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OPERATION OF LOW-SPEED GALLIUM-LUBRICATED TUNGSTEN SLIPRING ASSEMBLY IN VACUUM FOR 500 HOURS

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SUMMARY

Gallium was used as a lubricant for a tungsten hemisphere against a tungsten disk slipring assembly running in ultrahigh vacuum under a 100-gram load at 132 millimeters per minute. Contact current was 20 amperes dc, hemisphere positive. The slipring assembly showed good performance on the 500-hour period of the experiment.

The gallium film was displaced from the wear track at the start of the experiment and remained displaced for 10 hours, whereupon the gallium began to return to the wear track in the form of a small arc of continuous film. The arc gradually lengthened until, at about 200 hours, the ends of the arc united to form a continuous film of gallium in the entire wear track.

The contact electrical values began to stabilize at about 4 hours, indicating the end of the breakin period. Contact resistance at 4 hours was 0.150 milliohm. The concurrent contact noise was 0.170 milliohm peak to peak. At 500 hours, the contact resistance decreased to 0.065 milliohm, and the contact noise decreased to 0.009 milliohm peak to peak.

The coefficient of friction started and remained at 0.25 until the 38- to 40-hour period when it increased to 0.30. From 300 hours on, the coefficient of friction became unsteady occasionally reaching 0.35.

Maximum contact temperature (64.5° C) was reached after 5 hours of operation. It decreased slightly after 19 hours of operation.

Surface profilimeter traces across the disk wear track showed that the wear was extremely small and consisted of a small decrease in the height of the surface grooves. Hemisphere wear volume was 3.872×10^{-2} cubic millimeter which corresponds to a wear rate of 9.8×10^{-9} cubic millimeter per millimeter of sliding.

The obliteration of the original hemisphere grinding marks immediately outside the perimeter of the wear scar suggests some minute attack by gallium. However, spectrochemical analysis of the gallium film in the wear track of the disk did not detect the presence of tungsten in the gallium.

INTRODUCTION

Tungsten is a very attractive slipring material for both high voltage and high current applications in vacuum because it has both a high work function and a low electrical resistivity. In high voltage applications, a high work function is desirable because it curbs field emission which is the initiating phenomena for electrical breakdown (ref. 1). In high current applications, a low electrical resistivity will result in lower electrical losses in the contact. Lower electrical losses mean less contact heating which is especially important in vacuum since radiation is the only process in operation for dissipation of heat.

Operation of a dry tungsten slipring assembly in vacuum has resulted in a high coefficient of friction and intolerable variations in contact resistance (noise) during sliding (ref. 2). Some type of lubricant is needed to reduce the coefficient of friction and contact noise to useful values. It would be advantageous if the lubricant chosen had electrical properties similar to those of tungsten (in addition to being vacuum compatible) because full advantage could then be taken of the desirable electrical properties of tungsten.

A recent experiment (ref. 2) that used gallium as a tungsten slipring assembly lubricant in vacuum is an example of a slipring material and its lubricant having similar electrical properties. The use of gallium reduced the noise by a factor of 900 at the end of 10 hours of operation in addition to decreasing the contact resistance. A comparison of some of the pertinent properties of tungsten and gallium are shown in table I. Mercury is included in table I to show that the resistivity of gallium is about one-fourth that of mercury which is commonly used in moderate current (30- to 100-A) contactors sealed in a hydrogen atmosphere (ref. 3).

TABLE I. - PROPERTIES OF TUNGSTEN, GALLIUM, AND MERCURY

Material	Electrical resistivity, $\mu\Omega$-cm (a)	Work function, eV (b)	Temperature for vapor pressure of 10^{-8} torr, ^{o}C (c)	Toxicity (d)
Tungsten	5.5 at 20^{o} C	4.55	2000	Nontoxic
Gallium	[e]27.5 at 29.8^{o} C	4.2	620	Nontoxic
Mercury	98.4 at 50^{o} C	4.52	-70	Highly toxic

[a]Refs. 4 to 6.
[b]Refs. 4, 7, and 8.
[c]Ref. 9.
[d]Refs. 4 and 6.
[e]Liquid.

The good electrical compatibility of tungsten and gallium plus the good electrical performance observed near the end of the 10-hour experiment in reference 2 suggests that a similar experiment be made for a longer period of time using a higher contact current. The extended time experiment will show whether the contact can continue to provide good electrical results. Furthermore, an extended time experiment would better reveal any adverse effects that might occur from the longer term intimate physical contact of gallium and tungsten.

The objectives of this experiment are to determine, in vacuum: (1) the contact resistance, (2) the contact electrical noise, (3) the coefficient of friction, and (4) the wear of a hemisphere on disk slipring assembly using a purposely grooved tungsten disk with a swabbed gallium film as a lubricant.

The objectives were accomplished by means of an experiment of 500 hours duration using a 4.76-millimeter-radius tungsten hemisphere running against the gallium coated surface of a 50.4-millimeter outside-diameter tungsten disk running at a surface speed of 132 millimeters per minute in vacuum 10^{-10} torr. The load used was 100 grams. Contact current was 20 amperes dc hemisphere positive except for the first hour of operation when the contact current was limited to 5 amperes dc.

APPARATUS

Vacuum System

The ultrahigh vacuum system used for the 500-hour experiment is the same as that used for the 10-hour experiment (ref. 2). The vacuum system is divided into two sections having a common wall to isolate the drive shaft support bearings from the slipring assembly experiment. The drive shaft penetrates the common wall through a close clearance annulus which forms a molecular seal. Each section is pumped by its own individual ion pump. A liquid nitrogen cooled titanium sublimation pump aids in pumping the section containing the slipring assembly. Rough pumping is done with a set of three cryosorption pumps. Drive power from a direct-current electrical motor is brought into the vacuum system by a pair of 20 pole circular permanent magnets which face each other through a stainless steel diaphragm in one of the vacuum flanges.

