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BRUSH/SLIP RING SELECTION FOR HIGH POWER SATELLITE LOADS.(U)

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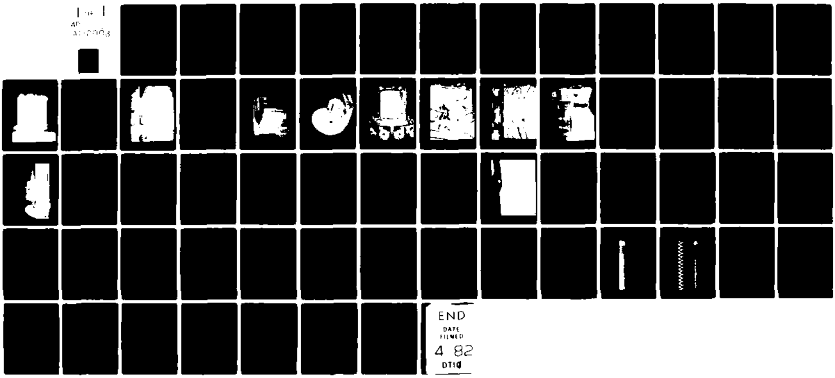

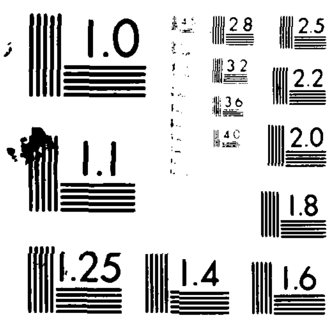

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ABSTRACT

This report presents the results of vacuum tests of dry lubricant brush materials for usage in slip ring assemblies of satellites with large electrical loads. Primary concerns of the test were brush voltage drop, wear rate, and operating temperature at high current densities with a slow slip ring angular velocity.

KEY WORDS

Angular Velocity
Brush Pressure
Brush Type
Current Density
Dry Lubricant
Electrical Contact
Operating Temperature
Slip Ring
Vacuum Level
Voltage Drop
Wear Rate

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2.0 PREFACE

2.1 With 1978 technology, the conceptual solar power satellite located in a 36,000 km geosynchronous orbit will transform energy from sunlight to electrical power by photovoltaic conversion. The solar array-generated power will be converted to RF power and transmitted to earth by means of a microwave beam. A receiving station on earth with its antenna, rectifiers, and inverters, will collect the microwave beam and convert the power to 60 hertz alternating current for delivery into an electric utility network.

2.2 One essential requirement in a satellite's electrical system is the ability to transfer power across a rotary joint that couples the Sun-facing power source with the Earth-oriented antenna. A brush/slip-ring assembly proves from literature surveys to be the best power transfer means due to its size, weight, cost, efficiency, and simplicity. The slip ring design concept under investigation consists of three concentric rings 15, 11, and 7 meters in diameter.

2.3 The primary problems of sliding electrical contacts in an ultra high vacuum or deep space are: cold welding, rapid wear, and signal distortion. However, electrical noise decreases to a negligible level and fluctuations in friction and wear become very small at slow sliding velocities.[1] With the addition of a surface lubricant, cold welding is prevented, rapid deterioration of slip rings and excessive wear of brushes is lessened, the coefficient of friction is decreased, fluctuations in contact resistance are minimized, and noise levels vanish.

3.0 SUMMARY

3.1 This report presents the test results of a 2014 hour test of four Boeing sliding contact materials:

a. 046-45, a molybdenum disulfide material,

b. 101, a silver tungsten sulfide material,

c. 8-92-2, a silver barium fluoride material,

d. 7-122-4M, a silver molybdenum disulfide material, mated with coin silver slip rings. The slip ring assembly used in this test was a modification of an AWACS microwave brush/slip ring assembly designed specifically for use in a low oxygen environment. Of primary concern of the test was the brush voltage drop with respect to an increasing current density. Secondary concerns were the operating temperature and wear rate of the brush material for various vacuum levels during the test. The test terminated on schedule for evaluation and equipment maintenance.

3.2 The testing criteria are as follows:

a. Voltage drop ≤ 0.1 volts across set of brushes

b. Wear rate ≤ 0.005 inches/17.2 km of slip ring travel

c. Current density = 180.1 - 360.1 A/in^2

d. Operating temperature ≤ 60°C (140°F)

e. Brush pressure = 4.5 - 11.25 psi

f. Vacuum range = 110 microns - 2×10^{-7} torr

These testing criteria were developed after reviewing:

a. The satellite conceptual design requirements

b. The state of the art literature search

c. The limitations of the test equipment.

3.3 Of the four Boeing-developed brush samples of 3.1, brush types 8-92-2 and 7-122-4M were the most successful in qualifying as suitable brush materials for application on a high power satellite. Of these two brush types, wear rate was the determining factor in the selection of 7-122-4M as the most probable brush type of the samples tested to be used on a high power satellite.

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3.4 The average brush wear of the 7-122-4M material was 0.00125 inches for the 2014 hour test. This is an average wear rate of 0.00059 inches per 17.2 kilometers of slip ring travel per year. At the maximum test current density, 360.1 A/in^2, the brush operating temperature range was 95-105°F. The typical minimum brush voltage drop was 74-83 millivolts.

3.5 Greater brush wear occurred on the brushes which were positioned beneath their respective rings in contrast with the brushes mounted on top of their rings. On the average, more brush wear occurred on the brushes that were mounted on the shorter of the two spring arm lengths. The major cause of the difference in brush wear between the two holders probably stems from the initial mounting and spring arm displacement.

3.6 Brush material overheating to the extent of operational failure was not encountered, even though material 046-45 displayed the highest operating temperature, 226°F, exceeding the test criterion of 140°F. The brush voltage drop, 0.55-.78 volts, of this same brush material at the maximum test current density also exceeded the test criterion. Because of these operating characteristics of the 046-45 material, it will be eliminated from future tests.

3.7 Brush material 101 displayed slightly higher operating characteristics than did the 8-92-2 and the 7-122-4M brush materials. Because this test was only preliminary, additional vacuum tests of the 101, 8-92-2, 7-122-4M, and other advanced brush materials should be conducted according to 3.2 before the most suitable brush for a high power satellite is selected.

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4.0 INTRODUCTION

4.1 Subject: This report presents the results of vacuum tests of four brush materials rubbing against coin silver slip rings. The level of vacuum ranged from 110 microns to 2×10^{-7} torr.

4.2 Purpose: This test was conducted in order to obtain design data for the selection of a brush/slip ring combination for a 30 year, one revolution per day, life operation in the vacuum of space of a rotary joint in a high power satellite application. These test results are to serve as reference data against which to compare the performance of other brushes that are specifically fabricated for space application.

4.3 Objective: This test was concerned with the performance capability of the available brushes suitable for space application. Of interest was the current density capability of the brushes; and also that value of current density at a maximum voltage drop of 0.1 volt d.c. The ultimate goal of testing is to find the optimum brush/slip ring combination where friction coefficients, voltage drops, and wear rates are at a minimum, and an acceptable brush life can be attained with high current densities.

4.4 Scope: This test was limited, by the cost of slip rings, to the available coin silver slip rings. The brush samples tested were developed by Boeing Metallurgical Laboratory for use on other projects. This initial test was bounded by the vacuum limit of the available vacuum chamber, and the ability of the stepper motor to sustain the designed slip ring angular velocity. Test time was limited to three months or 2000 hours.

4.5 Development: This report is divided into seven major parts: A. Test Elements, B. Test Development, C. Test Equipment, D. Test Results, E. Discussion, F. Conclusions, G. Recommendations.

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5.0 TEST ELEMENTS

5.1 SLIP RING ASSEMBLY

5.1.1 The slip ring assembly used in this test was a modification of an AWACS microwave brush/slip ring assembly shown in Figure 1. This assembly has a total of 84 coin silver slip rings; however, only the eight largest rings were used. Coin silver is harder (e.g., 132 HK_{100}) and more wear resistant than fine silver (e.g., 100 HK_{100}) and has an electrical conductivity of 83%. (International Annealed Copper Standard). These eight larger rings measured 15 inches in diameter, 1/2 inch wide and 1/16 inch thick. Figure 2, the test circuit schematic, shows the eight slip rings connected in series to complete the circuit.

5.2 Brush Assembly and Brushes

5.2.1 The brush assembly used in this test is shown in Figure 3. Each ring was contacted by a parallel set of identical brushes mounted on two different length cantilever spring arms. Positive and negative brush sets were produced with the series direction of current flow through the rings. Each brush rode in a separate track to minimize the effect of wear debris from the other brush. The brushes were in the form of buttons that were either cemented or soldered to the spring arm of the brush holder. In this type of holder, Figure 3, the arm served both as a conductor and as a cantilever spring for pressing the brush against the slip ring surface. The advantage of this type of brush holder is its simplicity whereas its disadvantage is in setting the brush contact force precisely and maintaining a constant force as the brush wears. A detailed description of the brush samples tested is in Table A.

TABLE A
BRUSHES TESTED

	Origination	Brush Material	Major Elements	# of Brushes	Brush Shape	Brush Size
1.	Boeing Met. Lab/Renton	046-45	80% MoS_2 15% Mo	4	Cylindrical	D=4.77 mm L=3.18 mm
2.	Boeing Met. Lab/Renton	101	52.94% WS_2 35.0% Ag	4	Cylindrical	D=4.77 mm L=3.18 mm
3.	Boeing Met. Lab/Renton	8-92-2	81.37% Ag 6.56% BaF_2	4	Square	W=4.227 mm L=3.18 mm
4.	Boeing Met. Lab/Renton	7-122-4M	72.5% Ag 13.0% MoS_2	4	Cylindrical	D=4.77 mm L=3.18 mm

