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LUBRICATION OF SLIDING AND ROLLING ELEMENT ELECTRICAL CONTACTS IN VACUUM

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TECHNICAL PAPER proposed for presentation at 1968 Annual Meeting of the American Society of Lubrication Engineers
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ABSTRACT

Sliding electrical contact problems in vacuum, and recent experiments in this field are reviewed in regard to the lubricants used. Attention is given to the relationship between surface contamination and the wear of graphite. Organic lubrication is reviewed and it is seen as an undesirable method of lubricating electrical contacts on the basis of the friction polymer data examined. Brief conclusions are drawn regarding the performance of the various lubricants on the basis of the experimental evidence. Thin, metallic films are seen as a promising method of contact lubrication, and several excellent methods of depositing these films are presented.

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INTRODUCTION

Some of the major problem areas 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 surface films, normally present on the surfaces of materials, play an important role in the behavior of materials during the process of sliding(1). When materials are operated in a vacuum environment, 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.

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 ultra high 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 occur because of dielectric outgassing and generation of friction polymers which 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 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 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 as possible lubricants for vacuum sliding electrical contacts because they possess a desirable combination of properties in (2). These properties are: (1) a laminar crystal structure and (2) a low bulk resistivity. 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 (3).

Other materials, such as teflon and polyimide (4, 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 same 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 does influence the operation of a circuit and this influence creates another criterion, electrical noise, which must be evaluated together with the friction and wear properties of the sliding electrical contact. 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, (6, 7).

However, the lubrication requirements are somewhat more severe because the bearings are usually required to support a load. Nevertheless, they have the advantage of multiple contact areas between the balls and races. This feature could possibly reduce electrical noise because of the greater probablity of maintaining continuous electrical conduction across the bearing.

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 [8].

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 inadvertant 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 MoS_2 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 precious metal alloy sliding electrical contacts in vacuum.

Graphite - High Altitude Brush Wear

Problems in the operation of sliding electrical contacts at reduced environmental pressures probably began with the phenomena of high altitude brush wear on electrical machines aboard aircraft which flew above 20 000 ft during World War II. Until this time, the lubricating ability of graphite was thought to be inherent in its crystal structure. Investigations (9) into the high altitude brush problem revealed that a small amount of water vapor must be present in the surrounding atmosphere to promote the lubricating ability of graphite.

The first practical solution to the high altitude brush problem was the addition of metallic halides (notably barium fluoride, BaF_2) to the brush material (10). However, the successful use of BaF_2 treated brushes depended on a time-consuming pre-filming procedure. To surmount this difficulty, dilute and concentrated molybdenum disulfide (MoS_2) and lithium carbonate impregnated brush materials have been developed which provide immediate high altitude protection (11). Other adjuvants and ring materials have also been tried (12). Some of these materials and their performance are shown in Tables 1 and 2. Recently, altitude protection has been slightly increased and the contact voltage drop reduced by plating slip rings with rhodium (11). Certain organic vapors have also been found to decrease the wear rate of graphite in a reduced pressure environment to its normal atmospheric values (13,14).

In the high vacuum range (10^{-8} torr), BaF_2 was not effective in preventing excessive wear of a 20% graphite-carbon specimen sliding against electrolytic silver (15). BaF_2 was, however, effective in the 10^{-2} to 10^{-3} torr range.

The best wear results in high vacuum, using a 100% electrographitized carbon sliding against various materials, were obtained when a transfer film of carbon was present on the mating surface (15). However, transfer films were absent on relatively oxide free materials (e.g., silver and gold). From these results, it was theorized that the transfer film was achieved by chemisorption of the carbon to the oxygen of the metallic oxide. These results are presented in Fig. 1. The failure of the BaF_2 adjuvant was also attributed to the absence of surface oxides (15).

The failure of graphite to lubricate has also been attributed to its poor adherance (16), and it was believed here also that the presence of surface oxides improved the adherance.

Some support for the surface oxide hypothesis has been offered by the analysis of normal commutator films generated by a graphite brush running against a copper commutator (17,18).

Other experimental results (19) indicated a relationship between the wear rate of graphite and the formation and destruction of surface oxides. It was subsequently found that any variable which affected the thickness of the oxide film, affected the rate of wear of the graphite brush. The optimum operation of a copper-graphite contact is achieved when a balance is obtained between surface oxide film formation and destruction. Some of the important variables which offset this balance are presented in Fig. 2.

