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FRICTION AND CONTACT RESISTANCE FOR GALLIUM-LUBRICATED LOW-SPEED COPPER SLIPRINGS IN VACUUM

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16. Abstract

Gallium (Ga) was used as a lubricant for slipring assemblies (hemisphere contacting a flat) of OFHC copper (Cu) or a beryllium-copper (Be-Cu) alloy that ran for 100 hr in vacuum at 1 rpm (132 mm/min) and carried a constant current of 20 A dc. The coefficient of friction was 0.2 to 0.3 for both materials, but the wear volume on each of the two OFHC Cu hemispheres used was at least 10 000 times greater than on the Be-Cu hemisphere. Both contact resistance (0.02 to 0.05 mΩ) and contact noise (0.001 to 0.0025 mΩ peak to peak) were low for the two materials. A noncontacting slipring assembly, using a Ga drop in a 0.5-mm gap, failed at 147 hr because of Ga drop disappearance.

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SUMMARY

Both thick and thin gallium films were used as lubricants for slipring assemblies of oxygen-free high-conductivity (OFHC) copper (Cu) or a beryllium-copper (Be-Cu) alloy (97.9 Cu-1.9 Be-0.2 nickel or cobalt). A slipring assembly consisted of a 4.76-millimeter-radius hemisphere (brush) contacting the flat surface of a 50.8-millimeter disk (slipring). All experiments were run at a speed of 1 rpm (132 mm/min) in vacuum (10^{-10} to 10^{-11} torr). Loads, where used, were 100 grams. One noncontacting slipring experiment was made by using a drop of gallium suspended in a 0.5-millimeter gap between the two components of an OFHC copper slipring assembly.

Two-hour screening tests, using a contact current of 33 milliamperes at 40 hertz, determined that a thick gallium film ($\sim 2.5 \times 10^{-3}$ cm) was the better film; hence, it was selected for a series of 100-hour experiments at a constant contact current of 20 amperes dc using both polarities. The slipring assembly with the thick gallium film provided a coefficient of friction in the range 0.2 to 0.3. The 100-hour wear volume on the OFHC copper hemispheres (1.05 mm^3, hemisphere positive; 3.24 mm^3, hemisphere negative) was at least 10 000 times greater than the wear volume on the beryllium-copper hemisphere (4.24×10^{-4} mm^3, hemisphere positive).

The OFHC copper slipring assemblies with the thick gallium film had a contact resistance in the range 0.02 to 0.043 milliohm. The beryllium-copper alloy slipring assembly showed a slightly higher contact resistance (0.039 to 0.051 mΩ) but a lower contact noise (0.001 to 0.002 mΩ peak-to-peak) than either of the two OFHC copper slipring assemblies (0.0014 to 0.0025 mΩ peak-to-peak, both polarities included). The contact resistance for the noncontacting slipring assembly (0.037 to 0.057 mΩ) was generally in the same range as all other experiments; however, the noise was about 10 times higher (0.011 to 0.017 mΩ peak-to-peak).

INTRODUCTION

A study of future broadcast radio and television satellite power requirements indicates that solar cell arrays are prime candidates for a power source (ref. 1). Missions that require substantial amounts of power (up to 50 kW) may require orientation of the arrays with respect to the sun and antenna pointing. Orientation will require rotation of the solar arrays relative to the satellite package. Hence, some device must be used to transmit electrical power in a high-vacuum environment between the arrays and the package while accommodating the necessary rotation. In addition, the device selected must have a long useful life because the projected life of these satellites is in excess of 5 years.

A simple device that will transmit electrical power and accommodate continuous rotation is the slipring. Since pure sliding is a characteristic of contacting slipring operation, a lubricant must be employed to reduce friction and wear of the slipring components. The vacuum slipring lubricants in general use today (molybdenum disulfide (MoS_2) and niobium diselenide ($NbSe_2$)) have relatively high electrical resistivities, and their use would result in significant power losses in a sliding contact operating at large currents unless many sliprings were operated in parallel. This method of attack is undesirable because of its complexity and added weight. Recent experiments have shown that a single, low-speed, gallium-lubricated beryllium slipring assembly can operate at a current of 20 amperes dc with low electrical losses, low noise, and relatively low wear for extended periods of time in an ultrahigh vacuum environment (ref. 2). Beryllium, however, does have two disadvantages for use as a slipring material: (1) it is generally considered to be a toxic metal, and (2) some difficulty was encountered in getting the gallium to wet the beryllium surfaces. (Wetting is considered necessary to obtain the lowest contact resistance.) These disadvantages indicate a need to investigate the possibility of using gallium to lubricate other slipring materials.

Since some success has been achieved with a vacuum rotary electrical contact employing oxygen-free high-conductivity (OFHC) copper in vacuum, both as a container material and as an electrode immersed in liquid gallium (refs. 2 and 3), OFHC copper was chosen for both the brush and slipring material for a part of this investigation. In addition, one experiment was conducted using a beryllium-copper alloy. The good wear results obtained in using unalloyed beryllium with gallium in reference 2 suggest that copper alloyed with beryllium might improve the wear characteristics over that of OFHC copper while still maintaining the wetting characteristics of copper.

The objectivies of this investigation were to determine the effectiveness of gallium as a slipring lubricant in vacuum for (1) contacting slipring assemblies fabricated from OFHC copper and from one beryllium-copper alloy and (2) a noncontacting OFHC copper slipring assembly using a drop of gallium suspended in a small gap between the brush and slipring.

The contacting slipring assembly consisted of a 4.76-millimeter hemispherically tipped rod (brush) sliding against the flat surface of a 50.8-millimeter-outside diameter disk (slipring). The noncontacting slipring assembly used the same components as the contacting slipring assembly, but a small gap was left between the tip of the hemisphere (brush) and the surface of the disk (slipring). All experiments were performed in ultrahigh vacuum (10^{-10} to 10^{-11} torr) at a sliding speed of 1 rpm (132 mm/min). Contact load, where used, was 100 grams. The friction force and contact resistance, or contact voltage drop, were measured during each experiment. Contact wear is reported as wear volume and was calculated from measurements of the wear scar diameters of the tips of the hemispheres.

APPARATUS

Vacuum System

The vacuum system is described in detail in reference 4. The vacuum chamber bakeout temperature was limited to 120° C to decrease gallium corrosion of the slipring components.

Contact Resistance Measurement System

The contact resistance measuring circuit is shown in figure 1. One lead from a current supply is connected directly to the electrically insulated hemisphere. The remaining current lead is connected to one end of an insulated copper cup containing liquid gallium. The disk is mounted on one end of an OFHC copper spindle that is completely insulated from the drive shaft. A ring machined on the other end of the spindle and immersed in the liquid gallium completes the electrical circuit. Separate leads were used for contact voltage drop measurement. One voltage lead is connected directly to the hemisphere, while the other voltage lead is connected to the end of the gallium cup opposite the current lead connection. The schematic diagram of figure 1 shows that the resistance of the gallium well is in series with the contact resistance. Separate measurements show that the resistance of the gallium well is very small compared with the usual values of contact resistance, so it can be neglected.