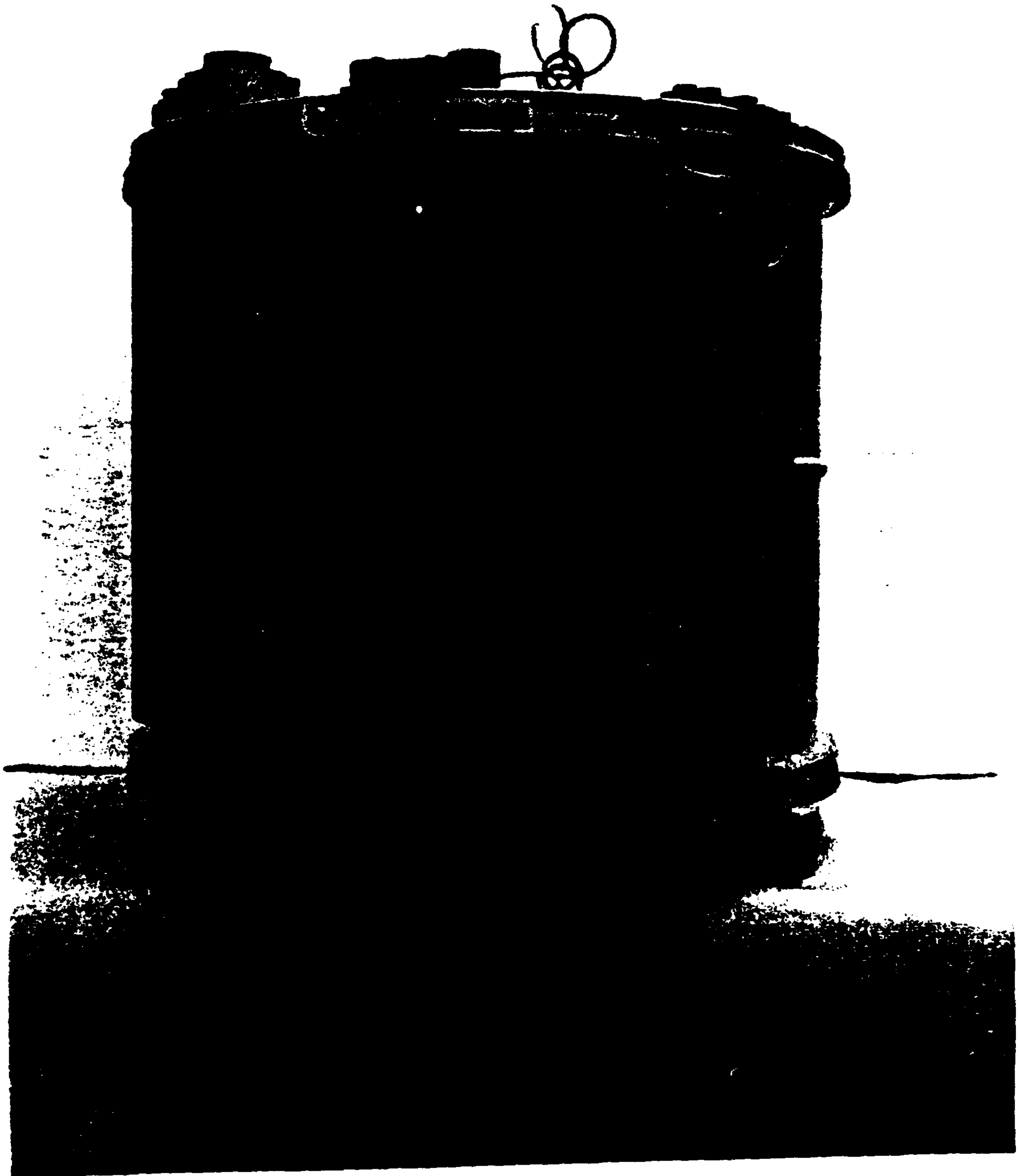

Figure 1. Slip Ring Assembly

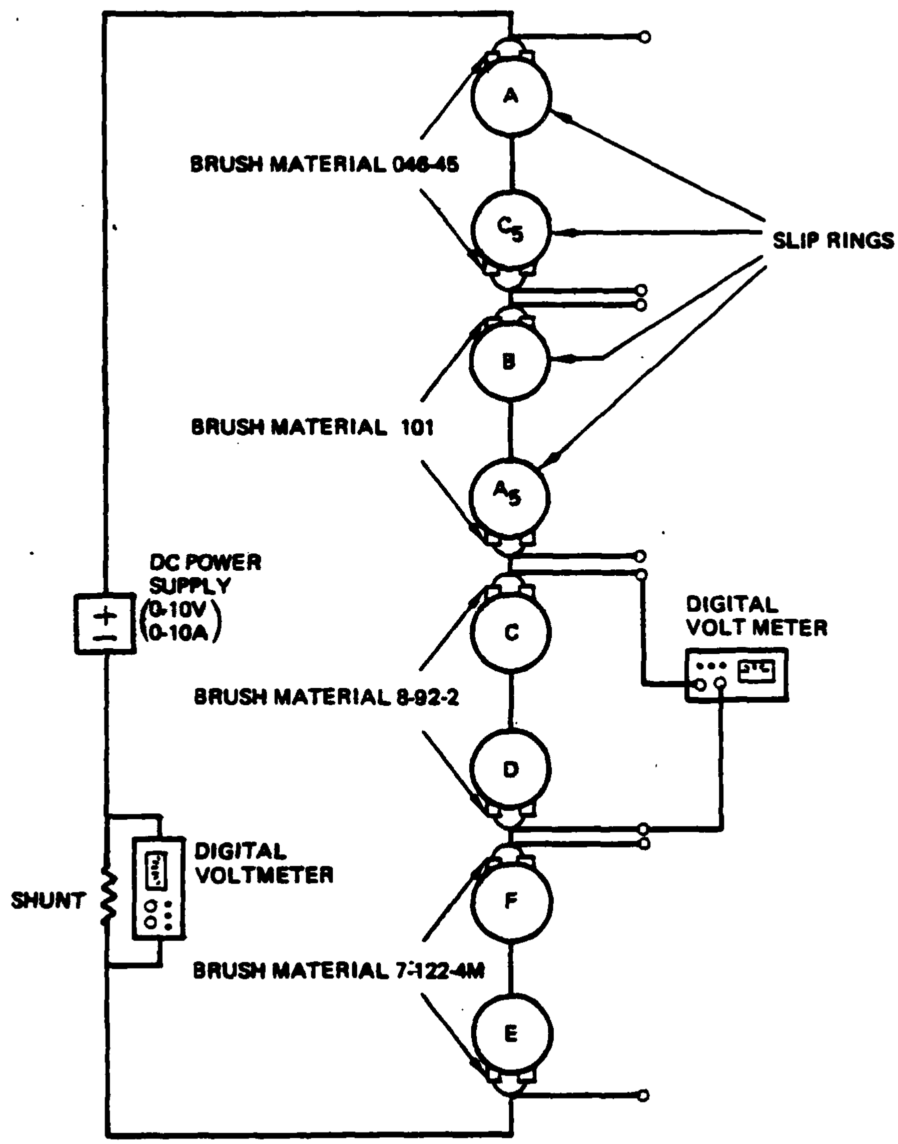

Figure 2. Test Circuit Schematic

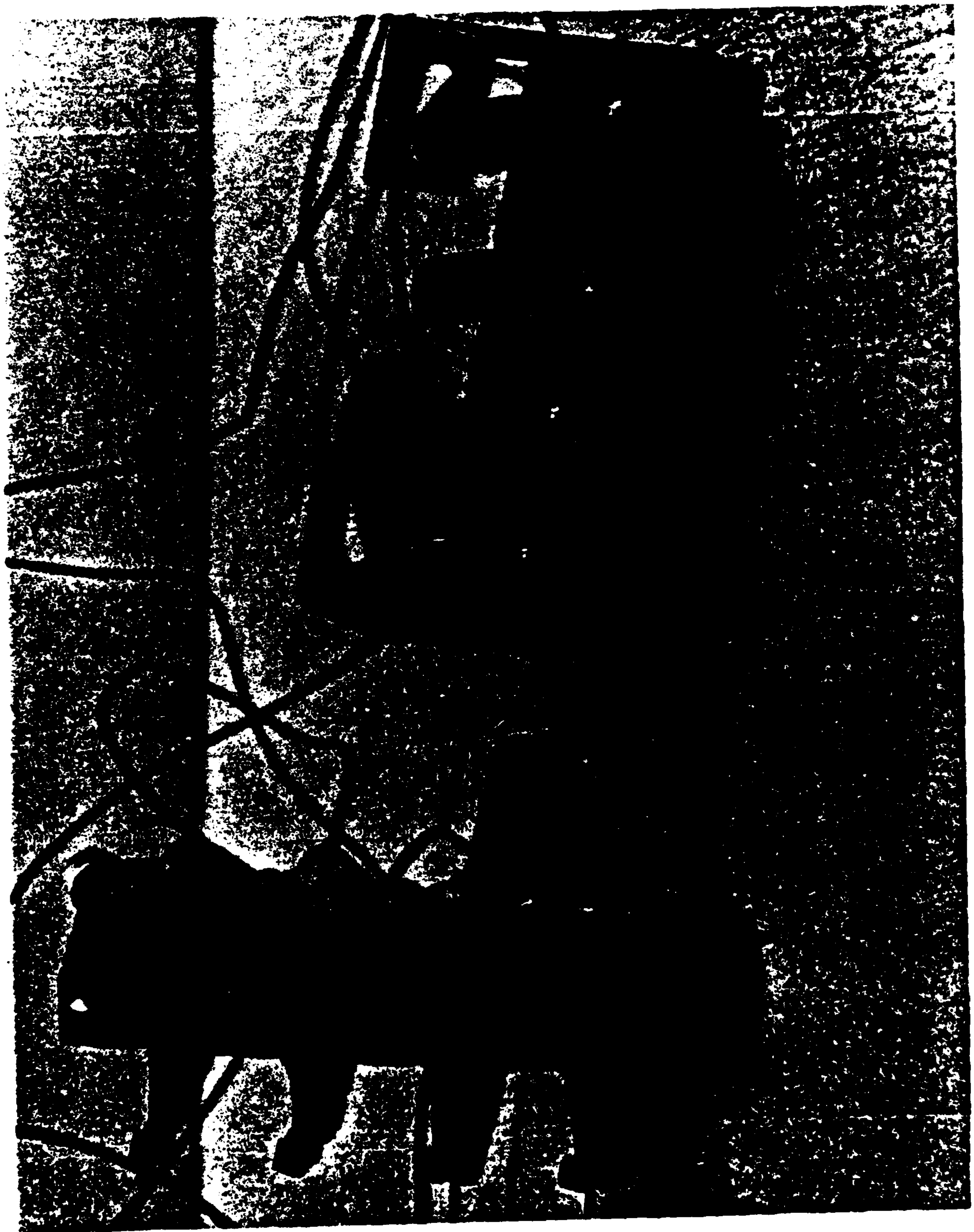

Figure 3. Brush Holders

6.0 TEST DEVELOPMENT

6.1 TEST SETUP

6.11 This test was conducted at ordinary atmospheric conditions in the micro-electronics laboratory, room 15F1, 18-22 Building, Kent, WA. The slip ring assembly used in the test, Figure 1, was removed from the Hughes AWACS rotary joint wave guide assembly. Mounted inside of the slip ring assembly in a vertical position was the stepper motor shown in Figures 4 and 5. This stepper motor/slip ring assembly was fitted to the base of the vacuum chamber as is shown in Figure 6 with feed throughs installed in the base of the vacuum chamber to provide the following: a. Power to and from the slip fings, b. Power to the counter, c. Power and controls to the stepper motor, d. Sensing for four sets of brushes, e. Thermocouple connections for four brushes.

6.12 Four different brush compositions were mounted on the 16 spring arms of the two brush holders of Figure 3, and seated to the surface of their respective slip rings before testing, Figure 7. Following a thorough cleaning of the slip rings, both brush holders and power and sensing connections were mounted as is shown in Figure 8. The amount of pressure of each brush on its mated slip ring was proportional to the following combinations: a. Length of the cantilever spring arm, b. Radius of curvature of the spring arm, c. Length of the mounted brush, d. Vertical displacement of the brush holder.

6.13 Subsequent to judicious cleaning of the vacuum chamber interior and its contents, the readied test assembly and equipment is shown in Figure 9.

6.2 TEST CONDITIONS

6.21 This test consisted of four independent variables and four dependent variables defined as follows:

A. Independent
   1. W, angular velocity of slip rings
   2. I, current through circuit
   3. P, brush pressure on ring
   4. V, chamber vacuum level