Severe graphite brush wear has also occurred in totally enclosed machines where silicone insulation was employed. Brushes, treated for satisfactory low humidity operation, also displayed excessive wear in atmospheres containing silicones. One explanation suggested that the hydrophobic silicone vapor was adsorbed on the surface of the graphite and prevented the normal action of water vapor. Others (20) attributed the excessive brush wear to the formation of abrasive oxides of silicone by oxidation of silicone vapor in the contact areas.

Compacts

It is generally felt that a continuous supply of lubricant is necessary to obtain a long useful life for sliding electrical contacts which must operate 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. Three compacts of this type will be discussed.

Graphite compacts. - Attempts to improve the electrical conductivity and heat conduction characteristics of graphite and yet retain its lubricating characteristics in air, have resulted in a number of useful metal impregnated graphite materials. Among these materials is the familiar silver impregnated graphite brush consisting of about 80% silver and 20% carbon.

Experiments using silver-graphite brushes running against ring materials of pure silver, pure copper, electroplated silver, electroplated gold, and rhodium plated gold in clean high vacuum environments, have led to very disappointing results (21-23). 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.

Molybdenum disulfide compacts. - Unlike graphite, MoS_2 is an effective lubricant in vacuum and it was natural to consider its possibilities as a lubricant for vacuum sliding electrical contact applications. MoS_2 generally appears in the form of silver-MoS_2 compacts which are fabricated into electrical brushes. Experiments (21,24) have shown that MoS_2 contents of not less than 10% were required for low brush wear. Fig. 3 shows that the rate of wear, but not the coefficient of friction, is greatly influenced by the amount of MoS_2 in these compacts.

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

Small percentages of copper and molybdenum have been added to the silver - MoS_2 compositions in attempts to improve their wear characteristics (21). Optimum values of copper content appeared to be about 2.5 weight percent whereas additions of molybdenum resulted in very poor performance. A silver-copper-MoS_2 brush material has been used to carry high currents (300 A/in.^{2}) in a vacuum of 10^{-9} torr (25).

It has been observed that MoS_2 lubricated systems were more electrically noisy in air than in vacuum (22,26). In connection with this observation, it is interesting to note that the lubricating qualities of MoS_2 are impaired by atmospheric moisture (25), and that the friction of materials lubricated with MoS_2 is higher in air than in vacuum.

Objections to the use of MoS_2 as an electric contact lubricant revolve around the fact that, in bulk form, it is a semi-conductor of rather high electrical resistivity (850 ohm-cm) which can cause signal distortion and excessive losses across the contact. Other undesirable effects of MoS_2 are summarized in reference 28.

Niobium diselinide compacts.- Another hexagonal layer-lattice compound which has given good results as an electrical contact lubricant in vacuum is niobium diselinide ($NbSe_2$). One very desirable property of this compound is its low bulk electrical resistivity (5×10^{-4} ohm-cm) which is comparable to that of graphite.

Investigations using $NbSe_2$ as a lubricant for sliding electrical contacts have been performed in vacuum (3). $NbSe_2$ was utilized in a compact containing 85% silver and 15% $NbSe_2$, which ran against a coin silver slip ring at an extremely slow speed (0.43 rev./hr).

Test results indicated that the $NbSe_2$ compacts operated with approximately half the contact voltage drop of equivalent MoS_2 compacts. 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. A comparison of the performance of MoS_2 and

$NbSe_2$ run under the same conditions is presented in Table 3.

Rolling Element Slip Rings

Lubrication by metallic films. - Rolling element bearings employed as slip rings, have been used successfully, particularly in rotating anode X-ray tubes. Modern rotating anode X-ray tubes, operating at high power densities, impose severe demands on the bearing materials and lubricant. X-ray tube bearings must operate under conditions of high vacuum (10^{-6} to 10^{-8} torr), high temperature (600 C), high speed (3 000 to 10 000 rpm), and carry anode currents up to 1 ampere (7).

For one particular X-ray tube application, the balls and races were fabricated from a tungsten-chromium-cobalt tool steel. These bearings have a full complement of balls and the lubricant is a silver film applied to the balls only (7). Useful lifetimes are from 1 000 to 10 000 hours. At room temperature, bearing lifetimes are said to be in excess of 10 000 hours (29).

