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Lubrication for Space Applications

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1.0 INTRODUCTION

Space tribology is a subset of the lubrication field dealing with reliable satellite and spacecraft performance. It encompasses the entire gamut of tribological regimes, including elastohydrodynamic lubrication (EHL), parched EHL, transient EHL, boundary lubrication, and mixed lubrication.

Historically, choices of space mechanism lubricants were based on space heritage rather than on the latest technology or best available materials. With the limited mission lives and minimal duty cycles of the early space program, this strategy was highly successful. As missions extended, other spacecraft components, such as electronics, batteries, and computers, failed before lubricated mechanisms [1]; however, during the 1980s and 90s, these ancillary components vastly improved and tribological systems have become one main factor limiting spacecraft reliability and performance. Although tribological components represent only a small fraction of the spacecraft's cost, they are often single point failures that cripple or debilitate expensive spacecraft.

The Galileo spacecraft is a classic example of single point tribological failure affecting the entire mission. The Space Shuttle Atlantis launched Galileo in 1989, starting a six-year journey to Jupiter. A high gain antenna, used to transmit control and telemetry data to earth, was one of the craft’s most important components. The umbrella shaped antenna was stowed closed behind a sun shield. In 1991, after the craft’s pass near the sun, the antenna was deployed; however, it only partially opened. Engineers concluded three of the 18 ribs in the antenna’s umbrella-like structure were stuck in place. Ground based tests [2] showed titanium alignment pins, which had been lubricated with a bonded dry film lubricant, had galled and subsequently seized due to lack of lubricant, causing the antenna failure. In this case, engineers salvaged the mission using the low gain antenna combined with data transmission advancements.

This chapter will discuss the following: basic lubrication ideas that play a major role in space mechanisms, space lubricant types, details of the most common space lubricants, mechanism components, testing and test facilities, and factors affecting lubricant selections.

2.0 LUBRICATION REGIMES

Lubrication separates surfaces in relative motion by interposing a third body that has low shear resistance, thus preventing serious surface damage or wear. The third body can be a variety of different materials; including adsorbed gases, reaction films, and liquid or solid lubricants.

2.1 Hydrodynamic, EHL, Mixed, and Boundary Lubrication

Depending on the third body type and thickness, several different lubrication regimes can be identified and are depicted in the Stribeck curve (Figure 1). Stribeck performed a series of journal bearing experiments in the early 1900's measuring friction coefficients as a function of load, speed, and temperature [3]. Later, Hersey performed similar experiments and devised a plotting format based on a dimensionless parameter, ZN/P [4]. The Stribeck/Hersey curve plots friction coefficient as a function of viscosity (Z), velocity (N), and load (P).

When the ZN/P value is high, surfaces are completely separated by a thick (>0.25 μm) lubricant film, which occurs at high speeds, high viscosities, and/or low loads. In this region, termed hydrodynamic lubrication, lubricant rheology determines the friction. As the ZN/P parameter decreases, the lubrication regime changes from hydrodynamic to elastohydrodynamic, then to mixed, and finally to boundary. The elastohydrodynamic lubrication (EHL) regime occurs in non-conformal, concentrated contacts where high

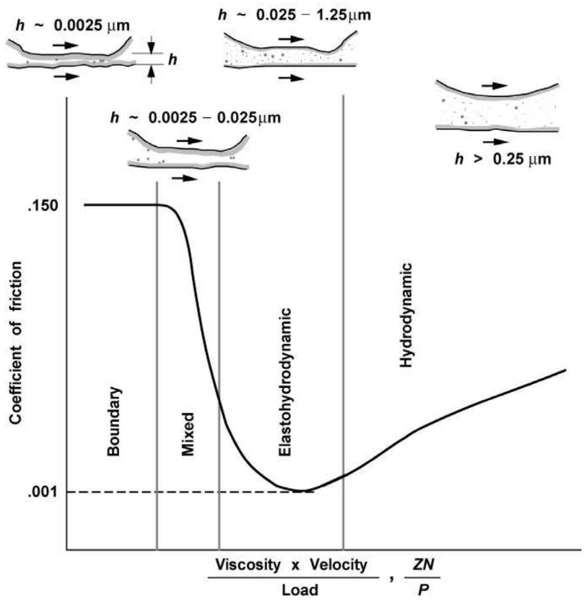

Figure 1 – Coefficient of friction as a function of viscosity velocity-load parameter [3]

loads cause surfaces to elastically deform and pressure-viscosity effects to occur in the lubricant. Film thickness in this regime ranges from 0.025 to 1.250 μm. As ZN/P continues to decrease, film thickness also decreases and surface interactions start taking place. This regime, where both surface interactions and fluid film effects occur, is referred to as the mixed regime. Finally, at low ZN/P values, the boundary lubrication regime is entered, where surface interactions are the primary factor determining friction coefficient and wear rate.

The boundary lubrication regime is a highly complex arena; involving metallurgy, surface topography, physical and chemical adsorption, corrosion, catalysis, and reaction kinetics [5, 6]. Formation of protective surface films, which minimize wear and surface damage, is the regime's most important characteristic. Typically, space mechanisms operate in the EHL, mixed, or boundary lubrication regimes, with the boundary lubrication regime being the most severe.

2.2 Factors Influencing Boundary Film Formation

Both lubricant and bearing surface chemistry govern film formation. Additional environmental factors, such as temperature, also influence the lubricant's film forming ability. The lubricant's physical properties determine the film's effectiveness at minimizing wear. Properties affecting film formation include shear strength, thickness, surface adhesion, film cohesion, melting point or decomposition temperature, and bulk lubricant solubility.

2.2.1 Starved EHL

An EHL subdivision, starved EHL, describes the situation occurring in ball bearings having a restricted oil supply, where pressure build-up in the contact inlet region is inhibited, resulting in a thinner film thickness than calculated by classical EHL theory [7, 8]. Starvation theory was first described by Wedeven [9] in the early 1970s.

2.2.2 Parched EHL

In many space mechanisms, instrument bearings are lubricated with a minimal amount of oil. When no free bulk oil is available to form a meniscus, starvation theory cannot adequately describe lubricant behavior. Another EHL subdivision, parched elastohydrodynamics, describes this behavior [10, 11]. Lubricant films in this regime are so thin that they are immobile outside the Hertzian contact zone. This regime is particularly important for space mechanisms because parched EHL bearings require the least driving torque and have the most precisely defined spin axis, making them an ideal choice for many applications.

2.2.3 Transient/Non-Steady State EHL

For space mechanisms, transient or non-steady state behavior is another important EHL area. In this area, load, speed, and contact geometry are not constant over time. Unlike steady state EHL behavior, non-steady state behavior is not well understood; however, many practical machine elements, including rolling element bearings, gears, cams, and traction drives, operate under non-steady state conditions. In particular, stepper motors, commonly used in many space mechanisms, operate in this state. This regime has been studied theoretically for line contacts [12 - 14] and experimentally for point contacts [15, 16].

3.0 LIQUID LUBRICANTS

For space applications, designers use both liquid and solid lubricants. Both have merits and deficiencies, which appear in Table 1 [17].

Table 1 - Relative merits of solid & liquid space lubricants [17]

Dry Lubricants	Wet Lubricants
Negligible vapor pressure	Finite vapor pressure
Wide operating temperature	Viscosity, creep and vapor pressure all temperature dependent
Negligible surface migration	Sealing required
Valid accelerated testing	Invalid accelerated testing
Short life in moist 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

3.1 Types of Liquid Lubricants

In the last three decades, space applications have used many different liquid lubricants, including mineral oils, silicones, esters, and perfluoropolyethers (PFPE). More recently, a synthetic hydrocarbon (Pennzane®) has been replacing many older lubricants. Each lubricant type will be discussed briefly; however, since the majority of current spacecraft use either a formulated Pennzane® or one of the PFPE lubricants, these two classes will be discussed in detail.

3.1.1 Mineral Oils

This lubricant class consists of a complex mixture of naturally occurring hydrocarbons with a wide range of molecular weights. Examples include V-78, BP 110, Apiezon C, Andok C (Coray 100) [18], and the SRG series of super refined mineral oils, including KG-80 [19]. The super refined fluids have been highly processed to remove polar impurities, either by hydrogenation or percolation through bauxite. Refining makes them poorer neat lubricants, but greatly improves additive response. While Apiezon C is still commercially available, production of all others was discontinued many years ago. Nevertheless, some companies have stockpiled SRG oils and still use them to lubricate momentum and reaction wheel bearings. SRG oils have an estimated shelf life in excess of 20 years [19].

3.1.2 Esters

Esters, which are available in a wide viscosity range, are inherently good boundary lubricants. In the 1970s, British Petroleum developed a triester base lubricant, which was laboratory tested but production stopped before it flew in space. Another ester, NPT-4 (neopentylpolyol ester), has been used in the past, but is no longer produced. Nye Lubricants also markets a series of low volatility neopentylpolyol esters (UC_4, UC_7, and UC_9).

3.1.3 Silicones

This fluid class was used early in the space program; however, silicones are poor boundary lubricants for steel on steel systems. Boundary lubrication comparisons of this fluid with a PFPE and a PAO have been reported [20] and Figure 2 shows relative lifetimes. Silicone performed poorly, degrading into an abrasive, polymerized product. Versilube F-50, a chloroarylalkylsiloxane, is an early example of this lubricant class.

3.1.4 Synthetic Hydrocarbons

Two synthetic hydrocarbon groups are available today: polyalphaolefins (PAO) and multiply alkylated cyclopentanes (MACs).

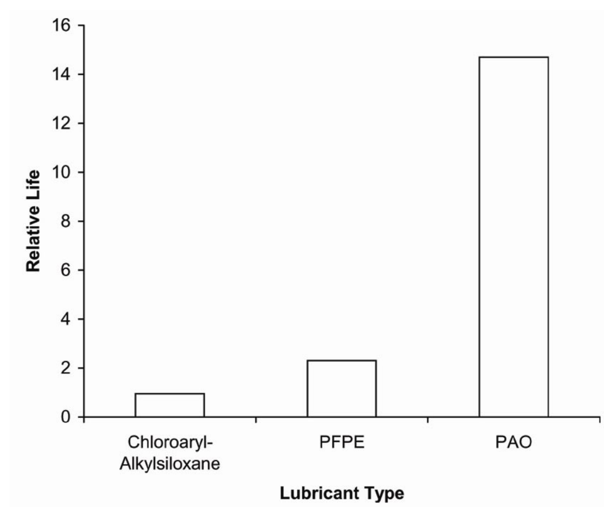

Figure 2 – Screening test results (scanner and mechanism) [132]

3.1.4.1 Polyalphaolefin (PAO)

Polyalphaolefins are made by the oligomerization of linear α-olefins having six or more carbon atoms [21]. (Shubkin, p 1-40) Nye Lubricants markets a number of PAOs for space applications and properties for three commercial PAOs appear in Table 2. A new synthetic hydrocarbon based on PAO chemistry has been developed [22].