Slipring Assembly Electrical Circuit

A drawing of the slipring assembly electrical circuit is shown in figure 1. The positive lead from a current regulated direct-current power supply is connected to a

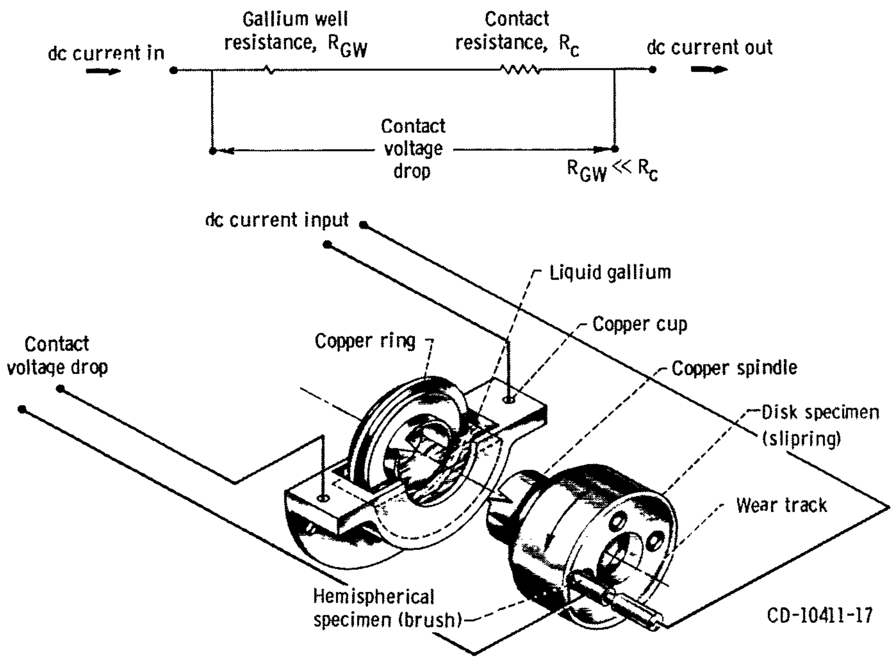


Figure 1. - Contact resistance measuring circuit.

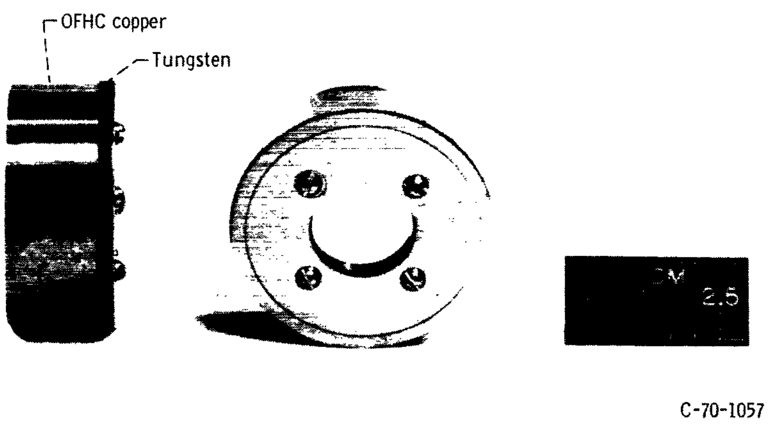


Figure 2. - Construction of typical disk specimen.

6.35-millimeter outside-diameter rear extension of an electrically insulated tungsten hemisphere by means of a gold-plated, friction fit push-on connector. The negative lead is connected to one side of an oxygen-free high-conductivity (OFHC) copper cup containing liquid gallium. The two part disk specimen (a 3.2-mm-thick tungsten disk backed up by an OFHC copper disk (fig. 2)) is mounted on an OFHC copper spindle that is completely insulated from the drive shaft. A ring machined into the opposite end of the spindle and immersed into the liquid gallium in the copper cup completes the current path to the slipring assembly.

Two separate leads are used for contact voltage drop measurements. One lead (gold) is connected directly to the hemisphere near its tip. The remaining lead (gold) is connected to the copper cup opposite the current connection.

A thermocouple is attached near the tip of the hemisphere and is used to measure the temperature in the vicinity of the contact interface.

Friction Force Measurement System

The friction force measurement system is shown in figure 3. The hemisphere is mounted in an insulated aluminum block that is affixed to one end of a cantilever beam. The friction force that is developed between the hemisphere and disk bends the beam.

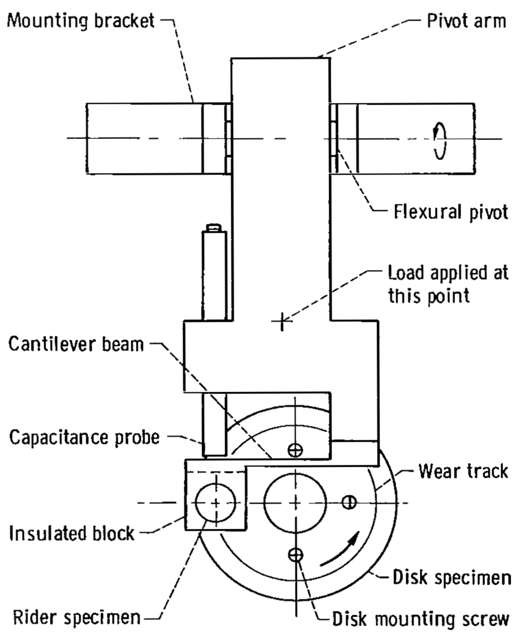


Figure 3. - Frictional force measurement assembly.

The displacement of the end of the beam (which is proportional to the frictional force) is sensed by a capacitance probe mounted normal to the direction of bending.

Slipring Assembly Material Preparation

The hemisphere was ground from a 9.52-millimeter outside-diameter tungsten rod. A 3-millimeter inside-diameter hole was electrical discharge machined about 4 millimeters back from the tip of the hemisphere for electrical lead and thermocouple connections.

The disk was electrical discharge machined from a 63-millimeter-square tungsten plate and ground to have parallel faces. One face was then reground to produce grooves approximately concentric with the circumference of the disk. The reground surface was checked and found to have a roughness of 0.3 to 0.38 micron, center line average (CLA).

