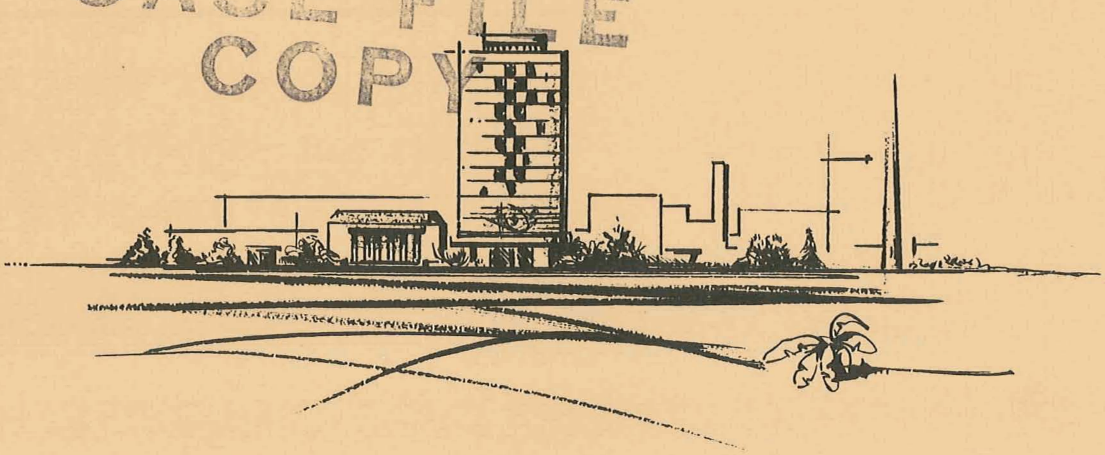
RESEARCH REPORT

INVESTIGATIONS OF THE POTENTIAL PERFORMANCE CHARACTERISTICS OF SELECTED CONTACT LUBRICANTS FOR APPLICATIONS IN MINIATURE SLIP-RING CAPSULES OF THE TYPE USED IN ST 124 M STABILIZED INERTIAL GUIDANCE PLATFORMS

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
George C. Marshall Space Flight Center
Huntsville, Alabama

Period of Report
(March 27, 1968, to April 30, 1970)



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FINAL TECHNICAL REPORT

on

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Contract Number NAS 8-21323

by

J. B. Baker, G. B. Gaines, and K. E. Meiners

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INTRODUCTION

Contacts of slip-ring capsules employed in ST 124M Stabilized Platforms are made from gold alloys. If the mating surfaces of such contacts are made clean – that is, if no lubricating substance is between the contact members – galling occurs and the contacts are damaged in such a way that unacceptably high electrical noise develops in the contacts. A small amount of a specific lubricant – Univis P-38* – is applied to the contacts of slip-ring capsules currently produced for ST 124 Platforms. Many such capsules have provided satisfactory performance, but there have been cases where contact noise introduced by the slip rings was unacceptably high.

Thus, it became desirable to search for even better lubricants for use on slip-ring contacts. Under an earlier Contract, NAS 8-11403, Battelle's Columbus Laboratories carried out a program to evaluate potential contact lubricants.

Using a flat, electroclad member as one contact and a Neyoro 28A** wire as the other, simulated substitutes for actual rotor ring and brush were used to evaluate more than 20 commercial liquids and greases. The evaluation showed that several lubricants could assure satisfactory contact performance if the contact temperature, wiping speed, and load were maintained within a proper range of values. The ability of any single commercial product to span the entire range of temperature and speed conditions encountered in actual slip-ring applications was not clearly shown. On the basis of the results for the commercial materials, it was possible to "predict" the properties of a more suitable liquid. Of the commercial materials examined, OS 124*** came nearest to providing adequate lubrication over the required range of temperatures and contact speeds; it was clear that the only serious deficiency of OS 124 was that its viscosity was somewhat greater than the optimum value needed for the contacts in question. A material with a lowered viscosity was prepared by blending 25 percent (by weight) MCS 210*** with OS 124. This lubricant blend provided the best overall performance in the evaluation studies with contacts which simulated real slip-ring contacts. The recommendation was made to NASA that the 75 percent OS 124-25 percent MCS 210 blend be evaluated on actual miniature slip rings.

As stated previously, the original studies with simulated contacts included over 20 different potential lubricants. To determine the degree to which the results from the simulated contact studies could be utilized in predicting the performance of a given

* A product of Humble Oil and Refining Company.

** A product of J. M. Ney Company.

*** Product of the Monsanto Company.

lubricant on actual miniature slip-ring contacts, it was desirable to subject lubricated slip-ring contacts to the same types of experiments as had been performed on simulated contacts. In this connection, Part I of this report gives the results of an evaluation program which investigated miniature slip-ring capsules that were manufactured by conventional techniques but that had contacts lubricated by the proposed new liquid lubricant.

Under the proper combination of temperature and wiping speed, fluids have been able to provide satisfactory wear and resistance behavior for comparatively long periods of service. It should not be expected, however, that such fluids would provide adequate lubrication indefinitely or that they would function adequately in a high vacuum environment. On the face of it, the use of solid-state materials to lubricate contact members promises potentially longer service life, a wider range of allowable wiping speeds, and operation under vacuum conditions. In this connection, Part II of this report gives the results of a limited program carried out at Battelle to evaluate the feasibility of constructing miniature slip-ring capsules with solid-state-lubricated contacts.

SUMMARY

This report comprises the final report on two similar, indirectly related phases of a single program. Part I deals with selective evaluation studies carried out on miniature slip-ring capsules DP 1501 and DP 1506 conventionally manufactured by Poly-Scientific* that were remanufactured to include on the contacts a proposed new liquid lubricant of 75 percent OS 124 and 25 percent MCS 210. Part II is concerned with a program to evaluate the feasibility of utilizing solid-state lubricants on the contacts of miniature slip-ring capsules.

The results of Part I showed that the electrical performance of contacts in actual slip-ring capsules lubricated by a blend of 75 percent OS 124 and 25 percent MCS 210 did not differ significantly from the behavior of simulated contacts that were used in an earlier program to evaluate several types of liquid lubricants. Low noise levels and low wear rates were achieved with contacts lubricated by this blend of lubricants.

Investigators at NASA and Poly-Scientific found unacceptably low insulation levels between many adjacent rings on capsules with the lubricant blend. Examination revealed that the loss of insulation was being caused by metallic particles that reached the epoxy barriers separating the rings. The source of the particles was identified as the contact surfaces. The presence of a large amount of lubricant causes the particles to "float" to the barriers where they may short out adjacent rings. The application of less lubricant or the use of raised barriers are potential methods for eliminating the problem.

The results of Part II of the program indicate that composite bodies composed of MoS_2 dispersed in a gold or gold-alloy matrix can function as one member of a contact pair in actual slip-ring capsules. Techniques were developed for fabricating homogeneous bodies with continuous current paths throughout and no large inclusions of the dispersed solid lubricant. Of those evaluated, a composite consisting of a gold-copper matrix with dispersed MoS_2 exhibits the best performance. Electrical measurements carried out on contacts composed of such bodies as one member, and Neyoro 28A as the other, indicate that noise levels can be achieved that are not seriously greater than those available with current-technology, liquid-lubricated slip-ring contacts.

*Poly-Scientific Division, Litton Precision Products.

Techniques were developed for fabricating rings from the gold-alloy dispersed-MoS_2 composite. Three experimental slip-ring capsules were fabricated with rings made of the composite material. Actual fabrication of the capsules was carried out by Poly-Scientific.

Two of the capsules have been operated for several tens of hours. The noise levels were comparable to those found earlier with the simulated contacts. The lowest levels measured corresponded to fluctuations in resistance of less than 7 milliohms during one complete revolution of the moveable contact. Every one of the contacts achieved this level part of the time, but variations of the order of 100 milliohms or so also were frequently encountered. The contact noise exhibited a pronounced dependence upon the amount of water vapor present in the capsule environment. The mechanism by which water affects the performance was not investigated.

PART I

SELECTED EVALUATIONS OF MINIATURE SLIP-RING CAPSULES WHICH HAVE CONTACTS LUBRICATED BY A BLEND OF OS 124 AND MCS 210 LUBRICANTS

The slip-ring capsules used for this investigation were provided by NASA. They consisted of three Poly-Scientific Type DP 1506 (80-circuit) assemblies and three Type DP 1501 (100-circuit) assemblies. All six capsules had failed to pass NASA's flight qualification tests in their original condition. They were returned to Poly-Scientific where they were remanufactured and the contact lubricant was changed to the OS 124, MCS 210 blend. The remanufacturing process for three capsules – DP 1501 SN 77, DP 1506 SN 181 and DP 1506 SN 189 – consisted of removing the original alloy gold surface from the rotor rings and plating on a new alloy surface. The reprocessing of the other three capsules – DP 1501 SN 81, DP 1501 SN 95, and DP 1506 SN185 – consisted only of solvent cleaning the parts and then applying the lubricant blend.

EVALUATION TECHNIQUES AND EQUIPMENT

The slip-ring capsules were mounted in organic-free chambers during the evaluation periods. An atmosphere of prepurified nitrogen gas was maintained at all times. The capsule barrels were removed to insure that the contacts themselves would make easy interchange with the atmosphere introduced into the chamber. A photograph of a typical capsule with the barrel removed is shown in Figure 1. The environment for the slip-ring capsules was created by purging the evaluation chambers with flowing prepurified nitrogen gas while the slip-ring capsules were at room temperature, by heating the

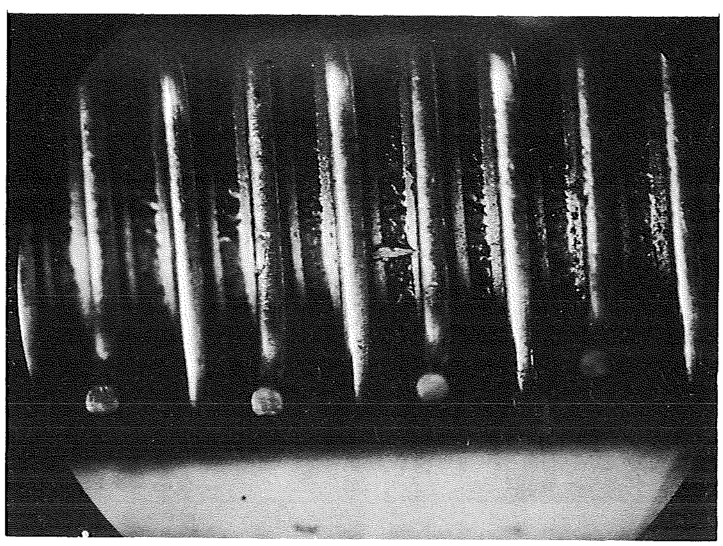

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FIGURE 1. ENLARGED VIEW OF SEVERAL RINGS AND BRUSHES OF SLIP-RING CAPSULE DP 1501 SN 77

evaluation chambers so that the slip ring was at a temperature of 43C, and by purging continuously for an additional hour with the nitrogen flowing at 1 cfh. When the experiment was to be performed at room temperature, the chamber was then cooled and the exhaust valve closed; when the experiment was to be performed at 43 C, the exhaust valve was closed following a purge of at least 1 hour at temperature and prior to initiation of rotor oscillation. In all cases, the lines to the nitrogen supply were kept open and the pressure maintained slightly above atmospheric to insure that outflow would be maintained through any undetected leak that might have existed.

A schematic representation of the circuit used to observe the dynamic resistance behavior of the minature slip rings is shown in Figure 2. The circuit is a modified version of the one used with the simulated contacts.

For contact-resistance measurements using the simulated contacts, it was possible to attach voltage probes to the contact members very near to the actual contact area. For the actual slip rings, the resistance of the leads was many times greater than the contact resistance. For this reason, a differential amplifier was used for the slip-ring dynamic-resistance measurements. By properly adjusting the current through a "dummy lead" and subtracting the voltage drop across the "dummy" from that across the contact under study, it was possible to detect only the changes in resistance as the brush moved over the rotor ring. Thus, all dynamic values given in this report for slip-ring contacts should be clearly understood to represent the amount by which the resistance varied during one complete oscillation of the slip ring.

As indicated in Figure 2, a circuit was included that indicated the position of the slip-ring actuating arm. In this way, the measured resistance variations could be associated with a specific location on the ring surface and with the linear speed of the contact at that particular portion of the wipe cycle.

DYNAMIC-RESISTANCE BEHAVIOR OF SLIP RINGS WITH CONTACTS LUBRICATED BY A BLEND OF OS 124 AND MCS 210

To provide a full basis for comparison of the results from the study of simulated contacts carried out under Contract NAS 8-11403 with the performance of actual miniature slip-ring contacts, the slip-ring capsules were subjected to (1) "long-stroke" evaluation at room temperature and at 43 C, (2) "short-stroke" evaluation at room temperature and at 43 C, and (3) variable-wiping-speed studies at room temperature and at 43 C. The results of these three experiments are presented in the following sections.

Slip-Ring Performance During Long-Stroke Operation

Slip-ring Capsule DP 1501 SN 81 was mounted in the evaluation chamber so that the capsule rotor could be rotated through an angle of 5 degrees; Capsule DP 1501 SN 95 was mounted in a chamber such that the deflection angle was 3-1/2 degrees. The 5 degree deflection caused the brushes to move about 13 mils in one direction; the 3-1/2-degree deflection caused the brushes to move about 9 mils in one direction. The magnitudes of the resistance variation as a function of brush position were observed periodically for circuits 1, 3, 5, 49, 51, 96, 98, and 100 during runs of at least 5×10^6

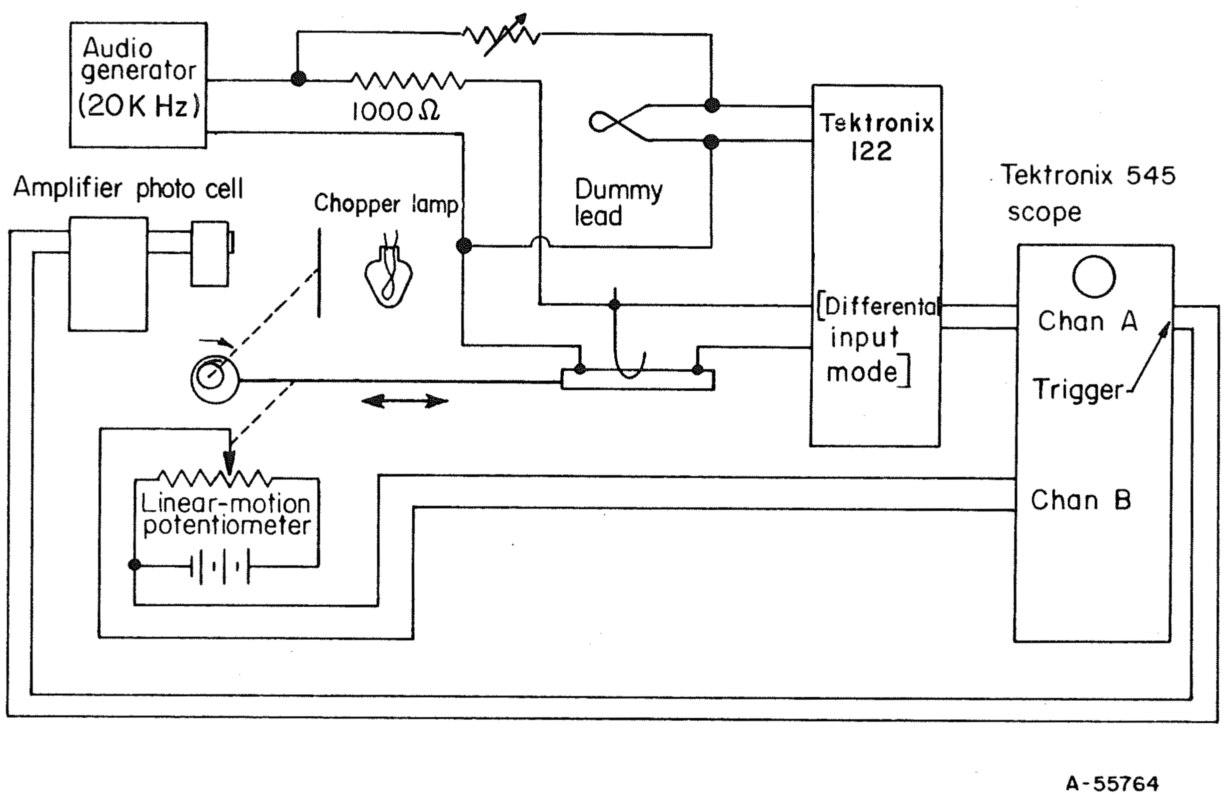


FIGURE 2. SCHEMATIC REPRESENTATION OF CIRCUIT FOR MEASURING DYNAMIC CONTACT RESISTANCE

cycles of rotor oscillation. In the long-stroke experiments, the capsules were evaluated first at room temperature, then at 43 C.

Of the 16 circuits for which dynamic resistance was monitored, the resistance variation for 11 was less than 2 milliohms at all times. Seven of the eleven circuits that exhibited consistently low dynamic-resistance variations were on Capsule DP 1501 SN 95. Half of the observed circuits on Capsule DP 1501 SN 81 exhibited resistance variations of about 5 milliohms or greater at least once during the run. The observed resistance variations for those circuits for which the variation exceeded 2 milliohms are listed in Table 1. As can be seen, the variations on all but Circuit 1 of DP 1501 SN 81 had dropped to low values for the final two measurements.

At the conclusion of the room-temperature experiments, the evaluation chambers were opened, the slip-ring rotors were adjusted so that the brushes would operate at new locations on the rotors, and the chambers were resealed, purged, and heated to 43 C. During a period of 283 hours of slip-ring operation at 43 C, no circuit ever exhibited variations in dynamic resistance exceeding 2 milliohms. Such behavior provides strong evidence that the larger variations at room temperature were caused by hydrodynamic lift effects. The results obtained in variable-wiping-speed experiments given later in this report show clearly that this is the case. One observation made, and not expected, was that the hydrodynamic lift effects were significantly greater when the brushes were moving in one direction than when they were moving in the other direction. Such asymmetric behavior had been observed in the simulated-contact studies where it could be accounted for by the unsymmetrical geometry of the contact supports. In the case of the slip-ring capsules, which have two brush wires with one wire on each side of the rotor, it would seem that the direction of travel should not affect the resistance. Those cases where the direction of travel did have an effect may indicate that one brush was making less-than-ideal contact with the rotor.