3.1.4.2 Multiply Alkylated Cyclopentanes

Multiply alkylated cyclopentanes (MACs) make up the second hydrocarbon class. These materials are synthesized by reacting cyclopentadiene with various alcohols in the presence of a strong base [23, 24]. The reaction products are hydrogenated to produce the final product, which is a mixture of di-, tri-, tetra- or penta- alkylated cyclopentanes. Varying reaction conditions controls the distribution. Originally, only one product, known as Pennzane® SHF-X2000 or Nye Synthetic Oil 2001A, was available for space applications, and is primarily the tri-2-octyldodecyl substituted cyclopentane [23]; however, Pennzane® SHF-X1000, a lower viscosity, higher volatility version is now available [25]. SHF-X1000 is primarily a di-substituted cyclopentane. A variety of formulated versions for both oils are also available. Properties of SHF-X1000 and SHF-X2000 appear in Table 3.

Recent experience with SHF-X2000 appears in Carré et al. [26]. A six-year life-test of a CERES elevation bearing assembly using a Pennzane®/lead naphthenate formulation yielded excellent results [27]. Additional life test data for another Pennzane®/lead naphthenate formulation for the MODIS instrument appears in VanDyk et al. [28].

Table 2 - Typical properties for three commercial polyalphaolefins

		OIL 132	OIL 182	OIL 186
Viscosity At:	210°F, SUS	39	62.5	79.5
	210°F, cs	3.9	10.9	15.4
	100°F, SUS	92	348	552
	100°F, cs	18.7	75.0	119
	0°F, cs	350	2700	7600
	Flash Point	440°F	465°F	480°F
	Pour Point	-85°F	-60°F	-55°F
Evaporation 6½ Hours at 350°F		2.2%	2.0%	1.9%
Specific Gravity @ 25°C		0.828	0.842	0.847

<ins>*3.1.5 Perfluoropolyethers (PFPE)*</ins>

These fluids, which are designated as either PFPE or PFPAE, have been commercially available since the 1960s and 70s in the form of a branched fluid (Krytox™) manufactured by DuPont [29], a linear fluid (Fomblin™ Z) (a similar product marketed as Brayco™ 815Z) [30], and a branched fluid (Fomblin™ Y) [31], both manufactured by Solvay Solexis. In Japan, Daikin [32] developed another linear fluid (Demnum™). Preparation and properties of these fluids appear in <ins>Synthetic Lubricants and High-Performance Functional Fluids</ins> [33]. Some typical lubricant properties appear in Table 4. PFPE fluid's high density, nearly twice that of non-PFPE fluids, is an advantage for EHL lubrication. For similar kinematic viscosities, PFPE fluids will yield almost twice the EHL film thicknesses compared to conventional fluids [34].

Table 3 - Typical properties of two Pennzane® Fluids

Property	SHF X-1000	SHF X-2000
Viscosity at 100°C (cSt)	9.4	14.6
Viscosity at 40°C (cSt)	60	108
Viscosity at –40°C (cSt)	N/A	80,500
Viscosity Index	131	137
Flash Point (°C)	290	300
Fire Point (°C)	N/A	330
Pour Point (°C)	-52	-55
Specific Gravity at 25°C	0.85	0.85
Coefficient of Thermal Expansion (cc/cc/°C)	N/A	0.0008
Total Weight Loss, 24h, 125°C, 10^{-5} Torr	<0.4%	<0.2%
Refractive Index at 20°C	1.4682	1.4671
Vapor Pressure at 125°C (Torr)	$6x10^{-8}$	$4x10^{-7}$

Table 4 - Physical properties of four commercial PFPE lubricants and Pennzane® SHF X-2000

Lubricant	Average Mol. Weight	Viscosity At 200°C, cSt	Viscosity Index	Pour Point, °C	Vapor Pressure, Pascal	
					20°C	100°C
Fomblin™ Z-25	9500	255	355	-66	$3.9x10^{-10}$	$1.3x10^{-6}$
Krytox™ 143AB	3700	230	113	-40	$2.0x10^{-4}$	$4.0x10^{-2}$
Krytox™ 143AC	6250	800	134	-35	$2.7x10^{-6}$	$1.1x10^{-3}$
Demnum™ S-200	8400	500	210	-53	$1.3x10^{-8}$	$1.3x10^{-5}$
Pennzane® SHF X2000	1000	330	137	-55	$2.2x10^{-11}$	$1.9x10^{-8}$

3.1.5.1 PFPE Formulations

Currently no space applications use liquid PFPEs with additives; although many PFPE soluble additives have been developed in recent years, including anti-wear, anticorrosion, and antirust additives [35-43]. Several different additives exhibited anti-wear behavior in a Krytox™ base stock in vacuum four ball tests (Figure 3) [41].

3.1.6 Silahydrocarbons

Silahydrocarbons, another newer space lubricant, were first introduced by the Air Force Materials Laboratory [44, 45]. These materials contain only silicon, carbon, and hydrogen; thus, do not exhibit the poor boundary lubricating ability seen with silicones, which contain oxygen. Additionally, these unimolecular materials have exceptionally low volatility and are available in a wide range of viscosities. Three silahydrocarbons types are available, based on the number of silicon atoms present in the molecule (i.e. tri, tetra, or penta) [46, 47].

Kinematic viscosities as a function of temperature were measured for a series of synthesized silahydrocarbons (Figure 4) [48]. For comparison, the plot includes Pennzane® SHF-X2000 data. As can be seen, the silahydrocarbon viscosity properties bracket the Pennzane® data. Table 5 lists the EHL properties of two silahydrocarbons [49]. Based on these values, silahydrocarbons will generate thicker EHL films than Pennzane® SHF-X2000 under the same conditions. Tribological properties of several silahydrocarbons appear in Jones et al. [50].

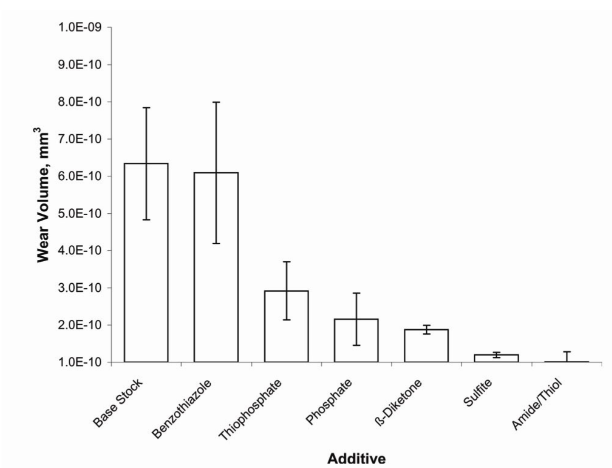

Figure 3 – Anti-wear behavior of several additives in Krytox™ base stock using a vacuum four-ball tribometer

Table 5 - Pressure-viscosity coefficient (GPa^{-1}) (α value) of two silahydrocarbons and Pennzane® [49]

Temp (°C)	Pennzane®	Silahydrocarbon	
		Tri	Penta
21	N/A	16±0.3	17±0.3
30	9.8±0.3	N/A	N/A
40	N/A	11±1	13.5±1

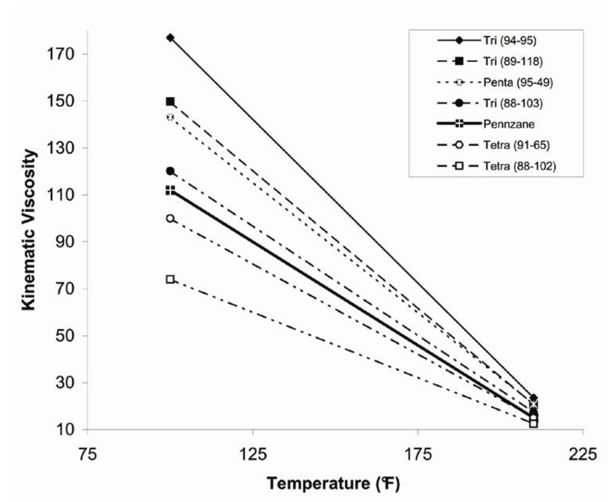

Figure 4 – Kinematic viscosity as a function of temperature for a series of silahydrocarbons [48]

3.2 Liquid Lubricant Properties

Numerous reviews of liquid lubricants for space applications have been published [51-53]. Liquid lubricant data also appears in some handbooks [54-56]. Since most applications today use either PFPEs or Pennzane® (MAC) formulations, these two classes are presented in more detail.

To function properly in a lubricated contact, a liquid lubricant has to possess certain physical and chemical properties. To be considered for space applications, the lubricant must have vacuum stability (i.e. low vapor pressure), low creep tendency, high viscosity index (i.e. wide liquid range), good elastohydrodynamic and boundary lubrication properties, and radiation and atomic oxygen resistance. In some applications, optical or infrared transparency is also important.

3.2.1 Volatility

Although space mechanisms use labyrinth seals extensively, lubricant loss can still be a problem for long-term applications [57]. For a fixed temperature and outlet area, lubricant loss is directly proportional to vapor pressure. Compared to conventional lubricants with similar viscosities, PFPE fluids are particularly good candidates (Figure 5) [58]. Vapor pressure data for four commercial PFPE fluids and Pennzane® SHF-X2000 appear in Table 4. Additional vapor pressure data is found in Nguyen and Jones [59]. A theoretical model to predict evaporative oil losses in spacecraft mechanisms has been reported [60]. Besides base oil volatility, additive volatility must also be addressed [61].

3.2.2 Creep

A liquid lubricant's tendency to creep, or migrate over bearing surfaces, is inversely related to its surface tension. Because PFPE fluids have unusually low surface tensions (γ_{LV}, 17 to 25 dynes/cm at 20°C), they are more prone to creep than conventional fluids such as hydrocarbons, esters, and silicones. Low surface-energy fluorocarbon barrier films, placed on bearing lands, are used to contain PFPE fluids within bearing raceways [62]. However, there is a tendency for PFPE fluids to dissolve the barrier films with prolonged contact [57], rendering them ineffective in preventing PFPE migration. Pennzane® based lubricants have higher surface tensions, thus are less prone to creep and are easier to contain. Sharp corner geometries also will minimize creep losses.

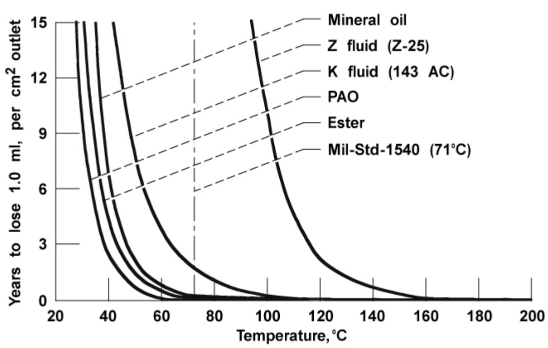

Figure 5 – Relative evaporation rates of aerospace lubricants [58]

3.2.3 Viscosity-Temperature Properties

Historically, liquid lubricated space mechanisms have not been exposed to wide temperature ranges. However, there is a trend for newer mechanisms to operate at lower temperatures (-10° to -40°C); therefore low pour point fluids that retain low vapor pressure and reasonable viscosities at temperatures between -40°C and 75°C are needed.

The viscosity-temperature slope of PFPE, un-branched fluids is directly related to the carbon to oxygen ratio (C/O) in the polymer-repeating unit (Figure 6) [63]. Here, the ASTM slope is used for the correlation. High values of the ASTM slope indicate large viscosity changes with temperature. Additionally, branching, such as the trifluoromethyl pendant group in the Krytox™ fluids, causes deterioration in viscometric properties. Comparison of ASTM slopes for three commercial fluids appears in Figure 7. Here the low C/O ratio fluid Fomblin™ Z has the best viscometric properties. The Demnum™ fluid, with a C/O ratio of three, has intermediate properties, while the branched Krytox™ fluid, has the highest slope.

