Final Report

ENVIRONMENTAL STUDY OF
MINIATURE SLIP RINGS

George C. Marshall Space Flight Center
Huntsville, Alabama 35812

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1 July 1965 to 1 September 1966

Contract No. NAS8-5251
Control No. TP-83367 (IF)
IITRI Project E6000

Prepared by

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Attn: PR-RDC

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This report was prepared by IIT Research Institute under Contract No. NAS8-5251, "Environmental Study of Miniature Slip Rings" for George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Propulsion and Vehicle Engineering Laboratory, Materials Division of the George C. Marshall Space Flight Center with Mr. J. C. Horton acting as Project Monitor.

FOREWORD

This is the Final Report of Phase III of IITRI Project E6000, entitled, "Environmental Study of Miniature Slip Rings." The report covers the period 1 July 1965 to 1 September 1966.

This program was conducted under the technical direction of J. L. Radnik. The project was administered by M. E. Goldberg, Assistant Director of Electronics Research. The cooperation of J. C. Horton of the George C. Marshall Space Flight Center is gratefully acknowledged.

Respectfully submitted,

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ABSTRACT

A laboratory investigation of the performance characteristics of miniature slip rings in vacuum was conducted. Unacceptable noise levels were developed in a very short time at high vacuum conditions. Noise voltage consisted of low frequency components and was independent of current, at least up to 25mA. Improved noise characteristics were obtained by using commercial vacuum lubricants or a niobium diselenide ring. Hard gold overplating did not result in an improved noise performance. A soft metal vapor plating technique was developed which gave substantially improved performance.

Author

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ENVIRONMENTAL STUDY OF MINIATURE SLIP RINGS

I. INTRODUCTION

This report summarizes the results of a laboratory investigation conducted during Phase III of IITRI Project E6000, "Environmental Study of Miniature Slip Rings," for the George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama. The program was concerned primarily with the study of long term operation of miniature slip ring assemblies in high vacuum of space, and was a continuation of two earlier programs, entitled "Investigation of Slip Ring Assemblies", in which the influence of ring, brush, and insulator materials on electrical noise and mechanical wear were investigated. Previous investigation established that destructive galling and erosion effects occurred in unlubricated systems which permitted high localized temperatures. These detrimental effects are aggravated by high vacuum. The reduced heat transfer characteristics in a vacuum environment increase the possibility of localized hot spots at contact points. The increased friction and surface damage due to cold welding of micro-asperities result in wear and high electrical noise. Surface lubrication with P-38 synthetic oil had been found to be effective in minimizing wear and maintaining low noise levels in a nitrogen atmosphere and at low vacuum levels.

Miniature slip ring assemblies are normally used to transmit electrical information across the axes of inertial platforms in space vehicle guidance systems. Excessive electrical noise at the sliding contact strongly interferes with circuit performance, particularly the null-seeking type of circuit.

The future requirements of space vehicle systems include satisfactory performance of miniature slip rings in severe environmental conditions that could exist during the extended space missions. One of such conditions is the high vacuum of outer space.

The investigation described herein was specifically directed toward problem areas encountered with a commercial 80-ring capsule used in launch vehicles. This capsule is described in Drawing GC-125209, entitled "Specifications for ST-124 Slip Ring Assemblies," issued by George C. Marshall Space Flight Center, Astrionics Laboratory. The capsule must be capable of complete 360° rotation even though its normal oscillation about a fixed operating point is only about 0.5 minutes of an arc. Its operating life in a launch vehicle is only about two minutes, but qualification and acceptance tests require a total life of about 75 hours. For the laboratory work of this program, experimental capsules were fabricated having the same ring and brush dimensions as the actual capsule in order to simulate the actual operating conditions as closely as possible.

II. PROGRAM OBJECTIVES AND SCOPE

The principal objective of this phase of the program was a comprehensive laboratory investigation of problems associated with operation of miniature slip ring assemblies in hard vacuum of space based on long term run-in tests. The program was divided into several basic tasks.

The objective of the first task was to design and fabricate experimental brush-ring assemblies using materials with good off-gassing properties.

As a second task, long-term run-in tests were to be conducted in high vacuum in order to identify the basic problem areas using as criteria the electrical noise performance and the mechanical wear. The wear debris accumulated during the run-in tests was to be collected to identify the chemical and metallurgical nature of debris deposits.

Once the problem areas had been identified, design approaches were to be developed for capsules capable of withstanding the stringent requirement of prolonged operation in space. Since it is well known that surface lubrication can improve the noise and wear characteristics of sliding contacts, the study of surface lubrication techniques compatible with both high vacuum environment and earth environment was to be investigated.

As a separate task, the investigation of the influence of electroplating conditions on properties of slip ring materials, which was started during the preceding phases of the program, was to be continued.

Some initial screening of different materials and lubricants was carried out in a nitrogen atmosphere as a matter of expediency and also to establish compatibility with earth environment.

III. TECHNICAL DISCUSSION

A. New Brush-Ring Assemblies

It is known that vacuum induced effects may modify the performance characteristics of slip rings. Out-gassing organic species from the dielectric base materials can condense on slip ring surfaces providing effective lubrication initially, but eventually resulting in formation of an insulating film through frictional polymerization. It is also thought that the active gases (O_2, N_2, CO_2, etc.) which are adsorbed on surfaces and dissolved in materials markedly reduce the effects of the vacuum environment for extended periods. Performance characteristics established during the initial out-gassing phases may change drastically when the active species are depleted or when the surface contaminants change their characteristics.

The following changes were made in the experimental assemblies used during the previous phases of the program in order to minimize off-gassing at high vacuum. The rings were made of copper instead of brass plated with soft gold. Experimental brushes were identical with those used previously. They were fabricated from 7 mil cold-worked Ney-Oro No. 28A wire. The brush wire pressure was adjusted to 2.5 grams. Brush blocks were machined from Mycalex 400. Mycalex is a trade name of glass-bonded mica made by Mycalex Corporation of America. It is certified as grade L432, precision-machinable material under MIL-I-10A specification for ceramic-grade electrical insulating materials and has excellent off-gassing characteristics. Fig. 1 shows the disassembled experimental capsule. Twelve such brush-ring assemblies were fabricated and goldplated. Two assemblies were forwarded to George C. Marshall Space Flight Center to be used in their in-house studies of noise produced by commercial capsules.

B. Off-Gassing Studies

The analysis of off-gas products from three different electrical component materials used in experimental capsules (Mycalex used in brush blocks, and Teflon used in lead wire insulation and in ring sleeves) was performed using the mass spectrograph technique. Preliminary studies were performed at elevated temperatures to promote off-gassing.

In all cases, the total sample, after breaking into small pieces, was used for analysis. The sample was placed in a tube, affixed to the vacuum system of the inlet and pumped down for one minute at room temperature with the diffusion pump. The pumping was terminated and the sample was heated from room temperature to 120°C over a 5 minute period during which time the off-gas products were allowed to expand into an evacuated reservoir. At the end of 5 minutes the sample was admitted to the spectrograph analyzer for analysis over a mass-to-charge ratio range of 12 to 200. A blank was similarly run for comparisons.

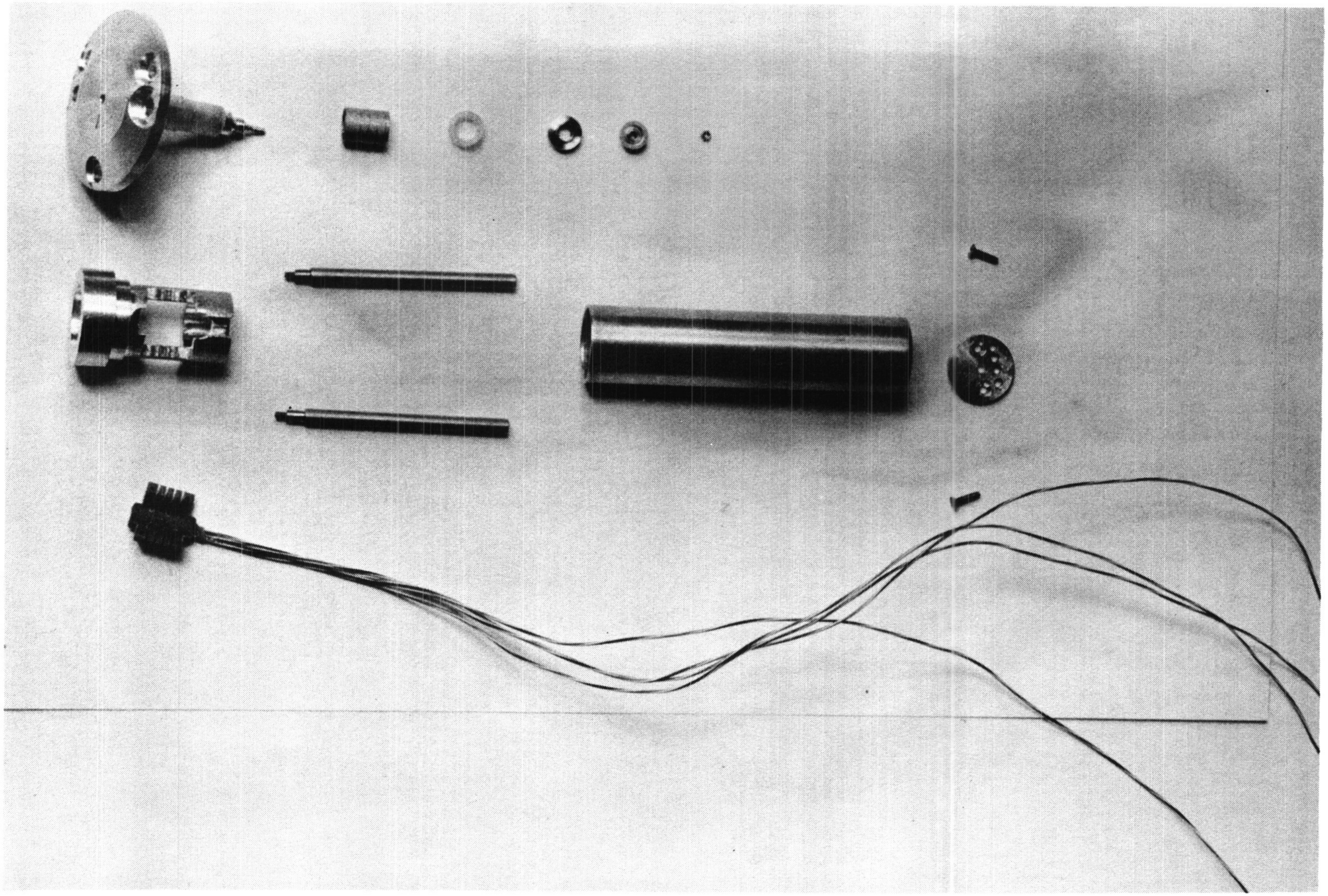

Fig. 1: Disassembled Experimental Capsule

Although the spectra for all of the samples were quite complex, the off-gas products for the Teflon samples appeared to be complex mixtures of fluorinated compounds and hydrocarbons. The Teflon wire insulation had a pronounced peak at m/e = 149 which is often characteristic of aromatic acids such as terephthalic acid or their esters. There was some lesser amount of this material in the ring which was made of a different grade of Teflon and no significant amount in the Mycalex 400. Mycalex 400 appeared to have predominantly hydrocarbon vapors. All samples off-gassed much air and water.

As a result of the experience obtained from performing the analysis at elevated temperatures, the previously used technique was modified. A special sample collection vessel was constructed to allow cold-trapping of gases from samples in a vacuum of 10^{-6} torr over prolonged periods of time. Liquid nitrogen was used and cold-trapping was allowed to proceed for seven hours. The results showed that no detectable quantity of off-gassing materials was obtained for either sample in the mass range of m/e from 12 to 260. This indicates that organic component materials with good off-gassing properties were selected for the experimental capsules.

C. Inert Atmosphere Tests

The object of inert atmosphere tests was the screening of different materials and designs. Slip rings that had performed well were then subjected to high vacuum tests. The drive apparatus and instrumentation developed during the initial phases of the program were used for these tests.

A new brush design was evaluated in a nitrogen atmosphere. In this design two brushes were cemented to the brush block to increase brush stiffness and prevent motion of brush wipers. The remaining two brushes were not modified so as to enable a direct comparison of noise performance of the two designs. After over 400 hours of run-in, no significant difference in noise performance was evident. Visual examination after the completion of the test showed about the same amount of debris present on all brush-ring surfaces.