Barium films have also successfully lubricated tool steel bearings in which cobalt or chromium was present is a quantity greater than a certain minimum amount (6). Bearing materials not meeting this requirement, were also successfully lubricated with barium films provided a layer of chromium was first vaporized onto the balls. From the results of these experiments, it was concluded that for good wear characteristics, the intermediate film should alloy with the base material.

A mixture of 80% barium and 20% chromium has been used to lubricate small (3/16 in. bore) lightly loaded, cobalt tool steel bearings operating in a vacuum (29). By periodically relubricating the bearings, extended bearing lifetimes have been obtained.

Lubrication by molybdenum disulfide. - Molybdenum disulfide has been used for the lubrication of rolling element bearings used as slip rings in a clean high vacuum environment (26). The best performance, at a test current of 10 ma., was obtained with bearing balls and races of 440-C stainless steel and a machined retainer fabricated from a compact containing 85% gold and 15% MoS_2. Noise values of from 2 to 4 milliohms were generally observed when using MoS_2 as a lubricant. Observation showed that MoS_2 films seemed to be more electrically noisy in air than in vacuum (26).

Lubrication by composites containing dielectric materials. - One experiment (26) using 440-C stainless steel balls and races ran very well mechanically but displayed a very high electrical noise level. An initial contact resistance of 1 ohm increased to an open circuit after a 1-hour operation in air. Subsequent operation in vacuum 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 for low noise electrical contact operation because of the buildup of an insulating film.

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 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 needed. This would add undesirable additional weight to the device.

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 (30-32) involving the sliding of some of the noble metals (gold, platinum, and palladium) and silver have shown that amorphous, polymeric substances are formed on the surfaces of these metals. Materials other than the noble metals also formed significant amounts of these polymeric materials (30).

The process of sliding does not seem to be required, since it has been shown that these materials can form spontaneously (32). The substances necessary for the initiation of these polymeric materials under static conditions was supplied by the outgassing of the organic dielectrics employed for electrical insulation in enclosed contact systems (32).

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

Organic fluid vapors have been used for the lubrication of precious metal slip rings operating under vacuum (33). These experiments employed precious metal alloy wires running in V-grooves of hard gold plated silver which were lubricated by low vapor pressure fluids. A synthetic ester gave the best performance. A hydrocarbon oil gave the poorest performance. These experiments gave up to 79 days of relatively noiseless operation.

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

A listing of the major results of the vacuum sliding electrical contact experiments is shown in Tables 4 and 5.

Consideration of Thin Films as Lubricants for Sliding Electrical Contacts in Vacuum

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.

In a space environment, thin films may be rapidly removed by evaporation in addition to being worn away. Therefore, serious consideration must be given to the evaporation rates of the film materials. If thin film of alloys are considered for lubrication, selective evaporation of the components of the alloy may take place (Raoult's law, 35). These factors can significantly shorten the useful lifetime of a thin film lubricant.

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 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 ultra-high vacuum. Metallic films are inherently good electrical conductors. Many of these metals have acceptably low vapor pressures, even at high temperatures, and they will maintain their physical and electrical integrity when exposed to the various types of radiation (29).

For these soft metallic thin films to function effectively as lubricants, the area of contact must be kept small. Experiments, involving thin metallic films as lubricants on hard substrates show, generally, that the coefficient of friction is a minimum when the film thickness is in the order of 2500 Å (1). Another interesting characteristic of thin film metallic lubricants is the decrease in coefficient of friction displayed as the applied load is increased (1).

One of the major problems encountered in the application of thin films as lubricants is that of adherance 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 adherance 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 create films which are firmly bonded to the base materials.

Thin film formation by vacuum vapor deposition. - The vacuum vapor deposition experiments (36) describe a process whereby gold films in the order of 1800 Å thick were deposited on a nickel-10% chromium alloy base material. Prior to the deposition of the film, the base material was cleaned and 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) 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 near this value for an extended period of time. An explanation for this result was based on the fact that the high temperature of the base material and some mutual solubility had formed a diffused region between the gold film and the base material which resulted in an excellent bond.

