NASA TECHNICAL MEMORANDUM

NASA TM X-52268

NASA TM X-52268

FACILITY FORM 602

N67-16048	
(ACCESSION NUMBER)	(THRU)
48	1
(PAGES)	(CODE)
	15
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

THE EFFECT OF THE SPACE ENVIRONMENT ON LUBRICANTS AND ROLLING ELEMENT BEARINGS

GPO PRICE $ ________

CFSTI PRICE(S) $ ________

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

by W. J. Anderson and D. C. Glenn
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at Conference on Lubrication and Wear - Fundamentals and Application to Design sponsored by the Institution of Mechanical Engineers
London, England, September 25-28, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1967

E-3790

THE EFFECT OF THE SPACE ENVIRONMENT ON LUBRICANTS AND ROLLING ELEMENT BEARINGS

by W. J. Anderson and D. C. Glenn

Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at

Conference on Lubrication and Wear - Fundamentals and Application to Design
sponsored by the Institution of Mechanical Engineers
London, England, September 25-28, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

THE EFFECT OF THE SPACE ENVIRONMENT ON LUBRICANTS AND ROLLING ELEMENT BEARINGS

by W. J. Anderson and D. C. Glenn

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

ABSTRACT

The effects of spatial environmental factors such as the very low ambient pressure and the absence of oxygen on lubrication are discussed. The low pressure causes liquids, and even solids, to boil away so that their vapor pressure and evaporation rates become important. Evaporation experiments with metals, liquids, greases and solid lubricants are discussed. Silicone oils and silicone based greases appear to have the lowest evaporative loss among the fluids investigated. Bearing experiments indicate that liquids and greases, when properly shielded, can provide longer bearing lives than bonded solid lubricants or metal platings. Silicone fluids yield the best bearing life, confirming the results of evaporation tests. Life results with bonded solid films are generally poor. Results are considerably better when the solid lubricant is used as a constituent in a solid-composite material. Bearing reliability in space applications may be a problem because considerable life scatter is observed where a particular lubricant or lubrication technique is evaluated in multiple tests. Life ratios of 10 were common.

TM X-52268

INTRODUCTION

The past decade has seen the advent of the age of space exploration and with it a multitude of lubrication problems associated with the operation of mechanisms in the spatial environment. The requirements that must be met by bearings operating in space are varied, and to think in terms of a single solution for the space bearing problem would be no more plausible than to try to apply a single bearing and lubrication system to all terrestrial applications. Indeed, bearings in spatial applications will see a range of temperatures, speeds, loads, ambient pressures, gravity fields, radiation dose rates, vibration levels, ionized gases and other factors; hence, the "space lubrication problem" is really a multitude of problems which require many distinctly different solutions.

In conducting research on lubrication in space, major attention must be paid to those environmental and operational factors which are markedly different from those on earth, and which are most likely to have significant effects on the lubrication process. Important environmental factors include: (1) the ambient pressure, which may range to 10^{-16} atmospheres; (2) radiation (solar, nuclear and cosmic); and (3) varying gravity (most probably near zero, but perhaps as high as or higher than on earth). Other factors, which may be important in some applications, include: (1) severe transient accelerations such as occur during launch, separation and reentry; (2) the presence of ionized and other abnormal gases, (3) particle impact in completely exposed systems, and (4) severe thermal conditions caused by poor heat transfer.

This review will be focused on the effects of low pressure and radiation, on lubricants and the lubrication of rolling bearings. Problems of environmental simulation and some of the more significant bearing experiments in vacuum are discussed. Space applications of fluid film bearings will not be discussed. Their use will be limited to completely sealed systems in which the primary problem appears to be fluid film instabilities associated with zero gravity operation.

DEFINITION OF THE SPACE ENVIRONMENT

Low Pressure

The most significant change from the terrestrial to the spatial environment is pressure level. The absolute pressure outside the atmosphere may range down to 10^{-13} torr. Farther out in interstellar space pressures may be as low as 10^{-16} torr. Figure 1 shows pressure as a function of altitude. The pressure drops to 10^{-6} torr at an altitude slightly greater than 200 kilometers, and to 10^{-9} torr at an altitude between 600 and 800 kilometers (refs. 1 and 2).

The immediate effect of very low pressures on lubrication is a marked increase in the evaporation rates of lubricants and materials. Dissociation of some materials may also take place. In a system completely exposed to the hard vacuum, a molecule leaving the surface would have very little chance of ever returning because of the extremely low probability of collisions occurring. Therefore, the vapor pressure of a lubricant in both bulk and thin film form becomes of immediate importance.

A second effect of low pressure, or the absence of a gaseous environment, is the increased difficulty in maintaining a satisfactory heat balance. Heat cannot be transferred convectively so that it must be transferred by conduction from the bearing to the mechanism and ultimately rejected to space by radiation. Unless careful attention is paid in the design of a mechanism to provide adequate heat transfer paths, bearing temperatrues may become unnecessarily high. It is advantageous to maintain bearing temperatures as low as possible to reduce lubricant losses due to evaporation.

Lack of Oxygen

The maintenance of surface contaminating films such as oxides, which are so important to the prevention of surface welding and galling, is also jeopardized by the low pressure which implies a relative scarcity of reactive gases such as oxygen. The effect is twofold. The abrasion of existing oxide coatings during sliding will produce wear debris and the lack of oxygen in the environment will prevent the reformation of the oxide film. Organic surface contaminants, on the other hand, will be lost by evaporation. One can envision the production of clean, nascent surfaces as a result of sliding in a hard vacuum with the ultimate consequence of surface welding and failure of the mechanism.

The relation of oxygen pressure and the time required for the formation of a 1 angstrom thick film of FeO is shown in figure 2 (ref. 3). At an oxygen pressure of 10^{-7} torr, a hypothetical 1 angstrom film is formed in only 1 minute. At 10^{-12} torr, the time required for film formation approaches a year. This is approximately the total pressure at an altitude of 1200 kilometers (fig. 1). In addition the principal gaseous species present in space at this altitude and beyond are atomic hydrogen and helium so that the partial pressure of oxygen is negligible. The probability of reformation of an oxide coating is therefore nil.

Radiation

Several types of radiation, discussed fully in references 3 and 4, may occur in space. Organic oils, greases and polymeric materials can suffer damage from energetic atomic particles and short wave length radiation such as γ- or X-rays or ultraviolet radiation from the sun. A complete discussion of the mechanism of radiation damage, given in references 3 and 4, is beyond the scope of this paper.

Suffice it to say that the levels of spatial radiation are not expected to tax the radiation stability of ordinary oils and greases. Reference 5 discusses the radiation stability of a number of lubricants and a typical radiation dosage to be expected in a space vehicle. The yearly radiation dose on the surface of a vehicle in polar orbit at a 2300 mile altitude is 2×10^9 ergs per gram carbon while the dose inside a o. 25 centimeter aluminum skin is 6×10^6 ergs per gram carbon. This radiation includes the Van Allen belt, and solar and cosmic radiation.

Radiation dosages required for threshold damage for several lubricating materials are shown in table I. The values shown are for static irradiation in air. All of the lubricating oils would be unaffected by several years exposure at the shielded space vehicle dose rate hypothesized above. Only the PTFE appears to be marginal, but many materials, PTFE included, have markedly better radiation resistance in the absence of oxygen than they do in air. The oxygen free spatial environment should therefore be of some benefit in this instance.

SIMULATION OF THE SPACE ENVIRONMENT

Open Systems

Duplication of the space-vacuum environment in a ground-based space chamber is impossible. Environmental factors such as gravity, meteorites, electromagnetic radiation, molecular types, molecular energy and many others cannot be duplicated. The validity of an experiment, however, does not hinge upon complete duplication, but on simulation of the environmental factors which are critical to that particular experiment. Surface contaminants have a profound effect on lubrication so care must be taken to eliminate all sources of contamination if a system which is open to space is being simulated. The space vacuum is characterized by an absence of oxygen which plays an important role in friction even if present in only minute quantities. Molecular incidence rates are such that, at 10^{-6} torr and 25° C, a monolayer of air will form in 2 seconds, assuming that all molecules adhere, figure 2 (ref. 6). If the partial pressure of oxygen were 10^{-6} torr then an oxide layer might very well form in seconds. At 10^{-9} torr the time for formation of a monolayer of air would approach 33 minutes. Pressure levels for critical friction experiments must be low enough to prevent reformation of surface oxides during the experiment. Oxygen partial pressure levels of 10^{-9} or 10^{-10} torr would be desirable.