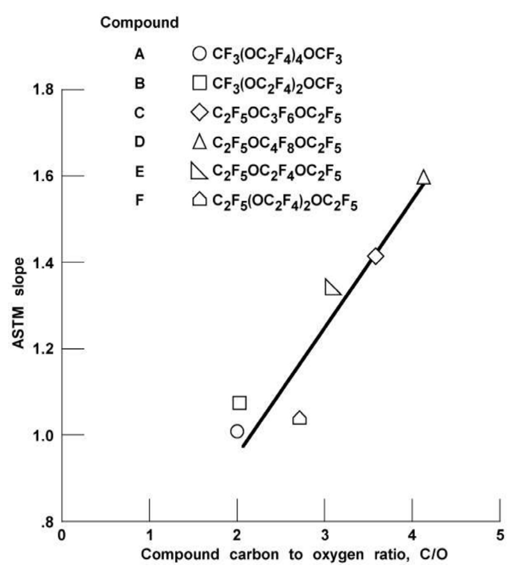

Figure 6 – Viscosity-temperature slope as a function of carbon-to-oxygen ratio [63]

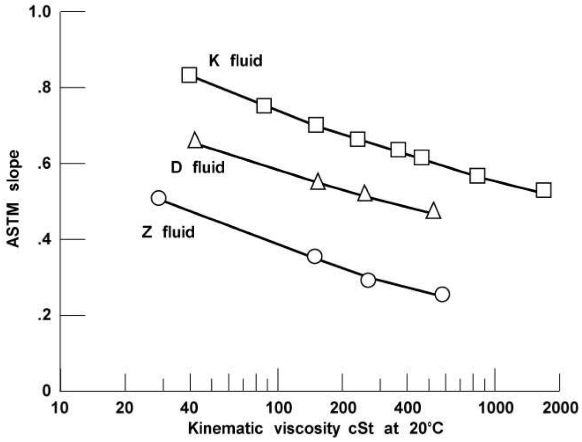

Figure 7 – Viscosity-temperature slope (ASTM D 341-43) as a function of kinematic viscosity at 20°C for Krytox™ (K), Demnum™ (D), and Fomblin™ (Z) fluids [63]

3.2.4 Elastohydrodynamic Properties

Successful operation of continuously rotating, medium to high-speed bearings relies on the formation of an elastohydrodynamic (EHL) film. Section 2.0 briefly discussed this regime and a more detailed discussion appears in [64]. Two lubricant physical properties influence EHL film formation: the absolute viscosity (μ) and the pressure-viscosity coefficient (α) [8].

Viscosity is influenced by molecular weight and chemical structure. Except for low molecular weight fluids, α values are only related to chemical structure [65]. Conventional, high-pressure viscometers [34, 66, 67] can directly measure pressure-viscosity coefficients or they can be measured indirectly by optical EHL experiments [68]. Conventional viscometry normally uses the Barus equation [69] for correlations:

$$\mu_p = \mu_o e^{\alpha p}$$

where:

μ_p absolute viscosity at pressure (p)

μ_o absolute viscosity at atmospheric pressure

α a temperature dependent but pressure independent constant

This implies that a log μ_p vs. p plot should yield a straight line with a slope of α. Unfortunately, this simple relationship is seldom obeyed. The pressure-viscosity properties that are important in determining EHL film thickness occur in the contact inlet, where pressures are much lower than in the Hertzian region. Therefore, the slope of a secant drawn between atmospheric pressure and approximately 0.07 GPa is typically used for film thickness calculations.

Table 6 - Pressure viscosity coefficients at three temperatures α^*, $PA^{-1} x10^8$ for several lubricants [33]

Lubricant	38°C	99°C	149°C
Ester	1.3	1.0	0.85
Synthetic Paraffin	1.8	1.5	1.1
Z Fluid (Z-25)	1.8	1.5	1.3*
Naphthenic Mineral Oil	2.5	1.5	1.3
Traction Fluid	3.1	1.7	0.94
K Fluid (143AB)	4.2	3.2	3.0

* Extrapolated

Some researchers [34] favor using a different pressure-viscosity parameter, the reciprocal asymptotic isoviscous pressure (α^*) based on work by Roelands [70]. Table 6 lists pressure–viscosity coefficients (α^*) for several lubricants at three temperatures (38°, 99°, and 149°C). Additional values of α^* as a function of temperature for Pennzane® X-2000, Nye 186 A and Fomblin™ Z-25 appear in Reference [71].

Figure 8 shows α values for a branched PFPE (Krytox™ 143AB). Data obtained by conventional (low shear) pressure-viscosity measurements are denoted with open symbols, while indirect measurements from EHL experiments (effective α values) are shown with solid symbols. Good agreement exists between the different sources as well as between different measurement techniques. Figure 9 contains similar data for an un-branched PFPE (Fomblin™ Z-25) as a function of temperature. Here, definite data grouping exists, with effective α values being substantially lower than conventional measurements values.

Two possibilities exist for this discrepancy. First, inlet heating can occur during the EHL measurements, leading to lower viscosities and lower film thicknesses which result in lower calculated α values. The second possibility is a non-Newtonian shear thinning effect, which can occur with polymeric fluids. Shear rates in EHL inlets can range from 10^5 to 10^7 sec^{-1} [72]. However, the EHL measurements do represent actual film thicknesses that may be expected in practice. Effective α values for several non-PFPE space lubricants, including Pennzane® SHF-X2000 base fluid and some Pennzane® formulations, appear in Table 7 [73].

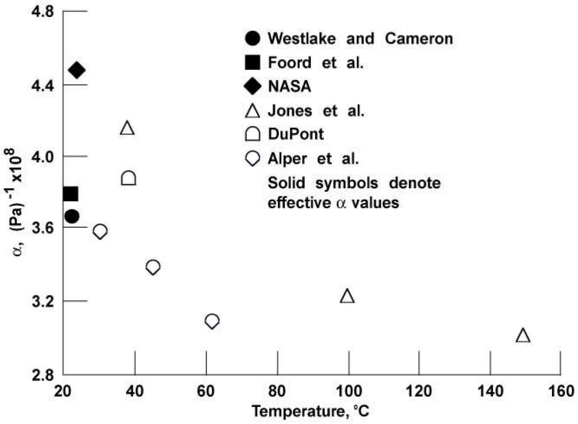

Figure 8 – Pressure-viscosity coefficients for PFPE Krytox™ 143AB as a function of temperature (for reference data, refer to [63])

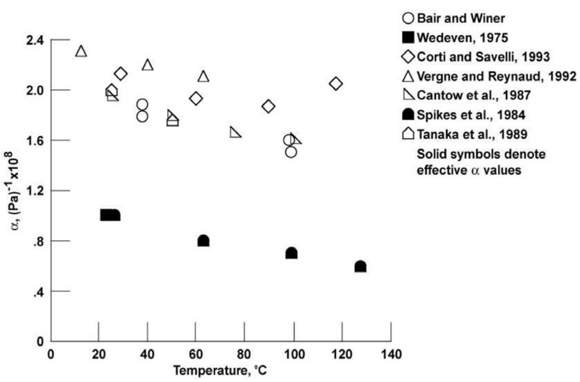

Figure 9 – Pressure-viscosity coefficients for PFPE Fomblin™ Z-25 as a function of temperature (for reference data, refer to [63])

Table 7 - Measured viscosities and calculated pressure viscosity coefficients (α values) for several space lub. [73]

Temp °C	Pennzane® 2001 – Synth. Oil	PAO-186 – Synth. Oil	NPE UC-7 – Ester	Pennzane® 2001 +5% Pb Nap	Pennzane® 2001 +3% Pb Nap
Viscosity cP					
40	88	90	37	98	96
80	19	21	10	21	21
100	12	13	6	12	12
120	8	8	4	8	8
Alpha GPa^{-1}					
40	11.0	12.5	6.5	12.0	10.0
80	9.5	9.0	5.0	9.0	9.0
100	7.0	7.0	5.0	6.5	7.0
120	7.0	5.0	5.0	6.0	7.0

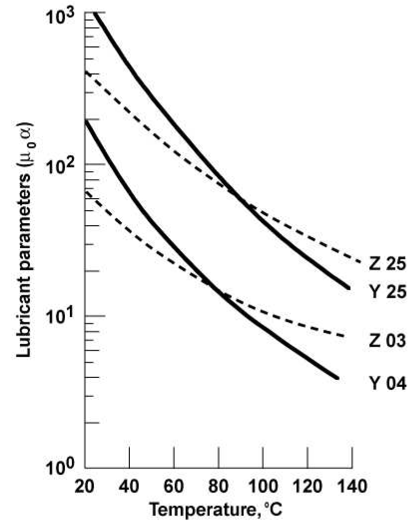

Figure 10 – Lubricant parameters for PFPE Y and Z fluids [65]

From EHL theory, the lubricant with the largest α value should yield the thickest film at room temperature, assuming approximately equal contact inlet absolute viscosities. However, in many applications, lubricants must perform over a wide temperature range. In these cases, the EHL inlet viscosity can be the overriding factor if the temperature coefficient of viscosity is high. This can cause a crossover in film thickness as a function of temperature between branched and un-branched PFPE fluids (Figure 10 [65]).

3.2.5 Boundary Lubrication

As described in Section 2.0, in boundary lubrication, surfaces are not completely separated, resulting in surface asperity interactions. In this regime, the most important requirement is the formation of protective surface films that minimize wear, surface damage, and friction. The lubricant and the contacting surface chemistry govern film formation. Non-additive hydrocarbons, mineral oils, and esters react in a boundary contact, producing "friction polymer" [74]. Except for electrical contacts, this material usually has a short-term, beneficial effect, but does represent a lubricant loss mechanism. However, conventional lubricants are usually formulated with anti-wear, anti-corrosion, extreme pressure, or anti-oxidant additives to enhance their performance and stability.

In contrast, PFPE boundary lubricant is a relatively inert, very pure fluid, which in past years contained no additives. If these fluids were truly inert, they would not provide any surface protection except for some local fluid film effects (micro-EHL) and wear debris removal. However, PFPE fluids do react with bearing surfaces, producing a series of corrosive products and a friction polymer, which, in turn, react with existing surface oxides to produce metallic fluorides [75-77]. The fluorides are effective, in-situ solid lubricants, which reduce friction and prevent catastrophic surface damage [75]. This is the current understanding of the PFPE's lubricating mechanism.

Unfortunately, the fluorides are also strong Lewis acids (electron acceptors) and readily attack and decompose PFPE molecules [77-79]. This causes the production of additional reactive species, which, in turn, produce more surface fluoride, resulting in an autocatalytic reaction, which may cause abrupt failure of a boundary-lubricated contact. Therefore, the very reaction that allows pure PFPE fluid use in boundary contacts, leads to an early destruction and accompanying contact failure, shown in Figure 11a. In contrast, a non-PFPE space lubricant, such as Pennzane® SHF-X2000, has a greater lubricated lifetime under boundary lubrication and a slower progression to failure, characterized by a gradually increasing friction coefficient (Figure 11b). It should be noted that PFPE degradation rates are highly dependent on the local contact conditions (i.e. surface passivation degree, surface oxide type and thickness, surface contamination level, temperature, load, speed, etc.).