The purity of the tungsten stock used was not less than 99.95 percent.

PROCEDURE

The hemisphere and disk were washed with a detergent solution and rinsed several times in absolute alcohol.

The hemisphere was installed directly into the vacuum chamber.

The disk was swabbed with a gallium film in atmosphere (starting purity, 99.999 percent) in the form of an annulus that covered the wear track zone. The weight of gallium used was 0.24 gram. The area of the disk covered was approximately 1000 square millimeters.

Forceful scrubbing was required to form a film on the surface of the tungsten disk. The finished film was not continuous but was interrupted by pinholes of various sizes where the gallium did not cover the tungsten surface.

Continuous measurements of contact resistance, friction force, and contact temperature were made. Contact electrical noise was determined by taking the difference between the highest and lowest values of contact resistance that occurred during any given 1-minute interval of time during the experiment. Contact noise is reported as milliohms peak to peak.

Contact wear was determined by measuring the wear scar diameter on the tip of the hemisphere after the experiment and calculating the wear volume. Wear is reported both as wear volume and wear rate.

Surface profilimeter traces were also made across the wear track on the surface of the disk to determine the relative amount of surface damage.

RESULTS AND DISCUSSION

The 500-hour data obtained from the operation of the gallium-lubricated tungsten slipring assembly was purposely divided into three consecutive time segments or regions. This division was based on the observed behavior of the gallium film on the face of the tungsten disk during operation. It must be understood that the regions, in reality, overlap somewhat and are not sharply defined as depicted in the figures. All three regions of operation (Region I, Region II, and Region III) are indicated on all figures that display the slipring assembly data against time.

Region I

The time segment defined by Region I occurs from the start of the experiment to 10 hours elapsed running time. The "break-in" period of the slipring assembly occupies a large portion of this time period as evidenced by the high rate of change of the contact resistance (fig. 4) and the large excursion in the contact noise values (fig. 5).

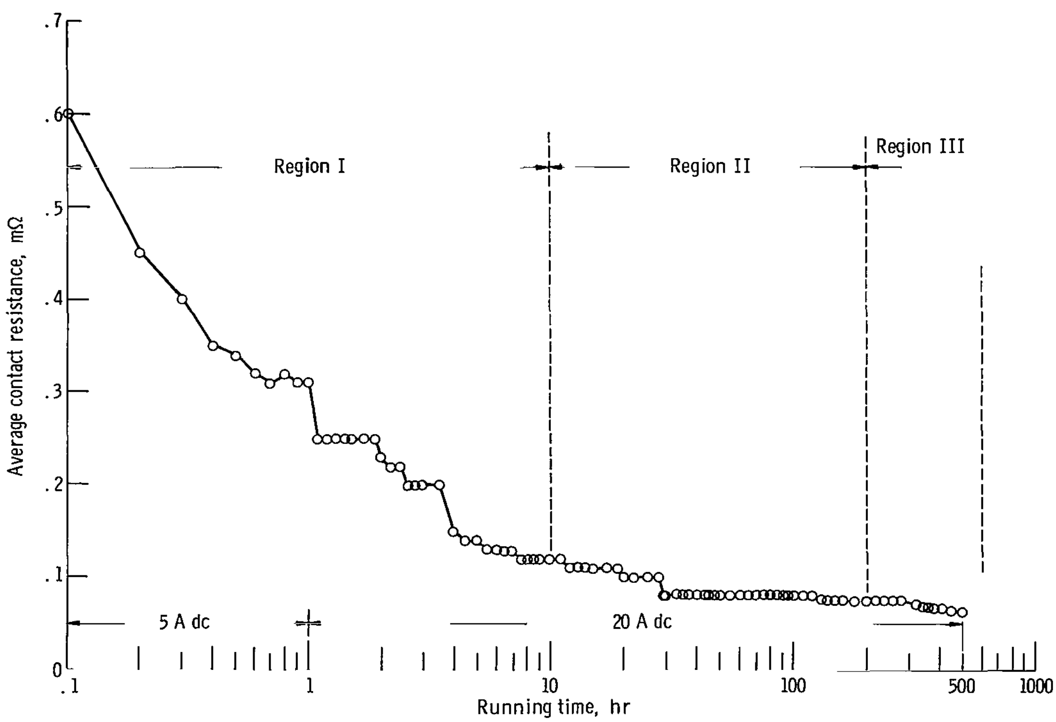


Figure 4. - Average contact resistance against time for tungsten disk with mechanically applied gallium film running against 4.76-millimeter-radius tungsten hemisphere. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current after 1 hour, 20 amperes dc; hemisphere polarity, positive; duration of experiment, 500 hours.

