Film	Solar Array Drives on ECS, EXOSAT and L-SAT. De-spin mechanism on GIOTTO (26). Successful use on ball bushes in S59 Star Spectrometer experiment on ESRO TD-1 Satellite (10).
MoS_2 (sodium silicate bonded)	Flexible duct joint linkage bearings on main engines of Saturn launch vehicles (temperature range of -190°C to 540°C).
MoS_2 and Sb_2O_3 (polyimide binder)	TRIAD Teeth on gear box gears and worm gears. APOLLO 17 Wavelength cam on U.V. Spectrometer. SAS-C Teeth on worm and spur gears. (27)
MoS_2, graphite and Au (sodium silicate binder)	TRIAD Teeth on worm and miter gears. Inner race, outer race and retainer on ball bearings. APOLLO 17 Drive motor R6 bearings and follower R.8 bearings on U.V. Spectrometer wavelength cam. SAS-C Inner race, outer race and retainer on ball bearings. Teeth on spur gears. (27)
Sputtered MoS_2	Ball raceways on thrust bearings on Spacecraft Gimbal Bearing TRIAD spacecraft (0.0015mm film). (27)
Carbon/Graphite	Seal application for an advanced aircraft refrigeration system. (Not much space application- effective only in the presence of moisture). (10)
TUFRAM	Wear parts on extrusion pumps, impellers, regulators, pneumatic and hydraulic valves and hydrocarbon and solvent processing equipment. Used in high performance automobile engine and transmission parts. (16)
NEDOX	Wear coatings on steel pump parts, impellers, guide tracks, construction equipment, tool components; used as mold release coatings in plastic molding applications. (16)

TABLE 5. WEAR LIFE OF SOLID FILMS (REFERENCE 6)

Material	k Cycles 980 N (500 min^{-1})	980 N (1000 min^{-1})
MoS_2	50	< 10
Graphite	< 10	< 5
$Sb(SbS_4)$	--	--
MoS_2 + $Sb(SbS_4)$	140	40
Graphite + $Sb(SbS_4)$	20	10
MoS_2 + Graphite	200	75
MoS_2 + Graphite + $Sb(SbS_4)$	500	100
Bonded Solid Lubricant	200	50

TABLE 6. STABLE FRICTION COEFFICIENT (REFERENCE 6)

		Lubricant			
Load N	Speed min^{-1}	Graphite	CSb-B	MoS_2	MSb-B
245	500	none	0.14-0.15	0.03-0.05	0.02-0.04
980	500	none	none	0.05	0.01-0.03
1470	500	none	none	none	none

TABLE 7. EXPERIMENTAL CONDITIONS FOR DATA IN TABLES 5 AND 6 (REFERENCE 6)

<u>Ring</u>	
outer diameter:	0.47 mm
material:	100 CrMn6 steel
hardness:	HRC 60
roughness of surface after sandblasting:	12 μm CLA
<u>Block</u>	
dimensions:	24 x 15 x 6
material:	90 MnCrV8 steel
hardness:	HRC 54
roughness of surface:	1.6 μm CLA

TABLE 8. WEAR TEST RESULTS FOR MoS_2 FILMS (500 - 1000 nm THICK) FROM DIFFERENT LABORATORIES (REFERENCE 25)

Wear Life, Thousands of Revolutions		
Pin-On-Disk	**Dual-Rub-Shoe**	**Thrust-Washer**
201	19[a]	600-700
—	55[c]	800
156	60[b]	300
45	35 K[a]	900

[a]Tested in air; [b]Air or vacuum; [c]Vacuum

Fleischauer[25] is doing extensive work in evaluation of solid films, especially MoS_2 formulations. Table 8 summarizes the wear lives obtained with three different contact conditions. The pin-on-disk tests were run at a load of 700 MPa. The results have shown that the wear life can be increased significantly if the MoS_2 is doped with antimony. Again, a wear life of 10^5 cycles is shown to be possible.

Rolling Contact

A critical aspect pertaining to bearing performance is the friction at the ball race interface where the ball rolls and spins against the races. Several traction experiments were conducted at Battelle by Tevaarwerk using a twin disk apparatus to evaluate the friction (traction) at this interface. The experiments involved loading a 52-mm sphere into contact with a rotating 100-mm cylinder. The sphere is skewed relative to the cylinder and the side-slip force is measured. This force can be related to traction. Figure 1 shows a compilation of the data obtained for four loadings (20, 40, 60, and 80 kg) and two lubrication conditions (dry and MoS_2-coated). The coating was about 0.5 micrometers thick. The maximum traction coefficient (L_T) for the dry contact was about 0.5. Whereas for tests with coated spheres the maximum coefficient ranged from 0.1 to approximately 0.2. The slope of the traction curve near zero slip was about the same for all tests.

