NASA TECHNICAL NOTE

NASA TN D-4476

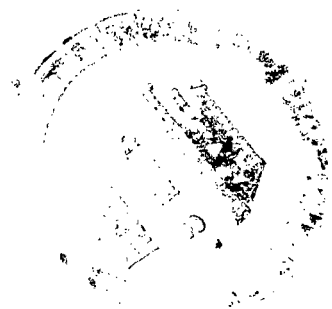*c. 1*

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The operation of sliding- or rolling-element electrical contacts in vacuum presents a problem because of the occurrence of high noise levels, high coefficients of friction and excessive wear rates due to the absence of beneficial surface films. Graphite cannot be successfully used in vacuum because its lubricating ability is dependent upon surface contamination. The use of molybdenum disulfide (MoS_2), although a good vacuum lubricant, is questionable because of its high bulk resistivity and semiconducting characteristics. Niobium diselenide, which has a lower resistivity than MoS_2, is also a good vacuum lubricant although its wear rate is somewhat higher than that of MoS_2 when run against the same base material.

Rolling-element slip rings have also been used successfully in high vacuum. Under the severe conditions encountered in rotating anode X-ray tubes, the use of thin silver films as lubricants have resulted in long useful lifetimes. MoS_2, utilized as a component of the bearing cage material, has also achieved some success under more moderate conditions. Dielectric cage materials, however, are not useful because of the buildup of an insulating film on the surfaces of the bearing components.

The use of high vapor pressure organic materials, as electric contact lubricants in a space environment, is questionable because of the possibility of undesirable polymer formation and the low radiation tolerance of such materials.

Thin metallic films are seen as a promising method of lubrication. Three methods of thin film deposition and the endurance lives of these films (obtained from friction experiments) are discussed. On the basis of the reviewed experimental data, some conclusions are made regarding the performance of the various electric contact materials and lubricants in vacuum.

INTRODUCTION

Some of the major problems for advanced spacecraft mechanisms are those of friction, wear, and electrical noise which are encountered in the operation of sliding

electrical contacts that must be exposed to the high vacuum, radiation and temperature extremes of space. The sliding electrical contacts associated with spacecraft mechanisms are required to operate reliably, with low noise and low contact resistance, for extended periods of time in a space environment. The selection of materials for this type of electrical contact operation is generally based on those materials which are known to work well in the earth's atmosphere. Under this condition, the surfaces of contact materials are covered by films of adsorbed or chemisorbed gases, water, sulphates, carbonates, and other contaminants. Experiments in the friction and wear field have established that these films play an important role in the behavior of materials during the process of sliding (ref. 1). When materials are operated in a vacuum environment, however, these beneficial films may be lost by wear, desorption, or evaporation. They cannot reform because the substance necessary for their reformation is absent in a vacuum. The absence of surface films will markedly change the behavior of materials employed in sliding electrical contacts (e.g., vacuum cold welding may occur). Under these conditions, the contact surface deteriorates rapidly. This results in excessive wear rates, a rise in the coefficient of friction, large contact resistance fluctuations, and intolerable electrical noise levels. In extreme cases, gross seizure can occur and render the mechanism completely useless.

For operation outside of the earth's atmosphere, some form of extrinsic lubrication is needed to reduce friction, wear, and electrical noise to reasonable values. All of this must be accomplished without greatly disturbing the basic function of the sliding electrical contact. In actual space applications, the problem of lubrication is further complicated by environmental factors such as ultrahigh vacuum, radiation, and temperature extremes. Each of these factors has its own peculiar effect on each type of lubricant. Under all conditions of operation, the electrical contact lubricant must not interfere with the electrical conduction across the contact interface. This requires that the lubricant be a fair electrical conductor and remain stable regardless of the type, magnitude, or duration of any environmental factors which may be encountered.

The sliding electrical contacts presently used in vacuum environments are generally adaptations of units used for aircraft applications. They are usually fabricated from the noble metals or their alloys and are electrically insulated by organic dielectrics. When operated under conditions of high vacuum, these units have a short useful life because of the absence of surface films. Additional problems can occur because of dielectric outgassing and possible generation of friction polymers which can occur because of the catalytic action of the noble metal surfaces. These polymers would be beneficial as lubricants, except for the fact that they are electrically insulating and therefore have an adverse effect on the electrical operation of the sliding contact.

The selection of lubricants for vacuum sliding electrical contacts has followed much the same pattern as the selection of the contact materials, that is, to employ lubricants

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which work well in the earth's atmosphere or the few lubricants which are known to work well in a vacuum environment. Notable examples of this approach are the use of graphite, molybdenum disulfide (MoS_2), high altitude brush materials, and certain organic lubricants. All of these materials, with the notable exception of MoS_2, fail to provide adequate lubrication unless elaborate precautions are taken to maintain an artificial atmosphere around the sliding electrical contact. MoS_2, although an excellent lubricant in vacuum, possesses a rather high bulk resistivity which can cause excessive electrical losses across a sliding contact lubricated with this material.

One group of materials, the "Heavy Metal Derivatives" as they are generally known, have recently received some attention (ref. 2) as possible lubricants for vacuum sliding electrical contacts because they possess a desirable combination of properties: (1) a laminar crystal structure and (2) a low bulk resistivity (see table I). Certain compounds in this group, notably niobium diselenide ($NbSe_2$), have been shown to be good lubricants for sliding electrical contact operation in a vacuum (ref. 3).

Other materials, such as teflon and polyimide (refs. 4 and 5) also are good vacuum lubricants. These materials are electrical insulators, but they can be made electrically conductive by adding a metallic component. Nevertheless, the use of these materials in a sliding electrical contact system can result in the buildup of an insulating film on the surface of the contact. If the voltage across the film is insufficient to puncture the film and establish metallic contact, the sliding contact, although showing low wear and low friction, would be useless because of excessive contact resistance.

The friction and wear problems encountered in the operation of sliding electrical contacts in a vacuum are not unlike those which occur in the operation of any other sliding system under the same conditions. The materials concepts developed by friction and wear experiments apply equally to sliding electrical contacts. However, these concepts must be modified to account for the electrical properties.

Additional problems are created by electrical sliding systems because of the flow of electrical energy across the interface. Ideally, the sliding electrical contact should behave as if it were not in the circuit. In the practical case, the sliding electrical contact influences the operation of the circuit to a degree which is dependent upon many factors. This influence creates another criterion, electrical noise, which must be evaluated together with the friction and wear properties of the sliding electrical contact.

Electrical noise may be defined as any unintentional modulation or distortion of a signal current flowing across the contact interface. The magnitude of electrical noise in a contact system is important because it interferes with the intelligibility of a desired signal. The majority of electrical noise encountered in sliding electrical contact systems is caused by variations in the area of actual contact which in turn causes variations in the contact resistance. Other contributions to the noise level of the sliding electrical contact may be made by the generation of thermoelectric voltages (Seebeck effect) and

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TABLE I. - PROPERTIES OF SOME HEAVY METAL DERIVATIVES STUDIED (REF. 2)