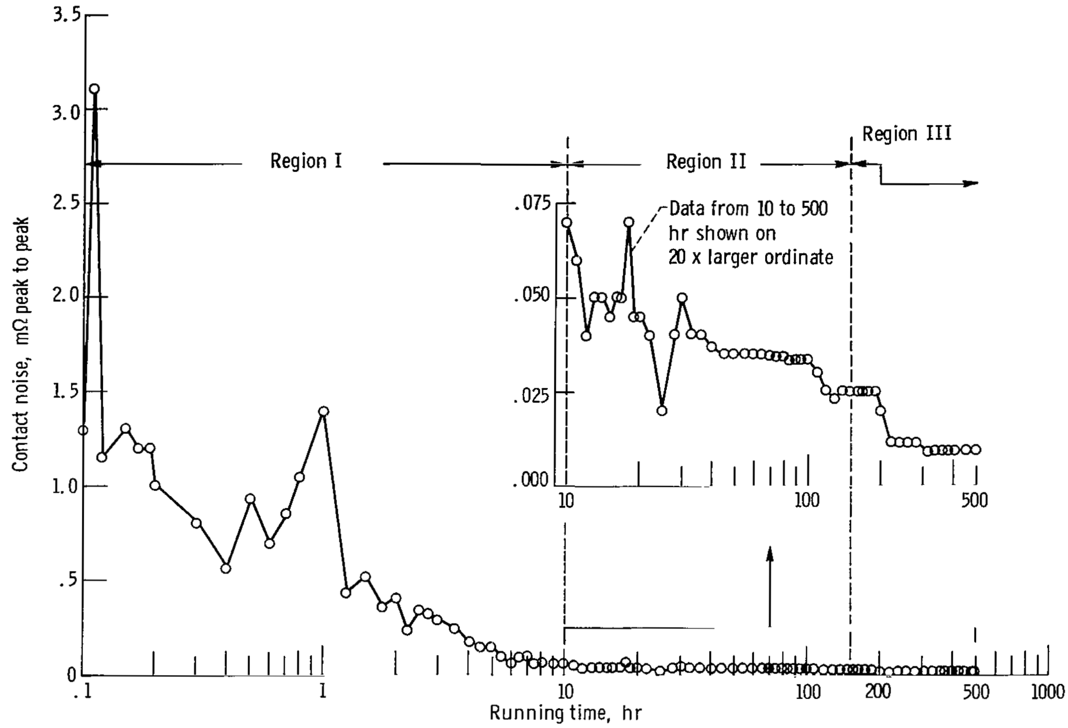


Figure 5. - Contact noise against time for tungsten disk with mechanically applied gallium film running against 4.76-millimeter-radius tungsten hemisphere. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current after 1 hour, 20 amperes dc; hemisphere polarity, positive; duration of experiment, 500 hours.

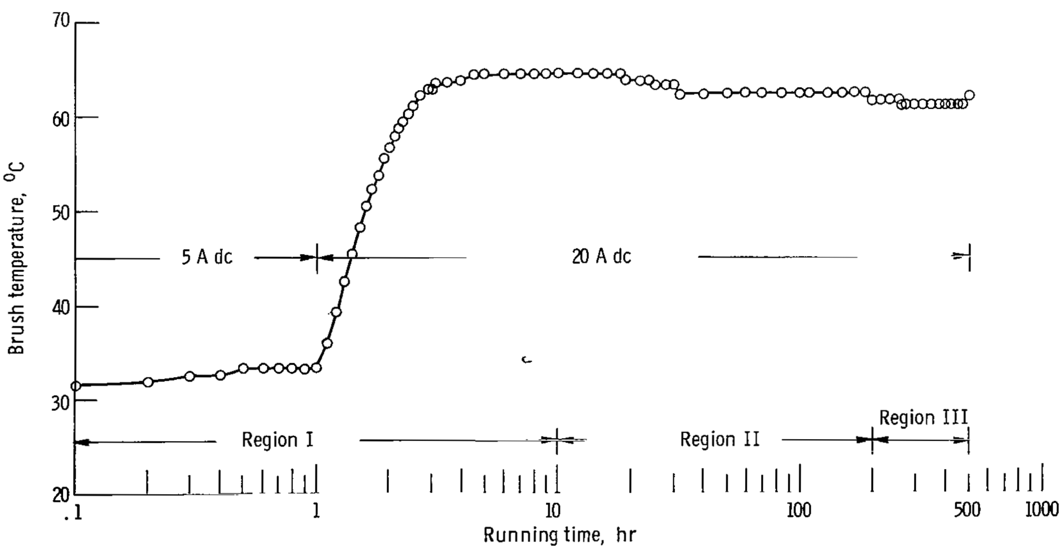


Figure 6. - Hemisphere temperature against time for tungsten hemisphere running against tungsten disk with gallium film. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current after 1 hour, 20 amperes dc; hemisphere polarity, positive; duration of experiment, 500 hours.

Also, during this segment of time, a large portion of the gallium film was displaced from the wear track zone (a characteristic also observed in the previous 10-hour experiment of ref. 2).

Two additional features of this initial segment of time are (1) a stabilization of contact temperature at 64.5° C (4 hr running time (fig. 6)) and (2) a constant coefficient of friction (f ≅ 0.25 (fig. 7)).

The end of Region I is characterized by relatively stable values of contact resistance (0.12 mΩ) and contact noise (0.07 mΩ peak to peak). The "break-in" period has ended and contact operation has stabilized, results similar to those observed for the earlier 10-hour experiment.

It is interesting to compare the data over the 10 hours of operation in the experiment of reference 2 with the data over the first 10 hours of the 500-hour experiment. This comparison is shown in table II. The values of contact resistance are similar

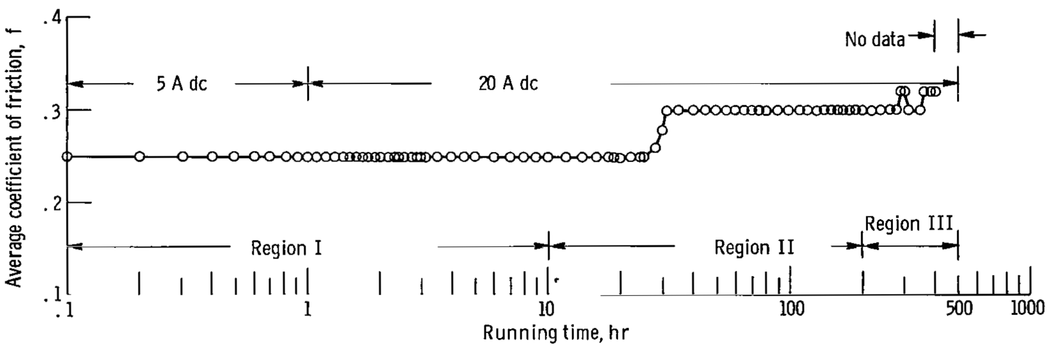


Figure 7. - Coefficient of friction against time for tungsten hemisphere running against tungsten disk with gallium film. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current after 1 hour; 20 amperes dc; hemisphere polarity, positive; duration of experiment, 500 hours.

