Liquid Lubrication for Space Applications

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ABSTRACT

This paper reviews the state of the art of liquid lubrication for space applications. The areas discussed are types of liquid lubrication mechanisms, space environmental effects on lubrication, classification of lubricants, liquid lubricant additives, grease lubrication, mechanism materials, bearing anomalies and failures, lubricant supply techniques, and application types and lubricant needs for those applications.

INTRODUCTION

The space age has brought with it lubrication problems that have not been experienced in the past. The problems include exposure to very low ambient pressures, radiation, and atomic oxygen, the presence of meteoroids, the absence of a gravitational field, and the use of nonmaintainable mechanical components. These problems have been addressed, but the reliability and life of mechanical components is still not adequate (Ref. 37).

Mission lives during the early years of the space age were in terms of minutes or hours. As progress has been made in developing space vehicles, the life requirements for mechanical components has increased. For example, the Space Station Freedom requirements dictate a life of 30 years. Setting requirements is easy, but what can we realistically expect to achieve with today's technology? Most mechanisms have relatively short lives. Few last for 30 years on Earth, with or without maintenance. Maybe your refrigerator compressor would last 30 years, but there are not very many others!

In the past, the electronics have limited the life of spacecraft, since these components generally failed before the lubrication system components. With the advent of improved electronics, lubrication and mechanism failure is now becoming the life-limiting factor on spacecraft. Life of mechanical systems is hard to quantify because there is currently no way to accelerate the testing of liquid lubricants, and very long duration tests must be performed. Further, it is difficult to duplicate space environmental conditions in a terrestrial environment. This complicates life prediction.

In addition to providing long component lives, liquid lubricants must not vaporize and contaminate sensitive optical equipment. Sealing the lubricants or using lubricants with low vapor pressures can prevent or contain the vaporization, but neither procedure is without difficulties. The few new low-vapor-pressure liquid lubricant formulations developed since the 1960's have boundary lubricating problems when used with some commonly used bearing materials. Research conducted to characterize the breakdown mechanisms of these fluids and to develop films or coatings to mitigate these problems is still in its infancy. The added complexity

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of a sealed mechanical systems increases torque and provides another possible failure mechanism.

This paper reviews the state-of-the-art of liquid lubricant technology as it applies to spacecraft lubrication. The areas discussed are the types of liquid lubricants, lubrication mechanisms, space environmental effects on lubrication, liquid lubricant additives, grease lubrication, mechanism materials, bearing anomalies and failures, lubricant supply techniques, and some applications and their lubricant requirements. The paper is based, in part, on an extensive literature search conducted by Mr. E.V. Zaretsky of the NASA Lewis Research Center (82).

TYPES OF LIQUID LUBRICATION

The four defined regimes of liquid lubrication are (1) hydrodynamic, (2) elastohydrodynamic, (3) boundary, and (4) mixed, which is a combination of elastohydrodynamic and boundary (Refs. 7, 19, and 34). The characteristics of the regimes are discussed in the first article of this Chapter.

When specifying a lubricant, it is very important to determine in which lubrication regime, or combination of regimes, the mechanism will be operating. The viscosity characteristics of a particular oil help determine the regime. During hydrodynamic and elastohydrodynamic lubrication, no contact takes place between the surfaces because the viscosity of the oil is high enough, the load is low enough, or the speed is fast enough to separate the moving surfaces. In these regimes, friction is very low, and no wear of the surfaces takes place. Ideally, one would always like to design a mechanism so that either of the above two lubricating mechanisms could take place, but this is not always possible since most space mechanisms rotate at slow speeds.

When the other two regimes of lubrication take place (mixed and boundary lubrication), rubbing contact between the surfaces takes place, and wear results. A lubricant in these two regimes must form a thin layer of a solid-like lubricant between the two sliding surfaces. To mitigate the wear and provide low friction, the solid-like lubricant material must adhere to both surfaces and shear under sliding contact. A good boundary-lubricant oil is capable (to a certain extent) of providing for the formation of the solid-like lubricant film by itself. However, chemical additives are often dissolved or suspended in the oils to optimize the process. In effect, the oil serves as a carrier for supplying the surfaces with a solid lubricant material or with a chemical that reacts with the surface to produce a solid lubricant material.

Problems have occurred in boundary lubrication when too heavy a solid-like lubricant film has been deposited on bearing raceways. The deposited film can cause mechanical noise (Refs. 37 and 82) during unidirectional sliding or torque bumps (Refs. 74 and 82) during oscillating bearing motion.

SPACE ENVIRONMENTAL FACTORS

Weightlessness

In space, supplying oil to where it is needed can be a problem since there is no gravity to pull it down. Fluid reservoirs and hydraulic system accumulators depend on gravity forces to provide phase separation or pump priming. In space the pump would run dry because the oil would float as a ball somewhere in the tank with no driving force pushing it towards the pump inlet. These techniques cannot be used in a weightless condition. Surface tension is the single

property that can be used to control a fluid in a weightless environment. Thus, the lubricating system must be designed with this fact in mind.

Volatilization

The absolute pressure does not affect the equilibrium partial pressure of the vapor over a solid or liquid phase of a particular material. The equilibrium partial pressure is a thermodynamic function of a particular molecular species and is determined when the rate of molecules returning to a surface equals the rate of molecules leaving that surface. What the absolute pressure does determine is the rate of return. This occurs since there is a probability of an evaporating molecule colliding with another molecule and being bounced back to the surface. In an absolute vacuum, no molecules are reflected, so all departing molecules are permanently lost and equilibrium is never attained. Strictly speaking, this only occurs when the vacuum is unbounded, i.e., when there are no walls. (Most space lubricants are contained in a nearly closed vessel.) Even so a high vapor pressure means that the rate of departure will be higher, and one should choose lubricants with the lowest vapor pressure possible.

For most satellite systems to date, volatilization has not been a serious problem. For one thing, a number of lubricants with relatively low vapor pressures are available (see section on lubricant classification). Further, very simple sealing methods, such a labyrinth seals, close shaft tolerances, and ball-bearing shields, can maintain an appreciable pressure differential and sharply reduce losses. Thus, the rate of fluid loss can be held low enough to provide mechanism lives of months or even years. Figure 1 gives the vapor pressures of some commonly used space lubricants and the time required for a 10-μm-thick film of lubricant to evaporate in vacuum (Refs. 47, 56, and 59). Figure 2 plots the time (in years) to lose 1.0 ml of lubricant oil per square centimeter of outlet area as a function of temperature for some common space lubricants (Ref. 23). The question is: for future systems, how much lubricant will be needed to obtain the desired life?

Evaporation Rate

In the "near vacuum" environment outside of the Earth's atmosphere, the absolute pressure is roughly 10^{-13} torr (Ref. 82). The operating pressure of water vapor in a sealed satellite is greater than 10^{-7} torr during the first year of orbit (Ref. 32). As a result, liquid lubricants evaporate at a significant rate. For a given liquid film, the evaporation rate can be estimated using the Langmuir's expression (Ref. 38):

$$R_{(evap)} = \frac{dm}{dt} = \frac{P}{17.14} \frac{M^{1/2}}{T^{1/2}}$$

where R is the evaporation rate, P is the saturation pressure (mm of Hg), M is molecular weight, and T is the temperature (K).

Roundtree and Todd (Refs. 58 and 59) used this equation, assuming $T = 323$ K (50°C) and $M = 2000$, to calculate the rate of evaporation of various lubricants (Fig. 1). As shown in the figure, mineral oils can rapidly evaporate in a matter of minutes to a maximum of a day, depending on the type of oil and on the saturation pressure. Perfluorinated polyethers, however, exhibit a much lower evaporation rate.

The effect of temperature on evaporation rate is also significant. Using a molecular weight M of 15 000, Leger and Dufrane (Ref. 38) present evaporation loss behavior as shown in Fig. 3. These data are particularly important since a space station component will be exposed

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to 175 000 thermal cycles over 30 years (Ref. 38) and since most low Earth orbit (LEO) satellites, according to Robin (Ref. 57), operate in a range of 280K to 320K.