Substituting standard bearing balls with ceramic or ceramic-coated balls can provide significant improvements in bearing lifetimes [80] when using a PFPE. TiC coated balls [81] have shown considerable promise in alleviating some lubricant degradation problems. By replacing 52100 steel balls with TiC coated balls, Gill et al. [82] has shown a nine-fold increase in bearing lifetime with a PFPE (Fomblin™ Z25). In accelerated life tests [83, 84] using a spiral orbit tribometer, lubricant lifetimes with another PFPE (Krytox™ 143AC) were extended by factors of two to four, depending on the stress level. Hybrid bearings have also been used for dry, unlubricated applications [85, 86].

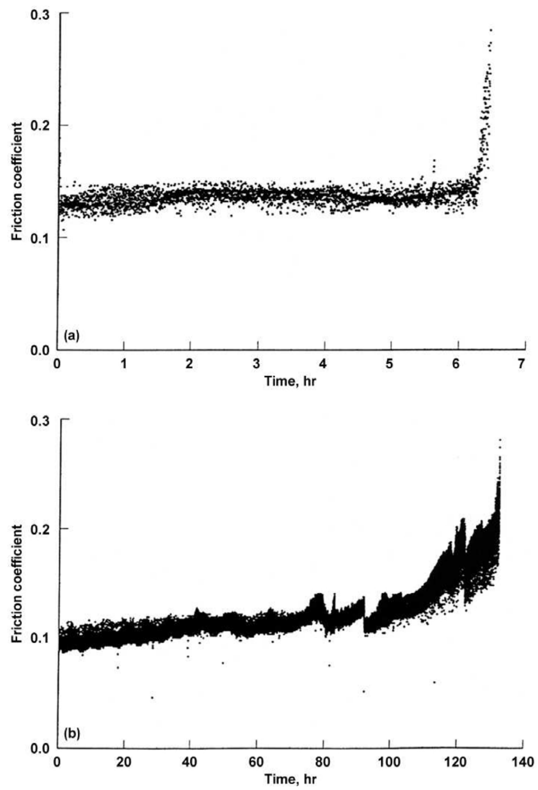

Figure 11 – Coefficient of friction as a function of time for (a) Krytox™ 143AC and (b) Pennzane® SHF-X2000 (spiral orbit rolling contact tribometer – note time scale difference)

4.0 GREASES AND SOLID LUBRICANTS

4.1 Greases

Space mechanism designers have extensively used greases based on PFPEs with PTFE thickeners (Krytox™ 240 series and Braycote™ 600 series). More recently, hydrocarbon greases based on Pennzane® SHF-X2000 (marketed by Nye Lubricants under the name of Rheolube™ 2000) are available. Performance of various Pennzane® based greases appear in Reference [87]. Also, new PFPE grease formulations (commercially designated as Braycote™ 700 and 701) incorporating a boundary additive have yielded significantly improved wear characteristics (Figure 12) [88]. Some PFPE based greases also contain sodium nitrite as a rust inhibitor. Studies have compared the lubricated lifetime of PFPE and MAC based greases under boundary lubrication

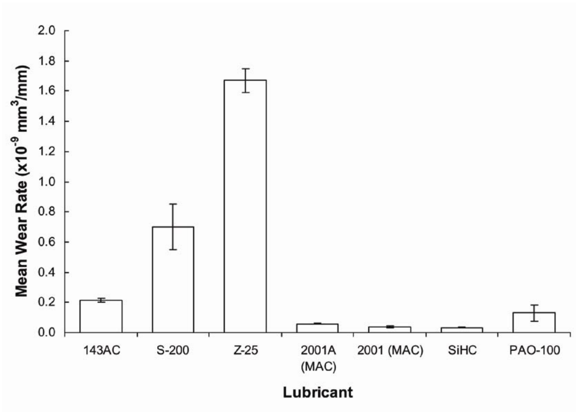

Figure 12 – Mean wear rates of steel lubricated with various PFPE formulated greases using a vacuum four-ball tribometer [88]

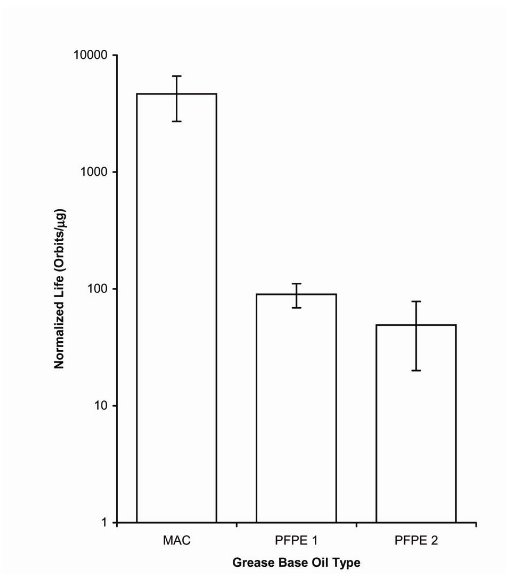

Figure 13 – Relative life of three space greases using the Spiral Orbit Tribometer [89]

conditions [89-91]. As with the base oils, MAC based greases have a longer lubricated life compared to PFPE based greases. Relative lives are shown in Figure 13 [89].

4.2 Solid Lubricants

Over the last 30 years, several solid lubricant classes have been used in space, including lamellar solids, soft metals, and polymers. Lamellar solids include transition metal dichalcogenides like molybdenum disulfide and tungsten disulfide. Soft metals include lead, gold, silver, and indium. Polyimides and polytetrafluoroethylene are polymeric materials that have lubricating properties. More recently, diamond-like-carbon (DLC) coatings are being investigated for space applications and discussed in Section 4.2.3.

Unlike liquid lubricants, metals and lamellar solids are applied as thin films (less than a micron), preferably by ion plating [92-94] or sputtering [92, 95, 96]. Another application method involves bonded films [97, 98], where lubricants are mixed with an organic binder and applied to the surface by spraying or dipping. The films, typically greater than 10 microns thick, are cured at high temperature. Sometimes self-lubricating polymers and polymer composites [99, 100] are used. Rolling element bearing cages and retainers or bushings are the main applications for solid lubricants. Today, ion-plated lead and various forms of sputter-deposited MoS_2 are the most common solid lubricants used in space mechanisms.

4.2.1 Ion-plated Lead

In Europe, ion-plated lead is the choice solid lubricant for precision spacecraft bearings and normally is used in conjunction with a leaded bronze cage. Lead coatings and cages saw early success in cryogenic space applications [101]. Other successful implementations include GIOTTO [102], OLYMPUS [103] and GERB [104]. Although not as common in the United States, the combination was used in SABER encoder bearings. Extensive data has been published on speed, thickness, and substrate surface roughness effects [105]. One disadvantage of this lubricant is limited life in air, where significantly higher wear rates occur and produce copious amounts of lead oxide. The debris also causes torque noise.

4.2.2 Molybdenum disulfide

For many years, molybdenum disulfide (MoS_2) has been successfully used in space applications [106-109]. In vacuum, these films display extremely low friction (0.01 or less). Optimized thin films (one micron or less) are deposited by sputtering. The film's tribological performance is extremely dependent on the sputtering conditions, which control the microstructure that, in turn, determines crystallinity, morphology, and composition [110].

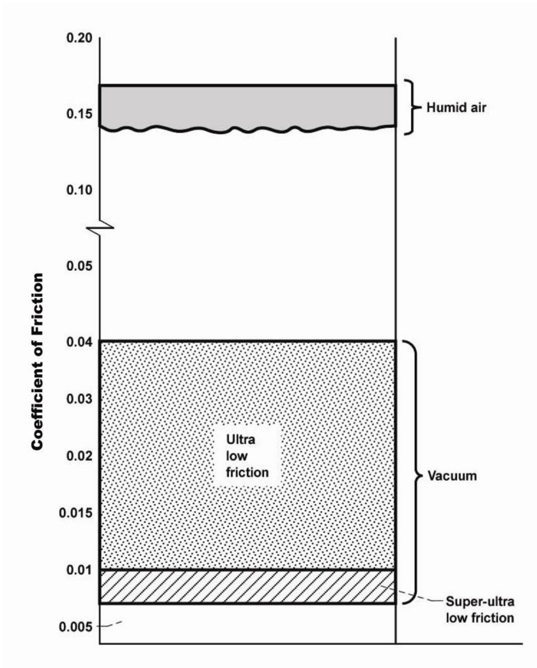

Figure 14 – Friction variation of sputtered MoS_2 films [95]

For instance, the presence of oxygen in the sputtering environment can affect both friction and wear life [111]. For more details about the sputtering process, see Reference [95]. Additionally, substrate surface roughness has a pronounced effect on friction and wear. For steel bearing surfaces, optimum durability occurs at a nominal surface roughness of 0.2 μm (R_a) [112].

Operating environment greatly affects the frictional behavior and life of MoS_2 films. In ultrahigh vacuum, these films display ultra-low friction (less than 0.01), shown in Figure 14. Under normal vacuum conditions, the friction may range from 0.01 to 0.04 with exceptionally low wear and long endurance lives. When the same films were tested in humid air, initial friction coefficients were near 0.15 and life was severely limited [106, 113]. Since many space mechanisms must be ground tested before launch, sometimes in room air, a great deal of research has been done to improve the film's performance under atmospheric conditions.

One method to improve atmospheric life has been to layer or co-deposit metals such as gold [114-116] with MoS_2 films. In this work, gold inclusions doubled the film durability in dry nitrogen and tripled or quadrupled it in air. Co-deposition with other metals (chromium, cobalt, nickel, and tantalum) has also shown synergistic effects [117]. Ion implantation with silver has also been reported to be beneficial [118], but not when co-deposited [117]. Co-deposition with titanium also improves the properties of MoS_2 films [119], making the films less sensitive to atmospheric water vapor than pure MoS_2 films. Accelerated test results on some films appear in Fusaro and Siebert [120]. Studies show the problems occurring in moist air are associated with water molecule adsorption at edge sites on the MoS_2 lattice [121].

Using a PTFE composite retainer is another method for enhancing MoS_2 endurance in ball bearings [122]. In gimbal bearing life tests [109], advanced MoS_2 films combined with PTFE-based retainers demonstrated lives in excess of 45 million cycles.

4.2.3 Diamond Like Carbon Coatings

Diamond like carbon (DLC) coatings are being examined for space applications. Because of their vast diversity, DLCs pose unique challenges. Previous studies [123 - 128] show a wide range of friction coefficients in vacuum or dry nitrogen, due to different deposition methods, different alloying elements, and a variety of multilayer structures. Recent studies [129-131] show films high in hydrogen (>40%) display low friction and low wear. While current DLCs have much higher wear rates than MoS_2 under vacuum, they show promise for future applications, particularly to provide a passivation layer on steel surfaces, which could extend PFPE lubricant lifetimes. An in depth review of solid and liquid lubricants appears in Reference [132].

5.0 MECHANISM COMPONENTS AND RE-LUBRICATION MECHANISMS

Nearly all spacecraft systems contain mechanisms requiring lubrication. With spacecrafts' ever expanding exploration roll, including the Martian surface and the atmosphere of Jupiter's moons, mechanism and lubricant demands are continuously growing. Each mission's unique challenge is to match the lubricant with the component's primary function and operating environment. Solar array drives, momentum, reaction, and filter wheels, tracking antennas, slip rings, scanning devices, sensors, rover wheels, robotic arms, antenna arrays, gearboxes, and actuators are some of the many components requiring lubrication. Each has unique hardware, mission requirements, and operating environment and therefore unique lubrication requirements.

