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NASA TM X- 67926

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EFFECT OF NEUTRALIZER POSITION ON ACCELERATOR WEAR FOR A 30-CENTIMETER DIAMETER ION BOMBARDMENT THRUSTER

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September, 1971

This information is being published in preliminary form in order to expedite its early release.

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E-6574

INTRODUCTION

Electron-bombardment thrusters should have lifetimes of order 10^4 hours to be considered for some space applications. A major lifetime problem encountered in the development of the SERT II thruster was the erosion of the accelerator grid by mercury ions originating in the region of the plasma bridge neutralizer and accelerator grid (ref. 1). These ions were focused onto a small area of the grid with energies approximately equal to the accelerator potential (-1600 V to -2000 V), wearing a groove in the accelerator grid. The resulting sputtered material and fragments from the grid eventually caused a short circuit across the extraction system grids resulting in the shutdown of the SERT II thrusters during the space flight (ref. 2).

In an effort to eliminate this accelerator erosion, neutralizer position was varied with respect to the accelerator grid on a 30-centimeter diameter thruster with a glass-coated accelerator grid presently being developed at Lewis Research Center. Insulated stainless steel strips representing approximately 0.6 percent of the total grid area were used to measure local impingement current in the region of the groove. The selection of the neutralizer position was determined by minimizing this current.

Extended tests were conducted at two neutralizer positions. The first position caused high local currents to the accelerator strips. In the second test this current was lower by a factor of 7. Wear measurements of the strip after these tests indicate a difference of about an order of magnitude in wear rate for the two positions. The lowest wear rate was equivalent to a total wear of less than 0.10 mm (3.9 mils) in 10^4 hours.

Apparatus and Procedure

Thruster

A 30-cm diameter electron bombardment thruster with a glass-coated accelerator grid was used for this investigation (ref. 3 and 4). The thruster provided a 1.5 amp beam current at a net accelerating potential of 1000v and an accelerator potential of -500v. The discharge chamber operated at a typical loss of 210 ev/ion, and although thruster propellant flow rates were not measured, propellant utilization efficiency (excluding neutralizer propellant flow rate) was estimated to be greater than 90 percent. Three stainless steel strips, each approximately 5 cm^2 in area, were mounted on the metal surface of the accelerator grid beyond the extraction hole pattern (fig. 1). These strips were insulated from the accelerator grid and connected to accelerator potential through a microammeter. Thus, the local impingement currents to these strips could be individually monitored. The thickness of the strips after extended testing was measured with a dial indicator micrometer with a resolution of 0.0025 mm (.1 mil) per dial division.

Neutralizer System

The plasma bridge neutralizer was mounted on a carriage which transversed an axial distance (parallel to the thruster axis) of about 14 cm, and a radial distance of about 9.5 cm (fig. 1). The carriage was motor driven and potentiometers were used to determine the position of the neutralizer tip orifice relative to the outermost (peripheral) accelerator grid extraction holes.

The neutralizer was similar to the SERT II neutralizer. The body was a 6.3 mm diameter tantalum tube. The tip was 1.3 mm thick 2 percent thoriated tungsten with a 0.38 mm cylindrical orifice in the center. The neutralizer anode (keeper) was a 6.3 mm diameter loop of 1.5 mm diameter tantalum wire. The anode was located approximately 1.5 mm downstream from the neutralizer tip.

A molybdenum planar probe with a surface area of 0.08 cm^2 oriented parallel to the thruster axis was mounted on the neutralizer carriage. This probe was biased -25v with respect to ground and was used to determine locations where the arrival rate of primary beam ions became excessive. These ions cause erosion of the neutralizer.

The thruster control set points maintained a stable 1.5 amp beam. The initial neutralizer position and operating point provided stable neutralizer operation. The neutralizer propellant flow rate was held constant by a proportional controller which sensed the neutralizer vaporizer thermocouple output and controlled the vaporizer heater power. Absolute vaporizer temperature measurements were not made.

The neutralizer position was systematically varied while the neutralizer propellant flow rate, neutralizer anode current and thruster operating point were held constant. Some difficulty was experienced maintaining stable neutralizer operation during a high voltage breakdown or other periods when the total neutralizer emission current (beam current plus neutralizer anode current) was reduced due to lower beam current. A neutralizer emission current controller was used to eliminate this problem. The location of the controller and the sensing resistor are shown in figure 2. When a beam current was extracted the controller adjusted the neutralizer anode current so the total neutralizer emission current was fixed. When the beam current was reduced (i.e. beam equal zero during high voltage breakdown) the sensed current was reduced. The controller then increased the neutralizer anode current, so that total neutralizer emission current was unchanged.