Other sources of contamination are the pumping system, and all the surfaces within the chamber. There is no perfect pumping system. Back migration of diffusion pump oil is a common problem with that type of pump. The authors of reference 7 were unable to find an effective cold trap and baffle system. Sputter ion pumps do not have the back migration problem but do have other problems. Although sputter ion pumps do not employ any fluids in their operation, hydrocarbons can be produced by the reaction of carbon and hydrogen bearing gases such as carbon-dioxide and water vapor (ref. 6). Their presence in the test chamber would probably be negligible, however, as long as the ion pump is not turned off. An oil diffusion pump of a given size is considerably less costly than an ion pump of similar capacity, but the need for complex cold traps and baffles may make it necessary to use a much larger diffusion pump. Although there exists a controversy about the relative utility of diffusion and ion pumps for vacuum systems in which lubrication experiments are being conducted, the use of ion pumps, where economically feasible, is probably advantageous. The results from contaminated experiments might be worthless and the cost saving false. Provision for ample cryopumping should always be included. Surfaces at liquid nitrogen temperatures are effective in pumping most gases, and surfaces at liquid helium temperature even more so.

To realize the importance of surface cleanliness in a vacuum chamber, one need only calculate the ratio of the number of molecules on the surface to those in the volume. For a monolayer of air at 250° C there are 2.4×10^{17} molecules on the surface of a 20.5 centimeter diameter sphere, and 4.8×10^{11} molecules in the volume at 10^{-9} torr pressure (ref. 6). Thus, there may be 500 000 times as many molecules on the surface as in the volume. The importance of prior bakeout and surface cleaning after pumpdown by electron or ion bombardment is readily apparent if a really clean vacuum system is to be obtained. This addition of energy to the molecules on the surface to drive them off simulates the action of high energy protons and electrons in space.

To simulate the evaporative losses in a system open to space two things must be provided: (1) a sufficiently low pressure so that the mean-free molecular path is large compared with the dimensions of the chamber (molecular flow conditions prevail), and (2) condensing surfaces which collect and retain molecules leaving the surface of the experiment. For all but the largest vacuum chambers, a pressure of 10^{-5} torr is sufficient for evaporation simulation. At this pressure, molecular flow conditions will exist in a system whose mean dimension is as great as 250 centimeters. Cryopumping surfaces are desirable and perhaps even mandatory for preventing back reflection of molecules, especially in experiments employing liquid lubricants.

Shielded Systems

In many devices on space vehicles, bearings may not be completely exposed to the hard vacuum. Pumping paths may be restricted by mechanism parts that shield the bearings so that they operate in an environment which is at a pressure considerably above that surrounding the vehicle. The most straightforward approach would be to conduct experiments with the entire vehicle, but this might be either impractical or impossible.

Simulation of the actual conditions the bearing will see can be accomplished if the vehicle design is known. The total area of the openings can be likened to an orifice of equivalent area. The loss rate for molecular flow through the orifice can be simulated by choosing a pump of the proper size (ref. 8). Table II illustrates loss rates for air flowing through orifices of various radii. The authors of reference 9 used a 1 liter per second ion pump to simulate the loss of volatile matter from a bearing in a shielded system.

EFFECT OF THE SPACE ENVIRONMENT ON LUBRICANTS

Evaporation of Metals and Solid Films

Metals. - The Langmuir equation has been widely used to calculate the rate of evaporation as a function of temperature for various materials. The rate of evaporation G in (g)/(sq cm)(sec) is given as

$$G = \frac{P}{17.14}\sqrt{\frac{M}{T}}$$

where P is the vapor pressure in torr, M the molecular weight and T the temperature in degrees Kelvin. The Langmuir equation assumes no back reflection of atoms. The vapor pressure can be expressed in terms of the heat of vaporization, L, the gas constant, R, and the temperature, T, as

$$P = Ce^{-L/RT}$$

The ratio $P/\sqrt{T}$ increases rapidly with increasing temperature so that the rate of evaporation will always increase with temperature. The Langmuir equation has been used to calculate the evaporation rates for various metals at different temperatures.

The evaporation rates for most metals are negligible at ordinary temperatures, but they may become significant at elevated temperatures, expecially for some of the softer metals which are of interest as low friction coatings. Buckley, et al., (refs. 7 and 10) conducted careful short time evaporation studies with a number of metals over a wide temperature range at 10^{-6} torr. Extrapolation of Buckley's data for metals of interest as low friction coatings are shown in figure 3. Extrapolation of short time evaporation data for pure metals is probably valid because they are generally linear with time. The data for cadmium and indium were compared with calculated evaporation rates obtained from the Langmuir equations using known vapor pressures. The agreement is good.

Buckley's data indicate that vaporization losses are negligible at room temperature, but at moderately elevated temperatures they can become significant. For example, at 200° C indium and silver exhibit losses due to vaporization of 0.02 to 0.025 centimeter per year. These are certainly not insignificant but, by comparison, the loss of cadmium at this temperature would be catastrophic (about 10 cm/year). In contrast to cadmium, gallium exhibits extremely low evaporation rates at temperatures as high as 400° C, and offers much promise as a lubricant for hard vacuum applications. The data obtained by Buckley shown in figure 3 were obtained with clean metals. The presence of a surface oxide coating may significantly affect the evaporation rate of a metal (ref. 11).

Solid lubricants. - The loss rates of solid lubricants in vacuum are generally considerably lower than those for liquid lubricants. Typical solid lubricants whose frictional characteristics appear to indicate potential usefulness in vacuum are molybdenum disulfide, tungsten disulfide and PTFE. Graphite does not appear to be a candidate for hard vacuum applications because it does not function in the absence of oxide coatings or adsorbed water vapor.

Phenomena governing the loss rate of solid lubricants, such as MoS_2, are very likely more complex than vapor pressure since the lubricants themselves are compounds and since various bonding agents may be used. Decomposition to the elements or to simpler compounds may take place (ref. 4). MoS_2 may decompose to metallic molybdenum and gaseous sulfur. Loss rates by reactions of this type can be calculated from the equilibrium constant for the reaction. In the case of solid lubricant coatings containing a binder, the relation controlling loss rates are even more complex so that extrapolation of short time experimental data may not be valid. Buckley (ref. 7) has shown that loss rates of several inorganic solid lubricants (e.g., MoS_2, WS_2, CaF_2, BaF_2) are quite low at temperatures to 176° C. Buckley also measured loss rates for 0.0025 centimeter thick molybdenum disulfide bonded coatings (ref. 7). Loss rates were quite low over a wide temperature range for ceramic, metal matrix, silicone resin and phenolic-epoxy bonded coatings. Changes in loss rates with temperature were not uniform due to differing temperature dependence on the loss rates for the MoS_2 and the various binders.

Evaporation of Liquids

Bulk liquids. - Most liquid lubricants may be unsuitable for long time exposure to hard vacuum because of their high vapor pressures. An additional problem with petroleum oils is that they are composed of molecules having a wide range of molecular weights and structures. This makes the use of the Langmuir equation for predicting evaporation rates invalid unless the distribution of molecular weights is known. The lower molecular weight fractions are more volatile and would evaporate more quickly. Thus, the rate of evaporation would decrease with time, so that data from short time evaporation tests cannot be extrapolated to predict long-time losses. Evaporation would be accompanied by a gradual increase in both viscosity and pour point. This could be important in applications where bearing torque is critical. Where petroleum oils or compounded synthetic oils containing additives are being considered, the effects of prior distillation on evaporation rate must be considered.

A number of studies have been made of evaporation rates of oils and greases. Data for several classes of liquid lubricants are reported in reference 12. Figure 4 shows results obtained at 10^{-5} torr and 60^{o} to 71^{o} C for some of the more promising liquids. Although six lubricant samples were evaporated simultaneously in a single chamber, close positioning of cryosurfaces to the lubricant samples probably minimized cross contamination.