Another brush design was evaluated both in a nitrogen atmosphere and in high vacuum. This design used a Nye-Oro 7 mil brush wire truncated along the axis with the resulting cord of the wire sitting in the ring groove. Both run-in tests indicated that there was no marked improvement in the noise performance as compared with the standard brush designs. Both tests were carried out for 300 hours of continuous rotation at 200 rpm with a brush current of 25 mA.

Two types of commercially available vacuum lubricants were initially evaluated in a nitrogen atmosphere. The composition of these lubricants is proprietary but it is known that they have low surface tension and good properties for vacuum operation. Both lubricants had acceptable noise performance and were later evaluated in a high vacuum. The results of tests in a nitrogen atmosphere are tabulated in Table IV.

D. High Vacuum Tests

1. Equipment

The high vacuum facility used for the tests consisted of the following: 24 x 24 in. steel chamber, refrigerated baffle, 10 in. NRC oil diffusion pump, and mechanical pumps. The nominal pumping speed of the diffusion pump was 1,700 liters per second at 10^{-5} torr. In order to prevent backstreaming of oil from the pump to the chamber, an optically dense refrigerated cold trap was placed between the chamber and the pump. The operating temperatures of this cold trap were: -190°F inlet temperature, and -130°F outlet temperature. The pressure was measured by means of an NRC Type 507 ionization gauge. A vacuum of 10^{-7} torr was achieved by this system. Fig. 2 shows the equipment used for high vacuum tests.

A mounting bracket was built to mount the capsule inside of the vacuum chamber. The magnetic drive used in previous tests had to be reworked to accommodate larger magnets because of the thicker glass in the vacuum chamber portholes.

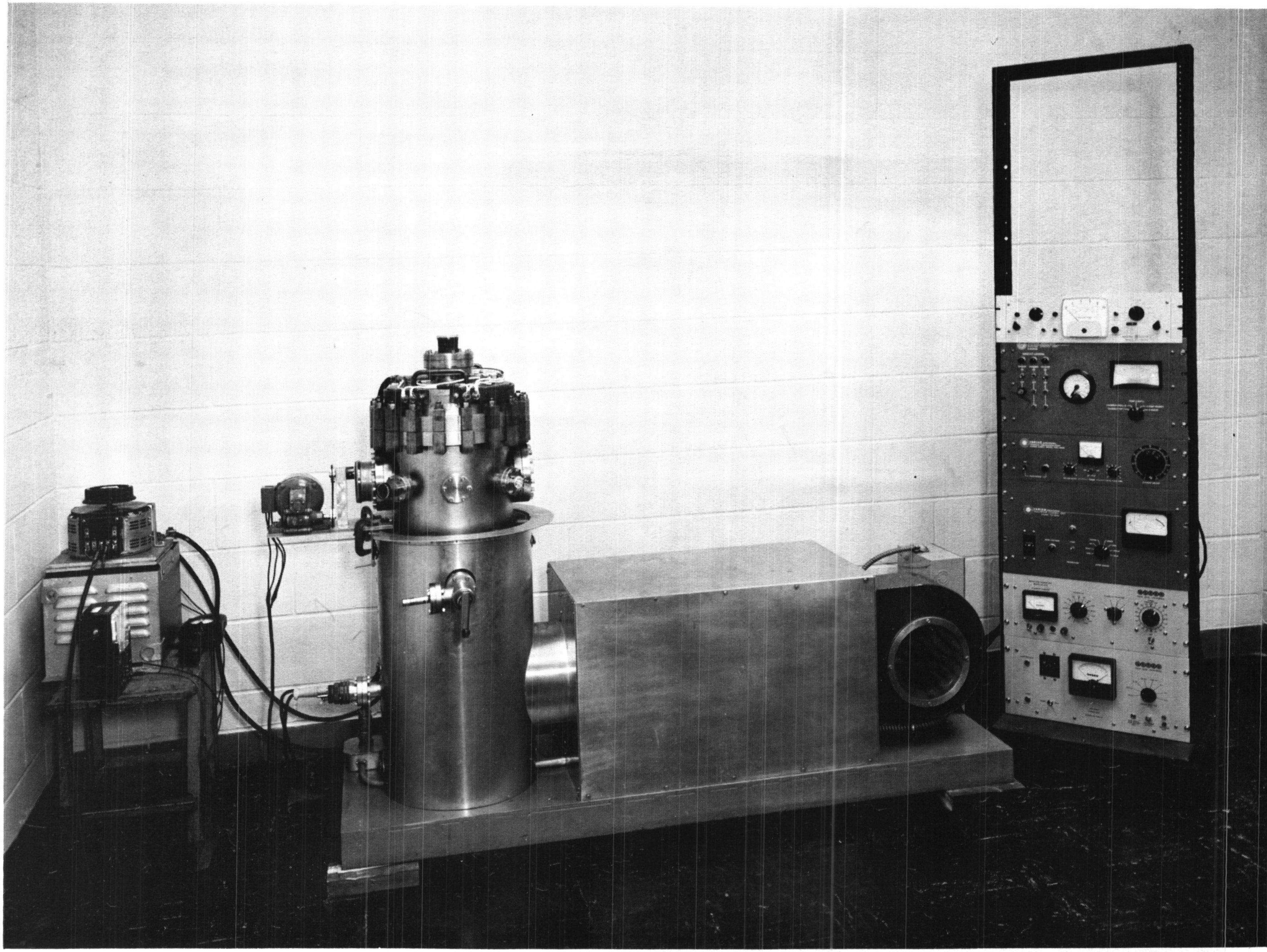

Fig. 2 - EQUIPMENT USED FOR HIGH VACUUM STUDIES

Several small holes were drilled into the capsule to prevent trapping of air inside of the capsule. A trial run was undertaken with Capsule 1-58 in a vacuum of 4×10^{-7} torr. After about one hour of operation, the capsule stopped and it appeared that the magnetic drive did not develop sufficient torque to rotate the capsule. After the vacuum chamber was pressurized, the capsule could again be driven. This was repeated two more times. It was assumed that the high vacuum operation of capsule and drive bearings caused a significant increase in drag torque. It was then decided that special vacuum bearings would have to be used. Several parts of the capsule and the drive system were modified to permit use of commercially available vacuum bearings. Bar Temp bearings manufactured by Barden Corporation were selected because of their outstanding high vacuum performance characteristics. These bearings are equipped with cages made of a highly compressed material of Teflon-coated glass fibers impregnated with molybdenum disulphide (MoS_2). The one-piece cage serves both as a ball separator and as a source of dry lubricant. As the bearing rotates, the ball rubs off minute quantities of the lubricant, depositing a light coating on the raceway. Bearing rings and balls are fabricated of AISI 440C stainless steel, hardened and dimensionally stabilized by a special heat treating process.

An additional problem that was observed during the trial run was the high ambient noise level due to a variety of electrical equipment operating in close proximity to the test set up. This problem was overcome by careful shielding and grounding.

2. Test Results of Experimental Capsules

The first run-in of an experimental brush-ring assembly was carried out in high vacuum for 250 hours of continuous rotation. The analysis of wear debris collected during this run-in was performed using the emission spectrograph technique. The analysis showed that hydrocarbons typical of diffusion pump oil were present in the debris. It became apparent that some backstreaming of oil had taken place during the test. This was traced to improper operation of the cold trap. Corrective measures were taken and subsequently two run-in tests were completed. Each test was run continuously at 200 rpm for approximately 280 hours in a vacuum of 1 to 2×10^{-7} torr. Two of the four brush-ring circuits were run-in with a current of 25 mA while the remaining two were open-circuited throughout the test except for periodic readings. After only a few hours of testing, the noise of both types of circuits reached a level of one millivolt and after approximately 60 hours, the noise increased to one volt. The final readings were between 1.5 to 2.0 volts.

Wear debris collected during the two run-in tests were analyzed separately by the emission spectrograph. Both analyses revealed the presence of hydrocarbons of the cycloalkane or alkene type. It appeared that complete elimination of contamination due to backstreaming through the diffusion pump was impossible in the system used at that time. It was decided to carry out further high vacuum studies in a system employing an ion pump. This system consisted of a five-inch diameter bell jar attached to a 25 liter per second Ultek Boostivac pump with titanium sublimation on a water cooled jacket. A run-in test was conducted in a vacuum of 5×10^{-7} torr. The electrical noise reached a level of one millivolt after about 24 hours of operation. At the conclusion of the test after 364 hours, the noise was in the order of two volts. These results demonstrated that unacceptable noise levels develop in a short time of operation of unlubricated miniature slip rings in high vacuum. Figs. 3 and 4 show a 15X magnification of the experimental ring and brushes after a run-in test.

Experiments were carried out to establish the relationship between the dc current in the brush-ring circuit and the electrical noise developed across the contacts. It was found that the noise level was independent of current, at least up to 25 mA.

3. Niobium Diselenide Ring

The application of electrical sliding contacts in space environment presents a difficult operating problem because most surfaces in rubbing contacts require a thin lubricating film or other adsorbed layer to provide low-friction sliding