Since a constant angle of beam divergence was assumed, the neutralizer position was specified by an axial distance from the accelerator grid and angle, α, measured with respect to the thruster axis along a line passing through the outermost accelerator holes (fig. 3). The angle of the axis of the neutralizer orifice with the axis of the thruster, θ, was held fixed at 10° for most tests. At each neutralizer position, the currents to each of the three strips, J_1, J_2, and J_3, were recorded.

The beam edge was determined by fixing the neutralizer and planar probe axial position and moving the system radially towards the thruster axis. The current collected by the probe was recorded as a function of radial position.

Results and Discussion

The area mapped (dictated by mechanical limits) with the movable neutralizer is shown in figure 3. It was first necessary to determine the beam edge because a major requisite for neutralizer lifetime and reliability is to position the neutralizer where it is unharmed by primary beam ions. The edge was conservatively defined as the locus of points of a constant planar probe current of 12 $\mu A/cm^2$ (1μA total current). Figure 3 shows the limits on accelerator position defined in the above manner for beam currents of both 1.0 and 1.5 A.

The strip currents were measured at each neutralizer location for neutralizer propellant flow rates of 76, 95, and 176 mA. Because high propellant flow represents a propellant weight penalty, most of the data presented is for a flow rate of 76 mA.

Figure 4 shows the current to each of the three accelerator strips (fig. 1) as a function of axial distance for constant α and a neutral propellant flow rate of 76 mA. Figure 4 shows that more current goes to strip 2 than to either of the other strips for all neutralizer positions. This was found to be true for propellant flow rates of 95 and 176 mA as well. This current J_2 is used as the best indicator of potential focused accelerator grid wear in this region for a given operating point. Figure 4 also shows a significant reduction in all strip currents as the neutralizer is moved axially downstream for the low values of α. Since the radial position was mechanically limited to 9.5 cm, these downstream axial positions could not be obtained at high values of α.

In order to better visualize the effect of the neutralizer positions on J_2, the data of figure 4 are cross-plotted on figure 5 in the form of lines of constant J_2. The gradients are obviously much greater when moving axially than radially.

It is possible to relate the current density to an area to a wear rate over that area analytically by the equation

$$J/A \times K = t/T$$

where

J	current, μA
A	area, cm^2
t	wear, mm
T	time, hr
K	proportionality constant, $(mm/hr)/(\mu A/cm^2)$

The constant K is equal to $(0.0038(S \times m)/\sigma)\times 10^{-4}$

where

S	sputtering yield, atoms/ion
m	molecular weight of target, amu
σ	density of target, gm/cc

The sputtering yield is a function of target material, bombarding ion species, and ion energy or, in this case, accelerator potential. For a given material and ion species, K is a function of accelerator potential only. A sputtering yield for 500 eV Hg ions on molybdenum of 0.63 atoms/ion was used (ref. 5). Using this value, a uniform current of 1 μA to strip 2 (~5 cm^2) would result in a wear of 0.005 mm (0.2 mils) in 10^4 hours. Thus 15 μA would result in 0.075 mm (3 mils) and 25 μA would result in 0.125 mm (5 mils) wear over a typical mission life.

In order to correlate strip current with strip wear rate, two extended tests were conducted. In Test I the neutralizer was positioned 3.8 cm axially and 4.6 cm radially from the reference point ($\alpha = 50^o$). The test ran for 140 hours at the operating conditions detailed in Table I. Also shown in this table are the currents and total charge accumulated on each of the strips.

In Test II, the neutralizer was positioned 8.9 cm axially and 7.6 cm radially from the reference point ($\alpha = 40^o$). The conditions for Test II are given in Table II.

At the conclusion of each test, the thickness of the strips was measured after they were removed. The strips are shown in figure 6. The edge wear was determined by comparing the thickness of the end points on each strip with the thickness of the strip under the tape which held the strips in place. The wear in the center was determined by comparing the center thickness with the average of the two end thicknesses. The comparison of the wear rates for the two tests are given in Table III for the locations shown in figure 6.