TABLE II. - COMPARISON OF RESULTS OF 10-HOUR EXPERIMENT WITH

FIRST 10 HOURS OF OPERATION OF 500-HOUR EXPERIMENT

Running time, min	Reference 2	Present experiment	Running time, min	Reference 2	Present experiment
	Contact noise, mΩ peak to peak			Contact resistance, mΩ	
1	1.600	(a)	1	0.876	0.700
10	.420	1.200	10	1.460	.500
100	.062	.475	100	.223	.250
600	.010	.070	600	.120	.120

[a]No data.

and the values of contact electrical noise are consistently higher, and effect which is not understood.

Region II

A migration of the gallium film on the surface of the tungsten disk back to the wear track zone signaled the beginning of Region II. Up to this point, most of the gallium film remained displaced from the wear track zone. The very beginning of this migration was observed as a small arc ($\sim 10^{\circ}$) of continuous gallium film in the wear track zone. As the arc lengthened, a small drop of gallium appeared at one end of the arc. As the hemisphere passed through the drop, a momentary decrease in contact resistance data was observed due to the momentary increase in the contact area. Thus, the gallium drop had the effect of increasing the contact noise during approximately the first half of Region II. The magnitude of the contact resistance decreases were not constant from revolution to revolution (especially near the beginning of drop formation); hence, the variations in the values of contact noise were quite large from the beginning of the region (10 hr) to about 40 hours elapsed running time (fig. 5).

The arc of continuous gallium film itself did not appear to affect the electrical contact data.

As the experiment continued, the arc lengthened until the ends of the arc united to form a circle of gallium film in the wear track, at which point Region II was terminated. As the ends of the arc of gallium film united, the drop of gallium that had remained at one end of the arc throughout the duration of Region II, disappeared. This action resulted in an immediate decrease in both the values and variations in the values of contact noise.

Perhaps, the most interesting feature of Region II is the increase in the coefficient of friction from $\bar{f} \sim 0.25$ (the value since the beginning of the experiment) to $\bar{f} \sim 0.30$ (fig. 7). The reason for this increase is not clear. However, the contact resistance did decrease significantly a few hours prior to the increase in the coefficient of friction (fig. 4). A few hours after the friction increased, the contact noise values became more stable (fig. 5).

Region III

Region III occupies the time period from 200 hours elapsed running time until the termination of the experiment at 500 hours. During the entire duration of Region III (300 hr), a continuous film of gallium was present in the wear track zone.

This region is characterized by a slow, steady improvement in electrical contact operation. In this period of 300 hours, the contact resistance decreased from 0.075 to 0.065 milliohm, a negligible decrease (fig. 4). The behavior of the contact electrical noise was similar. It decreased from 0.025 milliohom peak to peak to 0.009 milliohm peak to peak, a threefold improvement (fig. 5).

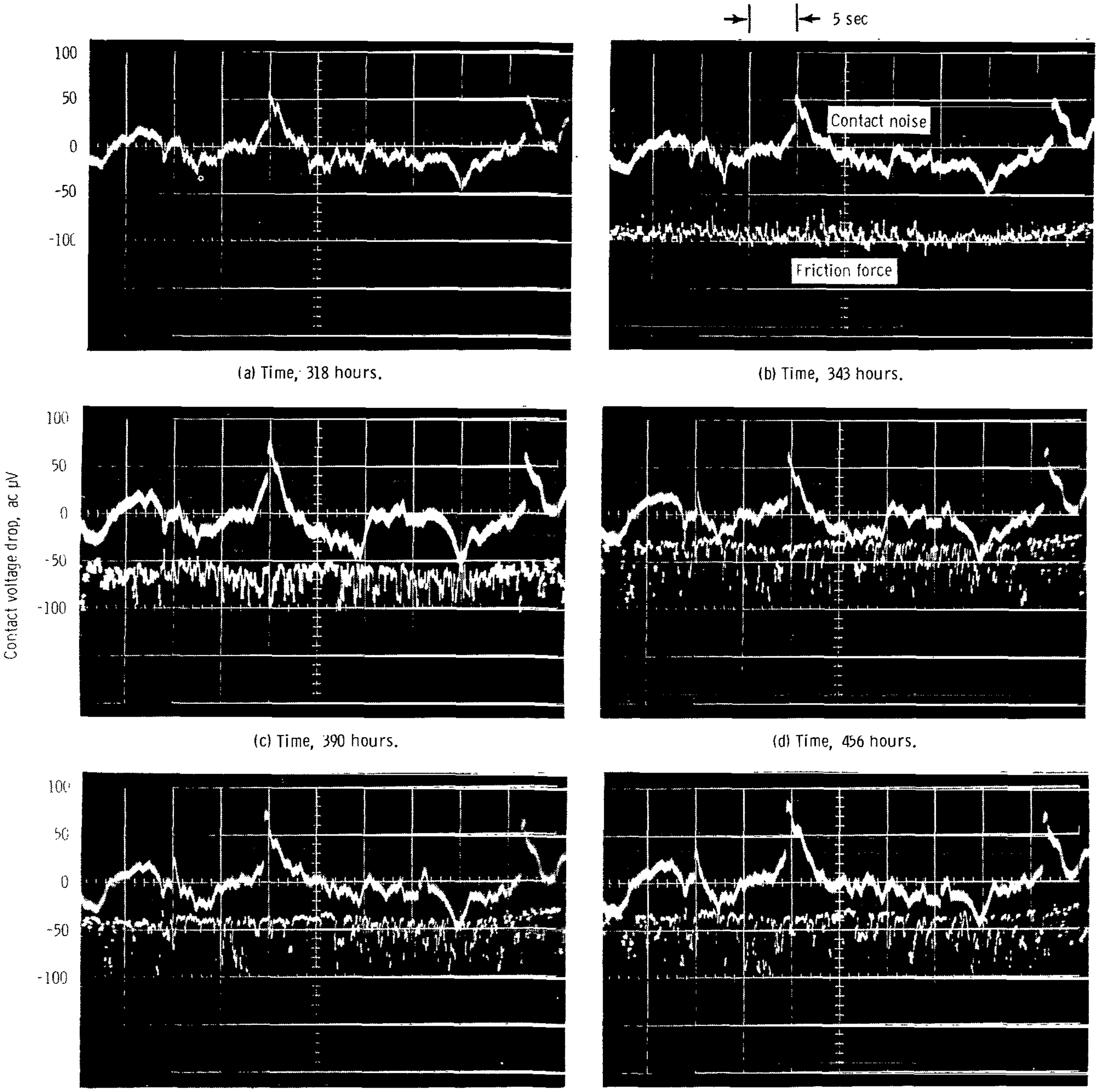
Starting at 320 hours elapsed running time, an oscilloscope with an attached camera was added to the contact resistance measurement circuit to determine if any sharp peaks of contact noise were present. A selected series of six from the many photographs taken are shown in figure 8. Since the oscilloscope y-axis amplifier was ac coupled (bandwidth, 0.06 Hz to 20 kHz), only the changes in contact voltage drop are shown. The most interesting feature found in comparing the six photographs is the stability of the waveform of the contact resistance during each revolution over a period of 180 hours. There is, however, an increase in the larger positive peak as the experiment accumulated running time.

