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IN-FLIGHT AND LABORATORY VACUUM-FRICTION TEST RESULTS

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16. Abstract

Coefficient of friction measurements were made for six unlubricated metal couples exposed to the space environment aboard the OV-1-13 spacecraft and exposed to laboratory vacuum. Materials studied included mutually soluble, partially soluble, and insoluble metal combinations. Two samples of each material couple were tested in space and in the laboratory using the disk and rider technique. Linear velocity was 0.10 cm/s (2.5 in/min) and rider normal load was 4.45 N (1 lb) for the gold versus silver couples and 8.90 N (2 lb) for the other combinations. Results showed that friction data obtained in a clean ion-pumped laboratory vacuum of 10^{-10} torr for materials with low mutual solubility can be correlated to operation in the vicinity of a typical scientific spacecraft that is exposed to an ambient pressure as low as 10^{-12} torr. The expected increase in coefficient of friction with solubility was shown. Material couples with high mutual solubility present the hazard of unpredictable drastic friction increase in orbit which may not be evident in laboratory testing at levels down to 10^{-10} torr. It was also shown that gross cold welding of unlubricated metals exposed to a satellite environment does not occur.

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INTRODUCTION

It is well recognized that the increased tendency of cold welding (friction) and wear in vacuum are potentially serious hazards to mechanical devices operating in space. When exposed to the space environment, conventional lubricants rapidly evaporate, oxide films disappear once disrupted, and chemically clean metal surfaces can come into intimate contact. The result is drastically increased friction and wear due to adhesion (cold welding).[1] This cold-welding phenomenon in space is of great interest to unmanned spacecraft instrument and equipment designers and especially to the manned space effort because such procedures as repeated orbital docking and assembly may be affected by cold welding.

A very widespread and costly effort was undertaken to investigate this problem under laboratory simulation of the space environment. At one time a count showed that approximately 100 groups (both government and industry) had been or were studying cold welding and wear. Most of these studies involve vacuum effects.

In view of the large expenditure of resources in this area, using laboratory techniques that may or may not have been giving valid data, it was felt that the time had come to establish conclusively just what and how bad were the problems in space regarding materials and components.

In contrast to the extensive laboratory investigations and in view of the recognized importance of the friction and wear problem, it was surprising that very little data had been, or were planned to be, obtained in the actual space environment. The only previously planned experiments were carried out by the Jet Propulsion Laboratory[2] on the early Ranger flights and the Air Force Rocket Propulsion Laboratory using the Experimental Research Satellite.[3]

OBJECTIVE

The major objective of this program was to determine the effect of the actual space environment on friction (cold welding) and wear of widely-used spacecraft materials. In addition to verifying or disproving laboratory results, this experiment was planned to establish a better definition of the degree of vacuum required for an adequate simulation of the space environment.

To achieve these objectives, restrictions had to be applied to the experiment design. Experiment operation, cleanliness, location on the spacecraft, and orbit were prime considerations.

APPROACH

It was decided that the disk and rider technique would be used for measuring cold-welding tendency and wear. Welding tendency was determined by measuring the strain induced in a cantilever beam supporting the rider. Semiconductor strain gages mounted on the beam were selected for this measurement. Seven disks and twelve riders were picked as a realistic sample size.

Cleanliness is mandatory when conducting experiments involving material surface effects.[4] Great care was required in designing the experiment to minimize the possibility of contaminating the material couples. Design of the drive train, instrumentation, and material selection had to be made with the objective of minimizing outgassing. The drive train had to be hermetically sealed and materials with vapor pressures less than 10^{-13} torr had to be used.

To minimize contamination by outgassing from the satellite and at the same time to give maximum exposure of the experiment to the space environment, it was necessary to mount the experiment on the outer surface of the spacecraft and to baffle it from any potential outgassing source.

Most of the laboratory test work was done at pressures of 10^{-8} to 10^{-9} torr; therefore, it was required that the orbit chosen for this experiment have an apogee that would expose the spacecraft to a pressure less than 10^{-10} torr, preferably 10^{-12} torr. This condition would shed light on the degree of vacuum required for adequate simulation.

The materials selected for study are commonly used in spacecraft and also have properties that enable the effects of mutual solubility and hardness to be studied. Materials were:

- Gold and silver
- 7075 anodized aluminum and 440C stainless steel (Rc60)
- 440C stainless steel (Rc60) and 440C stainless steel (Rc60)
- 440C stainless steel (Rc60) and nitrided Nitralloy 135 mod steel
- 440C stainless steel (Rc60) and 1020 carbon steel
- Be-Cu alloy 25 no. 190 heat treat and 440C stainless steel (Rc60)

Two samples of each of these combinations were tested with each experiment module (laboratory and orbital units).

IN-ORBIT PROGRAM

The Air Force Orbiting Vehicle-1 (OV-1) program appeared to be compatible with the experiment objectives.

Spacecraft

The OV-1 was developed by the Air Force to provide an economical, multipurpose vehicle that could accommodate and support a wide variety of scientific experiment payloads that would be launched aboard the Atlas booster. Basically, the satellite is a cylinder 68.5 cm (27 in) in diameter by 83.8 cm (33 in) in length with solar cell domes mounted on each end. Total overall spacecraft length is approximately 137 cm (54 in). The nominal total spacecraft weight is approximately 1330 N (300 lb), of which 750 N (170 lb) is scientific instrumentation. The secondary propulsion system (Figure 1) has the capability of placing this payload in an eccentric orbit with an apogee of 9250 km (5000 n.m.) and a perigee of 537 km (290 n.m.). This would carry the experiment into pressure regions ranging from 10^{-12} to 10^{-8} torr.

Telemetry

The OV-1-13 satellite telemetry is a pulse-code modulation, frequency modulation (PCM-FM) system. System capability permits combining analog and digital data into a serial pulse-train that gives a data rate of 2048 bits per second. This system permits readout of 253 prime channels of information and 64 channels of subcommutated information. Both real-time and stored data can be obtained. Stored data are accumulated on a reel-to-reel digital-data magnetic tape recorder. This recorder has a four-hour record capacity. In the playback mode the recorded data are reproduced in reverse order at 16 times the record rate (2048 bps record is played back at 32,768 bps). This permits the entire contents of the recorder to be transmitted in 15 minutes.

The spacecraft is spin-stabilized; hence, surfaces are alternately exposed to solar energy inputs and radiation into deep space. The use of thermal coatings applied to exposed surfaces is all that is normally required for thermal control.

Several factors in this experiment posed problems beyond those usually encountered by spacecraft scientific instrumentation. Because the experiment was to measure space-environmental effects, it was necessary to mount the module outside the satellite skin (Figure 2). This arrangement exposed the instrument to both direct sunlight and direct viewing of deep space. To compound the problem, thermal-control paints could not be used because of the possibility of contaminating the material surfaces under study. This

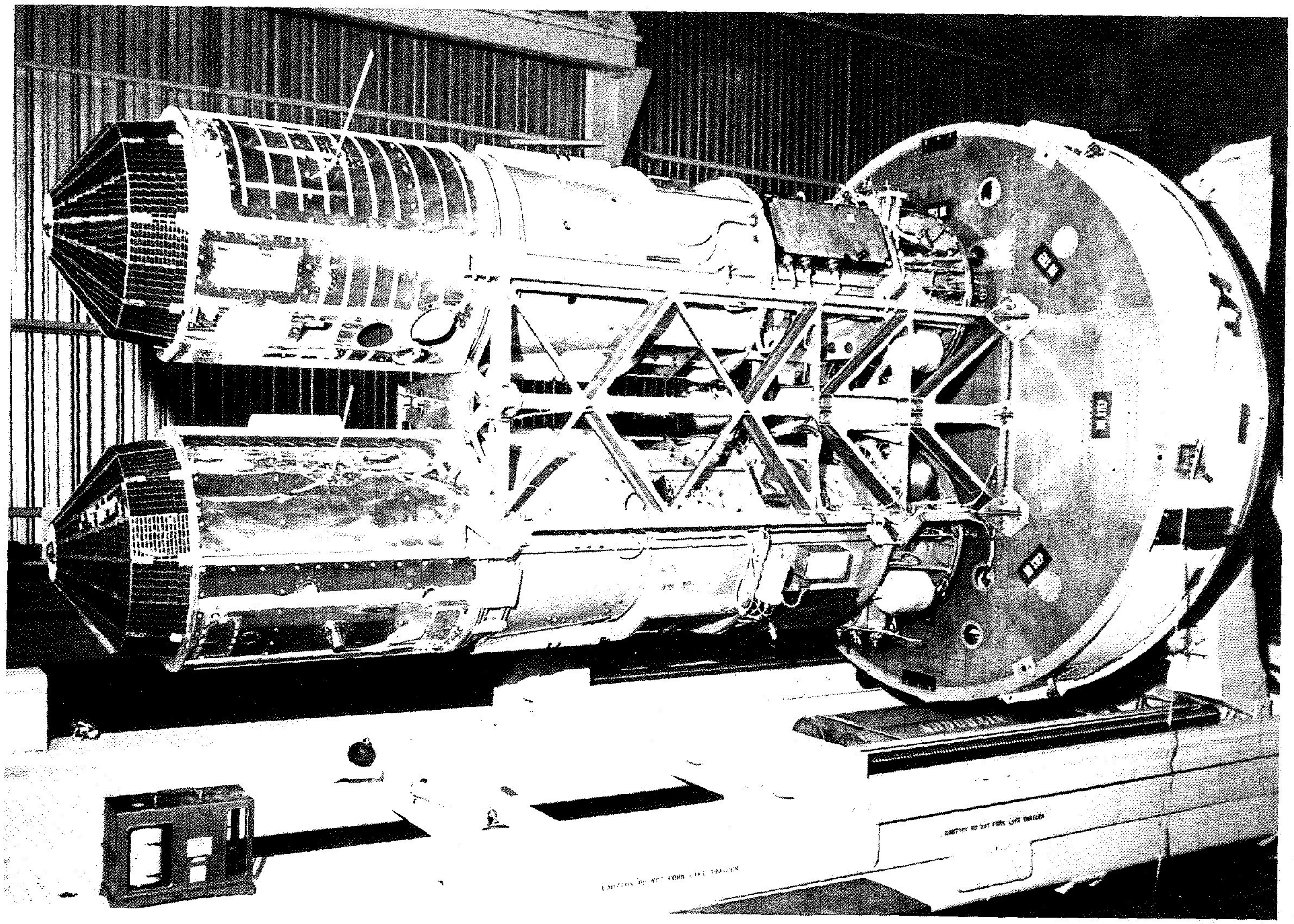


Figure 1. OV-1-13 mounted on secondary propulsion module.