Condensation

As a lubricant volitatizes, instead of the material being lost to space, it tends to form a cloud around the satellite, and in many cases condenses as a thin film onto the cold satellite surfaces. Sensitive satellites surfaces, such as windows, mirrors, lenses, grating spectrographs, etc., could be made useless by these films. Electrical contacts, slip rings, etc., also subject to contamination by the films, may be benefited by them.

The potential benefit or harm of lubricant contamination must be determined for each particular application. Designers should be aware of a possible problem and take it into consideration in their design. For short-life satellites without too many sensitive surfaces, it may be possible to simply isolate any sensitive surface from possible sources of contamination. For very long duration satellite applications, such as Space Station Freedom, oil volatilization will need to be minimized to prevent the buildup, over a period of years, of a cloud of oil vapor that could contaminate the whole station.

Lack of Reactants

The absence of reacting gases, especially molecular oxygen, in the space environment is an important consideration for the lubrication of mechanical components. It is well known that, in the absence of surface oxide films, friction coefficients of metals sliding on unlubricated metals can be extremely high (Refs. 4, 7, 11, 12, 14, 17, 18, and 28). In fact, in some instances complete welding of surfaces has been reported (Refs. 4, 12, 13, 17, and 18). The results of one such reporting is shown in Fig. 4 of experiments conducted on 52100 steel sliding against itself under a pressure of 2×10^{-7} torr (Ref. 17). During the first 30 min, the friction coefficient gradually increased from 0.2 to about 1.0. After 30 min, the friction coefficient rose rapidly to a value of about 4, and further sliding eventually resulted in stalling of the drive motor and complete welding of the specimens. It was felt that the initial low friction coefficient was due to the presence of iron oxides. Once the oxide film had been worn from the surface (and it could not reform since there was a limited supply of oxygen), complete and total failure occurred.

This loss of oxide film is an important consideration in the event of liquid lubricant starvation, even for a brief instant. Figure 5 shows the effect of air and vacuum environments on the wear of mineral-oil-lubricated 52100 steel (Ref. 55). The data indicate that wear in vacuum, i.e., in the absence of oxygen, is more erratic and higher than in air.

Evidence also suggests the importance of oxygen as a reactant with extreme-pressure (EP) additives. Table 1 (from Ref. 30) gives four-ball EP wear-test results for two additives and two lubricant base stocks. In each case, lower load-carrying ability in the absence of oxygen was demonstrated. It is also known that zinc dialkyl dithiophosphate (Ref. 30) and other lubricant additives have mechanisms involving oxygen. Unfortunately, there has not been much fundamental data collected over the years to evaluate the effect of the lack of oxygen and other atmospheric reactants on lubricant performance. The designer should keep in mind that the lack of air and the wearing away of surface oxide films could be a problem.

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Thermal Conductivity

In the absence of gravity there is no cooling due to natural convection. Frictional contacts very often take place over very small areas and generate high heat. The inability to transport heat away from these small contact areas can lead to yet higher local temperatures and lubricant breakdown. The problem can be more severe with solid lubricants than liquid lubricants, since the liquid lubricant can conduct away the built-up heat. However, if the amount of liquid lubricant is small or if it is not free to circulate, the behavior can be virtually the same as solid lubricants.

Meteoroids and Space Debris

Meteoroids or space debris should not have any deleterious effects on lubrication other than those associated with a direct, high-velocity impact. Such an impact to a fluid reservoir could cause the release of the lubricant and hasten starvation of the contact areas.

Radiation

Radiation in space can be categorized as electromagnetic or particulate. Electromagnetic radiation includes infrared, visible, ultraviolet, x ray, and gamma ray. Particulate radiation includes cosmic rays, trapped electrons and protons, and solar flares. The intensity of electromagnetic radiation varies inversely as the square of the distance from the Sun. At the Earth's distance from the Sun, 50 percent of the energy lies in the infrared and radiofrequency regions, 40 percent in the visible region, and 10 percent in the ultraviolet and x-ray regions. Of these, ultraviolet and x rays can do the most damage to organic materials. Such radiation can result in the ionization of many materials and can excite electrons to high energy states resulting in increased reactivity. Absorption of ultraviolet radiation can lead to crosslinking, chain scission, or random breaking of molecular bonds. Infrared radiation can thermally degrade a lubricant, and degradation can be accelerated by the combined effects of the above mentioned radiations.

Particulate radiation comes from the Sun, deep space, and the Van Allen radiation belts. The primary effects on materials and lubricants of particulate radiation are ionization and displacement. Ionization can occur from gamma rays, electrons, and protons; displacement, from protons. Organic materials or lubricants exposed to particulate radiation can experience chain scission, polymerization, or crosslinking (Ref. 28).

Current data on ultraviolet and other radiation exposures of materials and lubricants is limited, and few materials have been evaluated. Lubricant changes have not been rigorously accessed, but radiation will certainly be an important factor (Ref. 38). Fortunately, liquid lubricants are usually shielded from most of these radiation effects.

Atomic Oxygen

The major atmospheric constituent in low Earth orbit is atomic oxygen. Recently, it has been recognized as a potential life-limiting factor in long-lived satellites (Refs. 38 and 39). Experiments on two shuttle missions (STS 5 and STS 8) provided quantitative data on its possible effects. Carbon and silver react quickly enough to produce macroscopic changes in their structures: Carbon reacts to form volatile oxides; silver forms heavy oxide layers that flake and spall. Polymer materials such as epoxies, polyurethanes, and polyimides were also reactive with atomic oxygen.

Some representative reaction efficiencies are shown in Table 2. The efficiencies are expressed as the volume of material lost per incident oxygen atom. The data indicate that organic materials are very susceptible to atomic oxygen. The effect on liquid lubricants has not been studied but these data indicate they could be adversely affected if exposed to atomic oxygen.

Viscosity

The viscosity of a lubricant plays a significant role on a number of performance parameters. Simply, the evaporation rate of a lubricant decreases as the viscosity, i.e., the molecular weight, increases (see, e.g., Table 3 (Ref. 37)).

More importantly, the effect of the viscosity on the torque characteristics must be considered. Kannel and Dufrane (Ref. 37) present results for measured torque as a function of viscosity for various lubricants (Fig. 6). As shown, the effect of increasing viscosity is that the torque is increased. On the other hand, associated with increasing viscosity is the possibility of generating an elastohydrodynamic lubrication (EHL) film thickness at a lower rotational speed. Kannel and Dufrane (Ref. 37) point out that a speed of 80 rpm was needed to form a film thickness that could completely separate the balls from the races (i.e., to reach "lift-off") with KG-80 oil, whereas with SRG-40 lubricant, a rotational speed of 160 rpm was necessary.

Another important viscosity effect is that due to temperature. Figure 7 gives viscosity as a function of temperature for a homologous series of superrefined mineral oils (Ref. 37). Figure 8 gives viscosity as a function of temperature for several lubricants (Ref. 56). Note the wide range of viscosities obtained in these two figures.

In many space mechanisms, the rotational speed is extremely low. For example, in telescopes and instruments that must operate with high precision, the tracking accuracy must be much less than 1 rad/sec. Fleischauer and Hilton (Ref. 27) give the proposed performance requirement of a new system at pointing accuracy of ≤ 1 μrad with ≤ 0.25-μrad jitter. Under such conditions the lubrication mode is boundary, as the lift-off takes place at much higher speeds. Modeling and predicting the performance of the rolling-element bearings under such ultralow speeds is very challenging.

Another important consideration is the cage stability. Kannel and Dufrane (Ref. 37) state that when a low-viscosity lubricant is used, the reaction forces are small, and, therefore, slip is likely to occur under the lift-off conditions when surfaces are completely separated. More viscous fluids reduce the slippage but the associated torque will be higher.