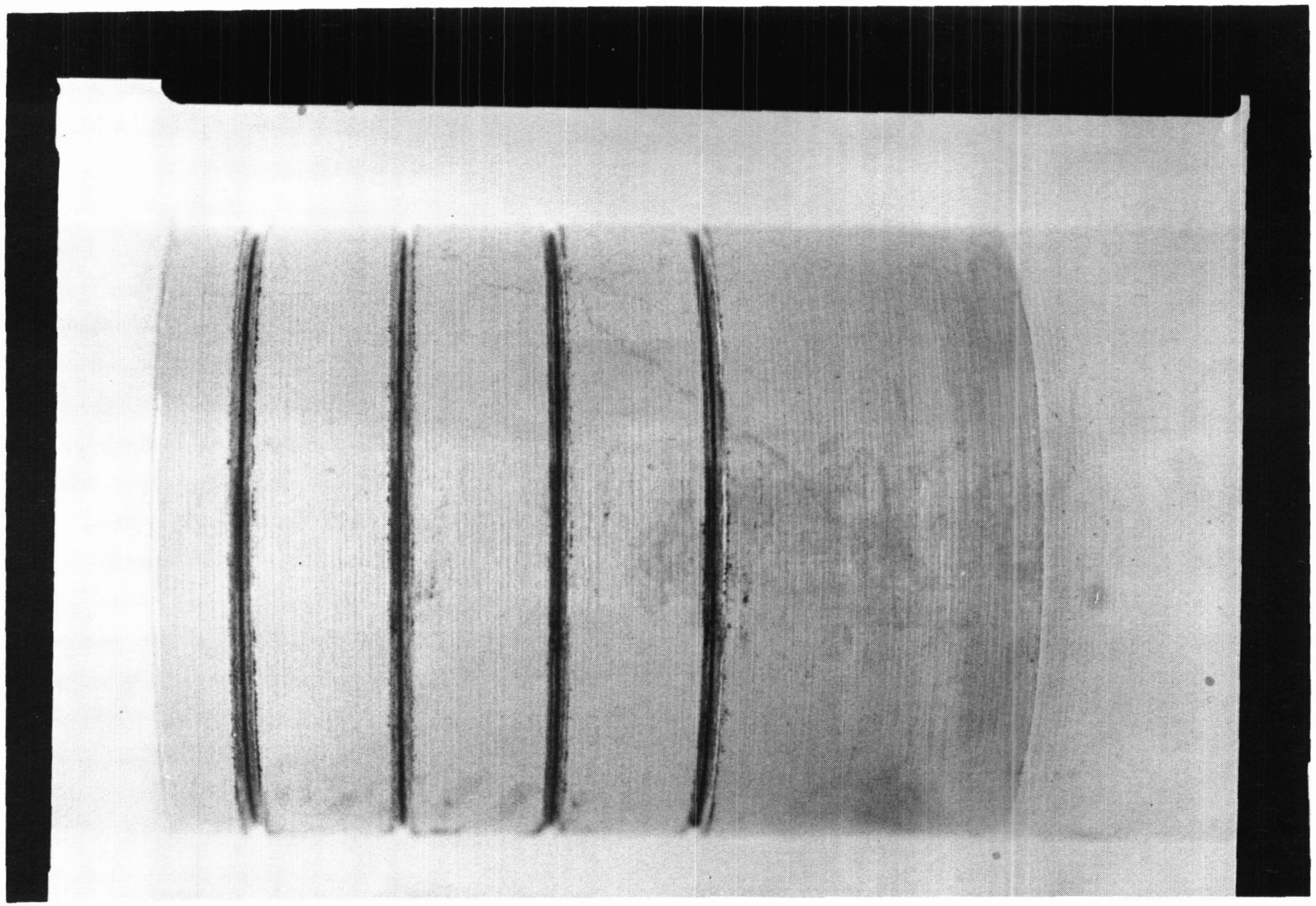

Fig. 3: Experimental Slip Ring After A Run-In Test

Magnification of 15

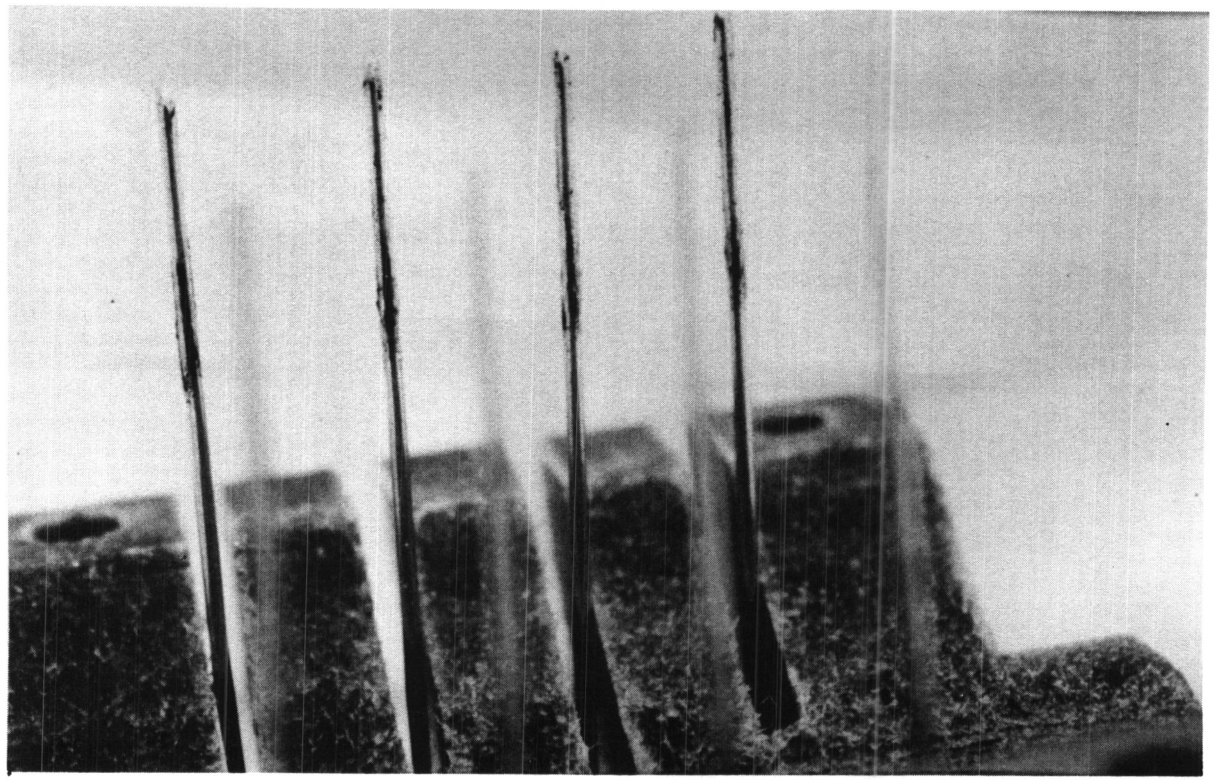

Fig. 4: Experimental Brushes After a Run-In Test

Magnification of 15

and to prevent seizing between the two contact members. To be suitable for space applications, sliding contact members must be mutually lubricating in the absence of all atmospheric components such as moisture. They must also be good electrical conductors and be capable of low, uniform contact resistance to carry the electrical load with a minimum of wear. These materials are metal-based composites containing small percentages of polytetrafluoroethylene and a dry lubricant such as niobium diselenide. The lubricant is held in small pockets throughout metal or high polymer matrices and forms dry films of self-lubricating material on the metal surfaces rubbing against the composites. These dry films transfer to other metal surfaces as they come into rubbing contact with the coated metal surfaces. Thus, the film continually transfers back and forth to heal any tiny faults that may occur in the films. The composites are now commercially available in both a silver and a copper matrix which are totally and homogeneously impregnated with the dry lubricant and film former.

An experimental ring was fabricated from niobium diselenide in a silver matrix form and run-in in a vacuum of 10^{-8} torr. After a few hours of continuous rotation at 200 rpm with a dc current of 25 mA in the brush-ring circuit, the noise reached a level of several millivolts and remained at this level throughout the remainder of the test which was terminated after 408 hours. A very small amount of wear debris was found in the grooves of the slip ring. The initial noise was at about the same level as that of unlubricated rings, but because of low wear, the noise did not increase after prolonged testing to the extreme levels of unlubricated rings.

4. Commercial Vacuum Lubricants

Two commercially available vacuum lubricants, that were initially screened in an inert atmosphere, were later evaluated in a high vacuum. Both were beneficial in improving noise characteristics. The initial noise was in the order of 200 to 400 microvolts and after over 350 hours of continuous rotation at 200 rpm in a vacuum of 10^{-7} torr with 25 mA of dc current the electrical noise was in the range of 600 to 800 microvolts.

5. Noise Spectrum

The electrical noise generated in the slip rings is damaging only as far as it interferes with the information transmitted across the axes of inertial platforms. The severity of this interference can be ascertained by studying the frequency spectrum of the generated noise. Tests carried out during the preceding phases of this program indicated that the capsule noise in an inert atmosphere consisted primarily of low frequency components. These results were confirmed also in a high vacuum. The upper cut-off frequency of the noise voltage was in the order of several kilohertz. Fig. 5 shows typical electrical noise wave forms.

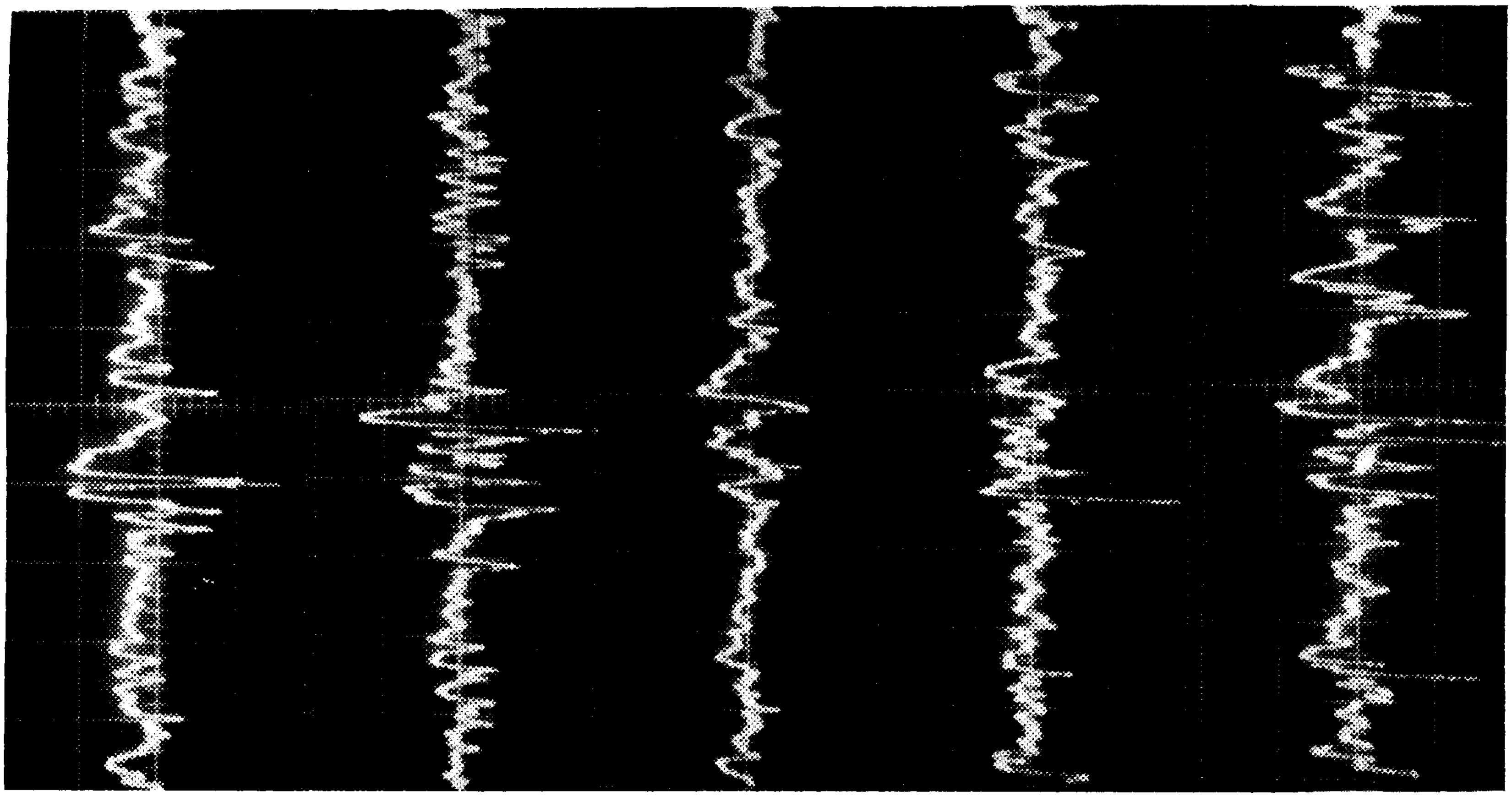

Fig. 5: Typical Electrical Noise Wave Forms

1 div. vert. = 200 microvolts
1 div. hor. = 50 milliseconds

E. Electroplating Studies

Two sets of duplex gold plated slip rings were prepared for use in noise studies. The Orotemp 24 gold plated brass rings were overlaid with 100 microinches of hard gold deposits by a second electroplating step. Two different hard gold bath formulations were employed. A summary of the plating conditions is given in Table I.

TABLE I

SUMMARY OF PLATING CONDITIONS USED IN PREPARING DUPLEX GOLD PLATED SLIP RINGS

GOLD BATH	TYPE OF DEPOSIT	CURRENT DENSITY (amps/ft^2)	TEMP. (°C)	pH
Orotemp 24*	24k, soft	5	50-55°	5.5-6.0
Orotherm HT*	24k, hard, acid bright gold	5	31°	4.3
Autronex NI**	hard, acid gold	5	31°	3.8

* Technic, Inc. proprietary formulation

** Sel-Rex Corporation proprietary formulation

Two rings of each of the Orotherm and Autronex deposits were prepared. The rings were run-in in a nitrogen atmosphere for 290 to 330 hours of continuous rotation at 200 rpm. A dc current of 25 mA was applied to each brush-ring pair for approximately half of the time and the direction of rotation was periodically reversed. In all four cases, the noise level remained in the 100 to 150 microvolt range except for short periods following the reversals of the direction of rotation. After the completion of the tests, the rings and brushes were examined macrographically up to the 30x power. The grooves of all rings were remarkably free of all wear patterns although there was a quantity of fluffy, black debris in the bottom of the grooves and on the brush wires. There appeared to be considerably more debris on both rings overlaid with Autronex type of deposits. A qualitative spectrographic analysis was performed with the collected debris. The characteristic emission lines were negative with respect to gold, platinum, silver and copper. One each of the two types of rings was cross-sectioned for metallurgical examination. Photomicrographs of such a cross-section are shown in Fig. 6. The light colored coating on the outside of the ring surface is nickel that was electroplated after the test to hold the corners during grinding and polishing. No significant wear was found in either type of overlay which agrees with the finding that the debris contained no gold.