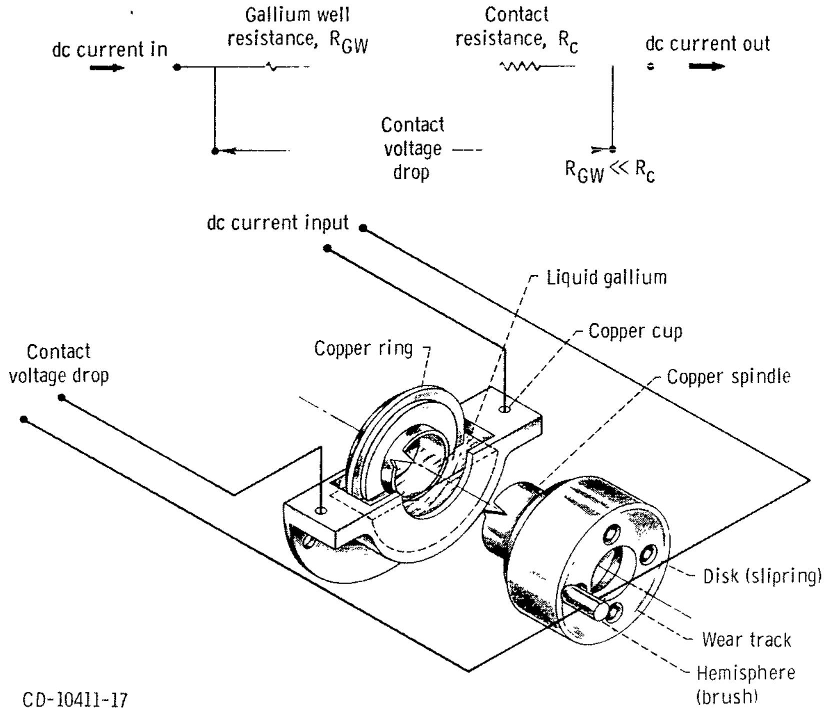


Figure 1. - Contact resistance measuring circuit.

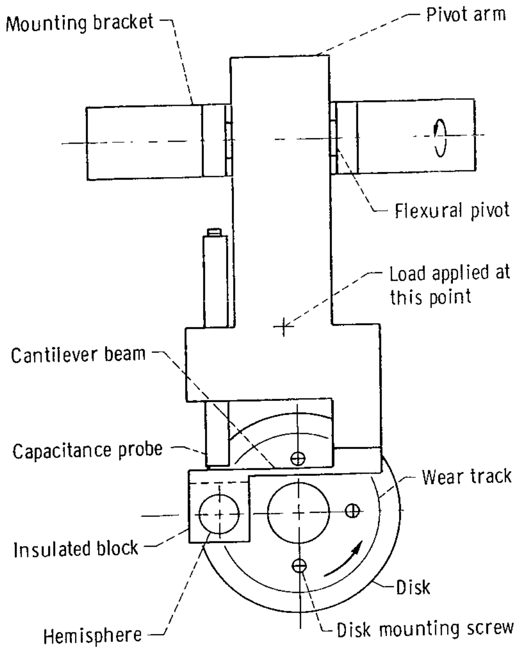


Figure 2. - Frictional force measurement assembly.

Friction Force Measurement System

A diagram of the frictional force measuring system is shown in figure 2. The hemisphere (brush) is held in an insulated block that is mounted on the free end of a small cantilever beam. The amount of beam displacement, which is proportional to the frictional force, is sensed by a capacitance probe. The output of the probe control is calibrated in grams force.

Slipring Assembly Materials

The copper slipring assemblies were fabricated from commercial OFHC copper and were used without annealing after machining. The beryllium-copper alloy slipring assembly was fabricated from ASTM B-196 rod stock (97.9 Cu-1.9 Be-0.2 Ni or Co) and heat treated to a Rockwell C hardness of 37. All components of all slipring assemblies were given a brief electropolish in orthophosphoric acid prior to either the application of a gallium film or the direct installation in the vacuum chamber without lubrication. The starting purity of the gallium was 99.999 percent.

Two types of gallium films were employed as lubricants: (1) a thick gallium film and (2) a thin gallium film. For those experiments in which a relatively thick gallium film was used as a lubricant, the gallium was applied to the disk by means of a cotton swab in the form of an annulus that covered the wear track zone. Sufficient gallium was applied to give a film thickness of about 2.5×10^{-3} centimeter (calculated from an increase in weight) with the disk in the horizontal plane. A slight scrubbing action with the cotton swab was necessary to get the gallium to wet both the OFHC copper and beryllium-copper alloy surfaces. The weight of gallium used per thick-film disk was about 0.652 gram.

The thin gallium film was obtained by starting with a thick gallium film and wiping off a large portion of the gallium with a paper towel prior to insertion in the vacuum chamber. It must be noted that the liquid gallium on all disk surfaces remained in the form of the original annulus and did not migrate beyond that area scrubbed by the cottom swab. In all experiments, a very small amount of gallium was also applied to the tip of the hemisphere.

PROCEDURE

Two-hour experiments were made with both a thick and a thin gallium film on an OFHC copper disk contacting an OFHC copper hemisphere in order to determine the better film. During these screening experiments, contact resistance measurements were made with a commercial ac milliohmmeter. The thick gallium film (which displayed the better performance during the screening experiements) was used as a lubricant for both OFHC copper and beryllium-copper slipring assemblies running for 100 hours at a constant contact current of 20 amperes dc. The contact resistance during the dc experiments was calculated from contact voltage drop measurements made with a microvoltmeter. The direct-current experiments were made with the polarity of the hemisphere both positive and negative. However, during any one experiment, the polarity was kept constant. Also in any one experiment, the disk and hemisphere were made of the same material.

Two noncontacting slipring assembly experiments were also performed by using the ac milliohmmeter for initial contact resistance measurement and a constant contact current of 20 amperes dc for an extended-time experiment. For these experiments, a drop of liquid gallium was suspended in a 0.5-millimeter gap between the surface of an OFHC copper disk, which had a thick gallium film, and the tip of an OFHC copper hemisphere, which had a small amount of gallium applied to it.

RESULTS AND DISCUSSION

Screening Tests

The results of the 2-hour screening tests (coefficient of friction, hemisphere wear volume, contact resistance, and contact noise) are shown in table I. These preliminary experiments produced several important results: (1) a thin gallium film is not a good lubricant for OFHC copper slipring assemblies, (2) a thick gallium film is a lubricant (coefficient of friction f of 0.2 to 0.3) for OFHC copper slipring assemblies and reduces both the contact resistance and contact noise by greater than a factor of 10 from that shown by a dry OFHC copper slipring assembly, and (3) the presence of a thick gallium film increased the wear volume on the tip of the OFHC copper hemisphere by a factor of 3.

The thin gallium film began to fail near the beginning of 13 revolutions of the disk, as shown in the data of figure 3. Parts of the friction trace are labeled to indicate film failure. Failure is characterized by an increase in the frictional force to some value above 100 grams ($f > 1$). A photograph of the disk with the thin gallium film after completing 24 revolutions in vacuum is shown in figure 4(a). The film is entirely worn through in the wear track area. Visual observation of the disk after removal from the vacuum chamber revealed that the film had a solid dull gray appearance unlike the bright, fluid, metallic appearance of normal liquid gallium. Apparently, the thin gallium film

TABLE I. - SUMMARY OF RESULTS OF SCREENING EXPERIMENTS WITH CONTACTING AND NONCONTACTING SLIPRING ASSEMBLIES

[Speed, 1 rpm (132 mm/min); load (contacting experiments), 100 g; vacuum, 10^{-10} to 10^{-11} torr; contact current, 33 mA at 40 Hz.]