The data of figure 4 are presented as cumulative weight loss as as function of time. More precisely, evaporation data should be presented as weight loss per unit area per unit time as a function of temperature. The data of figure 4 presupposes the use of constant surface areas exposed to evaporation for all samples, and close temperature control. These data, as well as grease evaporation data later on, are presented for the sole purpose of making qualitative comparisons. They should not be extrapolated to longer times or different temperatures, nor should the reader attempt to make quantitative translations of the data to a specific application.

As a class, the silicones suffered the least weight loss with time. Among the silicones the least evaporation occurred with the straight chain dimethylpolysiloxane. The best petroleum oil was a bright stock. Note in figure 4 the marked changes in evaporation rate (indicated by the slope of the curve) with time for the petroleum oils. This is an indication of the wide range of molecular constituents in these oils. In contrast the synthetics exhibit almost constant rates of evaporation. Oils with a wide range of molecular constituents would be likely to exhibit the greatest changes in viscosity. In reference 12 it was found that an aromatic petroleum oil increased more than 100 percent in viscosity. In contrast the synthetics did not increase in viscosity more than $4\frac{1}{2}$ percent.

Liquid monolayers. - The evaporation characteristics of bulk liquids appear to limit their usefulness in long life bearing applications in hard vacuum. However, it is well established that friction of surfaces with only a monolayer of lubricant present is comparable to that with much thicker lubricant films. Vapor pressure alone would not provide an accurate or even useful tool for predicting the evaporation rate of the last monolayer on a surface because of the presence of additional attractive forces between a very thin lubricant film and a solid surface. This is especially true for polar compounds, but it also applies to nonpolar compounds. Therefore, the prediction of liquid lubricant life on the basis of vapor pressure is likely to be conservative.

Gisser and Sodjian (ref. 13) studied the evaporation of nonpolar hydrocarbon monolayers from steel surfaces by measuring coefficients of friction after exposing the surfaces to various pressures. They found that monolayers remained intact at pressures considerably below the vapor pressures of the fluids. As an example, monolayers of η-dodecylamine (vapor pressure = 2.1×10^{-2} torr at 25° C) were still present (as indicated by an unchanged coefficient of friction) after exposure to pressures in the region of 10^{-6} torr.

Greases. - Grease evaporation test were conducted in references 12 and 14. In reference 14 it was found that the evaporation rate of a chlorophenyl oil-lithium soap grease agreed very well with that of the base oil over a range of temperatures. One would expect this to be true as long as the oil completely wets the exposed surface of the grease. These data are shown in figure 5. In reference 12 a 7 millimeter bore ball bearing lubricated by a 20 percent charge of the test grease and rotating at 60 rpm was used as the test specimen. The bearing was placed close to a cryogenic condensing plate to minimize back reflection. Some of these results are shown in figure 6. The best results were obtained with a highly aromatic petroleum oil with an indanthrene dyestuff thickener. Silicone base greases also gave good results. The ester base grease was poorest, exhibiting a weight loss some 25 times greater than the best grease. Loss of weight in greases results from evaporation of the fluid constituent so that a gradual thickening of the grease occurs. A typical grease becomes unserviceable when 40 to 60 percent of the oil is lost.

Grease tests at somewhat higher rotative speed and temperature were also reported in reference 12. Figure 7 illustrates data obtained at 1800 rpm and 121° C. Four of the six greases evaluated at the lower speed and temperature (fig. 6) are also shown in figure 7, but the order of results is quite different. The silicone greases were significantly better than the aromatic petroleum at 121° C. The data of figures 6 and 7 indicate the extreme importance of accurately simulating system conditions, and the dangers inherent in extrapolating data. The evaporation rate for a grease would be fairly linear as long as an ample quantity of fluid remains within the grease. As it becomes depleted of oil, however, the evaporation rate would probably decrease. In addition the viscosity and vapor pressure characteristics of lubricating oils change rapidly with temperature. Therefore, a valid prediction of the performance of an oil in vacuum demands an accurate simulation of both temperature and pressure.

EFFECT OF THE SPACE ENVIRONMENT ON BEARING SYSTEMS

Lubrication Techniques

Based on experimental evidence gained to date, liquid lubricants appear to be more effective in hard vacuum applications than solid lubricants used in their various forms (self lubricating materials such as PTFE, or precious metal platings). The loss of liquids through evaporation, however, limits the usefulness of many standard liquid lubricants in hard vacuum applications. Shields or seals can and have been used to reduce evaporative losses, but the increased bearing torque and drive power requirements that result may not be tolerable. The use of low vapor pressure lubricants has proved effective, but they generally have high viscosities which may result in excessive bearing torques at low temperatures.

Solid lubricants used as coatings can provide effective lubrication but problems with debris cause havoc with reliability, especially in small, instrument size bearings which are extremely sensitive to the most minute wear debris. The effectiveness of a coating is limited by the availability of the solid lubricant. When the coating is worn through, the effectiveness ceases. Therefore, attempts have been made to utilize solid lubricants in composite materials containing a solid lubricant and a binder material and sometimes additional self lubricating materials as well.

Experimental Results with Dry Bearings

Metal films. - One of the first bearing applications in hard vacuum was in rotating anode X-ray tubes. An instrument size bearing was required to rotate at fairly high speeds to support the rotating anode within the tube itself. Early work on this problem revealed that gold and silver platings fractions of a micron thick on the bearing parts provided adequate surface protection and lubrication so that reasonably satisfactory bearing life was achieved (ref. 12).

In reference 15 some 14 different metallic platings were evaluated as lubricants in the form of thin films in small high speed bearings for rotating anode X-ray tubes. Most successful of these platings was barium applied to bearings made of a high speed tool steel. Other ball materials used included SAE 52 100 steel (a high carbon chromium steel) an 18 percent chromium stainless steel, and a 75 percent cobalt, 25 percent tungsten carbide. However, the barium plating was not as effective on any of these materials as it was on the high speed tool steel.

It is interesting to note that the application of bearings to rotating anode X-ray tubes is one of the few vacuum applications involving an elevated temperature. With the X-ray load present, bearing temperatures may reach 600° C; under these conditions, the barium film life was found to be 50 to 100 hours.

Additional studies with thin metal platings (0.0007 mm) were reported in references 16 and 17. All of these studies were done with 3.17 millimeters bore bearings (R-2 size) operating at 10 000 rpm under a few grams load. The vacuum was maintained by an ion pump in the 10^{-7} torr range. In reference 16, it is reported that 17 pairs of bearings exhibited lives in excess of 500 hours. Gold platings were found to be most effective. Pure gold platings were less effective than gold platings containing additives of nickel, tin and cobalt, presumably because of better adherence of the latter.

In reference 17, six different combinations of race and ball plating were investigated. The best combination was found to be gold plated balls, silver plated races and a silver plated metallic retainer. Maximum life obtained was 2404 hours. The disconcerting feature of this work, and also of much of the other bearing work done in vacuum is the extreme scatter in bearing life. In the work reported in reference 17, bearing lives varied from 41 to 2404 hours with the same lubrication technique. Bearing failure was generally precipitated by minute flaking of the platings. This lead to an internal jam-up and complete failure of the bearing. As stated above, one of the obvious disadvantages of working with such small bearings is their extreme sensitivity to even the most minute debris.

Buckley conducted friction and wear tests (ref. 10) with gallium rich films. Gallium offers much promise as a lubricant in space applications because of its low vapor pressure and wide liquidus range. Bearing experiments with a 60 percent gallium, 20 percent indium and 20 percent tin alloy impregnated into porous bronze retainers, or as a rubbed-on film in full complement bearings have been conducted by the authors. Results, as indicated by bearing torque, were farily promising. For the 20 millimeter bore bearings run at 3550 rpm, 23 kilograms load at 10^{-7} torr, torque values were approximately 0.007 Newton meters for the bearing with the retainer, and 0.004 Newton meters for the full complement bearing. These torques correspond to coefficients of friction (referred to the bearing bore) of approximately 0.002 to 0.003 which compare favorably with a typical value of 0.0015 for an oil lubricated bearing.

Inorganic dry films and PTFE. - Instrument size R-3 bearings (4.76 mm bore diameter) were evaluated at 8000 rpm in reference 18. Bearings were run in pairs as rotor support bearings in small motors placed within the vacuum chamber. Table III shows a tabulation of results in an ion pumped system with a metal matrix bonded MoS_2 coating and a sodium silicate bonded MoS_2 coating. It is quite evident that a considerable scatter in bearing life results with the small bearing specimens. The use of a teflon retainer in conjunction with the silver matrix-MoS_2 coating on the races and balls improved life considerably.