An additional investigation was conducted to study the effect of a relatively harder substrate under the hard gold overplating. Previous experimental rings employed a soft gold basis metal for the overlays. Nickel, which has a well developed

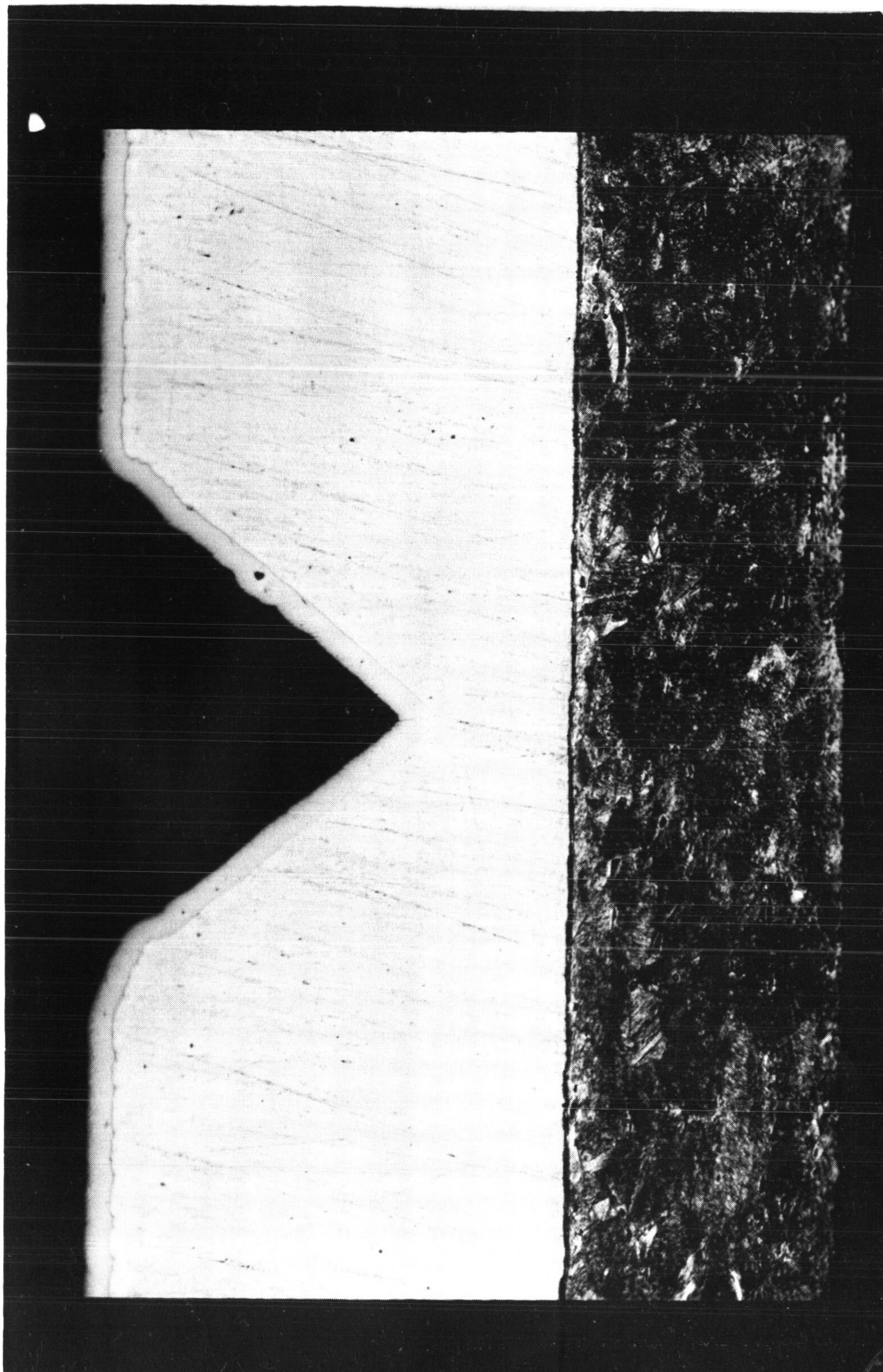

Fig. 6: Photomicrograph of the Cross-Section of
Autronex NI Gold Plated Ring. Magnification of 300

plating technology, was selected as the candidate harder substrate material.

Electroformed nickel sleeves were deposited from a sulfamate-type nickel plating bath onto thin-wall cylindrical copper shells. The sulfamate bath was selected for this study because the nickel obtained from such a bath possesses relatively low residual stresses. Specimens were plated at a current density of 144 amperes per square inch employing rapid rotation. Plating runs of 3 to 4 hours were required to build up the required thickness. The bath was operated at 45°C, and about 3.4 volts. The resultant deposits were lustrous, smooth, and showed a diamond pyramid hardness (DPH) of 285 under 100 gram loading.

Two types of overlays were used: Orotherm HT and Autronex NI. Both rings were run-in in a vacuum of 10^{-7} torr for over 300 hours. The Orotherm overlay ring had a final noise reading of 0.1 volt peak-to-peak and very little wear debris. The Autronex overlay ring had a noise reading of over one volt and a moderate amount of debris. These results indicated a very small improvement in noise performance of Orotherm overlaid nickel plated rings as compared with soft gold plated rings without hard gold overlays.

The effect of using ultrasonic energy during gold-plating was also studied. A 75-watt Sonogen Z ultrasonic unit operating at a frequency of 25 kHz was used to agitate an

Orotemp 24 gold bath operating at a current density of 25 ampere per square inch. After four hours of operation, two types of plate roughness were exhibited: a fine, pebbled, uniform type of surface, and a gross type of swirled trenching about the bottom areas. In the fine pebbled areas, the smoothness was better than in corresponding specimens plated without ultrasonic agitation. The swirled pattern was unacceptable, but some of the roughness could be eliminated by the proper combination of specimen location and rotation.

All results of run-in tests conducted in a vacuum are tabulated in Section IV, Table V.

F. Lubrication Studies

1. Introduction

The development of a lubricant system necessarily includes the development of a lubricant delivery technique. If the lubricant system is to be applicable for short term use, a one-shot delivery system would be a logical development; however, for a long term mission, a continuous or intermittent lubricant delivery technique has to be developed. Also, additional problems arise if the lubrication system must be compatible with other environments in addition to the vacuum environment, for example, earth environment during check-out or low altitude operation. For the scope of this program it was decided to limit the study to non-replenishing high vacuum lubrication techniques compatible with earth environment.

Apparatus was designed to study friction, wear, electrical noise, and lubrication of different materials in high vacuum. The apparatus consisted of a grooved shaft rotated in a vacuum chamber by a magnetic drive coupling. A weighed piece of 7 mil brush wire was placed in the groove and attached to a microforce transducer. The brush wire was adjusted to give a total weight of 2-1/2 grams, which is the load used in experimental capsules. The lubricant was deposited onto the shaft by evaporation while the shaft was rotating to give a uniform deposition. Shielding was provided to stop the lubricant from contaminating the system. The lateral force on the brush wire was measured with the microforce transducer. Knowing this force and the weight of the wire, the coefficient of friction can be calculated. Fig. 7 shows the apparatus used for lubrication studies.

The lubricant materials that were chosen for testing are soft metals. Using Rabinowicz's Concept of surface energy as a guide, the following hypothesis was developed. A low ratio of the cohesion force of a lubricant film to the adhesion force between the lubricant and the bearing surface tends to minimize friction between the bearing surfaces.

Desired parameters:

1. High adhesion to slip ring by film.
2. High adhesion to rider wire by film.
3. Low film cohesion.

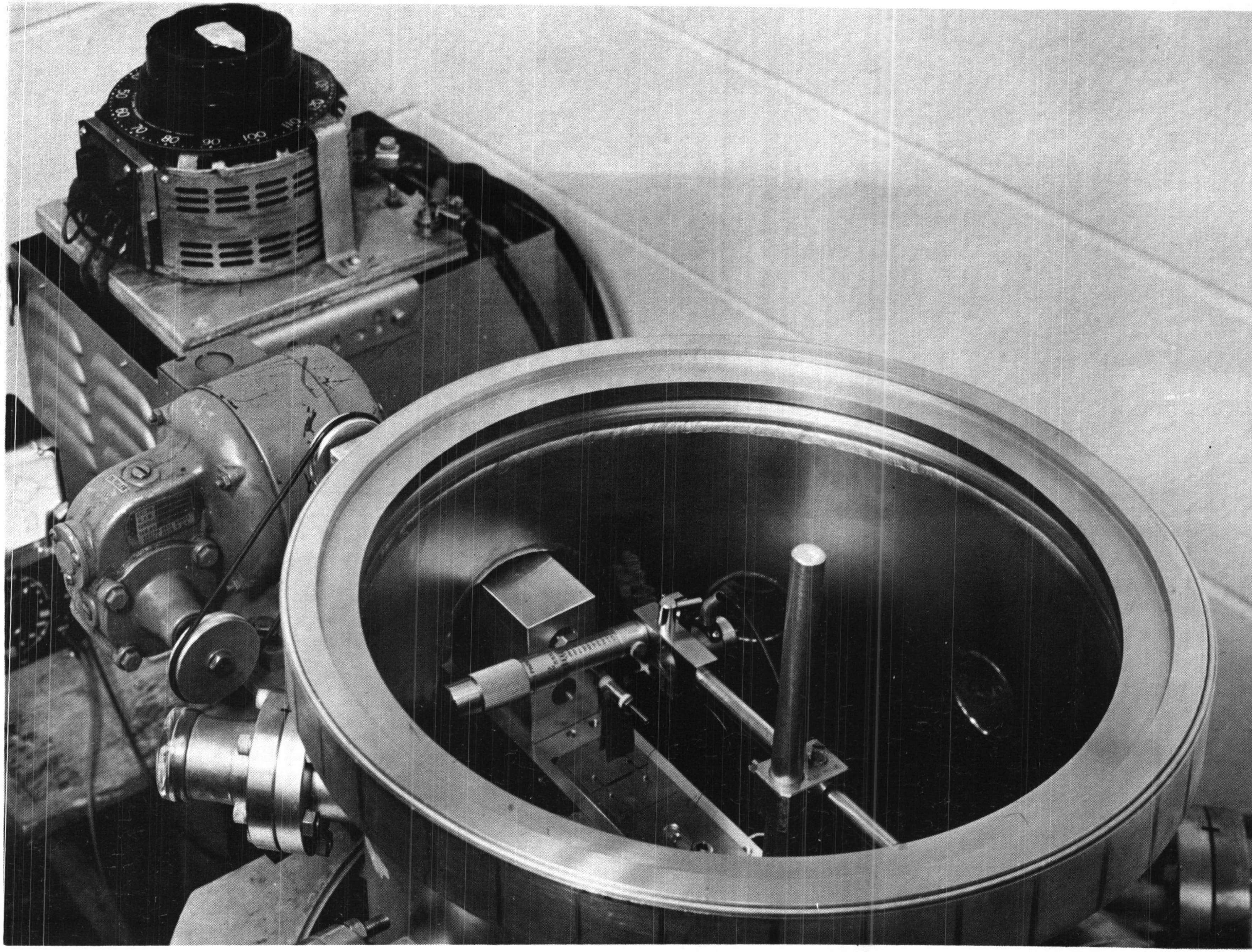

Fig. 7 - CLOSE-UP OF THE APPARATUS USED FOR LUBRICATION STUDIES

4. (1) and (2) imply good wettability by film and also that wetting does not go to completion and then start to "not" wet by alloying, intergranular penetration, etc.
5. Table II lists further desirable properties.
6. Table III lists some relevant constants for various metals from which candidates could be chosen.

There are several candidate metals which could be used. For example, indium satisfies various requirements in the hypothesis. It has an FC lattice while gold has an FCC, its atomic volume is nearly 2-1/2 times that of gold, thus effectively preventing alloying, and its melting point is over 900°C less than that of gold. Other candidate materials are rhodium, chromium, and gold.

A preliminary investigation of the stress in the brush and the contact between the brush and the slip-ring was performed. The maximum bending stress in the 7 mil wire brush with 2.5 g preload and 90° groove was approximately 20,000 psi. The maximum contact stress was on the order of 60,000 psi.