Slipring assembly materials	OFHC copper against OFHC copper			
Lubricant	None	Thin gallium film	Thick gallium film	Gallium drop in 0.5-mm gap
Surface wetted	----------	Yes[a]	Yes[a]	Yes[a]
Average coefficient of friction, f	1.5	[b]0.75	0.30	0
Average contact resistance, mΩ	0.35	[b]0.7	0.025	0.025
Contact noise, mΩ peak to peak	0.75	[b]0.45	<0.01	<0.01
Hemisphere wear volume, mm^3	10.25×10^{-3}	[c]4.2×10^{-3}	33.2×10^{-3}	(d)
Time to failure, hr	----------	0.2	No failure in 2 hr	No failure in 2 hr

[a] After slight rubbing.

[b] Before film failure.

[c] After 24 revolutions.

[d] Some corrosion of tip.

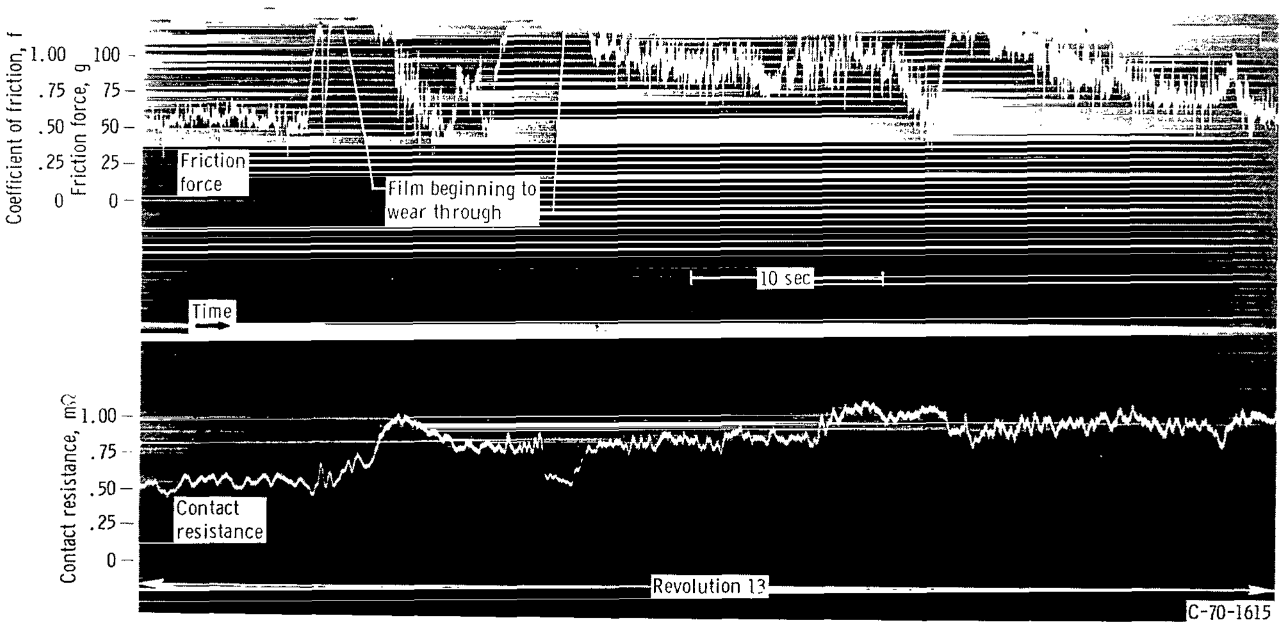
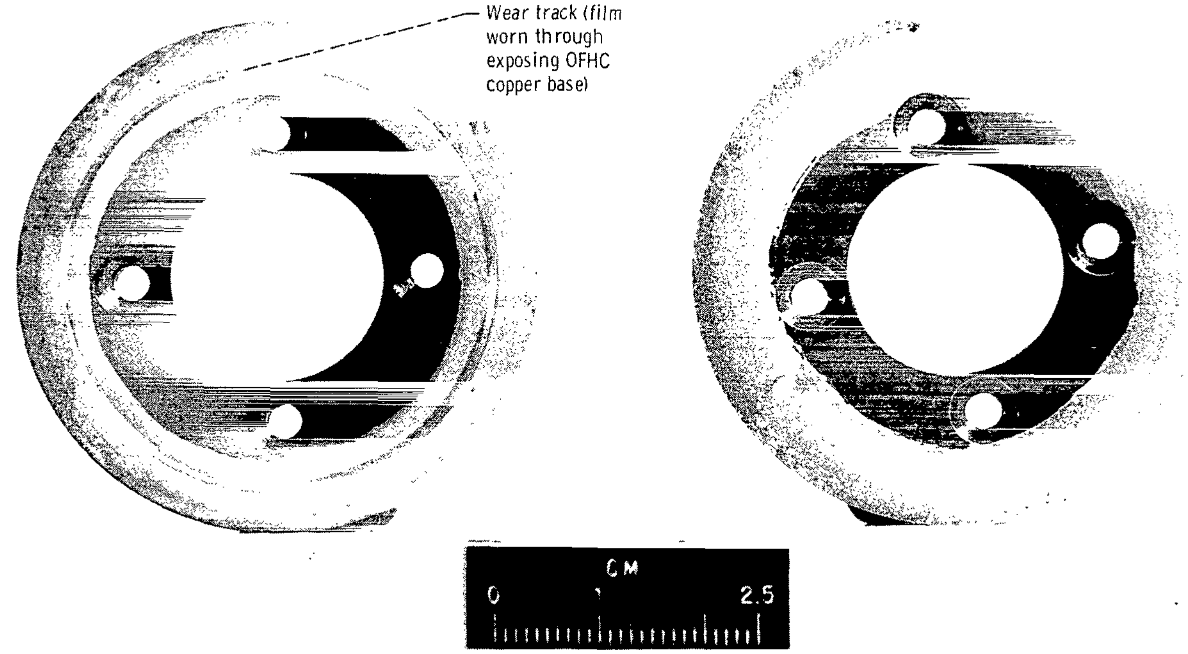


Figure 3. - Friction force and contact resistance against time for OFHC copper disk with thin gallium film running against OFHC copper hemisphere. Load, 100 grams; speed, 1 rpm (132 mm/min); vacuum, 10^{-10} to 10^{-11} torr.



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(a) Thin gallium film on OFHC disk after 24 revolutions.

(b) Thick (~2.5×10^{-3} cm) gallium film on OFHC disk after 120 revolutions.

Figure 4. - OFHC copper disks run against OFHC hemispheres. Load, 100 grams; speed, 1 rpm (132 mm/min); vacuum, 10^{-10} to 10^{-11} torr; contact current, 33 milliamperes at 40 hertz.

had reacted with the copper surface during the bakeout process to form a surface alloy. The friction data also point to some material other than liquid gallium on the copper surface, because the average coefficient of friction prior to film failure was about 0.75. This value is higher than the value of the coefficient of friction generally encountered with the use of gallium as a lubricant ($0.1 < f < 0.3$) (refs. 5 and 6).

X-ray diffraction analysis of the surface film was attempted, but only a few strong copper peaks could be identified. Other strong peaks were present but could not be even remotely matched with any X-ray diffraction data that could be found in the copper-gallium binary system. Furthermore, no gallium peaks were found.

The thick gallium film ran successfully for the entire 2-hour screening experiment, and no evidence of film failure was noted when the experiment was terminated. A photograph of this disk specimen taken after the 2-hour experiment (fig. 4(b)) shows that the film is intact and has the characteristic appearance of liquid gallium.