Compound	Crystal structure	Color	Molecular weight	Actual density, g/cm	Lattice parameter, Å (or ×10⁻¹⁰ m)		Resistivity, ohm-cm	Conduction type	Comparative coefficient of friction (in air)
					A-direction	C-direction			
Graphite	Hexagonal	Gray-black	12.01	2.25	2.455	6.69	2.64×10^{-3}	Metal	0.20
Cr_2S_3	Trigonal	Brown-black	200.18	3.972	5.941	11.18	(a)	----------------	----
Cr_2Se_3	Rhombohedral	Gray	340.9	-----	------	------	(a)	----------------	----
Cr_2Te_3	Hexagonal	Gray	486.8	-----	3.981	6.211	(a)	----------------	----
MoS_2	Hexagonal	Gray	160.07	4.80	3.16	12.295	8.51×10^2	P-semiconductor	.18
$MoSe_2$	Hexagonal	Gray	253.86	6.9	3.29	12.80	1.86×10^{-2}	Metal	.17
$MoTe_2$	Hexagonal	Gray	351.14	7.7	3.52	13.97	8.69×10^2	P-semiconductor	.19
WS_2	Hexagonal	Gray	247.98	7.50	3.29	12.97	1.44×10^1	N-semiconductor	.17
WSe_2	Hexagonal	Gray	341.78	9.0	3.29	12.95	1.14×10^2	P-semiconductor	.09
WTe_2	Orthorhombic	Gray	439.05	9.4	------	------	3.10×10^{-3}	Metal	.49
VS_2	Hexagonal	Gray	115.06	----	3.29	5.66	(a)	----------------	----
VSe_2	Hexagonal	Gray	208.86	----	3.34	6.12	(a)	----------------	.22
$VTe\delta$	Hexagonal	Gray	178.54	6.80	3.942	6.126	(a)	----------------	----
NbS_2	Hexagonal	Gray	157.03	4.41	3.31	11.89	3.10×10^{-3}	Metal	.08
$NbSe_2\beta$	Hexagonal	Gray	250.43	6.25	3.449	13.03	5.35×10^{-4}	Metal	.12
$NbTe_2$	Trigonal	Gray	348.11	7.6	10.904	19.89	5.74×10^{-4}	Metal	.53
$TaS_2\beta$	Hexagonal	Gray-black	245.08	7.05	3.346	12.32	3.33×10^{-3}	Metal	.05
$TaSe_2\alpha$	Hexagonal	Gray	338.87	8.6	3.431	12.737	2.23×10^{-3}	Metal	.08
$TaTe_2$	Trigonal	Gray	436.15	9.4	10.904	20.075	1.37×10^{-3}	Metal	.53
TiS_2	Hexagonal	Bronze	112.0	3.28	3.408	5.702	8×10^{-3}	N-semiconductor	.22
$TiSe_2$	Hexagonal	Dark purple	205.8	5.26	3.535	6.004	2×10^{-3}	Metal	.17
$TiTe_2$	Hexagonal	Black	303.1	6.34	3.760	6.480	1×10^{-4}	Metal	.33
ZrS_2	Hexagonal	Violet brown	155.4	3.82	3.662	5.809	1×10^1	N-semiconductor	.22
$ZrSe_2$	Hexagonal	Purple-brown	249.1	5.48	3.770	6.137	1×10^{-1}	N-semiconductor	.18
$ZrTe_2$	Hexagonal	Purple-brown	346.4	6.36	3.952	6.660	1×10^{-3}	Metal	.23
HfS_2	Hexagonal	Purple-brown	242.6	6.03	3.635	5.837	1×10^6	Nonconductor	----
$HfSe_2$	Hexagonal	Dark brown	336.4	7.46	3.748	6.159	2×10^1	N-semiconductor	----
HfTe	------------	------------	-----	----	------	------	---------	-----------------	----
ReS_2	Hexagonal	Black	250.33	----	3.14	12.20	---------	-----------------	----
Re_2Se_7	Hexagonal	Black	925.10	----	------	------	---------	-----------------	----
Re-Te	------------	------------	------	----	------	------	---------	-----------------	----
ThS_2	Orthorhombic	Purple-brown	296.2	7.36	------	------	1.0×10^7	Nonconductor	----
$ThSe_2$	Orthorhombic	Dark gray	389.9	-----	------	------	1.5×10^5	P-semiconductor	----
$ThTe_2$	Hexagonal	Black	487.2	-----	8.49	9.01	2×10^{-2}	Metal	----
$US_2\delta$	Hexagonal	Black	302.16	8.175	7.238	4.059	---------	Nonconductor	----
USe_2	Orthorhombic	Black	395.95	9.0	------	------	3.34×10^{-2}	Metal	----
$UTe\beta$	Hexagonal	Black	493.23	8.9	3.998	7.156	1.20×10^{-2}	Metal	----

[a]Chromium and vanadium derivatives vary in resistivity under heat and magnetic force.

electrical breakdown of insulating films.

These three factors, friction, wear, and electrical noise, will govern the useful life of a contact system. Any one of these may take precedence over the others, depending upon the particular application of the contact system.

Rolling-element bearings have also been used as electrical slip rings, particularly in rotating anode X-ray tubes (refs. 6 and 7). The problems encountered with the operation of these devices in vacuum are much the same as those described for the sliding-element slip rings. However, the lubrication requirements are somewhat more severe because the bearings are usually required to support a load. Rolling-element slip rings, nevertheless, have the following advantages:

(1) The multiple areas of contact between the balls and races represent a number of electrical contacts in parallel. This feature has the advantage of possibly reducing electrical noise because of the greater probability of maintaining continuous electrical conduction across the bearing.

(2) The need for a separate slip ring configuration is eliminated. The end result, in this case, would be a more compact device having less weight.

A disadvantage of using rolling-element slip rings is the additional wear (corrosive wear and pitting) of the bearing elements caused by an electrical current flowing through the bearing (ref. 8).

At the present time, rolling-element slip rings have limited applications.

OBJECTIVE

The objective of this report is to review the experimental work that has been done in the field of sliding- and rolling-element electrical contacts in vacuum to show the lubricating ability and the advantages or disadvantages of the various materials employed as lubricants. Solid, thin film lubrication of sliding electrical contacts will be discussed together with what seems to be the best methods for depositing these thin film lubricants.

The high altitude brush problem will also be considered, and some recent work on the relation between the surface oxide of the mating material and the behavior of the graphite as a lubricant both in air and vacuum will also be included.

EXPERIMENTAL RESULTS - A SURVEY OF THE FIELD

Some experimental work has been done in the field of sliding electrical contact lubrication in a vacuum. A comparison of the results from the various experiments is difficult because the experimental parameters and measurement equipment vary widely.

In many cases, the experimental results could have been influenced by such factors as (1) the type of pumping system used, (2) cross contamination among the various experiments being conducted simultaneously, and (3) the outgassing of the dielectric materials used for electrical insulation. Each of these factors can have an adverse effect on the results of the experiments. The various types of contamination generally upgrade the friction and wear performance of materials combinations sliding in vacuum, making them appear better than they would be in actual space applications. It is also possible that inadvertent contamination would degrade the electrical performance. Nevertheless, these experiments are useful because certain facts are apparent regardless of the experimental setup used.

Most of the experiments in vacuum were concerned only with the behavior of graphite or molybdenum disulfide compacts sliding against a few basic contact materials. Recent experiments have included $NbSe_2$. The remaining experiments utilize low vapor pressure organic fluids for vapor lubrication of sliding electrical contacts of precious metal alloys in vacuum.

Sliding-Element Slip Rings

Graphite - high altitude brush wear. - Problems in the operation of sliding electrical contacts at reduced environmental pressures were first encountered during World War II when it was discovered that graphite brushes in electrical machines aboard aircraft flying at altitudes above 20 000 feet (6000 m) displayed an abnormal amount of wear. The standard combination of materials employed in electrical machines at this time was a graphite brush running against a copper commutator or slip ring. This particular combination of materials was normally characterized by a relatively low, steady contact voltage drop, and low friction and wear. The excellent friction and wear characteristics were attributed to the hexagonal-layer lattice structure of the graphite crystal. The hexagonal planes containing the carbon atoms were held together in layers by relatively weak Van der Walls forces which permitted easy shear parallel to these planes. Thus, the lubricating ability of graphite was thought to be inherent in its crystal structure and there was no reason to expect any differences in its behavior in a reduced pressure environment. However, reduced pressure itself was not primarily responsible for the high rate of brush wear since increased rates of wear have been shown to occur at normal atmospheric pressure (ref. 9). Excessive graphite brush wear has been known to occur when the relative humidity was abnormally low. This problem was solved quite simply by artifically increasing the relative humidity. It was soon found that a small amount of water vapor or oxygen must be present in certain amounts in the surrounding environment to promote the lubricating ability of graphite.

The first notably successful approach to the problem of high altitude brush wear was made by impregnating the brush material with metallic halides (ref. 10). It was suggested (ref. 10) that these impregnants or adjuvants are able to generate a surface film by enhancing the oxidation of a copper slip ring through decomposition of the halides by frictional heat. However, adjuvants which are easily decomposed (lower heat of formation) are not as effective as the widely used barium fluoride (BaF_2), which has a high heat of formation. In addition, a silver slip ring which does not form a stable oxide behaves in a manner similar to copper in regards to high altitude brush wear and the action of adjuvants (ref. 11). Furthermore, X-ray data have shown that unchanged halides exist in the commutator film. The exact mechanism of the halide adjuvants is unknown.

As aircraft performance improved, more demands were placed on the aircraft electrical system and it soon became clear that BaF_2 treated brushes were inadequate. With this particular adjuvant, a prefilming operation was necessary for adequate protection. This meant that the electrical machine had to run for a specified length of time in a normal atmospheric environment to develop a film on the slip rings. This was a prerequisite for low brush wear rates. In this age of speed, this was obviously undesirable and there arose a need for materials which would provide immediate protection. To satisfy this requirement, dilute MoS_2 treated brush materials were developed (ref. 12). They proved to be generally satisfactory and possessed the desirable quick filming characteristic. However, for certain applications (aircraft starters and starter-generators), these materials proved to be unsatisfactory and the concentrated molybdenum disulfide carbon brush material was developed (ref. 12). A lithium carbonate impregnated electrographitic carbon brush has also been developed (ref. 12). This material is also capable of providing immediate protection, and it has proved to be particularly useful on aircraft electrical machines that did not operate well with any other type of brush. For applications requiring higher than usual current densities, in addition to quick filming characteristics, a metal-graphite brush has been developed. It has also been found suitable for low voltage applications.

Another approach to the problem of high altitude brush wear has been to employ materials other than copper for commutators or slip rings. It has been shown that high altitude aircraft brush wear does not occur with certain materials (ref. 11). The results of running a type D electrographitic brush (electrographitized pitch bonded artificial graphite) against various ring materials is shown in table II. It can be seen that excessive wear of the brush (under the experimental conditions) does not occur with all materials. Additions of tin or aluminum to copper in the percentages indicated do not affect the wear of the brush, whereas additions of manganese, nickel, or chromium do. It is interesting to note that graphite sliding or graphite does not display this type of wear. However, the altitude at which these tests were conducted was not given.