When selecting a lubricant for a mechanism component, many factors must be considered. One of the most fundamental criteria is the mechanism's operating regime (boundary, mixed, or EHL), which guides proper lubricant and additive selection. Another important consideration is mechanism design life and duty cycle. Since a mechanism has a finite lubricant amount and re-lubrication is almost never possible, lubricant degradation (consumption) is one of the most common types of mechanism failure. Understanding how the selected lubricant will interact with the mechanism (such as surface chemistry's relation to degradation rate, dewetting, creep, and lubricant evaporation paths) is vital to long-life operation. The mechanism's operating environment is another important design factor. For example, the lubricant used in a mechanism inside a satellite, which is exposed to mild temperatures (20°C to 50°C) and a vacuum environment, will be very different than the lubricant used in a rover wheel, which might see a temperature range -135°C to 30°C in a harsh, dusty, partial atmospheric environment.

5.1 Spacecraft Components

5.1.1 Electrical Contact Ring Assemblies

Electrical Contact Ring Assemblies (ECRA) [133] are a good example of unique lubrication requirements. Excessive electrical noise, usually due to surface contamination, is the most common failure mechanism in ECRAs [134]. Therefore, electrical signal integrity, even when the lubricant begins to breakdown, is one primary lubricant selection criterion. Since most ECRAs operate at low speed, good boundary or mixed regime lubrication properties are required for long life. Proper selection and understanding of the lubricant and its degradation product's electrical properties are vital to trouble-free ECRA operation.

5.1.2 Gyroscopes, Momentum and Reaction Wheels

Gyroscopes, which are used to measure changes in orientation, operate at high speeds, typically between 8,000-20,000 RPM with high accuracy. Fluctuations in the bearing reaction torque, noise, and excess heat generation can cause a null position loss in the gyroscope, making the bearings a vital gyroscope component. The ideal lubricant for a gyroscope provides a high level of wear protection, produces minimal friction, and has a low evaporation rate [20]. Due to the limited lubricant quantity, evaporation and degradation rates and creep properties must be well understood. Gyroscopes also contain another mechanism, the gimbal supports, which operate at low speed in the boundary regime only, presenting completely different lubricant selection criteria.

Momentum wheels, which typically operate between 3,000-10,000 RPM, pose their own lubricant selection criteria. Historically, the lubricant is the cause of the majority of problems experienced by momentum wheels, with the majority of wheel failures due to inadequate lubrication, loss of lubricant, or lubricant degradation [20]. As higher speed, higher energy wheels are designed; lubricants will be subjected to higher operating temperatures and stresses, which can increase creep or degradation rates. To ease lubricant limitations, current design practices include use of improved synthetic lubricants, labyrinth seals and barrier coatings, lubricant impregnated retainers, or a lubricant re-supply system.

Reaction wheels have similar design concepts as momentum wheels, but operate at lower speeds. The support bearings spend more time in the mixed lubrication regime. Therefore, reaction wheel lubricants must also have good boundary lubrication characteristics. Control moment gyroscopes (CMG) combine the aspects of the gyroscope and the momentum wheel to provide spacecraft attitude control. Therefore, considerations of both groups must be weighed when selecting a CMG lubricant [20].

5.1.3 Sensors

Many spacecraft use sensors containing rotating or dithering components supported by bearings. Proper lubricant selection is vital to ensure the sensor bearings are operating in the correct lubrication regime to fulfill mission life and environmental requirements. By adjusting the lubricant type and viscosity, the designer has control over the mechanism's characteristics. An example of a rotating mechanism is a scanning horizon sensor, used for spacecraft orientation. The device operates at moderate operational speeds (400-1,600 RPM), constant, moderate temperature, and low loads, making lubricant selection easy. On the other hand, sensors using oscillatory motion place a high demand on the lubricant. Typically, the oscillation angle is small and the bearing only operates in the boundary lubrication regime. With the small oscillatory angle, no new lubricant is brought into the contact zones [135]. Between the operating regime and the lack of fresh lubricant, the lubricant is in a high demand, severe operating environment. Mechanism designers should consider an option where the bearing can rotate after operating a predetermined amount of time, bringing fresh lubricant into the contact region.

5.1.4 One Time Use Mechanisms

Not all mechanisms require long-term lubrication. For example, satellite solar array or antenna deployment is a one-time operation. However, lubricant selection is also critical in these applications. If these mechanisms fail to deploy, the spacecraft's functionality will be greatly reduced or totally lost. These mechanism types have unique lubrication needs because they only operate once, are low speed applications, may have long dormancy before use, and may be subject to harsh (external space) environments. Usually, solid lubricants are a good choice for these applications due to their low friction properties and ability to stay in the contact region. However, failure to fully understand the system, its dynamics, and the buildup, testing, and final operating environmental effects can lead to crippling results, as evidenced by the high gain antenna failure on the Galileo spacecraft (see Section 1.0).

5.1.5 Actuators and Gearboxes

Gearboxes and actuators are other mechanisms requiring lubrication. With these mechanism types, the lubricant may not be subject to many duty cycles; however, these cycles may involve high lubricant stresses with long, dormant periods between cycles. Often, the mechanisms may not be re-lubricated between missions or require long terrestrial storage times. Because examination and re-lubrication is often an expensive, complicated, and time consuming process, understanding of how the lubricant may react with the actuator components during storage and non-operating times is important to ensure that mechanisms will function properly.

5.1.6 Planetary Rovers

With advancements in robotics, computers, and communications, autonomous rovers are set to be the planetary explorers of the near future. Rovers have many components needing lubrication and have unique lubrication requirements. During space travel, the lubricant will be subject to low pressure and controlled temperature of the spacecraft, but once deployed, it will be exposed to harsh environments, wide temperature ranges, various gaseous atmospheres, and other environmental conditions including dust and solid contaminants. Rover mechanisms include robotic arms to deploy instruments and manipulate the environment, mast assemblies to hold cameras and viewing devices, solar arrays to provide power, antennas and communication equipment masks, and a mobility system consisting of wheels, legs, and other moving components. In addition to the rover, the associated landing craft also has many lubricated mechanisms.

5.1.7 Other Mechanisms

Many other mechanisms that require lubrication are used in space. Some examples include solar array drives (SAD), screw drives, and many types of gears and transmission assemblies [136].

5.2 Re-lubrication Mechanisms

Because lubricant loss or degradation is a common reason for space mechanism failure, mechanism re-lubrication methods have been examined [53, 137]. Since it is impossible to service most spacecraft after launch, in-situ and remote re-lubrication systems have been explored to extend mission lives. Although currently not widely used, many devices have been developed, including: centrifugal oilers [138], positive commandable lubricators [139], wick feed systems [140], oozing flow lubricators [141, 142], lubricant reservoirs, porous retainers [143], and remote controlled, in-situ lubrication mechanisms [144].

5.2.1 Passive and Reservoir Re-Lubrication

Many systems, such as centrifugal oilers, wick feed systems, and porous retainers are passive systems. In these systems, lubricant either is constantly fed into the contact region or drawn into the contact region by surface tension. These systems drawbacks are added complexity, additional space, additional weight, and lack of control. While porous retainers do not take up space, in some cases they have been shown to act as lubricant sponges rather than lubricant suppliers [18].

Lubricant reservoirs provide a re-supply mechanism; however, they are typically bulky and continuously supply lubricant to the contact region. This often leads to excessive lubricant in the bearing, which can be just as detrimental to the instrument as insufficient lubricant. A newer version of the reservoir concept, the oozing-flow lubricator, has been developed. This system has a reservoir, but the designer can specify a controlled flow rate, which is controlled using a proprietary grooving system between the reservoir and the bearing. The groove geometry determines the flow rate, which is usually extremely low (micrograms per hour). This allows the designer to balance the degradation rate with the rate new oil is introduced into the contact region, thus avoiding an over or under lubrication situation. References 141 and 142 describe this system in more detail. All of the above listed re-lubrication systems are only applicable with liquid lubricants.

5.2.2 Active, In-Situ Re-Lubrication

A newer re-lubrication concept is a small, in-situ, remotely controlled, lubricant reservoir. With this concept, the device is remotely activated when bearing torque increases, which evaporates a minimal lubricant charge into the contact zone, thus reducing friction and torque back to an acceptable level. The control can either come from a ground-based command or with a sensor/controller integrated in the mechanism. Additionally, both solid and liquid lubricants can be used with this system. The concept was first used to combat solid coating wear [145-147] and perform in-situ deposition of a solid film coating [148]. Both types of in-situ lubrication worked well and the concept extended to liquid lubricants [137]. All these experiments showed that in-situ lubrication worked in a laboratory environment; however, a viable solution for real systems had not been developed. Marchetti et al. extended the concept to an attachment for an actual bearing and successfully demonstrated its functionality [144]. In this system, a porous ring is impregnated with a liquid lubricant and attached to the edge of the bearing. The system can turn on and off a heating element on the top of the ring. When the bearing requires lubricant, the heater is activated and lubricant is exuded, which re-lubricates the contact region. This system is a low power, low volume system, and can be easily adapted to many different bearings. The system has been successfully demonstrated with both PFPE and MAC lubricant classes.

While there are many re-lubrication systems available, the designer must balance the added weight, complexity, and power requirements with the mission life. Once again it is important to understand the whole mechanism, its function and design life, and how the selected lubricant will interact with the components in the system.

6.0 LUBRICANT TESTING AND ANALYSIS

With increasing demands and expanding operating environments of spacecraft mechanisms, new lubricants and additives are always under development. Since tribological failure is a leading cause of spacecraft mechanism malfunctions, new lubricants must undergo extensive ground based testing to ensure they will meet stringent mission requirements. In the past, lubricant selection has been based on 'heritage', or actual flight experience. In early space flight, this approach worked well because of short mission lives and minimal duty cycles. However, with today's longer missions and improved components, new lubricant properties must be well understood to ensure they will perform properly with the system and the environment.

6.1 Types of Testing

There are three levels of tribological testing: (1) tribometer, (2) component, and (3) system or mechanism. Each level has advantages and drawbacks as discussed in more detail below.

6.1.1 Mechanism and System Level Testing

Historically, mechanisms were qualified with either system-level tests on actual flight hardware or duplication of flight system conditions [134]. However, these tests are expensive, time consuming, and, with long life requirements of modern missions, often cannot be completed before launch. Unless a mechanism fails early, the tests are useless for lubricant selection. Additionally, since tests are long and expensive; only a few candidate lubricants can be tested. However, should an anomaly occur on orbit, system level tests are useful for trouble shooting or to develop a working solution. Due to the limitations of this testing, component and tribometer level tests were developed.

6.1.2 Tribometer Level Testing

Tribometer level testing involves measuring fundamental lubricant properties under various conditions. Tests are often short and the results quickly compared. This guides lubricant selection for more extensive testing or application in an actual mechanism. Usually, properties measured include friction coefficient, wear rate, bearing material effects, and atmospheric effects. Typical test devices include pin-on-disk, ball-on-disk, four-ball, block-on-ring, disc-on-disc, and several other geometries. Some newer tribometers, such as the Spiral Orbit Tribometer [149, 150], can determine the lubricant consumption rate in addition to the previously mentioned effects. For space applications, the facilities operate at ultrahigh vacuum, but can also introduce various gaseous atmospheres. All the devices operate in the boundary or mixed lubrication regime. At this test level, several lubricants and conditions can be quickly evaluated at relatively low cost, making it particularly valuable for selecting the best candidate for an application. However, most of these devices, which operate in pure sliding, do not simulate the contact conditions seen in the ultimate application; a major disadvantage. Some newer tribometers provide a more realistic simulation of ball bearing contact conditions.