Creep/Migration

Lubricant creep is affected by viscosity. Kannel and Dufrane (Ref. 37) performed a number of experiments in a vacuum chamber to study the spread of a lubricant over a period of 400 hr. Higher viscosity fluids crept much more slowly than the lower viscosity fluid. The lubricants tested were incapable of creeping across sharp edges, over a debris track of synthane, or against a thermal gradient. All these factors have an important practical implication to lubricant distribution and supply arrangements. The interested reader may also refer to a recent article by Roberts and Todd (Ref. 56).

Lubricant creep is also affected by temperature gradients. Figure 9 illustrates the migration patterns of the superrefined mineral oil KG-80 in the presence of a 2.2°C thermal gradient and in a zero-g environment. The figure indicates that the oil crept from warm to cooler areas.

CLASSIFICATION OF LIQUID LUBRICANTS

There are many different liquid lubricants that have been used in space. Table 4 lists commonly used space lubricants and some of their properties. Table 5 lists the molecular structures of these lubricants and of two new lubricants that may have potential for future space use. The following sections will discuss each class of liquid lubricants.

Silicones

Silicone fluids tend to have low vapor pressures and low pour points. For these reasons, during the early years of space exploration they were used quite often as space lubricants. But several problems occurred during their use. They tended to creep out of the contact zones, and they formed polymer deposits on rubbing and rolling surfaces. Polymer deposits can lead to rough running bearings and premature failure. Thus, silicone fluids were only moderately successful as lubricants, and today should not be considered as suitable lubricants for a spacecraft. They may be used for nonlubricating applications however, such as in hydraulic systems, as damper fluids, or as thermal conduction materials.

Mineral Oils

In general, mineral oils do not have low vapor pressures (Fig. 1). However, they are often used for space applications in completely sealed lubricant systems. These applications include momentum wheels, reaction wheels, de-spin mechanisms, etc. Generally, the mineral oils used are superrefined; that is, they have been refined to remove all of the light fractions of the oil, as well as polar impurities. Table 4 lists some mineral oils that have been used as lubricants in the U.S. and in Europe. For a complete list, see Refs. 42 and 43. Mineral oils are inherently good boundary lubricants, and boundary-lubricant additives are readily soluble in them. A multitude of data are available on superrefined mineral oils since they have long been used for aeronautics applications.

Perfluoropolyethers

Three main classes of perfluoropolyether (PFPE) fluids are available today. Table 5 presents the molecular structure of these three fluid types, and Table 4 presents some of their properties. Their commercial names are Fomblin, Krytox, and Demnum. Demnum has not yet been used in space.

The chemistry and the properties of these fluids seem to be ideally suited for space lubrication. They have very low vapor pressures, very low pour points, and higher viscosity indexes than mineral oils, and they are extremely inert. Their inertness poses one disadvantage: because very few materials are soluble in them, additives formulated for mineral oils are not usable. A new class of additives has been developed for use with PFPE's (Refs. 60 and 61), but currently there are no data available as to their effectiveness in space applications.

Perfluoropolyethers have been very successful for lubrication applications in the hydrodynamic or elastohyrodynamic regimes. But under boundary-lubrication conditions, they degrade. Table 6 lists some of the factors that influence the degradation of PFPE fluids. Degradation of the fluid can result in higher friction, bearing torque noise, excessive wear, and, eventually, bearing failure.

Mori and Morales (Refs. 47 and 48) found in their study of the decomposition of the three PFPE fluids in ultrahigh vacuum, that the reaction products were dependent on the particular molecular structure of the PFPE fluid when irradiated by x rays. They also studied the reaction of the three PFPE fluids with AISI 440C steel under sliding conditions at 25°C in a 3×10^{-8} Pa $(1\times10^{-10}$ torr) vacuum. All three reacted with the steel. The Fomblin fluid formed gaseous COF_2, while the Krytox and Demnum fluids produced only solid products. Fomblin is the only fluid that contained an acetal structure group $(-OCF_2O-)$.

Baxter and Hall (Ref. 3) suggest that the cause of Fomblin's degradation is the reaction of chemically active surface sites and/or wear particles with exposed radicals in the fluid. Zehe and Faut (Ref. 83) and Carré (Refs. 20 to 22) suggest that acid sites on metals or oxides of the metal could react with the PFPE lubricants to cause breakdown of the fluids. Table 7 lists some Lewis-acid-forming metals and their relative reactivity (Ref. 23).

Although a few studies have answered the question of why PFPE lubricants break down, none have shown how breakdown can be prevented. One solution has been to use ceramic-coated balls to reduce the number of acid sites. This will be discussed in a following section.

Other Synthetic Lubricants

Other fluids that have been used as lubricants for space are polyalphaolefin (PAO) and polyolester (POE). Their molecular structures are shown in Table 5. The vapor pressure of these fluids is not as low as PFPE's but they are lower than mineral oils. It has been found that removal of the light fractions of the oil can reduce the vapor pressure several orders of magnitude without affecting the room temperature viscosity (Ref. 71).

These synthetic hydrocarbons can be blended with conventional additives to provide the same protection against wear, oxidation, and corrosion as achieved by mineral oils. However, the low vapor pressures of these base stocks make the additives the most volatile constituents of the formulated lubricant. Thus, new additives with lower volatilities need to be developed.

A new class of synthetic lubricants, silahydrocarbons (SiHC), has shown potential for space application. The fluid has not been tested in an actual application, but the results of four-ball and traction tests are very encouraging (Refs. 60, 61, and 66). The structure of this class of fluids is shown in Table 5.

Another new class of fluids, which have been synthesized from hydrocarbons, has recently been prepared and evaluated (Refs. 76 and 77). The fluids, called multiply alkylated cyclopentanes (MAC's), were prepared by reacting dicyclopentadiene with aliphatic alcohols. It was found that fluid properties could be tailored to specific applications by varying the nature of the alcohols used in the synthesis. Kinematic viscosities at 100°C of some of the fluids ranged from 2 cS to 20 cS. Viscosity indices ranged from 71 to 178, and pour points were as low as -57°C (Refs. 76 and 77). The fluids are still experimental, but preliminary results indicate that vapor pressure of at least some of the formulations should be low. Their structure is shown in Table 5.

LIQUID LUBRICANT ADDITIVES

The types of additives that are formulated into conventional mineral oils were discussed in the first article of this chapter. While the technology of lubricant additives is very well developed for terrestrial applications, there are quite a few unanswered questions about their use in space applications.

For example, most additives were empirically developed for use in atmospheric conditions, i.e., with oxygen and water vapor present. It is not certain whether these additives will function in the same manner in vacuum, without oxygen and water vapor. Murray et al. (Ref.

50) reported that oil-lubricated ball bearings operated in vacuum experience high torque after prolonged running. When air was reintroduced, the torque returned to its previous low level. This indicated that oxygen and/or water vapor were necessary for optimum lubricant behavior.

An additional problem may occur because chemicals are added to oils to chemically react with a particular bearing steel. If other bearing materials are used for space mechanical components, these additives may not adequately react perform their function.

A further problem, not related to lubrication, may occur with PFPE fluids. Antirust additives are often added to space lubricants to prevent the rusting of mechanical components when they are stored in air, prior to launch. PFPE oils do not offer the same oxidation protection (because of oxygen permeability) as do mineral oils, and, as mentioned previously, they do not dissolve the usual antirust additives. Thus, rusting of parts lubricated with PFPE oil could occur if stored for long periods of time in air before launch. This is a further encouragement to use coatings that are unaffected by oxidation.

GREASE LUBRICATION

A grease is a semisolid liquid that consists of a liquid lubricant (oil) and a thickener. The oil does the lubricating while the thickener is used to hold the oil in place and provide a resistance to flow. The consistency of grease varies: it may be so hard that it could be cut with a knife or soft enough to pour.