Under some conditions friction in rolling contact can be lower with solid films than with grease lubrication. Todd and Bentall[14] present data (Figure 2) that illustrate this effect. Table 9 summarizes data for solid lubricated ball bearings. In some ball bearings, it is possible to extend the coating life by using transfer film technology[19,21]. In this technology the solid film is transferred from the bearing cage to the ball and races. The cage in essence is then the lubricant supply. Transfer film technology represents a good approach for extending the life of space bearings beyond that attained with solid lubricant coatings.

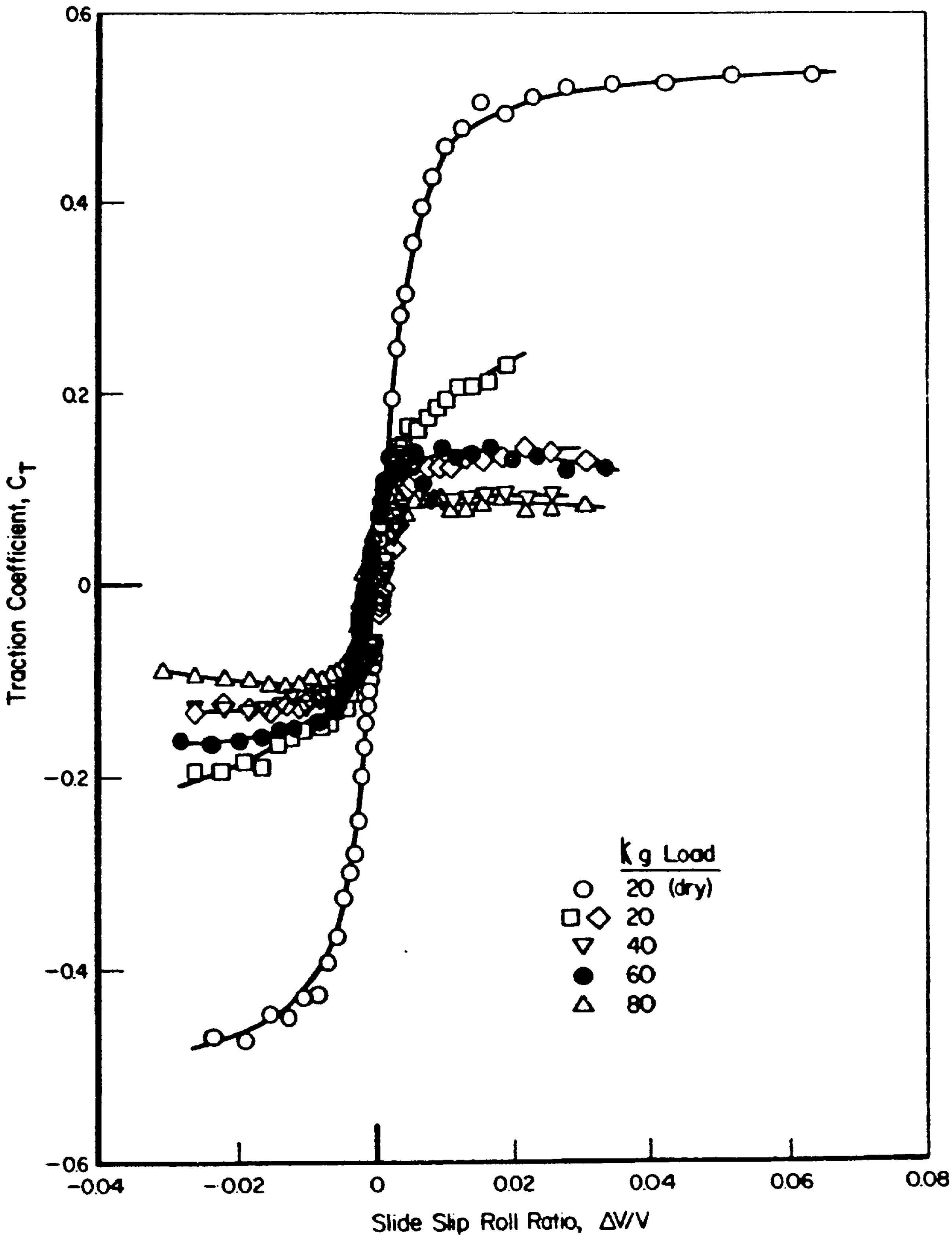

FIGURE 1. TRACTION BETWEEN ROLLING/SLIDING CYLINDERS

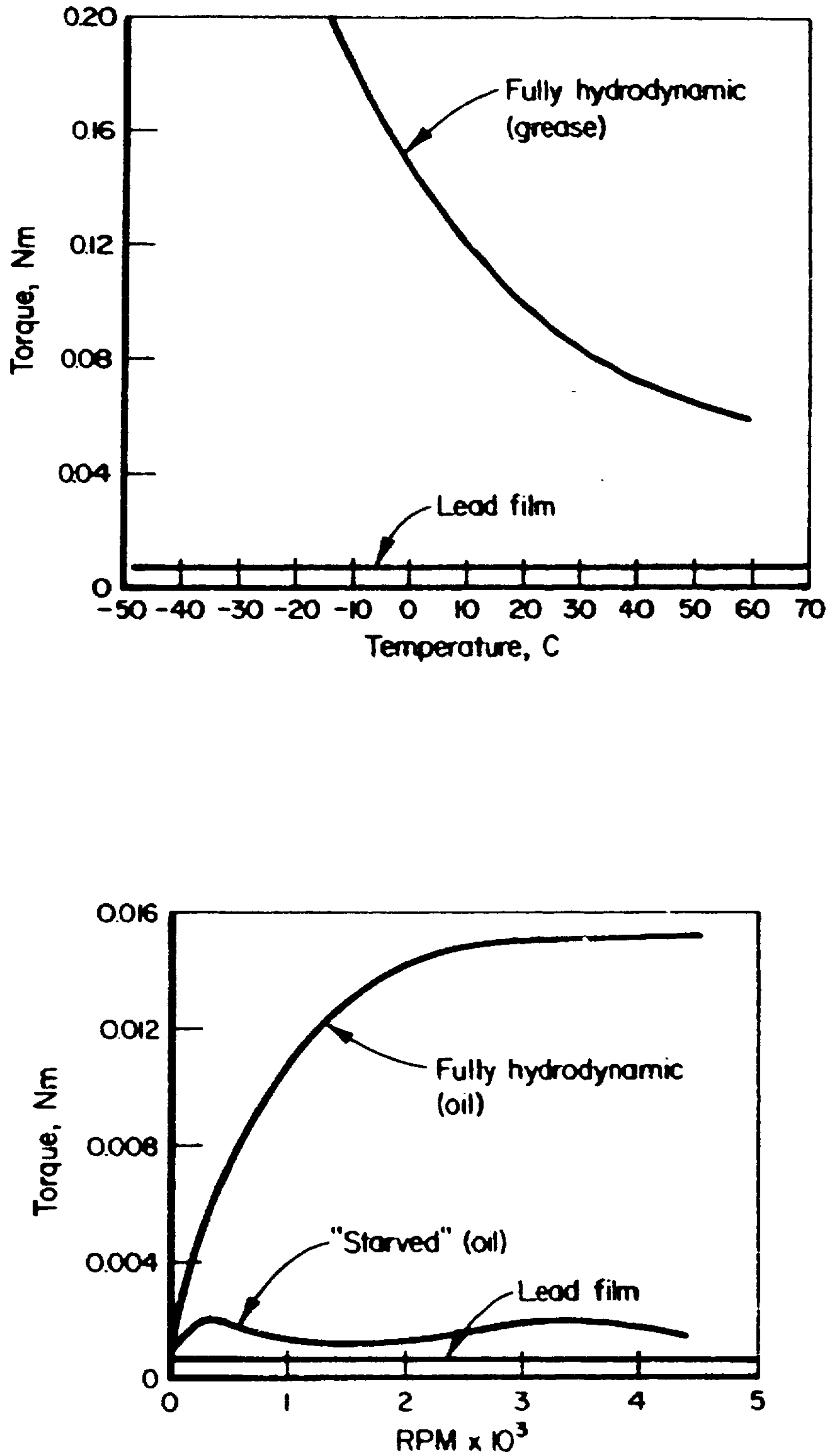

FIGURE 2. COMPARISON OF BALL BEARING OPERATING TORQUES SHOWING THAT SOLID FILM LUBRICATION CAN PRODUCE LOWER TORQUES THAN OBTAINED WITH LIQUIDS (REFERENCE 14)