The plating of slip rings with rhodium has been shown to have some promise. Ex-

TABLE II. - WEAR OF TYPE D ELECTRO-

GRAPHITE BRUSH RUNNING AGAINST

VARIOUS RING MATERIALS UNDER

HIGH ALTITUDE CONDITIONS

(REF. 11)

[Electrographitic type D (electrographi-
tized pitch bonded artificial graphite).]

Ring material	Rapid wear
Copper	Yes
Phosphor Bronze (10 percent Sn)	Yes
Aluminum Bronze (10 percent Al)	Yes
Manganin (13 percent Mn)	No
Cupro Nickel (30 percent Ni)	No
Monel (60 percent Ni)	No
Steel	Yes
18-8 Stainless	No
430 Stainless (16 percent Cr)	No
Nilvar (36 percent Ni)	No
Carbon	No
Silver	Yes
Chromium	No

periments with rhodium plated slip rings revealed a lower contact voltage drop, a lower operating temperature, and a slight increase in altitude protection (ref. 12).

Many solid inorganic compounds have been tried as adjuvants to promote the lubricating ability or graphite in atmospheres lacking suitable contaminants. Some of these are shown in table III. It was found that compounds, such as the oxides or those which tended to form oxides under the conditions of operation (e.g., silicates or molybdates), are generally unsuitable as adjuvants (ref. 11). It is interesting to note the exceptions. They all possess a hexagonal or lamellar crystal structure.

Materials other than those already indicated also promote the lubricating ability of graphite (ref. 13). Organic vapors, such as benzene or ammonia, have been shown to decrease the wear rate and electrical noise values of graphite under reduced pressures to its normal atmospheric value. A certain vapor pressure of the material must, however, be maintained in the surrounding environment to achieve this relatively low rate of wear (ref. 14). The required minimum vapor pressure is somewhat different for each material. A series of experiments showed that the efficiency of the lubricant vapor increases as the molecular chain length increases to an apparent optimum somewhat greater than 10 to 15 Å (10^{-9} to 1.5×10^{-9} m). In the best cases, only a few parts per million of the longer organic molecules were effective in establishing a low wear rate

TABLE III. - PERFORMANCE

OF VARIOUS ADJUVANTS FOR

GRAPHITE LUBRICATION

UNDER HIGH ALTITUDE

CONDITIONS (REF. 11)

Compounds	Adjuvants
Acetates	Good
Carbonates	Good
Halides	Good
Molybdates	Poor
Oxides[a]	Poor[a]
Phosphates	Poor
Silicates[b]	Poor
Sulfides	Good
Sulphates[c]	Poor

[a]Except ZnO whose performance was good.

[b]Except mica and vermiculite whose performances were good.

[c]Except Ag_2SO_4 whose performance was good.

for the graphite used.

In the high vacuum range (10^{-8} torr or 1.33×10^{-6} N/m^2), at least one well-known adjuvant, BaF_2, was not effective in preventing the wear of a 20 percent graphite-carbon specimen sliding on a surface of electrolytic silver. This adjuvant was, however, effective in the 10^{-2} to 10^{-3} torr (1.33 to 0.133 N/m^2) range (coefficient of friction, 0.075; wear not determined) (ref. 15). In running a 100 percent electrographitized carbon on surfaces of various materials, these experiments (ref. 15) revealed that the best wear results were obtained when a transfer film of carbon was present on the mating surface (fig. 1). However, a transfer film of carbon was not generated on all surfaces, being noticeably absent on the electrolytic silver and the gold plated surfaces. Since, under the experimental conditions, the silver surface and the gold surface were considered to be free of all residual surface oxide films, this seemed to indicate that an oxide film was a necessary condition for the generation of a carbon transfer film. In view of the aforementioned results, the transfer film was said to be achieved by chemisorption of the carbon to the oxygen of the metallic oxide. The failure of the BaF_2 adjuvant to promote the lubricating ability of the carbon used, was also attributed to the absence of residual surface oxides (ref. 15).
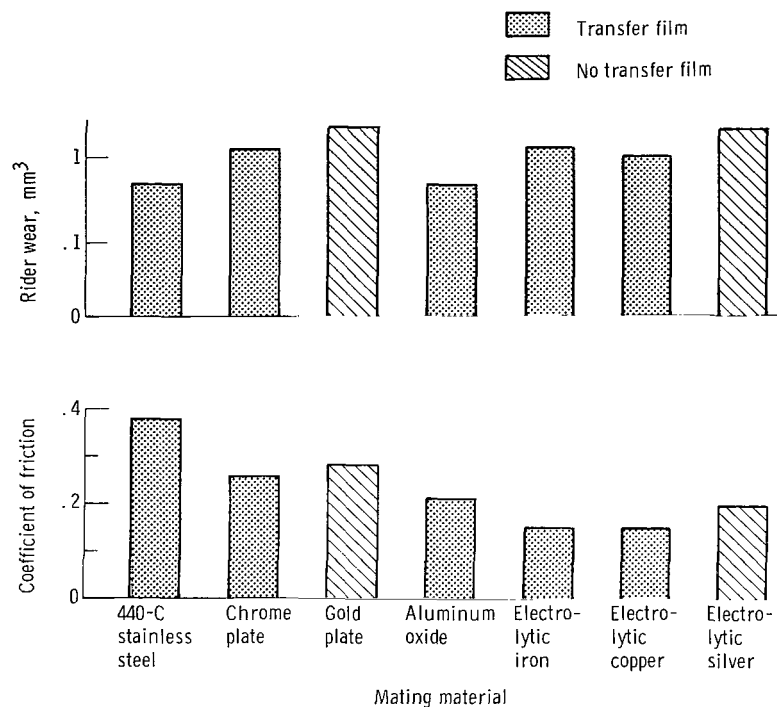
Figure 1. – Effect of mating materials on coefficient of friction and rider wear for 100 percent electrographitized carbon in vacuum (10^{-7} torr or 1.33×10^{-5} N/m²). Sliding speed, 198 centimeters per second; load, 1000 grams; duration of run, 1 hour (ref. 15).

The relation between surface oxides and the adherence of a graphite film has also been discussed elsewhere (ref. 16). In this instance, the failure of graphite to lubricate was attributed to its poor adherence to the surfaces to be lubricated. It was believed that the presence of surface oxides improved the adherence of the graphite but the mechanism of this phenomena was not discussed. Using this hypothesis, the high altitude brush problem was related to the reduced capabilities of oxide formation on the surface of commutator material in the oxygen deficient atmosphere which exists at altitudes greater than 20 000 feet (6000 m). The lack of surface oxides prevented the formation of a transfer film causing gross wear of the graphite brushes.

Analysis of normal films generated by a graphite brush running against a copper commutator offer some further support for the surface oxide hypotheses. It was found that the film was made up of two distinct layers, a layer of carbon on top of a layer of cuprous oxide (ref. 17). In addition, the thickness of the cuprous oxide layer was found to be a function of the operating temperature of the contact (ref. 18).

The wear rate of graphite also has been shown to be related to the formation and destruction of surface oxides, but in a rather unique way (ref. 19). In these experiments, an electrographite brush was run against a copper surface under both light and heavy loads in a normal atmospheric environment.

Under relatively light loads (50 g), the wear track on the copper surface appeared light brown in color and the interfacial electrical resistance slowly increased with time. Analysis of the film showed the major constituent of the surface film to be Cu_2O together with a small amount of graphite.

Under relatively heavy loads (500 g), a black layer of transferred graphite developed on the surface and the contact resistance remained low. Analysis of this black film showed very little CuO or Cu_2O present.

The experimental results suggested that the primary function of the surface oxide layer was to impede the transfer of graphite to the copper surface and so prevent the formation of a uniform transferred layer of graphite.

It was subsequently found that any variable which affected the thickness of the oxide film on the surface of the copper affected the wear of the graphite brush. The rate of wear reaches a limiting value when the oxide film is completely worn away and the transferred film of graphite becomes continuous (ref. 19).