The characteristics of the grease are largely determined by the thickener. If the thickener is hydrophobic, the grease will be unaffected by water; if the thickener has high-temperature stability, the grease will function at high temperatures, etc. Usually greases are thickened by soaps. A soap is a metallic element reacted with a fat or fatty acid. Metallic elements used to make soaps include: lithium, calcium, sodium, aluminum, and barium. In addition to soaps, lubricating additives such as PTFE graphite, and lead are sometimes used as thickeners. Additives are often added to greases to provide anti-oxidation, -rust, and -corrosion, improved load carrying ability, etc. Table 8 presents a list of some commonly used greases for vacuum applications. See Refs. 26, 42, and 43 for additional information.

MECHANISM MATERIALS

Choosing the correct material to make a mechanism is as important as choosing the right lubricant. Simply put, the incorrect choice of mechanism material can lead to the premature failure of a component regardless of the choice of lubricant. The chemical properties of the mechanism material can cause breakdown of the lubricant under sliding conditions or it can militate against the formation of boundary films necessary for adequate lubrication. The physical properties of the mechanism material are also important. It must have the necessary load-carrying ability (hardness), and it must have good tensile and compressive-stress properties.

In general, the guidelines established for terrestrial applications should also apply to space applications. For example, AISI 300 series stainless steel should never be used as a rolling- or sliding-contact material. Even though they may be a space-qualified material for structural applications, these steels do not have good load carrying properties and do not form good boundary-lubricant films, either with liquid or solid lubricants. When they fail, gross galling of the surfaces can occur.

When dealing with mechanism materials, one must separate the properties of the bulk from the properties of the surface. A mechanism will need particular bulk properties to carry the load, etc., and it will need particular surface properties to prevent lubricant degradation and to stimulate the formation of boundary-lubricant films. One way to separate bulk and surface

properties is to apply surface films or coatings to materials that would not ordinarily be used as mechanism materials. An example of this is the application of titanium carbide (TiC) coatings to rolling-element-bearing balls to reduce the degradation of PFPE films (Refs. 8 to 10). Another possibility is to ion implant certain materials into the surface of bearing materials to improve their surface reactivity or their wear resistance. Both of these techniques are relatively new technologies and need further development to improve their reliability.

TYPES OF BEARING ANOMALIES OR FAILURES

Cage Instability

Failure of bearings or anomalies in their behavior can be caused by increased bearing torque or the bearing torque variations that result from the erratic motion of a bearing cage (separator). The predominant reason for failure is the interaction between the cage and the ball. Under ideal conditions, the cage simply rotates with the balls. But, if for some reason the cage strikes a ball, the ball skids and generates a reactive force against the cage. This force can cause a rapid secondary motion to the cage, which is known as cage instability. Figure 10 (Ref. 37) is an example of typical torque fluctuations measured in a bearing operating in an unstable mode.

To prevent cage instability, the ball-and-race interfaces must be kept at the proper stiffness, and the energy developed by the ball-and-cage collisions must be absorbed at the proper rate at the interface. Stevens and Todd at the European Space Tribology Laboratory recognized three types of instability and showed ball spacing to be the principal controlling parameter (Refs. 70 and 75). Under their experimental conditions they showed that cage instability could be controlled by removing one or more balls or by making cages with unequally spaced ball pockets. Generally, low-viscosity fluids reduce cage instability more readily than a high-viscosity fluid, because the cage energy can be better absorbed by the shear losses in the lubricant films (Ref. 37).

Blocking

The European Space Tribology Laboratory (ESTL) reported progressive torque increases with hard-preloaded pairs of ball bearings when they were oscillated over an arc of 90 deg (Refs. 73 to 75). They referred to this phenomenon as "blocking." Lowenthal (Ref. 40) reported a similar phenomena on a preloaded pair of 27-mm-bore, duplex angular-contact ball bearings mounted face to face. Under repeated cycling, the drag torque increased from an nominal 14 N mm to as high as 127 N mm, nearly the stall torque of the drive motor.

Lowenthal related blocking to a ball misalignment that caused the balls to advance or recess from the average speed, thus squeezing the cage's pockets. Todd suggested that, in addition to misalignment, ball transverse creep was a necessary ingredient to produce blocking. Tight ball-and-race conformity (51.8 percent) readily produces blocking because of the sensitivity of ball speed to changes in contact angle. Under conditions of loose (57 percent) ball-and-race conformity, blocking has never been observed. Conformity is defined as race radius divided by the ball diameter.

Raceway Deposits

Torque spikes in oscillating bearings can also be caused by debris piling up at the end of the ball paths under repeated cycling (Ref. 53). The debris only builds up within the races when

the ball tracks do not overlap; otherwise, it is pushed to the outside of the ball tracks by the motion of the balls.

The source of the debris usually comes from lubricant breakdown, lubricant polymerization, or wear particles. Meeks et al. (Ref. 44) discussed the polymerization of F-50 oil-lubricated bearings. An inverse correlation was suggested to occur between the theoretical oil film thickness and the amount of polymer observed. Since the tests were performed below the polymerization or crosslinking point of the oil (589K), they speculated that the temperatures generated within microasperity contact points were enough to cause the oil to polymerize.

Lubricant Breakdown

Liquid lubricants can break down, polymerize, or crosslink due to high temperatures, radiation, or chemical reactions that occur during boundary lubrication. Since most lubricants are shielded from radiation in space, breakdown from this mechanism should not be a problem. As mentioned in the previous section, polymerization of oils has been postulated to occur, even though the bulk oil temperature is below the breakdown or polymerization point, due to the heat developed at microasperity contact areas.

Since very high temperatures can be created in the lubricant contact area, the area can in fact become a microreaction chamber. In this regard, the perfluoropolylethers (PFPE) have been found to break down under boundary lubrication conditions with certain metals or alloys. Several studies have been conducted to investigate the breakdown of these fluids. Morales (Ref. 46) has shown that various materials can catalytically cause the degradation of these fluids. His tests involved the heating of a thin film of PFPE fluid on various materials for 30 min in dry air at 345°C (653°F). The material that caused the greatest degradation was 440C bearing steel. Carré (Refs. 21 and 22) has inferred that under boundary lubrication conditions and in the absence of oxygen PFPE interacts with the steel surface to form iron fluoride (FeF_3).

Mori and Morales (Refs. 47 and 48) evaluated PFPE fluids under sliding conditions in a vacuum chamber. All fluids they tested formed metal fluorides on the sliding surfaces. The fluid that contained the acetal group also gave off gaseous products while the others did not. They concluded that the tribological reaction of the PFPE is primarily affected by the activity of the mechanically formed fresh surfaces of metals rather than the heat generated at the sliding contacts.

Parched Lubrication

An important consideration in liquid lubrication is that the fluid quantity must be adequate to supply enough fluid for hydrodynamic and elastohydrodynamic lubrication or for additive replenishment during boundary lubrication. If the fluid or additive replenishment is not adequate, a phenomenon known as parched lubrication will occur. Parched lubrication results in microasperity contact and can cause premature component failure.

LUBRICANT SUPPLY TECHNIQUES

To Seal or Not to Seal

Seals in general, whether static or rotating, add to the complexity of any mechanical system and, because of the possibility of a seal failure, lower the reliability. Ahlborn et al. (Ref. 1), in discussing the design criteria of liquid lubrication systems, suggest that sealed systems be

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avoided whenever possible. However, for long-duration space missions where contamination of sensitive vehicle surfaces or of planetary surfaces is undesirable, sealed mechanical systems may be a necessity.

As stated in a previous section, the rate of lubricant loss in unsealed systems is dependent on its vapor pressure. Ahlborn et al. (Ref. 1) recommend that the lubrication system be designed so that the lubricant lost by evaporation be limited to 10 percent of the total lubricant supply. One way to do this is to make the escape orifices so small that molecular rebound collisions reduce the outward flow. Zaretsky (Ref. 82) reviews controlled leakage in more detail.

Impregnated Cages

One way to increase the lubricant supply to bearing contact areas is to make the cage out of a porous material. The porous material most often used in the past has been a phenolic-based material. One of the problems with this material is that the porosity is directional: layers of cotton material in the phenolic cage are parallel to the bearing races. This precludes lubricant flow to the bearing races, since the oil can not flow perpendicular to the cotton layers.