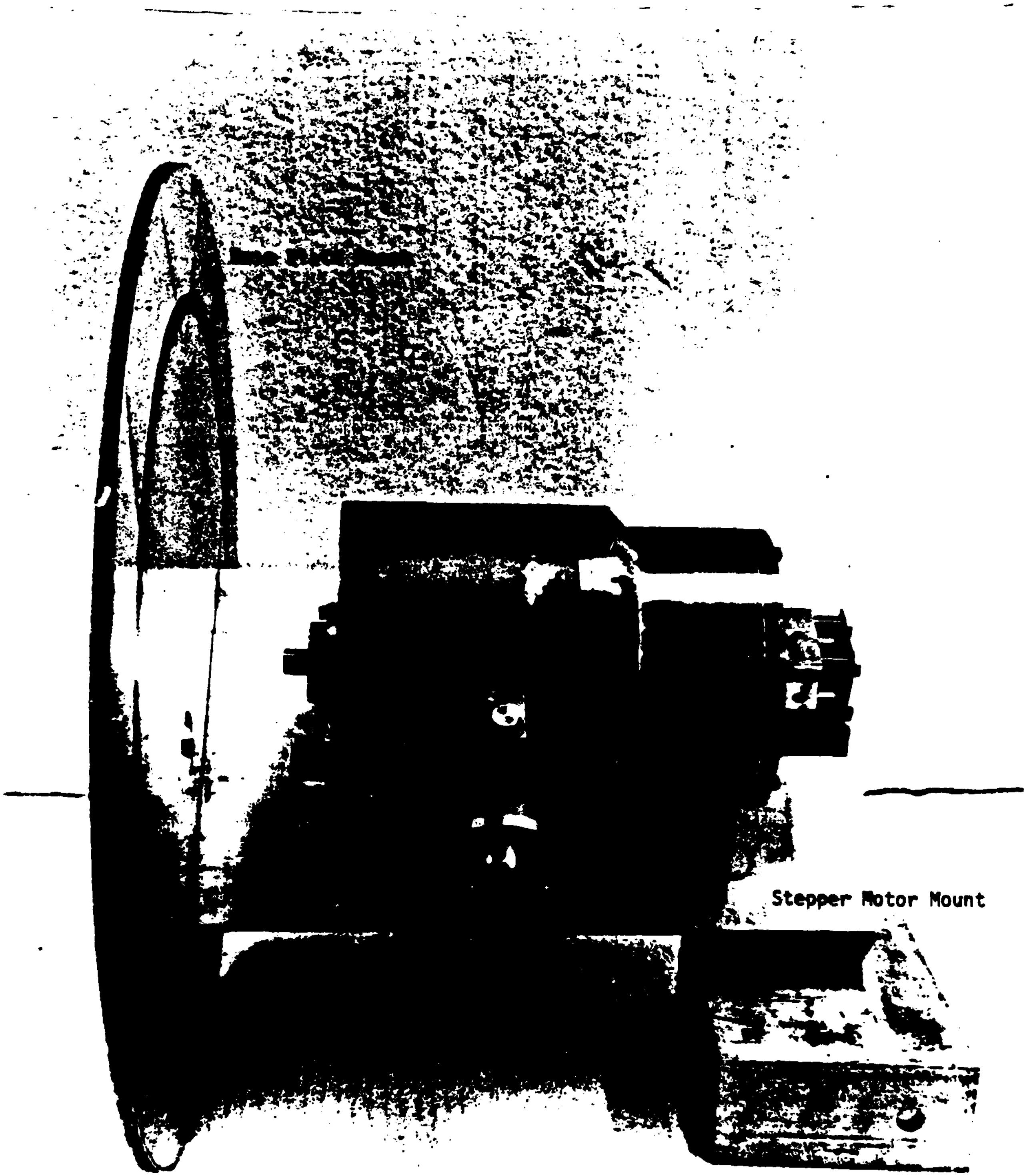

Figure 4. Stepper Motor

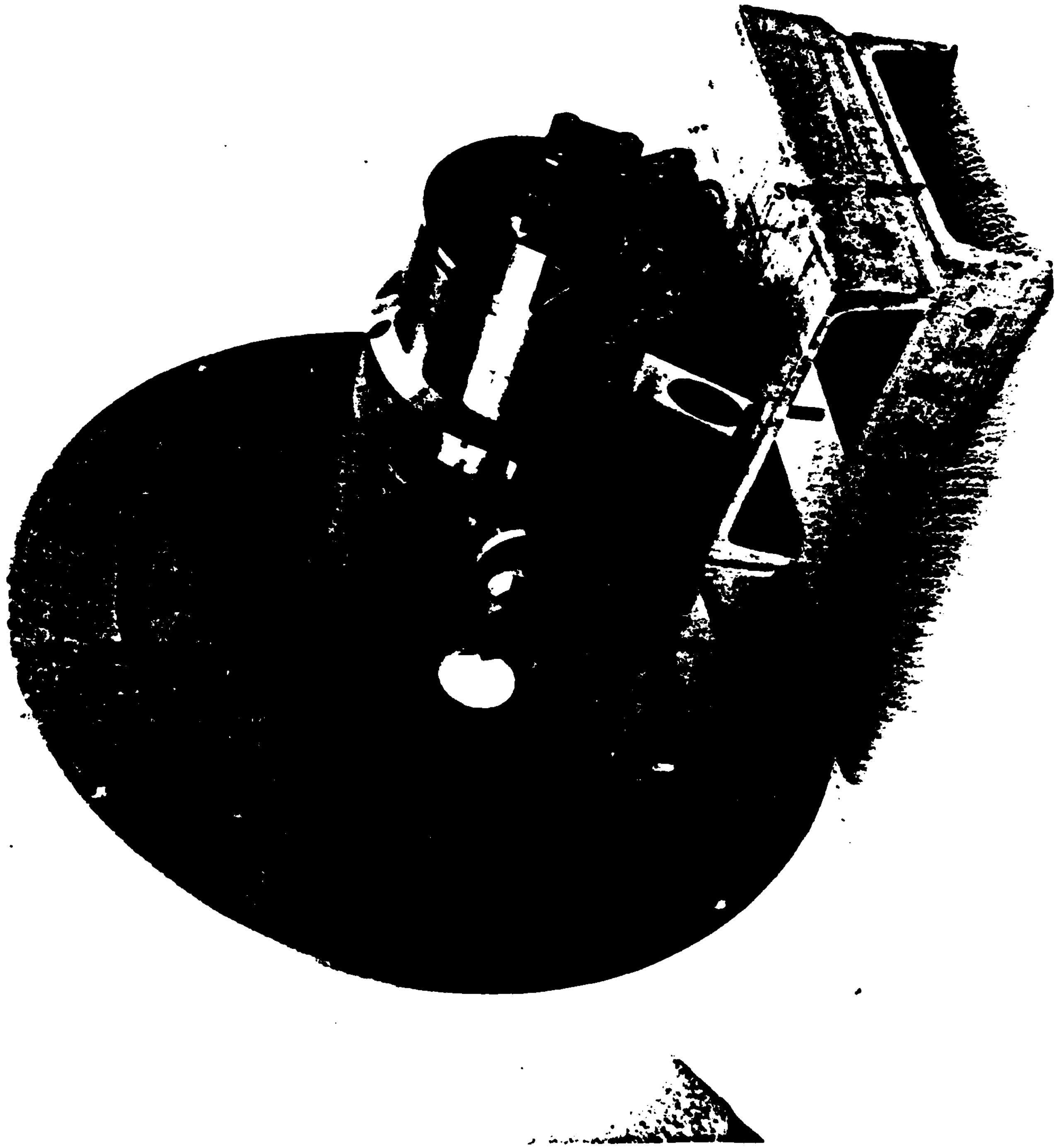

Figure 5. Stepper Motor

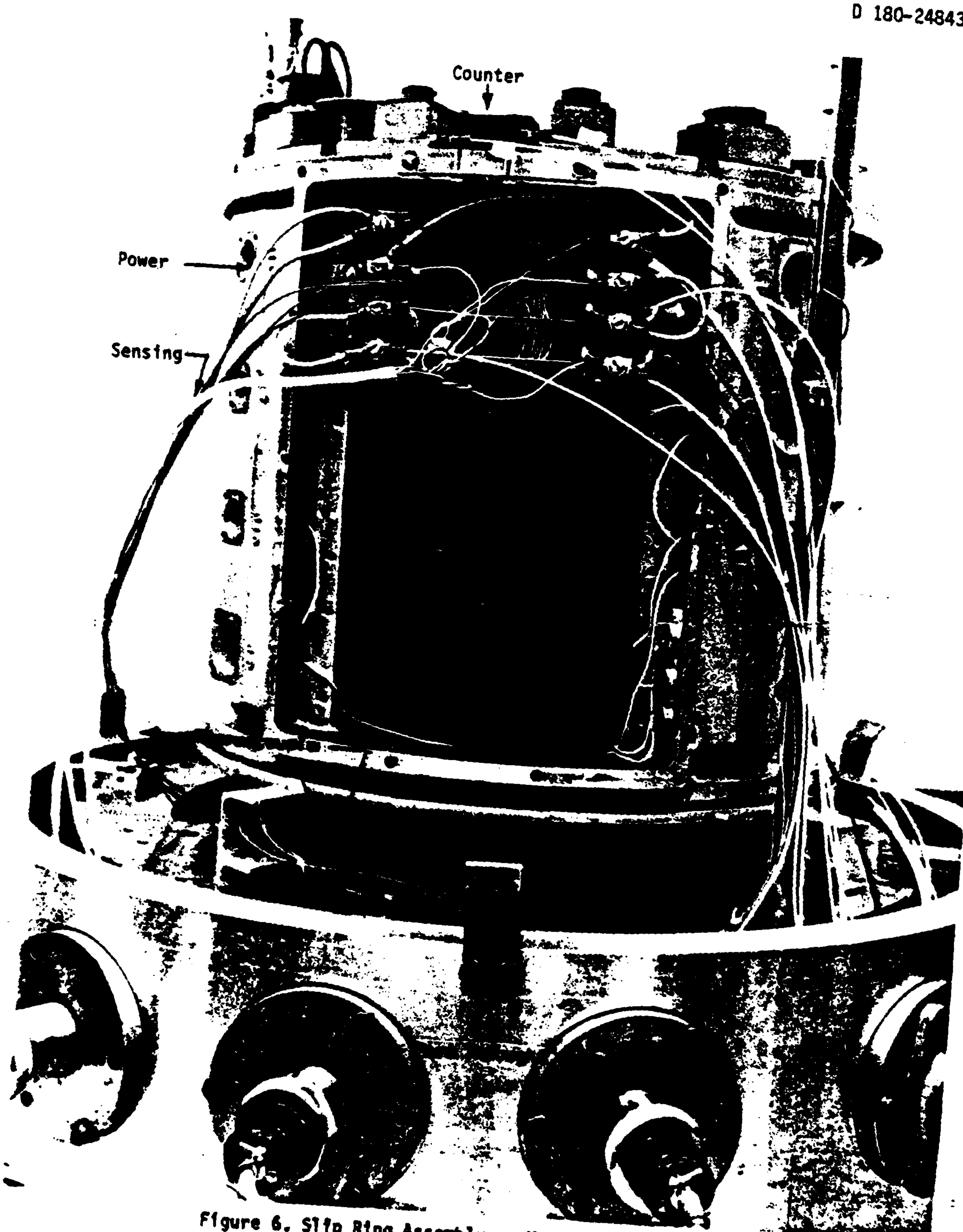

Figure 6. Slip Ring Assembly on Vacuum Chamber Base

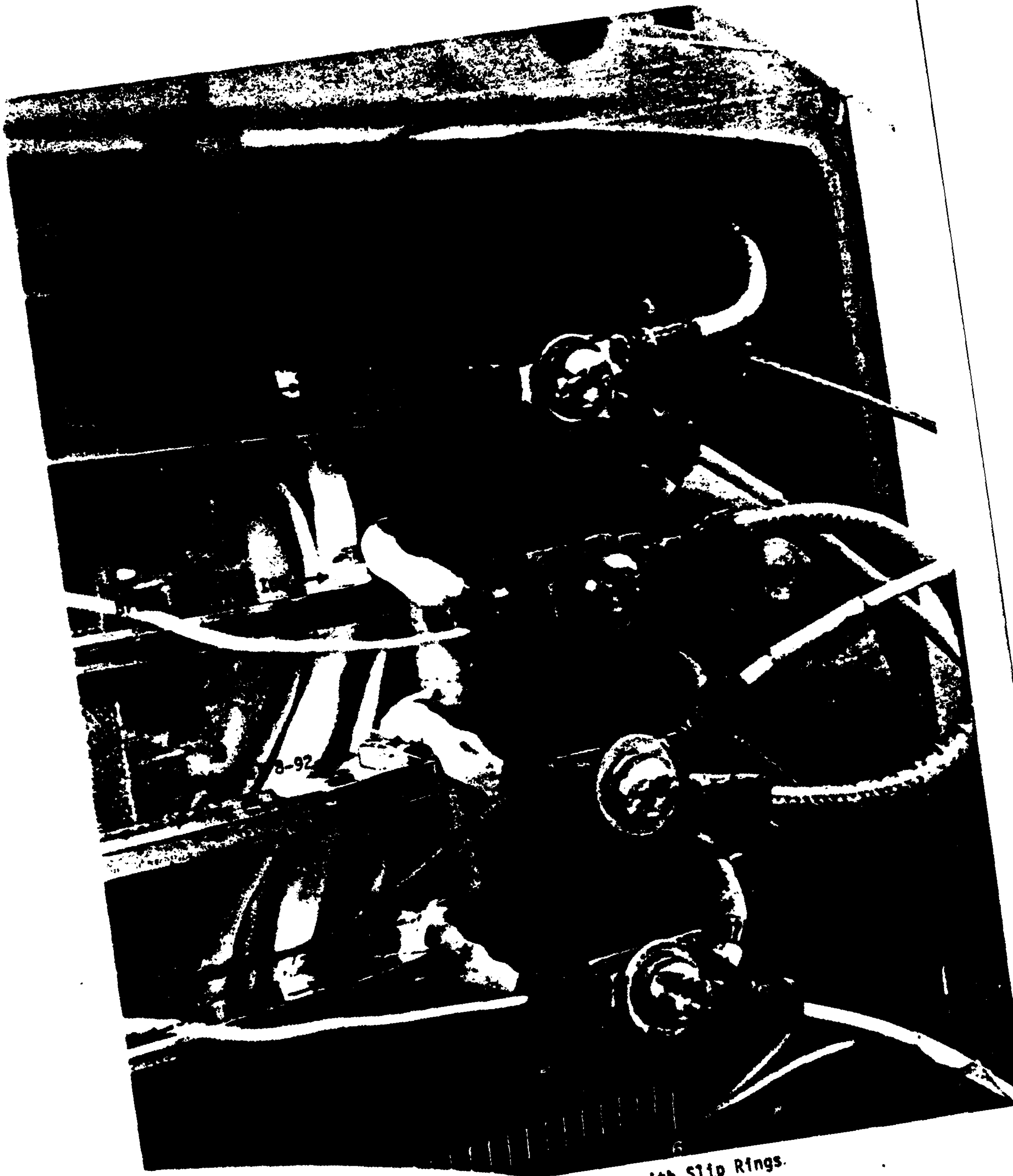

Figure 7. Brushes Seated with Slip Rings.

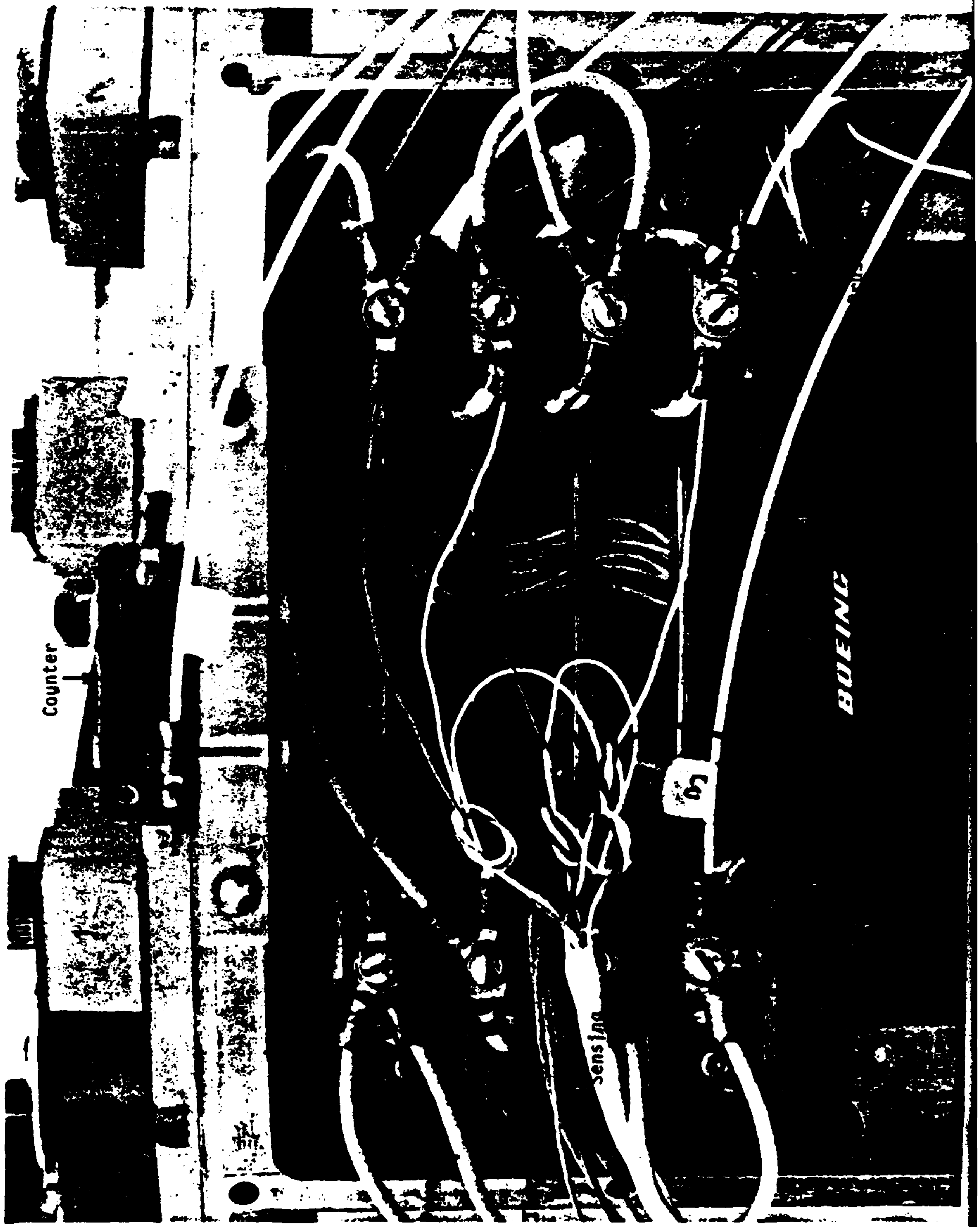

Figure 8. Brush Holders, Power and Sensing Connections

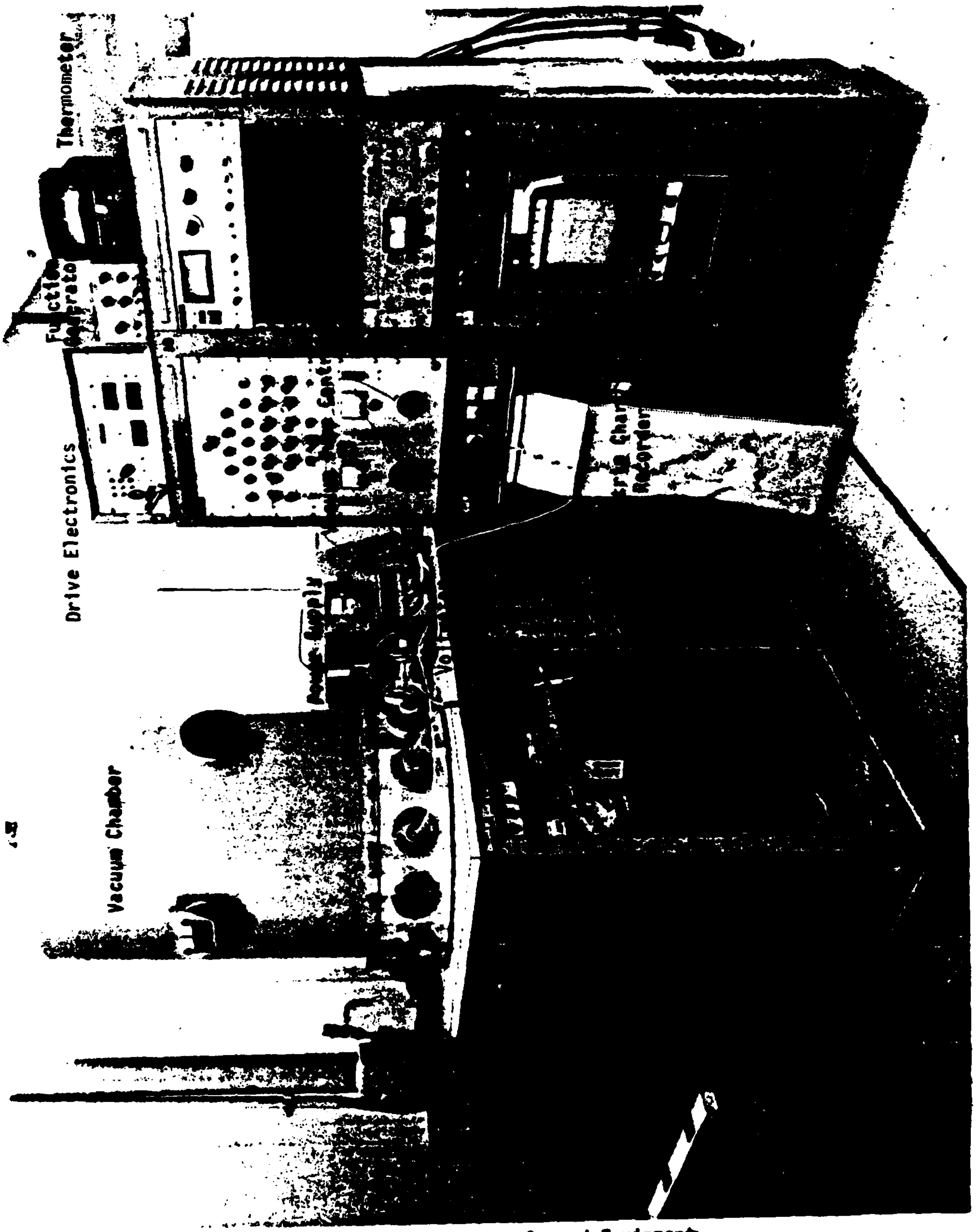

Figure 9. Test Assembly and Equipment

B. Dependent

1. ΔT, change in temperature of brush material
2. ΔV, change in voltage drop of a brush set
3. ΔL, change in length of brush
4. ΔR, change in resistance of brush material

6.22 For the accelerated test conditions, the designed angular velocity was calculated as follows. Because the largest diameter of the concentric slip ring design is 15 meters, and the ring is to travel one revolution in 24 hours, the total distance traveled is πD or: (3.14159) x (15 m) = 47.12 meters/revolution.

The angular velocity of the slip ring is:

$$W = \left(\frac{47.12 \text{ Meters}}{24 \text{ HR}}\right) \times \left(\frac{1 \text{ HR}}{60 \text{ Min}}\right) \times \left(\frac{100 \text{ cm}}{1 \text{ Meter}}\right) = 3.27 \text{ cm/minute}$$

The test slip rings have a diameter of 15 inches (38.1 cm). The distance traveled per revolution equals $\pi \times D$ or: (3.14159) x (38.1) = 119.69 cm/revolution. To simulate one day of space operation with the test equipment, a speed of .0273 RPM would be employed.

$$\text{RPM} = \frac{\text{Angular Velocity}}{\text{Distance per Rev}} = \frac{3.27 \text{ cm/min}}{119.69 \text{ cm/Rev}} = .0273$$

Because of the practicalities of test, the speed of the slip rings was accelerated 10.2 times to .279 rev/min(33.4 cm/min). This acceleration was also justified from the conclusions of a preliminary material bench test, references, and the ability of the stepper motor drive assembly.