TABLE 1. MAGNITUDES OF DYNAMIC RESISTANCE VARIATIONS FOR THOSE CIRCUITS WHICH EXHIBITED SIGNIFICANT VARIATIONS

Accumulated Hours of Operation	Variation in Dynamic Resistance, mΩ				
	DP 1501 SN 81 Circuit Number				DP 1501 SN 95 Circuit Number
	1	3	5	98	49
1/4	6.7	3.5	24.5	14	<1.8
40	<0.7	<0.7	4.6	<0.7	6.3
96	<0.7	4.9	3.5	<0.7	1.8
141	1.1	1.1	<0.7	2.1	2.1
192	2.8	2.6	9.8	<1.8	<0.7
265	16.6	2.1	2.8	<1.8	1.1
312	12.6	<0.7	2.8	<0.7	<1.8

Slip-Ring Performance During Short-Stroke Operation

Poly-Scientific Capsules DP 1506 SN 181 and DP 1506 SN 185 were used for the short-stroke studies. The angle of rotation of DP 1506 SN 185 was 1-2/3 degrees and for DP 1506 SN 181 the angle was 2-1/4 degrees. The stroke length for each capsule was about 0.004 inch under these conditions. The experimental procedures were the same as those used previously for the long-stroke studies. The capsules were operated for 5×10^6 oscillations at 43 C and then, at new brush locations, for 5×10^6 oscillations at room temperature. The variations in dynamic resistance over the wiping path did not reach 2 milliohms at any time during any of the runs for any of the circuits. The maximum wiping speeds were only about 0.2 cm/sec for the short-stroke experiments, and no hydrodynamic lift effects were expected. On the other hand, experience with the simulated contacts had shown that stick-slip behavior resulting from adhesive effects could occur at such low wiping speeds. Evidence of the effects of stick slip upon the dynamic resistance was carefully sought during the short-stroke experiments (and also during the variable-speed experiments in which even lower wiping velocities were employed), but none was ever detected. Thus it is clear that the contact geometry of the slip-ring capsules is well suited to applications which involve low-speed wiping.

Investigation of the Dependence of the Dynamic Resistance Upon the Wiping Speed

Capsules DP 1501 SN 81 and DP 1501 SN 95 were used for the variable-wiping-speed experiments. The rotation angle for Capsule DP 1501 SN 81 was again 5 degrees for DP 1501, it was again 3-1/2 degrees. The brushes were located so that they did not operate over any of the previously rubbed areas. In performing these experiments, the normal constant-speed motors which provide the sinusoidal motion to the actuating shaft were replaced by a variable-speed motor. The constant-speed motors operated at 1800 rpm, and were coupled to the contact drive through a 6:1 reducing gear to produce the normal oscillation period of 0.2 second. The data were obtained with the variable-speed motor, also coupled through a 6:1 reducing gear, operating at 1800, 2400, 2800, and 3200 rpm. The variation in dynamic resistance as the slip-ring rotor oscillated through one cycle for each of these motor speeds is shown in Table 2 for Circuit 98 of DP 1501 SN 81 and in Table 3 for Circuits 98 and 3 of DP 1501 SN 95. A second circuit was examined on DP 1501 SN 95 because the first circuit chosen did not exhibit appreciable hydrodynamic lift effects, even when the driving motor was operating at 3200 rpm. The second circuit, Circuit 3, was selected by searching out a circuit which exhibited hydrodynamic lift effects at a driving motor speed of 2800 rpm. Most of the other circuits of DP 1501 SN 95 were examined, but did not exhibit appreciable hydrodynamic lift effects at a motor speed of 2800 rpm. The maximum brush speeds are shown in the tables, rather than driving-motor speeds, because the different angles of rotation caused significant differences in brush speeds of the two capsules at a given motor speed.

The dynamic-resistance traces from which the data in Tables 2 and 3 were obtained show that the maximum resistance was greater for one direction of brush travel than it was for the other for the circuits in which the hydrodynamic lift effects were most pronounced (Circuit 3 of DP 1501 SN 95 and Circuit 98 of DP 1501 SN 81). For the other circuit, the magnitude of the variation does not depend upon direction of travel. Again it appears that one leg of the brushes may not have been making good contact with the rotor.

TABLE 2. DEPENDENCE OF THE MAGNITUDE OF THE DYNAMIC RESISTANCE VARIATIONS, IN MILLIOHMS, UPON MAXIMUM WIPING SPEED FOR DP 1501 SN 81

Circuit	Contact Temperature, C	Maximum Wiping Speed, cm/sec				
		0.025	0.52	0.69	0.81	0.92
98	24	--	.35	1.8	2.1	4.2
98	43	<.35	<.35	1.1	.7	<.7

TABLE 3. DEPENDENCE OF THE MAGNITUDE OF THE DYNAMIC RESISTANCE VARIATIONS, IN MILLIOHMS, UPON MAXIMUM WIPING SPEED FOR DP 1501 SN 95

Circuit	Contact Temperature, C	Maximum Wiping speed, cm/sec				
		0.0089	0.36	0.48	0.56	0.64
98	24	--	2.1	2.1	2.1	2.5
3	24	--	2.5	5.3	7.0	7.0
3	43	<.35	.35	.35	.35	.35

Each of the slip-ring capsules was also operated at very low driving-motor speeds. For DP 1501 SN 81, it was possible to achieve driving-motor speeds low enough to provide contact oscillating frequencies of one oscillation in 4.2 seconds; for DP 1501 SN 95, contact oscillating frequencies as low as one oscillation in 8.1 seconds were achieved. The very low contact speeds developed under these conditions were utilized to search for evidence of stick-slip effects in the dynamic-resistance behavior while the contacts were at 43 C. Even under these expectedly severe conditions, no stick-slip effects were detected. Besides the circuits listed in Tables 2 and 3, several others also were examined with the same results.

DISCUSSION OF DYNAMIC-RESISTANCE BEHAVIOR OF SLIP-RING CAPSULES LUBRICATED WITH THE OS-124-MCS 210 BLEND

The history of the slip-ring capsules used in these studies should be kept in mind when the results reported in the preceding sections are interpreted. Before they were shipped to Battelle, the capsules had been under test at the Marshall Space Flight Center for periods ranging (for the four capsules which underwent electrical evaluation at Battelle) from 1800 to 2100 hours. The tests at MSFC consisted of oscillating the brushes through an angle of 5 minutes of arc for 100 hours with an oscillation frequency of 6 Hz, then rotating the brushes through an angle of 365 degrees in one direction and through 365 degrees in the other direction, returning to the original oscillating point, and repeating the sequence. The brushes were positioned at new operating points for the studies at Battelle, but the accumulated wear effects on the brushes could not be compensated for. Thus, at the time the evaluation studies were made at Battelle, the brushes had already been oscillated for more than 77 x 10^6 individual wipes; the Battelle studies added at least 20 x 10^6 more wipes. Even after so much accumulated service, there was no direct evidence that contact wear had an influence upon the dynamic-resistance behavior of the slip-ring contacts.

The onset of any hydrodynamic-lift effects which were great enough to produce measurable dynamic-resistance variations appears to have occurred at about the same wiping speed, about 0.5 cm/sec., for the slip-ring assemblies as it did in the simulated contact studies. It is considered probable, however, that a circuit for which both legs of the brush wire are in good contact with the rotor could operate at considerably higher wiping speeds before hydrodynamic lift became a problem.

In general, the correspondence between the results with the slip-ring capsules and the simulated contact results is very good. Thus, one can have a great deal of confidence in using the sizeable amount of data in the reports covering Contract NAS 8-11403 to predict the suitability of a given lubricant for a given type of service.

One final observation concerning the evaluations carried out at Battelle is that the slip-ring brushes were not rotated during our experiments. It might be argued that large resistance variations would be more likely during 360-degree rotation, that is, during the period when the brushes were just moving out of, or into, the area wiped during the oscillatory operation.

RESULTS OF MICROSCOPIC EXAMINATION OF THE SLIP-RING ASSEMBLIES

Shortly after the six slip-ring capsules arrived at Battelle, NASA and Poly-Scientific became aware that many of the circuits on remanufactured and lubricated assemblies were failing to meet the required level of intercircuit insulation. It was decided that the capsules at Battelle should be open and examined to determine whether there were any physical indications of the cause for loss in insulation between adjacent circuits.

During the preoperation examination, the outside barrels were removed but the brush blocks were left in position. The capsules fell into two easily distinguishable groups, with three capsules in each group. One group consisted of Capsules DP 1501 SN 77, DP 1506 SN 181, and DP 1506 SN 189, that is, those capsules from which the original plating had been removed during the remanufacturing process. The contacts of this group were flooded with lubricant to the extent that lubricant completely bridged the epoxy barriers between rings. There were numerous flakes of gold on the barrier, and some of these flakes were large enough to simultaneously touch the rings on each side of the barrier. One such flake is visible in the central portion of Figure 1. Some of these flakes were lifted off the barriers of DP 1501 SN 77 with a probe. The flakes were found to consist of a single solid piece of metal which had an orange-peel texture similar to that of the electrodeposited rings. In addition to the "large" flakes, there were great numbers of micron-size particles of gold in the lubricant. Whenever the rotor was moved, many of these small particles became suspended in the lubricant and moved about freely, continuing to move for some time after the rotor became stationary. Many of the rings on these three assemblies had very irregular edges facing the epoxy barriers.

The slip-ring capsules in the other group - DP 1501 SN 81, DP 1501 SN 95, and DP 1506 SN 185 - had significantly less lubricant on the rings; the lubricant did not extend outside the grooves. It is possible that a thin layer of lubricant reached the surfaces of the barriers as a result of wicking, but if such a layer existed it was too thin to be detected microscopically. No metallic debris was detected on the barriers of any of this group of capsules. The edges of all of the rings were smooth. On Capsules DP 1501 SN 81 and DP 1506 SN 185, little, if any, wear debris was visible, even at the junctions of the brushes and rings. On DP 1501 SN 95, enough debris had collected in a number of circuits at the brush-ring interface to be easily detectable.

As mentioned previously, both Poly-Scientific and NASA found instances where the insulation between adjacent circuits was far less than that required. Capsule DP 1501 SN 77 had several circuits where the resistance between circuits was labeled as "dead short", and Capsule DP 1506 SN 181 had one instance of a "dead short" between adjacent circuits. The fact that all shorts occurred on "flooded" capsules suggested that the lubricant at least contributed to the problem.

The fact that only a relatively few circuits were shorted indicated that some factor besides the presence of the lubricant was involved. The barrier between two of the shorted rings on Capsule DP 1501 SN 77 was examined carefully with the aid of a microscope. A spot was found where a metal chip nearly bridged most of the barrier. Around the periphery of the chip, the surface of the barrier had a blackened appearance, suggesting that an electrical discharge might have occurred. A probe was used to scrape away the chip, and the resistance between the adjacent rings changed from a value of 1/2 megohm with the chip present to greater than 40 megohms with the chip moved. Other chips with blackened areas surrounding them were sought, and several were located. In each case, it was found that NASA or Poly-Scientific had detected a "short" between the rings at the sides of the chip. One case was found where the gold over the blackened area was an agglomeration of the very small gold particles, rather than being one of the larger gold chips. In this case, the resistance between adjacent rings increased to the megohm range when the aggolmeration of gold particles was broken up with the probe.

These results make it clear that the primary cause of the shorts between circuits is the presence of gold particles on the barriers. The presence of the lubricant undoubtedly makes it possible for gold flakes to move to their "shorting out" locations on the barriers.

What is not clear is the source of the gold flakes. The fact that many of the rings of the "bad" capsules had highly irregular edges while the edges of those on the unflooded rings were very regular led investigators at Battelle to speculate that a major source of the metal chips might be separation of irregular protrusions from the rest of the ring. It is understood that Poly-Scientific personnel investigated such a possibility by trying to pull particles away from the edges of the rings. They used a number of adhesive materials in such attempts, and the amount of gold that they were able to remove was neglibible. Thus, Poly-Scientific suggested that the source of the particles should be sought elsewhere. Definitive answers as to the source of the metallic particles were sought through electron-microprobe (EMP) and scanning-electron-microscope (SEM) examinations of both contact members and debris particles.

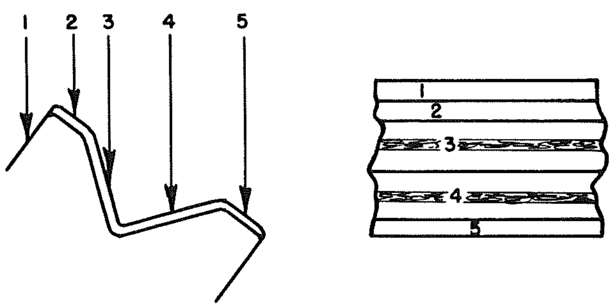
Analysis of Wear Debris From Liquid-Lubricated Slip-Ring Contacts

Various explanations for the presence of the gold flakes were hypothesized and then specific studies were designed to test the validity of each hypothesized explanation. Before presenting the results of the analytical studies, one important fact should be emphasized. Three slip-ring capsules were lubricated with the blend which did not develop low intercircuit resistance and on which little, if any, gold debris was visible. Known differences between these three capsules and the others that did develop excessive gold debris were: (1) the three low-debris capsules did not have any contact material removed during remanufacturing, they were merely cleaned prior to application of the blend; (2) the lubricant blend was present on the high-debris capsules to the extent that the barriers were covered with fluid while essentially all of the lubricant remained within the grooves on the low debris assemblies.

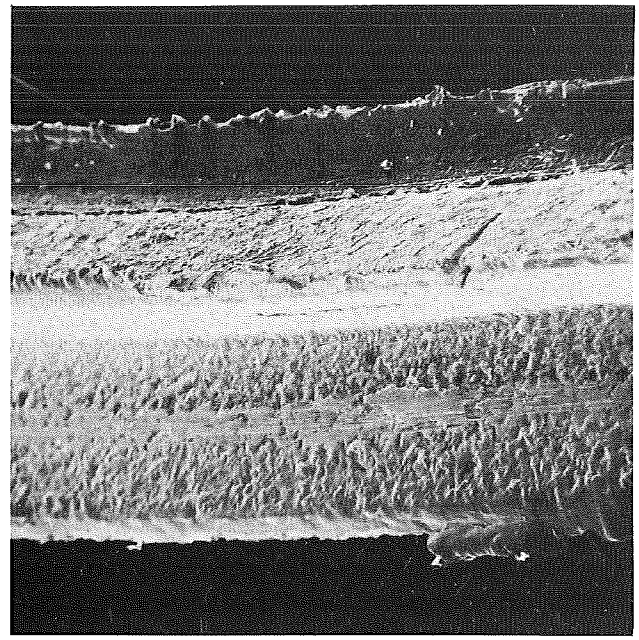
The first potential source of gold debris to be investigated was the possibility that a poor bond existed between the hard-gold surface layer of the rotor rings and the soft-gold main body of the ring and that sections of the hard layer simply "peeled-off".

Because of its great depth of focus at high magnifications, the SEM is uniquely suited to examining the surfaces of the rotor rings. Figure 3 shows SEM micrographs obtained on a section cut from a rotor ring of DP 1506 SN 181. Also included is a sketch (Figure 3a) to identify the various surfaces shown in the micrographs. In that portion of Figure 3b which corresponds to Area 3 of the sketch (i.e., in the white band running roughly horizontally across the photo), there is a dark line which appears in about the central third part of the line. (The exact reason for the line is unknown; it may be the area with which the wiper made contact during oscillatory testing of the ring. The reason for calling attention to the line in the present discussion is simply to use it as an aid to locating other points on the ring surface.) Directly below the left end of the line, on the opposite surface of the V-groove, two arch-shaped patterns can be seen. One arch is in the smeared area caused by the brush passing over the rotor surface; the other is immediately below the smeared metal, and is in part outlined by it. The area roughly centered on the lower arch is the area shown at higher magnification in Figure 3d. Directly beneath the right end of the dark line on Figure 3b is a particle in the wiper mark which gives the impression of being in relief. This particle and the area surrounding it were subjected to EMP analysis, the results of which will be given later. Figure 3c shows the junction between areas designated 1 and 2 on the sketch. This micrograph was obtained with the rotor section rolled farther onto its side than shown in the sketch.

Figure 3d reveals that the damage produced by the wiper during normal run-in by the manufacturer and some 2000 hours of subsequent testing at NASA did not extend through the intentionally created surface nodules. The dimensions of these particular nodules were not determined. Measurements taken on flat samples prepared by the same techniques indicated surface roughnesses ranging from 50 to 100 micro inches. Estimates, based upon comparison with known dimensions, indicate that the disturbed layer on the rotor ring is on the order of 50 microinches thick. Since the disturbed layer rather obviously does not penetrate to the bottoms of the nodules, it seems safe to assume that the original height of the nodules has not been reduced by more than about 50 microinches. It is also obvious that most of the material missing from the peaks has merely been smeared out to bridge the areas between peaks.

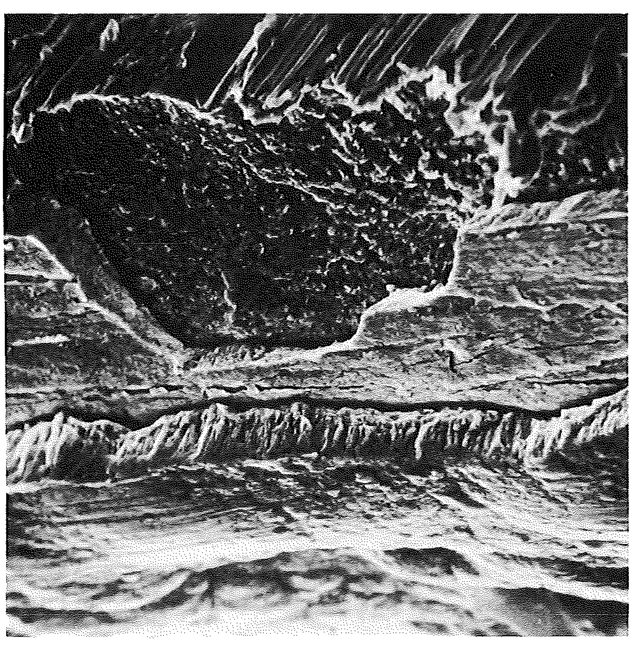


a. Sketch Showing Sample Orientation and Identifying Various Surfaces



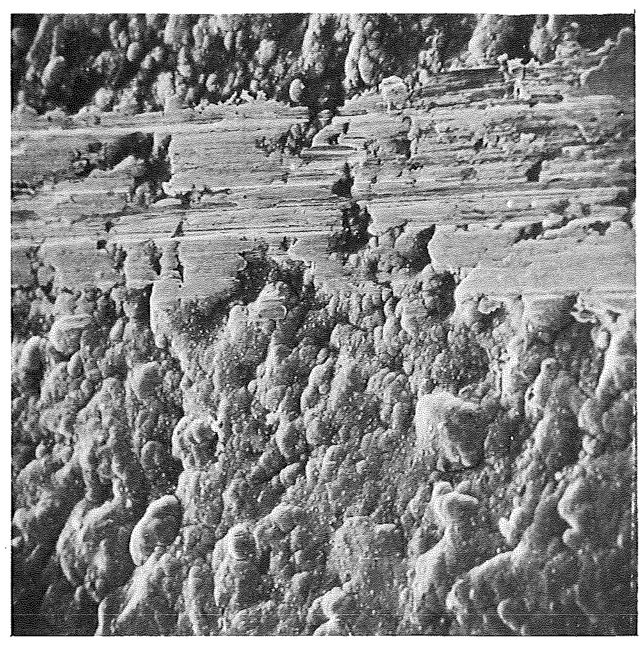
100X

b. Overall View of Ring Section



2000X

c. View of the Interface Between Hard Gold Overlayers and Soft Gold Body



500X

d. Beilby Layer Caused by Brush During Slip-Ring Operation

FIGURE 3. ELECTRON MICROGRAPHS OF A SECTION OF A ROTOR RING CUT FROM DP 1506 SN 181

Figure 3c shows the edge of a ring section in such a way that the interfaces between subsequent gold layers can be seen. There are two layers of hard gold because this ring was "remanufactured"; that is, the original hard-gold surface within the Vee-grooves was removed, but not from the rest of the ring, and a new hard-gold layer was then put on. One can get the impression from the shadows at the two interface lines that the hard-gold layers were not well bonded to the gold under them. Careful examination of several rings indicated that this is not the case; the layers are, in fact, well bonded. The portions of the hard layers that are missing were removed during the rather severe treatment attendant with removing the ring section from the epoxy body of the rotor. Other SEM views of ring sections revealed that the hard-gold layers were intact and continuous over the entire ring surface. Sections of several rings were examined and in each case the hard-gold layer was found to be complete. Subsequent comparison of these rings, with the aid of an optical microscope, with other rotor rings confirms that there are no areas where the hard-gold layer is missing on any of the rings.