More recently porous polyimides have been used as cage materials. Although sparse, the data show that the porous polyimides function well as long as their surfaces are properly conditioned. One must avoid closing the pores of the material during machining or contaminating them with machining oil or with abrasive particles. Since the porosity of these polyimides is uniform, there is no directional problems with lubricant feed.

Barrier Films

In order to keep the lubricant where it is needed in space, creep barrier films are often used. Generally, these films are not used in contacting areas within a bearing but are sometimes used on the lands of the raceways with ball riding cages. Barrier films are often used around gaps to prevent the lubricant from creeping into undesirable places. One material developed by the U.S. Naval Research laboratory to prevent creep is fluorinated methacrylate. The material is stable in air to 423K and in vacuum to 373K.

Ahlborn et al. (Ref. 1) discuss the differences among some commercial barrier films. They recommend that extreme care be taken in choosing a barrier film for a particular application. They have observed that some lubricant formulations have appeared to poison the surface of the barrier film and render it ineffectual.

Positive-Feed Systems

In order for a bearing to operate in the optimum manner, the lubricant supply must be adequate. If not, parched lubrication or starvation can occur. In space, because of the lack of gravity and because of the emphasis on low weight and minimal oil usage, it can be a challenge to keep the supply adequate. Different devices have been used to provide lubricant to the rolling-element bearing contacts, such as centrifugal oilers and single-stroke pumps (Ref. 29).

A positive-pressure feed system (Fig. 11) proposed by James (Ref. 31) consisted of a sealed lubricant reservoir pressurized by a flexible metal bellows and an external spring pack. A release valve, metering bellows, and metering valve were used to control the flow. The applicator tip (PTFE coated) was inserted between the outer and inner race. When the system was opened, a drop of oil formed on the applicator tip. As a ball passed the applicator tip, the

oil was wiped off the tip and onto the ball. Thus, the oil is slowly and uniformly transferred to the retainer ball pockets and to both raceways.

Wick lubrication has also been proposed for use in lubricating moderate speed bearings. In terrestrial testing, it has been shown feasible (Ref. 40). In this system a lightly spring-loaded wick, saturated with oil, contacts a sleeve adjacent to a bearing inner race. The oil travels from a reservoir to and through the wick by capillary action. Frictional contact against the sleeve causes a small amount of oil to be deposited. This oil once deposited could then migrate, aided by centrifugal forces into the bearing.

APPLICATIONS

Briscoe and Todd (Ref. 15) have prepared a list of important space mechanisms (nonexclusive) and brief details of these mechanism's lubrication needs. Table 9 presents this list. Given in the table are the application type, the duty cycle, desired life, the type of employment environment, and perceived lubrication requirements. In general, Briscoe and Todd feel there are four broad categories of tribological mechanical contact: low- and high-speed sliding contact and low- and high-speed rolling contact.

Briscoe and Todd (Ref. 15) believe that tribology is often overlooked by designers when building a mechanism and have defined what they call the first precept of space tribology.

"The optimum lubrication system for a space mechanism is an integral part of the mechanism design and not a process to be added when the design is complete."

CONCLUDING REMARKS

In the past, spacecraft liquid lubrication systems have preformed adequately in meeting their required lifetimes. Future requirements on lubricating systems may not be as easily accomplished, however. Requirements for longer lives, higher reliability, higher performance, and contamination are being specified. The current technology may not be adequate to meet these requirements—especially not, for long-duration missions planned to the Moon and Mars. On planetary surfaces in a dusty, abrasive, and possibly corrosive environment, the requirements for life, low maintenance, and reliability may be beyond the current state-of-the-art technology.

ACKNOWLEDGEMENT

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TABLE 1.—FOUR-BALL EXTREME PRESSURE WEAR TESTS

(from Ref. 30)

Lubricant	Load-carrying capacity	
	760 mm Hg	200 mm Hg
Petroleum	23.0	9.3
Petroleum + 5 percent TCP[a]	34.0	22.2
Petroleum + 5 percent ZnR_2S_2P[b]	52.1	37.9
Diester	20.9	15.1
Diester + 5 percent TCP	30.9	26.2
Diester + 5 percent ZnR_2S_2P[b]	39.1	37.3

[a]Tricresyl phosphate.
[b]Zinc dialkyl dithiophosphate.

TABLE 2.—REACTION EFFICIENCIES OF SELECTED MATERIALS WITH ATOMIC OXYGEN IN LOW EARTH ORBIT

(from Ref. 38)

Material	Reaction efficiency, $cm^3/atom$
Kapton	3×10^{-24}
Myler	3.4×10^{-24}
Tedlar	3.2×10^{-24}
Polyethylene	3.7×10^{-24}
Polysulfone	2.4×10^{-24}
Graphie/Epoxy: 1034C	2.1×10^{-24}
5208/T300	2.6×10^{-24}
Epoxy	1.7×10^{-24}
Silicones	$<1.7 \times 10^{-24}$
PTFE	$<0.05 \times 10^{-24}$
Carbon (various forms)	0.9 to 1.7×10^{-24}
Silver	Heavily attacked

TABLE 3.—EFFECT OF VISCOSITY ON EVAPORATION RATE OF LUBRICANTS IN VACUUM (10^{-6} torr)

(from Ref. 37)

Lubricant	Viscosity at 40°C, $10^{-6}m^2/\text{sec}$	Weight loss rate at 40°C, $\text{mg/cm}^2\cdot\text{hr}$
Super-refined paraffinic mineral oil:		
SRG 30	14	18
SRG 40	27	13
Perfluoro ether	8	2.2
	28	0.19
	357	0.0002

TABLE 4.—PROPERTIES OF SOME COMMONLY USED SPACE LUBRICANTS

Type of lubricant	Average molecular weight	Viscosity at 20°C, cS	Viscosity index	Pour point, °C	Vapor pressure, Pa	
					At 20°C	At 100°C
KG-80, mineral oil	-----	520	101	-9	1×10^{-6}	----
Apiezon C, mineral oil	574	250	----	-15	5×10^{-7}	----
BP 110, mineral oil	-----	120	108	-24	5×10^{-7}	----
BP 135, ester	-----	55	128	-45	1×10^{-6}	----
NYE 179, PAO	-----	[a]30	139	<-60	9×10^{-7}	----
Nye UC7, neopentyl-polyolester	-----	75	----	-56	7×10^{-7}	----
Nye UC4, neopentyl-polyolester	-----	44	----	---	3×10^{-6}	----
SiHC$_1$, silahydrocarbon, type 1	1 480	278	125	-50	-------	----
SiHC$_2$, silahydrocarbon, type 2	1 704	480	128	-15	-------	----
Fomblin, PFPE (bray 815Z)	9 500	255	355	-66	4×10^{-10}	1×10^{-6}
Krytox, PFPE	11 000	2717	----	-15	4×10^{-12}	1×10^{-7}
Demnum, PFPE	8 400	500$\pm$25	210	-53	7×10^{-9}	1×10^{-5}

[a]Viscosity at 40°C.

Table 5.—Molecular structure of some commonly used space lubricants.