6.23 The major requirements for a brush material to be acceptable are low voltage drop and low wear rate at high current densities. The test criteria are as follows:

1. Voltage drop: $\leq$ 0.1 volt
2. Current density: 180.1 A/in^2--360.1 A/in^2
3. Wear rate: $\leq$ 0.005 inches/17.2 Kilometer
4. Operating temperature: $\leq 60^\circ$C (140°F)
5. Vacuum range: 110 microns - 2 x 10^{-7} torr
6. Brush pressure: 4.5 - 11.25 psi
7. Angular velocity: 33.4 cm/min.

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6.24 The length of duration at each current level was determined by combinations of the following conditions:

1. Revolutions > 1000
2. Amount of brush wear at previous setting
3. ΔT of brushes
4. ΔV of brushes

6.25 Testing of the brush samples proceeded after the desired level of vacuum was attained. Testing was not disturbed as higher levels of vacuum were attained during each of the six parts of the test. A part of the test constitutes an ampere setting from 5-10 amperes which corresponds with the range of current densities of the TEST CONDITIONS.

7.0 TEST EQUIPMENT

7.1 POWER SUPPLY

7.11 The power supply used in the slip ring circuit of this experiment was a Hewlett-Packard 628 2A DC power supply with limits of: 0-10 volts and 0-10 ampere. (Boeing number: TBC 565075) The amount of current passing through the slip ring circuit was determined from the voltage drop across a calibrated brass shunt (BCX 151585) in series with the power supply and the slip ring as shown in Figure 2. The Western Instruments shunt limits were 10 millivolts per ampere.

7.12 The power supply used with the counter was a Quan-Tech DC power supply with limits of: 0-30 volts ¼ Ampere (BC# X94067).

7.2 MEASURING INSTRUMENTATION

7.21 Brush temperatures were measured by silver soldering the hot junction of copper/constantan thermocouples on the back side of the leaf spring directly perpendicular to the brush centers of the four types of brushes. Temperature was recorded on a Barber-Colman thermometer (TBX 159264) with limits: -300 to +400 degrees Fahrenheit.

7.22 Both the shunt voltage and the voltage drop across the brushes in each brush/slip ring circuit were monitored by a Dynasciences Digital Multimeter Model 440 (BC # 555758).

7.23 A Chatillon Dpp-80 pull scale, 5 lbs x 1 oz., was used to measure the spring arm pressure. BAC 535218-3.

7.24 A Hewlett-Packard 7100B strip chart recorder was used to monitor the continuously cycling voltage drop across the brush sets. The range on the variable speed recorder was 1 mv - 100 v. (BC# 567155)

7.25 A small counter was mounted on the slip ring assembly to monitor the revolutions of the rings.

7.3 VACUUM CHAMBER

7.31 The vacuum chamber used in this test was a Westinghouse bell jar type, shown in Figure 9. BC #532011. This vacuum system employs liquid nitrogen and a three pump configuration.

7.4 STEPPER MOTOR & ELECTRONICS

7.41 The stepper motor and drive electronics used to rotate the slip rings is shown in Figure 10. This stepper motor was designed specifically for space application for another project and was adapted for this test. The motor drive electronics (MDE # 180 34118 2 S/N002) is the test box for driving the stepper motor in either a clockwise or counterclockwise direction at a single step or continuous rate. From preliminary bench test conclusions, continuous rate and counterclockwise direction were selected for the vacuum testing. Additional equipment required to operate the motor drive electronics included a function generator to provide the external clock. A 4 volt square wave pulse at a frequency of 130 Hertz was required for the stepper motor to produce the designed angular velocity of the test slip rings. The function generator used was a Hewlett-Packard 3310A model.

Figure 10. Stepper Motor, Drive Electronics, Function Generator

8.0 TEST RESULTS

8.1 This vacuum test of brush materials terminated on schedule after a total log of 2014 hours ±1%, with the majority of the testing hours run at the designed slip ring angular velocity of 33.4 cm/min. Due to stepper motor failures, namely, the inability of the stepper motor to produce the torque to rotate the slip rings, the final 382 test hours were run with the pulse frequency to the stepper motor reduced from 130 to 80 Hertz. This new pulse frequency reduced the angular velocity of the slip rings from 33.4 to 16.2 cm/min. The average angular velocity for the test calculates to 30.1 cm/min for an average test acceleration of 9.2 times the expected spacecraft rate. Slip ring revolutions totaled 30193 for the test.

8.2 Table I compares the test results of each brush type with the current density, chamber pressure, brush operating temperature, and brush voltage drop for a number of testing hours. Table II and Table III list the wear rates of the 16 brushes tested, and the predicted brush wear, respectively. Figure 11 displays the change in the brush voltage with an increase in current. Figure 12 is a plot of the change in brush temperature versus the change in current. Variations in testing included: a. Current Range, 5-10 ampere, b. Vacuum range, 110μ-2.0×10^{-7}T. An evaluation of the brushes tested is in the DISCUSSION. Of the brushes tested, TABLE III lists their order of suitability in a high power space brush/slip ring assembly application.

8.3 At all operating currents, 5-10 amperes, the four types of brush/slip ring combinations yielded the following dissimilar results:

8.31 Slip rings A and C_5 were mated with Boeing brush # 046-45. This brush material had the greatest voltage drop and temperature rise of the four materials. The average brush wear for this material was .001 inches; the lowest of the four brush types.

8.32 Slip rings B and A_5 were mated with Boeing brush # 101. This brush material exhibited a substantial decrease in the voltage drop and operating temperature as compared with the 046-45 material. The average brush wear for this material was .00175 inches.

8.33 Slip rings C and D were mated with Boeing brush # 8-92-2. This brush material displayed the lowest voltage drop in the early stages and the lowest operating temperatures in the final stages of the test. The average brush wear for this material was .0035 inches; the worst wear rate of the four brush types.

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8.34 Slip rings E and F were mated with Boeing brush # 7-122-4M. This brush material displayed a low voltage drop and operating temperature similar to the 8-92-2 material. The average brush wear for this material was .00125; the second lowest of the four brush types.

8.4 Post test examination of the slip rings is as follows:

8.41 Slip rings A (lower) and C_5 (upper) were both streaked with a dark grey track. Powdered brush debris accumulated on both edges of both tracks on ring C_5. Ring A did not display accumulated debris, indicating that the excess debris had fallen on the brush holder and/or the ring below.

8.42 Slip rings B (lower) and A_5 (upper) were streaked primarily on the outer and inner edges of the brush tracks. Only ring B had accumulated powdered brush debris on the edges of the brush tracks, with the largest amount of debris on the outer edge.

8.43 Slip rings D (lower) and C (upper) displayed the most wear, imbedded debris, powdered and fragmented debris buildup on the slip ring surfaces with similar excessive debris buildup along the track edges. Traces of the 101 brush material debris from ring B was found imbedded in the surface build up of slip ring C. Excessive debris was not present along slip ring D, indicating that the brush debris had fallen to the assembly and ring below it.

8.44 Slip rings F (lower) and E (upper) were both streaked but at opposite extremes. Ring E was contaminated from the debris from the brushes on ring D. Excessive 8-92-2 brush debris was accumulated along the track edges. Only grey streaks were present and one half of the tracks on ring F. Figure 13 shows the streaking and accumulated debris on the rings.

8.5 The stepper motor stalled out four times during the test. The number of non stop revolutions and hours accumulated before each failure is as follows:

a. 2415,150; b. 7206,452; c. 1057,67; d. 1891,123. See Table I for the time of stepper motor failures with respect to the entire test.

A failure analysis of the stepper motor was not available. Preliminary indications suggest bearing failure to be the problem as the gear train displayed no excessive wear.

TABLE I

TEST RESULTS IN CONDENSED FORM

BRUSH TYPE	CURRENT & EQUIV. CURRENT DENSITY (A← →A/IN²)	CHAMBER PRESSURE (TORR)	BRUSH OPERATING TEMPERATURE RANGE (°F)	BRUSH VOLTAGE DROP RANGE (MV)	TEST RUNTIME (HRS)
046-45	5 ← → 180.1	110 μ-3.0E-6	109 125	310 - 460	436.0*
		1.0E-6	115 - 120	300 - 490	337.0*
	6 " 216.1	2.0E-6	138 - 140	360 - 540	66.5*
	7 " 252.1	1.0E-6	135 - 140	370 - 640	241.0**
	8 " 288.1	3.0E-7	155 - 160	450 - 580	151.5
	9 " 324.1	2.0E-7	175 - 187	500 - 670	210.0***
		1.0E-6	193 - 200	550 - 740	67.0**
		2.0E-6	190 - 206	554 - 780	219.0**
	10 " 360.1	5.0E-6	210 - 226	615 -	286.0*
101	5 " 180.1	110 μ-3.0E-6	81 - 89	70 - 106	436.0*
		1.0E-6	83 - 85	62 - 77	337.0*
	6 " 216.1	2.0E-6	85 - 86	73 - 89	66.5***
	7 " 252.1	1.0E-6	85 - 92	79 - 95	241.0
	8 " 288.1	3.0E-7	90 - 95	94 - 108	151.5
	9 " 324.1	2.0E-7	95 - 100	96 - 126	210.0***
		1.0E-6	100 - 105	114 - 132	67.0****
		2.0E-6	100 - 105	117 - 137	219.0
	10 " 360.1	5.0E-6	105 - 108	132	286.0*
8-92-2	5 " 180.1	110 μ-3.0E-6	79 - 85	41 - 49	436.0*
		1.0E-6	81 - 84	41 - 52	337.0*
	6 " 216.1	2.0E-6	84 - 85	48 - 59	66.5***
	7 " 252.1	1.0E-6	80 - 85	51 - 65	241.0
	8 " 288.1	3.0E-7	89 - 91	61 - 74	151.5
	9 " 324.1	2.0E-7	89 - 91	65 - 85	210.0***
		1.0E-6	94 - 100	77 - 92	67.0****
		2.0E-6	95 - 99	78 - 95	219.0
	10 " 360.1	5.0E-6	100 - 104	89 -	286.0*
7-122-4M	5 " 180.1	110 μ-3.0E-6	79 - 85	40 - 56	436.0*
		1.0E-6	80 - 85	40 - 59	337.0*
	6 " 216.1	2.0E-6	83 - 85	48 - 60	66.5***
	7 " 252.1	1.0E-6	83 - 87	56 - 71	241.0
	8 " 288.1	3.0E-7	89 - 91	64 - 77	151.5
	9 " 324.1	2.0E-7	89 - 91	67 - 87	210.0***
		1.0E-6	95 - 100	74 - 220	67.0****
		2.0E-6	96 - 100	74 - 366	219.0
	10 ← → 360.1	5.0E-6	101 - 105	83 -	286.0*

* Shut down for brush measurement
** Stepper motor failure
*** Stepper motor failure and brush measurement

Table II shows the amount of brush wear that occurred during this test. Table III lists in order of their suitability, according to wear, the brushes tested for the solar power satellite.

TABLE II
BRUSH WEAR

Material Brush Type	Brush Spring Location	Spring Pressure (ounces)	Measurement Before Test (inches)	Measurement After Test (inches)	Amount of Wear (inches ± .0005)
046-45	A_{LONG}↑	2	.160	.159	.001
046-45	A_{SHORT}↑	3	.165	.162	.003
101	B_{LONG}↑	2	.166	.165	.001
101	B_{SHORT}↑	3	.175	.172	.003
8-92-2	D_{LONG}↑	3	.190	.187	.003
8-92-2	D_{SHORT}↑	4	.185	.180	.005
7-122-4M	F_{LONG}↑	3	.172	.170	.002
7-122-4M	F_{SHORT}↑	4	.169	.168	.001
046-45	$C_{5\ LONG}$↓	3	.173	.173	.000
046-45	$C_{5\ SHORT}$↓	3	.175	.175	.000
101	$A_{5\ LONG}$↓	3	.185	.185	.000
101	$A_{5\ SHORT}$↓	3	.179	.176	.003
8-92-2	C_{LONG}↓	4	.185	.181	.004
8-92-2	C_{SHORT}↓	5	.186	.184	.002
7-122-4M	E_{LONG}↓	4	.188	.187	.001
7-122-4M	E_{SHORT}↓	3	.186	.185	.001

USE FOR TYPEWRITTEN MATERIAL ONLY

TABLE III

BRUSHES SUITABLE FOR HIGH POWER SPACE APPLICATION

	Brush Code	Brush Type	Slip Ring	Minimum Voltage Drop @ 360.1 A/in^2	Test Wear Rate in/36.14 km	Average Wear Rate (in/per yr) in/17.2 km	Predicted Wear (30 yrs.) in/516 km
1.	7-122-4M	$AgMoS_2$	coin Ag	83 mV	0.00125	0.00059	0.0178
2.	101	$AgWS_2$	coin Ag	132 mV	0.00175	0.00083	0.0250
3.	8-92-2	$AgBaF_2$	coin Ag	89 mV	0.0035	0.00167	0.050

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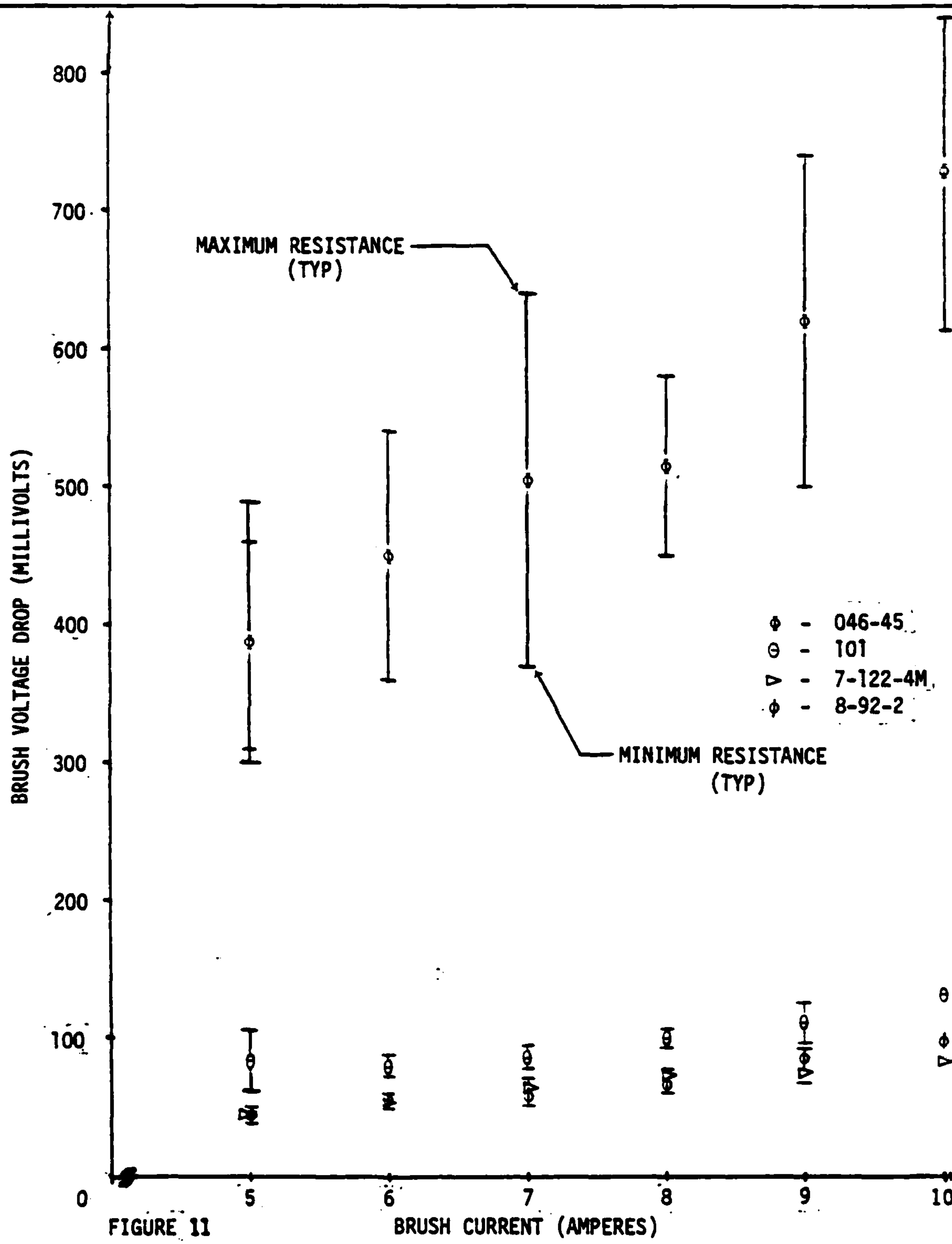
800
700
600
500
400
300
200
100
0
BRUSH VOLTAGE DROP (MILLIVOLTS)
MAXIMUM RESISTANCE (TYP)
MINIMUM RESISTANCE (TYP)
Φ - 046-45
Θ - 101
▷ - 7-122-4M
Φ - 8-92-2
5
6
7
8
9
10
BRUSH CURRENT (AMPERES)