Additional work in reference 18 with reinforced teflon retainers resulted in bearing lives considerably better than those with the inorganic dry film lubricants. Three tests were run in vacuum for 10 771, 11 248 and 12 636 hours, respectively. The bearings were generally still operable, but the retainer ball pockets were badly worn. Based on these very limited data system reliability might be improved with such a lubrication technique, but further work is needed in this area.

Somewhat similar results with dry film lubricants are reported in reference 9. These are shown on table IV. Four different bonded MoS_2 coatings, a solid MoS_2 composite retainer and a dioctyl phthalate oil as a reference were evaluated in 20 millimeter bore bearings at 1800 rpm. The four bonded coatings exhibited rather short lives when compared with the oil. The results with the epoxy bonded MoS_2 solid composite retainer were excellent, however. It performed very well for over 900 million revolutions (8300 hr) whereas the bonded films failed in as little as 1 million revolutions (9 hr).

These results suggest strongly that techniques must be developed for making additional solid lubricant available over and above that contained within the coating. Devine, et al., (ref. 19) have done work in this area. The technique used by Devine (discussed fully in ref. 2) consists of supplying reservoirs of the solid lubricant at critical locations such as at the retainer locating surface and in the ball pockets. This is done by means of punched indentations or machined slots in the surface to be coated. These are then filled with the solid lubricant. Significant increases in bearing life in air have been obtained using the reservoir technique.

An alternative approach to improving the availability of solid lubricant is to develop composite materials containing the solid lubricant. The retainer is then machined from the composite, such as the epoxy - MoS_2 material evaluated in reference 9 (table IV). Bowen (ref. 20) had done considerable work on composites for use as both bearing retainers and gears. The materials used by Bowen were compacted of a metal (Cu or Ag), PTFE and WSe_2. These were used as retainers in 305 size (25 mm bore diameter) bearings in low speed tests (35 to 50 rpm) at radial loads of 34 to 133 kilograms. Ambient pressures were in the 10^{-8} torr range. Each test assembly contained eight bearings and a number of gears which were run for 100 hours, after which their condition was carefully checked.

Results with the two composites are shown in table V. Both the 60 percent copper, 30 percent PTFE, 10 percent tungsten-diselenide and the 70 percent silver, 20 percent PTFE and 10 percent tungsten-diselenide materials performed well. Two sets of eight bearings, one with the copper composite retainers and one with the silver composite retainers, were operated for 200 hours (two test cycles) with very nominal retainer wear and negligible ball and race wear. Wear was somewhat lower with the copper composite.

These materials offer considerable promise for nominal speed applications in vacuum, but their potential in higher speed applications had yet to be determined. One of the problems inherent in compacted materials is their lack of tensile strength. Improved strength can be obtained by altering the composition, but usually at the expense of lubricating ability.

Optimum lubrication, necessary where torque requirements are critical, can be obtained with burnished MoS_2 films. Such films applied to bearings with porous bronze, cast bronze and nickel alloy retainers have been evaluated by the authors in 20 millimeter bore bearings at 3550 rpm in ion pumped systems at 10^{-10} torr. Bearing coefficients of friction (referred to the bearing bore) were less than 0.0003 in tests of approximately 30 hours duration. Coefficients of friction this low are difficult to obtain, even with optimum thin film oil lubrication. Life tests have not as yet been conducted with bearings lubricated with burnished MoS_2 films.

Oil and Grease Lubricated Bearings

The advantages of shielding to reduce evaporative losses of liquids or greases is physically obvious. The results of experiments with R-4, 6.35 millimeter bore diameter bearings, either with the bearing completely open to the vacuum chamber, or with a single shield, are shown in figure 8. The weight loss of grease in the open bearing is approximately 25 percent greater than with the single shield. While this increase appears to be rather nominal it represents a much larger percentage loss of the original oil content of the grease. The author of reference 12 states that a loss of 40 to 60 percent of the oil from a grease renders it unsatisfactory for ball bearing lubrication.

A broad scope investigation of a large number of liquids and greases, as well as the dry film lubricants discussed earlier, is reported in reference 18. This has been a continuing program over a number of years, the most recent results being reported in reference 18. Earlier results were reported in reference 5. The wide scope of lubricants investigated in this program provides a means for qualitatively comparing the performance of dry lubricants, liquids and greases under reasonably constant conditions. The data are presented solely for this purpose. In most of the experiments, pressure levels were on the order of 10^{-6} torr although in some experiments they ranged to 10^{-9} torr. The majority of experiments were conducted with an oil diffusion pump system, although some were conducted utilizing an ion pump system.

The more significant results obtained with the better oil lubricants are shown in table VI. Lives ranging upwards to more than 33 000 hours were obtained with the better fluids. In general, the best results were obtained with silicone oils of various compositions. Bearing temperatures in these experiments were rather nominal, being only a few degrees above room temperature. Retainers used were generally machined from cotton-phenolic laminates. The retainers were impregnated with oil prior to test. The average oil content of these bearings was on the order of about 50 milligrams although, for the fluorosilicone oil, it was as much as 81 milligrams.

Also reported in reference 18 are the results of a number of experiments with greases of various types. The grease lubricated bearings were also double shielded to contain the grease, but were fitted with ribbon retainers rather than the cloth-phenolic machined retainers. Some of the more significant results with greases are shown in table VII. A grease composed of a silicone oil, an organic thickner, and a solid lubricant produced the best results. That particular experiment was still running after 33 100 hours. A number of other greases provided lives without failure in excess of 20 000 hours.

From the results shown on tables VI and VII it is apparent that quite good results can be obtained in shielded bearings with relatively low vapor pressure oils and greases. Of the various classes of lubricants investigated, the silicone oils appear to give the best results.

Comparison of the results tabulated in tables III, VI and VII indicates that bearing life with the best oils and greases exceeds that with dry film lubricants. In contrast to lives of 20 000 to 33 000 hours with the best oils and greases, bearing life with the best inorganic dry film was on the order of 2500 hours. The use of PTFE provided bearing lives on the order of 10 000 hours. The advantages of utilizing dry film lubricants in vacuum (cleanliness and freedom from condensed oil vapors on critical surfaces) are sufficient to warrant further development of techniques for utilizing them. Too little attention has been paid to bearing design. The absence of the type of cooling obtained with recirculating oil lubrication makes it mandatory to provide greater than normal internal clearances to allow for internal expansions, and to provide for adequate heat flow paths from the inner race to avoid total loss of bearing clearance. The use of composite retainer materials, together with proper bearing design should result in much longer bearing lives with dry film lubricants.

The results reported in reference 18 agree quite well with earlier work reported in references 21 and 22. In reference 21 Corridan conducted experiments with the same bearings at about the same pressure level (10^{-6} torr), at a somewhat higher rotative speed of 11 500 rpm, and temperatures in the region of 160° C. Again the bearings were double shielded, but they operated under somewhat heavier loads (from 227 to 425 g). Lubricants investigated included silicone and diester fluids as well as silicone and high vacuum greases. As in reference 10, the best results were obtained with the silicone fluids and the silicone base greases.

Freudenlich and Hannan conducted tests utilizing even smaller bearings (3.18 mm bore diameter) in about the same temperature range as the work reported in reference 10, but at a lower speed (4000 rpm). Tests were conducted for a period of 1000 hours or until failure occurred. The oil or grease charge was approximately

15 to 20 milligrams. Many of the tests operated for the full 1000 hour life. Best results were obtained with a chlorinated silicone and a silicone grease.

Some observations made by the authors of references 18, 21, and 22 on the results with shielded bearings are worth noting. Where repeated tests are run there always exists some life scatter with the same lubrication technique due to the extreme sensitivity of the very small bearings to minute wear debris. Failures have usually been caused by partial or complete loss of lubricant, which results in wear and the formation of fine wear particles, principally from the retainer. Although one might expect that the principal mechanism of lubricants loss would be evaporation, it is also a possibility that creepage is partially responsible for lubricant loss. This is especially true in light of the fact, as stated in reference 18, that no general correlation was found between vapor pressure and lifetime. The silicone oils, which are generally regarded as being most prone to creep, have, however, given excellent results. Failures with greases were generally characterized by loss of fluid from the grease resulting in a hard residue. In one particular experiment in reference 18 the bearing failed and was found to be clogged with a dry sandy residue. In this particular experiment, the bearings had been exposed to a dose of gamma radiation equal to about 1.7×10^7 Roentgens.