Type of fluid	Molecular structure
Silicones	$R-Si(O-Si)_n O-Si-R$ with R substituents; $n = 0$ to 5, $R = CH_3$, $-\bigcirc$
Perfluoroethers (PFPE), Fomblin Z, Braycote 815Z	$CF_3-O-(CF_2-CF_2-O)_m-(CF_2-O)_n-CF_3$
PFPE, Fomblin Y	$CF_3-O-\left(\underset{F}{\overset{CF_3}{C}}-CF_2-O\right)_m-(CF_2-O)_n-CF_3$
PFPE, Krytox	$CF_3-CF_2-CF_2-O-\left(\underset{F}{\overset{CF_3}{C}}-CF_2-O\right)_m-CF_2-CF_3$
PFPE, Demnum	$CF_3-CF_2-CF_2-O-(CF_2-CF_2-CF_2-O)_m-CF_2-CF_3$
Polyalphaolefin (PAO)	$CH_3-\underset{(CH_2)_7}{\overset{CH_3}{CH}}-\left(CH_2-\underset{(CH_2)_7}{\overset{CH_3}{CH}}\right)_n-(CH_2)_9 CH_3$; $n = 1$ to 10
Polyolester (POE)	$R-\overset{O}{\overset{\|}{C}}-O-CH_2-\underset{CH_2-O-\overset{O}{\overset{\|}{C}}-R}{\overset{CH_2-O-\overset{O}{\overset{\|}{C}}-R}{C}}-CH_2-O-\overset{O}{\overset{\|}{C}}-R$
Silahydrocarbons (SiHC)	$R'-\underset{R}{\overset{R}{Si}}-R$ $R' = CH_3$ or CH_2CH_3 $R' = C_8$ to C_{12}
Multiply-alkylated cyclopentanes (MAC)	$\bigcirc\left(CH_2-\underset{(CH_2)_9-CH_3}{\overset{(CH_2)_7-CH_3}{CH}}\right)_3$

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TABLE 6.—FACTORS THAT INFLUENCE THE DEGRADATION OF PFPE FLUIDS

Promotes degradation	Retards degradation
Starved conditions	Fully flooded conditions
Low specific film thickness	High specific film thickness
Linear structure	Branched structure
Aluminum/titanium substrates	Hydrocarbon contamination
AISI 440C steel	Ceramic coatings
Temperatures >200°C	Low ambient temperatures
Sliding surfaces	Rolling surfaces
Vacuum environment	Atmospheric conditions

TABLE 7.—REPRESENTATIVE LEWIS-ACID-FORMING METALS

(Ref. 23)

Metal	Relative reactivity
Titanium	100
Aluminum	35
AISI 440C	22
Iron	12

TABLE 8.—COMMONLY USED GREASES FOR VACUUM APPLICATIONS

(From Refs. 26, 42, & 43)

Type of grease	Base oil	Thickener	Additives	General remarks
BP 2110	BP 110	--------	Lead, graphite	Rust inhibitor added (ESA grease)
BP 8135	BP 135	--------	Lead, graphite	Rust inhibitor added (ESA grease)
G-300	Methyl chlorophenyl polysiloxane	Lithium stearate	-------	(Ref. 6), for properties description
Apiezon	Hydrocarbon	PTFE	-------	Various formulation for different applications. (Refs. 42 and 43)
Braycote 3L-38RP	Fomblin Z25	PTFE	-------	Small traces of hydrocarbons improved performance (Ref. 70)
Micronic 803	PFPE	PTFE	-------	(Refs. 42 and 43)
Vac kote	Sythetic oils	Nonmelting	Various	(Refs. 42 and 43 for different formulations and properties)
M-8	Hydrocarbon	None	-------	
ES (MIL-G-25-760A)	Diester	--------	-------	Used on Skylab thermal control fan bearings
Si-6	Silicone	Lithium soap	-------	Has not performed well in vacuum, not recommended (Refs. 25 and 26)
FS-1	Fluorosilicone	Silica	-------	Not recommended for vacuum use in ball bearings (Refs. 25 and 26)
PFPE-1	PFPE	PTFE	-------	Used for Apollo telescope mount CMG actuators (Refs. 25 and 26)
PFPE-2	PFPE	Lithium soap	-------	Possesses a high viscosity index. (Refs. 25 and 26)
Krytox, 250AC, 260AC, 280AC	Krytox	PTFE	MoS_2, rust inhibitors	Different compositions depending on applications (Refs. 42 and 43)

TABLE 9.—COMMON SPACE MECHANISMS AND THEIR TRIBOLOGY NEEDS

[Ref. 15.]

Application	Duty	Life	Environment	Lubrication requirements
Solar array (Hold down points and latches)	Deploy and retract	50 operations	Space exposed thermal −60°C to −80°C launch vibration loads	Dry: High load capability, good fretting resistance
Focussing mechanism	Intermittent operation cycles 10,000–100,000	7 to 10 years	Space exposed thermal 0°C to 20°C	Dry: Low and consistent friction. Absolute freedom from contamination. Low wear rate. Corrosion protected.
Filter wheels, shutters, beam splitters, etc.	Intermittent operation 10,000–20,000 cycles	7 to 10 years	Space exposed thermal 0°C to 20°C	Dry or liquid: Low and absolute freedom from contamination. Corrosion protection.
Slip rings and brushes	1) Low speed continuous operation	7 to 10 years	Space exposed thermal −40°C to +65°C	Dry: Low and consistent friction. Absolute freedom from contamination. Low and consistent electrical noise.
	2) High speed, intermittent operation	7 to 10 years		Dry or liquid: Low wear rate, low electrical noise
Gears	1) Intermittent operation 1000 cycles	7 to 10 years in space	Space exposed thermal −40°C to +65°C	Dry or liquid: Low and consistent-friction. No contamination
	2) Continuous operation	7 to 10 years		Dry or liquid: Low wear and low friction. No contamination

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TABLE 9.—Continued.

Application	Duty	Life	Environment	Lubrication requirements
Momentum wheels	Continuous rotation at 3000 to 4500 rpm	7 to 10 years	Closed, low-pressure He	Liquid: Maintenance of a controlled flow of lubricant into EHL zone to achieve low and consistent torque. Low wear rate.
Solar array drive	Continuous rotation at 1 to 16 revolutions per day	7 to 10 years	Space exposed thermal −40°C to +65°C	Solid or liquid: Boundary lubrication with consistent torque. No contamination, moderate load, corrosion protection.
Antenna pointing mechanism	Slow intermittent operation over small angle and occasional fast tracking	7 to 10 years	Space exposed thermal −40°C to +65°C	Solid or liquid: Boundary lubrication with consistent torque. No contamination. Moderate to high load capacity, corrosion protection
Instrument pointing systems	Slow intermittent operation over small angle, very high precision	1 to 4 weeks 5 years storage	Space exposed thermal −20°C to +60°C	Liquid: Boundary lubrication with low and consistent torque. No contamination. High load capacity, corrosion protection
De-spin mechanism	Continuous operation at 15 to 60 rpm	7 to 10 years	Space exposed thermal −40°C to +65°C	Solid or liquid: Controlled quantity of oil or grease. Low and consistent torque over temperature range. Low wear rate, corrosion protection.

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TABLE 9.—Concluded.