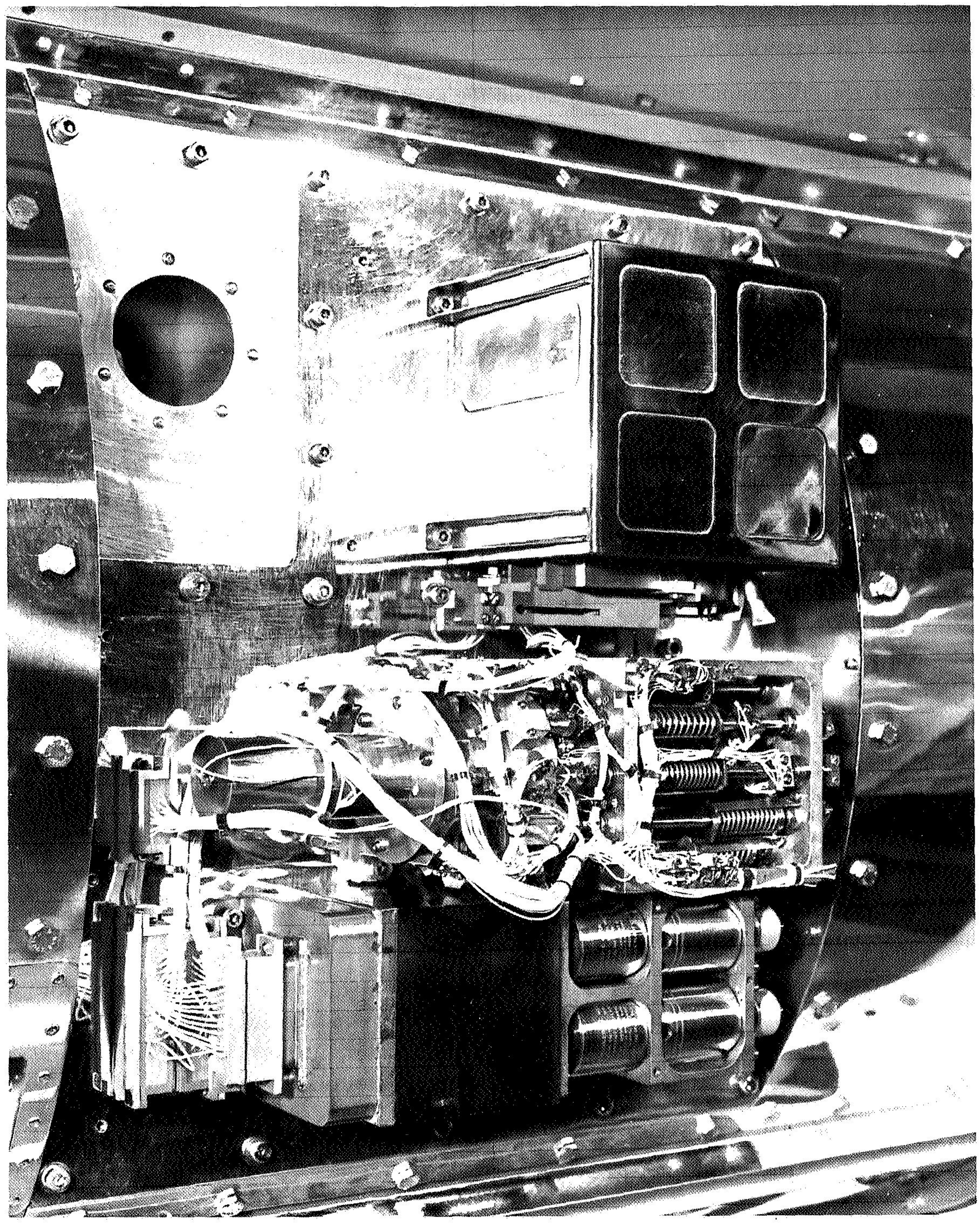


Figure 2. Friction-and-wear experiment mounted on spacecraft.

put great stress on sun and shadow time and reflectance and absorption of bare metallic surfaces of the experiment.

In general, the OV-1 capabilities ideally suited the experiment requirements.

Instrumentation

The basic friction-test mechanism consists of a hemispherical rider sliding on the flat face of a disk rotated at constant velocity. This geometry is simple and has been widely used in past investigations of vacuum effects on friction phenomena.

Parameters measured and telemetered are friction force, normal force, and displacement of the rider because of wear. These are measured by strain-gage transducers.

The rider support arm is designed with two flexible sections: one sensitive to friction force and the other sensitive to normal force. These sections are instrumented with epoxy-bonded, diffused-silicon strain-gages. The gages are arranged in a half-bridge configuration to increase the output signal and to cancel the apparent strain due to thermal expansion mismatch of the gage and substrate.

Normal load is applied by means of an independent, adjustable spring as shown in Figure 3. Normal load for the gold versus silver samples was 4.45 N (1 lb); all other metal couples were loaded to 8.90 N (2 lb). The occurrence of a given amount of wear (0.12 cm) of the rider will result in a corresponding motion of the load rod that will bring the rod in contact with the wear transducer, giving a single-point measurement of wear.

Seven disks are stacked on a common drive shaft and 12 rider assemblies are equally spaced around the periphery, giving a capability for measuring 12 material combinations. Surface velocity between disk and rider was approximately 0.10 cm/s.

In the event that the friction force on a particular couple reaches a level such that excessive power is required, the rider is removed from contact by means of a sealed pyrotechnic actuator. The electrical signal for firing the actuator is generated when the friction gage output exceeds a level corresponding to a coefficient of 3.3.

The drive train for the device incorporates two state-of-the-art devices. A brushless motor with solid-state commutation required only 3.5 W to drive the fully-loaded device. The motor drives an intermediate gearhead of 16.3:1. The motor and gearhead are enclosed in a hermetically sealed package to avoid contamination of the friction experiment and at the same time to maintain conventional lubricants on the high-speed drive elements. Transmittal of power through the hermetic package, together with an additional 72:1 gear reduction, was accomplished by a harmonic drive mechanism.

Considerable attention was given to lubrication of the few slow-moving parts exposed to the space vacuum. The spline (gear) of the harmonic drive mechanism is gold-plated and a light burnish of molybdenum disulfide is applied, run in, and the excess removed. Linear ball bushings, which float the transducer load rods, are in-situ coated with molybdenum disulfide. The drive shaft support bearings are equipped with a self-lubricating duroid retainer and shields.

The strain-gage transducers were designed to meet the following requirements:

Load range	Normal force: 0 to 13.3 N (3 lb) Friction force: 0 to 26 N (6 lb)
Maximum strain	5000 X 10^{-6} cm/cm (limited by the bond strength)
Natural frequency	2000 Hz
Sensitivity	Normal force: 13.5 mV/N Friction force: 6.8 mV/N

These requirements dictated the use of semiconductor strain-gages for the required sensitivity. Literature search[5] indicated that radiation exposure in a one-year orbit would not significantly affect the gage output. Silicon gages of p-type material are more radiation-resistant and were accordingly selected. The gages had a nominal gage factor of 100.

Experimental studies were conducted in a search for a bonding technique that would eliminate organic materials. Although two of these approaches (ceramic bonding and soft soldering) showed promise, neither could be flight-qualified in the time available. As a result, a high-temperature epoxy bond was selected for this application.

The transducer substrate chosen was 17-4 PH stainless steel. The gages are used in a half-bridge configuration with one gage in tension and the other in compression. The gage output as a function of load (strain) deviates only slightly from linearity within the desired range of operation, therefore compensation for this effect was not required.

The gages were compensated for temperature effects. First, the two gages in a half-bridge are tested for gage-factor change with temperature. Any mismatch is eliminated experimentally by a shunt resistor across the gage showing the larger change. Even with the gages matched for gage-factor change with temperature, the bridge sensitivity drops with increasing temperature. This effect is compensated by a resistor in series with the voltage supply to the bridge. At elevated temperatures, the bridge resistance increases, causing the current and the voltage drop across the series resistor to decrease. As a result, the voltage across the bridge and the bridge output will rise to compensate for the loss of sensitivity. The compensated transducers readily met the specification of less than ± 3 percent of full output drift over a temperature range of –20° to 60° C. Typical transducer linearity is shown by Figure 4.