TABLE 9. TORQUE BEHAVIOR OF SOLID LUBRICATED BALL BEARINGS (REFERENCE 14)

Method of Lubrication	Preload (N)	Cumulative time at 100 rpm (min)	Torque (N-m x 10^{-4}) to oscillation		Remarks
			Average (±)	Peak-Peak	
PTFE/MoS_2/ glass fiber cage, degreased races and balls	40	0 30 60	21 25 57	76 98 147	Progressive torque increase
MoS_2-coated raceways, Phenolic cage	100	0 5 15 30 60 74	34.5 31.5 42 45 39 failed by excess torque	148 156 246 282 168	Smooth start } trace } developing } spikes
IP lead on raceways, lead bronze cage	100	0 5 15 35 60 240	50 45 45 45 45 failed by excess torque	320 132 120 135 180	Spikes during run-in } very smooth } stable } torque traces

LIQUID/GREASE LUBRICATION

Advantages and Disadvantages

The primary advantage obtained with liquid lubricants is that bearing surfaces separated by hydrodynamic films of liquid lubricants have virtually no wear and thereby have the potential for indefinite lives. Liquid lubricants provide the viscosity needed for forming the hydrodynamic films, low shear strengths for low friction, cooling capability in recirculating systems, and the ability to minimize wear in low-speed (non-hydrodynamic) situations. Since no single lubricant can meet the often conflicting requirements of various applications for liquids, hundreds of specialty lubricants have been developed for aerospace applications[1]. The primary disadvantages of liquid lubricants are the need for containment, the propensity to creep, large changes in viscosity with temperature, and loss by evaporation under vacuum conditions. The use of thickeners to form greases provides a means of retaining the liquids in the needed region, thereby addressing one of the primary disadvantages. Greases are widely used for aerospace lubricants. The loss by evaporation greatly restricts the available liquids for vacuum applications to the few chemical species having low vapor pressures. The following sections consider the evaporation rates and the lubricating performance of liquids (and greases based on these liquids) in bearing applications.

Thermo-Vacuum Evaporation

The evaporation rate of lubricants in a vacuum is a function of their molecular weight, their vapor pressure, and the temperature. The Langmiur expression[28] relates these factors and permits predicting the loss rate when the vapor pressure and temperature are known:

$$R_{evap} = \frac{P}{17.14} \sqrt{\frac{M}{T}}$$

where,

P = vapor pressure (mm of Hg),

M = molecular weight, and

T = temperature of lubricant (°K).

The vapor pressure is strongly dependent on temperature, as shown for a perfluoro ether in Figure 3[22]. Perfluoro ethers are among the fluids having the lowest vapor pressures and are leading candidates for satellite applications exposed to vacuum. At the top of Figure 3 is the time predicted to evaporate a film 2.5 x 10^{-4} cm (100 microinches) thick in accordance with the Langmiur expression. With this strong temperature dependence, two conclusions are drawn:

1. The temperature of lubricant films exposed to vacuum must be controlled to retain the lubricant.

2. Provisions must be made for the reapplication of lubricant if temperature cannot be controlled to acceptable levels.

The chemical composition of a lubricant and its molecular weight are the dominating factors in determining the resulting vapor pressures and loss rates. For vacuum applications, silicones and perfluoro ethers have lower loss rates by 4 to 5 orders of magnitude compared with mineral oils (hydrocarbons) or diesters[29]. On the basis of loss rates by evaporation, the selection of lubricants is limited to the perfluoro ethers or silicones -- both from the standpoint of retaining the lubricant on the bearing surfaces where they are needed and of preventing contamination of optical systems by condensation of the evaporated lubricant. Table 10 presents properties of typical lubricants for space applications and Table 11 presents properties of typical greases[30]. As discussed in the next section, the wear performance of the various lubricants combined with the creep behavior of silicones further limits the practical choice to the perfluoro ether fluids.