Application	Duty	Life	Environment	Lubrication requirements
Rotating scanner	Continuous opera- tion at 15 to 60 rpm.	7 to 10 years	Space exposed thermal −0 to 20°C	Solid or liquid: Controlled quantity of oil or grease. Low and consistent torque. Absolute freedom from contamination.
Booms	(1) Deploy only	50 operations	Space exposed −40°C to +65°C	Dry: Consistent friction over temperature range
	(2) Deploy and retract.	100 opera- tions after long space stay	Space exposed launch vibra- tion loads	Dry: Consistent friction over temperature range and life. No contamination.
Solar array (hinges)	(1) Deploy only	20 operations	Space exposed −60°C to +80°C	Dry: Consistent friction over temperature range.
	(2) Deploy and retract.	50 operations after long space stay	Space exposed thermal −60°C to +80°C	Dry or liquid: Consistent friction over temperature range for long life required. No contamination.
Antenna deployment	Deploy only	20 to 50 oper- ations	Space exposed thermal −60°C to +80°C	Dry: Consistent friction over temperature range.
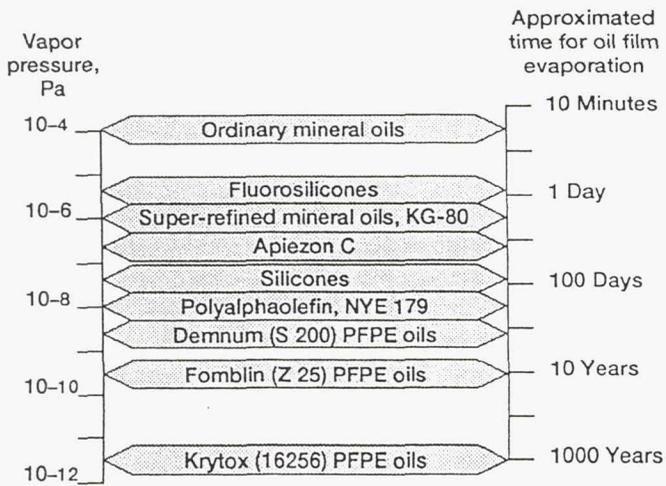
Fig. 1. Vapor pressure at 20 °C of commonly used space lubricants and approximated time for a 10-μm-thick film of lubricant to evaporate in vacuum. (Data taken from refs. 4, 7, 47, 56, 58, 59, 82).
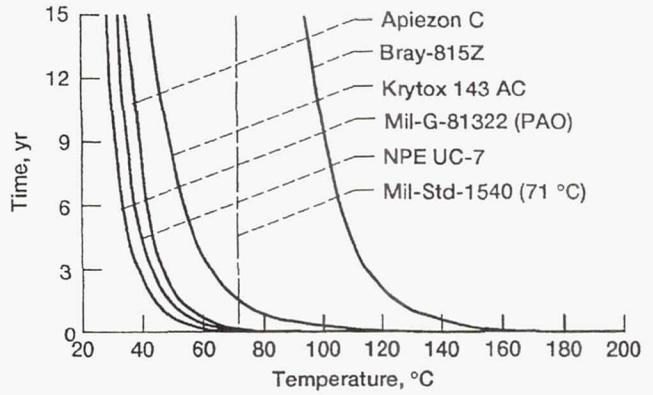

Fig. 2. Time in years to lose 1.0 ml of lubricant oil per cm^2 of outlet area as function of temperature (from Ref 20).
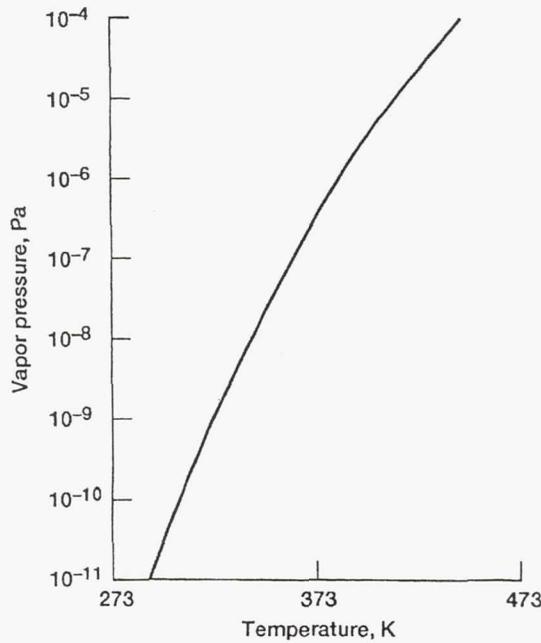

Fig. 3. Variation of vapor pressure as a function of temperature for a high-performance liquid lubricant (Ref. 38).
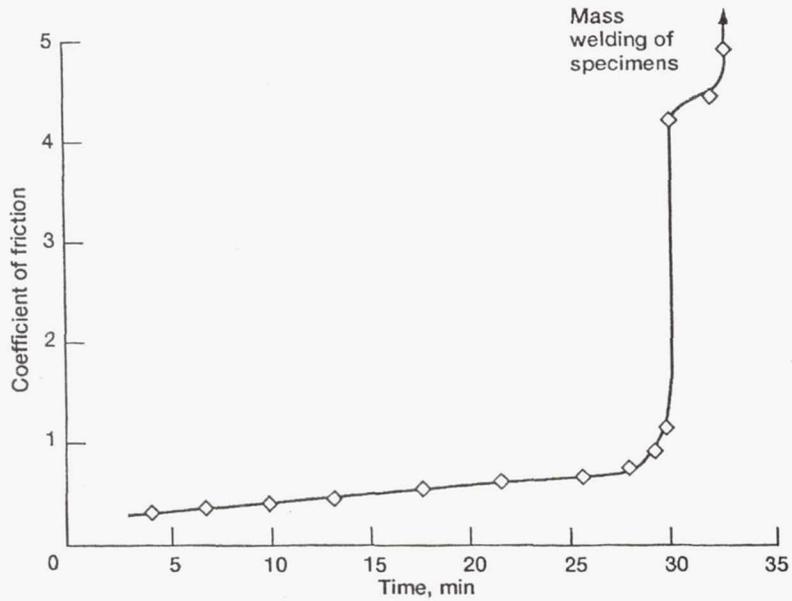
Fig. 4. Coefficient of friction as a function of time for 52100 steel sliding on itself unlubricated in a vacuum of 3×10^{-5} Pa. Sliding conditions: 2 m/s, 1 kg load (from Ref. 17).
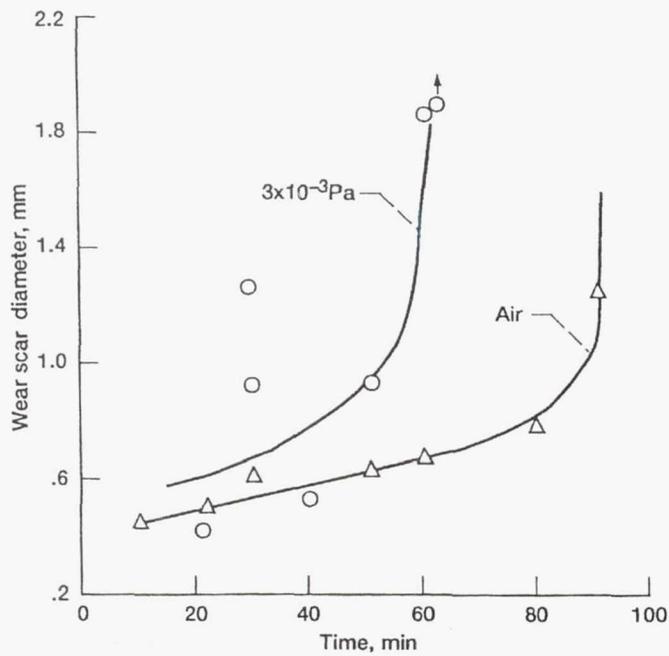
Fig. 5. Comparison of wear in air and in vacuum. Test conditions: cross-cylinder load tests, 0.64 cm hardened 52100 steel, 95 rpm speed, refined mineral oil lubricant, 1 hr test time at ambient temperature (from Ref. 55).

