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SPACE STATION LUBRICATION CONSIDERATIONS

Lubert J. Leger* and Keith Dufrane**

ABSTRACT

Future activities in space will require the use of large structures and high power availability in order to fully exploit opportunities in Earth and stellar observations, space manufacturing and the development of optimum space transportation vehicles. Although these large systems will have increased capabilities, the associated development costs will be high, and will dictate long life with minimum maintenance. The Space Station provides a concrete example of such a system; it is approximately one hundred meters in major dimensions and has a life requirement of thirty years. Numerous mechanical components will be associated with these systems, a portion of which will be exposed to the space environment. If the long life and low maintenance goals are to be satisfied, lubricants and lubrication concepts will have to be carefully selected. Current lubrication practices are reviewed with the intent of determining acceptability for the long life requirements. The effects of exposure of lubricants and lubricant binders to the space environment are generally discussed. Potential interaction of MoS_2 with atomic oxygen, a component of the low Earth orbit environment, appears to be significant and further study of the specific interactions is suggested.

INTRODUCTION

Examination of planned future space activities shows a significant increase in the need for large space structures. Within the American civil space program, the Space Station seems to be developing into a mature objective and future defense systems could also benefit from the use of large space structures. The cost of developing such systems will dictate long life, thirty years in the case of the Space Station. Designing for a specific life, rather than accepting system or component life limitations, will be implemented for the first time. These large systems will be launched in packaged form and deployed on orbit and therefore, will be lightweight and thin walled. Large, rotating joints of unique design will be required to orient the solar power systems.

The unique design, size, and life requirements for the Space Station mechanical systems, combined with a need to minimize in-space repair or refurbishment activities, dictates careful lubricant selection. Two lubricant selection considerations, which seem unique to large space systems, are the long life requirement, and effect of lubricant exposure to the space environment. This paper addresses both of these issues, but

*NASA Lyndon B. Johnson Space Center, Houston, Texas
**Battelle Columbus Laboratories, Columbus, Ohio

emphasizes the latter issue by applying information gathered on the effects of the space environment on materials over the last few years to lubricant systems. Some of the anticipated effects have not been considered before, but appear to be life limiting for lubricants in certain mechanism designs. This information is presented to make the designer aware of such effects and emphasize the need for further study of the potential interaction between lubricants and the space environment, rather than provide definitive solution guidelines. General issues which must be addressed in selection guidelines are outlined.

SPACE ENVIRONMENT EFFECTS

The Space Station's long life requirement demands that issues which may not have been important for relatively short-lived spacecraft operating in the low Earth orbital environment be reconsidered. Exposure of lubricated surfaces to the space environment may result in lubricant changes severely limiting component life and producing maintenance requirements which will be difficult, at best, to satisfy. A discussion of each aspect of the environment which may be important to lubricant life and performance, therefore, is appropriate.

Thermo-Vacuum

In a period of thirty years, Space Station components will be exposed to 175 000 thermal cycles. The depth of these thermal cycles will be controlled primarily by the optical properties of the surface in question unless active thermal control is provided. It may be difficult to provide the required lubricating and thermo-optical properties simultaneously for exposed lubricated surfaces. This difficulty, combined with a desire to conserve energy, certainly indicates that lubricants which perform over a large temperature range will be advantageous.

The vacuum environment, to which the lubricants will be exposed, is another important consideration. Although this subject area has been extensively addressed in both lubricant studies, as well as spacecraft design, the extended exposure may be life limiting for liquid film lubricants. For example, some of the best liquid film lubricants have vapor pressures as shown in Fig. 1, ref. 1, and by using the Langmuir expression (ref. 2), shown below, the evaporation rates of lubricant films can be estimated.

$$R_{\mathrm{evap}} = \frac{P}{17.14}\left(\frac{M}{T}\right)^{1/2}$$

P = vapor pressure (mm of Hg)
M = molecular weight (assume 15 000)
T = temperature of lubricant (°K)

Assuming an average molecular weight of 15 000 for this material and using the vapor pressure data, the time necessary to evaporate a film of 2.5 × 10^{-4} cm is shown on the upper axis of Fig. 1. As can be seem from the figure, the loss rate is a strong function of temperature. This is the worst case loss rate and can be reduced by enclosing the lubricant within the lubricated joint. Significant loss of lubricants in confinement will be complicated by the large size, long life, and thermal exposure of moving surfaces.