Two ring sections from the rotor of DP 1506 SN 181 were transferred from the SEM to the EMP and their surfaces were examined for the presence of various metallic constituents. It is known that the major constituents of the hard-gold alloy used on the ring surfaces are gold and nickel, the hardner. The brushes are formed from a Au-Ag-Ni alloy, Neyoro 28 A. It was expected that any spots where the original hard layer had been torn out of the ring, or any spots to which new metal had been transferred, would be revealed by variations in composition. Figure 4 shows a set of X-ray images obtained from the surface of a ring section that was not cleaned after it was removed from the rest of the rotor structure. That is, a small amount of the lubricant blend, epoxy particles, and a few metal particles (generated when the section was cut out) still are attached to ring surfaces. Figure 5 shows similar X-ray images obtained from a ring section that was carefully cleaned with acetone prior to examination. This is the same ring section shown in the electron micrographs of Figure 3.

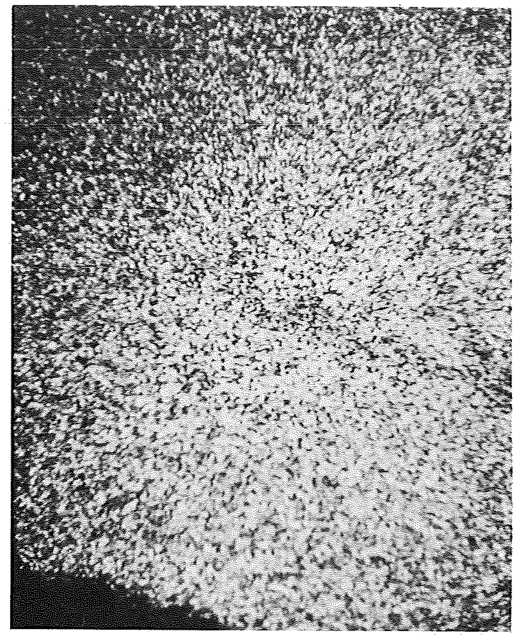
The results shown in Figure 4 are typical of nearly all the ring surfaces. Au and Ni are uniformly distributed and there is very little, if any, Ag. Thus the evidence is clear that, over most of the contact surface, no metal transferred from the brush to the ring. Figure 5 shows a spot on the ring where metal very clearly did transfer from the brush to the ring. This spot was one of the positions where the brush made contact during one of the long-term oscillatory tests. One other interesting feature is evident in Figure 5. The nickel concentration in the electrodeposited ring surface is quite obviously greater than that in the Neyoro 28 A. (Neyoro 28A is reported to contain 3 percent, by weight, nickel). Several other instances were seen where the nickel content of the electrodeposited alloy clearly exceeded that of Neyoro 28 A. In the remaining cases the concentration of nickel appeared to be very nearly the same in the two materials.

Ring Sections cut from Capsules DP 1501 SN 95 and DP 1506 SN 201 also were examined by EMP; no evidence was found of significant transfer of brush material to the ring surfaces.

Debris particles were lifted off the rotor of DP 1501 SN 95 by touching the particles with the tip of a 0.003-inch-diameter tungsten wire; lubricant on the particles caused the particles to remain on the tip of the wire. The wires, with the particles on their tips, were then introduced into the EMP and an analysis of the particles was carried out. The results indicated the presence of Au, but the indicated level for both Ag and Ni were no higher than the background. Since the results were the same for three different particles, the assumption was made that the most probable source of the particles was the 24-karat massive gold electrodeposit which forms the base of the rotor rings. This conclusion

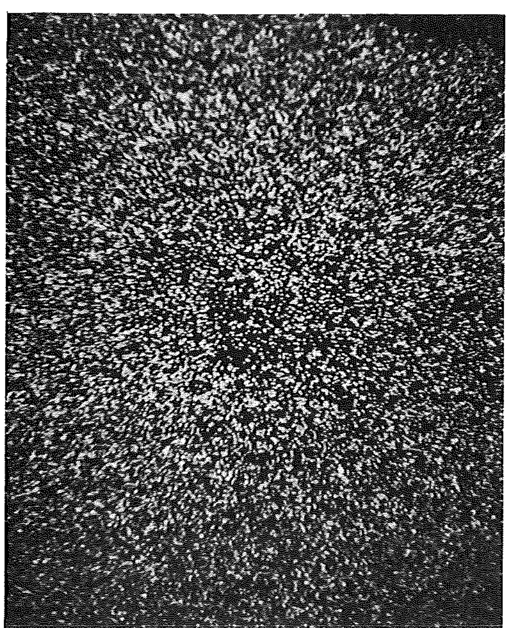
500X

a. Topography as Shown by Back-Scattered Electrons



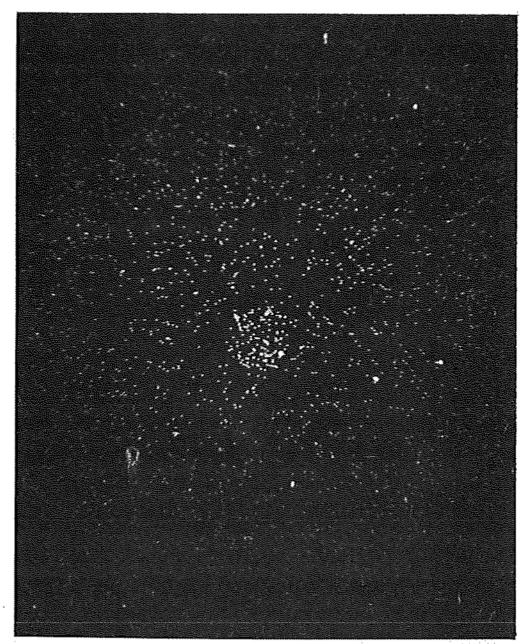
500X

b. Image Produced by X-Rays From Gold



500X

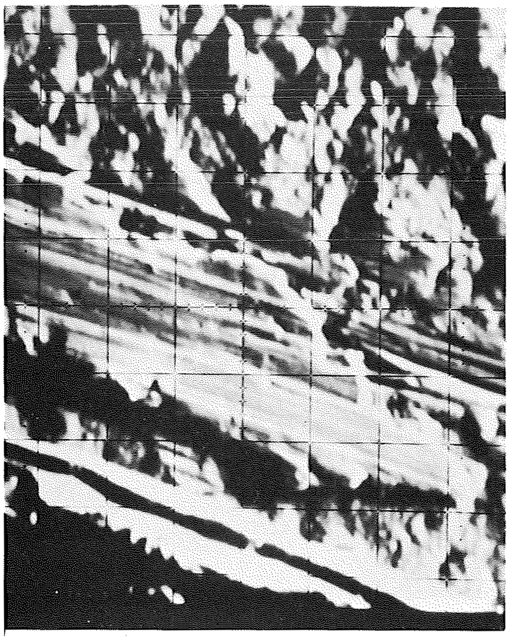
c. Image Produced by X-Rays From Nickel



500X

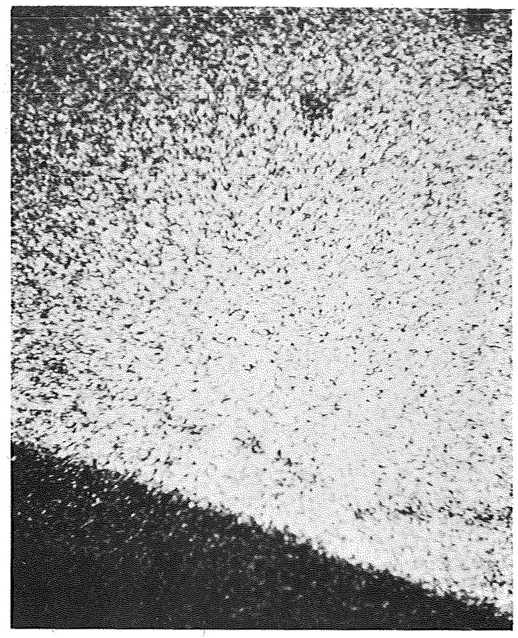
d. Image Obtained With Detector Adjusted for X-Rays From Silver

FIGURE 4. ELECTRON-MICROPROBE IMAGES OBTAINED FROM AN UNCLEANED SECTION OF A ROTOR RING REMOVED FROM SLIP RING DP 1506 SN 181



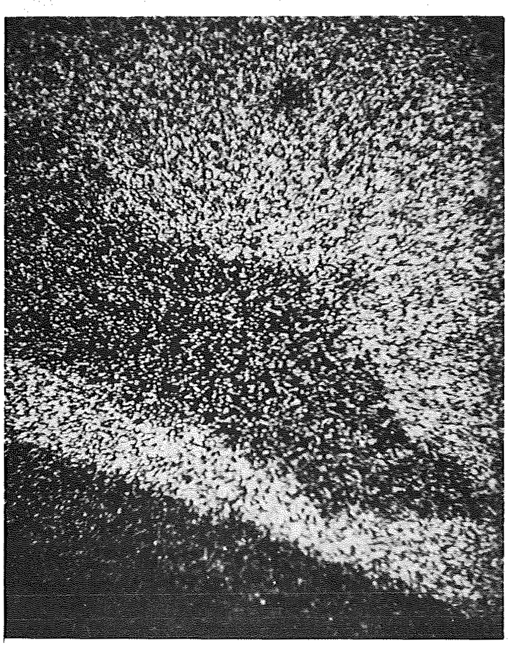
500X

a. Topography as Shown by Back-Scattered Electrons



500X

b. Image Produced by X-Rays From Gold



500X

c. Image Produced by X-Rays From Nickel

500X

d. Image Produced by X-Rays From Silver

FIGURE 5. ELECTRON-MICROPROBE IMAGES OBTAINED FROM A CLEANED SECTION OF A ROTOR RING REMOVED FROM SLIP RING DP 1506 SN 181

was communicated to Poly-Scientific and they attempted to verify it by thoroughly cleaning a capsule assembly so that all debris particles were removed, operating the capsule contacts for a known period, and examining the rotor for new particles. The presence of new particles would be strong evidence that the principal source of the particles did not lie in the underlayer of 24-karat gold. Poly-Scientific did observe numerous metal particles after the slip-ring capsule was operated, indicating that the assumption that the particles originated from the underlayer was erroneous. The work done at Poly-Scientific was carried out on Capsule DP 1506 SN 201. A history of this capsule has been provided by Poly-Scientific and is included in this report as Appendix A. (A sequential numbering s stem is employed in Appendix A to indicate the chronological order of the events.)

With the origin of the debris particles still unresolved, new EMP analyses were carried out. This time all specimens to be analyzed were placed on beryllium supports. This was done because it was suspected that the previous results were clouded by the presence of background radiation from the tungsten wires; the EMP equipment does not detect radiation from beryllium. Specimens for the new analyses were obtained from Capsules DP 1501 SN 95, DP 1506 SN 181, and DP 1506 SN 201. The specimens from DP 1506 SN 201 were provided by Poly Scientific.

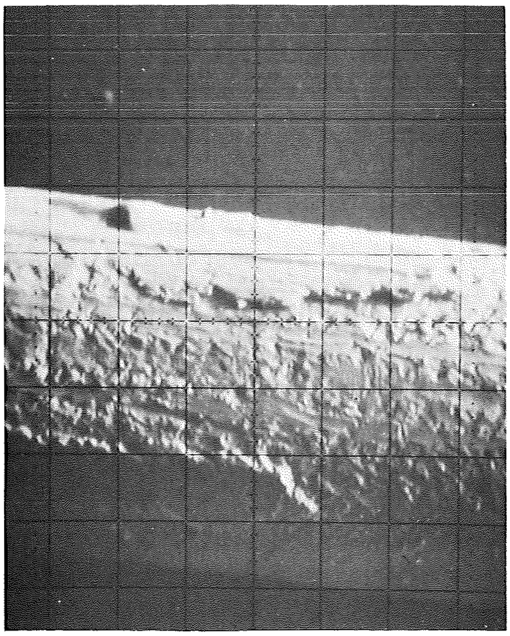
Figure 6 shows one end of the brush from Circuit 62 of DP 1506 SN 201. This brush was removed from the capsule in the condition represented by Point 10 in the history given in Appendix A. (The previous history of Capsule DP 1506 SN 201 at Point 10 of its life was essentially the same as the history of the six capsules that were examined at Battelle.) Two particles like those typically found attached to most brushes can be recognized in Figure 6a. The particles are located near the Points where actual contact occurs. The X-ray images show clearly that these particles contain no silver but do contain nickel; thus they clearly originated from the hard alloy coating of the rotor.

To fully interpret the data shown in the EMP images, one should know that the detector for back-scattered electrons is mounted above the specimens in a position nearly normal to the specimen surfaces and thus collects scattered electrons from most of the specimen surface. The X-ray detectors are mounted at the sides of the specimens so that quite often the X-rays from part of the specimen are screened from the detector by the specimen itself. This effect is detectable, but not severe, in Figure 6.

Only one set of X-ray images for brush wires is reproduced in this report. Exactly the same results were obtained for brush wires cut from Capsule DP 1506 SN 201 after additional operation beyond Point 10 (the second brush sample was removed at Point 16 - see Appendix A), and for wires cut from DP 1501 SN 95 and from DP 1506 SN 181 at the conclusion of the electrical-evaluation studies at Battelle.

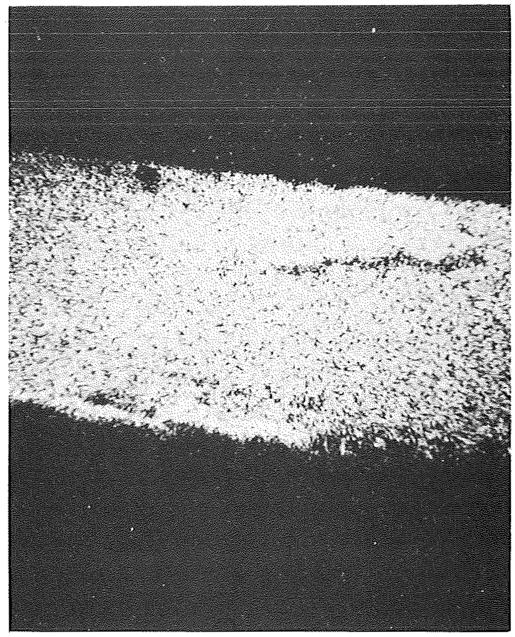
Thus, there can be no doubt that material is removed, through some processes of wear, from the surface of the rotor rings. Both SEM and optical microscopy indicate that the material must be removed in extremely thin pieces.

Figure 7 shows EMP results for a loose particle taken from the rotor of DP 1506 SN 201 at Point 9 of its life, that is just before the first brush wire was removed and Figure 8 shows a corresponding particle taken from the rotor at Point 16 of its life. Both particles clearly originated from the hard-alloy coating of the rotor. A second particle removed at Point 9 also had the composition revealed by Figures 7 and 8.