FIGURE 11

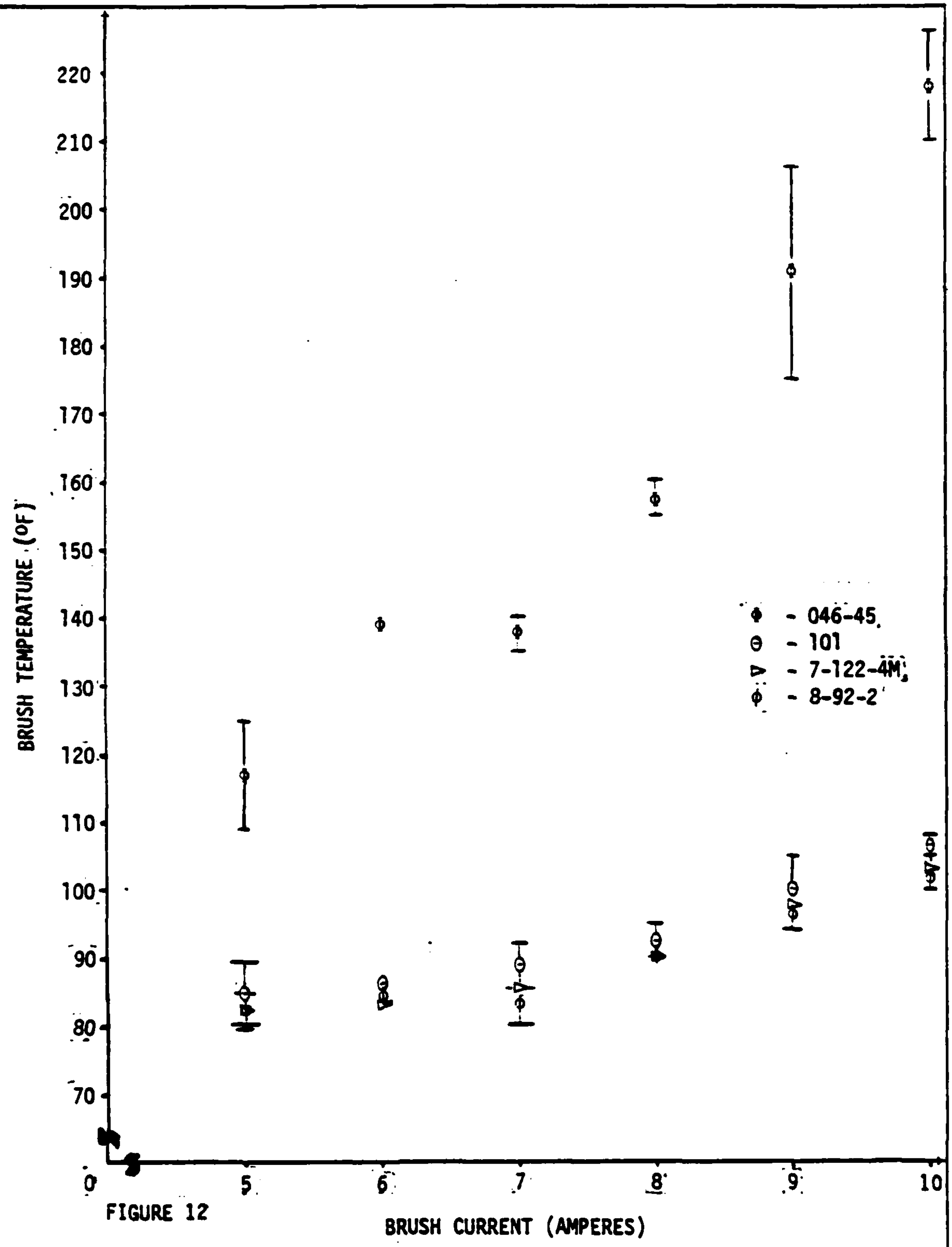
BRUSH TEMPERATURE (°F)
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
0
5
6
7
8
9
10
BRUSH CURRENT (AMPERES)
- 046-45
- 101
- 7-122-4M
- 8-92-2

FIGURE 12

Figure 13. Slip Rings and Debris

9.0 DISCUSSION

9.1 The objective of this test was to take the most promising in-house brush materials and evaluate them against the following criteria. The brush material is satisfactory for space application if: a. Its voltage drop between the brush pigtail and the slip ring is ≤0.1 volts, b. Its wear rate is ≤ 0.005 inches per 17.2 kilometers of slip ring distance traveled, c. Its current carrying capability is ≥ 180.1 A/in, d. Its operating temperature is ≥ 60°C (140°F).

9.2 Condensed test results are recorded in Table I, with comparative wear rates tabulated in Table II, and predicted wear in Table III. Figures 11 and 12 graphically illustrate the effects of increasing the current and the resultant change in the brush voltage and temperature.

9.3 The predicted physical phenomenon occurred, namely, that both an increase in brush temperature and brush voltage drop occurred in all brush materials with an increasing current density.

9.4. The operating temperatures at the current density of 360.1 A/in^2 suggest that if a slightly higher voltage drop were permitted, higher current densities could be employed in the testing of these same three types of brush materials, specifically, 101, 8-92-2, 7-122-4M.

9.5 The operating temperatures and wear rates of the three brush material types of 9.4 were acceptable for the standards described in this test. Only at the highest current densities did the voltage drop of the 101 material not qualify under the test criteria. Even though material 046-45 had the lowest wear rate, its voltage drop and the operating temperature make it unacceptable for future testing.

9.6 Variations in wear rates of similar brush materials were concluded to be dependent upon the following:

a. Spring arm pressure
b. Amount of contaminants encountered
c. Original mill work of the brush surface
d. Orientation of the granular matrix of the brush with the slip ring surface

9.7 A summary evaluation of the brushes tested is as follows:

9.7.1 046-45

This space-use brush was developed by Boeing Metallurgical Laboratory for the Air Force; contract number AF33(657)10384. This brush is not suitable for a high power satellite because its voltage drop and operation temperature exceed the required criterion. It does have excellent wear characteristics for space application.

9.7.2 101

This space-use brush was developed by Boeing Metallurgical Laboratory for the Air Force; contract number AF33(657)10384. This brush is probably suitable for a high power space application because of a low voltage drop, wear rate, and operating temperature at high current densities.

9.7.3 8-92-2

This space-use brush was developed by Boeing Metallurgical Laboratory for the Air Force; contract number F33615-70-C-1226. This brush is probably suitable for a high power satellite because the brush has the second lowest voltage drop and operating temperature at high current densities even though its wear rate is the greatest of those tested.

9.7.4 7-122-4M

This space-use brush was developed by Boeing Metallurgical Laboratory specifically for this brush test. This brush has the greatest probability of being suitable for a high power satellite because of its low voltage drop, operating temperature and wear rates at high current densities.

9.8 EXPERIMENTAL ERROR

9.8.1 The effect on the wear rate due to contamination from brush debris from one material type on another has not been studied. A first impression would indicate that any debris would act as a lubricant, thereby decreasing wear. Because the brush measurements were made with a micrometer, an error of at least ± 0.0005 in. was possible. The wear rate for each material type was computed as the average wear of the four brushes of each type. Measurement of the brush pressure taken with the pull scale, likewise, introduces some error.

USE FOR TYPEWRITTEN MATERIAL ONLY

10.0 CONCLUSIONS

10.1 This report presents the test results of a 2014 hour test of four sliding contact materials:

a. 046-45, a molybdenum disulfide material,
b. 101, a silver tungsten sulfide material,
c. 8-92-2, a silver barium flouride material,
d. 7-122-4M, a silver molybdenum disulfide material, mated with coin silver slip rings.

10.2 The testing criteria are as follows:

a. Voltage drop $\leq$ 0.1 volts across set of brushes
b. Wear rate $\leq$ 0.005 inches/17.2 km of slip ring travel
c. Current density $\geq$ 180.1 A/in^2
d. Operating temperature $\leq$ 60^{o}C (140^{o}F)
e. Brush pressure = 4.5 - 11.25 psi
f. Vacuum range = 110 microns - 2 x 10^{-7} torr

10.3 Of the four Boeing-developed brush samples of 10.1, brush types 8-92-2 and 7-122-4M were the most successful in qualifying as suitable brush materials for application on a high power satellite. Of these two brush types, wear rate was the determining factor in the selection of 7-122-4M as the most probable brush type of the samples tested to be used on a high power satellite.

10.4 The average brush wear of the 7-122-4M material was 0.00125 inches for the 2014 hour test. This is an average wear rate of 0.00059 inches per 17.2 kilometers of slip ring travel per year. At the maximum test current density, 360.1 A/in^2, the brush operating temperature range was 95-105^{o}F. The typical minimum brush voltage drop was 74-83 millivolts.

10.5 Greater brush wear occurred on the brushes which were positioned beneath their respective rings in contrast with the brushes mounted on top of their rings. On the average, more brush wear occurred on the brushes that were mounted on the shorter of the two spring arm lengths. The major cause of the difference in brush wear between the two holders probably stems from the initial mounting and spring arm displacement.

10.6 Brush material overheating to the extent of operational failure was not encountered, even though material 046-45 displayed the highest operating temperature, 226°F, exceeding the test criterion of 140°F. The brush voltage drop, 0.55-.78 volts, of this same brush material at the maximum test current density also exceeded the test criterion. Because of the operating characteristics of the 046-45 material, it will be eliminated from future tests.

11.0 RECOMMENDATIONS

11.1 Prior to additional testing, this test plan and procedure should be evaluated incorporating improvements where necessary without altering the test so as to invalidate the previous test results.

11.2 In order to confirm the superiority of a particular brush material, a spectrum of brush materials should be evaluated. Similar additional vacuum tests of the 101, 8-92-2, 7-122 4M brush materials and other advanced Boeing and vendor materials should be conducted before the most suitable brush for a high power satellite is selected.

11.3 An actual ring velocity test should be conducted to verify the validity of the accelerated tests. A continuously running test of one year duration should be conducted at the present design speed of the actual slip ring, 3.27 cm/min., rather than the accelerated test speed of 33.4 cm/min. A correlation can then be made with the two modes of testing to determine if the wear predictions are accurate. Only with a long term test can the wear rate be determined as a function of linear meters traveled. Special attention should be given to the current density of the brush material during the test.

11.4 Future tests should continue to use voltage drop, operating temperature, wear rate, and high current densities as the major test criteria. An investigation should be made to determine if more information is necessary, what additional tests might be administered, and subsequent requirements added to the basic criteria. An example might be to monitor the generated noise amplitude & character at the brush/slip ring interface.

11.5 Future tests should be conducted in environments other than the ambient temperature of the laboratory test chamber. Testing should be conducted in extreme hot and cold environments and in radiation and other space environments.

11.6 A statistically controlled test should be conducted where the characteristics of the most promising brush material types are incorporated in new brushes. These newly sintered brushes should be evaluated against criteria more stringent than the requirements of this test. The development of more efficient brushes will eliminate the massive quantity of brushes required, reduce the weight of the system, and set the limit for maximum power transfer across a rotating joint in space.
Confidence in a brush material will occur when continued test data provides a definite wear rate with long term predictability, and other brush characteristics, with respect to environmental and current density variations.

11.7 Future tests should use an initial current density of 300 A/in^2. This current density will aid in eliminating brush materials that cannot qualify under the designed test criteria.

11.8 Future tests using the same or a similar slip ring assembly should place the assembly so that rings are in a vertical rather than horizontal position. This vertical positioning of the slip rings will decrease the possibility of contamination of the lower brush/ring set from debris falling from the upper ring.

11.9 Future tests should use an external variable speed drive, with a hermetically sealed shaft feed-through, to power the slip rings. This will reduce the number of chamber backfills and pumpdowns which was the case with the stepper motor failures of this test.

12.A TEST PLAN

12.A1 BACKGROUND

12.A11 Large photovoltaic, high power satellites located in geosynchronous orbits will deliver usable electrical power to earth around 1990. These satellites will have solar cell array areas of about 120 km^2. A microwave beam will transmit the array-generated power to the Earth receiving stations. Earth receiving stations with their antenna, rectifiers, and inverters will collect the microwave beams and convert the power to 60 Hz alternating current for delivery to electric utility networks.

12.A12 The antenna on the satellites must point toward the receiving stations on Earth. The satellite solar array, which is pointed perpendicular to the sun's rays, will rotate with respect to the antenna at a rate of one revolution per 24 hours. With present technology, the best way of transferring electrical power from the solar array to the antenna is through a brush/slip ring assembly.

12.A2 TEST OBJECTIVES

12.A21 The objectives of the test described in this plan is to find the optimum brush/slip ring combination where friction coefficients, voltage drop, and wear rates are at a minimum, and a life of 30 years of one revolution per day operation in the vacuum of space can be attained with high current densities. Preliminary test tasks consist of the following:

1. Modify an AWACS microwave brush/slip ring assembly.
2. Procure brush samples.
3. Procure drive mechanism for operation in vacuum.
4. Construct and/or procure test assembly, power supplies, vacuum chamber, and monitoring instrumentation.
5. Develop and adapt a drive mechanism to power the slip ring assembly.
6. Mount brush materials on brush holders.
7. Adapt vacuum chamber with feed throughs for thermocouples, drive and slip ring power, and monitoring instrumentation.
8. Establish relative speed of slip rings such that meaningful predictions of 30-year brush life can be obtained in about 3 months.
9. Assemble instrumentation for monitoring brush voltage drops for various values of brush current density.

10. Make visual examinations of brushes and slip rings, measure brush length, and note initial milling and composition features.
11. Evacuate chamber, start tests, and monitor test parameters.

With the test in progress, the following schedule is required:

1. Daily measurements
2. 30-day measurements
3. 3-month measurements

Greater details of the above schedule are provided in the Test Procedure, Appendix 12.B.

12.A3 TEST CONDITIONS

12.A31 The test requirement is a voltage drop of $\leq$ 0.1 volts between the brush pigtail and the coin silver surface of the slip ring. A minimum current density for brush testing is 15 ampere per cm^2. The test is to run in a vacuum chamber with the vacuum ranging from 110 microns to 2×10^{-7} TORR (1.5×10^{-9} Pa). The linear velocity of the slip ring is to be accelerated from the actual 3.27 cm/min to 33.4 cm/min for reality in testing. Testing is to be done at ambient temperatures without radiation effects.