6.1.3 Component Testing

Testing specific system components is a compromise between tribometer and system level tests. Typically, components include ball bearings, ball screws, slip rings, or gears. Obviously, component tests are more expensive and time consuming compared to tribometer tests; however, they are considered more reliable and can duplicate anomalies seen in specific components, either in flight or during system level testing.

Most component level tests use angular contact bearings, operate in vacuum, and are non-accelerated; although sometimes limited lubrication, higher than normal loads, or elevated temperatures accelerate tests. Often, long-term component tests study liquid lubricants under boundary conditions. Component level tests are also applied to study lubrication regime transitions due to varying conditions and new solid/liquid lubricant combinations.

6.1.4 Life Prediction

Ideally, all mechanism designs should incorporate generous margins, assuring that design lifetimes are always achieved. For low duty cycle operations, this is easily accomplished; however, this is almost impossible for long-lived missions involving millions of cycles. Two options exist that can provide confidence when selecting a lubricant for long-life missions. First, the mechanism or component can be life tested before the final design. As mentioned previously, the cost and time involved usually eliminate this option. Second, looking at a 'heritage' mechanism, which has operated successfully in space for the duration in question, provides a database and allows for confidence that the mechanism will achieve its design life. However, these options are rarely possible.

Statistical methods for fatigue life predictions do exist, but fatigue is not a failure mode in space applications. Since most liquid or grease lubricated bearing failures and anomalies occur from lubricant loss or tribological consumption, a ball-pass or stress-cycle analysis can be used to estimate component life.

6.1.5 Lubricant Consumption Based on Ball-Pass/Stress-Cycle Analysis

In the boundary lubrication regime, lubricant is continuously consumed within the Hertzian contact zone. Lubricant degrades into a non-lubricating, friction polymer or into gaseous fragments, which are lost to the surrounding vacuum. As long as fresh lubricant is entrained into the contact zone, consumption occurs; thus, the consumption rate is directly related to the rotation rate. The Hertzian stress level also affects the consumption rate. Life generally decreases exponentially with increasing Hertz stress [84, 151].

However, for mean Hertzian stresses over a narrow range (0.4 to 0.6 GPa), the following equation shows a method of normalizing the consumption rate:

$$CDF = \sum B_c \bullet P_h$$

where CDF is the Cumulative Degradation Factor (sometimes referred to as lubricant stress cycles; in units of psi-crossings), B_c is the number of times a given spot on the inner raceway is compressed (ball crossings or passes), and P_h is the mean Hertzian contact stress at the inner raceway [152, 155]. Since this method normalizes data to units of psi-crossings, the CDF for any component or mechanism can be calculated and compared to existing life test data. This method was used to evaluate the AURA TES (Tropospheric Emission Spectrometer) Life Test Unit. The instrument's design lifetime was 7 x 10^6 scans; however, after approximately 2.2 x 10^6 scans, motor current increased, indicating increased bearing torque. Motor current continued to increase, which eventually resulted in shutdown at approximately 5 million scans. Upon disassembly, it was discovered that the encoder bearings, which were lubricated with Braycote™ 815Z, had failed. CDF calculations were done and compared to CDF values from several other bearing life tests (Table 8). From these comparisons, it is obvious that the encoder bearing lifetime was in family, not a premature occurrence. Therefore, it was concluded there was a very low probability the TES instrument would reach the seven million scan design life.

Table 8 – Measured cumulative degradation factors for several bearing life tests lubricated with 815Z

Bearing Life Test	**Mean Hertzian Stress (MPa)**	**Cumulative Degradation Factor for Initiation of Lubricant Degradation or Bearing Failure ($x10^{12}$ ball crossing-psi)**
TES LTU Encoder	503	2.0[a] (3.8)[b]
Ball Aerospace [152]	448	1.4[c] (2.0)[b]
Hughes (Flooded) [155]	648	2.8
Lockheed-Martin [158]	751	2.2 to 8.7 (Average 5.5)

[a] Start of motor current increases
[b] Test termination
[c] Initial torque increases

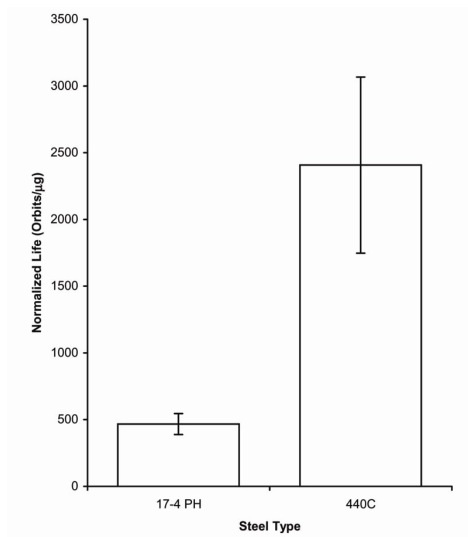

Figure 15 – Relative life of Pennzane® SHF-X2000 on two different bearing steels

6.1.5.1 Other Factors Affecting Consumption Rate

However, the consumption rate is also highly dependant on the lubricant and bearing surface chemistries. This is easily illustrated using Spiral Orbit Tribometry (discussed in detail in Section 6.3.1.1). Figure 15 shows an example of this effect for a formulated Pennzane® in vacuum with two different bearing materials (440C and 17-4 PH stainless steels). Lubricant life is drastically reduced with the 17-4 PH material. Other surface chemistry effects were observed in Pepper and Kingsbury [153]. In this work, the detrimental effect of increasing chromium concentration on Fomblin™ Z-25 degradation is shown.

6.2 Accelerated Testing

Accelerated lubricant testing is required to rapidly screen several lubricants and additive packages. Because accelerated tests typically do not involve actual flight hardware, testing is significantly less expensive. Generally, test results cannot be extrapolated to predict the life of components that are lubricated similarly but operate under different conditions [58]; however, accelerated testing can rank lubricant's life and performance relative to one another, providing an inexpensive way to screen several candidate lubricants. Once lubricants are screened using accelerated testing, the best candidates can continue to full scale life testing. Test times are usually days to weeks rather than months to years.

Test acceleration is typically achieved by subjecting the lubricant to a condition more extreme than the service requirements. Extreme conditions are produced by varying test parameters, including increasing speed, load, or temperature, adding contaminants, reducing lubricant quantity, or varying surface roughness [156]. When selecting which parameters to vary, understanding of how those parameters affect contact conditions and how the variations will relate to actual mechanisms is important. Ideally, accelerated tests should have as many parameters as close to an actual mechanism as possible. Because several different accelerated tests are required to measure various lubricant attributes, such as wear rates and boundary lubrication properties, a combination of tests is required to select lubricants for full mechanism testing. Solid and liquid lubricants have their own considerations when choosing a method for acceleration.

6.2.1 Accelerated Testing of Liquid Lubricants

For liquid lubricants, changes in speed, temperature, contact stress, or available lubricant could change the film thickness substantially and subsequently change the test's lubrication regime. As described earlier in this chapter, each lubrication regime has specific, different wear characteristics; therefore changing the lubrication regime could yield irrelevant results. However, the designer can change multiple parameters to maintain the proper lubrication regime. For example, if the speed is increased, the temperature can also be increased to try to maintain a constant lambda ratio (film thickness to composite surface roughness). When choosing what parameters to vary, it is important to understand how the variation will affect the contact and lubricant. For example, increasing the temperature might cause the lubricant to oxidize or react with contact surfaces differently than at the normal operating temperature. The designers must also consider if it is worth the effort to design a facility to maintain all the operating parameters. Ideally, the minimum number of parameters are varied. Additionally, accelerated testing with liquid lubricants does not account for time dependent parameters, including creep, loss of lubricant through evaporation and centrifugal forces, and in some cases lubricant degradation [58].

6.2.2 Accelerated Testing of Solid Lubricants

Accelerated life testing with a solid lubricant has fewer considerations. If a system uses only solid lubricants and operates at low speed, accelerated testing can be done simply by increasing the system speed. However, it is important to consider that the lubricant wear rate may be speed dependant and additional loads from inertial effects or component instability may be present [58]. However, as with liquid lubricants, the short-term tests do not account for long-term effects, such as exposure to various environments during storage, buildup, and operation.

6.2.3 Summary of Accelerated Testing Strengths and Weaknesses

Even with the limitations of accelerated testing, it is a valuable tool for quickly screening and evaluating several lubricants. Lubricants can be ranked relative to each other and compared to 'heritage' lubricants, providing vital information to help designers select lubricants or further tests. Additionally, additive performance can be quickly evaluated. With some modern accelerated testing equipment, such as the Spiral Orbit Tribometer, many parameters can be similar to actual mechanism conditions. Accelerated test limitations include chemistry effects, wetting, and lubrication regime changes with temperature, speed, and contact pressure, lack of standardized testing procedures, and coating fractures under high loads. Strengths and weaknesses are summarized in Table 9.

Table 9 - Strengths and weakness of accelerated tests [156]

Weakness	Strengths
Wetting condition with temperature	Easy to monitor
Chemistry changes with temperature and pressure	Use to enhance design
Oxidation changes with temperature and pressure	Use to validate model
Hydrodynamics region changes	Rapid baseline data generation
Wear/friction polymers changes	
Coating fracture under high load (solid lube)	Lower cost
Non-standardized	
Dynamic changes in cages and components	
Low confidence	

6.3 Facilities for Space Lubricant Testing

6.3.1 Facilities for Accelerated Testing

Accelerated test facilities for space mechanisms have some common features. To simulate the space environment, testing is done in a high or ultra-high vacuum chamber. Because of this, space lubricant test facilities are usually costly, most are unique, and test apparatus size is usually limited. As mentioned earlier, accelerated test apparatus do not use flight hardware or mockups, but rather very simple hardware with minimal parts. This keeps test costs low and usually provides specimens that can be easily analyzed after test completion.

Several different tribometers have been developed to qualify space lubricants. Because most space mechanism failures occur due to lubricant degradation rather then fatigue, degradation rates should be determined to help select lubricants. Several unique facilities measure one or more of the following: friction, substrate wear, lubricant degradation rates, lubricated lifetimes, or bearing system properties.

6.3.1.1 Spiral Orbit Tribometer (SOT)

A novel vacuum tribometer exists at NASA Glenn Research Center and is based upon a simplified, retainerless thrust bearing with one ball and flat races (Figure 16). The SOT is used to measure lubricant degradation rates and friction in boundary lubricated rolling/pivoting contact. One of the flat plates rotates and the ball, under load, is driven in a nearly circular orbit. However, the orbit is actually an opening spiral with the pitch directly related to the friction coefficient [150]. At the end of the orbit, the ball contacts the 'guide plate', returning it to the original orbit diameter. A force transducer, mounted in-line with the guide plate, measures the force exerted by the ball on the plate, which is directly related to the friction coefficient. For most of the orbit, the ball undergoes pure rolling with pivot or spin; however, when the ball is in contact with the guide-plate, rolling, pivoting, and sliding occur. This is the most tribologically severe part of the orbit, termed the 'scrub', where the majority of lubricant's tribo-degradation occurs. This is advantageous when doing post-test or in-situ analysis of degradation products (i.e. mass spectrometer signatures).