In both tests, the largest wear occurred at point A on strip 1 during Test I. This excessive wear is because of an exposed corner of the metallic neutralizer shield screen (fig. 1) near this point. The shield screen was operated at neutralizer potential and altered the electric fields, thereby focusing charge exchange ions on this area of strip 2. The focusing is particularly evident in figure 6(a). The actual wear at point A was 0.4 mm (1.7 mils).

In general, the total wear in Test I was from 2.2 to 11.1 times greater than the wear experienced during Test II. Excluding the excessive wear noted on strip 1, the maximum wear rate experienced in Test I was <.96 mm (38 mils)/ 10^4 hours versus a Test 2 wear rate of <.10 mm (4 mils)/10^4 hours. Both of these maximums were measured on strip 2. The experimental current densities of Tables I and II and wear rates of Table III determine a value for the constant K. These experimental results are compared with calculated results for iron (an approximation of stainless steel) and molybdenum in Table IV. The experimental values are as much as a factor of three greater than the calculated value. This is due in part to the use of the measured current over a 5 cm^2 area and the maximum measured wear while the calculated value assumes both the current and wear to be uniformly distributed over the 5 cm^2 area.

Figure 7 shows the increase in the value of the wear rate/current density, K, as a function of accelerator potential (ion energy) for various materials using sputtering yields from reference 5 and 6. All values of K are normalized to the case of 500 eV Hg ions on iron. Thus 2000 volt ions on a molybdenum grid would be expected to cause approximately 4.5 times the wear for the same current density. If the neutralizer position resulted in a current density of 3μA/cm^2 for a period of 10^4 hours, the maximum grid wear for 10^4 hours would be only approximately 0.5 mm (20 mils).

The thermal and structural advantages of molybdenum more than offset the reduced sputtering yield for tantalum. The values in figure 7 were determined using a sputtering yield based on normal incidence. However, the sputtering yield for mercury ions on molybdenum increases by a factor of nearly seven as the angle of incidence increases to 40° (ref. 5). Thus it is possible that the sputtering yield during latter portions of a mission could far exceed the yield at the beginning if the geometry is altered through sputtering to increase the angle of incidence. However, the variation of sputtering yield for tungsten (and possibly tantalum) with angle of incidence is less than a factor of 1.5 (ref. 5). Thus the use of a different metal in the area where neutralizer ion current is expected could reduce this problem.

In addition, if the groove alters the geometry of hole pattern of the accelerator grid, defocusing of primary ions can eventually occur, causing direct ion impingement. These ions will do sputtering damage to the grid at energies equal to the total accelerating voltage rather than accelerator potential (4.6 kV versus 1.6 kV for the SERT II case). Thus, locating the groove off the accelerator grid hole pattern by proper design of the accelerator grid and neutralizer shield screen could significantly reduce this accelerator grid erosion problem.

CONCLUSION

Tests were conducted with a movable neutralizer system to determine neutralizer locations which reduce accelerator grid wear on a 30-centimeter diameter thruster to an acceptable value. These tests indicated that positioning the neutralizer 8.9 cm downstream and 7.6 cm radially out from the outermost row of accelerator grid holes minimized the localized accelerator grid current due to neutralizer operation while positioning the neutralizer outside the ion beam. Extended testing for 280 hours gave wear rates less than 10^{-5} mm/hr (4×10^{-4} mils/hr). This corresponds to approximately .04 mm/hr (1.5 mils/hr) per microamp of accelerator current per square centimeter. This value is within a factor of three of calculated wear rates. Based on the experimental and calculated values, a wear of 0.5 mm (20 mils) in 10^4 hours would be expected on a molybdenum accelerator grid operating at 2000 volts, similar to the case of the SERT II thruster.

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TABLE I. - OPERATING CONDITIONS FOR TEST I - 140 HOURS

[Neutralizer position 3.8 cm axial, 4.6 cm radial, $\alpha = 50^{\circ}$, $\theta = 10^{\circ}$.]