Thin film formation by ion plating. - The deposition of a film on a base material may also be achieved by ion plating (37,38). In this method, the metal ions, because of their large kinetic energy, derived from the electric field, also form a diffused region much like the vacuum vapor deposition process described previously. Two major advantages of this method are: (1) that curved or shadowed surfaces may be plated without revolving the base material relative to the evaporant source, and (2) that the base material and film material need not be mutually soluble to form the diffused region.

The film deposited by this method is somewhat superior to the film deposited by the vacuum vapor deposition method. A friction experiment in vacuum (10^{-11} torr) (35) using an ion plated gold film 1500 Å thick on a nickel-10% chromium base material and niobium as the mating surface showed that the coefficient of friction was about 0.2 and had a greater lifetime than the film deposited by the previous method.

A comparison of the coefficient of friction and useful lifetimes of these gold films is shown in Fig. 4.

Thin Film Formation of Compounds by Ion Sputtering

The processes 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 above (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 (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.

Recent experiments in the friction and wear field (41), demonstrated that the process of ion sputtering can be successfully employed for the deposition of thin films of MoS_2. Friction experiments in vacuum (10^{-11} torr) showed that an ion sputtered thin film of MoS_2 (2000 to 3000 Å thick) deposited on a niobium base material and slid against a mating surface also of niobium had a coefficient of friction of about 0.09. This value is generally characteristic of bonded MoS_2 films.

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 a vacuum, shows 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 following conclusions are made on the basis of the experiments reviewed:

1. Graphite is not a good sliding electrical contact lubricant under high vacuum conditions where surface contamination is very low and therefore cannot be considered useful for the lubrication of low noise electrical contacts which operate in vacuum.

2. Molybdenum disulfide is a good sliding electrical contact lubricant in vacuum and the 12% MoS_2 - 88% silver compacts give acceptable performance when run against silver slip rings. The major objections to the use of MoS_2 compacts are the high resistivity and semi-conducting characteristics of the MoS_2 component.

3. Niobium diselenide is another good sliding electrical contact lubricant in vacuum and has the significant advantage of having a much lower bulk resistivity than MoS_2. The 12% $NbSe_2$-88% silver compacts when run against coin silver slip rings display lower electrical noise levels than the equivalent MoS_2 compacts although the wear is greater.

4. Organic vapor lubrication of precious metal sliding electrical contacts in a semi-closed system at relatively low pressure 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.

5. Dielectric lubricant materials would not be acceptable as an electrical contact lubricant in vacuum because of excessive electrical noise due to the buildup of an insulating film between the conducting surfaces.

6. Thin metallic films have been used successfully as rolling element electrical contact lubricants under the extreme conditions encountered in modern rotating anode X-ray tubes. This type of lubricant film is inherently a good electrical conductor and it is stable in vacuum. Furthermore, the materials, usually employed in these films have a relatively low vapor pressure at high temperatures.

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TABLE I. - WEAR OF TYPE D ELECTROGRAPHITE BRUSH RUNNING AGAINST VARIOUS RING MATERIALS UNDER HIGH ALTITUDE CONDITIONS (REF. 11)

[Electrographitic type D (electrographitized 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
Silver '	Yes
Chromium	No

TABLE II. - 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.

TABLE III. - 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			^oC	^oK	^oC	^oK	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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TABLE IV. - 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 V. - 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 $1.33{\times}10^{-6}$ 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

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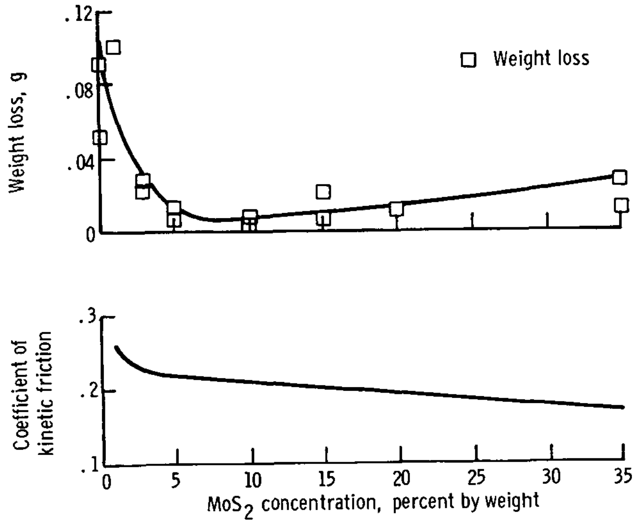

Figure 3. - Effect of MoS_2 concentration on wear and friction of hot-pressed bearing materials. Sliding speed, 2 540 cm/sec (5000 ft/min) load, 519 grams; duration of run, 1 hour; material: MoS_2, silver, and 5 percent copper (ref. 24).