Outgassing from liquid film lubricants can produce contamination on sensitive optical systems and must be considered as part of the lubricant selection process. The acceptability of the use of liquid film lubricants near such optical systems will depend upon the characteristics of the lubricant involved and mechanism design. Contamination requirements for the Space Station (contained in ref. 3) should be used as general guidelines for lubricant contamination assessment. These requirements address three items, vacuum volatibility, molecular deposition, and particle production, which are pertinent to lubricant selection.

Another aspect of joining or moving materials relative to each other in space that was once considered important and must be reconsidered for Space

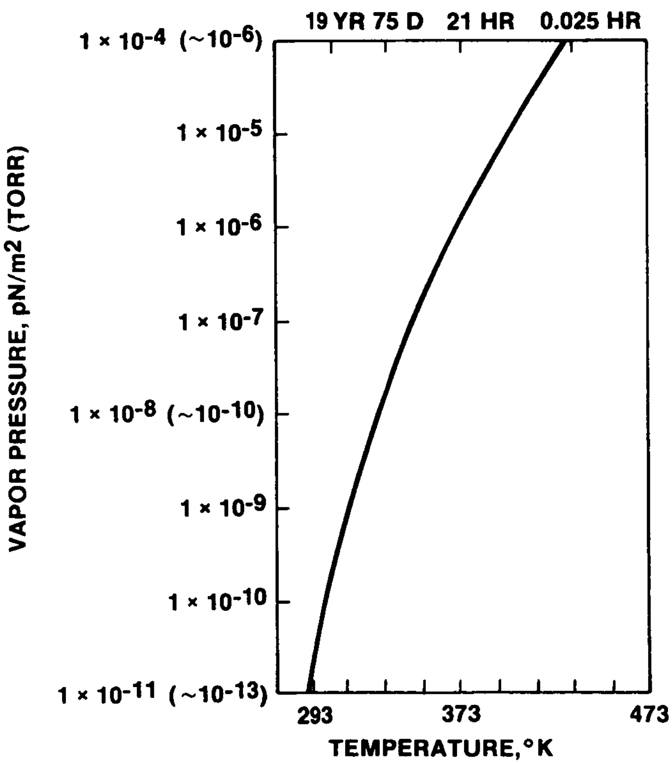

Figure 1. Vapor Pressure of High-Performance Liquid Lubricant

Station application is cold molecular welding. Impact of this consideration on past spacecraft has been limited in some cases because of short life and high localized pressure (contamination) associated with joint design. Both of these considerations will not be operative for the Space Station because of the long life requirement. Outgassing will be significantly reduced for two reasons, stringent contamination requirements, and long exposure to the thermo-vacuum environment. Cold molecular welding is even an important consideration for structural member, end fitting joints which must be capable of being disassembled at any point for repair of micrometeorite or debris damage. Certifying a coating for these joints, which would preclude cold molecular welding for thirty years, will surely be a challenge.

Ultraviolet Radiation

Some surfaces on the Space Station, such as the rotating joints (associated with the solar power systems) or tracks (for large remote manipulators), will be exposed to as much as twelve years of constant solar radiation during a thirty year life. Current data on ultraviolet exposures of materials is limited to one year exposure for a minimal number of materials. Lubricant changes on exposure to this environment have not been assessed, but will certainly be important for liquid film and organic based solid film lubricants.

Atomic Oxygen Effects

Atomic oxygen, the major constituent in the low Earth orbit (LEO) environment, has only recently been recognized (refs. 4 and 5) as being an important consideration in the design of surfaces of long-lived spacecraft. Several experiments have been conducted on Space Shuttle missions to quantify material degradation caused by atomic oxygen. Experiments on two of these missions, Space Transportation System (STS) 5 and STS-8, provide essentially all of the quantitative data available to date (see ref. 4). Of the two general classes of materials, metals and non-metals, the metals are the least reactive to atomic oxygen. More than 20 metal surfaces have been exposed during these Shuttle flight experiments and, of these, only three: carbon, silver, and osmium, interact quickly enough to produce macroscopic changes. Carbon interacts with atomic oxygen to form volatile oxides. Silver forms heavy oxide layers typical of oxidative attack, which results in loss of material by flaking and spallation. Osmium loses mass apparently through the formation and loss of OsO_4, which has a relatively high vapor pressure. Generally, all of the other metals have significantly lower interaction rates than carbon, silver, or osmium.