12.A32 The brush/slip ring assembly on a high power satellite will operate at a temperature of about 100^{0}C in a pressure of 10^{-11} Pa. Three concentric slip rings of diameters 15, 11, and 7 meters are in the present high power satellite design plans. Ultra high vacuum is not a concern in this initial evaluation of brush/slip ring conditions. Furthermore, a greater slip ring speed must be used in order to accelerate and project 30 years of operation in three months. Therefore, the test conditions in Table IV are adopted for this test.

TABLE IV

TEST CONDITIONS

		Expected at Spacecraft	To Be Used in Test
1.	Ambient Pressure, TORR	10^{-9}	10^{-6} $\pm$
2.	Current Density, A/cm^2	15	27.91⟷55.82
3.	Temperature, ^{o}C	100	Chamber Ambient
4.	Slip ring, peripheral velocity, cm/min.	3.27	33.4
5.	Brush Pressure, psi	not known	4.5--11.25

12.A4 TEST APPARATUS

12.A41 The test setup is shown in Figure 9. A detailed description of the brush holder slip ring assembly, power system, drive assembly, vacuum chamber and monitoring instrumentation is provided in the test report.

12.A5 TEST SAMPLES

12.A51 The brushes to be tested, their originations and a detailed description are identified in Table A of the test report.

12.A6 TEST DEVELOPMENT

12.A61 After the test setup has been assembled, all instruments shall be calibrated against standards traceable to the National Bureau of Standards. The test shall consist of making the measurements described in the TEST PROCEDURE, Appendix 12.B, and operating the brush/slip ring assembly in the vacuum chamber for three months.

12.A62 The following observations shall be made at the completion of the test:

1. Condition of slip rings
2. Nature of residue around brushes
3. Amount of brush and slip ring wear
4. Description of failures and distinctions
5. Comparison of current densities, brush wear, voltage drop, and temperature gradients of the four brush types tested.

12.A7 TEST REPORT

12.A71 The test report shall include the following:

1. Summary
2. Introduction
   a. Subject
   b. Purpose
   c. Objectives
3. Test Elements
4. Test Development
   a. Test Setup
   b. Test Conditions
5. Test Equipment
6. Test Results
   a. Evaluation of brushes tested
   b. Description of failures
7. Discussion
8. Conclusions
9. Recommendations
10. Appendixes
   a. Test Plan
   b. Test Procedure
   c. Literature Search

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12.B TEST PROCEDURE

12.B1 This test shall consist of measuring the wear rate of four brush materials for a range of current settings. Prior to actual testing, preliminary tasks are as follows:

I Clean vacuum chamber

II Calibrate instruments

III Connect thermocouples and power

IV Connect instrumentation and monitor the performance of the following parameters:

A. Brush pressure, psi

B. Brush temperature, ^{o}C or ^{o}F.

C. Brush voltage drop, millivolts

D. Brush current, amps

E. Linear speed of slip ring

V The detailed steps for testing the different types of brush materials are as follows:

A. Initial measurements

1. Brush measurements

   a. Detailed visual examination including sketches of brush and its defects

   b. Width and depth measurements to one thousandth of an inch

2. Ring measurements

   a. Detailed visual examination with sketches and/or photographs of wear and defects

   b. Thickness measurement to one thousandth of an inch

3. Brush pressure

4. Brush temperature

5. Brush resistance

B. Daily Measurements

1. The frequency of reading is dictated by the lineality of the test.

2. Brush current, amps

3. Brush temperature, ^{o}C or ^{o}F

4. Brush voltage drop, millivolts

5. Sliding speed, cm/min.

6. Chamber pressure, TORR

7. Note all unusual occurrences

C. 30 Day Measurements
  1. Repeat daily measurements
  2. Brush length
    a. Detailed visual examination including sketches of brushes and their defects
    b. Measure the length and width to onethousandth of an inch
  3. Ring thickness
    a. A detailed visual examination with sketches of wear and defects
    b. Measure the thickness to onethousandth of an inch

D. Three Month Measurements
  1. Repeat 30 day measurements

VI Stop the test and remove the test assembly and instrumentation from the test site.

12.C LITERATURE SEARCH

12.C1 The purpose of this section is to summarize the literature search on sliding electrical contact materials in combination with coin silver slip rings. Research has proven the inferiority of graphite as a lubricant.[2,3,4,5] Consequently, future tests will consist of materials that contain MoS_2 rather than graphite as a lubricant.

12.C2 Brush wear rates are dependent on two factors: mechanical wear and electrical wear. The mechanical wear rate increases as the relative speed of the surfaces in contact increases. The electrical wear rate increases as the current density in the brush is increased. The most important factor that influences brush wear are the mechanical characteristics of vibration, manufacturing tolerances, and clearances between the brush and the slip ring. Variations in atmospheric conditions, low pressure, lack of oxygen to maintain oxide films, temperature, contamination, outgassing of insulation, paint, lubricants, oil vapors, and humidity are also factors that influence brush wear rates. Excessive brush wear can also be attributed to lubrication starvation at the brush/slip ring interface which causes temperature gradients in elements with poor heat transfer characteristics. The brush material itself: its base grade, sintering technique, and treatment also affect the wear characteristics of a brush. For example, the ordinary graphite brush is useless in a brush slip ring assembly in a vacuum operation: its wear rate is extremely high and the slip ring also suffers damage.[2,3,4,5]

12.C3 In a comparison of dry and wet lubricated systems, the performance of the dry lubrication is found to be superior.[11] Wet lubrication gradually degrades with time while dry lubrication improves with time. The dry lubrication system performance is also independent of surface speed. The effects of evaporation and dissociation in a vacuum contributing to an accelerated loss of lubrication are more significant than those of weightlessness, space radiation, and temperature change.

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12.C4 Of the dry candidates,the majority of experimental evidence to date indicates molybdenum disulfide (MoS_2) to be superior as an electrical contact lubricant in an ultra high vacuum to its leading rival niobium diselenide ($NbSe_2$).[4,6,7,8,9] MoS_2 advantages are: less electrical noise, lower coefficient of friction, lower wear characteristics, and lower cost. The effectiveness of the lubricating film in decreasing friction is just as great in decreasing wear.

12.C5 MoS_2, having high electrical resistivity, is incorporated into the brush material which runs against the slip ring material, that has low electrical resistivity. Lubrication is provided by the continuous release of the MoS_2 as the brush material wears. Low contact resistance is provided by the silver component in the brush material. In an ultra high vacuum, adhesion of MoS_2 to the metal surface is strong because the metal surface is free from any protective film. Wear proceeds by the sliding between the MoS_2 layers and the flaking of the layers. Both overfilming and underfilming will result in high wear.

12.C6 In the initial stages of operation in an ultra high vacuum, MoS_2 contains many contaminants which increase friction. Contaminants are gradually desorbed and the coefficient of friction decreases with continued operation. An occasional stopping of the slip ring rotation in the initial test stages will aid more quickly the desorption and evaporation of the contaminants and in not producing excessive lubricant on the slip ring surface.

12.C7 Increasing the MoS_2 content in brushes results in:

a. decrease in friction coefficient
b. decrease in flexural strength
c. decrease in compressive strength
d. increase in electrical resistance
e. increase in lubricant transfer rate
f. decrease in density
g. decrease in hardness.

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The influences of the type and percent of the metal matrix are:

a. high metal content increases thermal conductivity
b. high metal content increases carbide formation
c. high metal contents are more difficult to machine
d. alloys influence hardness and machining characteristics.(10)

12.C8 The procedure for preparing compacts vary but, in general, the procedure is as follows. The lubricant powders are mixed with the metal matrix powders. The combination powder mixture is sintered in a die with the simultaneous application of pressure and heating/cooling in a vacuum. Once removed from the vacuum, the solid material is machined into the required brush dimensions.

12.C9 This test report describes an experiment of simulating one revolution per day slip ring operation in the vacuum of space. An increased speed of rotation was required to accelerate a 30 year life. The increased speed of linear velocity of the slip ring was still slow enough to not appreciably affect the brush wear. The ultimate goal was to find the optimum brush/slip ring combination where the brush voltage drop, friction coefficients, and wear rates are at a minimum and an acceptable life can be attained with high current densities.

12.D ORIGINAL TEST DATA

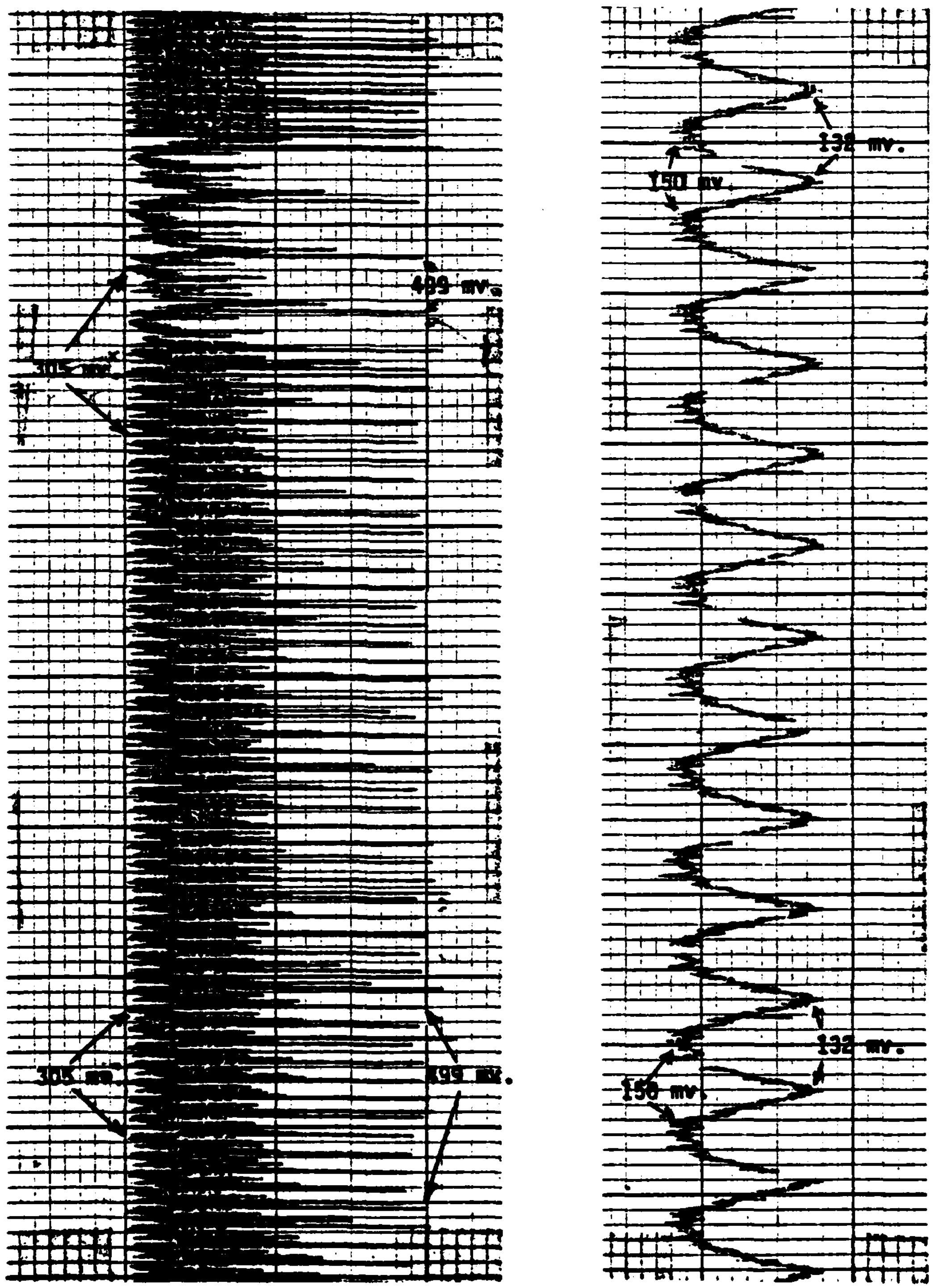
12.D1 The following seven pages of this section contain the original test data that was taken in this experiment.

12.D2 A sample of the voltage fluctuations across each set of brush type is shown on pages 44 and 45. The date when each strip chart recording was taken is located above its corresponding oscillating wave pattern.

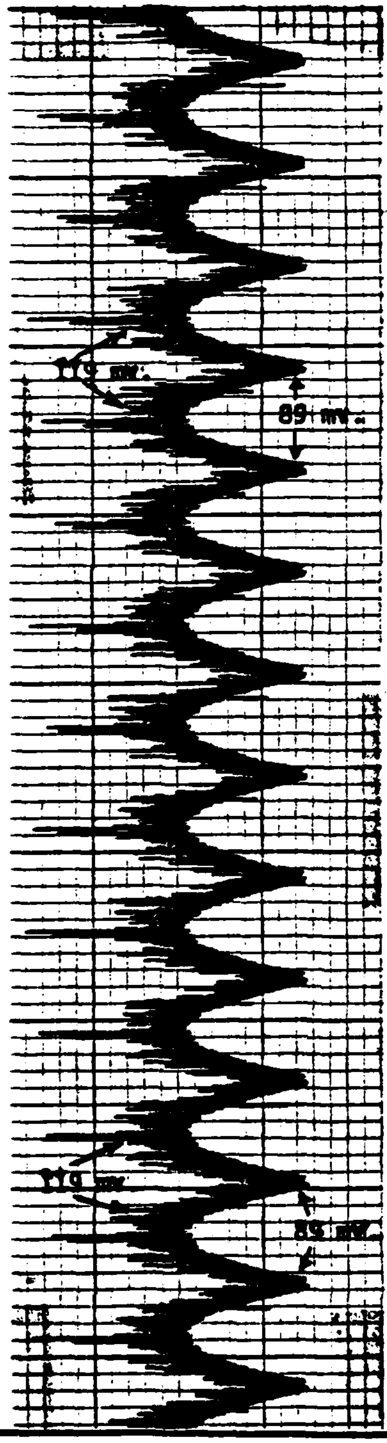
VOLTAGE FLUCTUATIONS

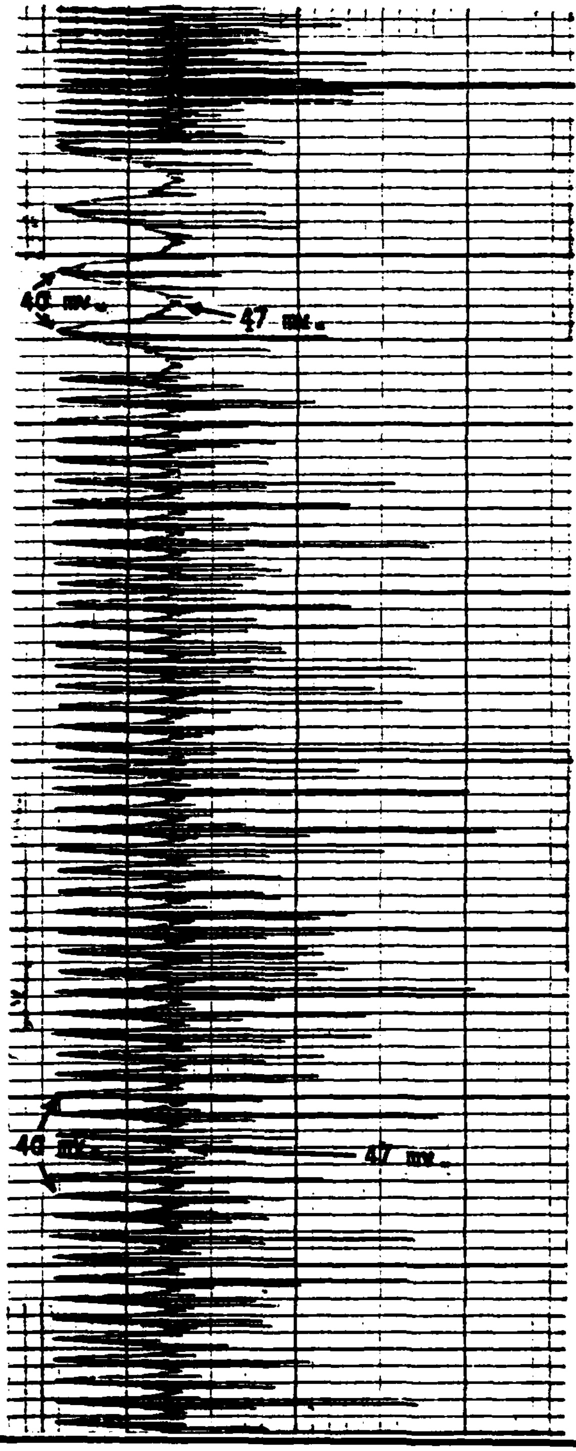
Date: 12/21/'77 pm
"SET I"
046-45 Material