The data obtained from the thick-gallium-film experiment showed that the slipring assembly ran with a lower coefficient of friction, lower contact resistance, and lower electrical noise than an OFHC copper slipring assembly run dry (table I). However, the presence of the gallium increased the wear volume by a factor of 3 over that of dry OFHC copper, which again indicates the corrosiveness of liquid gallium. The most notable effects of the thick gallium film were the decrease in contact resistance by a factor of 14 and the decrease in contact noise by a factor of 75 from those values obtained in the experiment with the dry OFHC copper slipring assembly (table I). The decrease in contact resistance is a result of both the mobility and wetting actions of the liquid gallium. Both these factors result in a filling of the voids and gaps in the contact zone that remain after loading because of the nature of solid contact and contact geometry (refs. 7 and 8).

The low value of contact noise (<0.01 mΩ peak to peak) is indicative of a stable contact area. The stability of the contact area is believed to be a function of the surface tension forces of the liquid gallium in the contact zone. The very slow sliding speed undoubtedly contributes to the degree of stability by not greatly disturbing these surface tension forces. It is possible that the surface tension forces, combined with the adherence of the gallium to the OFHC copper by its wetting action, may allow operation of this type of sliding electrical contact in a zero-gravity environment.

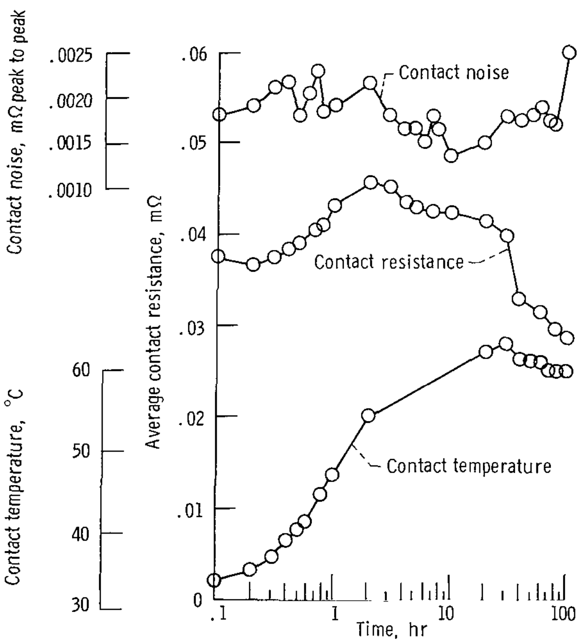
The great differences in the performance between the thin and thick gallium films are evidence that a certain amount of gallium does react with a copper surface. If an insufficient amount of gallium is present, all the gallium will enter into the reaction and form an alloy surface film that has undesirable friction and wear properties, as the experimental data show. An excess of gallium (a thick film), over that amount required to react with the copper surface, must be used so that the OFHC copper slipring will exhibit a coefficient of friction, contact resistance, and contact noise that are possible from gallium lubrication.

The increase in corrosive wear caused by the presence of a thick gallium film stimulated the design of an experiment in which there would be no actual sliding contact between the two members of the slipring. It was reasoned that this type of operation might reduce the wear due to the absence of mechanical loading and the associated energy it applied to the contact area. The noncontacting slipring consisted of a drop of gallium suspended in a 0.5-millimeter gap purposely provided between the tip of an OFHC copper hemisphere and the surface of an OFHC copper disk. The electrical current would be carried by the gallium drop, thus obviating the need for mechanical contact between the two parts of the slipring assembly. The drop was created by running the slipring assembly, which had a thick gallium film, under load for several revolutions and then removing the load. Since the gallium wet the OFHC copper surface, a drop of gallium remained suspended in the gap when the load was removed. This type of slipring assembly ran successfully for the duration of the 2-hour experiment with values of contact resistance (0.025 mΩ) and contact noise (<0.01 mΩ peak to peak) comparable to those obtained with the thick gallium film under load (table I). There was no measurable friction force with the measurement system at maximum gain. No wear scar was found on the tip of the hemisphere after the experiment (which indicated that contact had not occurred), although there was a noticeable corrosion of the copper surface where the gallium had come in contact with it.

Since the screening experiments showed the thick gallium film to be the better film, this type of film was chosen as a lubricant for contacting slipring assembly materials of OFHC copper and a beryllium-copper alloy that ran in a series of 100-hour experiments at a current of 20 amperes dc. Both positive and negative hemisphere polarities were used. The noncontacting slipring assembly was also chosen for an extended-duration experiment at a contact current of 20 amperes dc because of the large reduction in wear achieved with this type of operation.

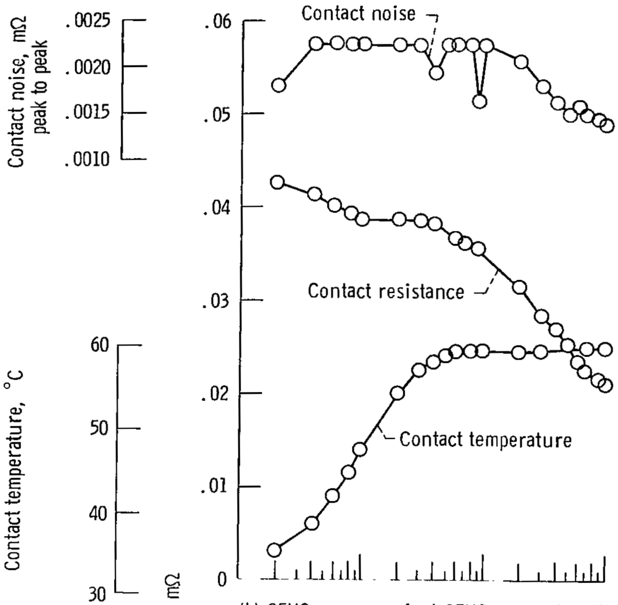
Extended-Duration Experiments at 20 Amperes Direct Current

Gallium-lubricated OFHC copper slipring assemblies. - The results of experiments conducted with the gallium-lubricated OFHC copper slipring assembly at 20 amperes dc are plotted in figures 5(a) and (b) and generally paralleled those obtained during the initial screening experiments. The data show the contact resistance to be in the range 0.020

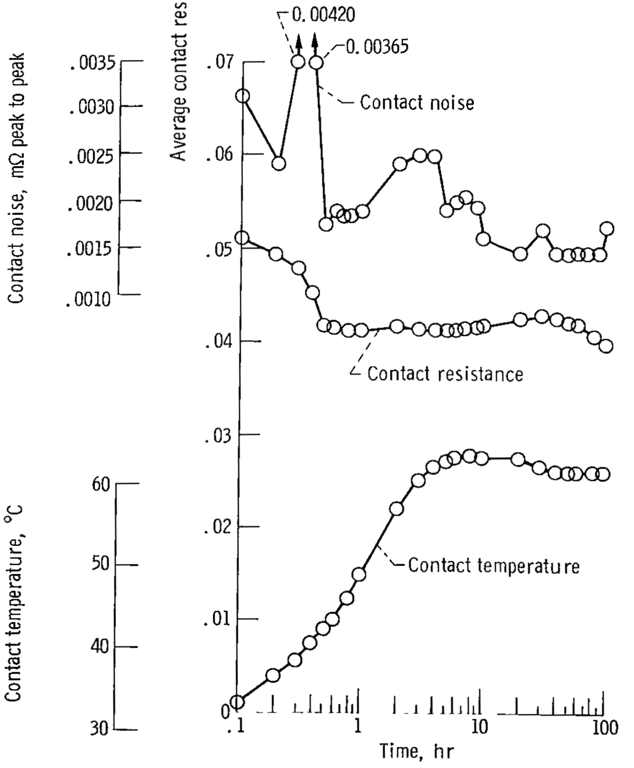


(a) OFHC copper against OFHC copper (hemisphere positive).