All organic materials such as epoxies, polyurethanes, and polyimides, which are commonly used on spacecraft surfaces are reactive with the LEO environment. Reaction efficiency does not seem to be strongly dependent on chemical structure. However, additives do seem to be significant, since they are often oxides or other less reactive components which shadow the organic matrix from the incoming ambient oxygen atmosphere. Reaction efficiencies for a representative set of materials are shown in Table I.

These efficiencies (expressed as the volume of material lost per incident oxygen atom) are derived by normalizing material recession by exposure fluence.

TABLE I.- REACTION EFFICIENCIES OF SELECTED MATERIALS WITH ATOMIC OXYGEN IN LOW EARTH ORBIT

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

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

To determine the effect on Space Station surfaces, only the total atom fluence and material description or reactivity is necessary. The fluences shown in Table II are derived by grouping the surfaces into three types of orientations relative to the velocity vector: forward facing, solar inertial, and deep space inertial, using the current constant drag Space Station flight approach (ref. 5). Assuming an exposed lubricant surface with an epoxy-based lubricant binder and a reaction efficiency of 1.7×10^{-24} cm^3/atom, the recession shown in Table II can be expected for a full thirty year exposure. Because a typical dry film lubricant application uses approximately 2.5×10^{-4} cm thick films, some of which are predominantly epoxy based, this type of lubricant would be lost or severely affected in less than ten days. For such thin and relatively reactive lubricants, even scattered atomic oxygen may become life limiting to organic binders used in lubricant films.

Other, nonorganic, lubricant binder systems should be less reactive than the epoxy system discussed above. Perfluoronated based polymers, which are used as both binders and lubricants, are considerably less reactive than their organic counterparts, as shown in Table I . Even with this lower reactivity, thin films ($\sim 2.5 \times 10^{-4}$ cm) could be totally removed in one year. Silicate, and glasses in general, are not reactive with atomic oxygen because of their highly oxidized state, and should, therefore, be adequate for use as binders for lubricant systems.

Examination of the reactivity of lubricating agents with the space environment indicates a need for additional study. The data from Table I represents the general reactivity of some lubricating agents. For example, perfluoronated oils and greases may be sufficiently stable to atomic oxygen so as not to preclude their use, consistent with the volatility limitations discussed earlier. Silicone based oils and greases have similar volatility limitations, but, in addition, are reactive, producing silicates in the process and possible changes in physical properties. Carbon, although not a candidate space lubricant, is reactive and should not be used in exposed configuration.

TABLE II.- SURFACE RECESSION PREDICTIONS FOR SPACE STATION COMPONENTS

Materials	Lifetime, Yr	Fluence, Atoms/cm^2	Recession*, cm (Mil)
Forward facing surface	30	1.5×10^{23}	0.25 (100)
Solar inertial	30	8.2×10^{22}	0.14 (55)
Deep space pointing	30	9.5×10^{22}	0.16 (64)

*Assumes an epoxy-based surface.

Study of the behavior of the mainstay space system lubricating agent molybdenum disulfide (MoS_2) in the atomic oxygen environment is required in order to properly define its potential for lubricating long life systems. Although no evaluation of the reactivity of MoS_2 to atomic oxygen has been conducted, it is known that MoS_2 does form molybdenum oxides in oxygen containing environments at elevated temperatures; therefore, reaction with atomic oxygen can be expected. If reaction proceeds to complete oxidation, two oxides, MoO_2 and MoO_3, are products that can be produced by the general reactions shown below.

$$MoS_2 + O \rightarrow MoO_2 + SO_x$$

$$MoS_2 + O \rightarrow MoO_3 + SO_x$$

Because of the high kinetic energy of the impacting atomic oxygen, it is not possible to predict the specific product of reaction. It is known, however, that MoO_2 is highly abrasive (ref. 6), and therefore, defining the reaction pathway is very important in determining the performance of MoS_2. Even conversion to the MoO_3 could change the lubricating properties significantly.

It is not possible, in the limited scope of this paper, to discuss the specific reactivities of all lubricating agents of interest. The examples covered describe lubricant interaction possibilities, which must be considered to ensure known life, and, hopefully, known long life. Generally, to ensure good performance, the oxidative stability must be carefully considered. Additionally, data on specific lubricants for use on the Space Station must be obtained to provide the basis for a thorough evaluation.