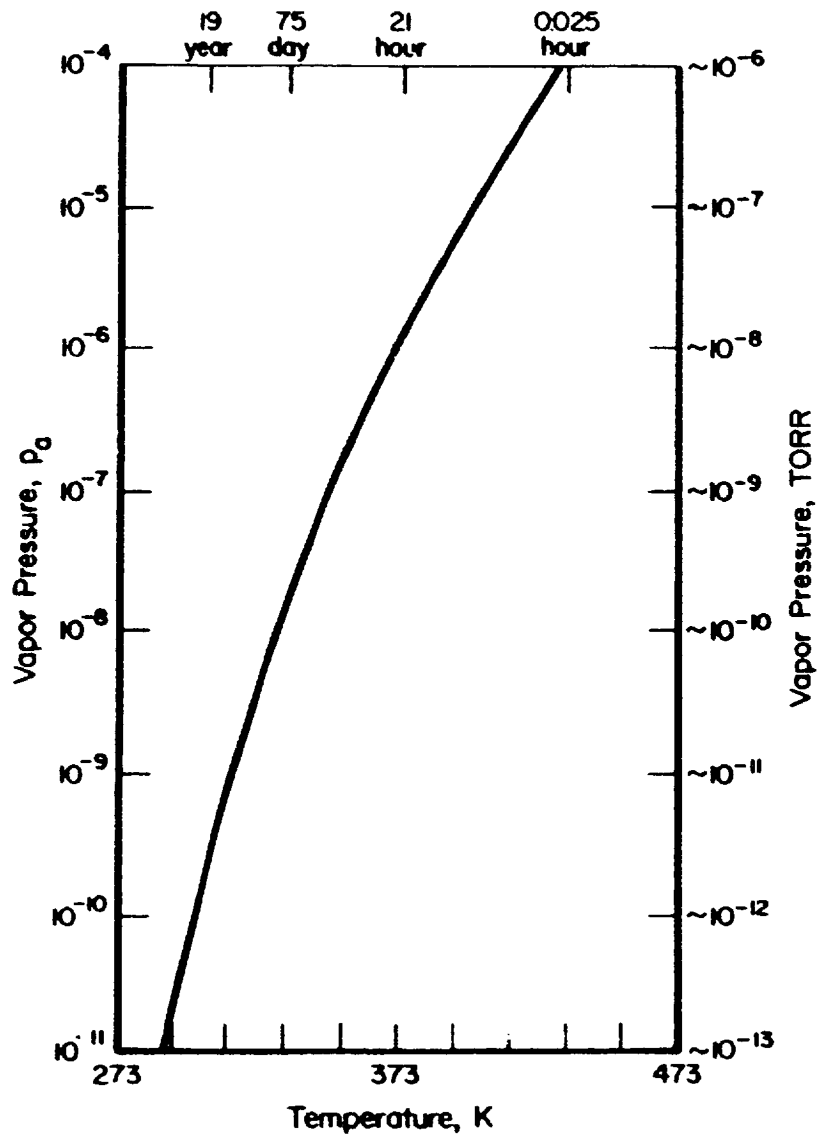

FIGURE 3. DEPENDENCE OF VAPOR PRESSURE ON TEMPERATURE FOR A PERFLUORO ETHER LUBRICANT (REFERENCE 22)

Friction and Wear Performance

Among the many properties provided by liquid lubricants for bearing applications, the ability to generate hydrodynamic films to separate the surfaces in relative motion and the ability to maintain low wear rates if the operating conditions prevent film formation are two of the most important properties. Film formation capabilities are largely determined by the viscosity, which is generally high in fluids selected to have low evaporation rates. Therefore, the ability to lubricate under very thin film (boundary) conditions is the performance property of interest.

Table 12 presents a summary of comparison data obtained from LFW-1 ring-on block tests with various lubricants and Type 440C rings and blocks(31). Of particular interest is the performance of the perfluoro ether (Krytox 143AB oil and Krytox 240AB grease) relative to the silicones, mineral oil, and diesters. No instances of galling were observed with the perfluoro ethers, but several instances of galling were encountered with the silicones, diesters, and mineral oils. Although the lowest wear was measured with the FS1265 silicones, its viscosity was also the highest, which may have influenced the results. The wear with the perfluoro ether was less than that measured with the mineral oils and was considered acceptable since no instances of galling occurred. As shown in Table 13, similar results were obtained in slow-speed sliding tests using a ball-on-flat geometry(32). The perfluoro ether (Fomblin Z25) had a friction coefficient tying the lowest of the five and a specific wear rate only slightly higher than the lowest recorded (a mineral oil with boundary lubricant additives). Based on friction and wear results such as these, a much lower propensity to creep, and satisfactory flight experience, the perfluoro ethers have displaced the silicones in spacecraft applications(33).