Figure 5. - Contact resistance against time for three experiments run with thick (~2.5x10^{-3} cm) gallium film on disk and small amount of gallium applied to tip of hemisphere. Load, 100 grams; speed, 1 rpm (132 mm/min); vacuum, 10^{-10} to 10^{-11} torr; contact current, 20 amperes dc; duration of run, 100 hours.



(b) OFHC copper against OFHC copper (hemisphere negative).



(c) ASTM B-196 beryllium-copper alloy against ASTM B-196 beryllium-copper alloy (hemisphere positive).

Figure 5. - Concluded.

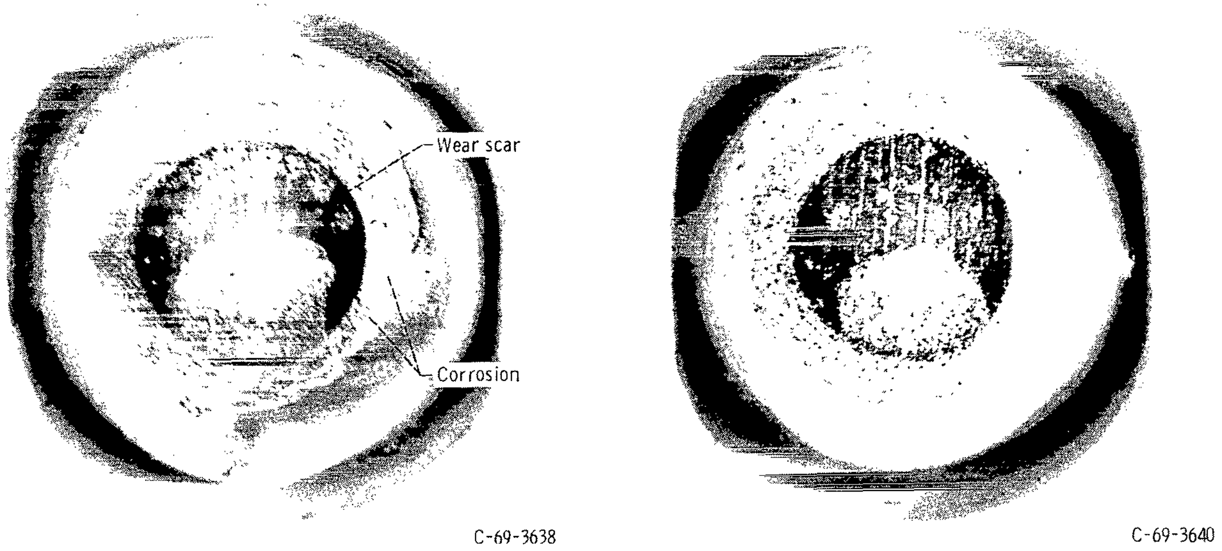
to 0.043 milliohm and the contact noise to be in the range 0.001 to 0.002 milliohm peak to peak (both hemisphere polarities included). A comparison of the data shown in figures 5(a) and (b) reveals some interesting differences in contact operation, which are listed in table II. It appears that hemisphere polarity had an effect on contact operation. The hemisphere polarity also appears to affect the wear volume on the tips of the OFHC copper hemisphers (table II). The wear volume was greater when the hemisphere was negative (3.24 mm^3) than when the hemisphere was positive (1.05 mm^3). Figures 6(a) (hemisphere positive) and 6(b) (hemisphere negative) show the large wear scars on the tips of the OFHC copper hemispheres after the 100-hour test at 20 amperes. Hemisphere polarity also appeared to have a slight effect on the coefficient of friction. The average coefficient of friction was somewhat higher for the positive hemisphere (0.25) than for the negative hemisphere (0.20) (table III). These differences in friction, wear, and electrical behavior of the OFHC copper slipring assemblies offer ample evidence for a polarity effect. However, caution must be used in making any general conclusions regarding polarity effects because of the relatively small amount of data. The relatively high wear encountered in the operation of gallium-lubricated OFHC copper slipring assemblies for a short period of time (100 hr) could prevent their use in applications requiring a long useful life.

TABLE II. - SIGNIFICANT DIFFERENCES BETWEEN DATA

SHOWN IN FIGURES 5(a) AND (b)

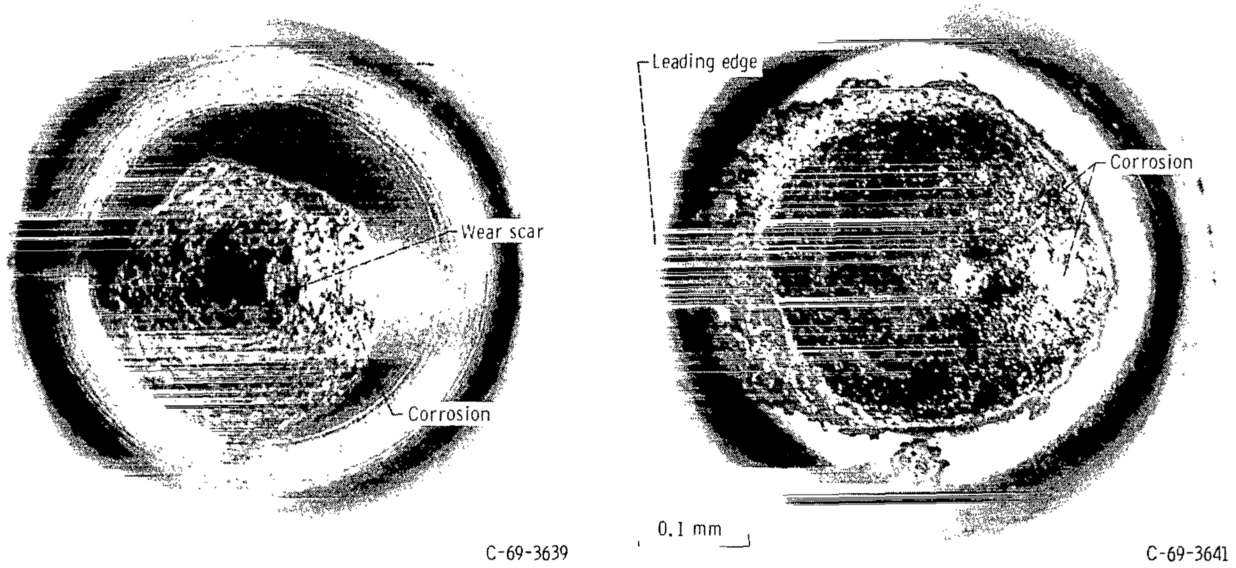
Hemisphere	
Positive (fig. 5(a))	Negative (fig. 5(b))
More consistent values of contact noise	More variation in values of contact noise
Contact resistance reaches peak before decreasing	Contact resistance steadily decreases
Contact temperature reaches peak then decreases slowly	Contact temperature continues to increase slowly

Microscopic examination of the undisturbed flat surface of the OFHC copper disks revealed what appeared to be many cubic-type crystals that had grown on the surfaces (figs. 7(a) and (b)). Initially, these crystals were thought to be pure gallium, and attempts were made to melt the crystals by heating the disks to about 60° C while under observation on the microscope stage. A heating period of several hours did not affect the size or shape of these tiny crystals. Therefore, it must be concluded that these



(a) OHFC copper (hemisphere positive).