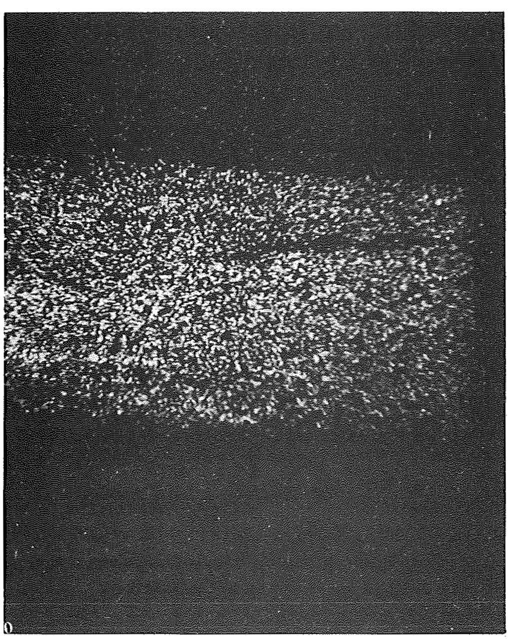
200X

a. Topography as Shown by Back-Scattered Electrons



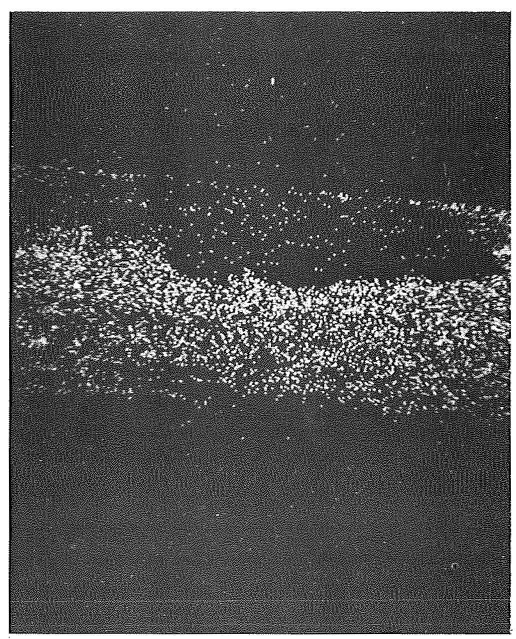
200X

b. Image Produced by X-Rays From Gold



200X

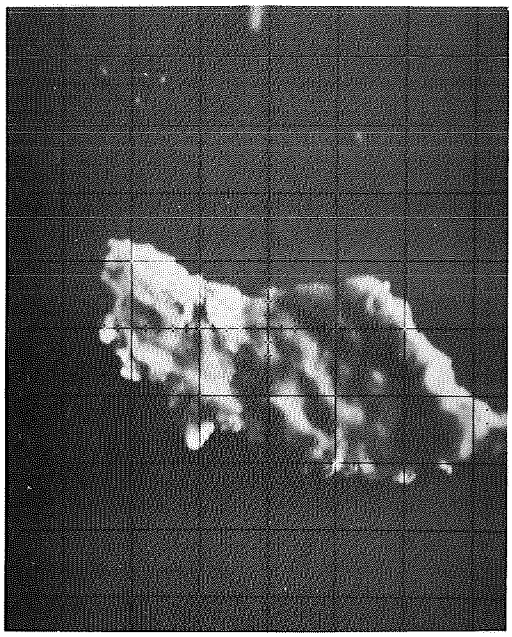
c. Image Produced by X-Rays From Nickel



200X

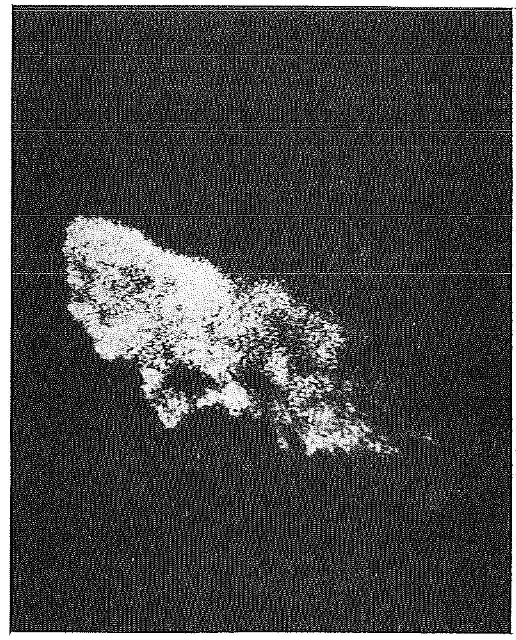
d. Image Produced by X-Rays From Silver

FIGURE 6. ELECTRON-MICROPROBE IMAGES OBTAINED FROM A BRUSH WIRE FROM CIRCUIT 62 OF SLIP RING DP 1506 SN 201



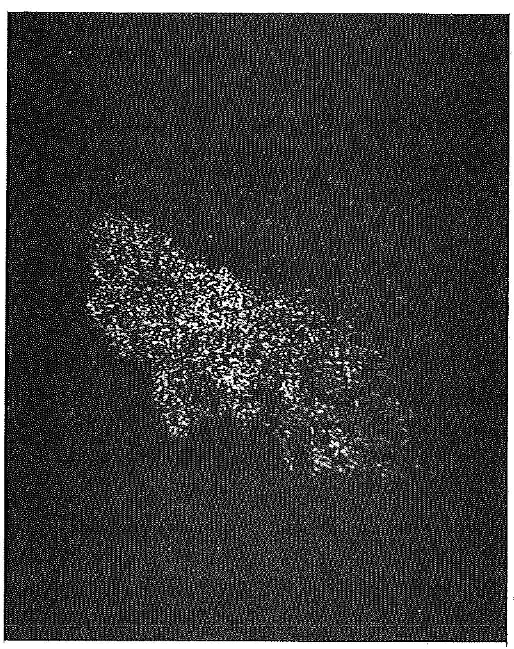
300X

a. Topography as Shown by Back-Scattered Electrons



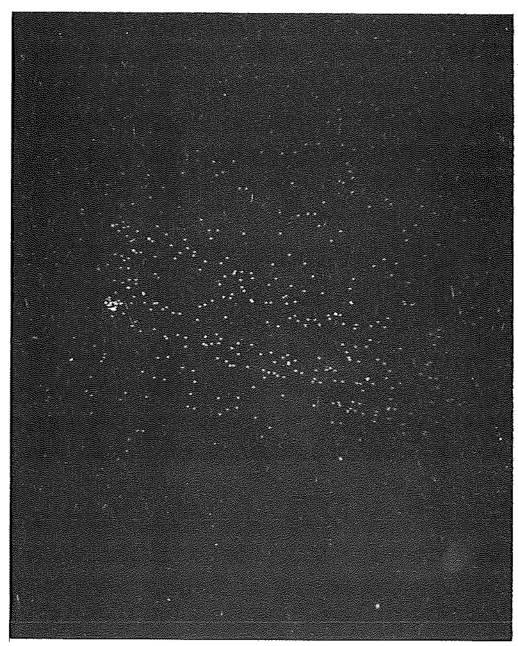
300X

b. Image Produced by X-Rays From Gold



300X

c. Image Produced by X-Rays From Nickel

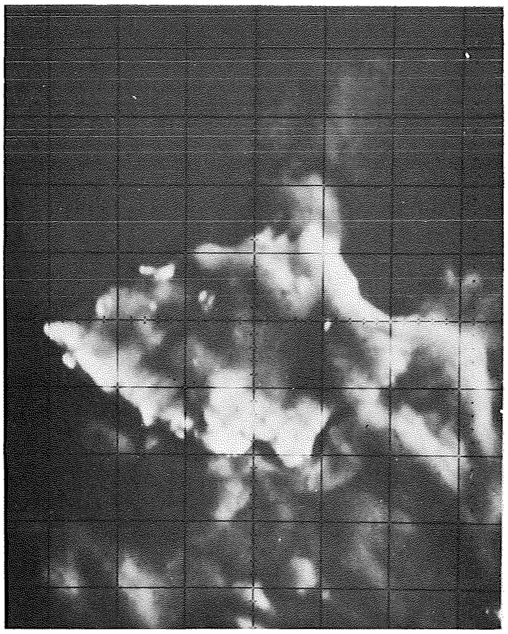


300X

d. Image Obtained With Detector Adjusted for X-Rays From Silver

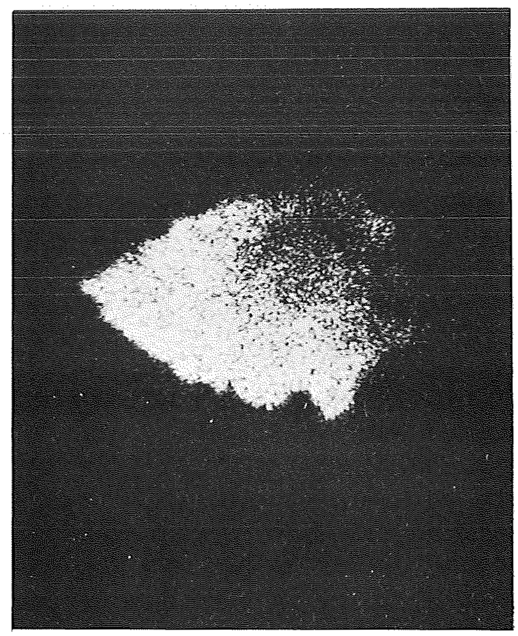
FIGURE 7. ELECTRON-MICROPROBE IMAGES OBTAINED FROM A PARTICLE REMOVED FROM SLIP RING DP 1506 SN 201 AT POINT 9 OF ITS LIFE

See Appendix A for history of unit.



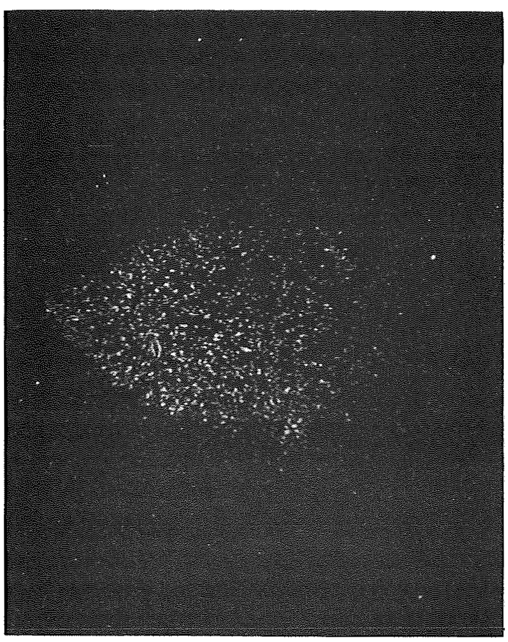
500X

a. Topography as Shown by Back-Scattered Electrons



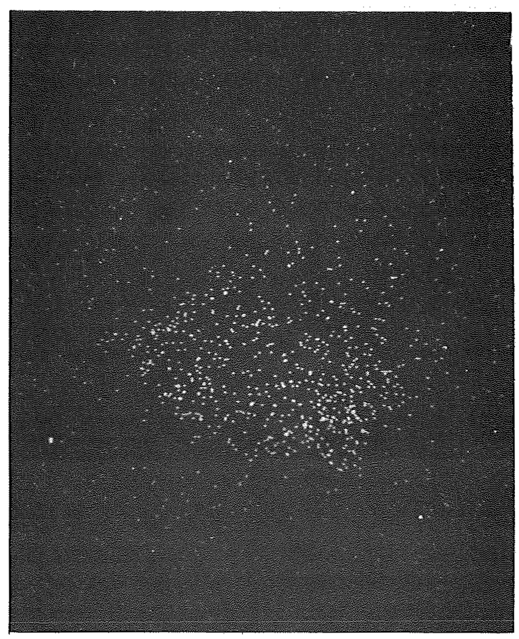
500X

b. Image Produced by X-Rays From Gold



500X

c. Image Produced by X-Rays From Nickel

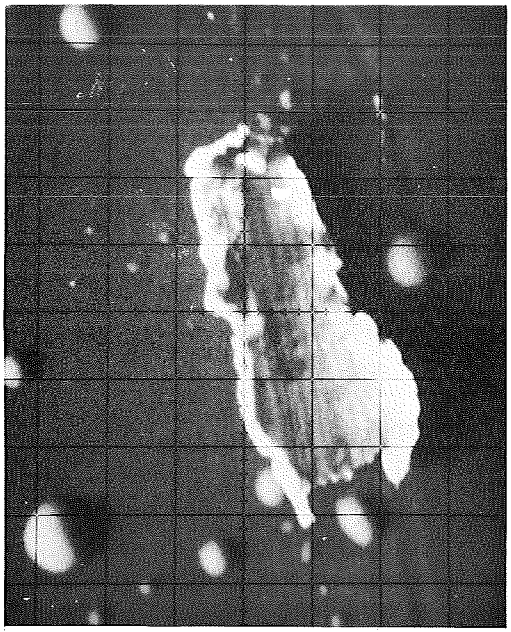


500X

d. Image Obtained With Detector Adjusted for X-Rays From Silver

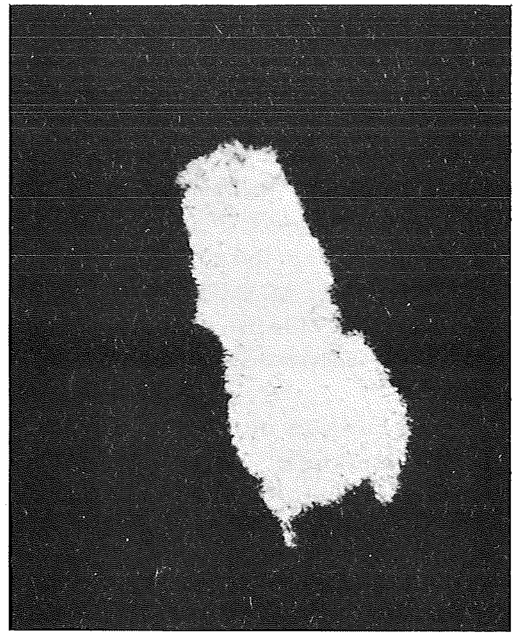
FIGURE 8. ELECTRON-MICROPROBE IMAGES OBTAINED FROM A PARTICLE REMOVED FROM SLIP RING DP 1506 SN 201 AT POINT 16 OF ITS LIFE

See Appendix A for history of unit.



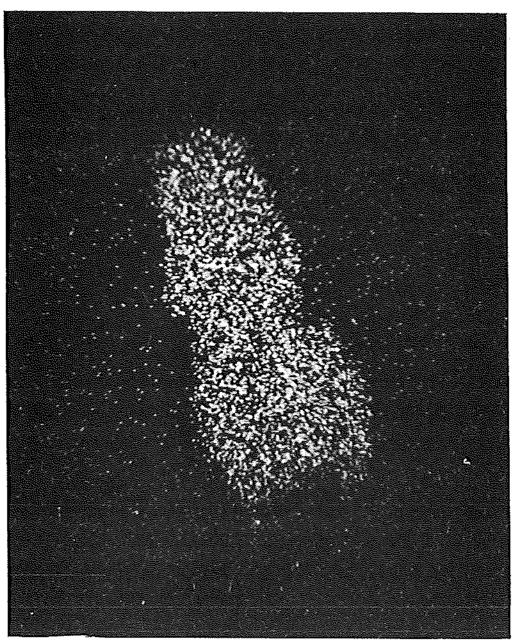
500X

a. Topography as Shown by Back-Scattered Electrons



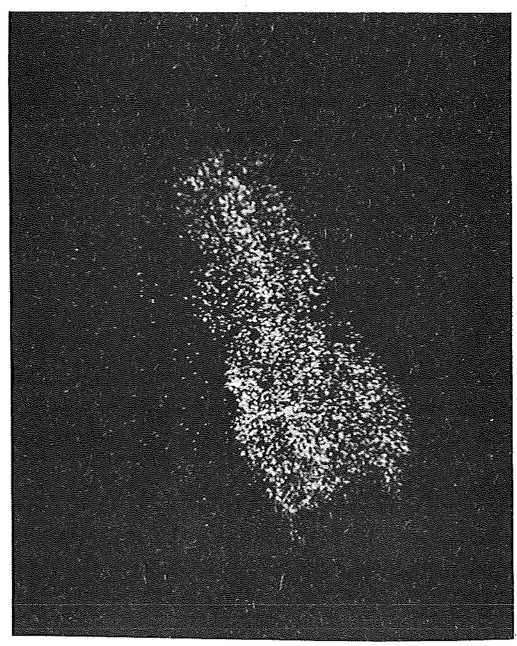
500X

b. Image Produced by X-Rays From Gold



500X

c. Image Produced by X-Rays From Nickel



500X

d. Image Produced by X-Rays From Silver

FIGURE 9. ELECTRON-MICROPROBE IMAGES OBTAINED FROM A PARTICLE REMOVED FROM SLIP RING DP 1506 SN 181

Figure 9 shows EMP images for a particle removed from Capsule DP 1506 SN 181 by washing the rotor in trichlorethane and then recovering the particle from the solvent. The analysis for a second particle recovered from the solvent was identical to that shown in Figure 9. Thus, at least a significant number of the debris particles on Capsule DP 1506 SN 181 obviously originated from the brush wires.

In contrast to the analysis of particles resting on tungsten wires, the second group of particles analyzed all clearly originated from the surfaces of the contact members. Thus, it is believed that the presence of tungsten resulted in the failure to recognize the presence of nickel in the first specimens. It is clear that silver was not present in the first specimens. On this basis, it is probable that the first particles also originated from the hard-alloy outer layer of the rotor rings.

These results establish that the majority of the debris particles originate from the contact surfaces. The evidence appears to be quite strong that the particles are generated as a result of wear processes, and are not due to inadequate cleaning or to poor plating quality. It is somewhat surprising that this problem exists because no indication of such behavior was recognized during the study with simulated contacts when some 30 to 40 10-million-wipe runs were carried out. The evidence seems to suggest that the metal comes off the contacts in extremely fine particles that subsequently are consolidated between the brush and the rotor. It may be that the geometry of the simulated contacts was such that the process of consolidation did not occur. Even so, very fine fretted-type particles were not detected in the simulated contact studies. Such fine particles were observed, however, for other, less promising lubricants. At the same time lubricant Univis P-38 was not included among the most promising candidates from the simulated contact study because the contacts immersed in it were littered with metallic particles after operating for some 10^7 wipes. In the few instances where direct comparisons under nearly the same conditions are possible, the wear of contacts lubricated by the blend was either less than or not greater than that of contacts lubricated with Univis P-38.

It may be that the density of the lubricant blend is so high that the debris is able to "float" in the lubricant and to move to positions where its presence causes intolerable consequences. In view of the demonstrated desirable electrical performance of the lubricant blend, it might be feasibile to use a much reduced amount of lubricant to eliminate "shorting" problems between circuits.

CONCLUSIONS FOR THE EVALUATIONS OF MINIATURE SLIP-RING CAPSULES WHICH HAVE CONTACTS LUBRICATED BY A BLEND OF OS 124 AND MCS 210 LUBRICANTS

In general, the slip-ring capsules that contained the OS-124, MCS-210 blend on the contacts performed quite well. There were instances where hydrodynamic-lift effects caused resistance variations of about 25 milliohms, but these cases occurred at wiping speeds greater than 0.5 cm/sec. The evidence suggests that the contact force may have been less than ideal for the circuits which experienced the larger hydrodynamic-lift effects. There was no indication of stick-slip problems, even at wiping speeds as low as 0.009 cm/sec. Even after the brushes have experienced about 10^8 individual wipes, the dynamic-resistance behavior did not exhibit any influence of wear. Thus, it would appear that the only reservation about the use of the OS 124, MCS 210 blend as a lubricant for slip-ring contacts would be that it might be necessary to limit the wiping speed when the operating temperature is 25 C or lower. This conclusion assumes, of course, that some means can be found for retaining satisfactory insulation levels between adjacent circuits.

There can be no doubt that the cause for the loss of insulation between circuits is the accumulation of metal particles, either in the form of an agglomeration of a large number of small particles or in the form of one "large" flake, on the epoxy barriers that separate the rings. At the present time the only suggestions for eliminating the effects of the offending metal particles are to reduce the amount of lubricant used or to provide raised barriers between the rings.

Finally, the results of this study permit considerable confidence in using the results of an earlier investigation, where the performance of a number of potential lubricants was evaluated on simulated contacts, to predict the performance of the same lubricants on actual miniature slip rings.

PART II

INVESTIGATIONS OF THE FEASIBILITY OF UTILIZING A SOLID-STATE LUBRICANT ON THE CONTACTS OF MINIATURE SLIP-RING CAPSULES

At the time this program was initiated very little effort had been directed toward the use of solid-state lubricants to improve performance of the contacts of miniature slip-ring capsules. On the basis of what information was available, and considering the special requirements imposed by the application to miniature slip rings, three possible systems were selected for a limited experimental evaluation program. The three systems were:

(1) Composites consisting of the dispersant MoS_2 in gold or gold-copper alloy matrices

(2) Composites consisting of the dispersant TaS_2 in gold or gold-copper alloy matrices

(3) Composites consisting of 50 weight percent gold and 50 percent of an amalgam of tungsten and gallium.

Gold was selected for the above systems because of its proven property of not forming tightly-bound surface films when exposed to normal atmospheric gases. MoS_2 was selected because it had been shown to offer promise in somewhat related applications. TaS_2 was chosen because the reported values of its friction coefficient and electrical conductivity were more favorable than those for MoS_2. Finally, the amalgam was selected because it was known to be a stable lubricant at relatively high temperatures.

The objectives of this part of the program were (1) to determine which, if any, of the above three systems offered the most potential as a contact member in miniature slip-ring capsules operating in nitrogen, (2) to determine the best configuration for utilizing such a material in an actual slip-ring capsule, and (3) designing and constructing sample slip-ring capsules which employ the most promising material as one of the contact members. At the outset of the program it was recognized that Poly-Scientific could more efficiently carry out the actual slip-ring fabrication, and arrangements to this effect were instituted early in the program.

EXPERIMENTAL EQUIPMENT AND TECHNIQUES

A number of factors – wear resistance, fabricability, weldability or solderability, and friction coefficient, for example – are important to the performance of a given contact pair. In the last analysis, however, the one property that is of dominant importance is the ability to transfer electrical energy from one contact member to the other without introducing intolerable resistance variations into the circuit when the contacts are sliding relative to each other. Consequently, major emphasis was placed upon dynamic-resistance behavior during this investigation.