The optimum operation of a copper-graphite sliding contact is achieved when a balance is obtained between surface oxide film formation and destruction. This balance can be disturbed by (1) electrical currents, (2) brush loads, (3) speed of operation, and (4) quantity of water vapor in the atmosphere (humidity) or surrounding environment. A summary of the effect of the variables on the wear of graphite is presented in figure 2.
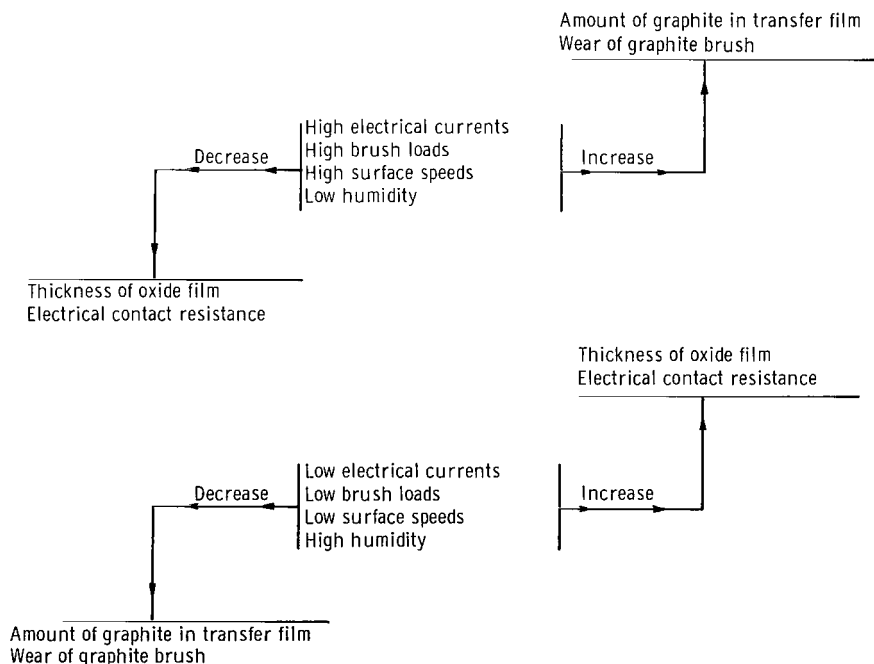

Figure 2. - Relation between conditions of operation, surface films, and electrical contact resistance for graphite sliding on copper (ref. 19).

Effect of silicones on the wear of graphite. - Silicone vapor has been shown to result in excessive graphite brush wear when sliding against copper. This serious problem has occurred when silicone insulation was used in totally enclosed machines. Moreover, extremely small concentrations, as low as 10 parts per million, were shown to cause severe graphite brush wear. Graphite brushes, treated for satisfactory low humidity operation, also displayed excessive wear when used in atmospheres containing silicones.

Since silicones are noted for their hydrophobic nature, it was theorized that the silicone vapor was adsorbed on the surface of the graphite brush and prevented the normal action of water vapor. Another hypothesis suggested that the silicone vapor was oxidized in the areas of actual contact to form the highly abrasive oxides of silicon, which were responsible for the rapid wear of the graphite brushes (ref. 20).

Compacts. - It is generally felt that a continuous supply of lubricant is necessary to obtain a long useful life for sliding electrical contacts while operated in a clean, high vacuum environment. This approach has manifested itself in the form of compacts which contain two components: (1) a lubricating component and (2) a component which has a high electrical conductivity. These products consist of a metal skeleton whose pores are filled with the lubricant. As the metal skeleton wears down, the lubricant is released from the pores of the material thus providing effective lubrication for extended periods of time. These types of compacts have the added feature of high conductivity (electrical and thermal) because of the metal skeleton. These types of materials are generally used as brushes which ride against slip rings of various material. Three compacts of this type will be discussed.

Graphite compacts. - Attempts to improve the electrical conductivity of graphite and yet retain its lubricating characteristic in air, have resulted in a number of useful metal impregnated graphite materials. Among these materials is the silver impregnated graphite brush consisting of about 80 percent silver and 20 percent carbon. The silver content of the brush provides a high current carrying capacity. The high silver content also results in better heat conduction characteristics than those found in a pure graphite brush. Manufacturers literature recommends that this type of brush be run against coin silver rings to obtain the lowest brush wear and lowest electrical noise in normal environments.

Experiments using silver graphite brushes (80 percent silver, 20 percent carbon) in clean, high vacuum environments have led to very disappointing results (refs. 21 to 23). In all cases, brush wear rates were extremely high and contact resistance fluctuations reached intolerable levels in very short periods of time. This behavior seems to be independent of the ring material used. The silver-graphite brushes have been run against slip ring materials of pure silver, pure copper, electroplated silver, electroplated gold, and rhodium plated gold. None of these materials were satisfactory as mating surfaces for this type of brush when operated in a clean vacuum environment.

Molybdenum disulfide compacts. - Unlike graphite, MoS_2 is an effective lubricant in a vacuum, and it was natural to consider its possibilities as a lubricant for vacuum sliding contact applications. MoS_2 is generally used in the form of silver-MoS_2 (Ag-MoS_2) compacts which are fabricated into electrical brushes. Experiments have shown that a certain amount of MoS_2 must be present in the compact to obtain the low rate of wear normally associated with pure MoS_2. In the Ag-MoS_2 compositions, MoS_2 contents of not less than 10 percent were required for low brush wear (ref. 21). The usual composition is 88 percent Ag and 12 percent MoS_2. Pure friction and wear experiments (no electrical current across the interface) also indicate that the optimum composition is about 10 percent MoS_2. These results were obtained in experiments using Ag-Cu-MoS_2 compositions running in air (ref. 24). It was shown that the MoS_2 content of the compacts must be greater than 5 percent to achieve a low rate of wear (fig. 3). A composition containing 10 percent MoS_2 seemed to be about optimum in these experiments also. The coefficient of friction was, however, little influenced in the range of 2 to 35 percent MoS_2.

The 88 percent Ag-12 percent MoS_2 compacts have enjoyed some success in high vacuum experiments (refs. 3, 21, and 22). Noise levels and wear rates have been very low when compared to corresponding graphite compacts running against the same materials under the same conditions. Under vacuum conditions, the best results with the MoS_2 compacts, were obtained using silver or rhodium plated silver as ring materials (ref. 22). The performance of copper as a ring material under these conditions was
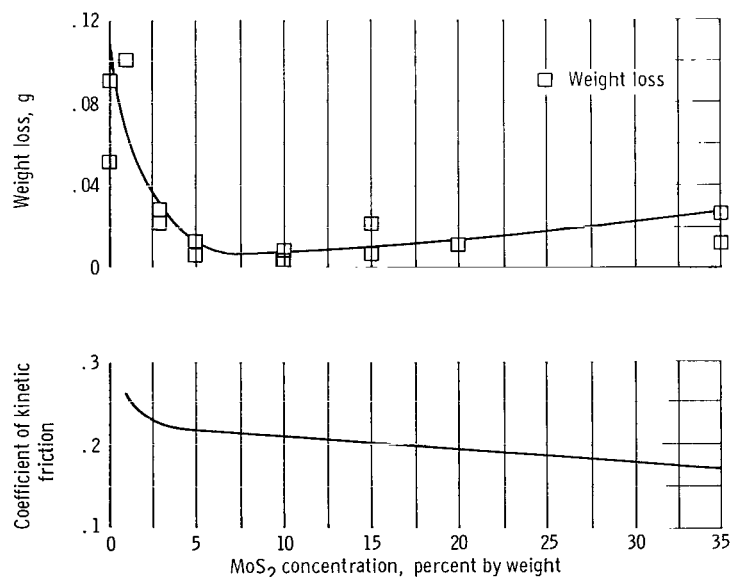

Figure 3. - Effect of MoS_2 concentration on wear and friction of hot-pressed bearing materials. Sliding speed, 2.54 centimeters per second; load, 519 grams; duration of run, 1 hour; material: MoS_2, silver, and 5 percent copper (ref. 24).

somewhat poorer than silver or silver compositions. No reasons were advanced as to the possible cause of this behavior.

Small percentages of copper and molybdenum have been added to the Ag-MoS$_2$ compositions, in electrical brush experiments in vacuum, in attempts to improve their wear characteristics (ref. 21). Increasing the copper content to 15 percent lowered the brush wear but increased the ring wear and electrical noise. Optimum value of the copper content appeared to be about 2.5 weight percent. The Ag-Mo-MoS$_2$ compositions were considered inferior to those containing copper, and experiments using a molybdenum component were discontinued in an early stage of testing. Ring materials employed in these experiments were either electrodeposited silver or electrodeposited gold. The ring wear with both of these materials was about equal; however, the electrodeposited gold caused greater wear of the brush material.

This particular Cu-Ag-MoS$_2$ composition has been used in a slip ring assembly which carried 75 amperes at 430 volts in a vacuum of 10^{-9} torr (1.33×10^{-5} N/m^2) (ref. 25). The brush current density was 300 amperes per square inch (46.5 A/cm^2), and the linear velocity was 424 inches per minute (10.8 m/min). In this case, this composite was run against a silver ring for a period of 700 hours. Peak electrical noise was 4 millivolts, and the brushes displayed a total wear of 0.015 inch (0.38 mm).

In general, the electrical noise levels of all material combinations tended to increase during operation. It was generally observed that the MoS$_2$ lubricated systems were more noisy in air than in vacuum (refs. 22 and 26). It has also been observed that the friction of materials lubricated with MoS$_2$ is higher in air than in vacuum. It has been shown that the lubricating qualities of MoS$_2$ are impaired by atmospheric moisture (ref. 27). Sliding electrical contact experiments have shown that, in air, a graphite lubricated system is slightly superior to an MoS$_2$ lubricated system using electrical noise as the criterion (ref. 22).

Objections to the use of MoS$_2$ as a lubricant for sliding electrical contacts revolve around the fact that, in bulk form, it is a semiconductor of rather high resistivity. Its characteristics can lead to signal distortion and excessive losses across the film. It is a P-type semiconductor and has a bulk resistivity of about 850 ohm-centimeters (ref. 2), which is about six orders of magnitude greater than the resistivity of the usual electrographitic brush material (10^{-3} ohm-cm). Other undesirable effects of MoS$_2$ can be summarized as follows (from ref. 28):

"The electrical resistance of molybdenite (natural MoS$_2$) is high at low potential, but drops as the potential rises. Partly this is caused by the heating effect of the current and partly by the action of the electrical field.