(b) OFHC copper (hemisphere negative).



(c) ASTM B-196 beryllium-copper alloy (hemisphere positive).

(d) OFHC copper with drop in 0.5-millimeter gap (hemisphere positive).

Figure 6. - Tips of hemispheres after 100-hour run against disks of same material coated with thick ($\sim 2.5 \times 10^{-3}$ cm) gallium film. Load, 100 grams; speed, 1 rpm (132 mm/min); vacuum, 10^{-10} to 10^{-11} torr; contact current, 20 amperes dc.

TABLE III. - SUMMARY OF RESULTS OF EXTENDED-DURATION EXPERIMENTS RUN AT CONSTANT CONTACT CURRENT OF 20 AMPERES D. C.

[Speed, 1 rpm (132 mm/min); load (except noncontacting experiment), 100 g; vacuum, 10^{-10} to 10^{-11} torr.]

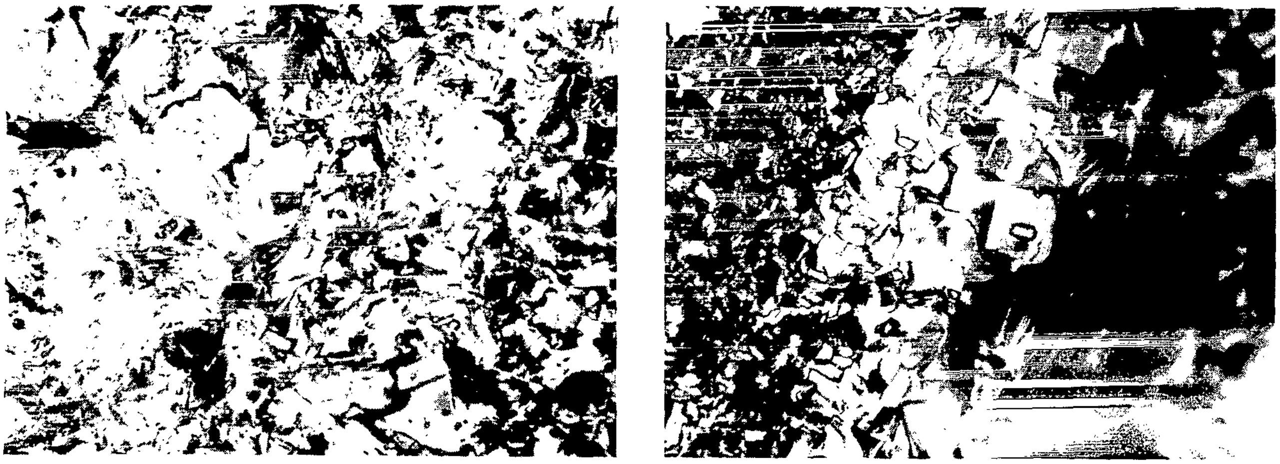
	Experiment			
	Contacting			Noncontacting
Disk (slipring)	OFHC copper	OFHC copper	ASTM B-196 Be-Cu alloy	OFHC copper
Hemisphere (brush)	OFHC copper	OFHC copper	ASTM B-196 Be-Cu alloy	OFHC copper
Lubricant	Thick Ga film on disk[a]	Thick Ga film on disk[a]	Thick Ga film on disk[a]	Ga drop in 0.5-mm gap[b]
Hemisphere polarity	Positive	Negative	Positive	Positive
Range of coefficient of friction	0.02 to 0.03	0.15 to 0.25	0.10 to 0.30	0
Average coefficient of friction	0.25	0.20	0.20	0
Total wear volume, mm^3	1.05	3.24	4.24×10^{-4}	(c)
Run time, hr	100	100	100	[d]147
Hemisphere equilibrium temperature, °C	60	60	61	70
Average contact resistance, mΩ, for				
0.1 hr	0.0375	0.0428	0.0510	0.0375
1.0 hr	.0432	.0388	.0412	.0410
10.0 hr	.0424	.0350	.0418	------
100.0 hr	.0288	.0204	.0398	.0575
Contact noise, mΩ peak to peak, for				
0.1 hr	0.0018	0.0018	0.0010	0.0175
1.0 hr	.0019	.0022	.0019	.0150
10.0 hr	.0014	.0022	.0016	------
100.0 hr	.0025	.0014	.0017	.0117

[a] Small amount of gallium also applied to tip of hemisphere.

[b] Thick gallium film on disk; small amount applied to tip of hemisphere.

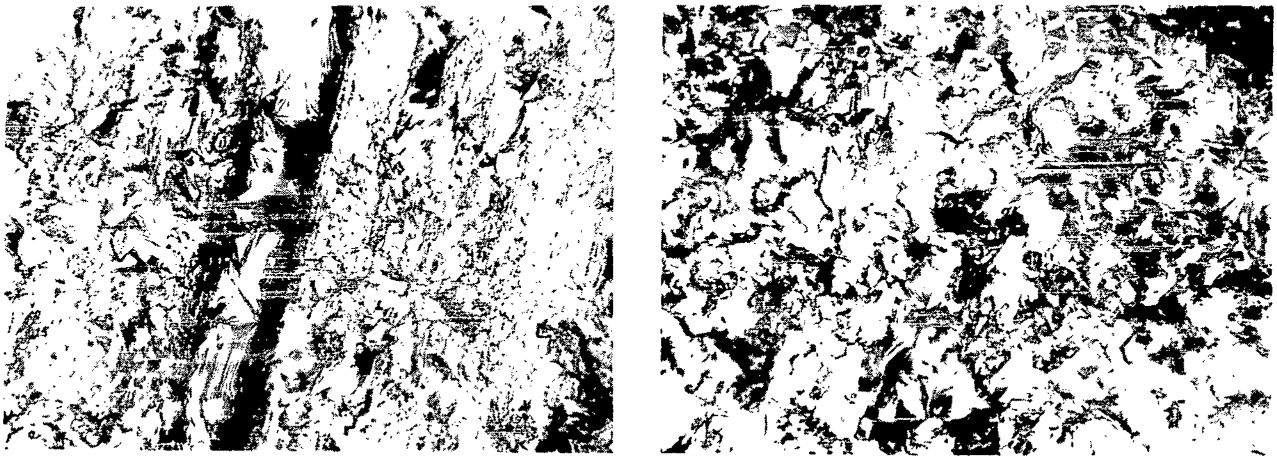
[c] Some corrosion of hemisphere tip.

[d] Gallium drop disappeared at 147 hr.



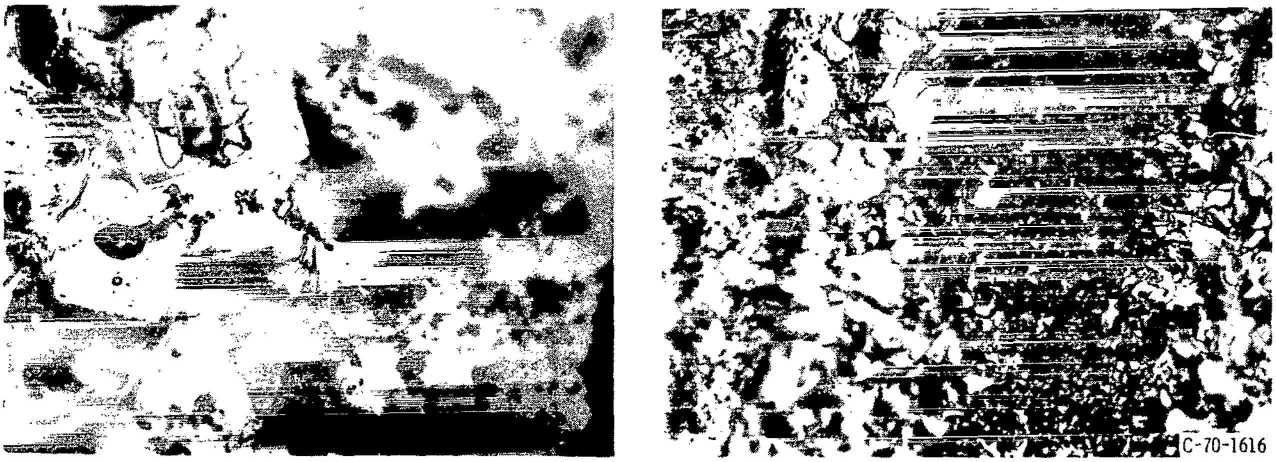
(a) OFHC copper, outside of wear track (hemisphere positive).