The evaluation of the relative merits of the selected materials and subsequent optimization studies were carried out with rectangular, flat composite bodies formed of the materials to be evaluated. They were rubbed by a second contact member which was a U-shaped wire formed from 0.030-inch-diameter Neyoro 28A wire. Reciprocating, simple harmonic motion with a period of 0.2 second was imparted to one contact member relative to the other, while a deadweight load of 10-11 grams was applied to the brush. The stroke length was nominally 0.022 inch. All experiments utilizing flat contacts were carried out in prepurified nitrogen gas since in its ultimate use the capsule is operated in nitrogen gas. Before each experiment was initiated, the chamber was purged for several hours by flowing nitrogen gas. All of the flat-contact experiments were conducted after, the chambers were heated to 100 C with nitrogen flowing at which time the exhaust valve was closed while leaving open the line back to the nitrogen supply.

The dynamic-resistance behavior was observed by making an oscilloscopic display of the voltage across the contacts while they were conducting a constant current of 28.2 milliamperes. The equipment used to observe dynamic-resistance behavior was essentially the same as that used in the work described in Part I of this report on page 5.

SPECIMEN PREPARATION

The electrical conductivities of MoS_2 and TaS_2 are considerably less than those of normal metals. As a consequence of this, one could anticipate that serious resistance variations would occur if the dispersed lubricant particles were large enough to totally support the wiper wire at certain positions along the area of rubbing. With this possibility in mind, powder-metallurgy techniques aimed at providing good dispersion of the lubricant and at preventing agglomerated lubricant particles were employed to prepare sintered composite bodies. The goal was to determine the least complex procedure capable of providing satisfactory composite contact specimens.

The first composite specimens containing dispersed sulfide lubricants were prepared by vacuum drying the powders*, mixing them in a "V" blender in an argon atmosphere, cold (green) pressing the powders to 20,000 psi at room temperature, and finally vacuum hot pressing them at 538 C for 2 hours at 10,000 psi. The calculated densities of the specimens prepared in this way were about 96-97 percent of the theoretical densities. Samples blended by this method are identified in subsequent portions of this report by inclusion of an "A" in the specimen designation, and the specimens as a group are referred to as "Type A" specimens.

Metallographic examination of the Type A specimens revealed that continuous metallic conduction paths were achieved in specimens containing MoS_2 and in specimens containing TaS_2. Some sulfide particles were found that had dimensions large enough so that the wiper wire at some points on the surface could have been in contact with lubricant only. The largest particles were approximately 0.002 inch across for dispersed MoS_2, and up to about 0.006 inch across for dispersed TaS_2.

The specimen-preparation process described above was modified in order to provide better dispersion of the sulfide lubricants within the gold or gold/copper matrices.

*All powders used in this program were passed through a 325-mesh screen.

The additional steps taken were intended to further break down the agglomerates that existed in the as-received powders and to achieve a more intimate mixture between lubricant and metal matrix. The revised blending procedure, producing what is called in this report "Type B" specimens, consisted of:

(1) Tumble mix constituents for several minutes

(2) Screen mixture through 200-mesh (74-micron-effective-diameter) sieve using 1/2-inch porcelain balls as a sieving aid

(3) Mix in "V" blender for 4 hours (normal air atmosphere)

(4) Dry in vacuum at 150 C for 2 hours; cool overnight in vacuum

(5) Mix in "V" blender for 4 hours (argon atmosphere)

(6) Ball mill using a 3:1-by weight (equal volume ratio) charge of 0.017-inch-diameter tungsten spheres as the milling medium (argon atmosphere).

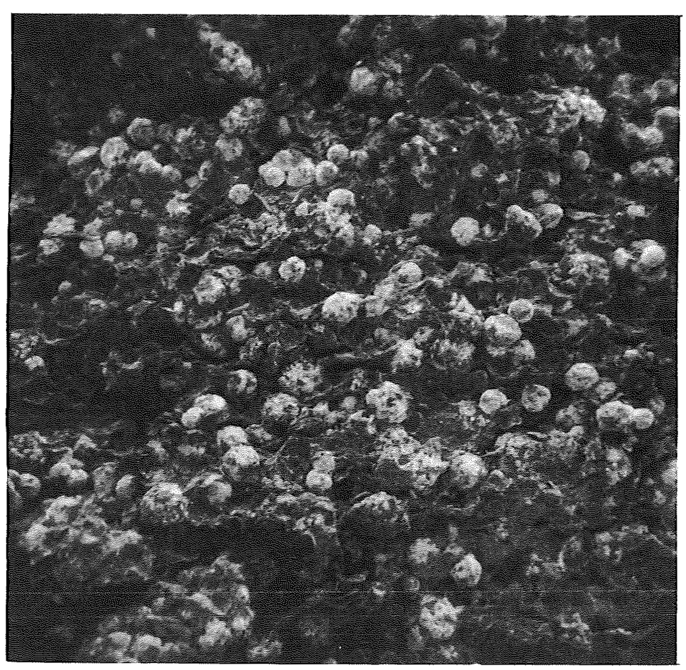
At the conclusion of Steps (3), (5), and (6) of the modified procedure, 0.95-g samples were withdrawn from the Au-2.5Cu-15MoS_2 blend, and die pressed at 40,000 psi to yield "green", square platelets 0.25 inch on a side and 0.080 inch thick. The calculated density of the platelet or green compact was 86 percent of theoretical, the same value obtained for specimens prepared by the original, simpler process. The "green" compacts were fractured and the fractured surfaces were examined in a scanning electron microscope at magnifications of 100, 500, 1000, and 2000 diameters. Samples of each of the constituent powders, unconsolidated and also compacted, at 40,000 psi were similarly examined to serve as standards for phase identification.

Figure 10 illustrates the microstructure of the Au-2.5Cu-15MoS_2 blend for three succeeding stages of processing: normal blending, blending after vacuum drying, and ball milling. Homogeneity of the microstructure is seen to steadily improve throughout the processing schedule. It can also be noted that the dispersion achieved after simple blending, as in Step (3), was already relatively good. In this case, Step (3), the light-colored spherical particles of the gold-copper matrix material and the dark-gray layered particles of the lubricant approximate the dimensions of an opening in a 325-mesh sieve (44 microns).

Examination of the uncompacted gold and lubricant powders, as shown in Figure 11, revealed that the condition that contributes most toward barring further improvement over the microstructure shown in Figure 10c is the difficulty in breaking up the gold agglomerates, rather than any problem with breaking up the MoS_2. The MoS_2 particles appear to be very loosely bound, and possess a particle-size range of 1 to 10 microns. The gold powder contains two types of structure: solid-appearing spheres ranging from 5 to 10 microns in diameter and "fluffy" spheres ranging from 10 to 20 microns in diameter. A number of spheres are tightly bonded together to form agglomerates that approach 50 microns in length. The beneficial effect of the blending schedule is believed to be both a breaking up of the gold clusters and the provision of an opportunity for the lubricant particles to seek out the holes that remain in the gold

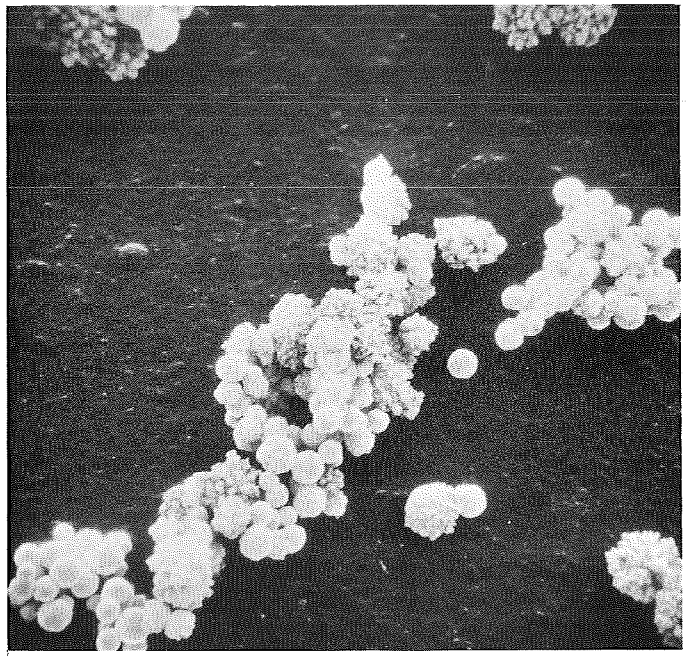
500X a. Normal Blending

500X b. Blending After Vacuum Drying



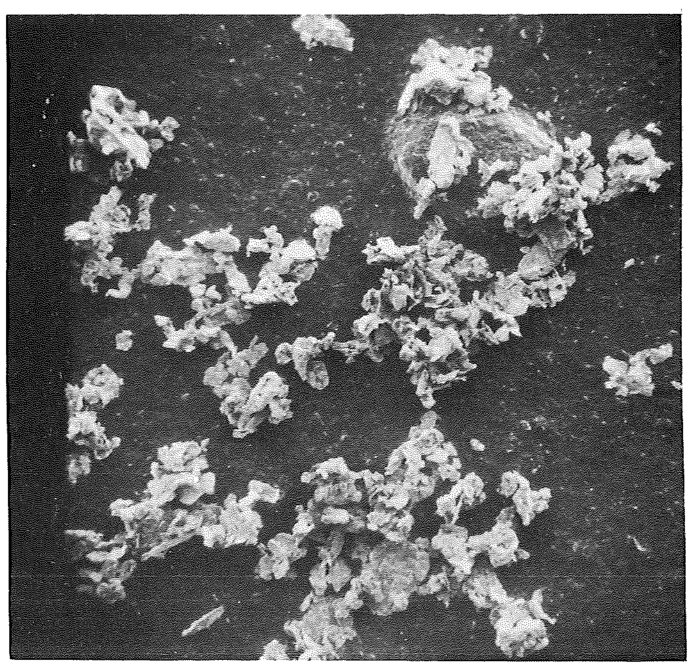
500X c. Ball Milled

FIGURE 10. GOLD-2.5Cu-15MoS_2 GREEN-PRESSED COMPACTS AFTER VARYING DEGREES OF BLENDING



500X

a. -325-Mesh Gold Powder



500X

b. -325-Mesh MoS_2 Powder

FIGURE 11. ELECTRON MICROGRAPHS OF UNCONSOLIDATED MATRIX AND LUBRICANT CONSTITUENT POWDERS

clusters. More complete breakdown of the gold constituent than that shown in Figure 10c may be difficult to obtain due to the high ductibility of the material; the clusters may deform rather than fracture.

Figure 12 illustrates the appearance of each of the three constituent powders in the green-pressed condition.

The revised processing procedure was used to prepare flat composite contact specimens with compositions as follows:

(1) Au-2.5Cu-15MoS_2

(2) Au-2.5Cu-10MoS_2

(3) Au-2.5Cu-6MoS_2

(4) Au-5.0Cu-15MoS_2

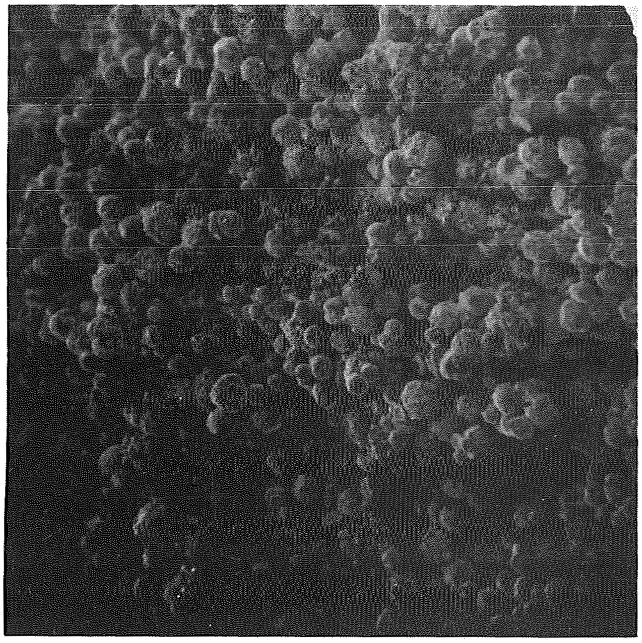
(5) Au-5.0Cu-10MoS_2

(6) Au-5.0Cu-6MoS_2 .

Following blending, the specimens were die pressed at 40,000 psi followed by a vacuum hot-pressing cycle of 538 C at 10,000 psi, held for 2 hours. Examples of the microstructure of a typical metallurgically polished surface and of the interior near the surface are shown, respectively, by the optical and SEM photomicrographs of Figure 13. By comparing Figure 10c with Figure 13a, it can be seen that the lubricant dispersion was not altered by the hot-pressing operation. The specimens produced utilizing the modified blending procedure were only 94 percent of theoretical density. Metallographic examination, as shown by Figure 13, revealed a structure apparently more open than had been obtained with the earlier, simpler blending process. The difference in hot-pressed densities at least partially explains the "open" areas, but the explanation for the difference in densities has not been determined. The density after die (cold) pressing was identical for the two types of specimens. Increasing the hot-pressing pressure to 30,000 psi did not increase the density of the second type of specimens.

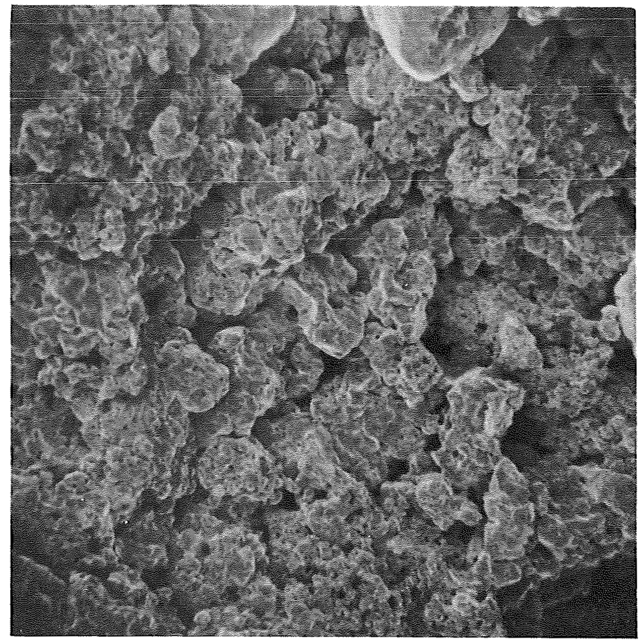
One side of each of the composite contact specimens was metallographically polished to provide controlled, reproducible surfaces for the electrical evaluation studies. Standard polishing techniques were employed.

Composite specimens consisting of a gold matrix and WSe_2-Ga as the dispersed lubricant were prepared by cold pressing at 10,000 psi, heating in air for 15 hours at 400 F, for 8 hours at 660 F, and finally for 8 hours at 900 F. The resulting specimens were extremely inhomogeneous in composition. Furthermore, they were highly insulating. Only a few areas within a specimen were found where more or less dense gold islands had formed. Resistances between points on these islands were relatively low. Because of the obvious inhomogeneity of the samples and their extremely high bulk resistance, no further evaluation studies were conducted on the amalgam-containing systems.



500X

a. Gold Powder



500X

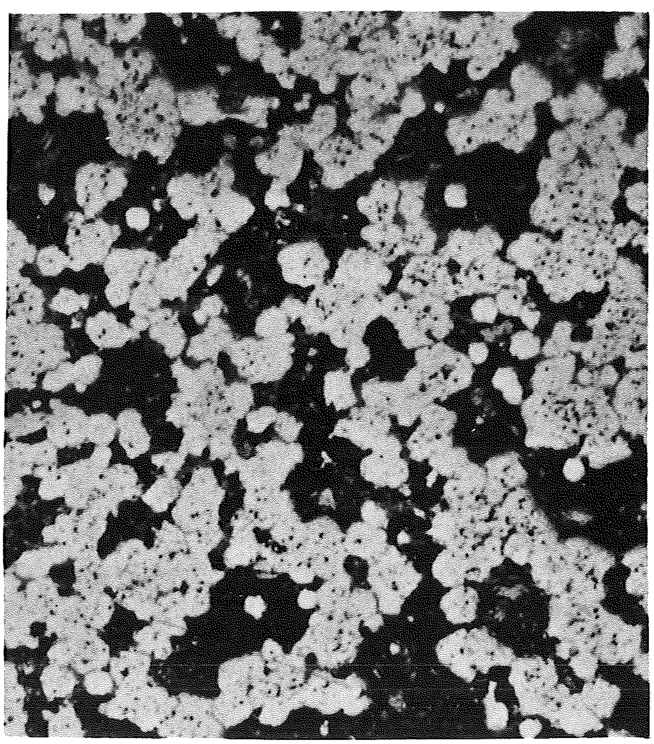
b. Copper Powder

500X

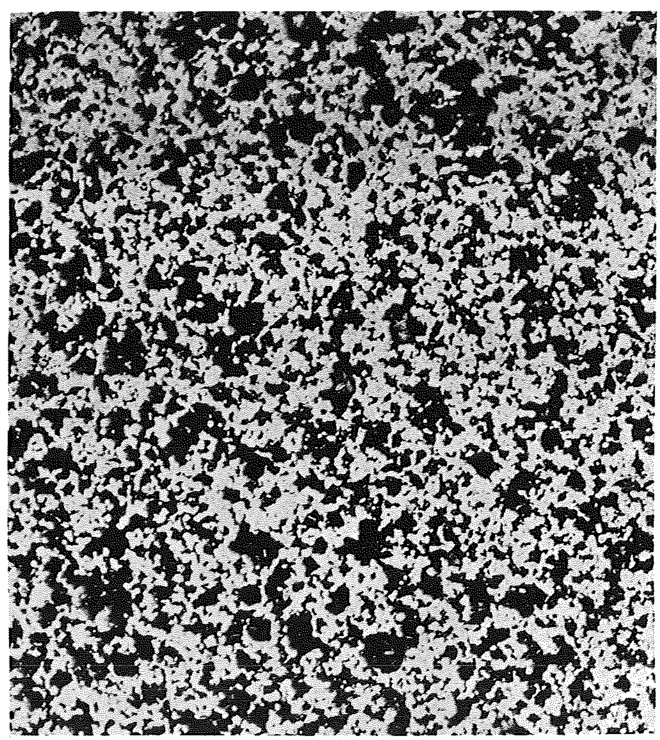
c. MoS_2 Powder

FIGURE 12. APPEARANCE OF MATRIX AND LUBRICANT CONSTITUENTS AFTER DIE PRESSING AT 40, 000 PSI

500X a. Electron Micrograph of a Fracture Surface Adjacent to the Polished Surface



500X b. Metallographically Polished Surface



100X c. Metallographically Polished Surface

FIGURE 13. GOLD-2.5Cu-15MoS_2 COMPACTS AFTER HOT PRESSING AT 1000 F AND 10, 000 PSI FOR 2 HOURS IN VACUUM

WEAR AND MECHANICAL PROPERTIES OF COMPOSITE CONTACT SPECIMENS

Two properties of considerable interest in selecting the most satisfactory material for contact application are the wear rate and the mechanical strength of the materials. An indication of the wear rates of the various specimens was obtained by taking profiles of the wear scars through the use of a Taylor-Hobson Talysurf instrument. Traverses through the scar were made in both the transverse and the longitudinal directions. Table 4 presents the maximum depth of the wear scar for each specimen for which Talysurf measurements were made, along with pertinent experimental details.