"As the temperature approaches red heat, MoS$_2$ is a fairly good conductor. Apparently there are several critical points in all this (temperature, voltage, electric field, etc.) and MoS$_2$ is also presumed to undergo allotropic modifica-

tion. Wide differences in electrical properties are found in different parts of
the same specimen and as well on different pieces of the mineral. Light falling
on the surface of molybdenite lowers its electrical resistance. Electric and
photoelectric effects vary erratically. Bi-metallic thermal effects vary also.
Careful measurements have shown a reversal of the current from high positive
values to high negative values when different specimens were used. This
occurs between MoS_2 and Cu or Pb.

"In the early development of wireless, molybdenite was one of the materi-
als used for detecting and rectifying radio waves. Its value for this purpose
was not great because of the extraordinary and unaccountable variation in its
action. Various investigators report tremendous variability in its electrical
properties of even different areas of the same crystal of molybdenite. This
accounted for its early abandonment for radio purposes."

Niobium diselenide compacts. - The undesirable electrical properties of MoS_2 have
stimulated investigators to seek other compounds that might be employed as lubricants
for sliding electrical contacts in vacuum. Compounds were sought which would possess
both good lubricating properties and low bulk electrical resistivity. One of the results of
these investigations is the compound $NbSe_2$. This compound has the hexagonal-layer lat-
tice structure (a = 3.45 Å or 3.45×10^{-10} m, c = 13.03 Å or 13.03×10^{-10} m) and might be
expected to show some promise as a lubricant (ref. 2). One very desirable property of
this compound is its low bulk electrical resistivity, which is on the order of 5×10^{-4}
ohm-centimeter. This value is six orders of magnitude better than that of the commonly
used MoS_2 and is comparable to that of graphite.

Investigations using $NbSe_2$ as a lubricant for sliding electrical contacts have been
performed in a vacuum to 10^{-8} torr (1.33×10^{-6} N/m^2) (ref. 3). $NbSe_2$ was utilized in a
compact containing 85 percent silver and 15 percent $NbSe_2$. This compact was employed
in the form of a brush which ran against a coin silver (90 percent silver, 10 percent
copper) slip ring. The test speed was extremely low (0.43 revolutions per hour), and the
test current density was in the order of 80 amperes per square inch (12.4 A/cm^2).

The results indicated that the $NbSe_2$ compacts operated with approximately half the

TABLE IV. - AVERAGE ELECTRICAL AND THERMAL CHARACTERISTICS OF SILVER CONTACTS

LUBRICATED WITH MoS_2 AND $NbSe_2$ IN VACUUM (10^{-8} TORR OR 1.33×10^{-6} N/m^2) (REF. 3)

[Average electrical noise level was less than 1 μV in range of 125 to 250 kHz (400-Hz passband).]

Lubricant material	Total test time, hr	Contact spring pressure		Double contact drop, mV	Double contact resistance milliohms	Temperature				Volume loss, mm^3	
						Contact		Space			
		psi	N/m^2			$^\circ C$	$^\circ K$	$^\circ C$	$^\circ K$	Anode	Cathode
MoS_2	1019	4.8	3.31	70	2.3	67	340	40	313	0.074	0.021
$NbSe_2$	1035	3.6	2.48	37	1.2	53	326	35	308	0.094	0.035

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contact voltage drop of the equivalent MoS_2 compacts (table IV). These data also show that the voltage drop was more stable. However, the wear was somewhat greater with the $NbSe_2$ compacts when compared to their MoS_2 equivalents. The results of these experiments further indicated that the anode (positive contact) wear rate was about three times the cathode (negative contact) wear rate and that the surfaces of the anode were somewhat rougher.

Rolling-Element Slip Rings

Lubrication by metallic films. - Another approach to the problem of maintaining an electrical current between two surfaces in relative motion, operating in a vacuum, has been to modify the contact configuration. This modification makes its appearance in the use of rolling-element bearings as slip rings instead of the sliding elements normally employed. Rolling-element slip rings have been used successfully in rotating anode X-ray tubes for a number of years. Modern rotating anode X-ray tubes, operating at high power densities, impose severe demands on the bearing materials and the lubricant. The conditions under which these bearings must operate are: (1) high vacuum, 10^{-6} to 10^{-8} torr (1.33×10^{-4} to 1.33×10^{-6} N/m^2), (2) high temperature, 475° to 600° C (748° to 873° K), (3) high speed, 3000 to 10 000 rpm, and (4) anode currents up to 1 ampere (ref. 7).

For one particular X-ray tube application, the balls and races of the rolling-element bearings were fabricated from a tungsten-cobalt-chromium tool steel which does not soften at the operating temperature. These bearings (which are also used as slip rings) have a full complement of balls (no retainer). The lubricant is a silver film which is applied to the balls only (ref. 7). Minimum useful lifetimes are around 1000 hours, but some bearings have attained lifetimes of 10 000 hours or more. At room temperature, lifetimes for all bearings are said to be in excess of 10 000 hours (ref. 29).

Vapor deposited barium films have successfully lubricated a tool steel bearing containing 9 percent cobalt and 4.5 percent chromium (ref. 6). However, a tool steel bearing containing 1.5 percent chromium was not lubricated unless an intermediate layer of cobalt was vaporized onto the balls prior to the deposition of the barium film. Lubrication was then satisfactory but the wear was high. If chromium was used as the intermediate layer, both lubrication and wear were good. From these experiments, it was concluded that, for good wear characteristics, the intermediate film should alloy with the base material. This alloying was apparently obtained with the chromium film as the interlayer, but not with the cobalt.

Combination layers of aluminum and barium also produced excellent results. Similar results were also obtained with combinations of barium with manganese, rhodium, and zirconium.

Of the many materials tried in these experiments (barium, gold, silver, tin, zinc, magnesium, calcium, aluminum, strontium, copper, iron, nickel, cobalt, platinum, and chromium) none were found to be better than barium, although some of these materials gave results similar to barium.

Barium-chromium mixtures have been used as a lubricant for small (3/16-in. or 0.48-cm bore) lightly loaded, cobalt tool steel rolling-element bearings operating in a vacuum (ref. 29). These bearings were lubricated with an 80 percent barium-20 percent chromium mixture which was evaporated onto the bearing. By periodically relubricating the bearings with the same mixture, these bearings have run 4800 hours at speeds of 3000 rpm and temperatures to 400° F (478° K). Periodic relubrication was accomplished by evaporating additional amounts of the mixture onto the bearing by energizing a heater wire containing the mixture in a V-groove.

Lubrication by molybdenum disulfide. - MoS_2 has also been used as a lubricant for rolling-element bearings used as slip rings (ref. 26). In these tests, two thrust-type bearings were loaded against each other with a force of 1 pound (4.44 N), and electrically connected in series. Tests were run in an ion pumped chamber which was rough pumped by sorption pumps. These pumping methods eliminated any test surface contamination due to the backstreaming of organic pumping fluids. The lubricant, MoS_2, was applied to the test bearings by two methods: (1) dipping the part in an alcohol suspension of MoS_2 and (2) formation of MoS_2 in situ. MoS_2 was also used in the form of compacts from which bearing cages were fabricated. The speeds of rotation varied from 200 to 5000 rpm, and the tests were performed in a vacuum of 10^{-9} torr (1.33×10^{-7} N/m^2). The test current was 10 milliamperes.

The best performance was obtained with the bearing balls and races fabricated from 440 C stainless steel with a machined retainer fabricated from a compact containing 85 percent gold and 15 percent MoS_2. Before running, this bearing was given a very light, initial application of MoS_2.

Noise values of from 2 to 4 milliohms were generally observed when using MoS_2 as a lubricant. In these experiments also, Devine (ref. 26) observes that the MoS_2 films seem to be more electrically noisy in air than in vacuum.

Lubrication by composites containing dielectric materials. - One experiment, using 440-C stainless steel balls and races with a machined retainer fabricated from a teflon, glass fiber, MoS_2 composition, ran very well mechanically but displayed a very high electrical noise level (ref. 26). An initial contact resistance of 1 ohm increased to an open circuit after operation in air for 1 hour. After operation in air, operation under vacuum conditions with a test current of 10 milliamperes showed that the contact resistance dropped to a value of from 15 to 25 ohms (quite high in comparison to any of the materials used in vacuum so far). These data indicate that a good vacuum lubricant, which is also a good electrical insulator, cannot be successfully used as a lubricant for

low noise electrical contacts. The buildup of an insulating film on the surface of the contact results in a high resistance contact in a vacuum and completely insulating contact in air (ref. 26).