TABLE II

DESIRABLE PROPERTIES OF SYSTEM

	I LUBRICANT	II SLIP RING	III RIDER
a.	Soft-weak in shear	Hard	Hard
b.	Forms film easily	Takes high finish	Takes high finish
c.	Atomic lattice different from II and III	(If possible II & III differ from one another)	
d.	Low surface tension	Must wet	Possibly not wet
		or	
		(Lubricant forms different alloys on II & III so that work of adhesion between II & III is minimized)	
e.	Low modulus of elasticity	High modulus	High modulus
f.	Low melting point for both film application and film shear	Relatively high melting point	Relatively high melting point
g.	Low vapor pressure if one shot application		
h.	High vapor pressure if supplied by continuous or specified time application		

TABLE III

PHYSICAL PROPERTIES OF MATERIALS

LUBRICANT	E MODULUS ELASTICITY psi (x 10^{-6})	HARDNESS	LATTICE TYPE	SURFACE TENSION DYNES/cm	VAPOR PRESSURE @600°C TORR	MELTING POINT °C	ATOM VOLUME cm^3/g-atom	COEF. EXPANSION (°C) x 10^{-6}	DENSITY g/cc	VISCOSITY CENTIPOISE	PRICE $
Barium			BCC(1)	195(1)	10^{-2} 617°C(2)	710(1)	39(1)	18(1)(3)	3.5		
Calcium	4(1)	2 Moh(1)	FCC(1)	255(1)	10^{-1} 683°C(2)	851(1)	25.9(1)	22 x (1i) 717 x (cu)	1.54		
Strontium			FCC(1)	165(1)	10^{-1} 623°C(2)	770(1)	34(1)				
Cadmium	10	2 Moh(1)	Hex.(1)	≈550(1)	1000 μ(2)	321(1)		38(3)(1i)	8.65	2.37 @ 350°C 1.63 @ 600°C	
Bismuth	4.6(1)		Rhombo Hedral	≈350(1)	10^{-2} 661(2)	271(1)	21.3(1)	13.3(1i)(1)	9.8	1.63 @ 300°C 1.00 @ 600°C	
Gallium		1.5-2.5 Moh(1)	Ortho-rhombic	≈700(1)	10^{-5} 757(2)	29.75(1)	9.8	18(1i)(1)	5.91	2.04 @ 30°C 0.592 @ 1000°C	3.00/g(1)
Indium	1.57(1)		FC Tet(1)	600(1)	10^{-5} 670(2)	156(1)	24.8(1)	24.8(1i)(1)	7.3	1.69 @ 200°C 1.32 @ 300°C	2.25/Troy oz (1)
Lithium			BBC(1)	≈400(1)	10^{-1} 623(2)	179(1)		56(1i)(1)	0.5	0.6 @ 180°C 0.44 @ 300°C	1.50/lb(1)
Lead	2.3(3)		Cubic like Cu(3)	460(3)	10^{-3} 627°C(3)	327(3)		30(1i)(3)	11.34	2.32 @ 400°C 1.54 @ 600°C	
Tin	6.8(3)		Tetrag(3)	560(3)	10^{-5} 882(2)	232(3)		24(1i)(3)	7.3	2.71 @ 300°C 0.81 @ 800°C	
Selenium			Hex.(1)		760 685°C(2)	217					7.00/lb(1)
Thallium(Tl)			Cubic(3)	400(1)	10^{-2} 615(2)	303	17.24(1)	28(1i)(1)	11.85		7.50/lb(1)
Zinc	14(3)		Hex.(3)		1 mm at 485°C(3)			34(1i)(1)	7.14	3.67 @ 500°C 3.29 @ 600°C	
Tungsten	59	37C(rock)	BCC				9.53(1)	4.98(1i)	19.3 @20°C(1)		
Gold	11.5	58 Ban(4)	FCC	130(5)	10^{-2} 987	1063	10.2	14	19.3		
Silver	11	25 Vick (4)	FCC	120(5)	10^{-2} 757°C	961	10.3	21	10.5		

(1) Rare Metals Handbook (3) Smithells Structure (5) Guy, Elements of Physical Metallurgy
(2) Dushman (4) Metals Handbook (1i) Linear (cu) Cubic

2. Test Results

During the first two preliminary test runs, several problems were encountered. An individual wiper arm of a brush was used and one of the problems in using this free floating rider was that sticking would occur between the brush and the ring causing the rider to unbalance. This problem was solved by carefully balancing the rider and making several mechanical adjustments to insure that no vibration was being transferred to the ring from the driver motor, and that alignment was very accurate. Another problem was in perfection of the sublimation technique. During the first two runs, an insufficient amount of indium was deposited onto the rings. This involved a redesign of the indium crucible using a tantalum boat. Fig. 8 shows the first indium coated ring. During the first successful run, the slip rings were rotated at 200 rpm with a 25 mA dc current in the brush ring circuit. The electrical noise averaged 5 millivolts in a vacuum of 10^{-7} torr. The force on the transducer was 2.6 grams. Sublimation of indium was continued for ten seconds. The force on the transducer rose sharply to 7.9 grams and then came back immediately after sublimation to 2.1 grams. The noise dropped to an average level of 0.1 millivolts. After ten minutes of operation the force was 1.6 grams and the noise level was 1.2 millivolts. After seven hours the friction had increased to 4.3 grams. No noise measurement could be made since one of the wires internally connected to the ring had

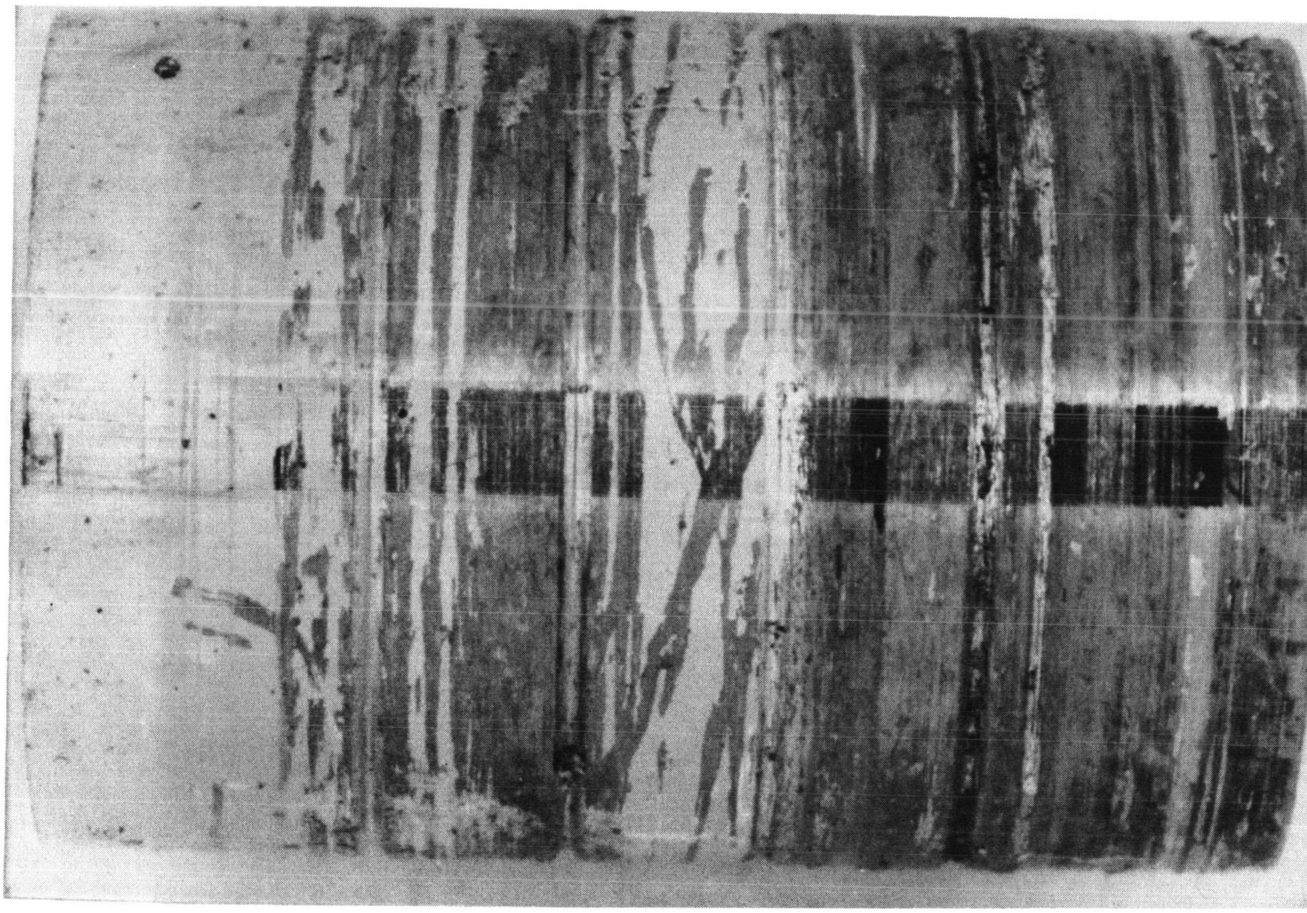

Fig. 8: First Indium Coated Ring

Magnification of 20

broken. The dramatic reduction of noise and friction immediately upon sublimation appeared to be very promising.

Additional test runs of an experimental slip ring with vapor deposited indium were carried out in a vacuum of less than 10^{-7} torr. The results obtained from previous tests have been confirmed. A dramatic reduction of noise level occurred upon sublimation. The sublimation technique has been improved to ensure a more uniform and sufficient deposition of the lubricant.

The object of another test was to study the durability of indium lubrication with respect to electrical noise. After 360 hours of continuous rotation at 200 rpm in a vacuum of 10^{-8} torr with 25 mA of dc current through the brush ring circuit, the electrical noise leveled off at 4 millivolts peak-to-peak. In a concurrently run test under similar conditions with unlubricated slip rings, the noise level increased to over two volts after 364 hours. Visual inspection of the indium plated ring indicated a uniform coating with very little debris and wear.

Fig. 9 shows an acceptable coating of indium. Fig. 10 shows the rider after use on an indium coated ring. Note the buildup of indium on gold wire. This buildup is shown also on Fig. 11. Figs. 12 through 15 show groove tracks of indium coated rings, after run-in tests.

Gallium was the next soft metal lubricant that was evaluated. In a test run of a slip ring with vapor deposited