At the outset of this program the most desirable surface finish for the composite flat-contact members was not known. A comparatively simple metallographic polishing procedure was employed to prepare the initial specimens. Later some specimens were operated with the wiper rubbing the "as-pressed" surface. As can be seen from Table 4, there was no significant difference in wear for these "as-pressed" specimens. On the other hand, their electrical performance was inferior to that of similar polished specimens, as will be shown in later paragraphs of this report.

Wear Properties

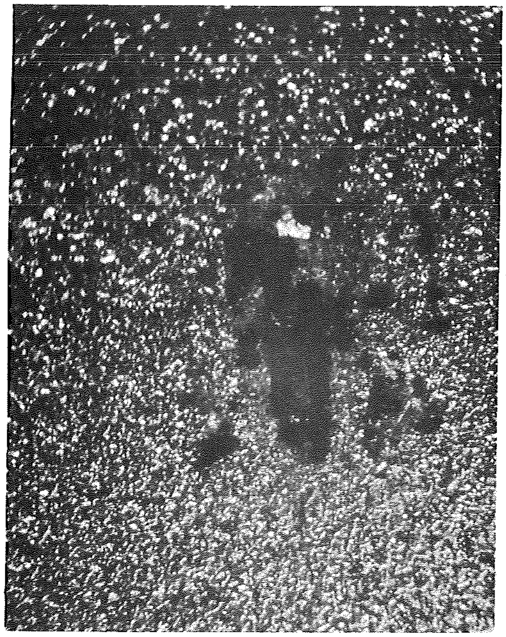
Sometimes it is possible to "wear in" a solid-lubricated bearing surface in such a way that subsequent wear is extremely small. The possibility of an "automatic" wear in for the composite flats containing MoS_2 or TaS_2 was investigated. Those specimens listed in Table 4 and identified as having undergone brief air exposure at 310 hours were used in the wear-in or "self-burnishing" experiments. At the 310-hour point, contact operation was interrupted and the chambers were opened. The contact members were separated, a camel-hair brush was used to remove as much loose debris as possible, the wiper was returned to its original wear track, the load was reapplied, the chamber was resealed and purged with nitrogen, and wiping was resumed without rebaking the chamber. The contacts then were operated for an additional 168 hours.

The wear data of Table 4 indicate that wear continued for both specimens which contained TaS_2 as the solid lubricant and also for the specimen with MoS_2 lubricant but with no copper in the matrix. The specimen which contained MoS_2 and copper exhibited a low amount of wear. The nature of the Talysurf profile for this contact member suggests that wear material may have rebonded to the matrix metal providing an apparent low amount of wear. At any rate, what was really sought in this particular experiment was an indication of whether or not, at some point of operation, the contact surface became sufficiently burnished and coated with lubricant so that subsequent wear was reduced. This information is more easily obtained by determining the amount of debris generated on the contacts subsequent to their "cleaning". Figures 14c and 14d show the debris on the two MoS_2 lubricated specimens. For purposes of comparison, Figures 14a and 14b show corresponding composite, flat contacts that were operated for 336 hours without cleaning. "Specimen 1" and "Specimen 2" are so worded in Figure 14 only to indicate that the photographs are of different specimens; they do not have any relation to other "Specimen 1's" or "Specimen 2's" in this report.

TABLE 4. RELATIVE WEAR OF GOLD OR GOLD ALLOY SPECIMENS CONTAINING LAMELLAR LUBRICANTS

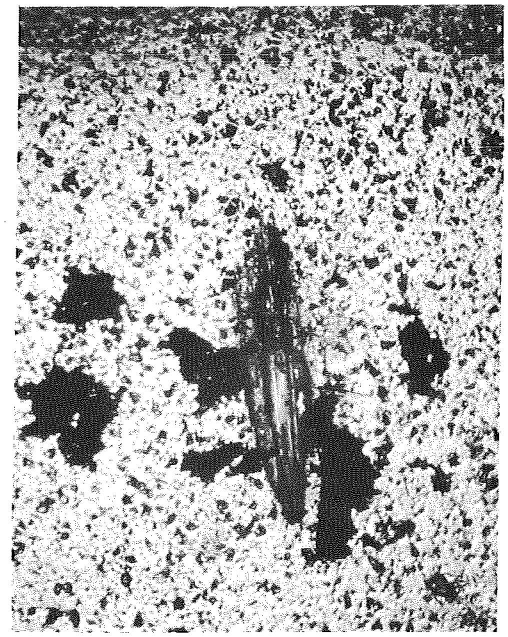
Specimen	Hours of Wiping	Greatest Depth of Wear Scar, μinch
Au-15MoS_2-A-3[(a)]	478	2,500
Au-15MoS_2-A-4	336	725
Au-2.5Cu-15MoS_2-A-1[(a)]	478	80
Au-2.5Cu-15MoS_2-A-3	336	700
Au-2.5Cu-15MoS_2-A-3[(b)]	333	550
Au-2.5Cu-15MoS_2-B-2	550	2,000
Au-2.5Cu-10MoS_2-B-2	550	3,150
Au-2.5Cu-6MoS_2-B-2	550	2,300
Au-5Cu-15MoS_2-B-1	550	2,050
Au-5Cu-10MoS_2-B-1	550	1,800
Au-5Cu-6MoS_2-B-1	576	2,000
Au-15TaS_2-A-2	336	1,500
Au-15TaS_2-A-3[(a)]	478	2,400
Au-2.5Cu-15TaS_2-A-1	336	1,400
Au-2.5Cu-15TaS_2-A-1[(c)]	333	1,300
Au-2.5Cu-15TaS_2-A-3[(a)]	478	2,400
Au-2.5Cu-15TaS_2-A-4[(b)]	333	1,100

(a) Brief air exposure after 310 hours of wiping.
(b) Wiped on unpolished side.
(c) Wiped by palladium wire.



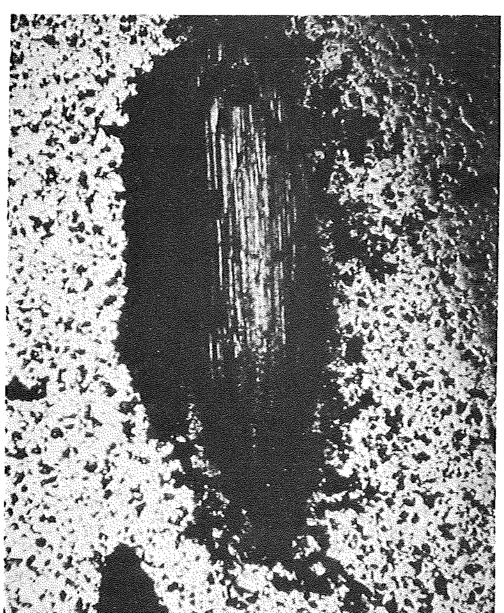
35X

a. Au:MoS_2 (Specimen 1)



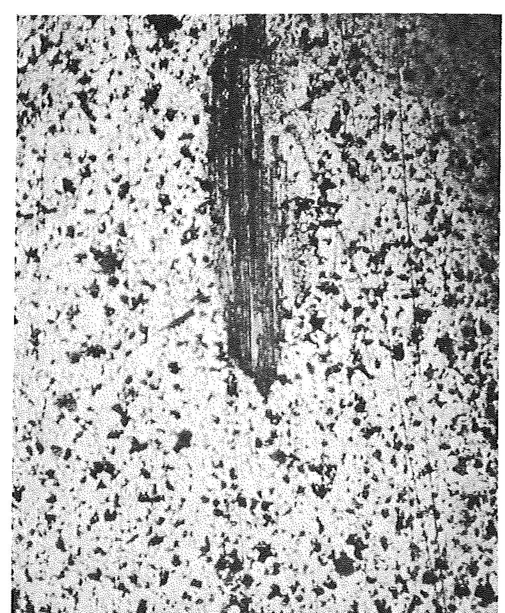
35X

b. Au-Cu:MoS_2 (Specimen 1)



35X

c. Au:MoS_2 (Specimen 2)



35X

d. Au-Cu:MoS_2 (Specimen 2)

FIGURE 14. INDICATION OF EFFECT OF MATRIX COMPOSITION ON WEAR OF METAL/LUBRICANT COUPONS CONTAINING MoS_2

See text for details.

Little, if any, debris was generated on the Au-2.5Cu-15MoS_2 specimen after it was cleaned, whereas a large amount of debris is seen on the specimen with no copper in the matrix. Both tantalum specimens (not shown) had large amounts of debris on their surfaces.

There was no knowledge at the time the self-burnishing experiments were performed that the particular dispersant/matrix composition ratio was near optimum. The Au-Cu-MoS_2 system was optimized only after making subsequent studies. Other specimens in which self-burnishing is sufficient to reduce the wear rate might have been produced by a detailed study of the effect of compositional variations. The point of the present discussion is that it was possible to achieve a reduced wear rate for the Au-Cu-MoS_2 system. This is the system that was ultimately selected for application in experimental miniature slip-ring capsules.

Mechanical Properties

The mechanical strengths of the various samples were evaluated by subjecting them to the ASTM test* for strength of compacted metal-powder specimens and by taking Vickers hardness readings. Specimens for the transverse rupture test were prepared by cutting regular specimens along their longitudinal centers to provide two specimens about 1/8 inch wide and 0.04 to 0.06 inch thick. Results of the transverse rupture tests are shown in Table 5. Also shown are average Vickers hardness numbers obtained on the undamaged portions of polished surfaces of the same specimens.

As might be expected, strength decreases as the MoS_2 content increases. The specimens with the higher copper content appear to be slightly stronger for the 10 and 6 weight percent MoS_2 specimens, but the difference is not great. For those specimens which contain 15 percent MoS_2, the Type A specimens appear to be significantly stronger than the Type B specimens. On the other hand, the hardness numbers for the two types do not differ greatly. Since the materials with the greatest strengths should be less susceptible to damage during fabrication of the slip-ring capsule, the composition with lower concentrations of MoS_2 would be preferred from the structural standpoint.

DYNAMIC-RESISTANCE PERFORMANCE

The method of recording the dynamic-resistance behavior of the various composite specimens was described in an earlier section of this report. To facilitate evaluation, the resistance data have been condensed into Table 6. In this table the highest value of dynamic resistance and also the lowest value during a given time increment are recorded. The listed maximum and minimum values of the resistance did not always occur during the same measurement, so the difference between the two values may be slightly larger than the corresponding actual "noise" level. Examples of typical dynamic-resistance traces are shown in Figure 15. The upper trace shows the resistance as a function of wiper position for a composite Specimen Au-2.5Cu-15TaS_2-A-1, which exhibited very high noise levels. The center trace shows one of the least noisy

*ASTM designation: B 312-58T.

TABLE 5. TRANSVERSE RUPTURE STRENGTHS[a] AND VICKERS HARDNESS NUMBERS FOR COMPOSITE SPECIMENS

Specimen	Rupture Strength, psi x 10^{-4}	Vickers Hardness[b]
Au-2.5Cu-15MoS_2-A-2	1.0 0.96	45.6
Au-2.5Cu-15MoS_2-B-3	0.69 0.70	42.6
Au-2.5Cu-10MoS_2-B-3	1.1 1.3	50.8
Au-2.5Cu-6MoS_2-B-3	1.6 1.8	65.9
Au-5Cu-15MoS_2-B-3	0.67 0.60	(c)
Au-5Cu-10MoS_2-B-2	1.5	66.2
Au-5Cu-6MoS_2-B-3	2.0 1.9	82.5

(a) Determined according to ASTM test, designation B 312-58T, using an 0.188-inch span between supports.
(b) Average of six determinations at 5-kg load.
(c) Surface too porous to permit determinations.

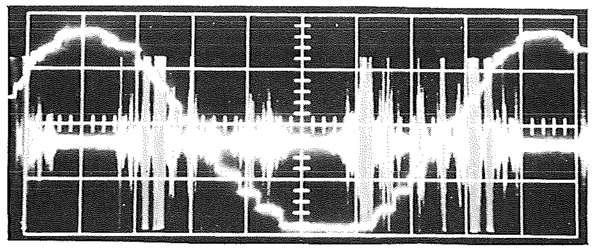
TABLE 6. MAXIMUM AND MINIMUM VALUES OF DYNAMIC RESISTANCE, IN MILLIOHMS, OBSERVED DURING SPECIFIED TIME INCREMENTS FOR COMPOSITE SOLID-LUBRICATED CONTACTS

	Time Increment of Total Test, hours										
Specimen	0-50	50-100	100-150	150-200	200-250	250-300	300-350	350-400	400-450	450-500	500-550
Au15MoS$_2$-A-3[a]	42-9	29-11	42-7	26-8	230-20	110-26	--	53-15	--	50-18	--
Au15MoS$_2$-A-4	120-28	190-32	--	29-22	350-28	28-22	38-23	--	--	--	--
Au2.5Cu15MoS$_2$-A-1[a]	22-8	15-8	19-10	66-11	--	--	63-11	12-9	--	40-18	--
Au2.5Cu15MoS$_2$-A-3	260-20	120-44	75-12	47-17	12-6	9-5	9-5	--	--	--	--
Au2.5Cu15MoS$_2$-A-3[b]	1100-13	70-17	--	750-25	880-42	--	400-39	--	--	--	--
Au2.5Cu15MoS$_2$-B-1	37-13	--	77-35	46-23	140-26	88-37	110-49	77-37	--	46-19	--
Au2.5Cu15MoS$_2$-B-2	22-12	25-14	29-14	25-13	28-15	20-13	29-12	46-17	40-14	40-14	67-21
Au2.5Cu10MoS$_2$-B-2	31-11	32-16	31-11	39-10	34-16	43-14	30-12	28-8	35-9	18-7	38-7
Au2.5Cu6MoS$_2$-B-1	370-14	--	47-12	35-12	49-12	35-9	230-10	72-17	--	27-10	--
Au2.5Cu6MoS$_2$-B-2	63-16	30-18	53-16	70-17	25-15	22-14	20-12	25-13	22-12	--	17-10
Au5Cu15MoS$_2$-B-1	100-25	110-39	91-56	89-47	--	130-53	320-70	240-98	--	1100-280	320-58
Au5Cu10MoS$_2$-B-1	98-12	44-13	48-14	30-12	--	84-12	32-14	70-13	--	27-11	43-12
Au5Cu6MoS$_2$-B-1	62-13	38-14	21-11	--	20-8	--	22-7	23-13	32-13	22-10	22-11
Au5Cu6MoS$_2$-B-2	45-7	--	20-7	33-10	32-8	20-7	58-10	20-10	15-8	--	--
Au15TaS$_2$-A-2	1300-8	120-14	35-10	300-10	18-9	700-9	15-9	--	--	--	--
Au15TaS$_2$-A-3[a]	27-4	1100-7	840-3	1160-6	1300-7	1400-6	1500-8	1600	--	1500-25	--
Au2.5Cu15TaS$_2$-A-1	110-7	390-8	210-14	170-12	1300-17	720-15	1400-9	--	--	--	--
Au2.5Cu15TaS$_2$-A-1[c]	1100-7	--	1100-14	--	1100-30	1100-32	1100-20	--	--	--	--
Au2.5Cu15TaS$_2$-A-3[a]	60-4	21-8	47-7	600-7	74-9	--	740-11	770-16	--	250-24	--
Au2.5Cu15TaS$_2$-A-4[b]	59-8	1000-8	--	860-16	890-25	--	980-18	--	--	--	--

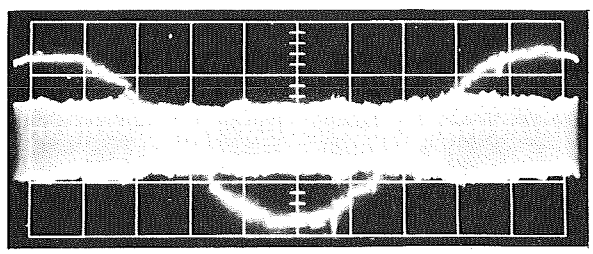
(a) Brief air exposure at 310 hours.

(b) Wiped on unpolished side.

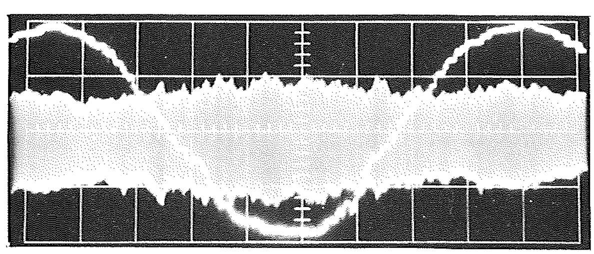
(c) Wiped by palladium wire.



(a) Resistance Scale: 1 Major Div. = 350 mΩ



(b) Resistance Scale: 1 Major Div. = 7 mΩ



(c) Resistance Scale: 1 Major Div. = 7 mΩ

FIGURE 15. EXAMPLES OF DYNAMIC-RESISTANCE TRACES ILLUSTRATING (a) THE NOISIEST CONTACTS, (b) THE QUIETEST CONTACTS, AND (c) TYPICAL "GOOD" CONTACTS

traces, obtained with Specimen Au-2.5Cu-15MoS_2-A-1, and the lowest trace shows a typical trace which was obtained with Specimen Au-2.5Cu-6MoS_2-B-2.

Although many of the features revealed in Table 6 are not understood, one trend may be noted which is understood to some degree. Those specimens for which the minimum dynamic-resistance values continually increase with added hours of operation appear to show the effects of accumulation of lubricant in the wear scar. There is fairly good correlation between consistently low minimum dynamic resistance values in Table 6 and high wear as shown in Table 4. The highest minimum dynamic resistance values found in Table 6 all occur for specimens which contain 15 wt percent lubricant.

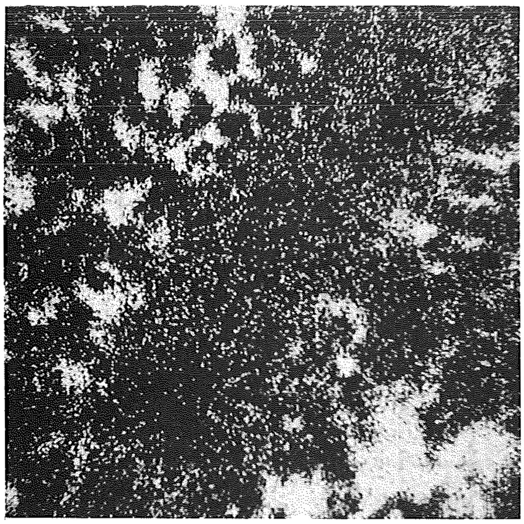
The electrical performance of those specimens containing MoS_2 is clearly superior to that of the specimens containing TaS_2. On the basis of the results for the Type A specimens, the presence of copper in the matrix is beneficial in producing lower resistance variations. Finally, the best electrical performance was obtained with specimens prepared by the modified blending process (Type B specimens), but there was considerable difference in the performance of supposedly identical contact specimens.