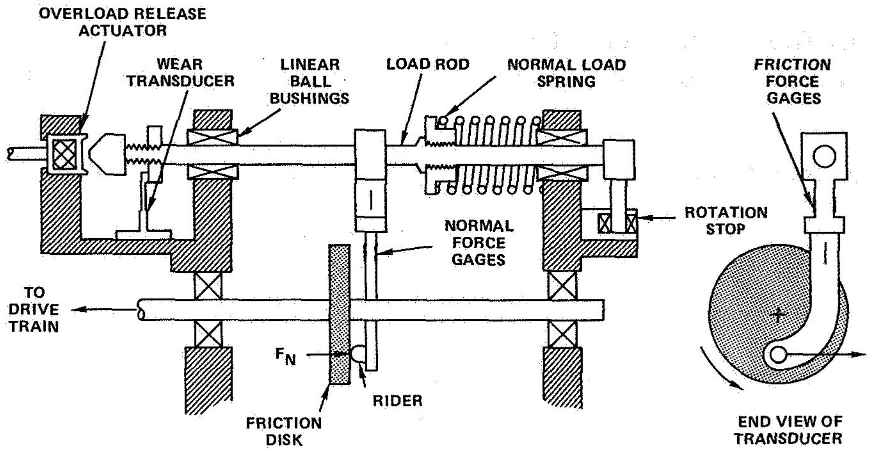


Figure 3. Schematic diagram of friction-test mechanism showing position of spring for application of normal load.

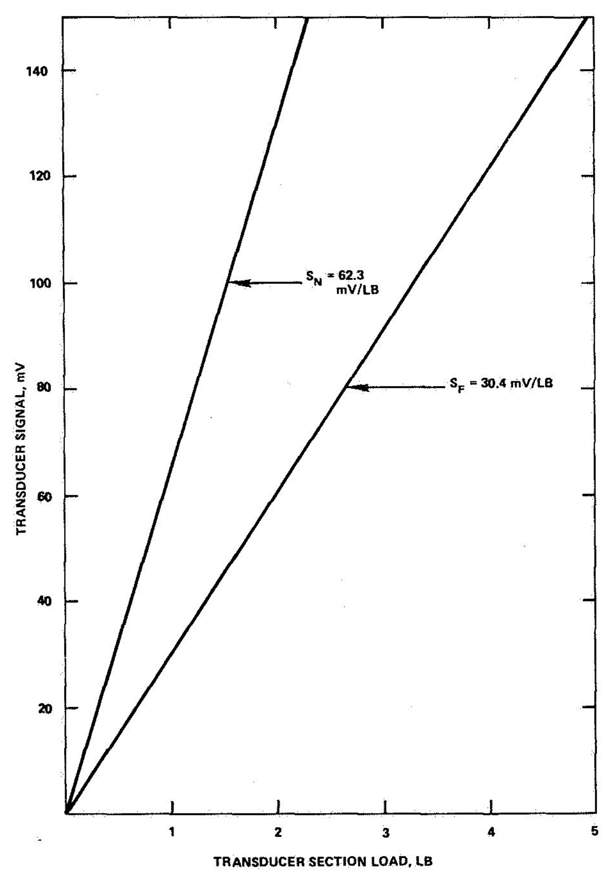


Figure 4. Transducer output as a function of load. Transducer substrate: 17-4 PH stainless steel; 3.00-V excitation; S_N = normal load; S_F = friction load.

The relatively high output of the semiconductor strain-gage transducers made feasible the use of individual linear integrated-circuit amplifiers. Thus the complexity of commutation is avoided and redundancy is attained. Some penalty in power drain is inherent in the individual amplifier approach. It was desired that the amplifier stability and temperature drift performance would at least equal that of the transducers. This was, in fact, achieved by careful burn-in and selection. A sample of 500 commercial μA709 amplifiers was burned in over a temperature range of -40° to 100° C; 250 were selected because of minimum change in offset current.

The schematic for the strain-gage half-bridge, the series-shunt resistor-type temperature compensation, and the integrated-circuit amplifier is given by Figure 5.

Ancillary circuits are required for the following:

- Converter regulators for supplying -3 V (± 0.5 percent) for the strain-bridge excitation, ± 9 V for unregulated amplifier power, and 5 (± 0.5 percent) V for temperature sensors
- Thermistor temperature sensors for in-flight temperature monitoring
- Shaft rotation sensor for status monitoring of the drive train
- Timer for turning the experiment on and off at a 10 percent duty cycle to extend the lifetime of the material couples

The experiment is wired with solid conductor, Teflon-insulated wire to minimize trapped gasses and to provide a control of the outgassed materials (Figure 6). Teflon and the minute amount of epoxy bonding material for the gages are the only organic materials permitted in the friction-measurement environs.

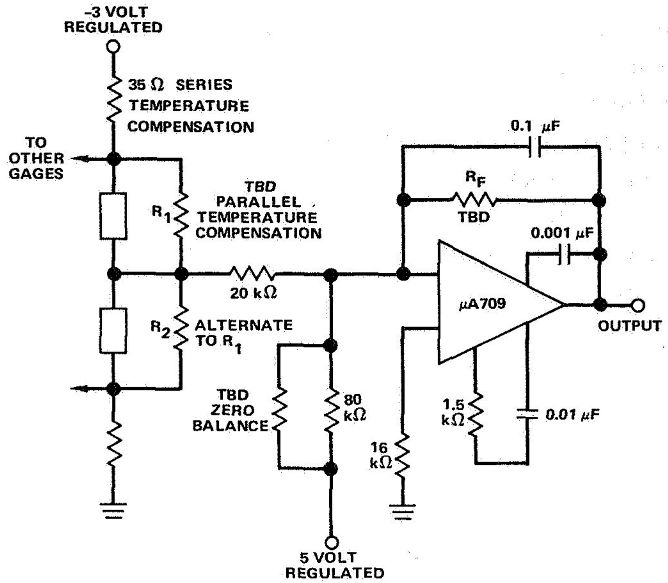
Test Program

The instrument was qualified for launch vibration at the following levels:

	Prototype	Flight qualification
Sine vibration	8g vector	5g vector
Random vibration	6g	6g

The prototype disclosed large displacements of the normal load rods when the vibration was parallel to the rod (thrust axis). As a result, vibration stops were incorporated to limit the excursion of the rod and thus prevent overstressing of the normal load strain-gages. Two units were subsequently qualified at flight levels with no significant shifts in the strain-gage transducers.

The experiment was qualified for thermal vacuum over a temperature range from 0° to 60° C and vacuum from 10^{-9} to 10^{-7} torr. These tests were conducted in an oil-free,



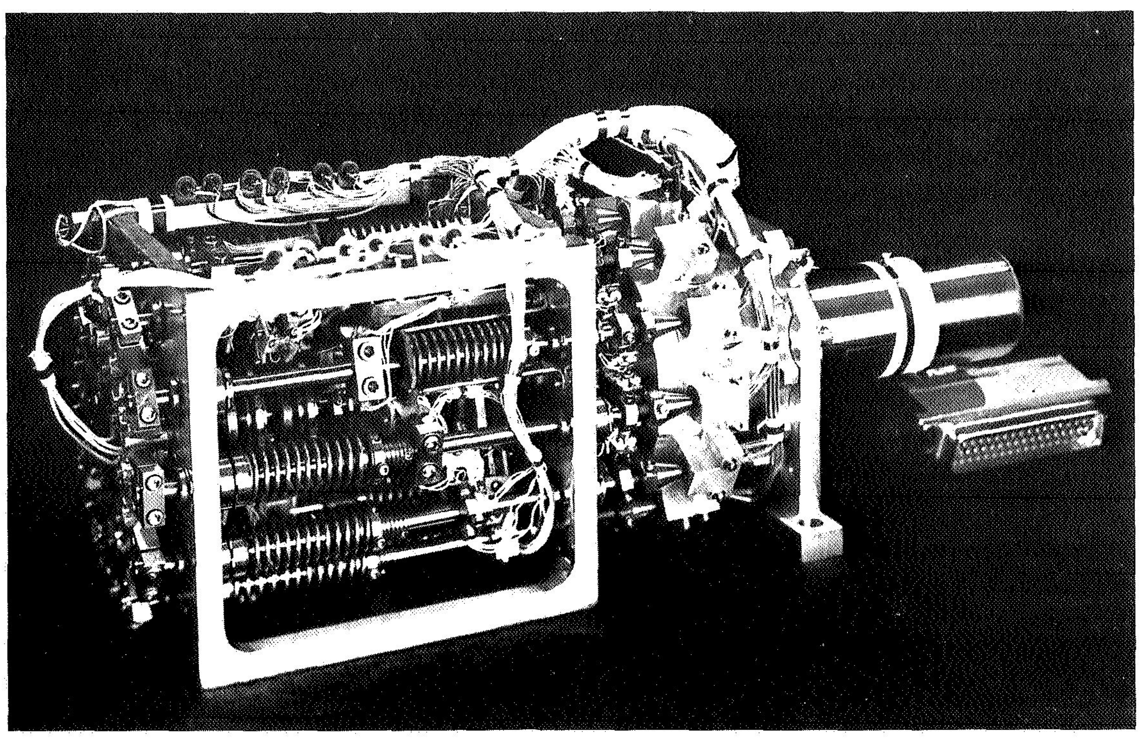


Figure 6. Friction-and-wear module.

ionization-pumped system and are the source of the vacuum-friction data discussed in the next section.