Although the author of reference 18 states that the results obtained in oil diffusion pump systems and ion pump systems did not seem to be appreciably different, some of the lubrication techniques which were evaluated in both systems appeared to give better lives in the diffusion pump systems. Possible contamination from diffusion pumps would be much more critical in bearings lubricated by metal and inorganic dry film lubricants than in oil or grease lubricated bearings. The dry film lubricated bearing tests from reference 18, reported in table III, were all conducted in an ion pumped system. The majority of the oil and grease lubricated bearing tests from reference 18, reported in tables VI and VII, were run in an oil diffusion pumped system.

The great majority of the bearing experiments in vacuum have been conducted with instrument bearings at nominal loads or with larger bearings (20 to 25 mm bore diameter) at either very light loads or low rotative speeds. Very little work has been done where even reasonably severe conditions of load and speed exist simultaneously. This is probably justified since it will not be necessary to contend with severe loads and speeds in many space applications. Such applications will occur, however, so some work is being done in this area.

In reference 23 four liquid lubricants (a polyphenyl ether, a polysiloxane, a sebacate and a high viscosity mineral oil) were evaluated as impregnants in cotton-cloth phenolic retainers of 20-millimeters bore ball bearings. Bearings were run at 3550 rpm under axial loads of 2270 to 4540 grams at 10^{-6} torr for 1 hour or until the torque exceeded 0. 141 Newton-meters. It was found that, under these conditions of load and speed, the lubrication technique was inadequate. The cotton-cloth phenolic material was unable to feed the lubricant fast enough to wet the bearing surfaces. Varying the weave of cloth in the retainer produced no significant improvements in bearing torque with the mineral oil, which was the best of the four oils evaluated. These results are in sharp contrast to those obtained with liquid lubricant impregnated retainers in reference 18 under more nominal test conditions, and may indicate that severe lubrication problems exist in bearings required to operate at significant loads and speeds in vacuum.

Space Applications

An interesting application of oil lubrication utilizing high resistance flow paths between the bearing and space was used in the TIROS II meteorological satellite (ref. 24). An infrared radiometer contained eight instrument ball bearings operating at 2750 rpm. The bearings were lubricated by a diester oil (vapor pressure, 10^{-4} torr) initially impregnated into two porous nylon reservoirs in each bearing cavity. Small clearances around the shaft (0.012 mm) minimized the flow of oil molecules into space. The radiometer operated several thousand hours in orbit without any apparent bearing difficulties.

A summary of the approaches to lubrication problems on the Ranger, Mariner and Surveyor spacecraft is shown in table VIII (ref. 25). Bearing systems operated up to the maximum of 109 days required for the Mariner voyage to Venus. The general approach was to use oils and greases with low evaporation rates or dry film lubricants where loads and speeds required them. In long exposure application bearings and gears were sealed where possible. PTFE (teflon) or reinforced teflon bearings were utilized where speeds and loads were low. Silicone oils were widely used in shielded bearings.

SUMMARY

The lubrication of relatively moving surfaces in a spatial environment is complicated by the presence of a very low ambient pressure, radiation (spatial and nuclear) and the absence of a gravitational field. The low pressure causes liquids, and even solids, to boil away so that their vapor pressure and evaporation rates become important. Evaporation rates for metals at ordinary temperatures are insignificant, but some of the softer metals of interest as low friction coatings (such as cadmium and indium) exhibit significant evaporative losses at elevated temperatures. Gallium exhibits extremely low evaporation rates over a wide temperature range and has potential as a lubricant. The Langmuir equation can be used with calculated vapor pressures to predict the evaporation rates of metals and fluids (of known molecular weights) with good accuracy.

As a class, silicone fluids showed the lowest evaporation rates. Evaporation rates for a chlorophenyl silicone grease agreed with those for the fluid indicating that the evaporation properties of the oil are important in determining grease behavior. Comparative evaporation rates of different greases obtained from bearing tests

varied with rotative speed and temperature. This indicates that exact simulation of system conditions is important if grease performance is to be properly assessed. Silicone base greases appear promising.

Experimental studies of lubricant monolayers indicate that they remain intact on solid surfaces at pressures considerably below their vapor pressures. Bulk fluid evaporation studies are, therefore, probably conservative and more work needs to be done on the evaporation of thin films. On the basis of evaporation loss rates, solid lubricants such as MoS_2 appear to be promising for vacuum applications.

The validity of an experiment in vacuum depends on simulation of the critical environmental factors. Surface contaminants have a profound effect on lubrication, so all sources of contamination must be eliminated. For this reason, ion pumps are preferred over oil diffusion pumps, with supplemental pumping by cryosurfaces to prevent back reflection of molecules. In critical friction experiments, the partial pressure of oxygen must be kept low enough so that reformation of surface oxides cannot occur during the experiment. In evaporation experiments it is sufficient to provide a pressure level low enough so that the mean-free path (molecular) is large compared with the chamber dimensions, together with condensing surfaces which trap molecules leaving the surface of the experiment.

Liquid and grease lubricants provide longer bearing lives than do solid lubricants in instrument size, lightly loaded bearings. Among the more promising liquids, the silicones appear to be best. This result agrees with evaporation data. A wide scatter in bearing life (life ratios of 10 were common) results when a particular lubricant is evaluated in multiple tests. This indicates that reliability may be a problem and that small bearings are probably a poor choice of test specimen because of their extreme sensitivity to even the most minute debris. In larger bearings at higher loads, liquid lubricants impregnated into cloth-phenolic retainers were found to provide marginal lubrication under the particular conditions studied.

Life results with bonded solid lubricant coatings were considerably poorer than those with liquid lubricants. Solid lubricants offer more promise when used as constituents in composite materials, although work needs to be done to improve the tensile strength of composites for high speed applications. More attention needs to be paid to bearing design to account for the absence of lubricant cooling and the poor heat transfer which prevails in vacuum.

REFERENCES

1. Jastrow, Robert: Lunar and Terrestial Atmospheres. Advances in Astronautical Sciences. Vol. 5, Horace Jacobs, ed., Plenum Press, 1960, pp. 338-345.
2. Bisson, Edmond E.; and Anderson, William J.: Advanced Bearing Technology. NASA SP-38, 1964, pp. 259-287.
3. Atkins, J. H.; Bisplinghoff, R. L.; Ham, J. L.; Jackson, E. G.; and Simons, J. C., Jr.: Effects of Space Environment on Materials. National Research Corp., Aug. 15, 1960. (Contract No. AF-33(616)-6288.)

4. Jaffe, Leonard D.; and Rittenhouse, John B.: Behavior of Materials in Space Environments. Paper No. 2033-61, ARS, Oct. 1961.

5. Young, W. C.; Clauss, F. J.; and Drake, S. P.: Lubrication of Ball Bearings for Space Applications. ASLE Trans., Vol. 6, no. 3, July 1963, pp. 178-191.

6. Santeler, Donald J.; Jones, Donald W.; Holkeboer, David H.; and Pagano, Frank: Vacuum Technology and Space Simulation. NASA SP-105, 1966.

7. Buckley, Donald H.; Swikert, Max; and Johnson, Robert L.: Friction, Wear, and Evaporation Rates of Various Materials in Vacuum to 10^{-7} mm Hg. ASLE Trans., Vol. 5, no. 1, Apr. 1962, pp. 8-23.

8. Dushman, Saul: Scientific Foundations of Vacuum Technique. Second ed., John Wiley and Sons, Inc., 1962.

9. Brown, R. D.; Burton, R. A.; and Ku, P. M.: Long-Duration Lubrication Studies in Simulated Space Vacuum. ASLE Trans., Vol. 7, no. 3, July 1964, pp. 236-248.

10. Buckley, D. H.; and Johnson, R. L.: Gallium-Rich Films as Boundary Lubricants in Air and in Vacuum to 10^{-9} mm Hg. ASLE Trans., Vol. 6, no. 1, Jan. 1963, pp. 1-11.