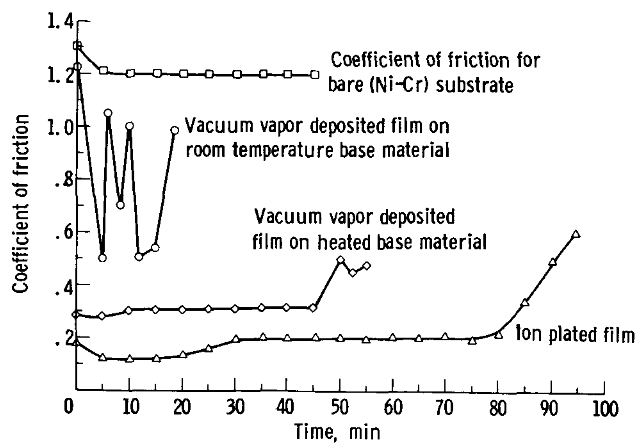

Figure 4. - Coefficient of friction of niobium sliding on Ni-10 percent Cr alloy with gold deposited film in vacuum. Sliding speed, 2.54 centimeters per second; load, 250 grams; ambient temperature (ref. 42).

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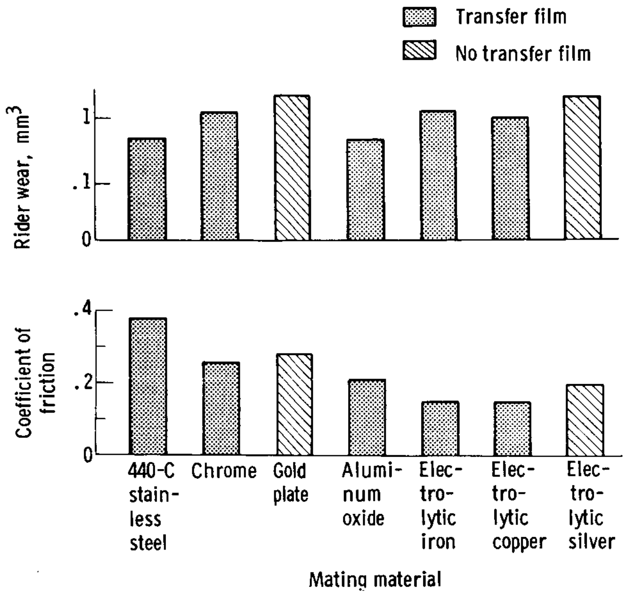

Figure 1. - Effect of mating materials on coefficient of friction and rider wear for 100 percent electrographitized carbon in vacuum (10^{-7} torr or 1.33×10^{-5} N/m^2). Sliding speed, 198 centimeters per second; load, 1000 grams; duration of run, 1 hour (ref. 15).

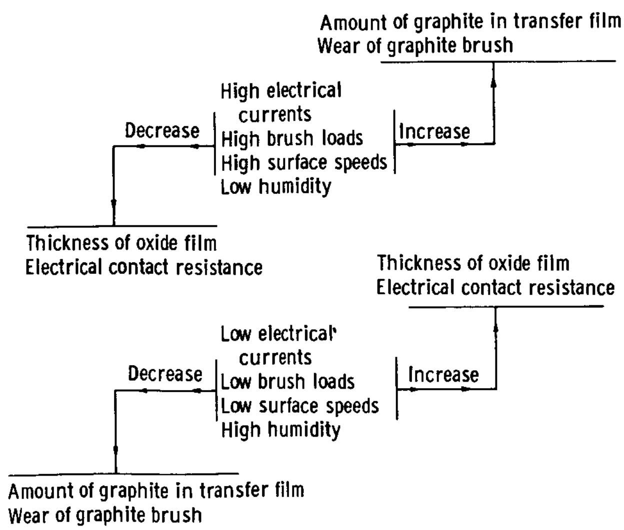

Figure 2. - Relation between conditions of operation, surface films, and electrical contact resistance for graphite sliding on copper (ref. 19).