TABLE 10. PROPERTIES OF SOME COMMONLY USED SPACE LUBRICANTS (REFERENCE 30)

Type of Lubricant	Ave Molecular Weight	Viscosity at 20°C, cS	Viscosity Index	Pour Point, °C	Vapor Press. Torr, at 20°C	Vapor Press. Torr, at 100°C
KG 80, Mineral Oil	---	520	101	-9	$<1 \times 10^{-8}$	---
Apiezon C, Mineral Oil	574	250	---	-15	3.5×10^{-9}	---
BP 110, Mineral Oil	---	120	108	-24	4×10^{-8}	---
BP 135, Ester	---	55	128	-45	8×10^{-9}	---
NYE 179, PAO	---	30 (40°C)	139	< -60	6.6×10^{-9}	---
NYE UC7, Neopentyl - Polyolester	---	75	---	-56	5.1×10^{-9}	---
NYE UC4, Neopentyl - Polyolester	---	44	---	---	2.1×10^{-8}	---
SiHC[1], Silahydrocarbon	1480	278	125	-50	---	---
SiHC[2], Silahydrocarbon	1704	480	128	-15	---	---
Fomblin, PFPE (Bray 815Z)	9500	255	355	-66	2.9×10^{-12}	1×10^{-8}
Krytox, PFPE	11,000	2717	---	-15	3×10^{-14}	1×10^{-9}
Demnum, PFPE	8400	500 ± 25	210	-53	5×10^{-11}	1×10^{-7}

TABLE 11. COMMONLY USED GREASES FOR VACUUM APPLICATIONS (REFERENCE 30)

Type of Grease	Base Oil	Thickener	Additives
BP 2110	BP 110	---	Lead, Graphite
BP 8135	BP 135	---	Lead, Graphite
G-300	Methyl chlorophenyl polysiloxane	Lithium Stearate	---
APIEZON	Hydrocarbon	PTFE	---
BRAYCOTE 3L-38RP	Fomblin Z25	PTFE	---
MICRONIC 803	PFPE	PTFE	---
VAC KOTE	Synthetic oils	Nonmelting	Various
M-8	Hydrocarbon	none	---
ES (MIL-G-25-760A)	Diester	---	---
Si-6 (Bray 815Z)	Silicone	Li Soap	---
FS-1	Fluorosilicone	Silica	---
PFPE-1	PFPE	PFTE	---
PFPE-2	PFPE	Li Soap	---
KRYTOX, 250AC, 260AC, 280AC	Krytox	PTFE	MoS_2, Rust Inhibitors

TABLE 12. COMPARISON OF VARIOUS LUBRICANTS BASED ON WEAR OF TYPE 440C BLOCKS IN LFW-1 RING-ON-BLOCK TESTS (FROM REFERENCE 31)

Common Name	Type	Viscosity (cs at °C)	Revs (K)[a]	Scar Width (mm)
Versilube F50	Methylchlorophenylsilicone	52/38	10.4[b]	1.52[b]
FS1265	Fluorosilicone	300/25	$> 1 \times 10^3$	0.76
SF1147	Methylalkylpolysiloxane	49/25	30.8[b]	1.52[b]
SRG40	Mineral	27/38	$> 1 \times 10^3$	2.03
Krytox143AB	Perfluoralkylpolyether	85/38	$> 1 \times 10^3$	1.78
L245-x	Diester	20/25	2.1[b]	0.76[b]
P-10	Diester + 5% TCP	15/38	$> 1 \times 10^3$	1.27
Andok-C	Mineral Oil Grease	--	40.8[b]	1.27[b]
Krytox 240AB	Perfluoroalkylpolyether Grease	--	$> 1 \times 10^3$	1.27

a. Revolutions to reach friction coefficient of 0.33 at 667N (150 lb) load, in thousands.
b. Test terminated because of galling; scar width at time of galling

TABLE 13. FRICTION AND WEAR RESULTS WITH EN31 STEEL BALLS SLIDING ON EN31 STEEL DISKS IN PRESENCE OF FIVE DIFFERENT LUBRICANTS (REFERENCE 32)