Organic Vapor Lubrication

Organic lubricants are extremely useful materials when used within their limitations. They are effective only in a narrow range of temperature. They are severely degraded by exposure to radiation, and they have relatively high vapor pressures. In practical applications, the use of organic lubricants in a vacuum environment would require an enclosure to prevent excessive evaporation and rapid loss of the lubricant. The enclosure would also serve to maintain a lubricant atmosphere around the contact configuration. If the electrical contact requires rotation, seals would be required. This would add undesirable additional weight to the device. This would be a definite disadvantage in the case of components destined for space flight. These high vapor pressure materials can also be a source of trouble because of the possibility of escaping vapors from the enclosure and consequent condensation on nearby surfaces. The escape of these vapors from the enclosure could be particularly troublesome if condensation occurred on optical devices (such as mirrors or lenses) which were operating in the vicinity.

Organic vapor lubrication of sliding electrical contacts also seems undesirable from another aspect. Experiments involving the sliding of some of the noble metals (gold, platinum, and palladium) and silver in an atmosphere containing organic vapors have shown that amorphous, polymeric substances are formed on the surfaces of these metals (refs. 30 to 32). The quantity of the polymeric material formed varied from metal to metal. Palladium formed a larger quantity than gold, and silver formed much less than either gold or platinum. Gold alloys (gold-platinum and gold-palladium) were more active than pure gold. Materials other than the noble metals also formed significant amounts of these polymeric substances. Table V shows these materials. Of the 30 materials combinations examined, 21 showed polymer formation.

The process of sliding does not seem to be required, since it has been shown that these polymeric materials can form spontaneously (ref. 32). There is no need to introduce hydrocarbon vapors artifically into an electrical system because the substance necessary for the initiation of these materials can be supplied by the outgassing of the organic dielectrics employed for electrical insulation. The polymeric formation abilities of some dielectrics are shown in table VI. Experiments using common dielectric materials, such as paper-phenolic, Kel-F (polytrifluorochlorethylene), and TFE (polytetrafluorethylene), also show generation of these polymeric materials (ref. 32).

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TABLE V. - BEHAVIOR OF VARIOUS SLIDING SURFACES IN BENZENE VAPOR

[4×10^6 wipes; 1.7×10^{-4}-m stroke; 120 Hz; 30-g force; in benzene-saturated air except where otherwise indicated (ref. 30).]

Sliding system[a]	Weight of frictional product, μg	Description of frictional product
Pt/Pt	40	Dark brown polymer, powder
Pd/Pd	38	Dark brown polymer, powder
Pd/Pd (Benzene-saturated H_2)	35	Dark brown polymer, powder
Ru/Ru	22	Dark brown polymer, powder
Pt 6 percent, Au 69 percent, Ag 25 percent/Pd	20	Brown polymer, powder
Pd 25 percent, Au 75 percent/Pd 25 percent, Au 75 percent	15	Dark brown polymer, powder
Ta/Ta	14	Gray polymer, powder
Pd 60 percent, Cu 40 percent ("unordered")/Pd 60 percent, Cu 40 percent ("unordered")	13	Dark brown polymer, powder
Quartz/Pd	[b]12	Brown polymer, powder
Au 91.7 percent, Ag 8.3 percent/Pd	12	Brown polymer, powder
Rh/Rh	10	Light brown polymer, powder
Pd 60 percent, Cu 40 percent ("ordered")/Pd 60 percent, Cu 40 percent ("ordered")	9	Dark brown polymer, powder
Au 70 percent, Ag 30 percent/Pd	8	Dark brown polymer, smeary powder
Mo/Mo	8	Light brown polymer, powder
Cr/Cr	8	Mixed tan and light brown polymer
Au/Pd	5-8	Dark brown polymer, smear
Pd 5 percent, Au 95 percent/Pd 5 percent, Au 95 percent	[b]5	Brown polymer, powder
Pt 6 percent, Au 69 percent, Ag 25 percent/Pt 6 percent, Au 69 percent, Ag 25 percent	[b]5	Brown polymer, powder
Pd/Quartz	[b]3-5	Brown polymer, powder
Au/Au	[b]1-3	Dark brown, smeary polymer
Ag/Pd	[b]1-3	Dark brown, smeary polymer
Ni/Ni	None	Yellow brown oxide
Ni/Ni (Benzene-saturated H_2)	None	Metallic wear products
Ag/Ag	None	Little wear
Cu/Cu (Benzene-saturated H_2)	None	Some metallic wear
Quartz/Quartz	None	Fine quartz wear powder
Fe/Fe (Benzene-saturated H_2)	None	Wear products
V/V	None	Brown oxide
W/W	None	Oxide formed
Zn/Zn (Benzene-saturated H_2)	None	Wear products

[a]First member of pair is slider.
[b]Estimated microscopically.

TABLE VI. - FRICTIONAL POLYMER FROM VAPORS RELEASED BY ORGANIC

STRUCTURAL MATERIALS

[Pd/Pd; 6-cycle cam-driven device; 14×10^6 wipes; 1.7×10^{-4}-m stroke (ref. 30).]

Piece part or material	Temperature		Polymer yield, μm
	$^\circ F$	$^\circ K$	
Relay coil with cellulose acetate interleaving	125	325	34
Relay coil with Mylar interleaving	125	325	11
Relay coil, wire only (enameled)	125	325	8
Phenol fiber spoolheads (2C)	120	322	29
Phenol fiber cards (#4)	120	322	22
Phenol fiber cards (#4) after baking at 110° C for 48 hr	120	322	<5
Durez 265 molded relay structures	120	322	Trace
Phenolic resin molding compound (#2)	120	322	5
Selectron terminal strip	80	300	None
Lucite relay contact cover	80	300	19
Cellulose acetate-butyrate contact cover	80	300	<5
Neoprene grommets	80	300	<5
"Scotch" electrical tape, white	80	300	<5
Wire, cotton, acetate rayon, lacquer (insulation)	80	300	12
Wire, polyvinyl chloride (insulation)	80	300	22
Foils			
Laminated Mylar (polyethylene terephthalate)	120	322	Trace
Koppers polystyrene	80	300	8
Tenite II, 217A	80	300	Trace
Benzene-saturated air (for comparison)	80	300	130

Tests have shown that these polymeric materials have the ability to reduce the wear of some materials under certain conditions, although they are electrical insulators and will degrade the performance of the electrical contact. This is another case where friction and wear are reduced and electrical noise increased. However, these substances are quite fragile, and arcing of the contact will destroy the deposit.

Recent experiments seem to indicate that an absorbed surface film is necessary for polymer formation (ref. 31). It has also been thought that oxygen also enters into the reaction (ref. 31). If adsorbed films and oxygen are required for this process, the behavior of organic lubricants, in vacuum, might be quite different from their behavior in air.

A few experiments have been conducted in vacuum using organic vapor lubrication for sliding electrical contacts. Being aware that the observation of polymer formation was not the primary objective of these experiments, there was no mention of the genera-

TABLE VII. - SUMMARY OF MATERIALS EMPLOYED IN VARIOUS SLIDING ELECTRICAL CONTACT EXPERIMENTS IN VACUUM

Brush material	Lubricant	Brush material composition	Ring material	Remarks	References
Silver-MoS_2	MoS_2	88 percent silver, 12 percent MoS_2	Silver Rhodium plated silver	Acceptable for use in vacuum. Better performance in vacuum than in air.	33
Silver-copper-MoS_2	MoS_2	82.5 percent silver, 15 percent MoS_2 2.5 percent copper	Electroplated silver Electroplated gold	Addition of copper hardens silver, resulting in less brush wear. Gold rings caused greater brush wear.	21
Silver-molybdenum-MoS_2	MoS_2	--------------	-----------	Poor results, erratic performance, excessive noise, brush arcing.	21
Silver-$NbSe_2$	$NbSe_2$	85 percent silver, 15 percent $NbSe_2$ (not optimized)	Coin silver (90 percent silver, 10 percent copper)	Slightly greater wear than equivalent MoS_2 compacts. Better noise performance in vacuum.	3
Silver-graphite	Graphite	80 percent silver, 20 percent graphite	Pure silver Electroplated silver	Extremely poor performance in vacuum. Slightly better than equivalent MoS_2 compacts for atmospheric use.	21, 23, and 33
Precious metal alloy wire	Synthetic ester Chlorinated silicone Hydrocarbon diffusion pump oil	Proprietary	V-grooves of hard gold plate on silver	Lubrication in vacuum supplied by evaporation of fluid in semisealed container. Synthetic ester gave best performance. Hydrocarbon oil gave poorest performance. Slip rings ran with low noise for 79 days.	33

TABLE VIII. - SUMMARY OF MATERIALS EMPLOYED IN VARIOUS ROLLING ELEMENT ELECTRICAL CONTACTS IN VACUUM

Ball material	Race material	Retainer composition	Lubricant	Remarks	References
440-C stainless steel: gold plated	Both races 440-C stainless steel: gold plated	85 percent gold, 15 percent MoS_2	MoS_2	Bearing given light, initial application of MoS_2 before running. Best running of several combinations of materials used.	26
440-C stainless steel: gold plated	Both races 440-C stainless steel: gold plated	Teflon, glass fiber, MoS_2 composition	Teflon, MoS_2	Operated well mechanically, but electrically noisy in both air and vacuum.	26
Tungsten-cobalt-chromium tool steel	Tungsten-cobalt-chromium tool steel	No retainer Full complement of balls	Silver film applied to balls only	Good operation in vacuum (10^{-8} torr or 1.33×10^{-6} N/m^2) temperatures to 600° C and speeds to 10 000 rpm. Used for rotating anode X-ray tube bearings.	7 and 29
Tungsten-cobalt-chromium tool steel	Tungsten-cobalt-chromium tool steel	Not known	Evaporated barium film	Good lubrication and wear if cobalt, chromium, or aluminum are deposited as an intermediate layer. Early work on rotating anode X-ray tube bearings.	6
52100 Steel	52100 Steel	Laminated phenolic	Chlorinated methylphenyl silicone (vacuum impregnated)	Microscopic pitting damage observed at currents as low as 0.167 ampere. Voltage drop across bearing gradually decreased during test.	8

tion of these polymeric substances under the experimental conditions.