The instrument was integrated and tested on the OV-1-13 with the following results:

- Electrical, RF, and magnetic interference tests showed no interference with the satellite systems or the other sensitive experiments
- Thermal-vacuum (including solar-simulation) tests established the worst-case condition as the cold temperature and demonstrated the capability of the passive temperature control to maintain a predicted range of 0° to 15° C
- Satellite vibration test with a 1g vector input resulted in no degradation. The vibration test demonstrated that the strain-gage transducers maintain remarkable stability under mechanical abuse. The other unknown factor was the stability with time. Table 1 gives stability data for a complete set of transducers measured at the beginning and end of an 8-month interval. The drift figures shown include both the transducer and integrated-circuit amplifier circuit. In only one case did the drift exceed the design specification, the drift in this instance being in the amplifier circuit.

Results of the Orbital Experiment

The friction-and-wear device was operated in orbit throughout the 18-month life of the OV-1-13 satellite. The experiment was turned on and data recorded on an average of one orbit per week. Because the duty cycle was designed for 3 minutes of operation out of 30, this schedule resulted in an average of 6.5 turn-on intervals per week. This totals approximately 500 intervals of 3-minute duration for a total running time of about 25 hours.

Seizure or Cold Welding

Indication of cold welding (operation of the overload pyrotechnic actuators) occurred for three of the couples. These couples and the time after launch when each event occurred are given in Table 2.

The normal load and friction force transducer outputs for these couples went to their precise zero force levels, which is conclusive evidence that the overload pyrotechnic actuator had functioned, removing the transducer from contact with the disk. All of these events occurred within 1 second of turn-on of the experiment.

In the case of the gold-silver and stainless steel-stainless steel couples, seizing occurred at the initial turn-on of the orbit. The last friction readings of the preceding orbit were not unusually high. In the case of the Be-Cu and stainless steel couple, seizure occurred at the fifth turn-on of the orbit. The friction level had been high (μ=0.8 to 1.45) during the earlier intervals of the orbit, but not as high as it had been the previous week. Thus, it appears that seizures of this type occur suddenly and cannot be anticipated even with knowledge of the history of the friction coefficient for the particular metal couple.

Table 1
Stability of Strain-Gage and Amplifier Zero Levels at
Ambient Temperature.

Friction Force			Normal Force			Wear		
Initial	8 Months	Change*	Initial	8 Months	Change*	Initial	8 Months	Change*
–	–	–	0.340	0.378	0.8	2.529	2.486	-0.9
0.315	0.310	0.1	0.427	0.276	-3.0	2.506	2.496	-0.2
0.293	0.368	1.5	0.918	0.808	-2.2	2.574	2.516	-1.1
0.240	0.172	-1.3	0.442	0.385	-1.1	2.525	2.497	-0.5
0.322	0.352	0.6	0.282	0.238	-0.9	2.510	2.474	-0.7
0.240	0.188	-1.4	0.307	0.237	-1.4	2.463	2.479	0.3
0.210	0.233	0.5	0.329	0.343	0.3	2.536	2.520	-0.3
0.173	0.170	-0.06	0.439	0.419	-0.4	2.496	2.466	-0.6
0.154	-0.076	-4.6	0.503	0.400	2.0	2.515	2.471	-0.9
0.428	0.460	0.6	0.654	0.606	-1.0	2.416	2.403	-0.2
0.345	0.417	1.4	0.843	0.827	-0.3	2.484	2.422	-1.2
0.267	0.323	1.1	0.722	0.696	-0.5	–	–	–

*Percent of full scale.

Table 2
Couples Exhibiting Cold Welding

Couple No.	Material Combination	Time After Launch (hr)	Number of Turn-ons Prior To Event
1	Gold and silver	33	1
3	Be-Cu and stainless steel	2250	59
7	Stainless steel and stainless steel	3720	79

Coefficient of Friction Data

Detailed plots of the coefficient of friction as a function of orbit are given in Appendix A. The vertical bars indicate the range of the readings during the given orbit number. The average values of friction coefficient as a function of time in orbit are shown in Figure 9 in the section entitled "Comparison of Orbital and Laboratory Results."

Gold and Silver

These metals are mutually soluble and were expected to cold weld. One sample apparently welded almost immediately while the second sample ran at a very high and slowly increasing friction level (μ = 1.0 to 2.0) for the duration of the test.

Aluminum and Stainless Steel

Both samples ran very smoothly at an almost constant value of $\mu = 0.5$.

Stainless Steel and Stainless Steel

One sample welded after 3720 hours while the other ran at a relatively high (μ = 0.6 to 0.9) friction level for the duration of the test.

Stainless Steel and Nitrided Steel

Both samples ran at an intermediate level of $\mu \sim 0.7$ for the test duration.

Stainless Steel and Carbon Steel

After an initial rise both samples ran at an intermediate level of $\mu = 0.6$ for the test duration.

Be-Cu and Stainless Steel

These metals were expected to form adhesive contact. One sample apparently welded after 2250 hours; the other survived initially high levels and operated for the remaining time at a relatively low level.

One of the most striking observations is that after the first month, the coefficients of friction for all of the materials remained at an almost constant level except for the samples that seized.

Wear Data

None of the samples wore the amount required, 0.115 cm (0.045 in), to give an indication on the wear transducer. Couple no. 12 (gold and silver) was not instrumented for wear because of telemetry channel limitations.

LABORATORY TEST PROGRAM

A program of laboratory test was conducted in conjunction with the flight experiment. The flight backup experiment was placed in an oil-free vacuum chamber and was operated on the same duty cycle and for the same time duration (18 months) as the experiment on the OV-1-13 satellite. The objective was to obtain data for the selected metallic couples comparable to that obtained in the actual orbital environment.

Vacuum System

The vacuum system employed was a stainless steel belljar with a 500 l/s ionization pump. Supplementary pumping was provided by titanium sublimation filaments operated at 40 A. Roughing of the system was accomplished with molecular absorption sieves chilled with liquid nitrogen. The system is typical of commercially available oil-free ultrahigh vacuum facilities. Figure 7 shows the test arrangement for the orbital simulation test.

Because of a leak in the hermetic seal of the motor on the flight backup unit, the device was driven by a motor external to the chamber. Motion was transmitted through the belljar wall by means of a bellows-sealed crank. In all other ways the test device was identical to the flight unit.

Pressure measurements were made at the locations shown in Figure 8 using Baird-Alpert ionization gages. The gage adjacent to the test device indicated that a pressure of 1.5 to 2.0×10^{-10} torr was maintained throughout the duration of the orbital simulation test.

Laboratory Test Results

The laboratory test was completed as planned with the experiment operated on the same schedule as the prior in-orbit test. No seizure of any couple was observed in the laboratory test. Coefficient of friction data as a function of time are given in Appendix B.

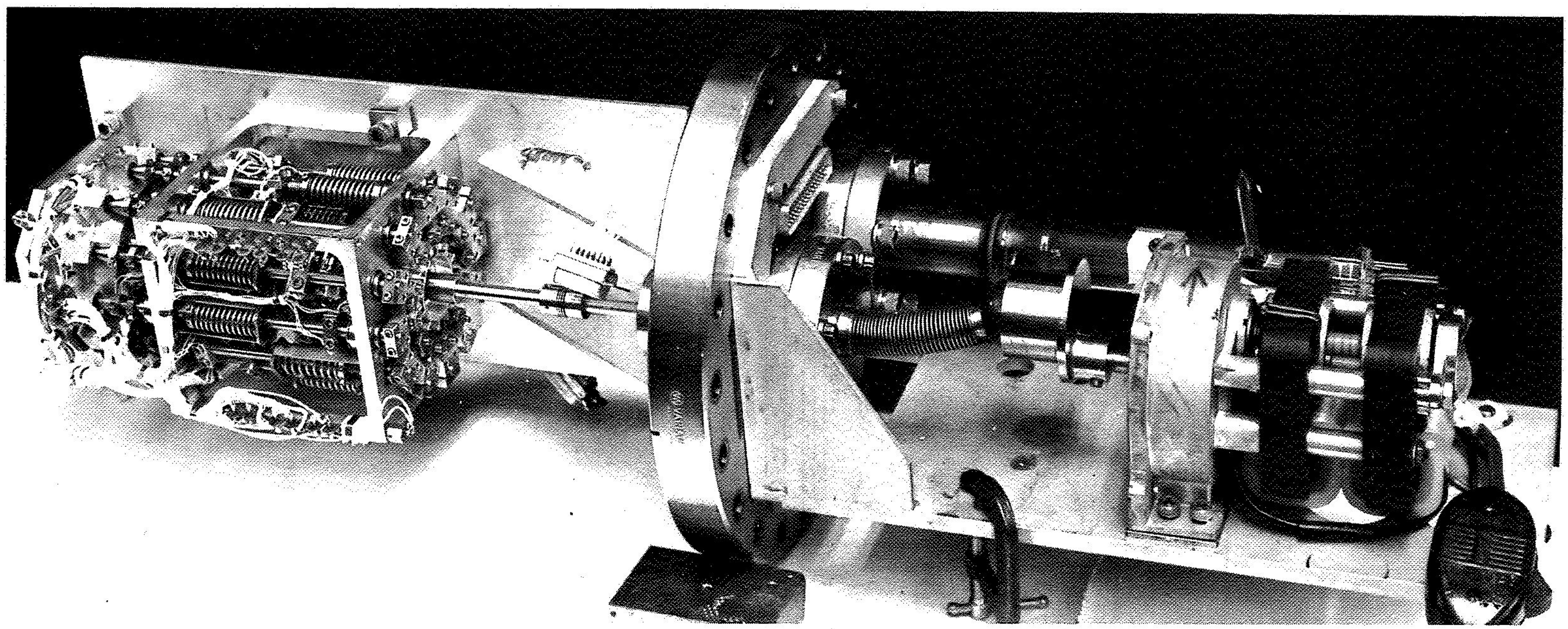


Figure 7. Experiment arrangement for laboratory vacuum test.