11. Johnson, R. L.; Buckley, D. H.; and Swikert, M. A.: Studies of Lubricating Materials In Vacuum. Paper presented at the USAF, Southwest Research Institute Aerospace Bearing Conference, San Antonio, Mar. 25-27, 1964. Available as NASA TM X-52009.

12. Lewis, Paul: Lubrication in the Environment of Space. Proceedings of the International Symposium on Lubrication and Wear. D. Muster and B. Sternlicht, eds., McCutcheon Publishing Corp., Berkeley, Calif., 1965, pp. 905-939.

13. Gisser, H.; and Sadjian, S.: Evaporation of Organic Compounds from Metal Surfaces at High Vacuum. Proceedings of the Space Lubrication Conference, NASA and ASLE, New York, May 3, 1963. Rep. No. FL-210-53 (DDC No. AD-439844), Department of Defense, Sept. 1963.

14. Buckley, Donald H.; and Johnson Robert L.: Evaporation Rates for Various Organic Liquid and Solid Lubricants in Vacuum to 10^{-8} Millimeter of Mercury at 55^{o} to 1100^{o} F. NASA TN D-2081, 1963.

15. Atlee, Z. J.; Wilson, J. T.; and Filmer, J. C.: Lubrication in Vacuum by Vaporized Thin Metallic Films. J. Appl. Phys., Vol. 11, Sept. 1940, pp. 611-615.

16. Evans, Harold E.; and Flatley, Thomas W.: High Speed Vacuum Performance of Gold Plated Minature Ball Bearings with Various Retainer Materials and Configurations. NASA TN D-2101, 1963.

17. Flatley, Thomas W.: High Speed Vacuum Performance of Miniature Ball Bearings Lubricated with Combinations of Barium, Gold and Silver Films. NASA TN D-2304, 1964.

18. Clauss, Francis J.: Lubrication Evaluation. Lockheed Missiles and Space Co., Apr. 1966.

19. Devine, M. J.; Lamson, E. R.; and Bowen, J. H., Jr.: The Lubrication of Ball Bearings with Solid Films. Paper No. 61-LUBS-11, ASME, May 1961.

20. Bowen, Paul H.: Solid Lubrication of Gears and Bearings in a Space Environment. ASLE Trans., Vol. 7, no. 3, July 1964, pp. 227-235.

21. Corridan, R. E.: Summary Report: Bearing and Lubrication Study. Advanced Tech. Lab. Div., American Standard Corp., June 30, 1959.

22. Freudenlich, M. M.; and Hannan, C. H.: Problems of Lubrication In Space. Lubrication Eng., Vol. 17, no. 2, Feb. 1961, pp. 72-77.

23. Smith, L. Dale; Glenn, Dean C.; and Scibbe, Herbert W.: Evaluation of Impregnated Lubricants in Ball-Bearing Retainers at 10^{-6} Torr. NASA TN D-3259, 1966.

24. Weinreb, Marius B.: Results of Tiros II Ball Bearing Operation in Space. Meteorology Branch, Goddard Space Flight Center, NASA, Mar. 1961.

25. Thompson, R. P.: Space Lubrication Problems at JPL. Tech. Memo. 33-148 (NASA CR-53034), Jet Propulsion Lab., Calif. Inst. Tech., Sept. 2, 1963.

TABLE I. - RADIATION DOSAGE

REQUIRED FOR THRESHOLD

DAMAGE (REF. 5)

[Static irradiation in air.]

Material	Dosage, ergs/gm (C)
Polyphenyl ethers	1000×10^{8}
Mineral oils	500
Dimethyl silicones	1
Methyl phenyl silicones	100
Chlorinated silicones	50
Dibasic acid esters	500
Silicate and disiloxane esters	100
Phenolic (filled)	300
Polyester	90
Polytetrafluoroethylene (teflon)	0.02

TABLE II. - LOSS RATES

THROUGH SIMPLE

ORIFICES[a]

[Molecular flow of air at 25° C.]

Orifice radius, cm	Loss rate, liters/sec
0.1	0.367
.2	1.466
.5	9.166
1.0	36.66
2.0	146.6
5.0	916.6

[a]Ref. 8.

TABLE III. - BONDED DRY FILM LUBRICATED BEARING DATA[a]

[R-3 bearings (4.75 mm bore diam); 8000 rpm.]

Lubricant	Radial load, g	Pressure level, torr[b]	Bearing temperature, °C	Life, hr	Remarks
Metal-bonded MoS_2 on races balls and retainer	137	6×10^{-7} to 4×10^{-8}	71 to 84	1533	Failed. Broken retainer
Races and retainer only	137	6×10^{-7} to 2×10^{-7}	65 to 77	457	Failed. Broken retainer
Races and balls, teflon retainer	135	2×10^{-6} to 2×10^{-7}	57 to 62	8117	Discontinued. Ball pockets badly worn.
Races and balls, phenolic retainer	137	2×10^{-6} to 7×10^{-7}	57 to 60	2554	Failed. Worn pockets and broken retainer.
Sodium silicate bonded MoS_2 on races and retainers after grit blasting	80	8×10^{-6} to 9×10^{-8}	71 to 82	2213	Failed. Excessive wear.
	61	6×10^{-6} to 10^{-7}	56 to 82	174	Failed
	137	8×10^{-7} to 2×10^{-7}	77 to 93	245	Failed
	80	2×10^{-6} to 2×10^{-7}	60 to 84	772	Failed
	137	5×10^{-6} to 9×10^{-8}	22 to 78	343	Failed
	137	760	22 to 50	132	Failed. Run in air.
Sodium silicate bonded MoS_2 on races and retainers after surface pretreatment	77	8×10^{-6} to 8×10^{-7}	71 to 77	1862	Broken retainer
	77	760 to 2×10^{-7}	22 to 60	28	Bearing frozen
	77	8×10^{-6} to 8×10^{-7}	65 to 70	1796	Complete failure
	77	10^{-3} to 2×10^{-7}	65	25	Bearing frozen

[a]Ref. 19.

[b]All tests run in an ion pumped system.

TABLE IV. - BONDED DRY FILM LUBRICATED BEARING DATA[a]

[204 size bearings (20 mm bore diam) 1800 rpm, 340 gram axial load 22^0 to 32^0 C bearing temperatures.]

	Pressure level, torr[b]	Life, rev	Exposure to vacuum, days	Remarks
Silicate bonded MoS_2, Ni cast iron retainer 440C ss races cobalt alloy balls	4×10^{-6}	1×10^{6}	13	Gross transfer of retainer material to races evident in both tests.
Silicate bonded MoS_2, Ni cast iron retainer, 440C ss balls and races	4×10^{-6}	36×10^{6}	206	Gross transfer of retainer material to races evident in both tests.
Epoxy bonded MoS_2 on races and porous bronze retainer	1.5×10^{-5}	6×10^{6}	30	------------------------------
TiO_2 bonded MoS_2 on races and porous bronze retainer	1.5×10^{-6}	2.5×10^{6}	---	Excess lubricant probably caused test stoppage.
Metal - bonded MoS_2 on races and porous bronze retainer	1×10^{-6}	1.5×10^{6}	15	Transfer of retainer material to races and balls had occurred.
Epoxy - MoS_2 solid composite retainer	7×10^{-6}	$>900\times10^{6}$	420	Performed very well
Dioctyl phthalate-570 mg impregnated into porous bronze retainer	3×10^{-6}	275×10^{6}	150	Torque higher than other long life bearings. Gross transfer of retainer material to balls and races.

[a]Ref. 9.

[b]In all tests the dry film was applied to the races and retainer.

[c]All tests run in an ion pumped system.

TABLE V. - COMPOSITE RETAINER MATERIAL RESULTS[a]

[305 size bearings (25 mm bore diam) 100 hour tests.]

Lubricant (retainer material)	Speed, rpm	Radial load, kg	Pressure level, torr	Bearing temperature, ^{o}C	Remarks
60 percent Cu, 30 percent PTFE, 10 percent WSe_2	47	34	3×10^{-8}	41^{o}	Retainer weight loss insignificant lubrication satisfactory.
	35	116	1×10^{-8}	-------------	7 to 19 milligrams retainer weight loss in eight bearings (average, 13 mg). Bearing lubrication excellent. Same bearings as in 47 rpm test.
	35	114	7×10^{-8}	-------------	7 to 31 milligrams retainer weight loss in eight bearings (average, 21 mg). Bearings in excellent condition.
70 percent Ag, 20 percent PTFE, 10 percent WSe_2	33	133	3×10^{-8}	49^{o}	5 to 49 milligrams retainer weight loss in eight bearings (average, 22 mg).
	35	114	7×10^{-9}	-118^{o} for 40 hours. Temperature raised to 149^{o} over a 20 hour period. 149^{o} for 20 hours	10 to 24 milligrams retainer weight loss in eight bearings (average, 18 mg). Same bearings as in 33 rpm test.