SUMMARY OF LUBRICANT SELECTION CONSIDERATIONS

The potential interactions of lubricants discussed in the sections above are summarized in this section to provide a more succinct set of issues to be addressed in lubricant selection. The discussion is divided into two parts; it addresses sealed mechanisms, and mechanisms in which lubricants may be exposed to space.

Sealed Mechanisms

Sealed mechanisms do not present any special lubricant problems, except for long life. Long life for certain mechanisms, such as the solar power system rotating joint, may be twenty to thirty years, or full life, in the ideal case. The alternative to this full life objective is refurbishment, which, in turn, requires the development of in-space repair or refurbishment techniques. Although on the surface this approach may appear to be the most expedient, such activities are found to be difficult, a safety concern if the crew is involved, and as a minimum, requires crew time. At this point in time, such activity should be relegated to emergency conditions only, and all efforts should be directed to selecting lubricants and joint designs which provide full life. Such an approach, which applies to both sealed and exposed mechanisms, will provide maximum programmatic benefits.

Mechanism Open to Space

The issues which should be considered for lubricants exposed to space, in their use configurations, are shown in Table III. Lubricants have been categorized into five different types, generally covering all lubricants appropriate to space system application. The issues applicable to each type of lubricant are listed. Except for the standard functional performance and long life issue, the importance of each issue is proportional to the extent of lubricant exposure to the environment; specific assessment for a given mechanism depends upon more mature design information. These issues should be considered early in mechanism design, eliminating life limiting effects.

ADDITIONAL STUDIES

As indicated earlier, studies of the effects of atomic oxygen on lubricants have not been conducted. In light of the potential interactions of MoS_2 with atomic oxygen, this represents a severe shortcoming in the lubricant data base which must be addressed. Providing sufficient information in time to support Space Station design will be difficult because of limited capabilities for simulating the atomic oxygen effects expected for a twenty to thirty year life. This limitation is further complicated by the need for rather large samples of exposed lubricants to perform lubricant performance evaluations. The initial step should examine chemical changes in specific lubricants when exposed to atomic oxygen.

Two opportunities exist for obtaining information on chemical changes in a limited number of lubricants. A flight experiment conducted in support of the Space Station and referred to as Evaluation of Oxygen Interaction with Materials III (EOIM III) represents one approach. The other approach is to perform exposure experiments in atomic oxygen beam facilities which are designed to simulate the space environment. Several facilities are currently under development (ref.7). Detailed chemical analysis of exposed samples should reveal major reaction pathways, for example, the loss of sulfur in the case of MoS_2, and may even provide kinetic information on important reactions. Identification of the specific products of reaction may be more difficult, especially in the case of MoS_2. As simulation facilities become more mature, extensive evaluations, including coefficient of friction, should be possible.

CONCLUSIONS

The brief examination of issues related to Space Station lubricant selection indicates the importance of space environment interactions in defining lubricant performance in mechanisms which are open to space. Under long life conditions, vacuum volatilization will certainly have to be considered for oil and grease based lubricants. Reaction of atomic oxygen with exposed, or partially exposed mechanisms, will be important for organic based lubricating agents and binders and may react with MoS_2, producing significant changes in lubrication performance. These interactions need to be understood as soon as possible to ensure support of Space Station design activities to be conducted over the next several years.

TABLE III.- SPACE STATION LUBRICATION SELECTION CONSIDERATIONS

Lubricant Type	Not Exposed to Environment	Exposed to Environment
Liquid films (low vapor pressure)	• Functional performance • Long life	• Loss of lubricant by vaporization • Contamination of nearby systems • Reactivity with atomic oxygen • Effects of UV radiation • Functional performance and long life
Dry films with organic binders	• Functional performance • Long life	• Reactivity of binder and lubricating agent with atomic oxygen • Particle release • Functional performance and long life • Effects of UV radiation
Dry films with inorganic binders	• Functional performance • Long life	• Reactivity of lubricating agent with atomic oxygen • Particle release • Functional performance and long life
Metal or metal oxide films	• Functional performance • Long life	• Functional performance and long life
Polymer films and liners	• Functional performance • Long life	• Reactivity with atomic oxygen • Effects of UV radiation • Functional performance and long life

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