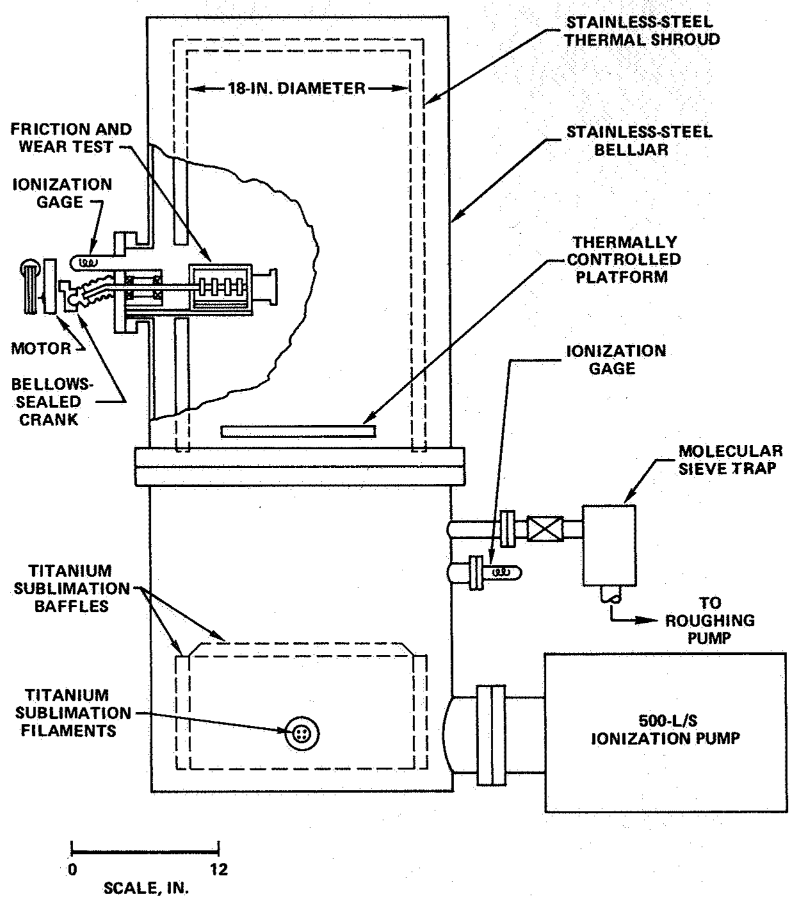


Figure 8. Vacuum-test arrangement.

COMPARISON OF ORBITAL AND LABORATORY RESULTS

Friction coefficient measurements in orbit and in the laboratory (average values) are compared in Figure 9. Both the absolute values and the time trends are in very good agreement for all of the metal couples.

The notable difference in the two groups is the occurrence of seizures in three of the flight couples. The corresponding couples in the laboratory test were marked by high and erratic friction, but levels sufficient to trigger the overload actuator did not occur.

Two possible explanations may be postulated for this difference:

(1) The space environment created cleaner surface conditions so that greater adhesion occurred.

(2) The faster time constant of the flight drive-motor resulted in a higher transient starting torque. This possibility is considered unlikely due to the high natural frequency of the friction-sensing transducer and the low pass filter in the overload actuator circuit. No evidence of a transient starting peak was observed in laboratory vacuum tests of the actual flight experiment and motor.

CONCLUSIONS

It is concluded that for clean metal couples that are not mutually soluble, testing in an oil-free laboratory vacuum approaching 10^{-10} torr will give good results for friction coefficient versus time. These results are quite representative of what can be expected in the vicinity of a typical scientific satellite that is exposed to pressure as low as 10^{-12} torr. As can be seen from the data, the absolute magnitude and the general shape of the plots of coefficient of friction as a function of time are in good agreement.

For materials with a high degree of mutual solubility, however, there is a hazard of unpredictable drastic friction increase which may not be evident in laboratory testing, even at levels down to 10^{-10} torr.

Further, a relatively simple, lightweight, and low-power friction-and-wear-test device has been developed that may be flown on scientific spacecraft and is readily testable in laboratory systems. In addition, the silicon strain-gages used proved to be compatible with the space environment, and long-term drift and radiation damage were not experienced.

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National Aeronautics and Space Administration
Greenbelt, Maryland February 21, 1973
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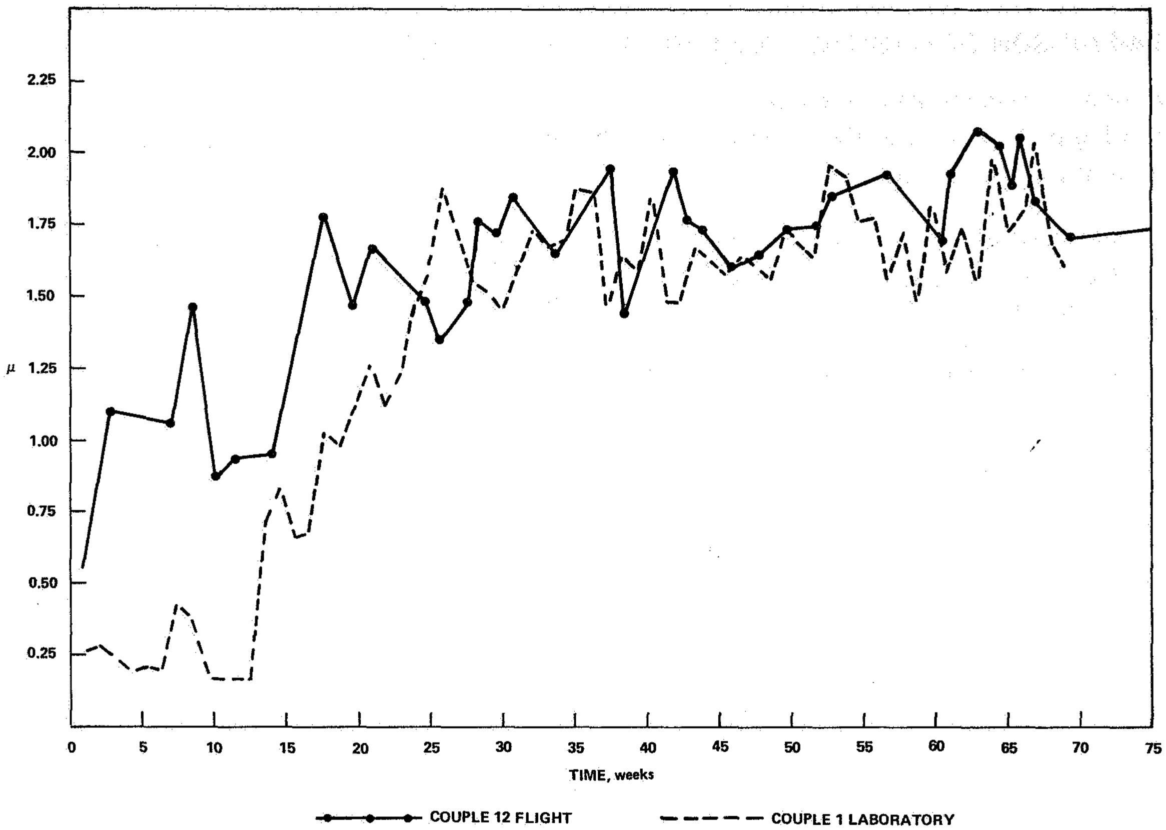
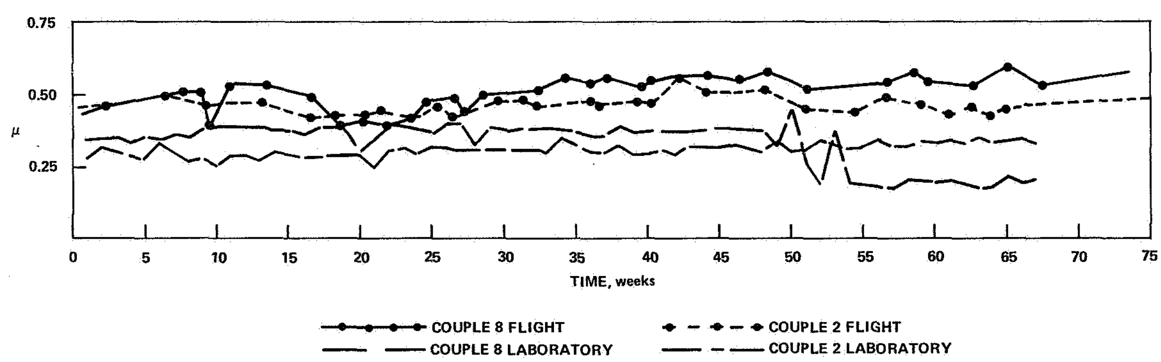
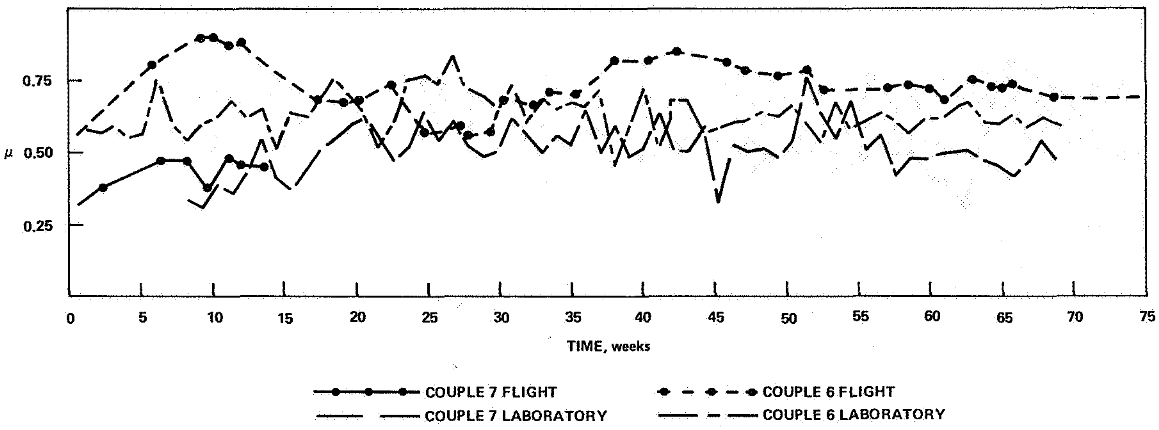


(a) Gold and silver couples.