(a) Thruster parameters

Net accelerating potential, V	1000
Accelerator potential, V	500
Beam current, A	1.5
Impingement current, average, mA	34.2
Neutralizer keeper voltage, average, V	11.51
Neutralizer - ground (coupling) voltage, average, V	12.56
Neutralizer keeper current, A	0.55

(b) Strip parameters

Strip Number	1	2	3
Strip area, cm^2	5.28	4.64	4.86
Total ions for test, μA hr	4796	13602	5819
Average current, μA	34.3	97.2	41.6
Ions/area for test, μA hr/cm^2	908	2931	1191
Average current density, $\mu A/cm^2$	6.5	20.9	8.6

TABLE II. - OPERATING CONDITIONS FOR TEST 2 - 280 HOURS

[Neutralizer position, 8.9 cm axial, 7.6 cm radial, $\alpha = 40^{\circ}$, $\theta = 10^{\circ}$.]

(a) Thruster parameters

Net accelerating potential, V	1000
Accelerator potential, V	500
Beam current, A	1.5
Impingement current, average, mA	43.7
Neutralizer keeper voltage, average, V	11.48
Neutralizer - ground (coupling) voltage, average, V	12.41
Neutralizer keeper current, A	0.58

(b) Strip parameters

Strip Number	1	2	3
Strip area, cm^2	4.78	4.74	4.76
Total ions for test, μA hr	850	3400	935
Average current, μA	3.03	12.15	3.34
Ions/area for test, $\mu A\ hr/cm^2$	178	717	196
Average current density, $\mu A/cm^2$	0.63	2.56	0.70

TABLE III. - SUMMARY OF ACCELERATOR STRIP WEAR

(a) Total wear × 10^2, mm

<table>
<tr><th rowspan="2">Test</th><th rowspan="2" colspan="3">Strip</th><th colspan="9">Location</th></tr>
<tr><th colspan="3">Left</th><th colspan="3">Center</th><th colspan="3">Right</th></tr>
<tr><td>1</td><td colspan="3">1</td><td colspan="3">1.65</td><td colspan="3">1.17</td><td colspan="3">0.51</td></tr>
<tr><td>2</td><td colspan="3">1</td><td colspan="3">0.51</td><td colspan="3">0.25</td><td colspan="3">0.18</td></tr>
<tr><td>1</td><td>2b</td><td>2a</td><td>2c</td><td>1.47</td><td>1.32</td><td>0.64</td><td>1.27</td><td>1.35</td><td>0.25</td><td>0.36</td><td>0.61</td><td>1.02</td></tr>
<tr><td>1</td><td colspan="3">2 (TYP)</td><td colspan="3">1.32</td><td colspan="3">1.35</td><td colspan="3">0.61</td></tr>
<tr><td>2</td><td colspan="3">2</td><td colspan="3">0.20</td><td colspan="3">0.25</td><td colspan="3">0.28</td></tr>
<tr><td>1</td><td colspan="3">3</td><td colspan="3">0.94</td><td colspan="3">1.12</td><td colspan="3">1.14</td></tr>
<tr><td>2</td><td colspan="3">3</td><td colspan="3">0.25</td><td colspan="3">0.10</td><td colspan="3">0.15</td></tr>
</table>

(b) Wear rate × 10^5, mm/hr

<table>
<tr><th rowspan="2">Test</th><th rowspan="2" colspan="3">Strip</th><th colspan="9">Location</th></tr>
<tr><th colspan="3">Left</th><th colspan="3">Center</th><th colspan="3">Right</th></tr>
<tr><td>1</td><td colspan="3">1</td><td colspan="3">11.70</td><td colspan="3">8.33</td><td colspan="3">3.63</td></tr>
<tr><td>2</td><td colspan="3">1</td><td colspan="3">1.80</td><td colspan="3">0.91</td><td colspan="3">0.63</td></tr>
<tr><td>1</td><td>2b</td><td>2a</td><td>2c</td><td>10.5</td><td>9.42</td><td>4.54</td><td>9.06</td><td>9.62</td><td>1.80</td><td>2.54</td><td>4.34</td><td>7.26</td></tr>
<tr><td>1</td><td colspan="3">2 (TYP)</td><td colspan="3">9.42</td><td colspan="3">9.62</td><td colspan="3">4.34</td></tr>
<tr><td>2</td><td colspan="3">2</td><td colspan="3">0.73</td><td colspan="3">0.91</td><td colspan="3">0.99</td></tr>
<tr><td>1</td><td colspan="3">3</td><td colspan="3">6.70</td><td colspan="3">7.97</td><td colspan="3">8.15</td></tr>
<tr><td>2</td><td colspan="3">3</td><td colspan="3">0.91</td><td colspan="3">0.35</td><td colspan="3">0.53</td></tr>
</table>