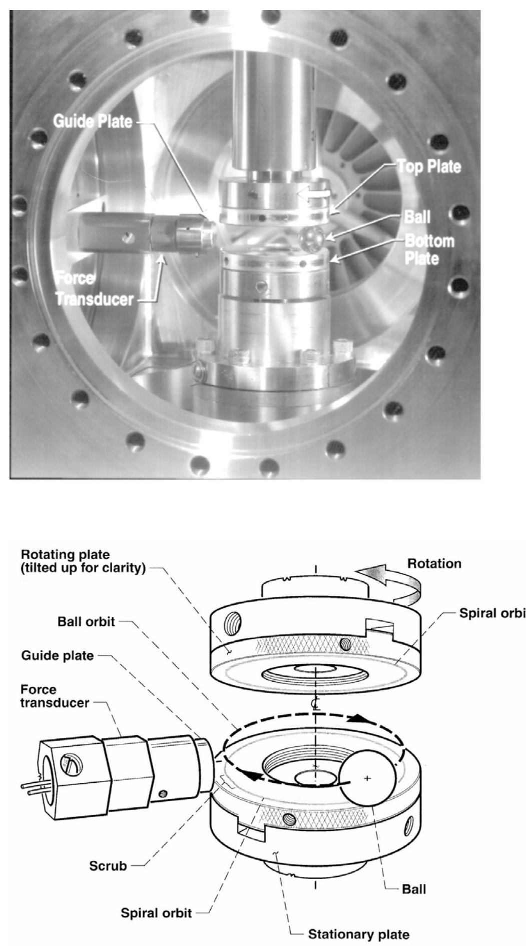

Figure 16 – Spiral orbit rolling contact tribometer (overview and detail)

Lifetime is controlled in two ways. Typically, the facility operates with a minute amount of liquid lubricant (~50 μg). With this lubricant quantity, the entire amount is degraded, usually limiting test times to less than one or two days. Varying load, which changes stress and therefore changes degradation rates, is another method for controlling lifetimes.

The facility can operate either in ultra-high vacuum (10^{-9} Torr) or with various atmospheres. Loads between 45 to 450 N are used and, by varying the ball diameter, achieve mean Hertzian stress between 0.5 and 5.0 GPa. Ball rotational speeds between 4 and 100 RPM have been used. A full description of the tribometer and its kinematics can be found in References 150, 154, and 157.

The advantages of this facility over more traditional systems are: the ball undergoes rolling, pivoting, and sliding contact – typical of a real bearing, short lifetimes due to finite lubricant quantity, simple operation, and easy post-test sample analysis. Because the ball remains a sphere with no wear, post test analysis can be extremely detailed. Additionally, there is excellent correlation between relative lifetimes obtained using the SOT and actual bearing tests. Relative lifetimes for several space lubricants appear in Figure 17 [159] and comparisons with actual bearing tests appear in Reference 158. To date, the majority of SOT tests were done with liquid lubricant; however, the facility has also been used to study greases and thin solid films.

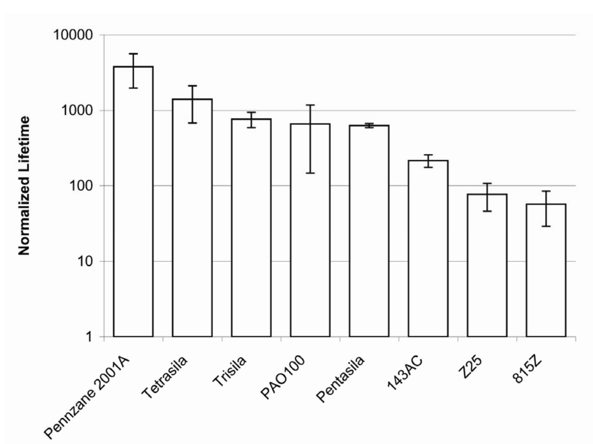

Figure 17 – Relative lifetimes of several space lubricants using the SOT tribometer [158]

6.3.1.2 Vacuum Four-Ball Tribometer

Figure 18 shows a tribometer developed at NASA Glenn Research Center. This tribometer is used to measure wear of materials. The facility is based upon a four-ball configuration and designed to test lubricants under pure sliding conditions. Three balls are fixed in a cup and immersed in lubricant while a fourth ball is mounted on a rotating shaft (Figure 19). The rotating ball is brought into contact with the stationary balls, generating wear scars on the stationary balls. The test is stopped every hour to measure the wear scar diameters and calculate the wear volume. Using a special platform, the wear scars can be measured without removing the balls from the cup [160], allowing the test to resume exactly where it was stopped. A test takes four hours and, upon completion, wear volume is plotted as a function of sliding distance. The wear rate (wear as a function of time) is calculated from the slope of the line.

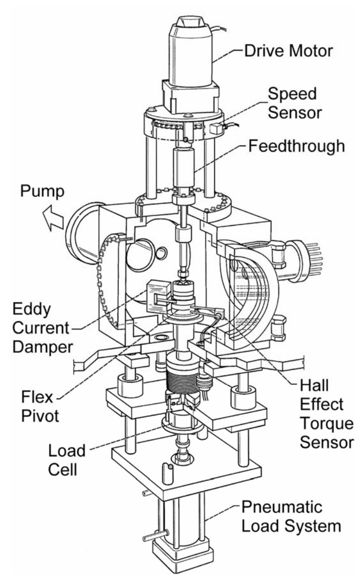

Figure 18 – Overview of four-ball vacuum tribometer

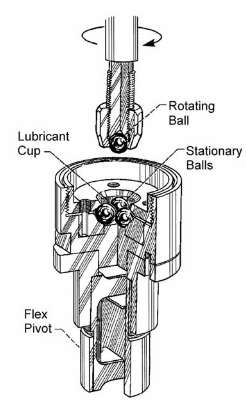

Figure 19 – Detail of four-ball vacuum tribometer

Typical tests are run with 9.82 mm diameter balls, 100 RPM, room temperature, a vacuum level of at least 10^{-6} Torr, and an initial Hertzian stress of 3.5 GPa. However, as the wear scars develop and the contact area increases, the contact stress drops. This apparatus rapidly provides information about the wear-resisting capability of a lubricant or additive package. In general, lubricants exhibiting high wear rates correlate with lower bearing lifetimes.

6.3.1.3 Vacuum Pin-on-Disk Tribometer

Figure 20 shows an ultra-high vacuum pin-on-disk tribometer [161] for solid film coating tests. The pin-on-disk facility is used to measure friction and wear rates in sliding conditions. The apparatus is a simple setup using a stationary pin with a known end diameter loaded against a rotating disk coated with the desired lubricant. Loads, typically less than 1000 grams, are applied by a dead weight system directly above the pin. The friction force displaces the pin tangentially. The tangential pin displacement is measured and the friction coefficient directly calculated. The rotating mechanism is enclosed in a vacuum chamber and tests are typically run at a vacuum level of at least 10^{-9} Torr. The rig can also be back-filled with a variety of gases to study their effects on the lubricants.

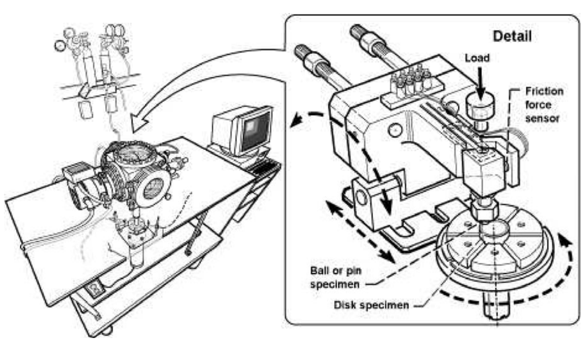

Figure 20 – Ultra-high vacuum pin-on-disk tribometer

6.3.2 Facilities for Component Life Testing of Space Lubricants

6.3.2.1 Eccentric Bearing Test Apparatus

Aerospace Corporation [134] developed an apparatus based upon a 22.1 mm diameter bearing. In this test, the bottom (rotating) raceway is flipped over and the flat side polished to a 0.25 μm finish. This configuration allows the lower raceway to be mounted with eccentricity. The intentional misalignment accelerates the wear process and the flat surface operates at a higher stress level than the curved raceway. Both conditions induce more severe tribological conditions. Additionally, post-test analysis is easier on a flat surface.

Figure 21 shows the eccentric bearing tester. The lower raceway is mounted to a rotating shaft and rigidly supported. The upper raceway is placed inside an assembly containing a load cell. The load is induced into the bearing by compressing springs that push on the upper raceway fixture. The eccentricity can be altered from 0 to 3.06 mm and introduces a skidding element into the ball motion, greatly accelerating lubricant degradation. It also provides a wide wear track, making post-test surface analysis easier.

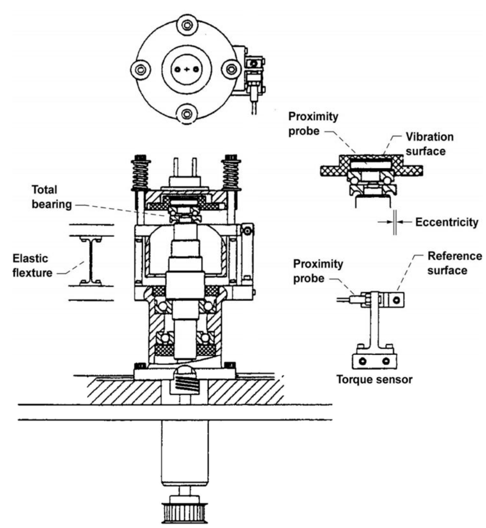

Figure 21 – Aerospace Corp.'s eccentric bearing test mechanism [132]

A set of aluminum flexures connects the upper housing to the lower housing, allowing the upper housing to flex slightly. Deflection is measured through a proximity sensor mounted in the lower housing. From the deflection, operating torque is calculated. The entire assembly operates under vacuum of approximately 10^{-7} Torr. A similar test device exists at the European Space Tribology Laboratory [162].

6.3.2.2 GOES Bearing Test Facility

A vacuum bearing test facility at NASA Glenn Research center is a good representation of component level testing. It was originally developed to study filter wheel bearings from the Geostationary Operational Environmental Satellite (GOES) when it was discovered that bearings onboard GOES missions were operating at a higher temperature than expected. Concerns about the bearing's operating regime arose and that a change in lubrication regime would severely shorten bearing life due to lubricant degradation.

This facility isolates a single bearing inside a vacuum chamber (Figure 22). An in-line torque meter and load cell monitor bearing health. Cross-bearing resistance is also measured and used to determine the bearing's operating regime. Load is applied through a dead weight system. The facility operates at a vacuum level to 1×10^{-6} Torr. This system's advantage is the ability to isolate a single bearing, which is useful for studying bearing characteristics without the complexity of an entire system. Some tests on GOES filter wheel bearings are in References 163 and 164.

Because of the system's simplicity and success with the GOES bearing investigations, the facility underwent many design modifications making it a more flexible test facility. The system can be adapted to accept almost any size bearing (up to 100 mm) and heating and cooling modifications were added. The facility's operating range is -40°C to 100°C. An advanced stepper motor system accommodates complex motion profiles in addition to rotary and oscillatory motion. The system has been used to investigate toroid issues, torque spikes, and lubricant regime transition temperatures of component bearings.