Observation of the face of the disk revealed that the larger positive peaks in the contact resistance trace (fig. 8) were a result of a breaking away of a drop of gallium that had collected around the area of contact. Both visual observation and the contact resistance trace showed that these actions occurred at approximately the same locations on the surface of the disk as it revolved.

The second trace that appears in most of the photographs is the frictional force. This trace is synchronized with the contact resistance trace so that variations in friction and contact resistance may be compared. Unfortunately, the trace could not be corrected for zero drift, so the coefficients of friction shown in the photographs are not comparable. The sharp downward peaks in the friction trace were correlated with a squeaking shaft support bearing that became progressively worse as the experiment continued.

To determine if the direct-current constant current power supply contributed to the observed slipring noise, a battery was temporarily substituted for the power supply. The photographs in figure 9 show a comparison between slipring noise obtained with the power supply and that obtained with the battery as an energy source. Since only 17.5 amperes could be obtained with battery operation as opposed to 20 amperes with the direct-current power supply, the amplitude of the battery trace is reduced. Otherwise, there is no significant difference between the two traces showing that the observed noise consists of only slipring noise and amplifier noise.

A photograph of the face of the disk specimen after the conclusion of the 500-hour experiment is shown in figure 10. It is representative of the appearance of the face of the disk from the termination of Region II (200 hr elapsed running time) to the conclusion of the experiment. Note that most of the gallium film which originally occupied about 1000 square millimeters has migrated to the wear track region.



(a) Time, 318 hours.

(b) Time, 343 hours.

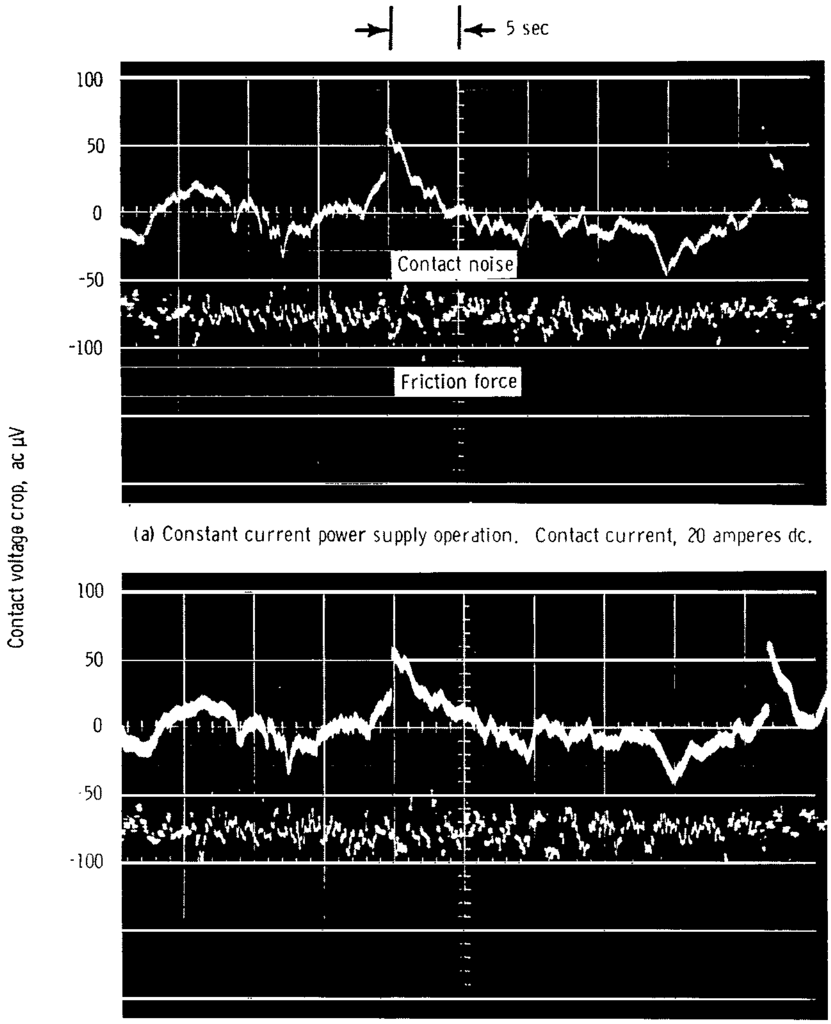
(c) Time, 390 hours.

(d) Time, 456 hours.

(e) Time, 482 hours.

(f) Time, 500 hours.

Figure 8. - Oscilloscope traces of contact voltage drop and friction force at various times. Oscilloscope bandwidth, 0.06 hertz to 20 kilohertz; sweep rate, 5 seconds per centimeter.



(a) Constant current power supply operation. Contact current, 20 amperes dc.

(b) Battery operation. Contact current, 17.5 amperes dc.

Figure 9. - Comparison of contact voltage drop waveforms for constant current power supply operation and battery operation. Elapsed running time, 365 hours.