[a]Ref. 21.

TABLE VI. - OIL LUBRICATED DOUBLE SHIELDED BEARING DATA[a]

[R-3 bearings (4.75 mm bore diam); 8000 rpm.]

Lubricant	Retainer material and lubricant charge	Radial load, g	Pressure level, torr	Bearing temperatures, °C	Pump type	Life, hr	Remarks
Paraffinic petroleum oil	Synthane 50 mg	79	5×10^{-6} to 3×10^{-8}	60 to 104	Ion	14 340	One bearing failed-filled with oil residue
	Linen base phenolic 42 mg	136	2×10^{-8} to 3×10^{-9}	71 to 77	Ion	20 436	Still running, exposed to 5.5×10^{7} Roentgens of gamma radiation.
Experimental paraffinic petroleum oil	Synthane 52 mg	81	10^{-7} to 10^{-8}	54 to 77	Diffusion	23 454	Still running
Fluoro-silicone oil	Synthane 81 mg	78	10^{-3} to 10^{-8}	60 to 94	Diffusion	33 649	Still running
High phenyl content silicone oil	Synthane 68 mg	136	10^{-6} to 4×10^{-7}	71 to 96	Diffusion	23 996	Still running

[a]Ref. 19.

TABLE VII. - GREASE LUBRICATED DOUBLE SHIELDED BEARING DATA[a]

[R-3 bearings (4.75 mm bore diam)[b]; 8000 rpm.]

Grease type and charge	Radial load, g	Pressure level, torr	Bearing temperature, $^{\circ}C$	Pump type	Life, hr	Remarks
Methylphenyl silicone oil with dye thickener, 96 mg	77	10^{-3} to 10^{-8}	68 to 98	Diffusion	20 147	Discontinued both bearings in good condition
76 mg	138	8×10^{-7} to 2×10^{-7}	121° for 12 346 hr balance 54 to 71	Diffusion	18 846	Still running
84 mg	136	2×10^{-8} to 7×10^{-9}	82 to 91	Ion	5 518	Failed dry sandy residue in bearings. Also exposed to 1.7×10^{7} roentgens gamma radiation
Silicone oil-aryl substituted urea thickener 64 mg	74	5×10^{-8} to 2×10^{-8}	65 to 80	Diffusion	16 742	Still running
93 mg	79	5×10^{-8} to 2×10^{-8}	54 to 77	Diffusion	16 749	Still running
Silicone oil with organic thickener and solid lubricant, 50 mg	79	10^{-3} to 10^{-8}	65 to 93	Diffusion	33 100	Still running
Aryl urea thickened methylphenyl silicone	136	10^{-6} to 10^{-9}	60 to 93	Diffusion	25 319	Test stopped. Ok.
Ammeline thickened inhibited, high-phenyl content silicone oil	137	10^{-6} to 10^{-9}	60 to 91	Diffusion	25 223	Test stopped. Ok.

[a]Ref. 19.

[b]All bearings had ribbon retainers.

TABLE VIII. - EXAMPLES OF SPACE CRAFT LUBRICATION PROBLEMS[a]

Type	Ranger		Mariner		Surveyor	
	Problem	Solution	Problem	Solution	Problem	Solution
Short life short storage	1. Solar-panel actuator 2. Solar-panel hinges 3. Gamma-ray extension boom 4. Lyman-alpha telescope scanner	1. Silicone oil, sealed internally, dry lube externally 2. Self-aligning monoball, silicone grease 3. Silicone oil, sealed internally 4. Low-speed stepping motor, dry-film lube; high-speed actuator, silicone-oil sealed	1. Solar-panel actuator 2. Solar-panel hinges 3. Latches	1. Same as Ranger 2. Self-aligning monoball, filled teflon 3. Same as Ranger	1. Solar-panel positioner 2. Landing-gear hinges 3. Omni-antenna hinges 4. Latch-mechanisms	1. Dry lube on hard anodize 2. Dry lube 3. Dry lube 4. Same as Ranger
Medium to long storage, short operation	1. Omni-antenna hinge	1. Dry lube; actuator dash pot used silicone oil, sealed	1. Planetary scan instrument mount	1. Actuator sealed; some gears dry lubed; high-speed motor, silicone oil, outside bearing, reinforced teflon	1. High-gain antenna	1. Impingement graphite coating on worm gear, dry lube other parts
Medium storage, long life	None		None		1. Television drivers 2. Surface-sampler arm	1. Impingement graphite coating on bearings and gears 2. Teflon bearings
Short storage, long life	1. High-gain antenna drive	1. Sealed actuator gears, dry-film lube; shaft bearing, silicone oil. Worms used extreme-pressure grease; (seal consists of double "O" ring)	1. High-gain antenna drive 2. Temperature-control louvers	1. Same as Ranger except no worms 2. Teflon-coated bushings	1. Temperature control switches	1. Teflon-coated bushings

[a]Ref. 27.

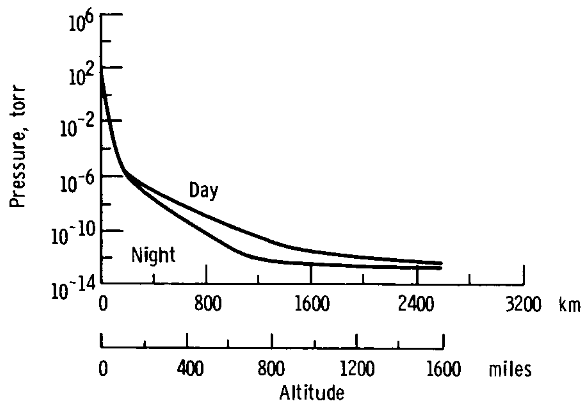

Figure 1. - Pressure as a function of altitude (ref. 1).

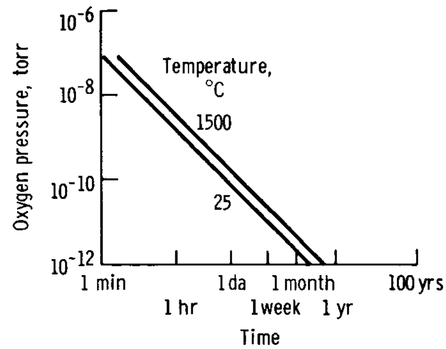

Figure 2. - Time required to form hypothetical 1-angstrom-thick film of FeO on iron (ref. 3).

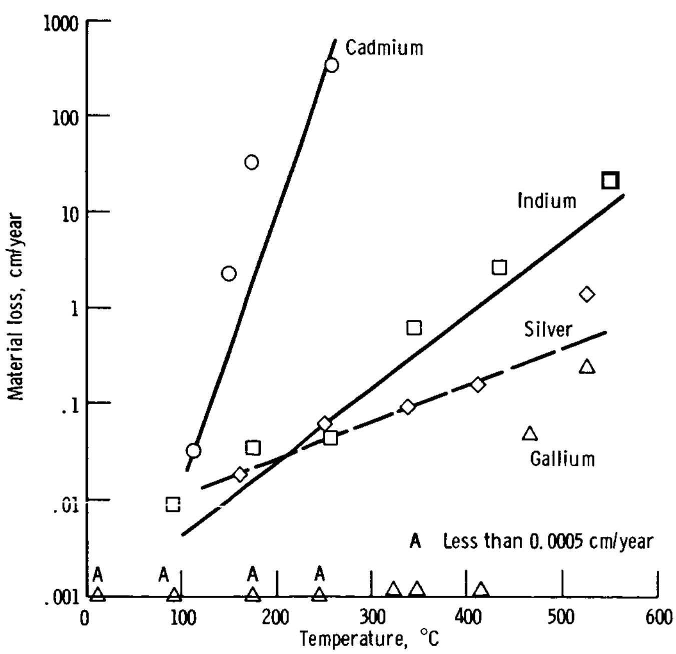

Figure 3. - Evaporation rates for various metals in vacuum. Pressure, 10^{-6} torr (refs. 7 and 10).