Date: 3/28/'78 pm
"SET 2"
101 Material



VOLTAGE FLUCTUATIONS





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DATE	PRESSURE	# of ROTATIONS	BRUSH TEMPERATURE (°F) AS	CS	E	C	BRUSH VOLTAGE DROP (mv) SET 1 "RED"	SET 2 "GREEN"	SET 3 "BLUE"	SET 4 "BLACK"	INITIALS OF DATA RECORDER
11/14a.		Reset to "0"	75°	82°	75°	75°	400-500	83-130	41-48	39-46	DKH/GH
11/14p.	4×10⁻⁵	116	81°	121°	79°	80°	350-460	11-116	41-49	40-53	DKH 11/14p.
11/15a.	180µ	395	83°	110°	81°	81°	350-450	71-106	41-49	40-56	DKH 11/15a.
11/15p.	1×10⁻⁵	515	83°	120°	82°	82°	320-410	71-104	41-49	41-55	DKH 11/15p.
11/16a.	175µ	797	83°	110°	82°	80°	320-440	71-94	41-49	41-53	DKH 11/16a.
11/16p.	7×10⁻⁶	918	84°	119°	83°	82°	320-450	71-89	41-49	41-55	DKH 11/16p.
11/17a.	140µ	1197	84°	110°	80°	80°	320-440	73-90	41-49	41-54	DKH 11/17a.
11/17p.	9×10⁻⁶	1320	84°	118°	81°	84.5°	320-430	70-88	41-49	41-54	DKH 11/17p.
11/18a.	140µ	1596	83°	110°	81°	80°	320-440	71-97	41-49	41-54	DKH 11/18a.
11/18p.	9×10⁻⁶	1720	84°	119°	84°	83°	310-430	71-86	41-48	41-53	DKH 11/18p.
11/21a.	600µ	2404	85°	109°	88°	84°	310-430	67-83	41-49	41-55	DKH 11/21a.
11/21p.	5×10⁻⁶	2934	89°	125°	89°	87°	320-430	71-86	41-49	41-54	DKH 11/21p.
11/22a.	160µ	3213	88°	112°	83°	82°	320-440	71-86	41-49	41-56	DKH 11/22a
11/22p.	3×10⁻⁶	3336	86°	119°	84°	83°	310-440	74-100	41-49	41-56	DKH 11/22p
11/23a.	110µ	3618	85°	114°	82°	81°	320-440	72-103	42-49	41-53	DKH 11/23a
11/23p.	0.5×10⁻⁶	3740	84°	118°	82°	80°	310-420	70-93	41-48	41-51	DKH 11/23p.
11/28a.	350µ	3740	73°	95°	73°	69°	360-460	70-92	41-48	39-53	DKH 11/28a
11/28p.	3.5×10⁻⁶	3856	80°	118°	79°	79°	330-450	70-86	41-48	41-50	DKH 11/28p
11/29a.	[illegible]	4131-42	83°	113°	80°	80°	340-460	72-83	41-48	41-52	DKH 11/29a
11/29p.	6×10⁻⁶	4185	85°	125°	75°	75°	390-550	78-115	42-49	40-48	DKH 11/29p
11/30a.	2×10⁻⁶	4461	85°	125°	72°	82°	330-420	74-98	43-50	41-49	DKH 11/30a
11/30p.	(7.5×10⁻⁶)	4583	88°	125°	85°	85°	320-390	79-89	42-50	41-49	DKH 11/30p
12/1 a.	(60µ) (6.5×10⁻⁶)	4584	70°	105°	75°	75°	350-420	79-130	41-49	40-46	DKH 12/1a
12/1 p.	(45×10⁻⁶)	4682	78°	118°	70°	78°	330-400	72-86	41-49	40-48	DKH 12/1p
12/2 a.	55	reset	68°	105°	70°	70°	340-420	72-89	41-49	40-48	DKH 12/2a
12/2 p.	(5×10⁻⁶)	FORGOT TO (4605)	79°	116°	78°	77°	330-410	70-85	41-48	40-48	DKH 12/2
12/5 a.		[illegible]						172 previous [illegible]			[illegible]

Margin notes: 11/23a.–11/23p.: "[illegible] RIVIN"; 11/29a.: "→ 72 measurement"; 11/29p.: "continue"; 12/1 a.: "STOP"; 12/1 p.: "— STOP"; 12/2 a.: "Start".

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USE FOR TYPEWRITTEN MATERIAL ONLY

DATE	PRESSURE	BRUSH TEMPERATURE °F A5	C5	B	C	BRUSH VOLTAGE DROP (mv) SET 1 Red	SET 2 Green	SET 3 Blue	SET A Black	SIGNATURE (INITIALS)		REVOLUTIONS		TOTAL RUNNING TIME
12-5 a.														
12-5 p.														
12-6 a.	6x10^-6	71	71	71	71	No Current Flow / No Pwr Applied				DKH	—	No Rotation		0
12-6 p.	6x10^-6	73	100	72	72	5 Amps Applied				DKH	12/6 p	No Rotation		0
12-7 a.	3.5x10^-6	78/79	85/120	78/78	78/78	(340-410)	(68-78)	(41-47)	(40-48)	DKH	12/7 a	300	[290 (No I)]	17 hrs
12-7 p.	3 x10^-6	85	120	80	80	(320-390)	(68-79)	(41-49)	(40-48)	DKH	12/7/73	404 → No I acc		7
12-8 a.	2.5x10^-6	80	80	80	80	PWR SUPPLY FAILURE				DKH	12/8 a.	690	(No I)	13
12-8 p.	3x10^-5 (Degas)	105	142	103	104	(320-400)	(69-78)	(44-52)	(42-51)	DKH	12/8 p.	811	51	
12-9 a.	3x10^-6	84	119	82	84	(320-390)	(65-76)	(42-49)	(40-48)	DKH	12/9 a.	1106		25
12-9 p.	3x10^-6	83	119	80	81	(318-390)	(65-77)	(42-49)	(40-51)	DKH	12/9 p	1212		6
12-12a.	1x10^-6	69	69	69	69	No Current Flow / Pwr off for wkend				DKH	12/12 a.	1213		START
12-12p.	1.5x10^-6	79	115	76	76	(318-390)	(63-75)	(41-49)	(39-47)	DKH	12/12 p	1290		5
12-13a.	2x10^-6	84	120	82	82	(318-400)	(63-74)	(42-49)	(40-54)	DKH	12/13 a	1585		17.5
12-13p.	2x10^-6	84	120	83	82	(318-390)	(63-75)	(42-49)	(40-50)	DKH	12/13 p.	1689		6.5
12-14a.	2x10^-6	84	118	82	83	(318-410)	(65-75)	(42-50)	(40-57)	DKH	12/14 a.	1990		17.5
12-14p.	2x10^-6	84	118	82	83	(318-380)	(64-75)	(42-49)	(40-61)	DKH	12/14 p.	2096		6.5
12-15a.	1.5x10^-6	84	119	83	82	(318-410)	(64-75)	(42-49)	(40-58)	DKH	12/15 a	2404		18
12-15p.	1.5x10^-6	84	118	82	82	(308-400)	(63-75)	(42-49)	(40-50)	DKH	12/15 p	2503		6
12-16a.	1.5x10^-6	84	118	82	83	(318-420)	(64-75)	(42-49)	(40-57)	DKH	12/16 a	2816		18.5
12-16p.	1.5x10^-6	84	118	83	83	(318-440)	(64-75)	(42-49)	(40-56)	DKH	12/16 p	2906	269	5.5
12-19a.	1x10^-6	84	118	83	83	(318-460)	(64-74)	(42-50)	(41-72)	DKH	12/19 a	3990		6.5
12-19p.	1x10^-6	84	118	82	83	(318-440)	(65-75)	(42-50)	(40-48)	DKH	12/19 p	4108		7.5
12-20a.	1x10^-6	84	118	83	83	(306-475)	(65-74)	(42-50)	(40-125)	DKH	12/20 a	4380		16.5
12-20p.	1x10^-6	84	118	83	83	(304-460)	(65-71)	(42-50)	(40-79)	DKH	12/20 p	4503		7.5
12-21a.	1x10^-6	84	117	83	82	(303-493)	(63-74)	(42-50)	(40-47)	DKH	12/21 a	4773		11.5
12-21p.	1x10^-6	84	117	85	83	(305-499)	(63-74)	(42-50)	(40-47)	DKH	12/21 p	4893		7.5
12-22a.	1x10^-6	85	118	84	84	(302-502)	(63-74)	(42-52)	(40-51)	DKH	12/22 a	5169		16.5
12-22p.	1x10^-6	85	118	84	83	(305-490)	(62-73)	(42-52)	(40-47)	DKH	12/22 p	5287		7.5
12-23a.	1x 10^-6	85	118	84	84	(307-490)	(63-73)	(42-51)	(40-47)	DKH	12/23 a	5559		16.5
12-23p.	1x10^-6	85	117	83	83	(301-408)	(62-73)	(42-51)	(40-47)	DKH	12/23 p.	5674	.39	7

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DATE	PRESSURE	REVOLUTIONS	BRUSH TEMPERATURE °F A5 (2)	C5 (1)	E (4)	C (3)	BRUSH VOLTAGE DROP (mv) SET 1 (Red)	SET 2 (Green)	SET 3 (Blue)	SET 4 (Black)	INITIALS		TOTAL RUNNING TIME	
	5×10^{-5}	0	72	72	72	72	*	*	*	No Current *	DKH	@ 0 Amps	0	
1-3 a	4×10^{-5}	0	75	111	71	73	**	**	**	No Rotation **	DKH	@ 6 Amps	0	
1-3 p	2×10^{-5}	29	76	138	74	75	(429-529)	(76-91)	(50-59)	(48-60)	DKH	@ 6 Amps	1.5 HR	[illegible]
1-4 a	$.25 \times 10^{-6}$	315	85	138	83	84	(385-465)	(52-90)	(51-59)	(49-57)	DKH	@ 6 "	17 "	[illegible]
1-4 p	$.2 \times 10^{-6}$	433	86	140	85	85	(371-440)	(73-89)	(50-59)	(48-60)	DKH	@ " "	7 "	[illegible]
1-5 a	1.5×10^{-6}	722	85	139	85	85	(365-445)	(75-89)	(50-59)	(49-58)	DKH	@ " "	17 "	[illegible]
1-5 p	1.5×10^{-6}	821	85	138	85	85	(362-431)	(74-88)	(50-59)	(48-57)	DKH	@ " "	7 "	[illegible]
1-6 a	1.5×10^{-6}	1119	86	138	85	85	(359-498)	(74-89)	(48-51)	(50-59)	DKH	@ " "	17	[illegible]
1-6 p	1.5×10^{-6}	1232	90	160	85	85	(430-543)	(82-114)	(59-69)	(57-73) shutdown	DKH/GWH	@ 7 "	7	3:30
1-9 a				140	87	87						@ 7 A	[illegible]	
1-9 p	$.2 \times 10^{-6}$	2425	95	140	87	87	(370-450)	(81-94)	(53-63)	(57-71)	GWH	@ 7A	72	3:30
1-10 a	$.1 \times 10^{-6}$	2715	92	128	85	70	(390-470)	(80-95)	(52-63)	(56-68)	GWH	@ 7A	17	[illegible]
1-10 p														
1-11 a	$.1 \times 10^{-6}$	3103	85	135	83	80	(420-640)	(79-91)	(52-62)	(57-71)	GWH	@ 7A	23	7:15
1-11 p	$.2 \times 10^{-6}$	3233	87	137	82	85	(420-630)	(79-93)	(52-64)	(52-68)	GWH	@ 7A	8	3:30
1-12 a	$.1 \times 10^{-6}$	3510	86	138	85	85	(420-570)	(76-89)	(51-60)	(56-66)	GWH	@ 7A	16	7:45
1-12 p	$.1 \times 10^{-6}$	3634	86	135	85	85	(420-580)	(81-91)	(54-63)	(56-67)	GWH	@ 7A	7.5	8:03
1-13 a	$.5 \times 10^{-6}$	3647		Failure	Start 14:00		1/13/78							
1-13 p	$.9 \times 10^{-6}$	4748	85	140	85	85	(420-575)	(81-93) -92	(54-64) -63	(56-70)	GWH	@ 7A	67.5 Hr	9:30
1-16 a	↓	↓											↓	↓
1-16 p	$.8 \times 10^{-6}$	4849	/	/	/	/	(420-570)	(82-92)	(53-63)	(56-66)	GH	@ 7A	6 Hrs	3:40
1-17 a	1.3×10^{-6}	5121	87	135	85	85	(420-565)	(82-93)	(53-65)	(57-67)	GH	@ 7A	17 Hrs	8:30
1-17 p	$.5 \times 10^{-6}$	5234	93	160	94	90	(460-580)	(94-106)	(62-74)	(66-76)	"	@ 8A	7 hrs	3:20
1-18 a	$.7 \times 10^{-6}$	5514	90	155	90	90	(450-580)	(94-106)	(63-71)	(66-76)	"	@ 8A	17 hrs	8:30
1-18 p	—	—											—	
1-19 a	$.7 \times 10^{-6}$	5928	95	160	90	90	(460-580)	(94-10[illegible])	(62-74)	(65-76)	"	@ 8A	25.5 hrs	10 A
1-19 p	$.6 \times 10^{-6}$	6011	92	157	90	90	(455-580)	(94-108)	(62-74)	(66-76)	"	"	5 hrs	3:00
1-20 a	$.5 \times 10^{-6}$	6293	92	155	90	90	(455-580)	(94-109)	(62-74)	(64-77)	"	"	17 "	[illegible]
1-20 p	$.5 \times 10^{-6}$	6402	92	160	90	90	(455-5[illegible])	(94-10[illegible])	(61-74)	(64-76)	"	"	[illegible]	[illegible]
1-23 a														