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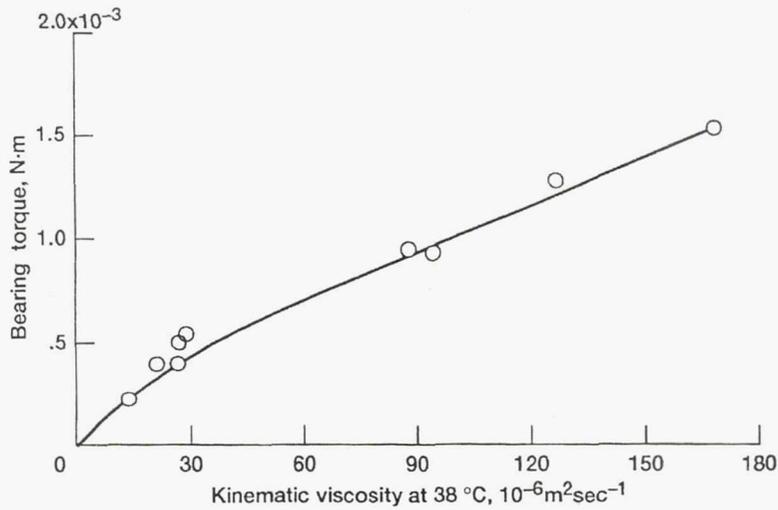
Fig. 6. Measured bearing torque as a function of lubricant viscosity for various lubricants at 25°C for and R-6 bearing at 480 rpm (from Ref. 37).
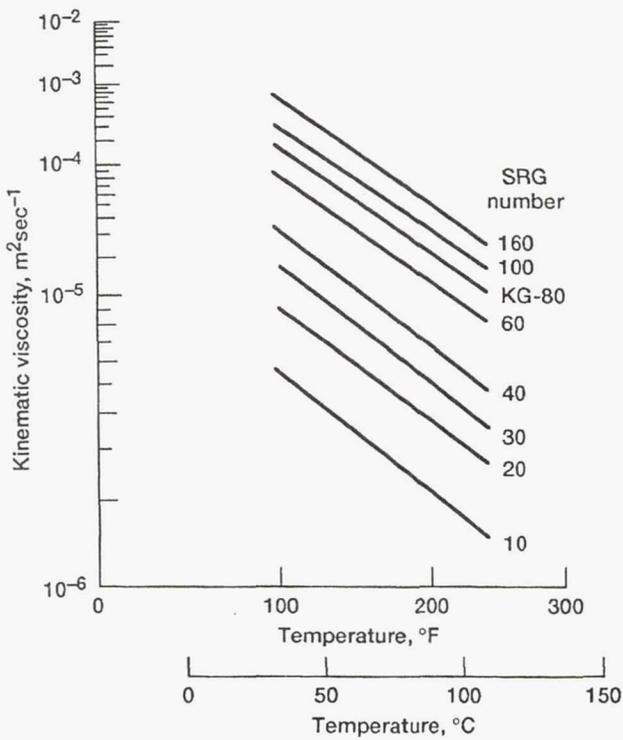

Fig. 7. Viscosity as a function of temperature for a homologous series of super-refined mineral oils (from Ref. 37).
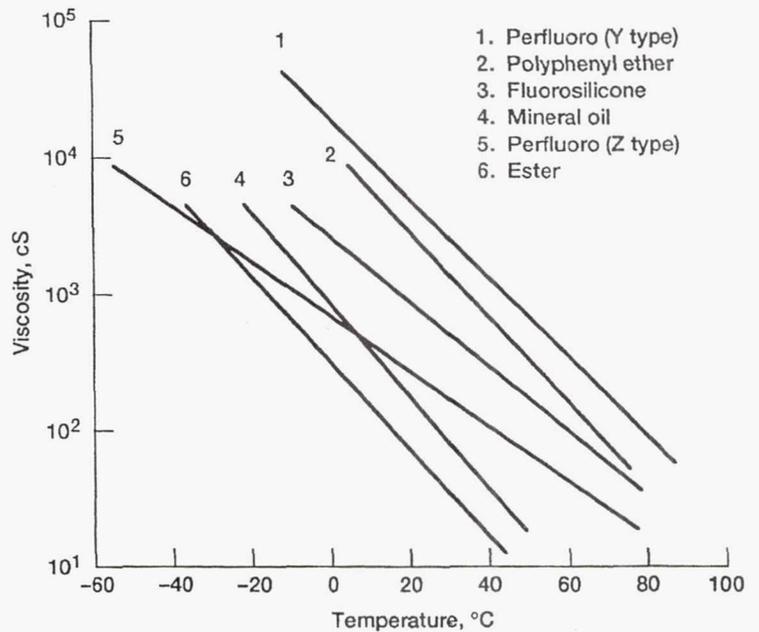
Fig. 8. Typical changes in viscosity with temperature for various types of lubricants (from Ref. 56).

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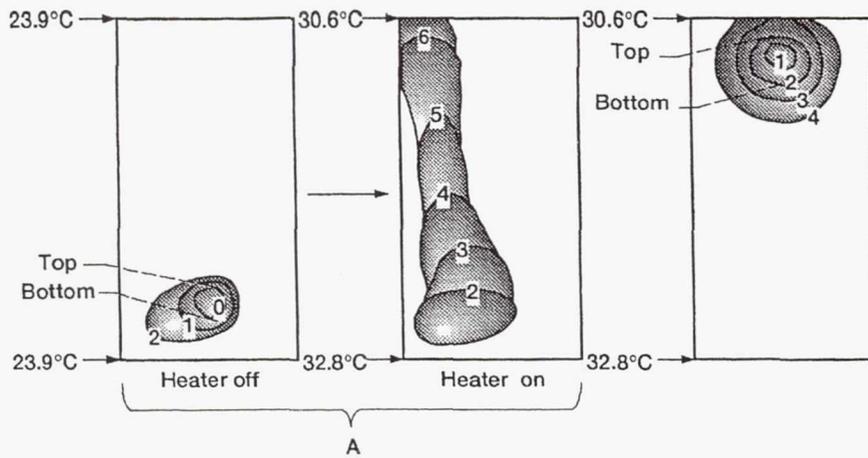
Fig. 9. Migration patterns of superrefined mineral oil KG-80 in the presence of a 2.2°C thermal gradient (from Ref. 37).
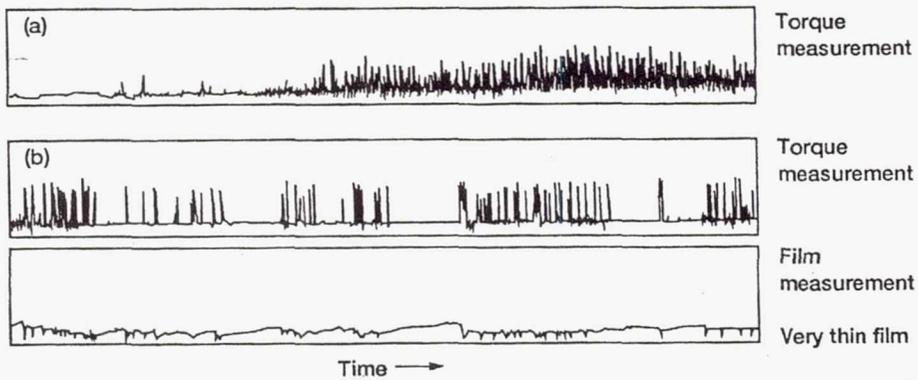

Fig. 10. Bearing torque and film thickness measurement with (a) dry bearing, (no lubricant) and (b) two drops of oil (meager lubricant). Torque spikes imply instability (from Ref. 37).
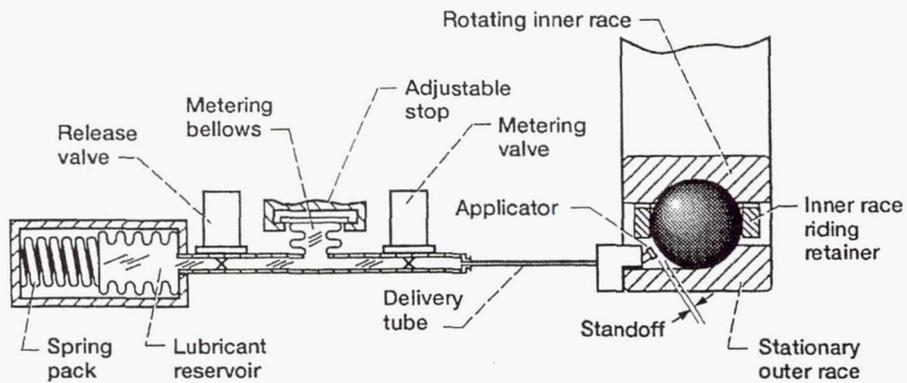

Fig. 11. Positive commandable lubricator for satellite bearing applications (Ref. 31).

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This paper reviews the state of the art of liquid lubrication for space applications. The areas discussed are: types of liquid lubrication mechanisms, space environmental effects on lubrication, classification of lubricants, liquid lubricant additives, grease lubrication, mechanism materials, bearing anomalies and failures, lubricant supply techniques, and some applications and lubricant needs for those applications.

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