Lubricant	Vapor Pressure at 20° C (torr)	Description and Comments	Mean Friction Coefficient	Specific Wear Rate ($m^3/Nm \times 10^{-15}$)
Apiezon C	4×10^{-9}	Mineral oil with no additives. Used as a reference oil	0.20	0.93
BP 135	7.9×10^{-9}	Synthetic, tri-ester base. Boundary lubricant and anti-oxidant additives.	0.12	1.04
BP 110	3.7×10^{-8}	Mineral oil base, high viscosity. Refined to give low vapor pressure. Boundary lubricant additives.	0.13	0.41
KG80	$< 10^{-8}$	Petroleum base with boundary lubricant additive, Tricresyl-phosphate. Also anti-oxidant.	0.13	0.69
Fomblin Z25	$< 5 \times 10^{-12}$	Synthetic fluorinated oil. High density, low surface tension. High temperature/viscosity index. No boundary lubricant additives.	0.12	0.49

Notes:
1. EN31 is equivalent to 52100 steel.
2. Total load on three balls was 4N.
3. Sliding speed was 3×10^{-3} m/s.

Besides the Krytox and Fomblin fluids, the Bray Oil Co. has produced a series of lubricants by further distilling and refining the Fomblin fluid base stock to produce Bray 815Z oil and 3L38RP grease, which have had flight experience in spacecraft mechanisms. The products are now available through the Bray Products Division of Burmah-Castrol, Inc. Braycote 601 is the new designation for the 3L38RP grease.

ATOMIC OXYGEN

Published data have shown that at altitudes between 200 and 650 km, the atmosphere is primarily atomic oxygen, see Figure 4. According to Ledger and Visentine, "Interactions between spacecraft surfaces and high-velocity (~ 8 km/s) oxygen atoms within the low earth orbit environment produce significant changes in surface properties of many materials". Ledger[22,36] presents reaction efficiency for composite polymers and organic films (Table 14). The data were taken from experiments performed on Space Shuttle flights STS-S (100 km altitude) and STS-8 (225 km altitude). Effects of atomic oxygen and material recession have also been evaluated by others[34,35].

For unfilled organic materials surface recession was on the order of 1.8×10^{-4} cm for STS-5 specimens and 1.2×10^{-3} cm for STS-8 specimens. The total fluence (over 40 hours) was about 1×10^{20} (STS-5) and 3.5×10^{20} (STS-8). The general comments by Ledger and Visentine are:

1. Materials containing only carbon (C), hydrogen (H), oxygen (0), or nitrogen (N) have high reaction rates in the range of 2.5×10^{-24} to 3.0×10^{-24} cm^3/atom.

2. Perfluorinated and silicone polymers are more stable than the organics by at least a factor of 50.

3. The reaction rates for filled organic materials are dependent on the oxidative stability of the fillers. For example, materials filled with metal oxides have lower reaction rates than those filled with carbon.