Organic fluid vapor, in addition to having been used for lubricating graphite sliding systems (refs. 13 and 14) has also been used for the lubrication of precious metal slip rings operating under vacuum (ref. 33). These experiments employed precious metal alloy wires in V-grooves of hard gold plated silver. Three low vapor pressure organic fluids were considered: (1) a chlorinated silicone, (2) a hydrocarbon diffusion pump oil, (3) a synthetic ester. The slip rings were lubricated by enclosing them in small glass jars along with a small amount of glass wool which contained a quantity of the selected lubricant. The pressure during operation was in the 10^{-5} to 10^{-6} torr (1.33×10^{-3} to 1.33×10^{-4} N/m^2) range.

Lubrication with organic fluid vapors provided up to 79 days of relatively noiseless operation. The synthetic ester gave the best performance, followed by the chlorinated silicone. The hydrocarbon oil gave the poorest performance of the three fluids tested (ref. 33). The electrical noise level was also found to increase substantially when the specimens were operated at a higher value of direct current.

Small amounts of contamination, obtained by the warming up of the vacuum system cold trap, were found to "heal" the noisy contacts resulting in low noise operation. Water vapor pressures of from 5 to 25 torr (6.65×10^2 to 3.32×10^2 N/m^2) were also found to "heal" the contacts.

A nonhalogenated silicone oil has also been successfully used for the lubrication of precious metal slip rings in vacuum (ref. 34).

A listing of the major results of the vacuum sliding electrical contact experiments is shown in tables VII and VIII.

CONSIDERATION OF THIN FILMS AS LUBRICANTS FOR SLIDING ELECTRICAL CONTACTS IN A SIMULATED SPACE ENVIRONMENT

Solid, thin film lubrication is seen as a most likely method for the lubrication of sliding electrical contacts in a space environment. Some attention must be given, therefore, to the possible behavior of thin films under these conditions.

Serious consideration must be given to the evaporation rates of the film material (because of the relative thinness of the film). Thin film removal can also be accelerated by being bombarded with the various types of particulate matter which exists in space. This continuous bombardment would also result in a slow change in the resistivity of the film which would cause possible changes in the operation of the electrical circuit of which it is a part. As the film approaches complete removal, the nascent contact surfaces will approach each other very closely, and cold welding of the asperites will begin. Gross surface damage will eventually occur and cause an increase in friction and excessive

electrical noise.

Since the great majority of electrical contacts are completely insulated electrically (and hence thermally), any change in the value of friction would result in a higher bulk temperature than that which would occur if the electrical contacts were directly attached to a large structure or heat sink. This effect would also tend to accelerate the evaporation of the thin film toward the end of its useful life.

The melting point of a material is not a sufficient criterion for the choice of a thin film contact lubricant in a vacuum. Materials, whose melting points differ by only a small amount, may have evaporation rates that differ by many orders of magnitude at a given temperature (e.g., tin and zinc).

If alloys are considered for lubrication, selective evaporation of the components of the alloy may take place (Raoult's law, ref. 35). This process would result in a change in the composition and hence a change in the properties of the material. Of particular interest in electrical contact operation are the changes in the electrical and mechanical properties. A change in hardness for example, would alter the friction and wear characteristics of the material. This in turn would affect the electrical noise values. A large change in electrical resistivity might cause excessive electrical losses across the contact.

Presently, solid thin film lubrication (as deposited surface films) suffer one serious disadvantage. The lubricant films generally have a finite life. This type of lubricating film is not self-healing. When the film is worn through in the contact area, its useful life is ended.

Thin Films Of Soft Metals

Soft metals, with low shear strengths, can be used as lubricants for sliding electrical contacts which must operate under conditions of ultrahigh vacuum. This type of lubrication is especially useful for this purpose because the metallic thin films are inherently good electrical conductors and would present a minimum of interference to the passage of an electrical current across the contact interface. Furthermore, many of these metals have very low vapor pressures even at high temperatures. This property is extremely important because of the very thin films which are ordinarily used as lubricants. Thin, metallic lubricant films are also desirable because they will maintain much of their physical and electrical integrity when exposed to the various types of radiation (ref. 29).

For these soft metallic thin films to function effectively as lubricants, the area of contact between the sliding solids must be kept small (ref. 1). This requirement is fulfilled by the use of base materials which possess a high hardness or high yield strength. Consideration must also be given to the electrical conductivity of these hard materials in order to minimize the electrical losses across the contact configuration.

Experiments involving thin, metallic films as lubricants on hard substrates show,

generally, that the coefficient of friction is a minimum when the lubricant film thickness is in the order of 2500 Å (10^{-5} cm) (ref. 1). Thicker films result in larger areas of contact, whereas thinner films do not entirely prevent base metal contact on those materials having an average surface finish. If the base materials were highly polished, it is conceivable that much thinner films might be effective as lubricants.

One interesting characteristic of metallic film lubricants is the decrease in the friction coefficient displayed as the applied load is increased (ref. 1). This has been observed on thin, electroplated indium films (10^{-4}-cm thick) on a steel base material. Values of the coefficient of friction fell to 0.04 at a load of 8 kilograms as compared to a coefficient of friction of 0.2 at a load of 0.4 kilogram. This phenomenon could possibly be advantageous in sliding electrical contact operation in environments where mechanical vibration is a problem and heavy loads must be used to maintain a reliable contact.

Any of the results discussed previously could, of course, be modified by utilizing methods other than electroplating to apply the thin film to the base material.

One of the major problems encountered in the use of thin, metallic films as lubricants is that of adherence or bonding of the metallic film to the base material. An essential requirement for an enduring thin film lubricant is that the film be firmly bonded to the base material. Poor film adherence manifests itself in a very short useful life as a lubricant. In many cases, the film is ruptured the instant sliding begins.

Several methods are presently available for depositing thin films of various materials on a variety of base materials. These methods permit close control of the film thickness and, most important of all, the films are firmly bonded to the base material. These general characteristics make these methods extremely attractive for deposition of thin film lubricants on sliding electrical contacts. The various methods will each be discussed in the following paragraphs.

Thin film formation by vacuum vapor deposition. - The vacuum vapor deposition experiments of reference 36 describe a process whereby gold films in the order of 1800 Å (1.8×10^{-7} m) thick were deposited on a nickel-10 percent chromium alloy base material. Prior to the deposition of the film, the base material was cleaned and thermally etched in high vacuum by means of an electron gun. The gold was then evaporated from a filament type source and onto the still hot base material.

Friction experiments in vacuum (10^{-11} torr or 1.33×10^{-8} N/m) using this gold film as a lubricant and niobium as the mating surface showed that the coefficient of friction was relatively low (0.3) and remained low for an extended period of time. This result was achieved because of the good bond between the base material and the film. An explanation for this was based on the fact that the high temperature of the base material and the satisfaction of an alloying requirement (some mutual solubility) had formed a diffused region between the gold film and the base material. This diffused region "matches" the properties of the base material to the properties of the thin film.

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Thin film formation by ion plating. - The deposition of a film on a base material may also be achieved by ion plating (refs. 37 and 38). In this method, the film material (a metal) is evaporated into an argon plasma where it is ionized. The ionized material, which is now positively charged, is accelerated toward the base material which is maintained at a high negative potential (several thousand volts) relative to the evaporant source. The metal ions, because of their large kinetic energy derived from the electric field, penetrate into the base material and form a diffused region much like the vacuum vapor deposition process described previously. The ion plating method, however, has several significant advantages:

(1) The base material need not be heated.

(2) Curved or ''shadowed'' surfaces may be plated without revolving the base material relative to the evaporant source.

(3) The base material and film material need not be mutually soluble to form the diffused region.

(4) The deposited film has good uniformity over the entire surface area of the base material.