(b) OFHC copper, outside of wear track (hemisphere negative).



(c) OFHC copper, center of wear track (hemisphere positive).

(d) OFHC copper, center of wear track (hemisphere negative).



(e) Beryllium-copper alloy, outside of wear track (hemisphere positive).

(f) Beryllium-copper alloy, center of wear track (hemisphere positive).

Figure 7. - Micrographs of disk surfaces run 100 hours. Load, 100 grams; speed, 1 rpm (132 mm/min); vacuum, 10^{-10} to 10^{-11} torr; contact current, 20 amperes dc.

crystals are not pure gallium but must consist of copper and gallium in some unknown proportion.

The appearance of both OFHC copper disks in the wear track region was quite different from that outside the wear track region (figs. 7(c) and (d)). The crystals were smaller and less plentiful. This difference is believed to be due to the continuous disturbance of the wear track area by the passing of the hemisphere that upset continuous crystal growth.

Gallium-lubricated beryllium-copper alloy slipring assemblies. - Because of the excellent 500-hour wear results shown by a gallium-lubricated beryllium slipring assembly (ref. 2), it was reasoned that the presence of a small amount of beryllium in copper might improve its wear characteristics when used with gallium. Consequently, a copper-beryllium alloy (ASTM B-196), heat treated to a Rockwell C hardness of 37, was chosen as a slipring assembly material. For these experiments, a positive hemisphere polarity was chosen because of the lower amount of wear shown by this polarity in the experiments with the OFHC copper slipring assembly. No difficulty was experienced in swabbing a thick gallium film on the surface of the alloy disk. The gallium wetting characteristics of the disk appeared to be the same as those of OFHC copper; consequently, it was anticipated that the contact resistance and contact noise results would be similar to those of the OFHC copper slipring assemblies. The data shown in figure 5(c) verified the anticipated results. The contact resistance for the gallium-lubricated alloy slipring assembly was only slightly higher (0.04 to 0.05 mΩ) than that of a similar OFHC copper slipring assembly (0.02 to 0.043 mΩ). This slight difference is believed to be due to the higher electrical resistance of the alloy, which is about six times greater than that of copper (ref. 9). The electrical noise shown by the Be-Cu alloy slipring assembly was generally lower and had less amplitude than that shown by the OFHC copper slipring assembly. The wear volume on the tip of the Be-Cu alloy hemisphere was only 4.24×10^{-4} cubic millimeter, which is at least 10 000 times less than the wear volume on either OFHC copper hemisphere under the same conditions (table III). An examination of the tip of the alloy hemisphere revealed only a small wear scar surrounded by an area of corrosion where the gallium was in contact (fig. 6(c)). The alloy hemisphere equilibrium temperature was 61° C, approximately the same as that for the OFHC copper experiment. The low values of contact resistance and electrical noise coupled with a relatively low rate of wear make this combination of materials appear attractive for extended operation in a vacuum environment. Although there is a large difference in running time, the wear volume on the tip of the alloy hemisphere (4.24×10^{-4} mm^3) at the end of 100 hours compares favorably with the wear volume of a pure beryllium hemisphere (7.5×10^{-4} mm^3) (ref. 2) at the end of 500 hours of operation. The Be-Cu alloy has the advantages of being more easily wet by the gallium and less toxic than pure beryllium. However, a larger amount of corrosion was evident on the Be-Cu hemisphere than on the pure Be hemisphere. This could be a serious disadvantage of the Be-Cu alloy, especially if it remained in contact with liquid gallium for long periods of time. Nevertheless, the Be-Cu alloy shows enough promise to be considered as a material for long-term experiments.

The appearance of the surface of the Be-Cu alloy disk was similar to that of the OFHC copper disks (fig. 7(e)). However, the crystals were much larger, which gave the surface of the disk a rough appearance to the naked eye. Attempts were also made to melt these crystals (60° C max), but, again, no effect on the size or shape of the crystals was noted.

The crystals in the wear track were smaller than those observed on other surfaces of the disk (for the same reason as that given in the discussion of the OFHC copper disk surfaces (fig. 7(f)).

A summary of the results of the 100-hour contacting-slipring-assembly experiments is given in table III.

Noncontacting slipring assembly. - The noncontacting slipring assembly for the 20-ampere dc experiments was formed in the same manner as described in the section on the screening experiments. A positive hemisphere polarity was also chosen for the experiment. Because of the small amount of wear that could be expected with this type of slipring, an experiment of 250 hours duration would be made. However, the predetermined running time was never achieved because this slipring failed (open circuit) at 147 hours running time (see fig. 8). Slipring failure was forecast by a relatively rapid

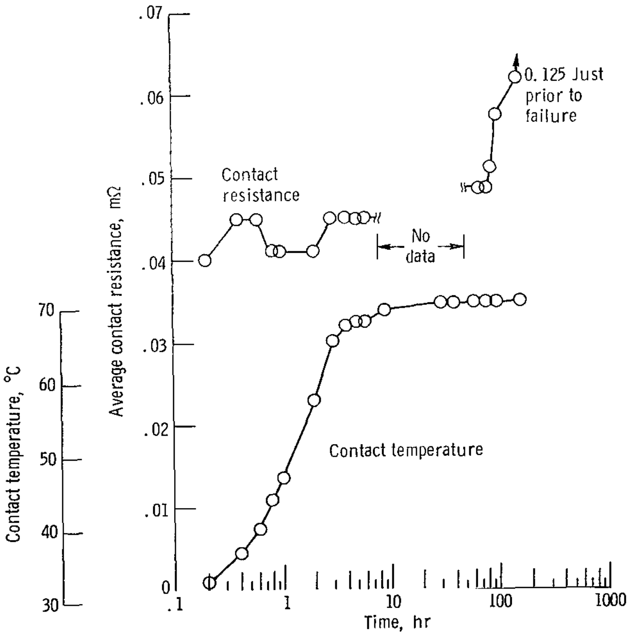


Figure 8. - Noncontacting OFHC copper slipring assembly (gallium drop in 0.5-mm gap). Hemisphere positive.

rise in contact resistance during the last 50 hours of running time prior to failure (fig. 8). The actual rise in contact resistance from the onset of failure to failure was about 0.060 milliohm. The actual value of contact resistance in the instant before failure was 0.125 milliohm. Fortunately, failure occurred during a time when visual observation of the actual failure was possible. Observation showed that contact failure was due to a disappearance of the gallium drop. The phenomenon believed ultimately responsible for contact failure is the "pinch effect" (refs. 10 and 11). The pinch effect is a result of the compressive action of the magnetic lines of force within a current-carrying conductor. This magnetic force squeezes or pinches the conductor. If the magnetic force is great enough (large current), the force will exceed the yield point of the material, and the conductor will collapse. In the cases of liquid conductors, there is little resistance to this pinching action; consequently, much less current is required to pinch it. Perhaps if the noncontacting slipring assembly were operated at a lower current or designed differently, its operating lifetime might be extended.