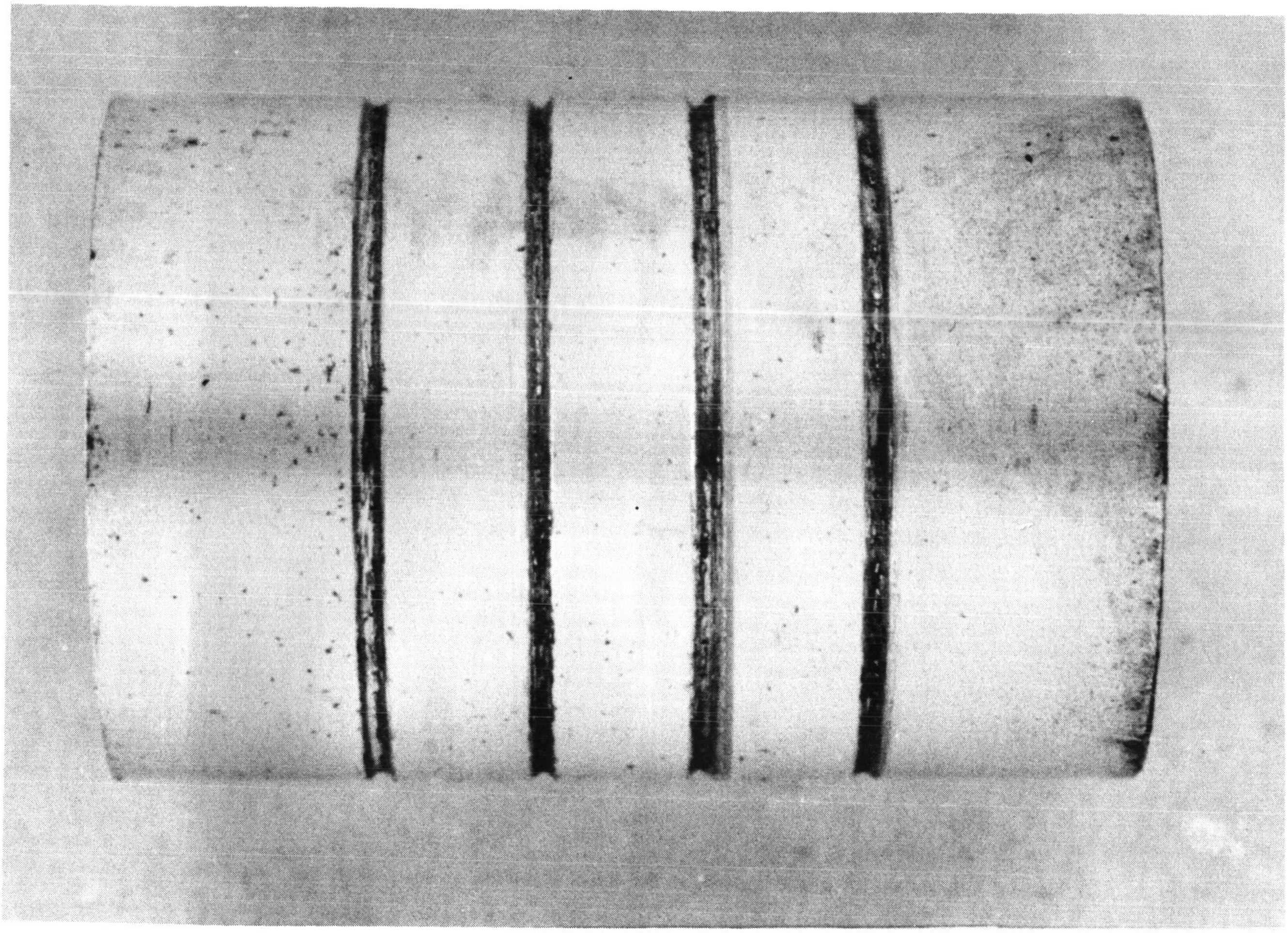

Fig. 9: Indium Coated Ring

Magnification of 18

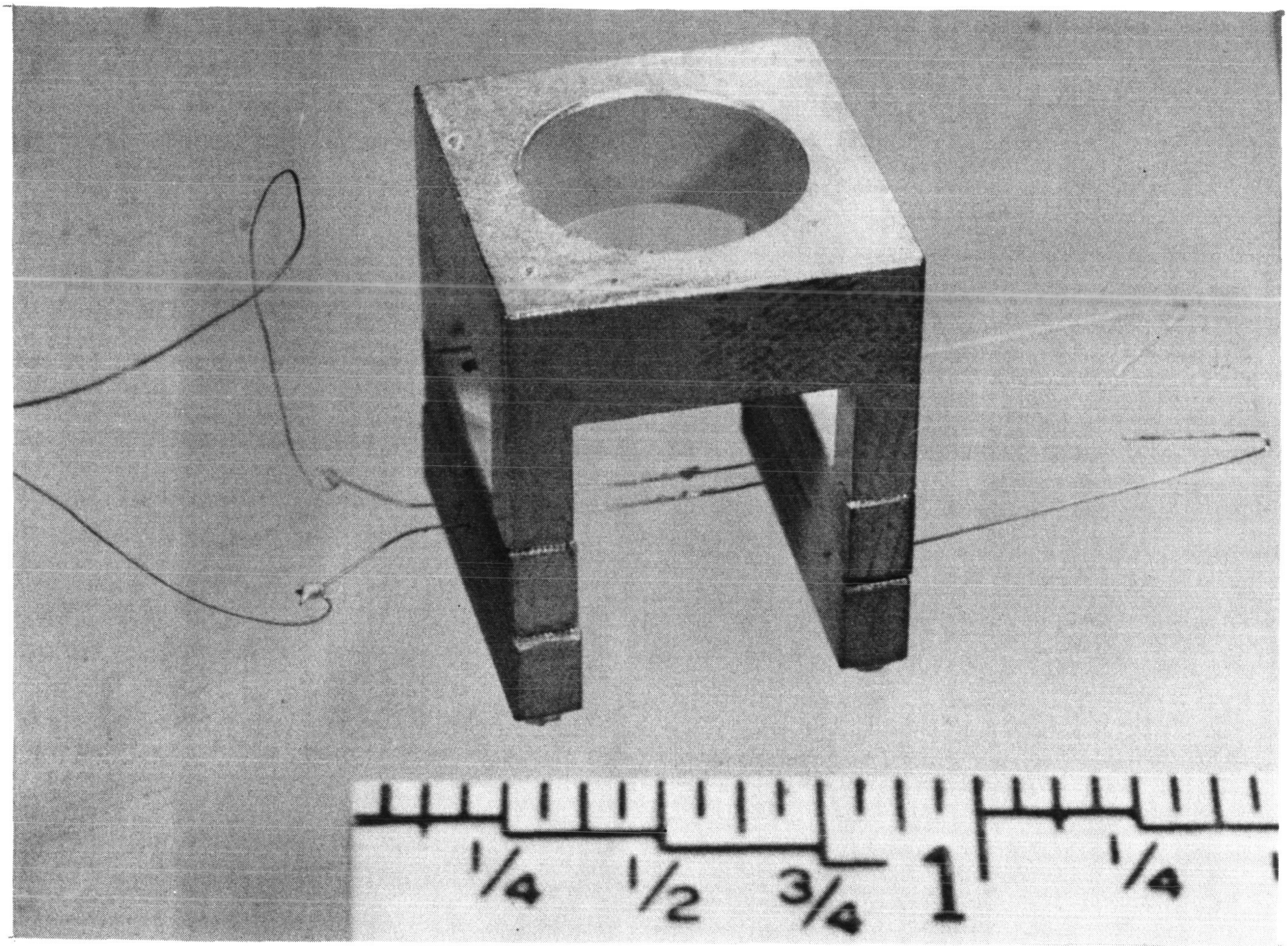

Fig. 10: Rider after Use on Indium Coated Ring

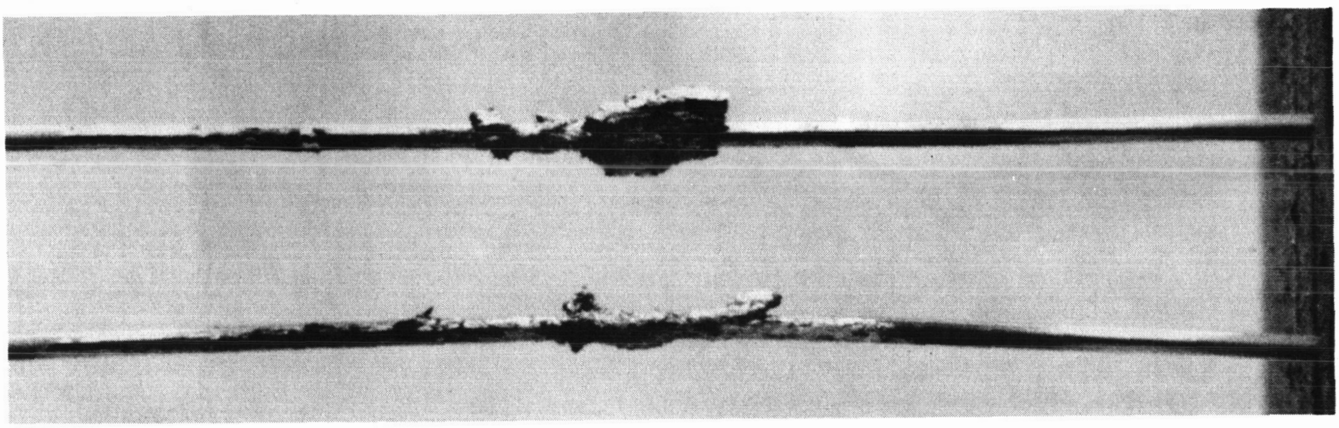

Fig. 11: Indium Build Up on Gold Wire of the Rider
Magnification of 20

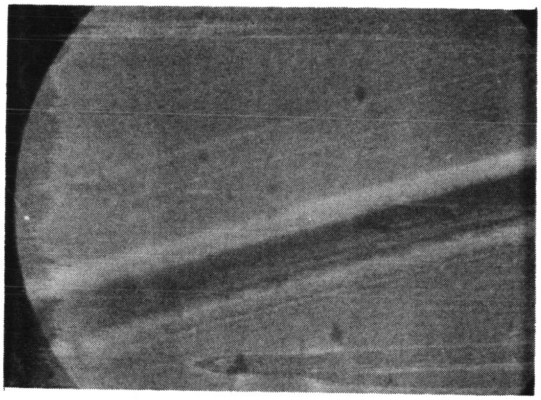

Fig. 12
Magnification of 25

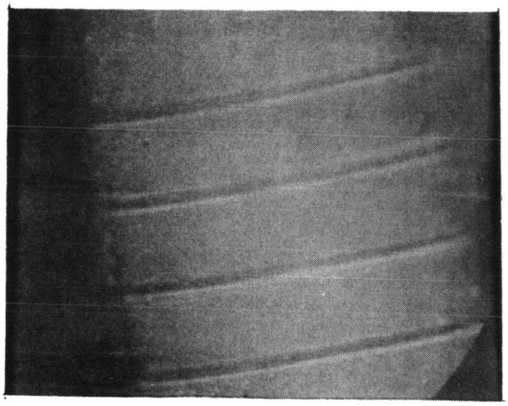

Fig. 13
Magnification of 20

Groove Track of Ring #88 Coated with
Indium after 367 Hours of Running

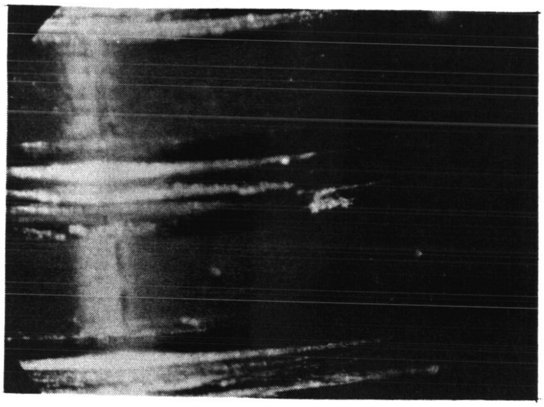

Fig. 14

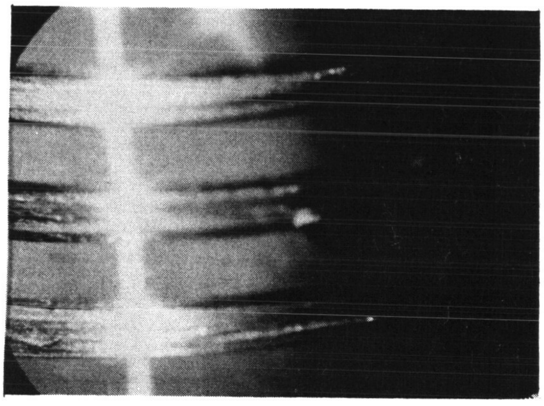

Fig. 15

Groove Track of Ring #89 Coated with
Indium after 70 Min. of Running
Magnification of 20

gallium the initial noise was 1,200 microvolts. During the sublimation, the noise decreased to 300 microvolts and after more than 900 hours of continuous rotation in a vacuum of 10^{-7} torr, the noise leveled off at one millivolt peak-to-peak. Visual inspection of the gallium plated ring indicated a uniform coating with very little debris and wear. Figs. 16 and 17 show the groove tracks of gallium coated rings after 433 hours of running. Note absence of any debris.

Measurements of friction were made both on indium and gallium coated rings, and on the niobium diselenide ring. Fig. 18 shows the niobium diselenide ring. The right groove track is after 45 hours of running and the left track is unused (as received). The results of friction and noise measurements are shown in Figs. 19, 20, and 21 and in Section IV Table VI.