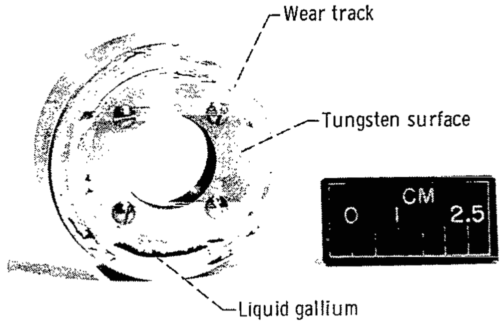


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Figure 10. - Tungsten disk with gallium film. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current after 1 hour, 20 amperes dc; duration of experiment, 500 hours.

Disk Wear

The gallium film was wiped from a portion of the wear track prior to microscopic examination of the wear track area. The wear track area was difficult to locate. The only distinguishing feature between the wear track area and the area outside of the wear track was the slightly darker appearance of the wear track area. Microphotographs were taken, but they did not resolve the slightly darker wear track area.

Surface profilimeter traces were taken across the same area of the tungsten disk (gallium wiped off) and one of the traces is shown in figure 11. Examination of the profile traces show that the wear on the surface of the disk is negligible. The wear track is distinguished from the unworn area by a rounding off and a small decrease in the height of the peaks of the surface grooves. The profile traces show that the surface retains much of its original roughness in the wear track despite contact with liquid gallium and the passing of an electrical current of 20 amperes direct current for a

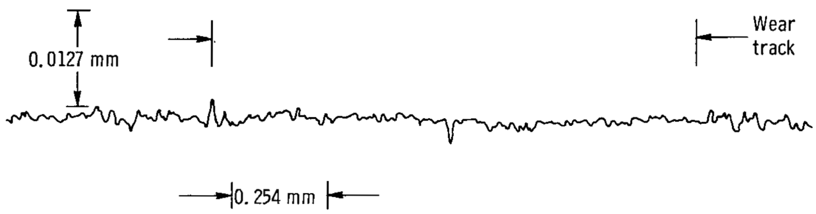

Figure 11. - Surface profile trace across wear track on surface of tungsten disk. Vacuum, 10^{-10} torr; contact current after 1 hour, 20 amperes dc; duration of experiment, 500 hours. Vertical magnification, 2000; horizontal magnification, 100.

period of 500 hours.

Two different samples of the gallium film in the wear track area were taken for a qualitative spectrographic analysis to determine if tungsten was present in the gallium film. The results of the analysis together with the control sample are shown in table III. Tungsten was not detected in any of the samples. This result implies that the gallium film will retain its original properties for a very long period of time on a tungsten surface since the gallium film does not appear to be seriously contaminated by the tungsten under the

TABLE III. - RELATIVE INTENSITIES OF ELEMENTS FOUND BY SPECTROGRAPHIC ANALYSIS OF CONTROL GALLIUM AND GALLIUM FILM TAKEN FROM DIFFERENT AREAS OF WEAR TRACK ON TUNGSTEN DISK AFTER 500 HOURS OF OPERATION AT 20 AMPERES dc IN VACUUM

Element	Control (not used)	Wear track sample	
		1	2
Silver	Very weak	Moderate	Moderate
Aluminum	Faint trace	Faint trace	Faint trace
Copper	Weak	Moderate	Moderate
Gallium	Very strong	Very strong	Very strong
Tin	Trace	Faint trace	Faint trace
Tungsten	Not detected	Not detected	Not detected

conditions of this experiment. This result also shows that the amount of tungsten wear debris, which must be trapped by the gallium film, is insignificant for 500 hours running time.

Hemisphere Wear

A photograph of the tip of the hemisphere after the 500-hour experiment is shown in figure 12. The hemisphere wear volume was 3.872×10^{-2} cubic millimeter. This corresponds to a wear rate of 9.8×10^{-9} cubic millimeter per millimeter of sliding. In comparison with the 10-hour experiment (ref. 2), the wear of the hemisphere was increased by a

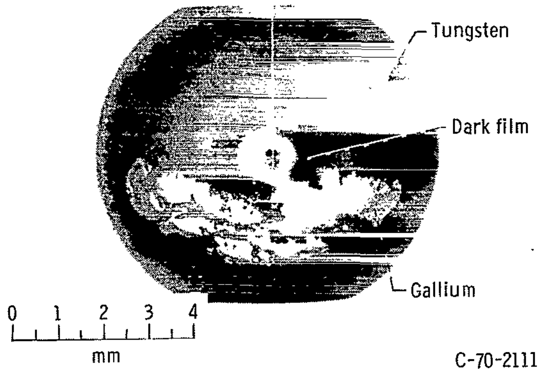

Figure 12. - Tip of tungsten hemisphere running against tungsten disk with gallium film. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; contact current after 1 hour, 20 amperes dc; hemisphere polarity, positive; duration of experiment, 500 hours.

factor of 29, although the running time was greater by a factor of 50. A photomicrograph of the wear scar, after the gallium was wiped from the surface, is shown in figure 13. An enlargement of an area of the hemisphere adjacent to the wear scar (fig. 13) shows some surface irregularities. Some grinding marks produced in making the hemisphere are pointed out in the photomicrograph. As the wear scar area, produced by actual mechanical contact is approached from the point of the grinding marks noted in the figure, the grinding marks become obliterated. The obliteration process cannot be mechanical because the area is outside of the mechanical contact area (defined by the wear scar area). In dry experiments (no gallium) using the same materials, grinding marks are found in their original form up to the perimeter of the wear scar. Since liquid gallium was present in and around the contact area in the 500-hour experiment, its presence must be responsible for the obliteration of the surface grooves. The obliteration of the surface grooves indicates a removal of a small amount of hemisphere material in this area, by other than mechanical means. One possible explanation is gallium corrosion that is accelerated by the high current density in the contact area.