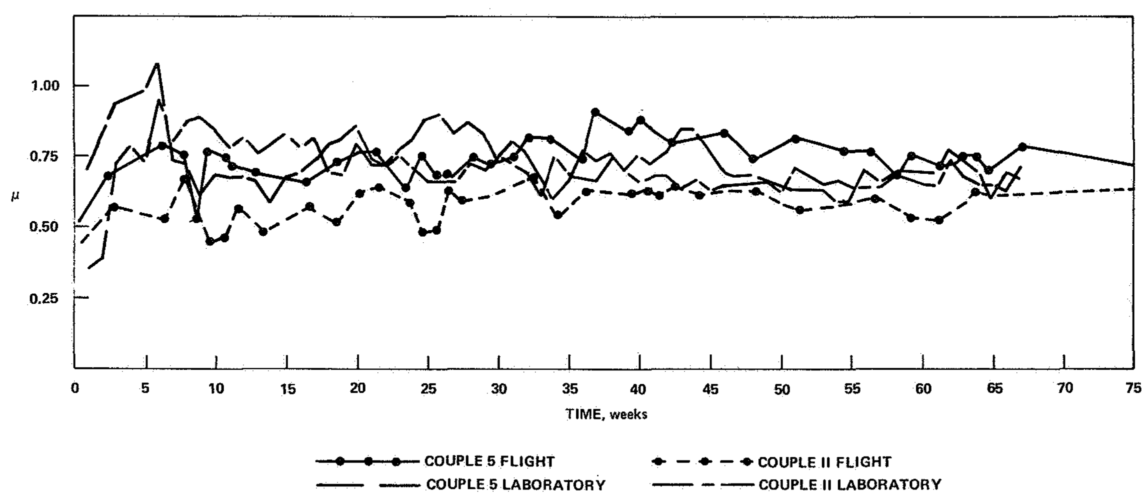


(b) Aluminum and stainless-steel couples.

Figure 9. Comparison of orbital and laboratory friction test results.

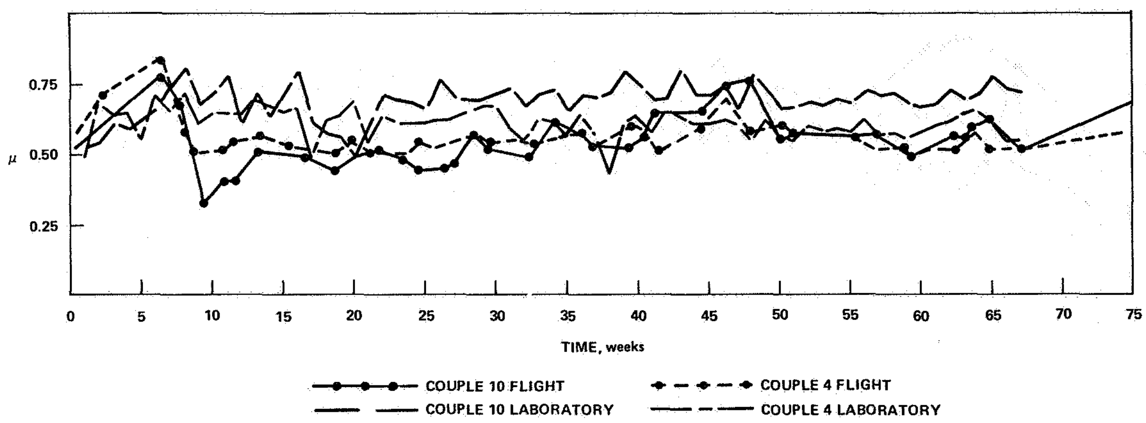


(c) Stainless-steel and stainless-steel couples.

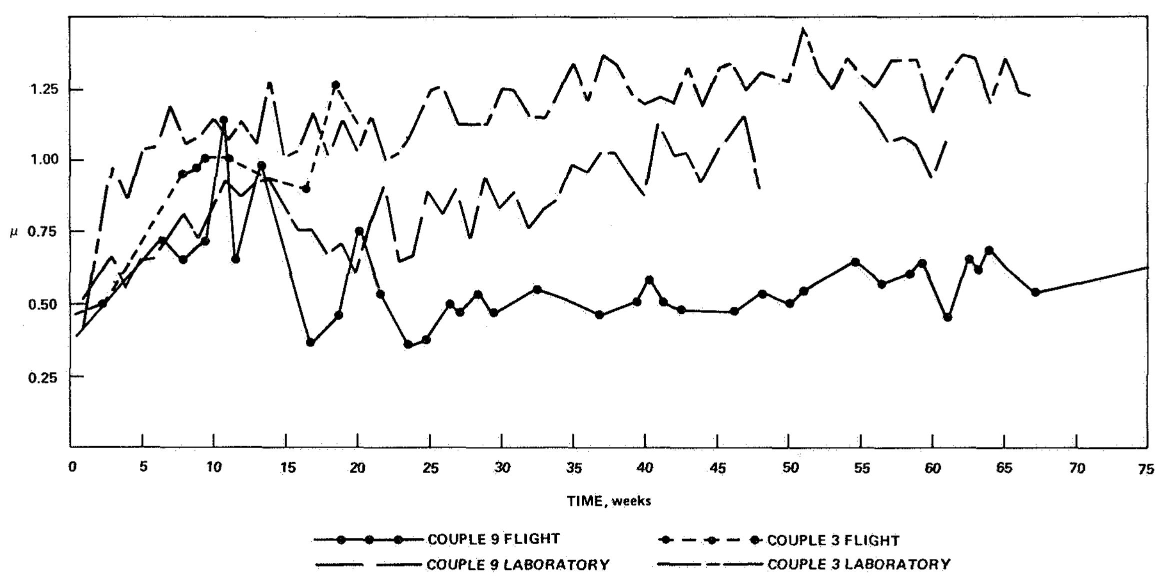


(d) Stainless-steel and nitrided steel couples.

Figure 9 (continued). Comparison of orbital and laboratory friction test results.



(e) Stainless-steel and carbon steel couples.



(f) Be-Cu and stainless-steel couples.

Figure 9 (continued). Comparison of orbital and laboratory friction test results.

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4. D. R. Milner and G. W. Rowe, "Fundamentals of Solid Phase Welding," *Met. Rev.* 7 (28), 1962.
5. J. F. Kircher and R. E. Bowman, *Effects of Radiation on Materials and Components*, Reinhold Pub. Corp. 1964.

APPENDIX A

COEFFICIENT OF FRICTION AS A FUNCTION OF ORBIT NUMBER

Figures A-1 to A-6 contain detailed plots of the coefficient of friction as a function of orbit number.

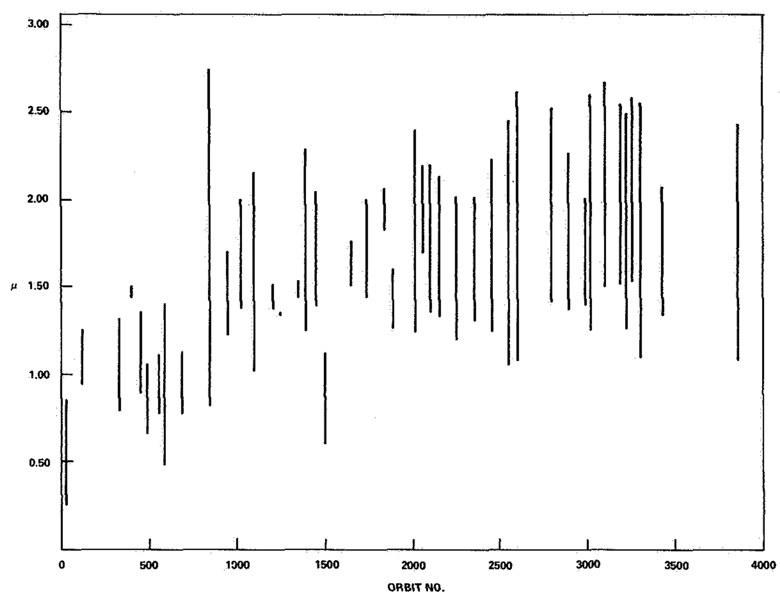

Figure A-1. Gold and silver couple 12.