Change Oil 8A 08:53

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DATE	PRESSURE	# OF REVOLUTIONS	BRUSH TEMPERATURE (°F) A5 (L)	C5 (L)	E (H)	C (H)	BRUSH VOLTAGE DROP (MV) SET 1 "red"	SET 2 "green"	SET 3 "blue"	SET 4 "black"	INITIALS	RUNNING TIME TOTAL HOURS	TIME OF MEASUREMENT
1-23 a.												8A	
1-23 p.	3×10^{-7}		91	155	89	88					ZH	9A 73H	4:15
1-24 a.	2.7×10^{-7}	7863	95	175	90	90	500-670	96-123	69-85	67-86	GWH	9A 17¾	10:00
1-24 p.	2.7×10^{-7}	7954	95	175	90	90	495-665	96-124	67-85	68-87	"	9A 5½	3:30
1-25 a.	2.8×10^{-7}	8229	95	175	90	90	500-660	98-126	67-84	67-86	"	9A 17	8:30
1-25 p.	2.2×10^{-7}	8336	95	175	90	90	510-650	100-125	68-85	67-86	"	9A 6½	3:10
1-26 a.	1.8×10^{-7}	8615	95	180	90	90	510-640	97-123	67-84	67-87	GWH	9A 17¼	8:25
1-26 p.	2×10^{-7}	8720	95	175	90	90	500-670	100-122	68-84	68-86	"	9A 6	3:45
1-27 a.	1.8×10^{-7}	9015	98	180	90	90	500-640	99-121	65-84	67-86	"	9A 18¼	9:00
1-27 p.	1.8×10^{-7}	9122	100	177	90	90	500-660	100-122	67-85	69-87	"	9A 6½	3:35
1-30 a.	1.8×10^{-7}	0240	100	180	90	90	510-650	98-121	67-84	67-86	"	9A 19 +48	10:45
1-30 p.	1.8×10^{-7}	0312	100	180	90	90	510-670	100-120	67-84	70-87	"	9A 5¼	3:00
1-31 a.	1.8×10^{-7}	stopped @ 0855	98	187	95	72	FAILURE OF STARTER MOTOR				"	9A 43	10:30

DATE	PRESSURE	REVOLUTIONS	BRUSH TEMPERATURE °F A5	C5	E	C	BRUSH VOLTAGE DROP (mv) SET 1 (RED)	SET 2 (GREEN)	SET 3 (BLUE)	SET 4 (BLACK)	AMPS	INITIALS	TOTAL RUNNING TIME HRS	OF MEASUREMENT
2-1 a.							MEASURED BRUSH LENGTH							
2-13a.														
2-13p.														
2-14a.	BROKEN(?)	0855	98	195	96	90	MIN-MAX	MIN-MAX	MIN-MAX	MIN-MAX	9A	DH	0	12:30
2-14p.	" ≈ 6"	1178	100	198	96	94	580-690	121-141	77-91	75-210	9A	DH	19 Hrs	7:30
2-15a.														
2-15p.	—	1321	100	193	99	100	570-656	114-130	75-89	75-205	9A	GEM	26:45	4:15
2-16a.	—	1583	100	195	95	95	587-656	115-130	75-89	74-227	9A	GEM	42:45	8:15
2-16p.	—	1710	103	200	100	95	553-744	117-132	77-92	74-311	9A	GEM	50:30	4:00
2-17a.		1912	105				FAILURE OF STARTER MOTOR				9A	GEM	67 hrs	8:30
2-17p.														
2-20a.														

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E	PRESSURE	REVOLUTIONS	BRUSH TEMPERATURE (F) A5 (2)	C5 (3)	E (4)	C (5)	BRUSH VOLTAGE DROP (mv) SET 1 "RED"	SET 2 "GREEN"	SET 3 "BLUE"	SET 4 "BLACK"	INITIALS	AMPS	TOTAL HOURS	TIME OF MEASUREMENT
3-6a	2x10^-6	0	80	180	78	75	594-794	116-135	77-91	73-211 6.5mv	DKH/GM	9A	0	1:15 P.M
3-6p	2x10^-6	53	88	190	86	85	585-780	119-135	74-90	73-263	GM	9A	3	4:00 P.M
3-7a	3x10^-6	316	100	200	98	95	572-746	120-136	78-93	74-267	GM	9A	19	8:00 A.M
3-7p	2.8x10^-6	444	105	202	100	97	575-740	120-136	78-94	75-320	GM	9A	27	4:00 P.M
3-8a	2.2x10^-6	714	103	198	100	95	572-725	121-137	78-94	75-300	GM	9A	43	8:00 A.M
3-8p	2.1x10^-6	840	103	203	100	98	568-740	122-137	78-94	75-320	GM	9A	51	4:00 P.M.
3-9a	1.8x10^-6	1110	102	198	100	98	562-727	120-134	79-94	75-334	GM	9A	67	8:00 A.M.
3-9p	1.7x10^-6	1234	105	200	94	95	558-734	119-134	78-95	75-311	GM	9A	75	4:00 P.M
3-10a	1.7x10^-6	1454	100	200	100	95	554-714	119-134	80-95	75-366	GM	9A	91	8:00 A.M
3-10p	3.3x10^-5	1578	103	200	98	96	554-714	117-133	78-95	75-414	GM.	9A	97 (+24) 123	4:00 A.M.
		[illegible]	[illegible] 100	[illegible] 125	102	97	voltage	drops no	good due to	stepper motor malfunction	GM	9A	(116.8)	1:00 P.M.
3-13a	8x10^-6	1891		@	80		Stepper	motor runs	extremely	slow	DH	9A	0	12 pm
3-19N	6.5x10^-6	1891	100	206	96	96	590 →	118 →	79 →	75 →	DH	9A	72	12 pm
3-20N	7x10^-6	2279	102	210	99	97					GM	9A	76	4 pm
3-20p	4.4x10^-6	2307												
3-21N	6x10^-6	2457	100	205	100	96	560 →			94	DH	9A	96	12 pm
3-21N	6x10^-6	2459	103	205	98	97	620 →			83 →	DH	10A	96	12 pm
3-21p	5.5x10^-6	2493	105	210	101	100					GM	10A	100	4 pm
3-22	[illegible]x10^-6	2736	107	215	102	102					GM	10A	124	4 PM
3-24N	9x10^-6	3115	106	226	103	102	615 →			23 →	DH	10A	168	12 pm
3-24p	9.4x10^-6	3160	104	223	101	103		132 →	89 →		GM	10A	172	4 PM
3-28N	5x10^-6	3432	106	219	103	102					DH	10A	264	12 pm
3-29p	2.4x10^-5	3713	105	215	105	104					GM	10A	292	4 pm
3-31N	5x10^-6	4152	108	216	103	101					DH	10A	336	12 pm
4-3a	5x10^-6	4839											382	9:30 am
	T	4839									TOTAL	HRS	505	

April 3 → Test completed → Remove Test Assembly & Equipment

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13.0 REFERENCES

1. H.-Chr. Goetting W. Wilkens, "In Situ Measurements on the Combined Effects of Ultrahigh Vacuum and Operating Conditions on the Performance of Sliding Electrical Contact Materials With Special Reference to Extremely Low Speeds," DFVIR-Brunswick Research Center.

2. Ibid.

3. J. Clauss and M. K. Kingery, "Sliding Electrical Contact Materials for Use in Ultrahigh Vacuum," J. Spacecraft Vol. 4, No. 4, April 1967, pp. 480-485.

4. J. Przybyszewski, "Lubrication of Sliding and Rolling Element Electrical Contacts in Vacuum," NASA-Lewis Research Center, ASLE Preprint No. 68AM 4C-3, May 6-9, 1968, pp. 68-94.

5. H. M. Briscoe and E. L. Robbins, "The European Space Tribology Laboratory," European Space Agency Bulletin, August, No. 6, pp. 37.

6. N. E. Lewis, et al, "Friction, Wear, and Noise of Slip Ring and Brush Contacts for Synchronous Satellite Use," IEEE Transactions PHP Vol. PHP 9, No. 1, March 1973, pp. 15-27.

7. C. L. Harris and D. Wyn-Roberts, "Friction and Wear Studies in Ultra-High Vacuum and the Evaluation of Electrical Slip Rings," Proc. Instr. Mech Engrs 1968-69, Vol. 183 Pt 3I, Paper 7.

8. R. L. Johnson and D. H. Buckley, "Lubrication and Wear Fundamentals for High-Vacuum Applications," Proc. Instr. Mech Engrs 1967-68, Vol. 182 Pt 3A, Paper 31.

9. N. E. Lewis, "The Synergistic Effects of Slip Ring-Brush Design and Materials," Report: Poly-Scientific Division, October 1974.

10. J. W. Van Wyk, "Solid Lubricants in Action," ASLE Annual Meeting, May 4-8, 1970.

11. A. C. Cunningham, "Long Life Slip Rings for Vacuum Operation," 5th Aerospace Mechanisms Symposium, NASA-Goddard Space Flight Center, June 15-16, 1970.

14.0 BIBLIOGRAPHY

1. BRISCOE, H. M.; Robbins, E. J. "The European Space Tribology Laboratory", European Space Agency Bulletin, August, 1977, No. 6.

2. CLAUSS, F. J.; Kingery, M. K. "Sliding Electrical Contact Materials for Use in Ultrahigh Vacuum", Lockheed/Arnold Engineering, J. Spacecraft Vol. 4, No. 4 April 1967. p. 480-485.

3. CLAUSS, F. J. "Sliding Electrical Contacts for Ultrahigh Vacuum", Materials Sciences Laboratory, Lockheed Missiles and Space Company, Contract # AF-40(600)-1070, April 1965.

4. CUNNINGHAM, A. C. "Long Life Slip Rings for Vacuum Operation", Hughes Aircraft Company, November 1970

5. DALLEY, K. R.; O'Donnell, P. J. "Design and Performance of Electrical Contacts for Use in Ultra-High Vacuum", Marconi Space and Defence Systems LTD., 1975, p.p.48.

6. DRABEK, S. "Performance of Solid Lubricated Contacts in Spacecraft", General Electric Company Space Systems, September 1969.

7. DROZDOV, Y. N.; Pavlov, V. G.; Rozentsveyg, I. I. "Method for Investigating Energy Losses in Dry Friction Joints with Rota-Print (rotary) Lubrication", 1968, Document No. FTDHT-23-376-69.

8. DULLINGHAM, M. M. "Progress Report on the Lubrication of Bearings and Slip Rings in Vacuum", Marconi Space and Defence Systems LTD., January 1974-March 1975, Prepared for ESA under ESTEC Contract No. 1852173.

9. ELLIOTT, Brothers "Report on the Vacuum Evaluation of Slip Rings and Brushes for Space Applications", Space and Weapons Research Laboratory, Prepared for ESRO under ESTEC Contract # 416/67SL.

10. GLOSSBRENNER, E. W. "Slip Ring Assemblies for Spacecraft Devices", Litton Industries Poly-Scientific Division Materials and Processes Laboratory.

11. GOETTING, H. C.; Wilkens, W. "Functional Properties of Sliding Electrical Contacts at Continuous and Discontinuous Low Speed Operation in Ultrahigh Vacuum", European Space Tribology Symposium, April 1975.

12. GOETTING, H. C.; Wilkens, W. "In Situ Measurements on the Combined Effects of Ultrahigh Vacuum and Operating Conditions on the Performance of Sliding Electrical Contact Materials with Special Reference to Extremely Low Speeds", Brunswick Research Center (DFVLR), Contract 002-152/74-RF.

USE FOR TYPEWRITTEN MATERIAL ONLY

13. HARRIS, C. L.; Wyn-Roberts, D. "Friction and Wear Studies in Ultra-High Vacuum and the Evaluation of Electrical Slip Rings", Institution of Mechanical Engineers Proceedings, August 1968. Vol. 183 Pt 31 p. 50-60.

14. HALTMER, A. J. "Friction and Wear of Solid Materials Sliding in Ultrahigh Vacuum and Controlled, Gaseous Environments", General Electric Co. Missile and Space Division, April 1969.

15. HENSLEY, W. D. "Design and Fabrication of Materials Test Fixture for Vacuum Test to be used for Testing and Evaluation of Slip Rings and Brushes", Litton Industries Poly-Scientific Division.

16. HINRICKS, J. T.; Loran, T. J.' Friebel, V. R. "Lubrication for Long-Term Aerospace Applications", Ball Brothers Research Corporation, October 1972.

17. HORTON, J. C. "Sliding Electrical Contact Materials", George C. Marshall Space Flight Center, Symposium on Technology Status and Trends, p. 95-99. N66-17716.

18. JOHNSON, R. L.; Buckley, D. H. "Lubrication and Wear Fundamentals for High-Vacuum Applications", Lewis Research Center Lubrication Section, February 1967.

19. LEWIS, N. E.; Cole, S. R.; Glossbrenner, E. W. "The Synergistic Effects of Slip Ring-Brush Design and Materials", Litton Systems, Inc. Poly-Scientific Division, Prepared for Goddard Space Flight Center, October 1974.

20. LEWIS, N. E.; Cole, S. R.; Glossbrenner, E.W.; Vest, C. E. "Friction, Wear, and Noise of Slip Ring and Brush Contacts for Synchronous Satellite Use", IEEE Transaction, Vol. PHP9, No. 1, March 1973, p. 15-22.

21. MATSUNAGA, M.; Hoshimoto, K. "Frictional Behavior of Molybdenum Disulphide in High Vacuum - Part II", Wear, 1976, p. 371-384.

22. MATSUNAGA, M.; Hoshimoto, K.; Uchiyama, Y. "Frictional Behavior of Molybdenum Disulphide in High Vacuum", Wear, 1972. p. 185-192.

23. MC NAB, I. R.; Wilkin, I. R. "Carbon-fibre Brushes for Superconducting Machines", Internation Research and Development Company.

24. MEEKS, C. R.; Christy, R. I.; Cunningham, A. C. "Accelerated Vacuum Testing of Long Life Ball Bearings and Sliprings", Hughes Aircraft Company Space Systems Division, Fifth Aerospace Mechanisms Symposium, p. 127-134.

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25. NASA TECH BRIEF, "Improved Molybdenum Disulfide - Silver Motor Brushes Have Extended Life", May 1964, Brief 63-10479.

26. NASA TECH BRIEF, "Machine Tests Slow-Speed Sliding Friction in High Vacuum", October 1967, Brief 67-10379.

27. O'DONNELL, P. J.; Harris, C. L.; Warwick, M. G. "The Lubrication of Bearings and Slip Ring in Vacuum", Marconi Company LTD., 1972, Prepared for ESRO under ESTEC Contract No. 763169.

28. PENTLICKI, C. J.; Glossbrenner, E. W. "The Testing of Contact Materials for Slip Rings and Brushes for Space Application", Comsat Labs/Poly-Scientific supported by INTELSAT, p. 157-172. October 1971.

29. PERRIN, B. J.; Mayer, R. W. "Lubrication of DC Motors, Slip Rings, Bearings, and Gears for Long-Life Space Applications", Ball Brothers Research Corporation, May 1968.

30. PRZYBYSZEWSKI, J. S.; "Lubrication of Sliding and Rolling Element Electrical Contacts in Vacuum", Lewis Research Center, NASA, May 1968. ASLE 68AM 4C-3.

31. PRZYBYSZEWSKI, J. S.; Spalvins, T. "Friction and Contact Resistance During Sliding in Vacuum of Some Low-Resistivity Metals Lubricated with Sputtered Molybdenum Disulfide Films", Lewis Research Center, NASA, April 28, 1969.

32. PRZYBYSZEWSKI, J. S.; "Tungsten as a Slipring Material for Use with Gallium Lubrication in Ultrahigh Vacuum", Lewis Research Center, February 1971, NASA TN D-6184.

33. SHOBERT II, E. I. "Brushes", Machine Design, April 11, 1974. p. 168-170.

34. SHOBERT II, E. I. "Review of Sliding Electrical Contacts for Space Applications", Stackpole Carbon Company, September 1969.

35. ULRICH, D. R. "An Analysis of the Variation in Wear Life of Hot Pressed Molybdenum Disulfide-Silver Electrical Contact Brushes in Vacuum", George C. Marshall Space Flight Center, October 1964.

36. VAN WYK, J. W. "Electrical Noise Tests of Boeing Lube-Composite Slip-Ring Materials", Boeing Aerospace Metallurgical Division, November 7, 1967.

37. VAN WYK, J. W. "Solid Lubricants in Action", Boeing Aerospace Metallurgical Division, ASLE Annual Meeting, May, 1970.