As in the screening experiments, no frictional force was detected in the gallium drop experiment. The contact resistance, before the onset of failure, was comparable to those values obtained using the same slipring materials under load (see table III). Contact noise, however, was larger by a factor of 10. The large values of contact noise was believed to result from instabilities in the shape of the gallium drop in the contact zone. Visual observation revealed the occurrence of hollow spots (which were self-heating) that occasionally appeared in the outer edge of the drop. It is evident that these hollow spots would greatly disturb the contact area and hence would be responsible for the large amount of contact noise observed. The hollow spots are believed to be a manifestation of the pinch effect because they were not observed during the lower current screening experiments.

The larger value of contact noise could not be conveniently plotted in figure 8; consequently, it is presented in a separate figure (fig. 9) and compared with the electrical noise shown by a loaded slipring assembly with the same polarity using the same materials.

A photograph of the tip of the OFHC copper hemisphere is shown in figure 6(d). There is no wear scar but considerable corrosion, as might be expected from the results of the screening experiments. The general shape of the corroded area seems to show how the liquid gallium flowed through the contact zone during the experiment. There appeared to be a pileup of gallium in front of the hemisphere and a trailing-off around the sides and to the rear of the hemisphere. The corrosion on the tip of this hemisphere (fig. 6(d)) appears to be more severe than on any of the others (figs. 6(a) to (c)).

The results of the noncontacting slipring assembly experiment are also summarized in table III.

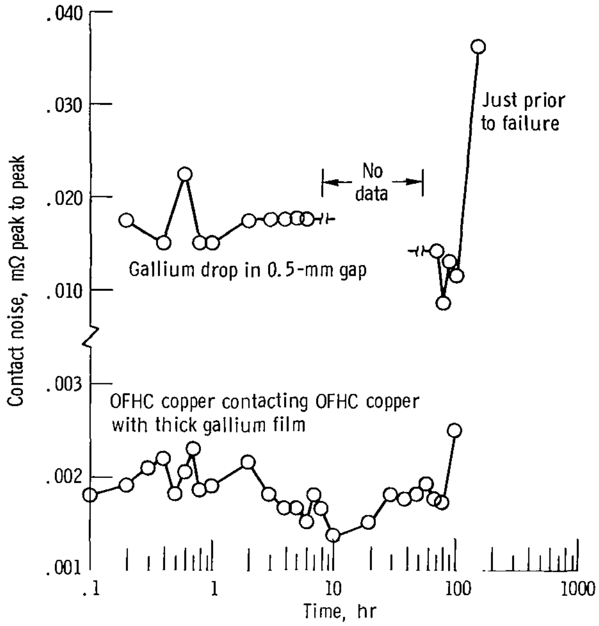


Figure 9. - Comparison of contact noise values obtained from noncontacting experiment and thick-gallium-film experiments using same materials (OFHC copper) and hemisphere polarity (positive). Speed, 1 rpm (132 mm/min); vacuum, 10^{-10} to 10^{-11} torr; contact current, 20 amperes dc.

SUMMARY OF RESULTS

Results were obtained from the investigation on the use of gallium as a lubricant for oxygen-free high-conductivity (OFHC) copper and a beryllium-copper alloy slipring assemblies in vacuum. The following results were obtained for the low-current screening experiments:

1. A thin gallium film on an OFHC copper disk contacting an OFHC copper hemisphere failed at 13 revolutions of the disk, whereas a thick gallium film (same material) did not fail at the end of 120 revolutions (2 hr).

2. The amount of wear on the tip of the OFHC copper hemisphere run in the 2-hour thick-gallium-film experiment was greater than the amount of wear in a similar experiment which was run dry.

3. A noncontacting slipring assembly (gallium drop in 0.5-mm gap) ran for 2 hours with a low, steady contact resistance.

The following results were obtained for the 20-ampere direct-current endurance experiments:

4. OFHC copper hemispheres (both positive and negative) ran against OFHC copper disks with thick gallium films for 100 hours at 20 amperes dc and showed low average

contact resistance (<0.05 mΩ) and low electrical noise (<0.0025 mΩ peak to peak).

5. Hemisphere wear volume for the 100-hour OFHC copper experiments was high for both hemisphere polarities. However, the wear volume for the negative polarity hemisphere (3.24 mm^3) was greater than that for the positive polarity hemisphere (1.05 mm^3).

6. A noncontacting slipring assembly (gallium drop in 0.5-mm gap) ran for 147 hours at a contact current of 20 amperes dc (hemisphere positive) before failure due to gallium drop disappearance. The average contact resistance was generally in the same range as that for the loaded thick-gallium-film experiments. However, the electrical noise was 10 times greater.

7. A beryllium-copper alloy hemisphere (positive polarity only) ran against a beryllium-copper alloy disk with a thick gallium film for 100 hours at 20 amperes dc and showed low average contact resistance (<0.051 mΩ) and low electrical noise (<0.002 mΩ peak to peak).

8. Hemisphere wear volume for the 100-hour beryllium-copper alloy experiment was about one ten-thousandths of the wear volume shown in the best OFHC copper experiment.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 27, 1970,
129-03.

REFERENCES

1. Anon.: Aerospace Electronic Systems Technology. NASA SP-154, 1967.

2. Przybyszewski, John S.: Friction and Contact Resistance for Low Speed Gallium Lubricated Sliding Electrical Contacts of Beryllium in Vacuum. Proceedings of Seminar on Sliding Electrical Contacts for Vacuum and Space, Virginia Polytechnic Institute, Blacksburg, Virginia, 1969, pp. 91-115.

3. Przybyszewski, John S.; and Spalvins, Talivaldis: Friction and Contact Resistance During Sliding in Vacuum of Some Low-Resistivity Metals Lubricated with Sputtered Molybdenum Disulfide Films. NASA TN D-5349, 1969.

4. Przybyszewski, John S.: Stress-Strain Behavior of Cold-Welded Copper-Copper Microjunctions in Vacuum as Determined from Electrical Resistance Measurements. NASA TN D-4743, 1968.

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

6. Kuczkowski, Thomas J.; and Buckley, Donald H.: Friction and Wear of Low-Melting Binary and Ternary Gallium Alloy Films in Argon and in Vacuum. NASA TN D-2721, 1965.

7. Bowden, F. P.; and Tabor, D.: The Friction and Lubrication of Solids. Clarendon Press, Oxford, 1950.

8. Williamson, J. B. P.; and Hunt, R. T.: The Microtopography of Solid Surfaces. Res. Rep. 59, Burndy Corp., Jan. 26, 1968.

9. Lyman, Taylor, ed.: Properties and Selection of Metals. Vol. 1 of Metals Handbook. Eighth ed., American Society for Metals, 1961.

10. Maninger, R. C.: Preburst Resistance and Temperature of Exploding Wires. Exploding Wires. Vol. 3. William G. Chace and Howard K. Moore, eds., Plenum Press, 1964, pp. 47-64.

11. Thewlis, J., ed.: Encyclopaedic Dictionary of Physics. Vol. 5. Pergamon Press, 1962, pp. 509-510.

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