E-3790

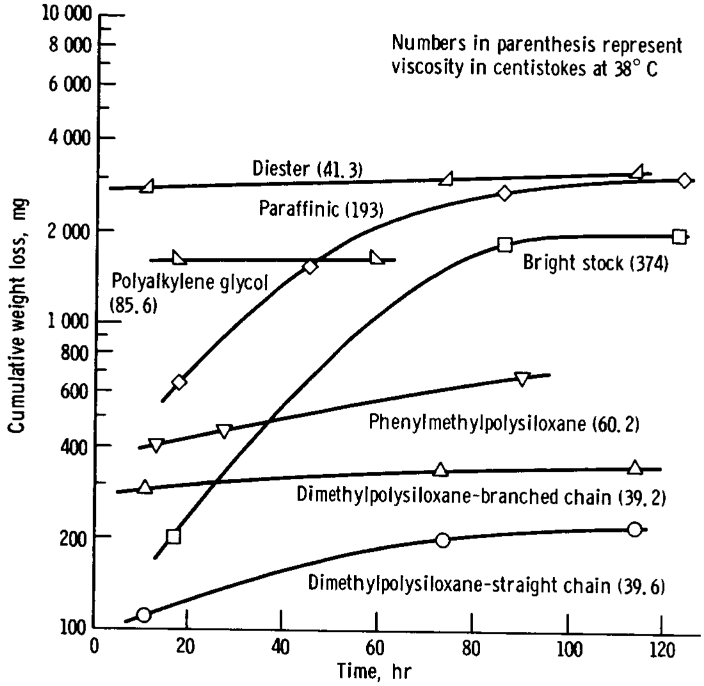

Figure 4. - Evaporation data for promising oils at 60° to 71° C and 10^{-5} torr (ref. 12).

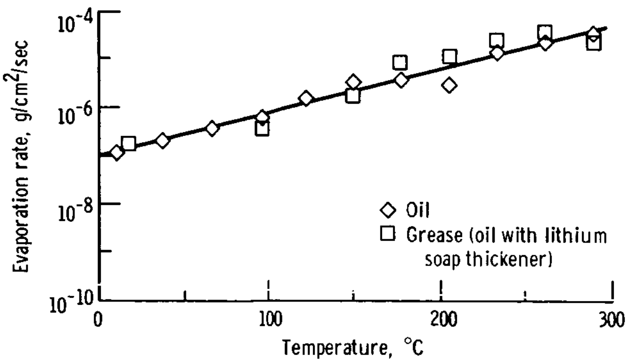

Figure 5. - Evaporation rate of chlorophenyl silicone oil and chlorophenyl silicone oil - lithium soap grease at 10^{-6} torr over a range of temperatures (ref. 14).

E-3790

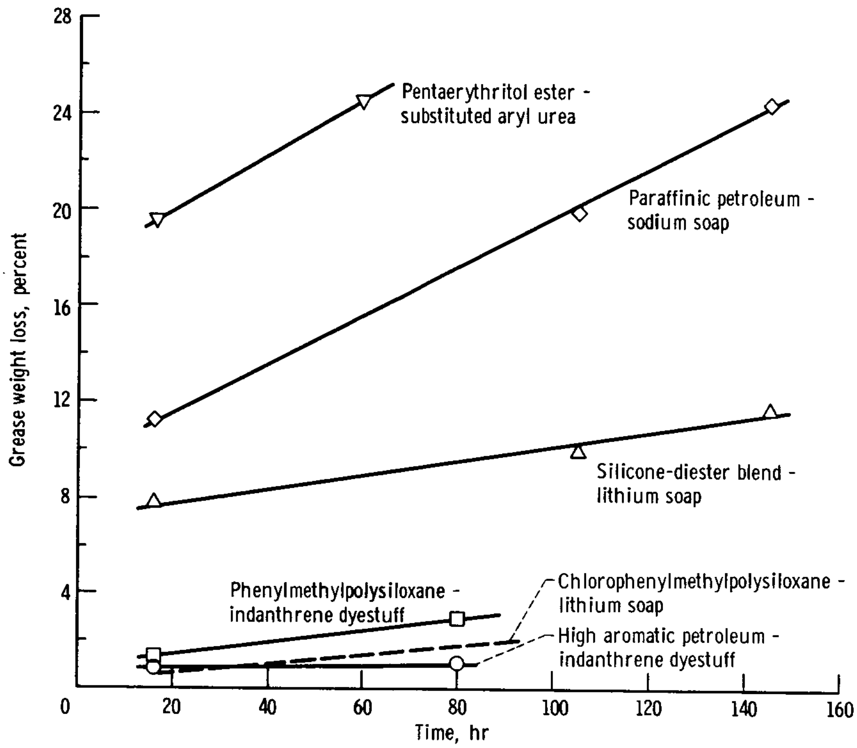

Figure 6. - Evaporation results for low speed grease tests at 45° to 48° C. Size 37 (7 mm bore) brgs.; 60 rpm; 10^{-5} torr (ref. 12).

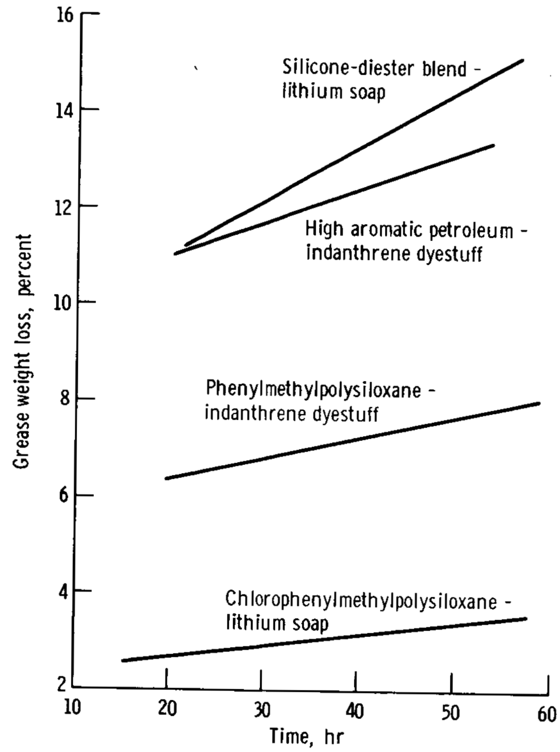

Figure 7. - Evaporation results for greases at 121° C. R-4 bearings (6.35 mm bore); 200 gm axial load; 1800 rpm; 10^{-5} torr (ref. 12).

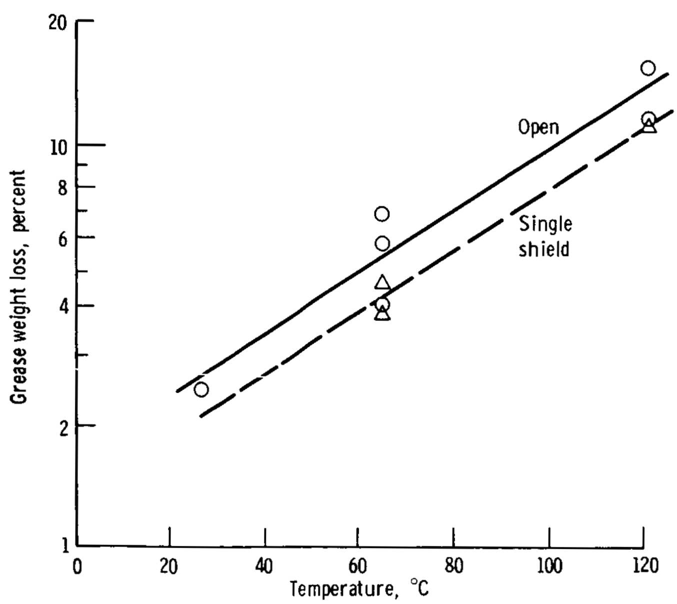

Figure 8. - Evaporation results for silicone-diester blend, lithium soap grease. R-4 bearing; 200 gm axial load; 1800 rpm; 10^{-5} torr; 48 hour test (ref. 12).