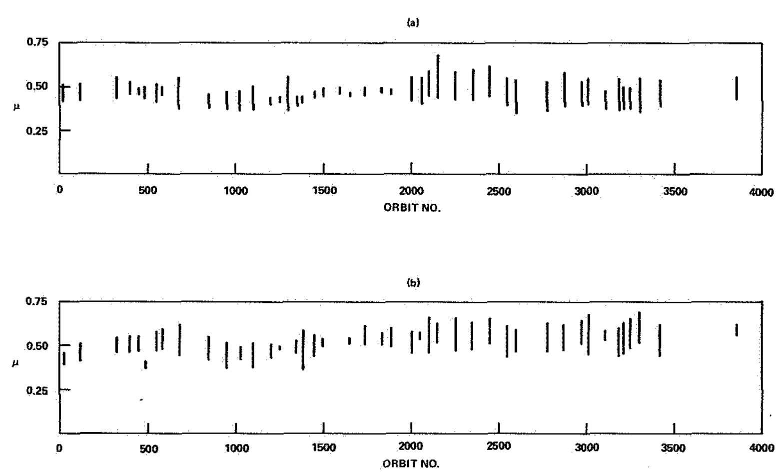

Figure A-2. Aluminum and stainless steel: (a) couple 2; (b) couple 8.

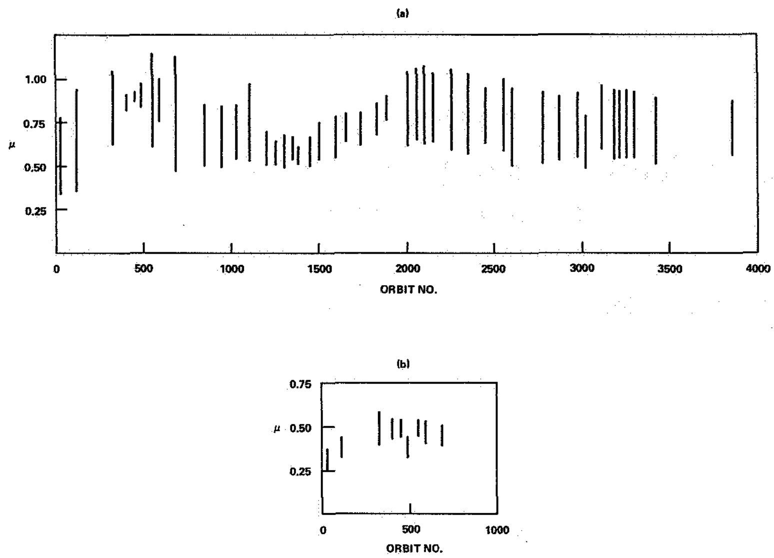

Figure A-3. Stainless steel and stainless steel: (a) couple 6; (b) couple 7.

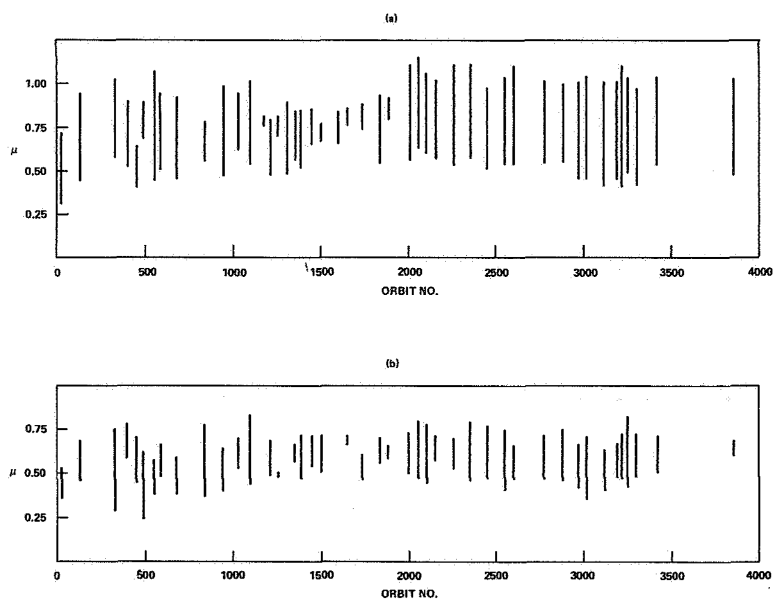

Figure A-4. Stainless steel and nitrided steel: (a) couple 5; (b) couple 11.

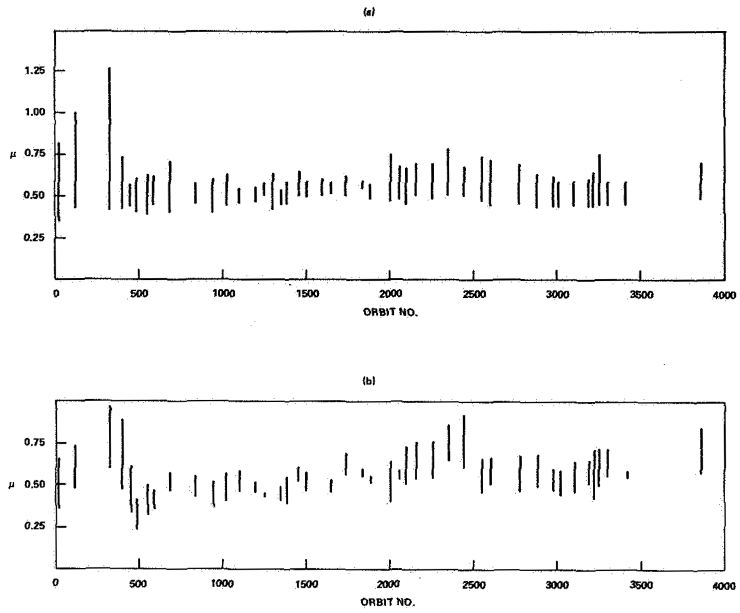

Figure A-5. Stainless steel and carbon steel: (a) couple 4; (b) couple 10.

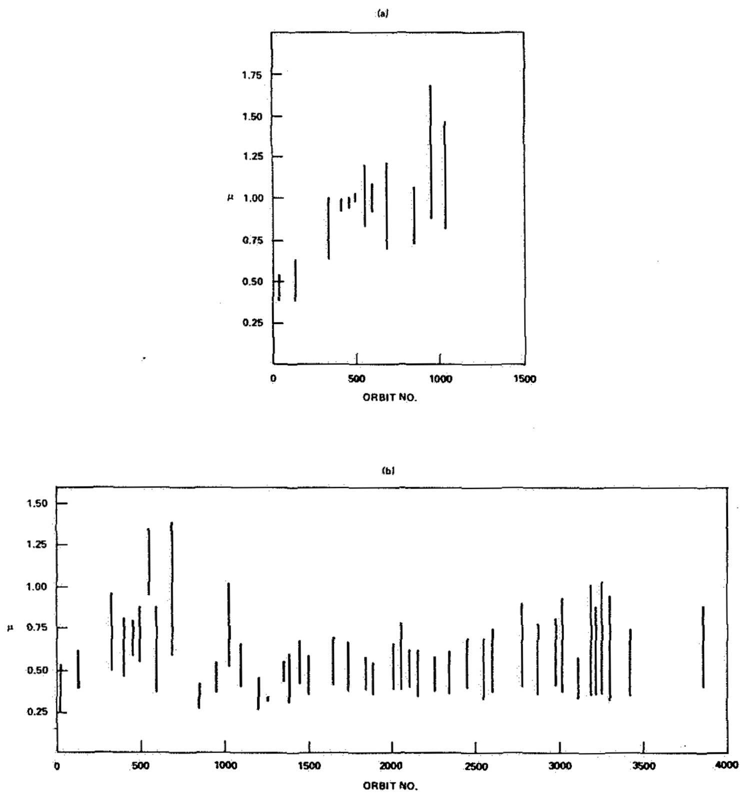

Figure A-6. Be-Cu and stainless steel: (a) couple 3; (b) couple 9.

APPENDIX B

COEFFICIENT OF FRICTION AS A FUNCTION OF TIME IN THE LABORATORY

Figures B-1 to B-6 contain detailed plots of the coefficient of friction as a function of time in the laboratory.

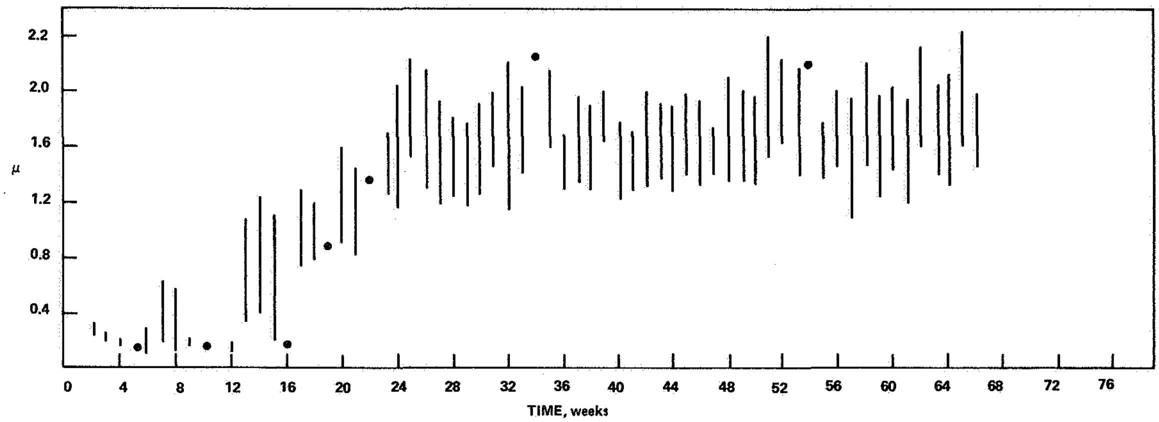

Figure B-1. Gold and silver couples.