(5) The base material is continuously cleaned (by argon ion bombardment) previous to and during the deposition of the film material; this results in improved adherence of the film.
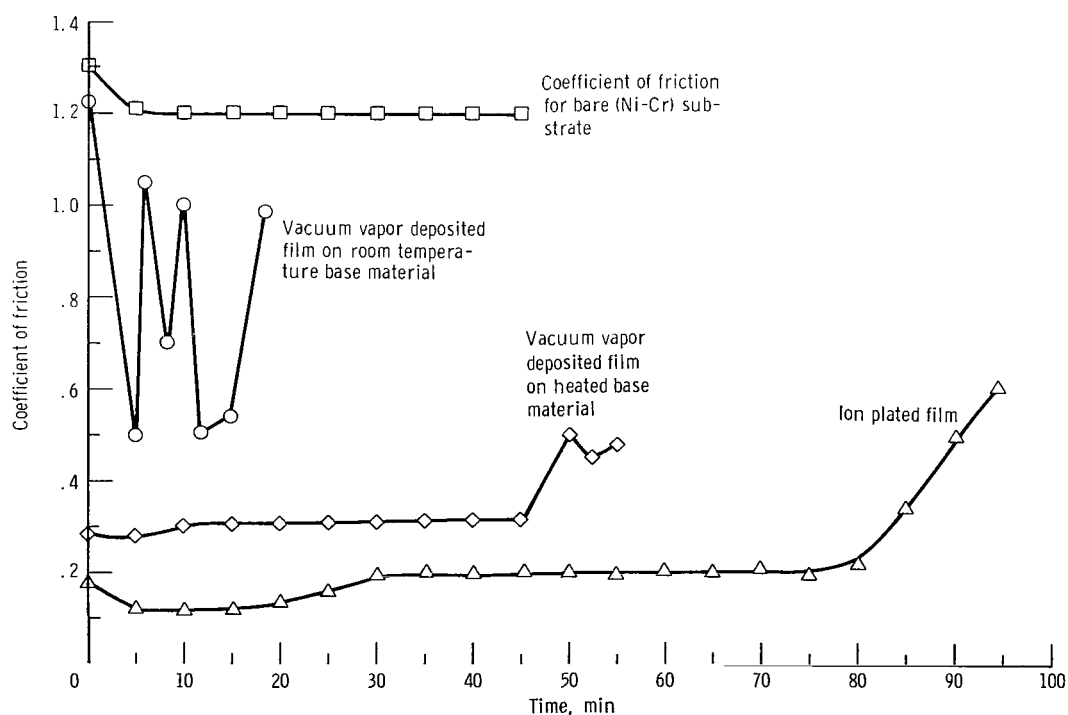

Figure 4. - Coefficient of friction of niobium sliding on Ni-10 percent Cr alloy with gold deposited film in vacuum. Sliding speed, 2.54 centimeters per second; load, 250 grams; ambient temperature (ref. 42).

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(6) Any film material already deposited, having poor adherence, is sputtered off, reionized, and redeposited.

The films deposited by this method are somewhat superior to the films deposited by the vacuum vapor deposition method. A friction experiment in vacuum (10^{-11} torr or 1.33×10^{-9} N/m) using an ion plated gold film 1500 Å (1.5×10^{-7} m) thick on a nickel-10 percent chromium base material, and niobium as the mating surface, showed that the coefficient of friction was about 0.2. Furthermore, the lifetime of the film was somewhat longer than the same film deposited on the same base material by the vacuum vapor deposition method. A comparison of the coefficients of friction and the useful lifetimes of these gold films is shown in figure 4.

Thin Film Formation Of Compounds By Ion Sputtering

The process of vacuum vapor deposition and ion plating suffer one limitation. In both of these processes, the film material must be heated to the point of evaporation or sublimation. Furthermore, the film material must retain its molecular integrity throughout the process if the film on the base material is to have the same composition as that of the parent material. Compounds, which dissociate before reaching the temperature required for evaporation or sublimation, cannot be employed in these processes. Another recent technique, ion sputtering, does not require primary heating of the film material, and hence it is not subject to the limitations described previously (ref. 39).

In this process, the films are produced by positive ion bombardment of a negatively charged quantity of film material. This action results in a physical knocking off of surface atoms (sputtering) of the film material which is then deposited on a base material in close proximity to the film material. The plating of curved surfaces will require rotation of the base material relative to the film material.

The ion sputtering process is extremely versatile and is reported as being capable of depositing "anything on anything". This process opens up a vast new field of possibilities because it enables deposition of materials, as thin films, which were impossible to deposit by conventional methods. Some of these materials include glass, ceramics, plastics, semiconducting compounds, and alloys. Insulating materials, however, require the use of a radio frequency power source, but nevertheless these materials can be successfully sputtered (ref. 40). Furthermore, the refractory metals (tungsten, rhenium, tantalum, and molybdenum) can be sputtered with ease. However, the sputtering rates for all of these materials vary widely.

This process makes possible the deposition of a myriad of thin films which may possess desirable qualities for the lubrication of sliding electrical contacts or other sliding mechanisms in a vacuum environment.

Recent experiments in the friction and wear field have demonstrated that the process of ion sputtering can be successfully employed for the deposition of thin films of MoS_2 (ref. 41). Friction experiments in vacuum (10^{-11} torr or 1.33×10^{-9} N/m) showed that an ion sputtered thin film of MoS_2, 2000 to 3000 Å (2 to 3×10^{-7} m) thick, deposited on a niobium base material and slid against a mating surface also of niobium, had a coefficient of friction in the order of 0.09. This value is generally characteristic of bonded MoS_2 films. The materials were run at low speed, 2.5 centimeters per second, under a load of 250 grams. The experiment ran with low friction for 5 hours. When the experiment was terminated at the end of 5 hours, the MoS_2 film still had not failed. This remarkable endurance life is again characteristic of the excellent adhesion of the film material to the substrate material and demonstrates that thin films can function successfully as lubricants for an extended period of time.

CONCLUSIONS

The review of the literature, involving sliding electrical contacts in vacuum show that lubrication of sliding electrical contacts is necessary if these contacts are to operate with a low electrical noise level for an extended period of time. The nature of a sliding electrical contact, in combination with the space environment in which it must operate, demands a lubricant which must satisfy the following major criteria:

1. The lubricant must be stable under all expected variations of the environment.

2. The lubricant must not seriously interfere with the electrical conduction across the contact interface.

3. The lubricant must reduce the friction and wear of the sliding contact to reasonable values.

4. If the contact is not enclosed, the evaporation rate of the lubricant, under the expected environmental conditions, must be low. The adverse effects of the condensation of the evaporated material on nearby surfaces should also be considered.

Using these criteria as a basis for evaluation, some conclusions can be made concerning the performance of the materials which were used as vacuum electrical contact lubricants in the experiments reviewed in this report.

Graphite

Under high vacuum conditions, where surface contamination is very low, graphite is not a lubricant and therefore cannot be considered useful for extended operation in a vacuum. Its lubricating ability is dependent upon surface oxides or other contaminants, which are absent in a vacuum. Silver-graphite compacts are, however, slightly superior to the equivalent molybdenum disulfide compacts for operation in the earth's atmosphere.

Molybdenum Disulfide

The 12 percent molybdenum disulfide-88 percent silver compacts give acceptable performance in vacuum when run against silver slip rings. The main objection to the use of this compact is the relatively high bulk resistivity and semiconducting characteristics of the molybdenum disulfide.

Niobium Diselenide

Brushes fabricated from a 12 percent niobium diselenide-88 percent silver compact display excellent performance in vacuum. The noise levels, with coin silver as a mating surface, are lower than those obtained with the equivalent molybdenum disulfide compacts, although the wear is somewhat greater. The most significant advantage possessed by this material is its low bulk resistivity.

Organic Lubricants

Organic vapor lubrication of precious metal sliding electrical contacts in a semi-closed system at relatively low pressures has resulted in very long useful lives and low noise levels. The possibility of the formation of insulating deposits of friction polymer, with this combination of materials (organic lubricants and precious metals), and the low radiation tolerance of these organic materials make their acceptability for extended space applications questionable.

Composites Containing Dielectric Materials

The few experiments that have used composites containing dielectric materials for sliding or rolling electrical contacts in vacuum have shown that these materials result in a noisy contact. The contact becomes noisy because of the development of an insulating film between the two conducting surfaces. If the film thickness becomes such that it cannot be broken down electrically, the contact, although showing low friction and wear, would have an infinite electrical resistance (open contact). This fundamental observation can be extended to include any lubricant material which is a dielectric and forms a transfer on the mating surface. Therefore, this class of materials would not be acceptable as an electrical contact lubricant in vacuum.

Thin Metallic Films

Thin, metallic film lubricants seem, at present, to offer the greatest number of possibilities as a lubricant for sliding or rolling electrical contacts in a vacuum. Rolling-element electrical contacts have operated successfully with thin, metallic film lubricants under extreme conditions encountered in modern rotating anode X-ray tubes for long periods of time. This type of lubricant film is an inherently good electrical conductor.

Furthermore, the materials, usually employed in these films, have a relatively low vapor pressure at high temperatures and are stable in vacuum. There are several excellent methods available for applying these films to a base material. These methods also enable almost any type of film to be fabricated. The number of material combinations is large. The most pronounced disadvantage of this type of lubrication is that the useful life of the lubricant film is limited. Continued research in the area of thin, metallic lubricant film durability in vacuum certainly is desirable. The results would be invaluable.

Lewis Research Center,
    National Aeronautics and Space Administration,
        Cleveland, Ohio, November 30, 1967,
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