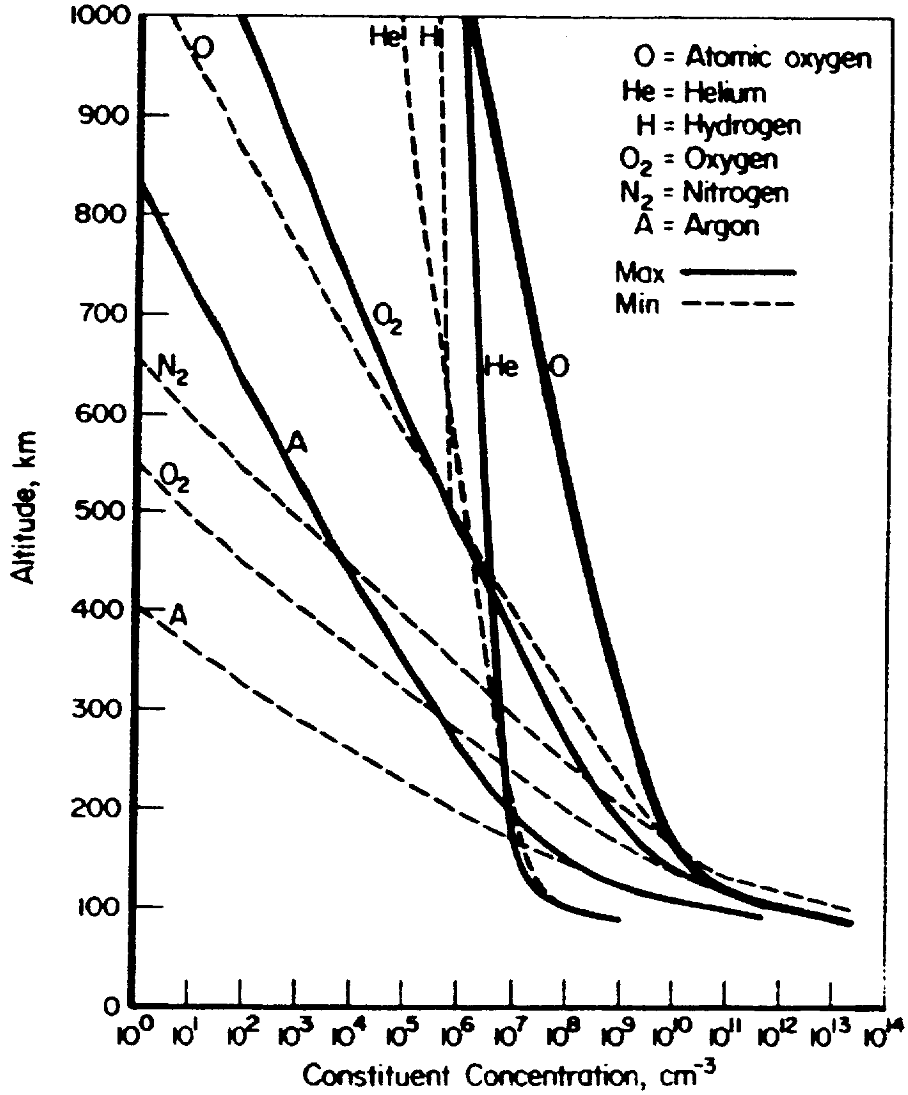

FIGURE 4. ATMOSPHERIC COMPONENTS (REFERENCE 22)

TABLE 14. REACTION EFFICIENCIES OF SELECTED MATERIALS WITH ATOMIC OXYGEN IN LOW EARTH ORBIT (REFERENCE 22)

Material	Reaction Efficiency, 10^{-24} cm^3/atom
Kapton	3
Mylar	3.4
Tedlar	3.2
Polyethylene	3.7
Polyimide	3.3
Polymethylmethacrylate	3.1
Polysulfone	2.4
Graphite/epoxy	
1034C	2.1
5208/T300	2.6
Epoxy	1.7
Silicones	< 0.02*
White paint A276	0.3 to 0.4*
Black paint Z302	2.3*
Perfluorinated polymers	
Teflon, TFE	< 0.05
Teflon, FEP	< 0.05
Carbon (various forms)	0.9 to 1.7
Silver (various forms)	Heavily attacked

*Units of mg/cm^2 for STS-8 mission. Loss is assumed to occur in early part of exposure; therefore, no assessment of efficiency can be made.

4. From a macroscopic standpoint, metals, except for osmium and silver, are stable. Metals such as copper do form oxides, but at lower rates than for osmium and silver.

Because of the reactions with organic materials, liquid lubricants and dry film lubricants having organic binders must be protected from exposure or selected with a knowledge that continual degradation will occur. In the case of thin solid films using an epoxy-based binder, exposure to atomic oxygen may degrade the binder in a matter of days(22). For practical systems requiring exposure, therefore, inorganic binders, such as silicates, may be required to avoid the problem.

If a spacecraft is to operate for 30 years and typical lubricated surfaces are on the order of 1 micrometer thick, the sputtering effect of atomic oxygen must be negated. Fortunately, while surface erosion due to sputtering may degrade the ram facing exterior structure it does not appear that this is a viable mechanism for degrading solid lubricants in bearing assemblies. For surface erosion to occur as a result of sputtering by atomic oxygen in a Low Earth Orbit (LEO), a direct (geometrically linear) path from the space environment to the solid lubricant must be available. Because the atomic oxygen has energies on the order of only a few eV, surface recession or erosion is the result of a low energy sputtering process. Low energy sputtering should only affect materials with very low atomic or molecular bonding energies and in any case would produce material loss by primary (i.e., surface) collisions only. To produce secondary atomic collisions or an atomic collision cascade that could affect more than just the exposed surface, energies in excess of 20 keV for most solids are required.

However oxidation of the solid lubricant as a result of exposure to atomic oxygen in an LEO may provide a viable mechanism for degradation. The collection of atomic oxygen due to orbital motion may channel an adequate oxygen atmosphere to the unsealed bearing and thereby preclude the assumption of a vacuum environment. Furthermore, the ambient temperatures at LEO altitudes range between 627 to 927 C and the surface temperatures of the spacecraft range between -73 to 127 C(35, pg. 596) so that thermally activated oxidation becomes a possibility.

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