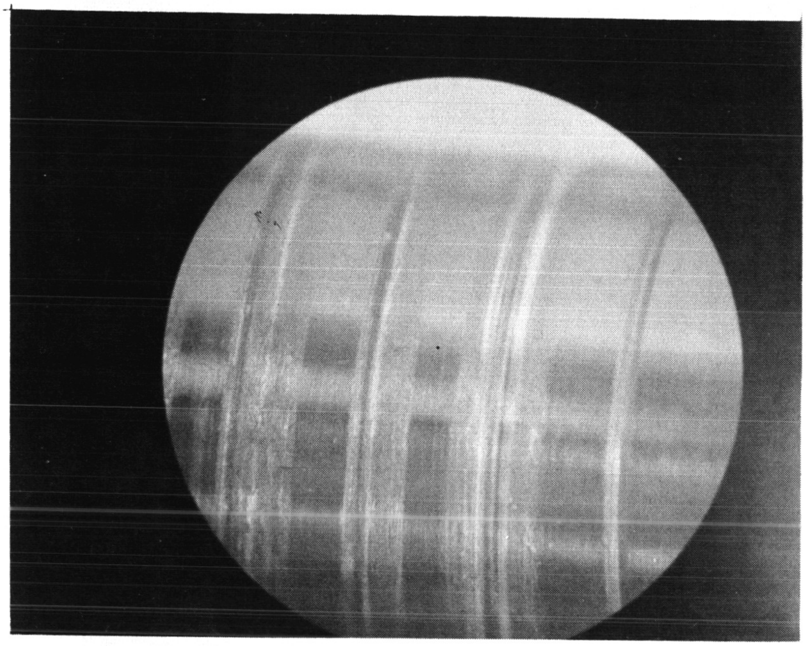

Fig. 16

Magnification of 15

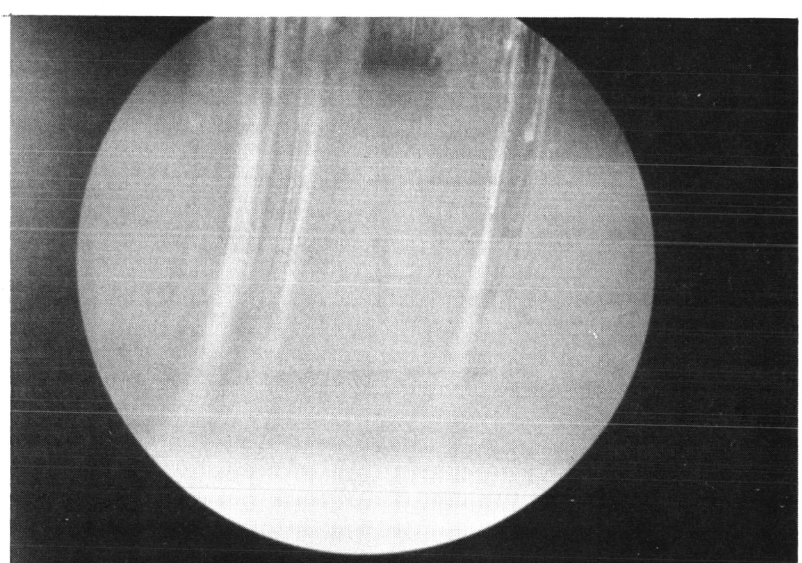

Fig. 17: Groove Track of Ring Coated with Gallium after 433 Hours of Running

Magnification of 20

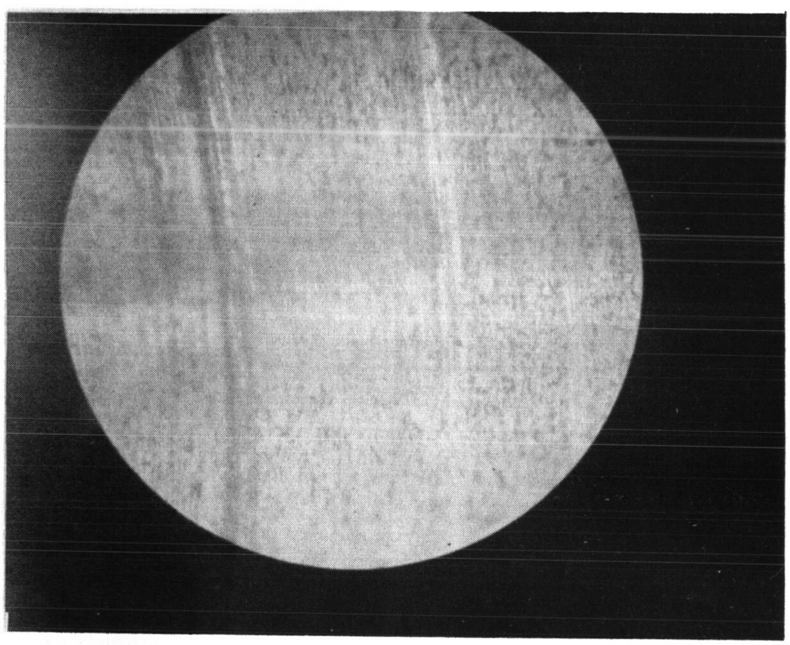

Fig. 18: Niobium Diselenide Ring
Magnification of 20

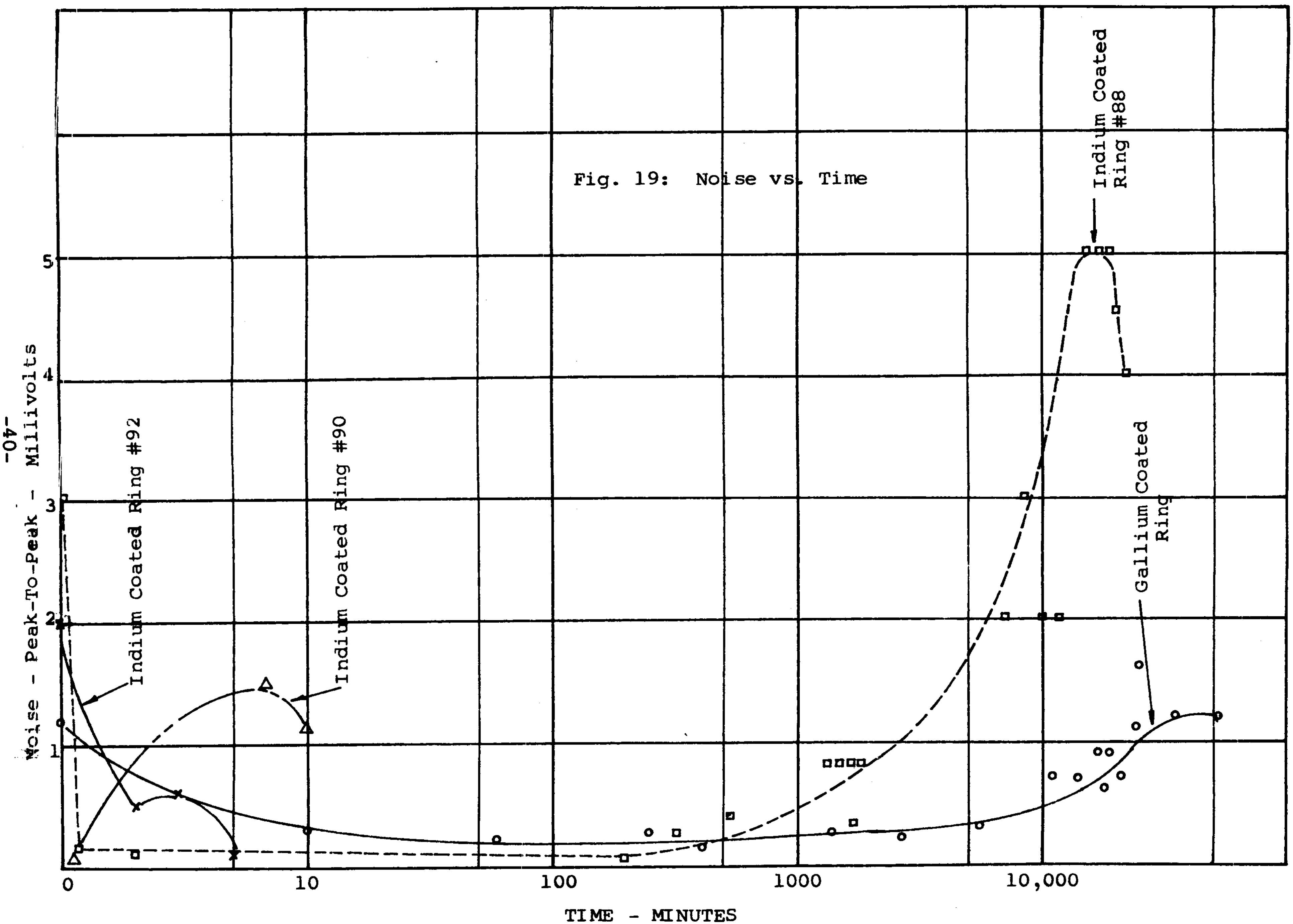

Fig. 19: Noise vs. Time

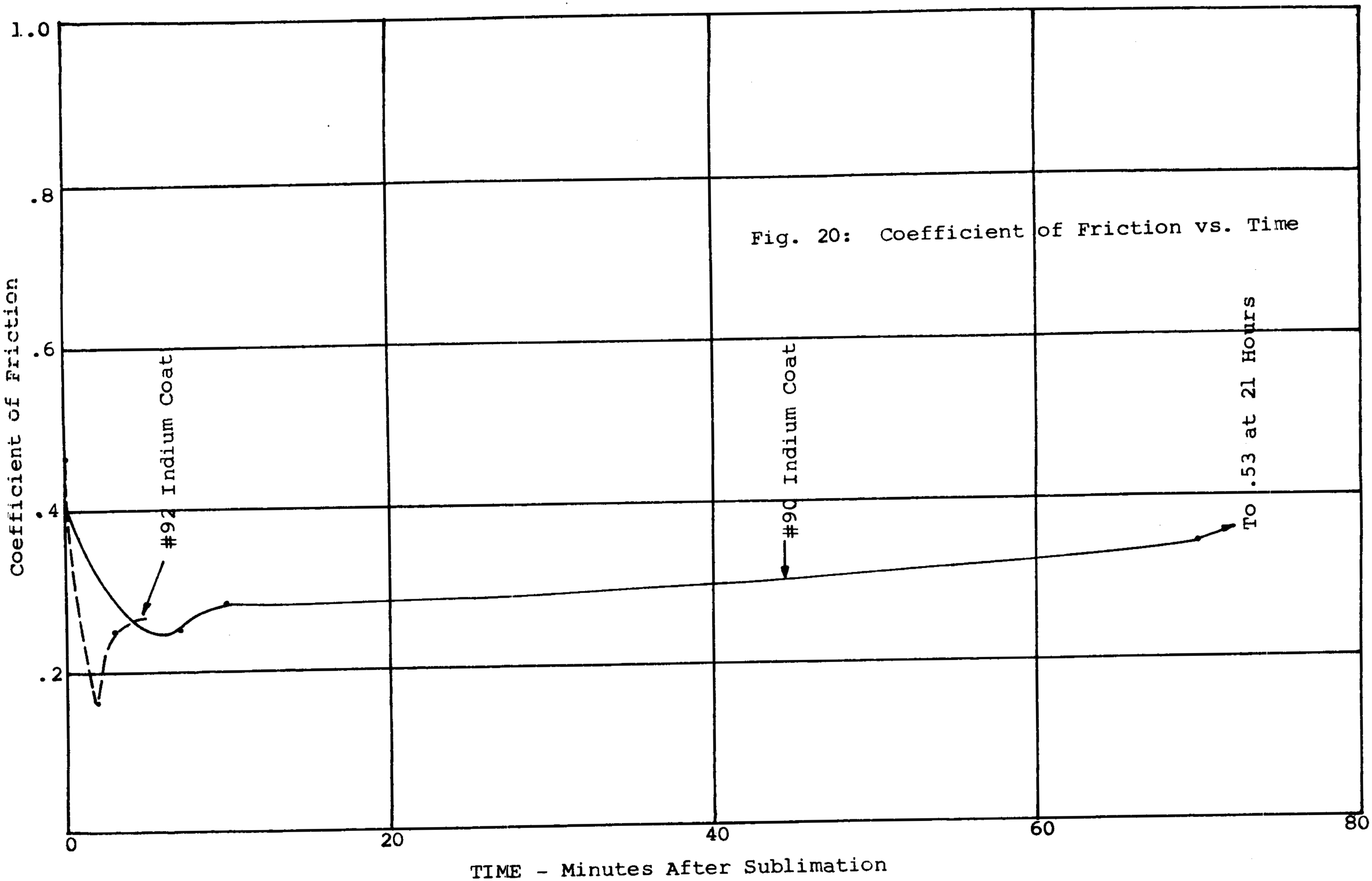
Fig. 20: Coefficient of Friction vs. Time
Coefficient of Friction
1.0
.8
.6
.4
.2
0
20
40
60
80
TIME - Minutes After Sublimation
#92 Indium Coat
#90 Indium Coat
To .53 at 21 Hours