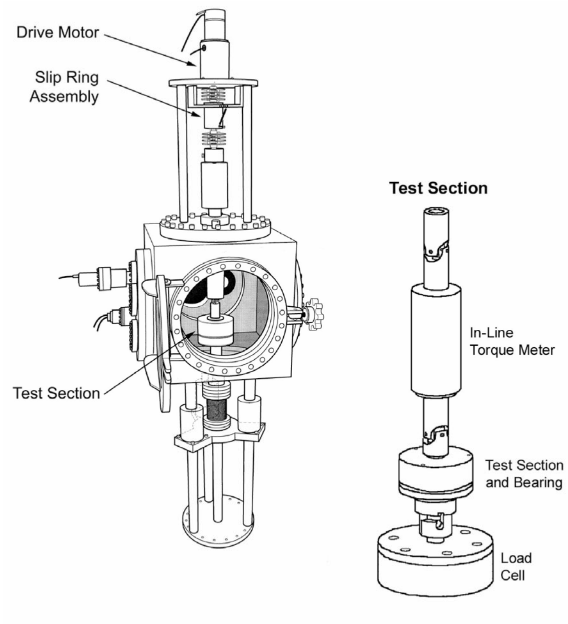

Figure 22 – GOES bearing test facility (overview and detail) [164]

7.0 LUBRICANT SELECTION

Lubricant selection for space applications is unique for several reasons. The lubricant must have extremely low vapor pressure, operate at a variety of temperatures, be a good boundary lubricant, and have a low consumption rate, which is defined as the rate at which the lubricant degrades into a non-lubricating material. Consumption rate is the most vital factor for space lubricants because virtually all bearing failures are due to lubricant degradation, not bearing fatigue or wear.

7.1 Relative Life and Wear Characteristics

Various Pennzane® formulations have been compared to other hydrocarbons (PAOs) and PFPEs in eccentric bearing tests [26]. The data, shown in Figure 23, indicates that a Pennzane® formulated with antimony dialkyldithio-carbamate yielded a lifetime several times that of a PFPE (Krytox™ 143AB). Linear ball screw tests at ESTL (European Space Tribology Laboratory) [165] compared several lubricants. These included Fomblin™ Z-25 oil, Braycote™ 601 grease,

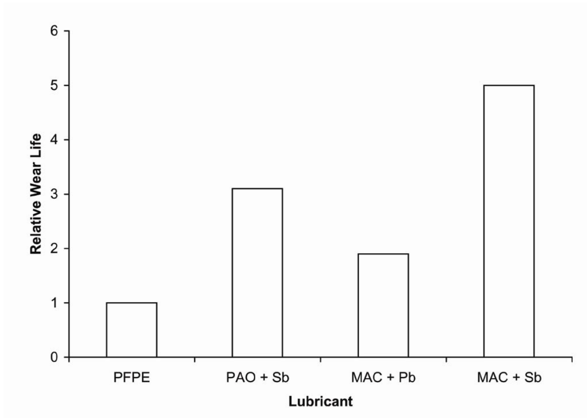

Figure 23 – Eccentric bearing screening test results for PFPE, PAO, and MAC oils [26]

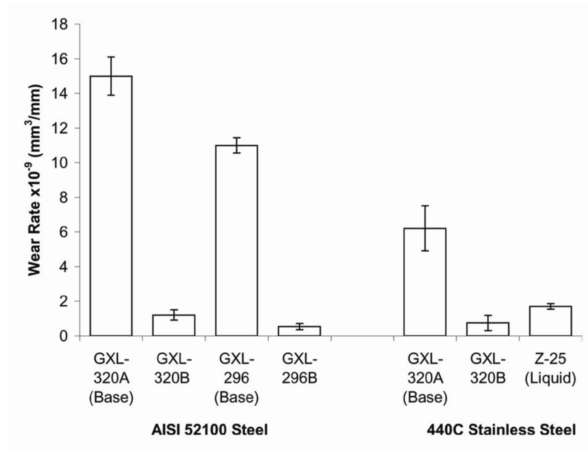

Figure 24 – Mean wear rates of various space lubricants using a vacuum four-ball tribometer [48]

Pennzane® SHF X-2000 oil, sputter coated MoS_2, ion-plated lead, and Braycote™ 601 + ion plated lead. The two PFPE lubricants failed rapidly. The Braycote™ 601 + ion plated lead combination reached the full 2 million cycle test requirement; however, ion plated lead alone failed at 400K cycles. MoS_2 survived the full test, but some polishing of the contact zone was noted. The Pennzane® oil completed the test, but lead screw wear occurred and some dewetting was noted.

Earlier work at ESTL [166] compared several solid and liquid lubricants' performance in oscillating ball bearings. Three liquid/grease lubricants were tested with phenolic cages: Fomblin™ Z-25, Braycote™ 601, and Pennzane® SHF X-2000. Torque levels were measured over 10 million oscillations. For a low angle of oscillation (±0.5°), Fomblin™ Z-25 yielded average torque levels 1.5 times that of Braycote™ and approximately 3 times that of Pennzane®. At ±5°, mean torque measurements were similar for all three lubricants, but Pennzane® exhibited the lowest levels. Finally, at ±20°, the Z-25 yielded the highest torque, Braycote™ was intermediate, and Pennzane® was the lowest.

Long-term angular contact bearing tests were also reported by Gill [167]. Pennzane® SHF X-2000 was tested at 200 and 1,400 rpm for 10^8 and 10^9 revolutions, respectively. The bearings did not fail, but did suffer from oil starvation due to evaporation losses. It was not clear if this was due to insufficient sealing or related to a lubricant batch problem; however, it was noted that similar tests with PFPE oils have never failed due to starvation by oil evaporation.

A vacuum four-ball tribometer [168] has been used to rank various space lubricants according to wear rates (Figure 24), including three PFPEs, Pennzane® base fluid, a formulated Pennzane®, and two other unformulated fluids (a silahydrocarbon and a PAO). In general, higher wear rates represent lower lifetimes in space.

7.2 General Mechanism Effects

In space applications, many factors influence a mechanism's lubricated life. Because lubricant degradation, not mechanical wear or fatigue, is the most common cause of failure, understanding how various design parameters affect the mechanism and its tests is critical. Selection of materials, stress levels, environment, and operational parameters (speed, load, etc.) all play a major role in the success of a lubricated space mechanism.

7.2.1 Stress Level Life Relation

It has been shown that, under boundary lubrication, the lubricated lifetime is directly related to the operating stress level [84, 151]. The life/stress relationship is exponential; therefore, a small change in stress level can have a significant effect on the lubricated life. Proper bearing sizing, resulting in reduced operating stress, is one way designers can easily increase mechanism lifetimes.

7.2.2 Environmental Effects

Since some lubricants, such as MoS_2, are greatly affected by environment, the designer should carefully consider all of the mechanism's operating atmospheres. Not only is the final operating environment important, but also the environments during build up, storage, and run-in testing. Because some liquid lubricants or additives may have a high vapor pressure and evaporate quickly, tests, including accelerated tests, should be done as close to the final vacuum level as possible. The mechanism's operating temperature is another important consideration. Relatively small temperature changes can greatly affect the lubrication regime and driving torque. Finally, exposure to other external environmental factors, such as radiation, can accelerate lubricant degradation and should be carefully considered before final lubricant selection is made.

7.2.3 Mechanism Speeds

As with temperature, a mechanism's operating speed can have a great effect on the operating regime. Small changes in speed can shift a bearing from the boundary regime into the mixed or even EHL regime. Because lifetime and lubrication mechanisms change greatly with the operating regime, this is an important consideration when designing component or system level tests. When designing a test, both speed and temperature can be adjusted to try to maintain the proper lubrication regime; however, other heating effects such as evaporation and oxidation rates should be considered.

7.2.4 Retainers and Ball Separators

Use of retainers or other ball separators, such as toroids, can greatly affect mechanism lifetimes. For example, if a porous retainer material is improperly selected or if it is not fully impregnated with lubricant before build up, it can act as a sponge, taking lubricant from the mechanism during operation which can lead to contact starvation [18]. In addition, humidity induced dimensional changes can occur in phenolic retainers [169]. Toroid design, implementation, and material interactions with the lubricants must also be carefully examined before final selection can be made. Improper toroid material selection can accelerate lubricant breakdown due to tribochemical reactions. Additionally, improper toroid application, such as placing them on every ball or using a bearing with too much space between balls, has led to torque anomalies, excessive toroid wear debris in the bearing, and total bearing seizure. When selecting retainer and toroid materials, the designer should consider how the material will interact with both the mechanism and the lubricant.

7.2.4.1 Retainerless Bearings

One way to eliminate retainer problems is to remove it entirely. This is not a widely accepted practice due to concerns over ball-to-ball contact. By classical EHL theory, no film exists in ball-to-ball contact because the relative surface speed is zero. However, research has shown that a protective lubricant film does exist between balls [170, 171] and classic EHL theory does not adequately describe this contact [7, 8]. Several bearings have been operated for hundreds of hours without ball-to-ball failure [141, 142]. Other advantages of eliminating the retainer are greater load distribution among more balls (when compared to the equivalent bearing with a retainer), resulting in a lower operating stress, elimination of possible cage instabilities, and elimination of a source for wear debris in the bearing. While not a standard practice, a designer should not rule out retainerless bearings if the ball separator is causing problems in a mechanism.

7.3 Cleaning and Surface Preparation

Cleaning or surface treatments are an important part in the preparation of lubricated space mechanisms. Some space lubricants' degradation rates can be particularly sensitive to changes in bearing surface chemistry [63]. Traditionally, space mechanisms were cleaned with trifluorotrichloroethane (CFC 113) or 1,1,1-trichloroethane (TCA), both ozone-depleting chemicals (ODC). During the 1990s, production of ODCs was ceased and several studies were conducted on alternate cleaning methods [172-176]. Although results varied, all the studies showed both positive and negative cleaning effects on the mechanism's lubricated life. Although surface cleaning techniques do not have as great an effect on lifetime as the materials used or the mechanism design, it is still a factor that should be specified before buildup to ensure the longest lubricated life.

Because many space lubricants are sensitive to surface chemistry, surface passivation is another technique used to extend lubricant life under boundary lubrication. With this technique, the bearing surfaces are passivated to become less chemically active, reducing the rate the lubricant reacts with the surface; thus increasing lifetime. Several passivation methods exist, including chromic acid, tricresyl phosphate (TCP) presoak, high temperature chromic acid, and ultra-violet ozone. Many studies have been conducted to study passivation effects with various classes of lubricants [177-187]. While TCP treatment improved results with mineral oils and synthetic esters, surface passivation did not have a significant effect with PFPE lubricated systems [186, 187].

8.0 SUMMARY

This review is intended to provide a current state-of-the-art review of the lubrication technology for space mechanisms, not an in depth study. For more details, the readers are directed to the following sources: NASA Space Mechanisms Handbook, edited by Robert L. Fusaro, NASA/TP-1999-206988; Space Vehicle Mechanisms Elements of Successful Design, edited by Peter L. Conley, John Wiley & Sons, Inc, New York, 1998 and Space Tribology Handbook, edited by Emyr W. Roberts, European Space Tribology Laboratory, 2nd Edition, 1997.

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