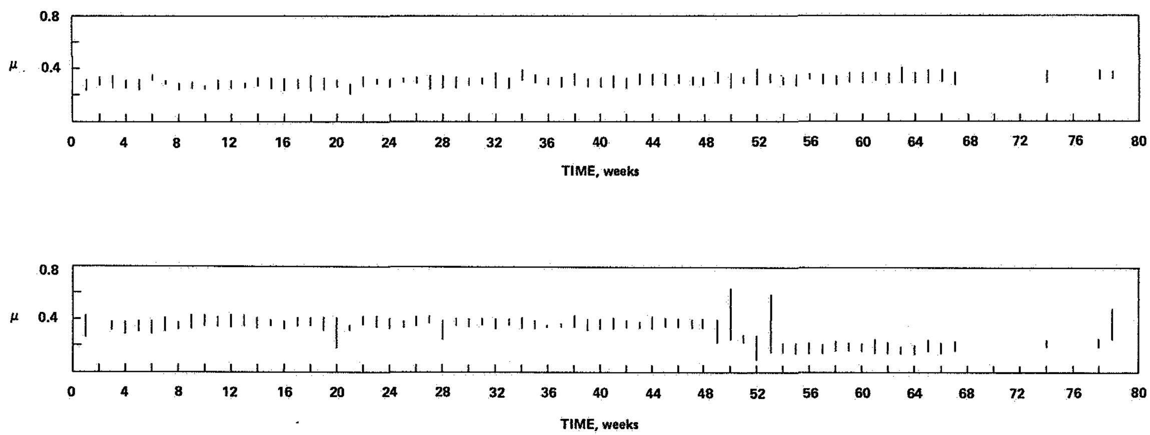

Figure B-2. Aluminum and stainless-steel couples.

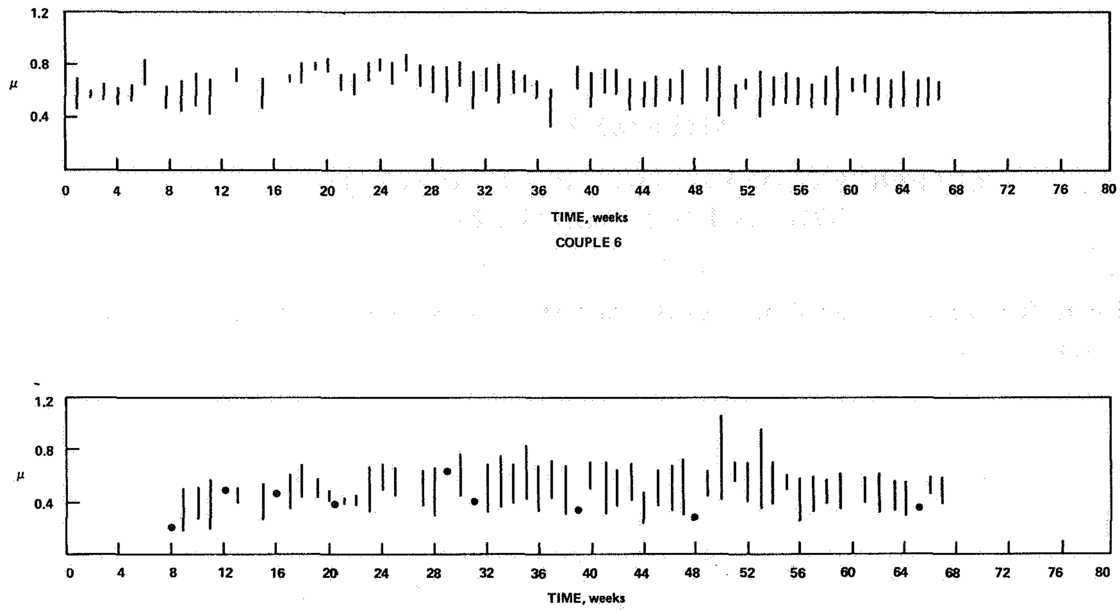

Figure B-3. Stainless-steel and stainless-steel couples.

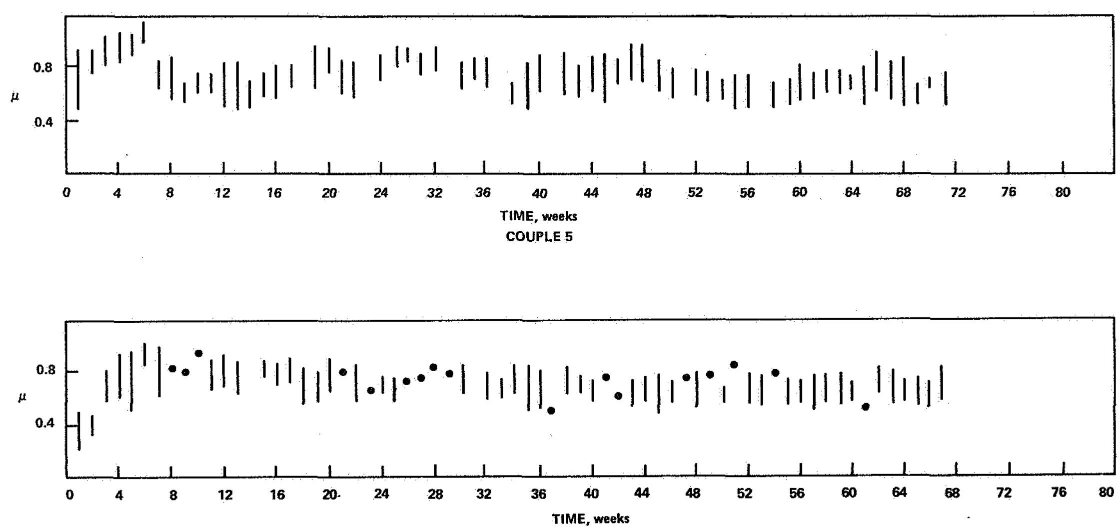

Figure B-4. Stainless-steel and nitrided steel couples.

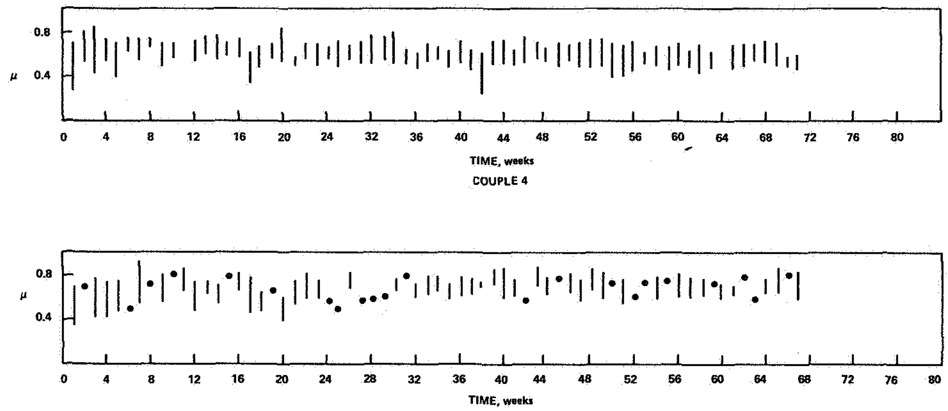

Figure B-5. Stainless-steel and carbon steel couples.

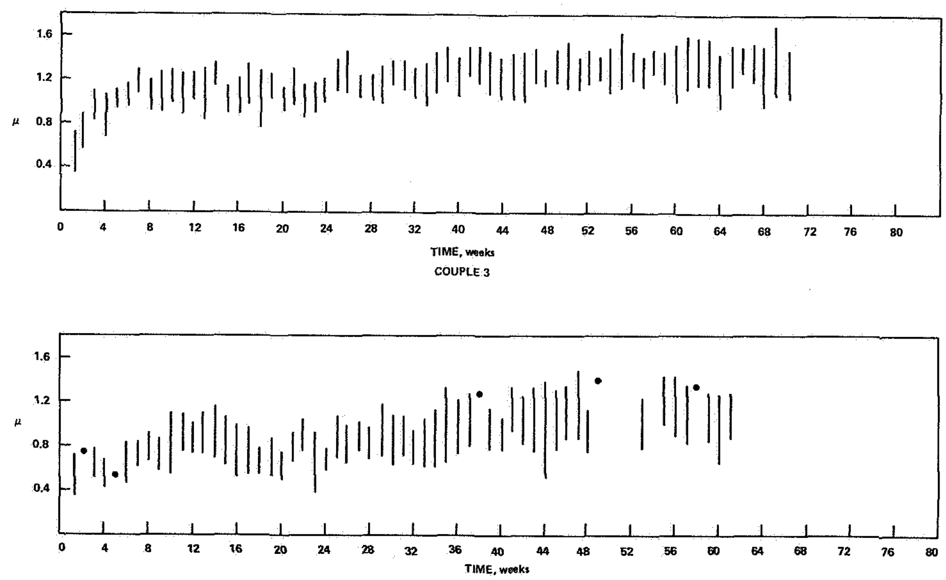

Figure B-6. Be-Cu and stainless-steel couples.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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