STUDIES OF THE COMPOSITION OF WEAR DEBRIS

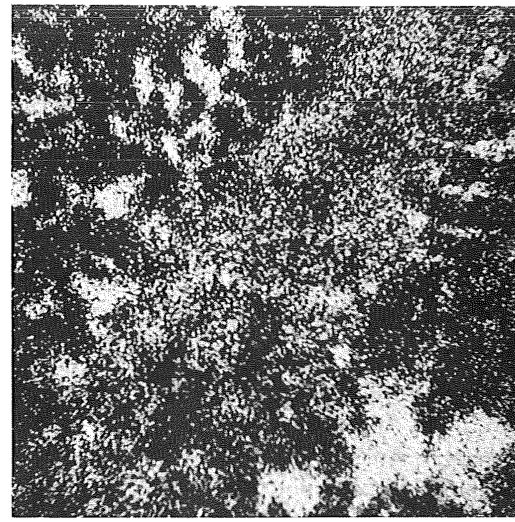
Wear debris on the Type A specimens containing MoS_2 bore strong resemblance to carbon-containing debris seen in former contact studies carried out under Contract NAS8-11403. By contrast, the debris on the coupons containing TaS_2 appeared to be purely metallic in nature. Specimen Au-15MoS_2-A-4 and Specimen Au-2.5Cu-15TaS_2-A-1 were installed in an electron-microprobe analyzer and examined for C, Au, Si, Ca, P, K, Cl, Zn, and S. In addition, the coupon containing MoS_2 was scanned for Mo and the specimen containing TaS_2 was scanned for Ta. A portion of the wear scar and at least one large debris particle were examined.

Carbon was found to be a constituent of some of the rather sizable, agglomerated pieces of wear debris on the Au-15MoS_2 coupon. The source of the carbon was not determined, but among the potential sources are contamination during cleaning, failure of cleaning procedures to completely remove previous organic contaminants, carbon diffusion into the specimen during hot pressing in graphite dies, or contamination present in the starting MoS_2 material. Contamination due to inadequate cleaning is considered most probable since the carbon was found only in the debris generated by the rubbing, and was not found on undisturbed surfaces. The only other elements detected in the microprobe examination were those known to be the major constituents of the specimens.

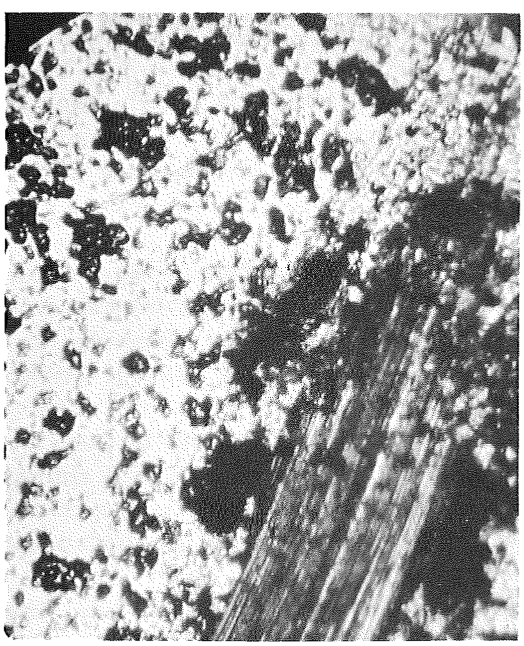
Photographs of the results of the microprobe scans for S, Mo, and C are shown in Figure 16 for a specimen containing dispersed MoS_2. Figure 17 shows scans for S, Ta, and Au taken from a specimen containing TaS_2. Areas which are whiter than the background indicate the presence of the "scanned for" element. Light micrographs, with a magnification of about 1/4 of the magnification for the microprobe scans in Figure 16 and about the same magnification in Figure 17, are included to indicate the general area scanned.



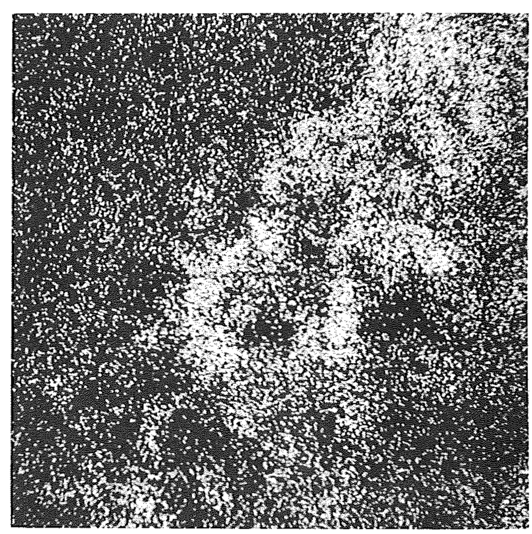
a. Sulfur



b. Molybdenum



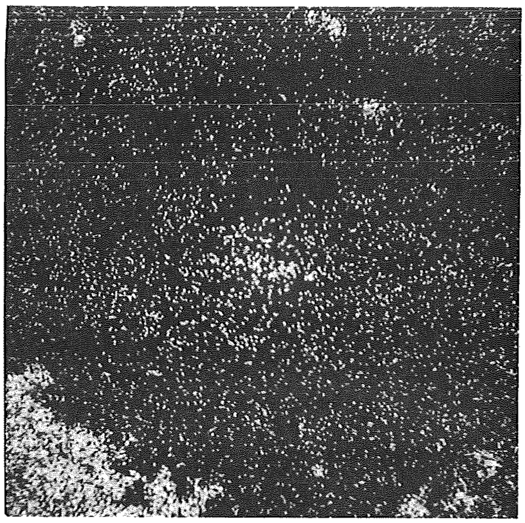
c. Light Micrograph



d. Carbon

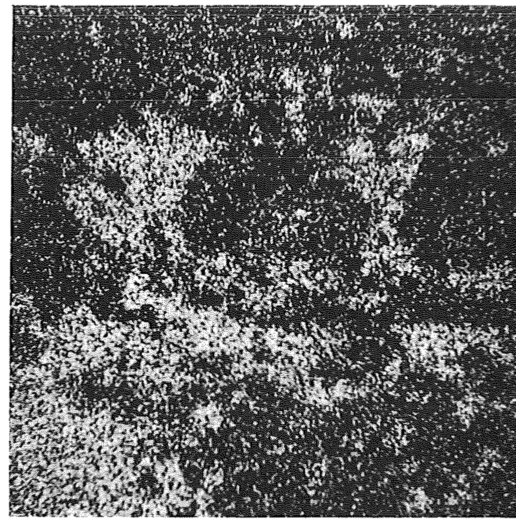
FIGURE 16. ELECTRON-MICROPROBE SCANS AND LIGHT MICROGRAPH OF A WEAR PARTICLE ON Au:15MoS_2 COUPON

Magnification of d is ~1/4 of microprobe scans.



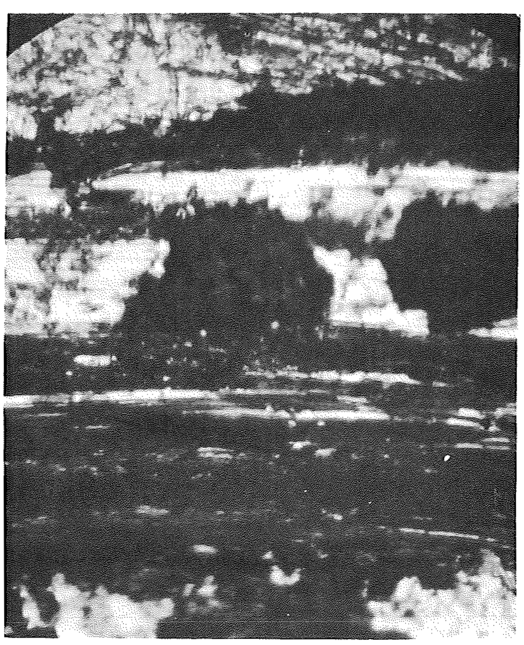
200X

a. Sulfur



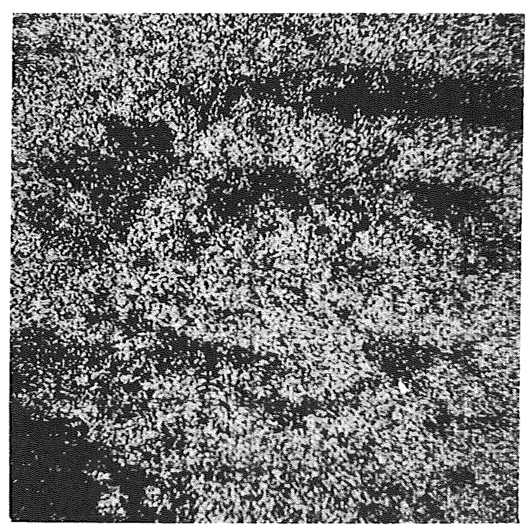
200X

b. Tantalum



180X

c. Light Micrograph



200X

d. Gold

FIGURE 17. ELECTRON-MICROPROBE SCANS AND LIGHT MICROGRAPH OF WEAR PARTICLES AND PART OF THE WEAR SCAN ON Au-2.5Cu:15TaS_2 COUPON

The area scanned by the microprobe on the specimen containing MoS_2 was centered on the elongated black particle (to the left of the wear track) running along a diagonal from the lower left to upper right corners of the light micrograph (Figure 16c). The particle takes up much of the diagonal in the microprobe scans. Other scans, not shown in Figure 16, were made of the wear-scar area (lower right quadrant of the light micrograph).

One might expect the results to show that the wear debris is made up of gold and MoS_2. It is not. Note in Figure 16 that the particle contains essentially no sulfur, considerable Mo (Figure 16b), and much carbon (Figure 16d). A scan for gold, not shown, indicates some gold but not a large amount. Clearly, sulfur exists separate from the molybdenum in the wear debris. Observations of Figures 16a and 16b reveal that MoS_2 particles do exist on the surface layer of the unrubbed portion of the specimen surface. Thus, the separation is a consequence of the rubbing action. Significantly though, the scans in the wear track, not shown, indicate that a rather uniform film of MoS_2 is distributed in the track.

Turning to the electron-microprobe results from scanning the specimen containing TaS_2 (Figure 17), the first result of importance to be noted is the presence of large metallic particles in the wear track. (Note that in Figure 17, the magnification of the light micrograph, Figure 17c, is about the same as that of the electron scan photographs.) The two particles seen prominently in Figure 17c are principally gold. A disturbing result is that the wear track contains Ta (Figure 17b), but little sulfur (Figure 17a). That is, the lubricant was not smeared over the surface of the wear track as happened with the specimen (or coupon) containing MoS_2. The fact that no carbon (not demonstrated in Figure 17) was formed in the wear debris is also in contrast to the results with the specimens containing MoS_2. With both types of specimens, however, sulfur was separated from its companion metallic element.

The remainder of the Type A specimens were examined in the electron microprobe analyzer to determine the extent to which the wear scar area was coated with lubricant. The X-ray images produced by the microprobe equipment revealed that there were fairly uniform coatings of lubricant over the wear scars for all of the composite specimens that employed MoS_2 as the lubricant. In the case of two specimens containing 2.5 percent copper and 15 weight-percent TaS_2, little, if any, sulfur remained in the wear scars. There were discrete areas, however, where tantalum was detected in the scars. Oxygen was sought, and detected in fairly high concentration in the same locations as the tantalum. The oxygen may have become associated with the tantalum during air exposure subsequent to the wiping, but, clearly, the ultimate acquisition of oxygen occurred only where the lubricant was subject to rubbing. In contrast to this behavior, the tantalum and sulfur occurred together at every point in the wear scar area of a TaS_2 composite specimen with no copper, and also in the wear scar area of a TaS_2 specimen which did contain copper but which was rubbed by a palladium wire.

It has been known for some time that water vapor can cause significant variations in the lubricating behavior of MoS_2. A recent work* indicates that the effects of water are reversible and are attributable to physical adsorption. Workers at BCL and others have reported that MoS_2 reacts with water vapor to form H_2S, even for very low H_2O concentrations, and that the H_2S subsequently may react with copper. One would suspect that any H_2S which might be formed in these experiments might also react with the silver in the Neyoro 28A wipers.** Thus, the effects of water vapor may explain why

*Pritchard and Midgley, J. W., "The Effect of Humidity on the Friction and Life of Unbonded Molybdenum Disulphide Films", Wear, 13, 39-50 (January, 1969).

**The composition of Neyoro 28A is Au/22 weight percent Ag/3 weight percent Ni.

significant loss of sulfur was observed only when Neyoro 28A wipers were used. It appears that TaS_2 reacts with water vapor more readily than does MoS_2. This conjecture is based on the fact that the odor of H_2S is easily detected when a sample vial containing a composite specimen with TaS_2 lubricant is opened after it has been left sealed for a few weeks. No such odor is detectable for specimens which contain MoS_2. The potential reaction between MoS_2 and H_2O and the subsequent reaction of H_2S with other constituents of the system may represent a detriment to long shelf-life, but this is not known to be the case at the present time.

DESIGN AND CONSTRUCTION OF EXPERIMENTAL MINIATURE SLIP-RING CAPSULES WITH SOLID-STATE-LUBRICATED CONTACTS

The results of the studies employing simulated contacts indicated that, of those evaluated, the composite bodies having the composition Au-5Cu-6MoS_2 offered the most promise from the standpoints of dynamic-resistance behavior and mechanical strength. Some of the composite contact specimens were cut into thin slices to determine if the material had sufficient strength to be fabricated and handled as thin parts of the size envisioned for miniature slip rings, i.e., about 0.020-0.025 inch in thickness and 1/8 inch in diameter. The thin slices, while fragile, appeared to be capable of withstanding the required stresses if reasonable care is exercised. Next, small copper and Neyoro 28A lead wires were soldered to the edges of some of the slices. It appeared that acceptable joints could be obtained, but the strength of the composite bodies was such that the joints were far from strong. Slices, and subsequently rings approximately the size anticipated for the sample slip rings, were forwarded to Poly-Scientific so that they could evaluate the prospects for obtaining satisfactory results with the proposed composition.

The conclusions reached by Poly-Scientific were that the material was more fragile than they considered desirable and that it was not possible to achieve ring-to-lead joints with strengths of the magnitude that they routinely achieved with usual materials. On the other hand, they concurred with Battelle in the conclusion that it would be feasible to use composite body rings of the proposed composition and configuration in the construction of experimental slip-ring capsules.

On the recommendation of the MSFC Technical Representative, it was decided that an existing Poly-Scientific slip-ring capsule, the DP 1511, should be modified to provide for the inclusion of solid-state-lubricated contacts.

Changes made at the design stage were:

(1) Slip-ring diameter was increased to provide room for the necessary solder joint at the ring-to-lead connection.

(2) The number of brushes contacting each ring was reduced from two to one in order to reduce the amount of machining to which the composite rings would be subjected and to increase the minimum thickness of the machined part of the ring.

(3) Raised epoxy barriers were introduced to prevent wear debris from bridging the insulators between adjacent rings.

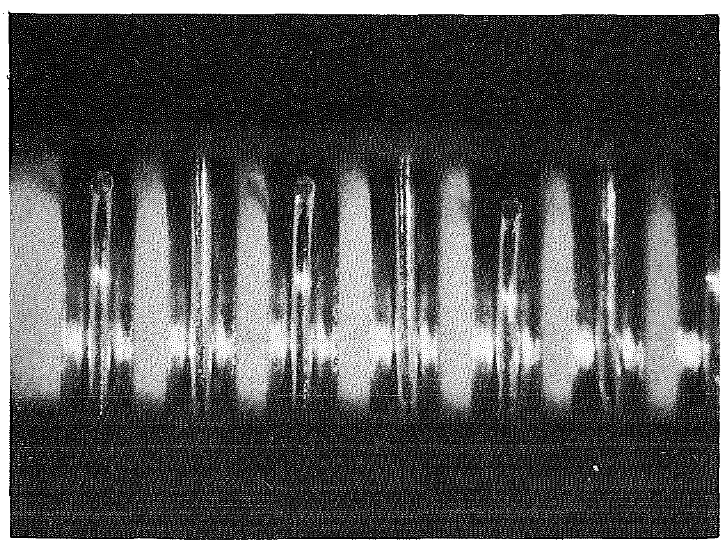
(4) To accommodate the raised barriers, the diameter of the bearing at one end was increased. This in turn required that a special bearing seat be added as a separate component at the other end.

(5) Because of anticipated greater wear for the composite rings (as compared to liquid-lubricated electrodeposited rings) the brush force was increased slightly to compensate for about 0.001 inch of relaxation.

Three modified DP 1511 capsules (given the designation DP 2061 by Poly-Scientific) incorporating all of the above design changes were constructed by Poly-Scientific. From the standpoint of fabrication and processing, Poly-Scientific reported that:

> Problems in fabrication arose from the nature of the ring material. In summary, there was difficulty in obtaining a reliable solder bond to the ring for lead connections, and the conventional hand soldering techniques occasionally caused cracking of the relatively weak ring material. Normal grinding procedures were too rigorous for the slip-ring fabrication, resulting in gross cracking of the first slip-ring capsule; special cautions, such as reduced feed rate for the grinding wheel, had to be exercised.
>
> Fabricating the rings to conventional thickness and diameter tolerances proved to be difficult, and most rings were hand lapped and turned to size to preclude potential loss of entire slip-ring capsules during mold loading and casting, or due to poor brush-to-ring alignment.

Should the sample slip rings offer performance characteristics which are superior, in some important respect, to current technology capsules, it does not appear that the problems described above would be difficult to remedy.



15X

FIGURE 18. ENLARGED VIEW OF SOME OF THE RINGS AND BRUSHES ON EXPERIMENTAL SLIP-RING CAPSULE DP 2061 SN 1

Figure 18 shows some of the rings and brushes on a finished experimental capsule. The three experimental capsules fabricated were designated DP 2061 SN 1, DP 2061 SN 3, and DP 2061 SN 4.

EVALUATION OF THE ELECTRICAL RESISTANCE BEHAVIOR OF EXPERIMENTAL CAPSULES EMPLOYING SLIP RINGS CONTAINING MoS_2

Poly-Scientific was specifically requested not to run-in the experimental slip-ring capsules. Thus, no more than a few tens of rotations of the units occurred before the capsules were installed in a chamber with a controlled atmosphere where the dynamic-resistance behavior could be monitored.

The chosen mode of operation of the capsule during the measurement of dynamic-resistance behavior of the contacts consisted of a continuous, unidirectional rotation of the rotor, at 25 revolutions per minute. The wiping speed was very near 0.5 cm/sec under these conditions. Circuits 1 and 2, 3 and 4, 5 and 6, 7 and 8, 9 and 10, and 11 and 12 were paired by connecting their respective brush leads. Dynamic-resistance characteristics of the various circuit pairs were observed with the same equipment used in the simulated contact studies. The capsule barrels were removed during the time the capsules were mounted in the evaluation chamber to facilitate changing the atmosphere at the contact surfaces when the chamber was purged. As in all of the development studies, the atmosphere for capsule evaluation was intended to be prepurified nitrogen gas. As will be explained in following paragraphs, certain aspects of the early capsule performance suggested that the performance could be sensitive to certain additions to the atmosphere, so the performance in other atmospheres was examined. Thus, the contacts of both DP 2061 SN 1 and DP 2061 SN 3 were exposed to nitrogen bubbled through water and the contacts of DP 2061 SN 1 also were exposed to dry oxygen. In order to avoid possible problems due to differences in thermal-expansion properties, the slip-ring capsules were kept at room temperature at all times.