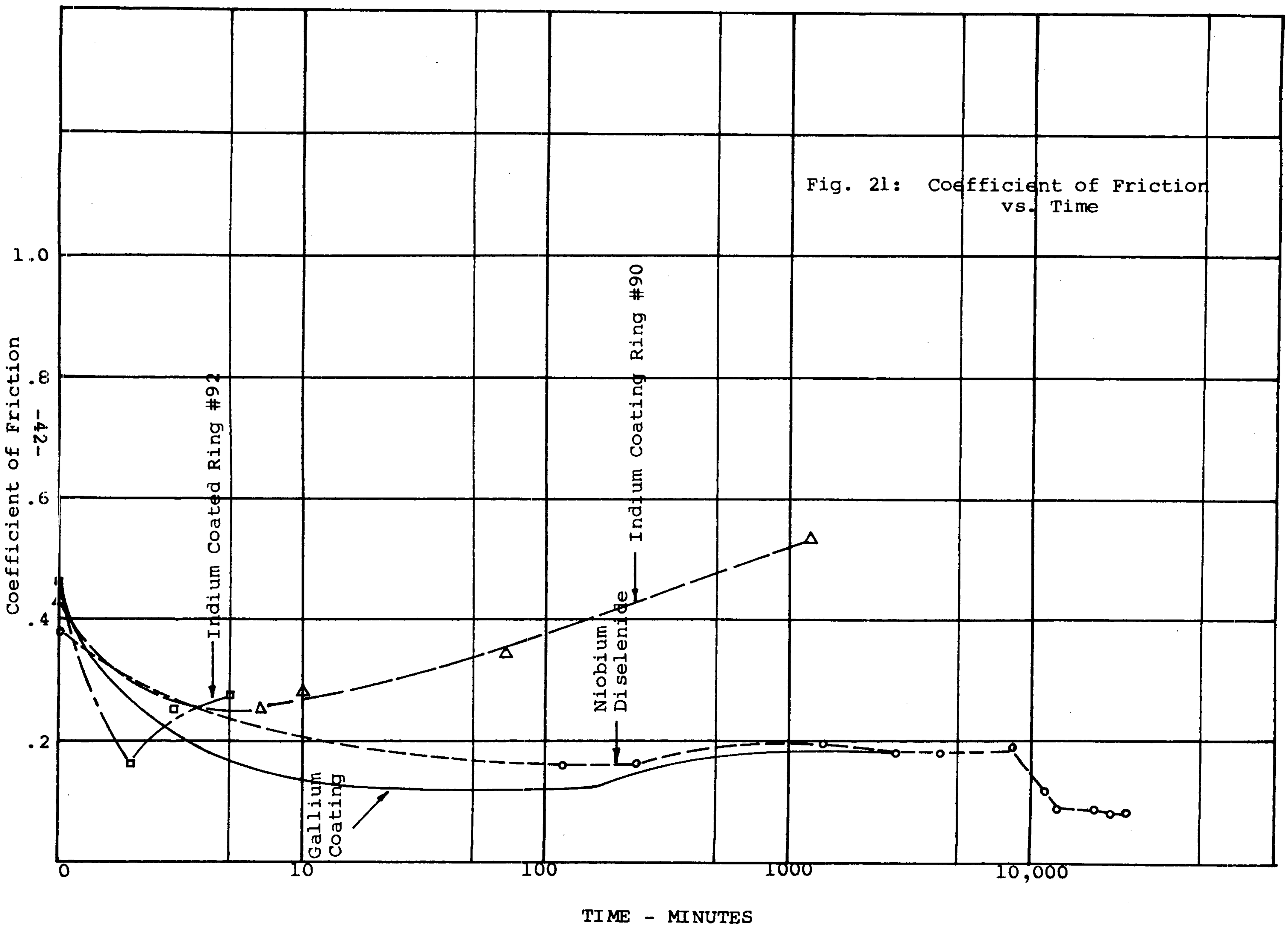
Fig. 21: Coefficient of Friction
vs. Time
Coefficient of Friction
1.0
.8
.6
.4
.2
0
10
100
1000
10,000
TIME - MINUTES
Indium Coated Ring #92
Indium Coating Ring #90
Niobium
Diselenide
Gallium
Coating

IV. TABULATION OF DATA

Tables IV and V give the tabulated results of inert atmosphere and high vacuum tests. Table VI gives the results of lubrication studies.

TABLE IV

RESULTS OF INERT ATMOSPHERE TESTS

TEST CONDITIONS	TIME-HOURS	PEAK-TO-PEAK NOISE-MICROVOLTS
New brush design	0 428	20 100
Orotherm HT	0 330	50 100
Autronex NI	0 298	40 150
Orotherm HT	0 288	40 150
Autronex NI	0 331	40 100
Truncated Wire	0 302	40 150
Autronex NI	0 840	20 120
Lubricant A	0 240	50 700
Lubricant B	0 552	50 250
Lubricant A	0 624	150 300

TABLE V

RESULTS OF HIGH VACUUM TESTS

TEST CONDITIONS	VACUUM TORR	TIME HOURS	PEAK-RO-PEAK NOISE MILLIVOLTS
Capsule 2-64	5×10^{-6}	0	0.150
	5×10^{-6}	253	1500
Capsule 2-73	10^{-6}	0	0.05
	10^{-6}	216	300
Capsule 2-74	2×10^{-7}	0	0.5
	2×10^{-7}	288	1000
Capsule 2-75	5×10^{-6}	0	0.5
	10^{-7}	284	2000
Truncated Wire	3×10^{-7}	0	0.2
	10^{-7}	302	1500
Ion Pump, Capsule 2-76	8×10^{-7}	0	0.5
	4×10^{-7}	364	2000
Autronex on Nickel	5×10^{-6}	0	300
	10^{-7}	336	1100
Orotherm on Nickel	10^{-7}	0	0.4
	10^{-7}	312	100
Lubricant A	10^{-6}	0	0.2
	8×10^{-7}	352	0.6
Niobium diselenide	10^{-6}	0	1.0
	2×10^{-8}	408	5.0
Lubricant B	3×10^{-6}	0	0.4
	10^{-7}	384	0.8

TABLE VI

RESULTS OF LUBRICATION STUDIES

Condition	Ring No.	Time	Coefficient of Friction	Force (grams)	Noise Peak-to-Peak (25 ma Current)	Pressure (torr)
Gold Ring, Indium Film Evaporation	90	Before Sub.	.43	2.4	5 MV	1×10^{-7}
		Sub. for 10 sec	---	---		
		5 sec	.37	2.1	0.1 MV	
		7 min	.25	1.4	1.5 MV	
		10 min	.28	1.6	1.2 MV	
		70 min	.34	1.9	------	
		21 hrs	.53	2.9	------	
Gold Ring, Indium Film Evaporation	92	Before	.46	2.6	2 MV	5×10^{-8}
		Sublimation	---	---	---	
		2 min	.16	.9	.5 MV	
		3 min	.25	1.4	.6 MV	
		5 min	.27	1.5	.2 MV	
		Back to Air	.30	1.7	1.5 MV	Ambient
Gold Ring, Indium Film Evaporation	89	Before (30 min run in)	--	---	.3 MV	6×10^{-9}
		Sublimation	--	---	------	
		20 sec	--	---	.3 MV	
		70 min	--	---	.2 MV	
Gold Ring, Indium Film Evaporation	88	Before (30 min run in)	--	---	.3 MV	8×10^{-9}
		Sublimation	--	---	------	
		2 min			.100 MV	
		3 hrs, 20 min	--	---	.050 MV	
		5 hrs, 40 min	--	---	.250 MV	
		9 hrs, 00 min	--	---	.400 MV	
		23 hrs, 10 min	--	---	.800 MV	
		25 hrs, 10 min	--	---	.800 MV	
		26 hrs, 40 min	--	---	.300 MV	

TABLE VI (cont'd.)

Condition	Ring No.	Time	Coefficient of Friction	Force (grams)	Noise Peak-to-Peak (25 ma Current)	Pressure (torr)
Gold Ring, Indium Film Evaporation	88 (Con'd)	Sub. more indium				
		26 hrs, 50 min	--	---	.300 MV	
		29 hrs, 00 min	--	---	.800 MV	
		5 days	--	---	2 MV	
		6 days	--	---	3 MV	
		7 days	--	---	2 MV	
		8 days	--	---	2 MV	
		11 days	--	---	5 MV	
		12 days	--	---	5 MV	
		13 days	--	---	5 MV	
		14 days	--	---	4.15 MV	
		15 days	--	---	4 MV	
Gallium Evaporation Unnumbered Gold Ring	--	Before 1 hr run	--	---	1.200 MV	1×10^{-7}
		Sub. gallium				
		10 min.	--	---	.300 MV	
		1 hr	--	---	.200 MV	
		4.3 hrs	--	---	.250 MV	
		7.0 hrs	--	---	.120 MV	
		1 day	--	---	.250 MV	
		2 days	--	---	.200 MV	
		3 days	--	---	.220 MV	
		4 days	--	---	.300 MV	
		8 days	--	---	.700 MV	
		9 days	--	---	.900 MV	
		10 days	--	---	.700 MV	
		11 days	--	---	.900 MV	
		12 days	--	---	.600 MV	
		13 days	--	---	.900 MV	
		14 days	--	---	.600 MV	
		15 days	--	---	.700 MV	
		16 days	--	---	1.000 MV	
		17 days	--	---	1.100 MV	

TABLE VI (cont'd.)

Condition	Ring No.	Time	Coefficient of Friction	Force (grams)	Noise Peak-to-Peak (25 ma Current)	Pressure (torr)
Gallium Evaporation Unnumbered Gold Ring (Continued)	--	21 days	--	---	1.600 MV	
		22 days	--	---	1.200 MV	
		24 days	--	---	1.300 MV	
		25 days	--	---	1.200 MV	
		29 days	--	---	1.100 MV	
		30 days	--	---	1.100 MV	
		31 days	--	---	1.200 MV	
		32 days	--	---	1.000 MV	
		35 days=	--	---	1.100 MV	
		36 days	--	---	1.200 MV	
		37 days	--	---	---	
		38 days	--	---	1.000 MV	
Gallium Evaporation New Ring	--	4 hr run in Sub. Gallium	.50	2.80	---	7×10^{-8}
		5 min	.16	.92	---	
		3 hrs	.13	.75	---	
		5 hrs	.16	.92	---	
		24 hrs	.18	1.00	---	
		46 hrs	.18	1.00	---	
Niobium Diselinide Ring in Silver Matrix NOTE: New rider installed	--	Start	.38	2.00	---	7×10^{-7}
		2 hrs	.16	.83	---	
		4 hrs	.16	.83	---	
		24 hrs	.19	1.00	---	
		48 hrs	.18	.96	---	
		3 days	.18	.96	---	
		6 days	.19	1.00	---	
		8 days	.11	.58	---	
		9 days	.09	.50	---	
		13 days	.09	.50	---	
		15 days	.08	.42	---	
		16 days	.08	.42	---	
		17 days	.08	.42	---	

V. SUMMARY AND CONCLUSIONS

The results of the investigation conducted during this phase of the program based on close to 10,000 hours of testing can be summarized as follows:

A. Run-in tests of unlubricated experimental capsules in a high vacuum showed that unacceptable noise levels were developed in a short time.

B. Electrical noise generated in high vacuum consisted primarily of low frequency components.

C. Proper selection of organic component materials eliminated the off-gassing problems.

D. Noise level was independent of current, at least up to 25 mA.

E. A soft metal vapor plating technique was developed which resulted in a substantially improved noise performance.

F. Two commercially available vacuum lubricants were beneficial in improving noise characteristics.

G. Hard gold overplating both on soft gold and on nickel did not result in improved performance.

H. The niobium diselenide ring had better noise performance than soft gold rings.

VI. RECOMMENDATIONS

The results obtained during this program show several possible approaches to improve the performance of miniature slip rings in a high vacuum. Therefore, it is recommended that the following activities be further pursued:

A. Further work on plating of slip rings, preferably with a hard metal such as chromium. This would give a correlation with the present data in which all plating was done with soft metals. The literature indicates that some of the hard metals such as chromium should perform well under vacuum.

B. The use of a vapor plating technique developed by IITRI in which the slip ring could be directly plated with a solid lubricant which would have a very tenacious bond. Preliminary results using this process indicate that this might be a very fruitful area.

C. A study to determine the effects of cleaning under vacuum conditions. The type of cleaning to be investigated would be glow discharge and ion or electron bombardment. A more thorough cleaning of the rings could cause a more tenacious bond between the evaporated material and the ring to occur, and this might lead to some improvement in the performance of the slip rings.

D. A continuation in the investigation of the use of other composite lubricant materials. The results of using the niobium diselenide ring are promising, however, the noise level was not commensurately low with the coefficient of friction. Other composite materials could supply both a low coefficient of friction and a low noise.

E. The concept of using precious metal addition agents in gold electroplating baths for the purpose of obtaining harder deposits is basicially sound. Although experimental work to date on this approach to electroplating more wear-resistant gold has shown negative results, it is recommended that the work be continued to higher addition agent levels than hitherto investigated. The maximum level of addition agents in past work was 1 per cent; levels of 10 per cent or higher should be investigated.

F. Further study of commercially available lubricants of the non-hydrocarbon, non-silicone type.

G. A fundamental study of the mechanism of friction and wear under vacuum conditions. The results of this study could be used in the design and fabrication of a slip ring which would greatly eliminate the wear and debris particle buildup from accumulating in the ring grooves which appears to cause much of the noise.

H. A basic study of performance of lubricated, low current contacts other than slip rings in a high vacuum.

VII. CONTRIBUTING PERSONNEL AND LOGBOOKS

Significant contributions to the overall effort of this program were made by the following IITRI staff members:

Off-gassing Studies and Spectrographic Analysis --

H. J. O'Neill,
Research Chemist

Electroplating Studies and Hard Gold Overlays --

W. H. Graft,
Research Metallurgist

Laboratory Evaluation --

O. M. Kuritza,
Research Engineer and

I. L. Krulac,
Experimental Engineer

Lubrication Studies --

M. L. Lerner
Research Engineer

Capsule and Apparatus Fabrication --

M. Holzer, Jr.,
Model Maker

Technical Direction --

J. L. Radnik
Manager
Power Systems and Components

The detailed laboratory data is contained in IITRI Logbooks C14069, C14223, C14942, C15698, and C16915.