Further examination of the tip of the hemisphere revealed an extremely thin black to gray colored film concentric with the contact area (pointed out in figure 13). This film persisted through vigorous wiping of the tip of the hemisphere to remove the adhered gallium for wear scar diameter measurements. No indications of a similar film were found on the disk although the wear track was slightly darker than other areas of the disk. The lack of a visible dark film on the surface of the disk might be due to the fact that only a small area of the disk was in contact with the hemisphere at any one

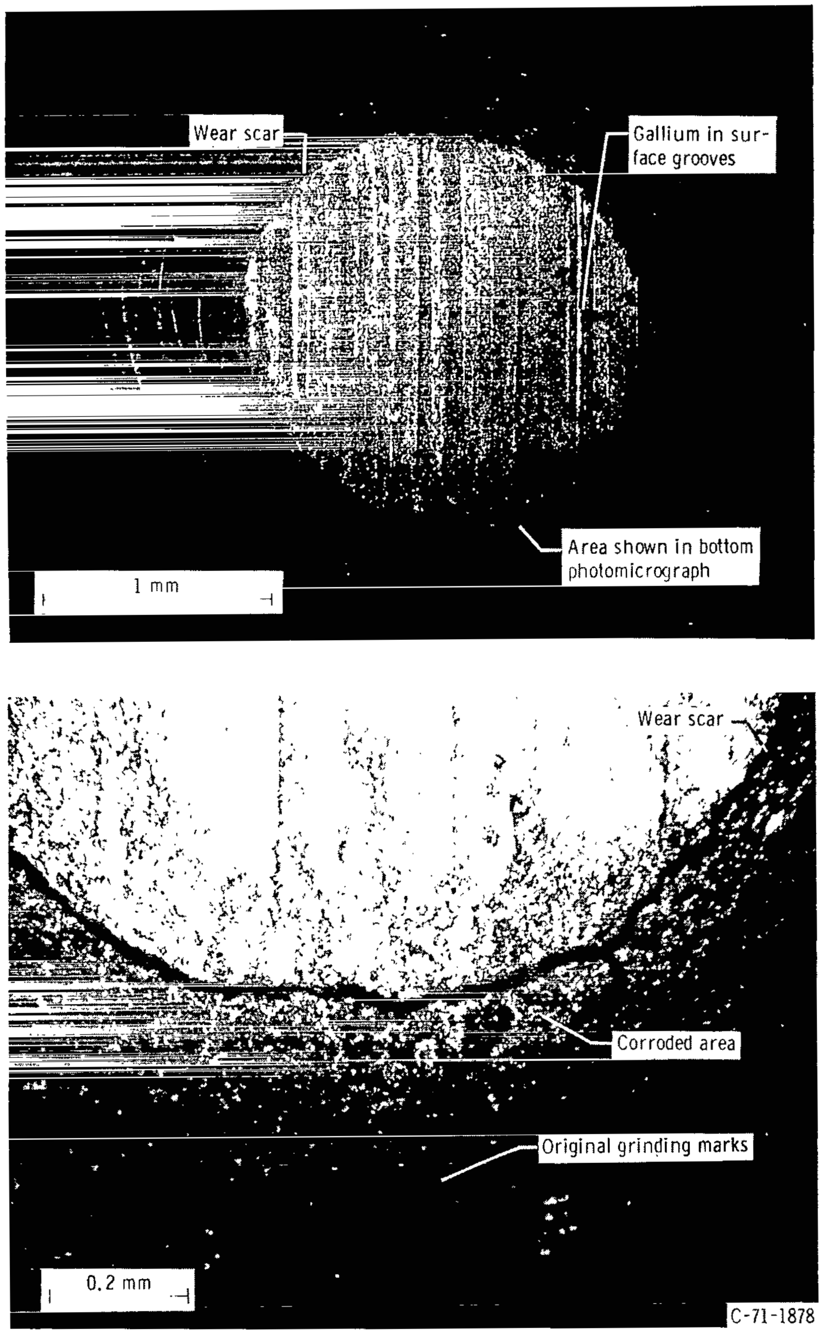

Figure 13. - Photomicrographs of wear scar on tip of tungsten hemisphere after running against tungsten disk with gallium film. Speed, 132 millimeters per minute (1 rpm); load, 100 grams; vacuum, 10^{-10} torr; contact current after 1 hour, 20 amperes dc; hemisphere polarity, positive; duration of experiment, 500 hours. (Gallium wiped from surface.)

time whereas the hemisphere was in continuous contact with the surface of the disk. No analysis was attempted because of the extreme thinness of the film.

SUMMARY OF RESULTS

A 500-hour slipring experiment using a slipring assembly consisting of a tungsten hemisphere running against a tungsten disk with a gallium film at a speed of 132 millimeters per minute in ultrahigh vacuum carrying a current of 20 amperes dc was made and the following results were obtained:

1. The gallium lubricated tungsten slipring assembly showed good performance in vacuum (10^{-10} torr) over a period of 500 hours.

2. The gallium film on the surface of the disk was displaced from the wear track region at the start of the experiment and remained displaced for approximately 10 hours.

3. After approximately 10 hours of operation, the gallium began to migrate back to the wear track beginning as a small arc (5° to 10°) of continuous gallium film in a particular location in the wear track.

4. After approximately 200 hours of operation, the end of the arc of gallium film united to form a complete circle of continuous gallium film in the wear track.

5. After 10 hours of operation, the contact noise was 0.070 milliohms peak to peak and decreased to 0.009 milliohms peak to peak at the end of the experiment (500 hr).

6. After 10 hours of operation, the average contact resistance was 0.120 milliohm and decreased to 0.061 milliohm at the end of the experiment.

7. Oscilloscope traces synchronized to display the waveform of contact resistance changes for one revolution, showed the shape of this waveform to be remarkably stable during the last 180 hours of operation.

8. Surface profile traces across the wear track on the disk (gallium wiped off) show that the wear is negligible, and that the surface retains much of its original roughness.

9. The wear volume on the tip of the hemisphere was 3.872×10^{-2} cubic millimeter which corresponds to a wear rate of 9.8×10^{-9} cubic millimeter per millimeter of sliding

10. The coefficient of friction remained at approximately 0.25 during the first 40 hours of operation whereupon it increased to 0.3. After 300 hours of operation, it became unsteady, occasionally reaching values of 0.35.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 14, 1971,
129-03.

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