With Capsule DP 2061 SN 1 installed in it, the chamber was purged with flowing nitrogen. With a flow rate of one cfh, the flow was continued for 2-1/2 hours. Following purging, the valve which connected the chamber to the exhaust nozzle was closed and the chamber remained connected to the nitrogen supply; the chamber pressure was kept slightly higher than atmospheric pressure.

With Capsule DP 2061 SN 3 mounted in it, the chamber was purged for 16 hours with a flow rate of 0.2 cfh before the contacts were operated. Nitrogen was allowed to continue to flow at the same rate throughout the first 27 hours of contact operation.

As a result of mechanical difficulties encountered with the rotating mechanisms in the chamber during the early operation of DP 2061 SN 1, the capsules were operated only during normal working hours of the day for most of their periods of examination. To give an accurate account of the treatment which each capsule received, histories of the capsules are given in Appendixes B and C.

Dynamic-resistance characteristics were determined by observing, during one complete rotation of the moving contacts, the magnitude of the difference between the resistance of a given circuit pair and its associated leads and that of a fixed "dummy" consisting of an equivalent amount of lead wire. Values of the variation in resistance obtained at various times during the period of operation are given in Table 7 for DP 2061 SN 1 and in Table 8 for DP 2061 SN 3. The actual period of time required to make observations of all six circuit pairs was approximately 10 minutes. Each set of measurements reported in Tables 7 and 8 is indicated as having been obtained at the mean time for that series of measurements. Not all of the accumulated measurements are included in the tables, but sufficient data are shown to provide an accurate picture of the magnitude and manner of variations with time.

The dynamic-resistance behavior of the two experimental capsules was the same in that the resistance variations were large at the outset of contact operation and, after a period, decreased drastically. The large variations during early life are presumed to be caused by the presence of a contaminant film. The variation in resistance becomes much less when the film is "rubbed away". The behavior of the two capsules was different in that the size of the resistance variations was much larger for DP 2061 SN 1 and remained large for a much longer period of operation. This probably indicates that the contaminant film was thicker on the contacts of DP 2061 SN 1 than on DP 2061 SN 3.

As noted in Appendix B, it was necessary to expose capsule DP 2061 SN 1 to laboratory air briefly after about 24 hours of operation. This brief air exposure appeared to produce a sizeable increase in the magnitude of the dynamic-resistance variations on Circuit Pair 3-4. Just prior to air exposure, the maximum variation was about 21 megohms. Immediately following air exposure and a subsequent 1-1/4-hour purge at 3 cfh, the maximum variation had increased to 560 mΩ. The large variations did not persist long, however and, as can be seen from Table 7, the variations for all of the contacts gradually grew smaller until all became too small to measure.

It will be remembered that the possibility was pointed out that the presence of water vapor might alter the behavior of contacts containing dispersed MoS_2. The change in resistance behavior brought on by brief air exposure was assumed to be a manifestation of the effects of water vapor.

To further investigate the possible effects water vapor might exert on contact performance, dry oxygen and then wet nitrogen were introduced into the contact chamber while Capsule DP 2061 SN 1 was being evaluated. Between the introduction of the oxygen and the introduction of the wet nitrogen, the chamber was purged with prepurified nitrogen for many hours.

Introduction of dry oxygen had the relatively minor effect of slightly increasing the magnitude of the resistance variations for some of the contact pairs. These increases were not as great (the highest observed value was 184 megohms) as the corresponding changes that resulted from the previous air exposure. (The data shown in Table 7 for 33 hours, 55 minutes and 34 hours, 10 minutes were obtained with O_2 in the chamber.)

During the period of the dry-nitrogen purge of oxygen from the chamber, the general size of the resistance variations became larger than that during the dry-oxygen phase. The data in Table 7 for 36 hours, 40 minutes and for 39 hours were obtained during this period.

TABLE 7. MAGNITUDES OF DYNAMIC-RESISTANCE VARIATIONS AS A FUNCTION OF HOURS OF OPERATION FOR SLIP-RING CAPSULE DP 2061 SN 1

Accumulated Time of Operation	Variation in Dynamic Resistance, mΩ(a), for Indicated Circuit Pair					
	1-2	3-4	5-6	7-8	9-10	11-10
(50 min)	6.7Ω	5.4Ω	1.5Ω	1.2Ω	7.5Ω	3.9Ω
2 hr (30 min)	6.7Ω	5.0Ω	1.3Ω	600	4.3Ω	3.5Ω
7 hr (30 min)	7.4Ω	2.1Ω	1.7Ω	980	560	1.4Ω
16 hr (15 min)	32	21	114	21	670	--
26 hr (40 min)	<7	<7	<7	<7	<7	<7
30 hr (40 min)	<7	<7	<7	<7	18	<7
33 hr (55 min)	<7	10	18	14	--	<7
34 hr (10 min)	--	7	--	184	84	--
36 hr (40 min)	49	35	--	114	245	--
39 hr	52	52	77	105	140	45
40 hr	--	--	17.5	10.5	--	49
44 hr (30 min)	--	--	25	184	--	--
47 hr (30 min)	224	290	210	228	116	193
56 hr (30 min)	32	87	14	77	66	21

(a) Values are in mΩ unless otherwise indicated.

TABLE 8. MAGNITUDES OF DYNAMIC-RESISTANCE VARIATIONS AS A FUNCTION OF HOURS OF OPERATION FOR SLIP-RING CAPSULE DP 2061 SN 3

Accumulated Time of Operation	Variation in Dynamic Resistance, mΩ(a), for Indicated Circuit Pair					
	1-2	3-4	5-6	7-8	9-10	11-12
(5 min)	880	820	270	14	39	81
(12 min)	25	<7	--	--	--	--
4 hr (15 min)	--	--	200	--	--	91
8 hr	300	114	1.1Ω	110	150	88
17 hr	140	166	250	260	390	131
27 hr	100	100	88	21	31	98
36 hr	31	140	190	60	81	100
36 hr (45 min)	11	70	<7	<7	<7	49

(a) Values are in mΩ unless otherwise indicated.

Figure 19 shows the size of the dynamic-resistance variations as a function of time during periods just before, during, and after the period when the capsule contacts were exposed to wet nitrogen. Data are presented for Capsules DP 2061 SN 1 and DO 2061 SN 3. In both cases, Contact Pairs 3 and 4 were chosen for detailed observation because the prewater-exposure resistance variations were large. The wet nitrogen was produced by bubbling prepurified nitrogen through deionized water.

The data shown in Table 7 for 40 hours and in Table 8 for 36 hours, 45 minutes were obtained with water vapor intentionally introduced into the chamber. The introduction of water vapor produced a dramatic decrease in the size of the dynamic-resistance variations. Other contact pairs, examined less often, exhibited decreases to even smaller variations than those indicated on Figure 19. The size of the resistance variations for both capsules reached a minimum value during the first 1/2 hour of exposure to water vapor, then increased somewhat as exposure continued. The size of the resistance variations for DP 2061 SN 1 also passed through a minimum value as the water vapor was being removed by purging. The minimums in the size of the resistance variations suggest an optimum water vapor concentration which results in the lowest contact noise.

The increase in size of resistance variations apparently resulting from brief air exposure is more likely attributable to the provision of a "drier" atmosphere by the purge which followed the air exposure. The increase in size of resistance variations resulting from introduction of dry oxygen into the chamber also probably was caused by an actual reduction in the amount of water vapor in the atmosphere of the contacts.

Whether or not all the large changes in performance encountered with the experimental capsules were due to the presence or absence of water vapor could not be determined by these brief investigations. Certainly, performance is very sensitive to the presence and magnitude of water vapor. The degree to which such atmospheric effects are important in the potential application of the slip-ring capsules will depend on the particular atmosphere in which they operate. The rather fragmentary data that this program was able to generate suggest that the contacts may tend to stabilize with resistance variations of the order of 30 megohms in most environments. The variations reported here represent rather sharp spikes observed with an oscilloscope. Other methods of evaluation may be less sensitive to such spikes.

CONCLUSIONS CONCERNING THE FEASIBILITY OF LUBRICATING MINIATURE SLIP-RING CAPSULES WITH SOLID-STATE LUBRICANTS

This program has clearly demonstrated the feasibility of fabricating and assembling miniature slip-ring capsules having rings with dispersed solid-state lubricant. Certain problems were encountered, but they did not impose severe restrictions upon fabrication techniques. Continued development undoubtedly would lead to improved methods of composite-body ring fabrication and lead attachment which would result in acceptable yield rates. Also, even stronger rings likely could be developed if needed. Feasibility still needs to be established in the areas of electrical performance and service life. Studies of the simulated contacts and the experimental slip-ring capsules both indicate that contact noise may be somewhat higher than can be obtained from optimum liquid-lubricated capsules during their early life. The performance of the solid-lubricated

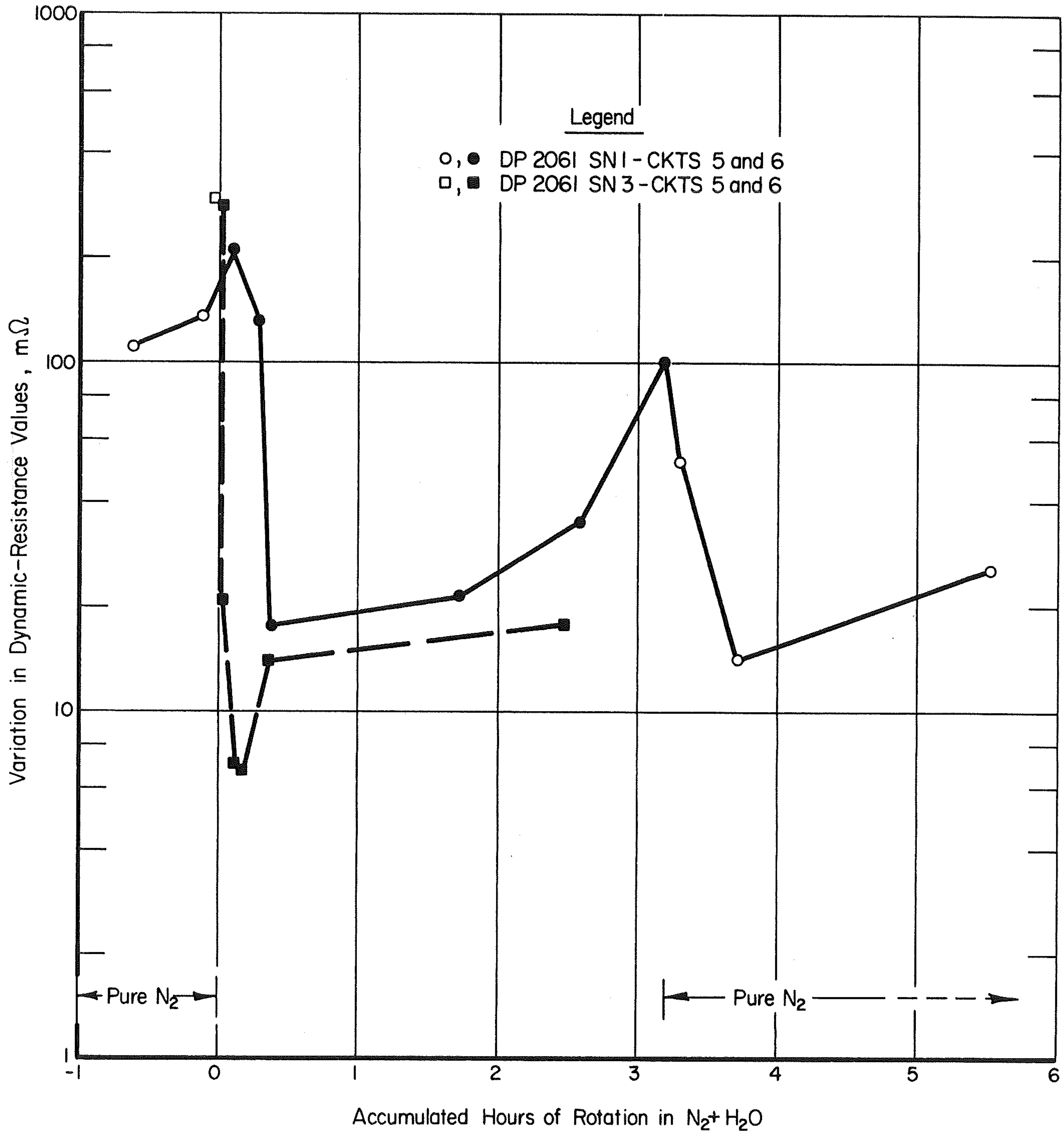


FIGURE 19. EFFECT OF WATER VAPOR ON THE MAGNITUDE OF THE DYNAMIC-RESISTANCE VARIATIONS OF MoS_2 LUBRICATED SLIP-RING CONTACTS

contacts in pure nitrogen is believed to indicate their potential utility in vacuum environments. Under vacuum conditions, a slight penalty of somewhat higher contact noise may be acceptable. Another factor which might be of some consequence in certain applications is that the torque required to move the MoS_2-lubricated contacts is significantly lower than that required for corresponding liquid-lubricated contacts.

APPENDIX A

HISTORY OF DP 1506, SN 201

APPENDIX A*

HISTORY OF DP 1506, SN 201

1. Originally passed acceptance tests and shipped from Poly-Scientific. (March 1968.)

2. Rejected at MSFC for noise during screening tests. (15 circuits had noise greater than 20 milliohms after 100 hours of test.) (June 1968.)

3. Returned to Poly-Scientific for skim-cutting, replating of hard gold, and lubrication with 25 percent MCS 210 and 75 percent OS124. (March 1969.)

4. Skim cut, replated, and lubricated with MCS 210 and OS124. (June 1969.)

5. Failed noise, torque, and circuit resistance. (June 21, 1969.)

6. Cleaned and relubricated, as per MSFC and BCL (failed noise, torque, and insulation resistance). (June 27, 1969.)

7. Passed noise at MSFC, but failed insulation resistance after testing. Insulation resistance failure was attributed to loose particles by MSFC, BCL, and P-S.

8. Returned to P-S for examination as to origin of loose particles. (October 28, 1969.)

9. Loose wear particles were removed for examination by BCL and P-S. (November 1969.)

10. Brushes were removed for examination at BCL and P-S.

11. Unit was thoroughly cleaned in trichloroethylene and carbon paths removed until no gold particles could be found (30X).

12. Unit was ultrasonically cleaned in 75 percent OS124 and 25 percent MCS 210. One gold particle was visible at 30X, but it was too small for removal by conventional means. Unit was then cleaned in trichloroethane.

13. The resistance between all circuits were greater than 10^{11} ohms.

14. Capsule was reassembled and heavily lubricated with mixture of MCS 210 and OS124.

15. Capsule was run for 200 hours at 2 rpm.

16. High-potential shorts were measured between ≈ 20 circuits and numerous gold particles were observed in the interior of the capsules.

17. Particles which were removed before and after the run-in (15) were sectioned and found to be layered. The particles were conglomerates of smaller particles which appeared to have been highly worked.

---

* This section was prepared by Poly-Scientific.

18. "Prows" were observed in transverse and longitudinal sections of the brushes which were removed before and after the last run (15).

19. Brush wear was very slight; e.g., not visible at 285X.

APPENDIX B

HISTORY OF THE EVALUATION OF SLIP-RING CAPSULE DP 2061 SN 1

APPENDIX B

HISTORY OF THE EVALUATION OF SLIP-RING CAPSULE DP 2061 SN 1

Date	Time	Action or Condition
2-19-70	1:45 p.m.	Start purging with N_2; flow rate = 0.5 cfh
2-20-70	8:25 a.m.	Close exhaust valve
	2:00 p.m.	Open chamber to correct thermocouple problem
	2:10 p.m.	Start N_2 purge, ICFH
	4:35 p.m.	Close exhaust valve
2-23-70	8:34 a.m.	Start motor
	1:37 p.m.	Stop motor, 5 hr 3 min accumulated operation
	3:50 p.m.	Discovered motor not running; unobserved 1 hr 10 min, uncertainty 55 min; accumulated operation 6 hr 2 min ± 55 min
	4:06 p.m.	Start motor
	5:40 p.m.	Stop motor; accumulated operation 7 hr 36 min ± 55 min
2-24-70	8:15 a.m.	Start motor
2-25-70	8:10 a.m.	Discovered motor not running, uncertainty 7 hr 25 min; accumulated operation 24 hr 6 min ± 8 hr 20 min
	8:20 a.m.	Opened system to remove feed-through
	9:45 a.m.	Start N_2 purge; flow rate = 3 cfh
	11:00 a.m.	Close exhaust valve and start motor
	5:37 p.m.	Stop motor; accumulated operation 30 hr 43 min ± 8 hr 20 min
2-26-70	8:10 a.m.	Start motor
	10:15 a.m.	Replace N_2 with dry O_2 flow rate = 0.6 cfh

Date	Time	Action or Condition
2-26-70	11-40 a.m.	Stop motor; accumulated operation 34 hr 13 min ± 8 hr 20 min
	12:15 p.m.	Close exhaust valve, then inlet valve
	12:30 p.m.	Start motor
	1:16 p.m.	Open valves to purge chamber with N_2; flow rate = 1 cfh
	5:07 p.m.	Reduce N_2; flow rate to 0.5 cfh
	5:30 p.m.	Stop motor; accumulated operation 39 hr 13 min ± 8 hr 20 min
2-27-70	8:12 a.m.	Start motor
	8:50 a.m.	Start bubbling N_2 through deionized water; flow rate = 0.5 cfh
	10:36 a.m.	Stop motor; accumulated operation 41 hr 37 min ± 8 hr 20 min
	11:25 a.m.	Start motor
	12:02 p.m.	Start purging with pure N_2; flow rate = 1 cfh
	5:26 p.m.	Close exhaust valve
	5:30 p.m.	Stop motor; accumulated operation 47 hr 42 min ± 8 hr 20 min
3-2-70	8:16 a.m.	Start motor
	5:16 p.m.	Stop motor; accumulated operation 56 hr 42 min ± 8 hr 20 min

APPENDIX C

HISTORY OF THE EVALUATION OF SLIP-RING CAPSULE DP 2061 SN 3

APPENDIX C

HISTORY OF THE EVALUATION OF SLIP-RING CAPSULE DP 2061 SN 3

Date	Time	Action or Condition
3-3-70	4:33 p.m.	Start purging with N_2; flow rate = 0.4 cfh
	5:15 p.m.	Reduce flow rate to 0.2 cfh
3-4-70	9:00 a.m.	Start motor
	5:16 p.m.	Stop motor; accumulated operation 8 hr 16 min
3-5-70	8:11 a.m.	Start motor
	5:33 p.m.	Stop motor; accumulated operation 17 hr 38 min
3-6-70	7:57 a.m.	Start motor
	5:30 p.m.	Close exhaust valve, stop motor; accumulated operation 27 hr 11 min
3-9-70	8:11 a.m.	Start motor
	5:05 p.m.	Stop motor
3-10-70	8:36 a.m.	Close inlet valve, start motor
	9:00 a.m.	Start bubbling N_2 through deionized water
	11:30 a.m.	Stop motor and change to pure N_2 purge; flow rate = 2 cfh; accumulated operation 38 hr 59 min
	1:00 p.m.	Close exhaust valve

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