TABLE IV. - SUMMARY OF WEAR RATE, CURRENT DENSITY PROPORTIONALITY CONSTANTS FOR TESTS AND THEORETICAL CONDITIONS

[Ion Energy = 500v]

	K $\frac{mm/hr}{\mu A/cm^2}$
Test 1	4.67×10^{-6}
Test 2	3.96×10^{-6}
Iron (calc.)	1.67×10^{-6}
Molybdenum (calc.)	2.54×10^{-6}

E-6574

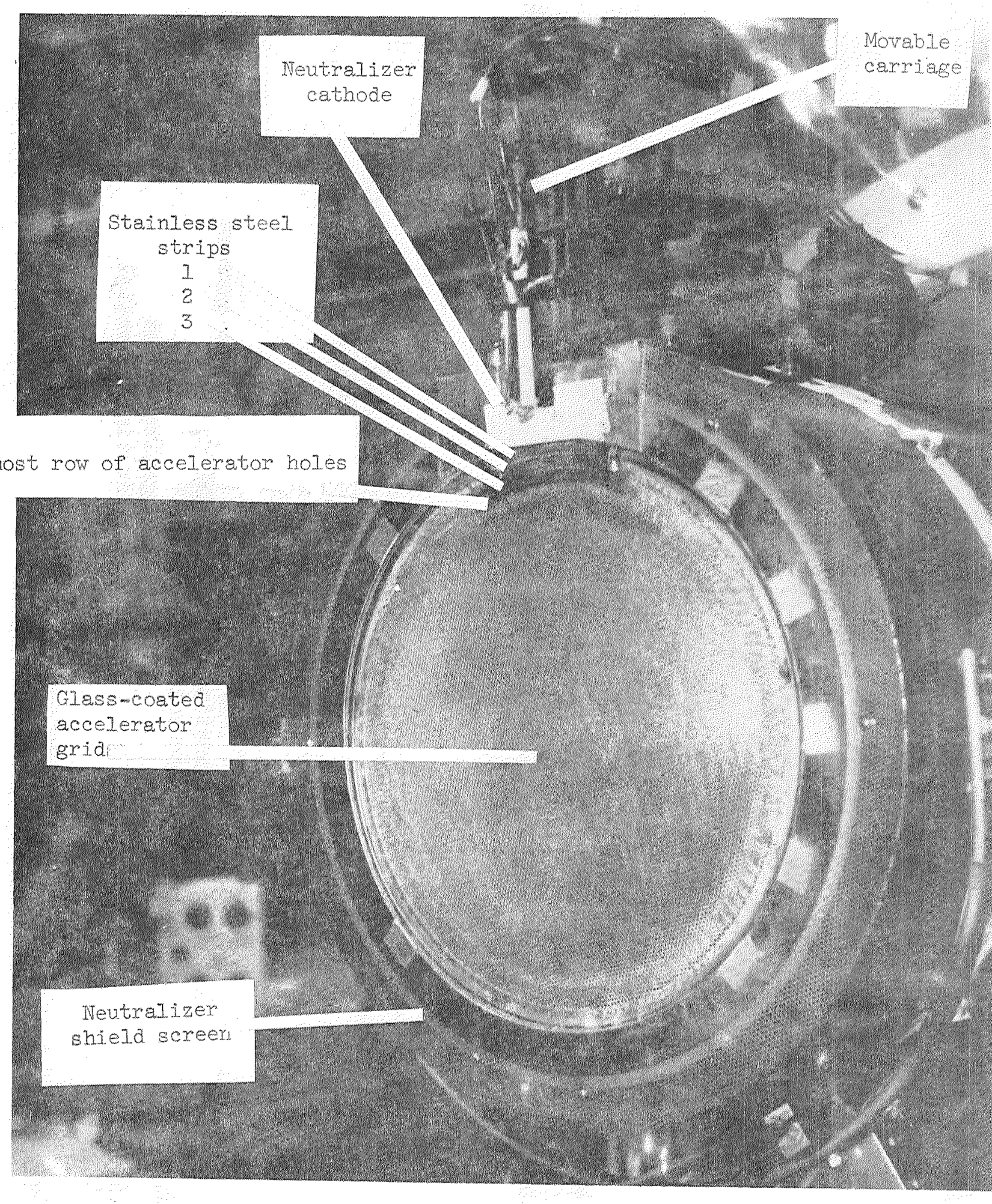
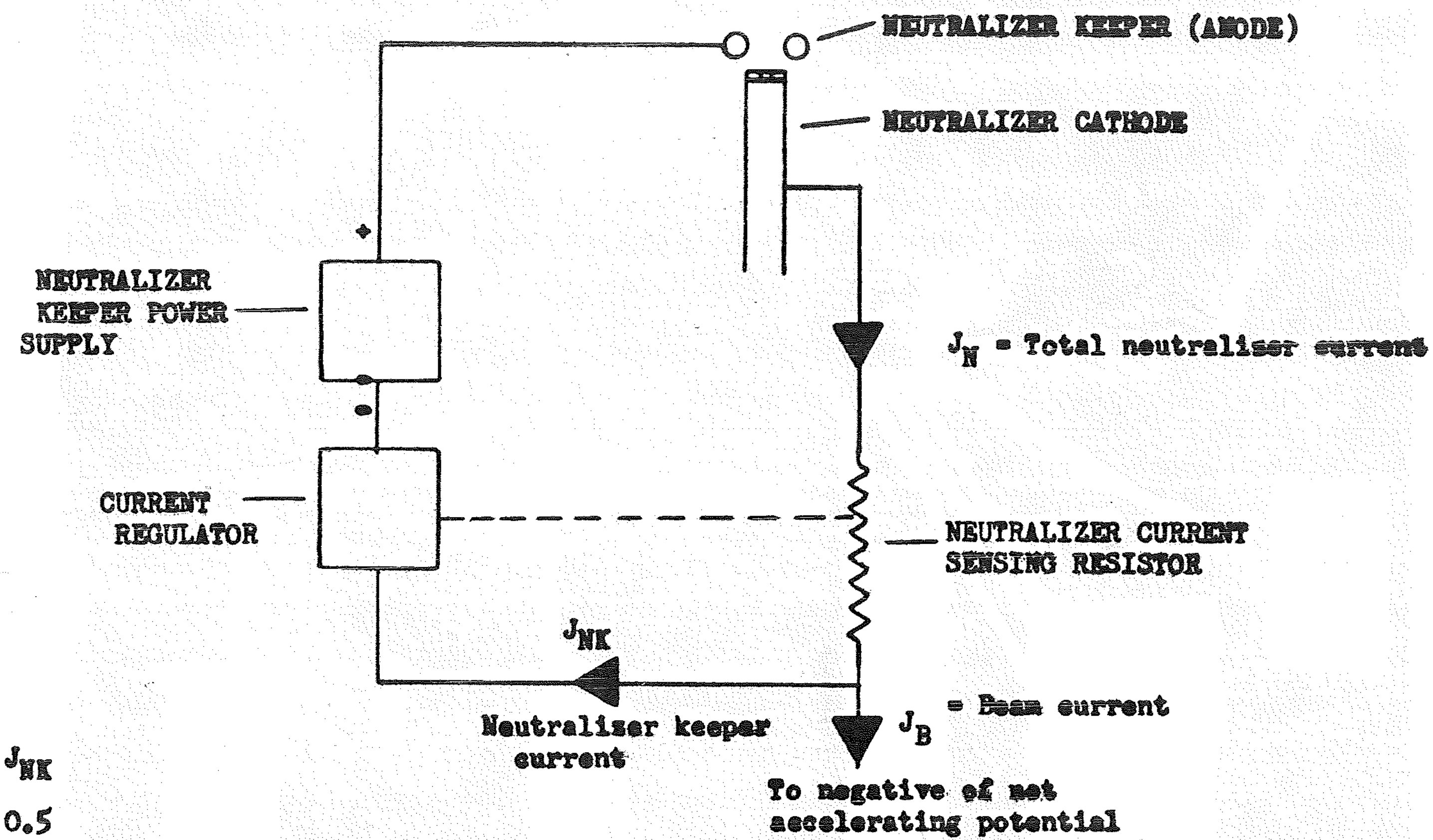


Figure 1. - 30-cm diameter thruster with movable neutralizer



$J_N = J_B + J_{NK}$

$2.0 = 1.5 + 0.5$
$2.0 = 0 \;= 2.0$

FIGURE 2- Schematic of neutralizer current controller.

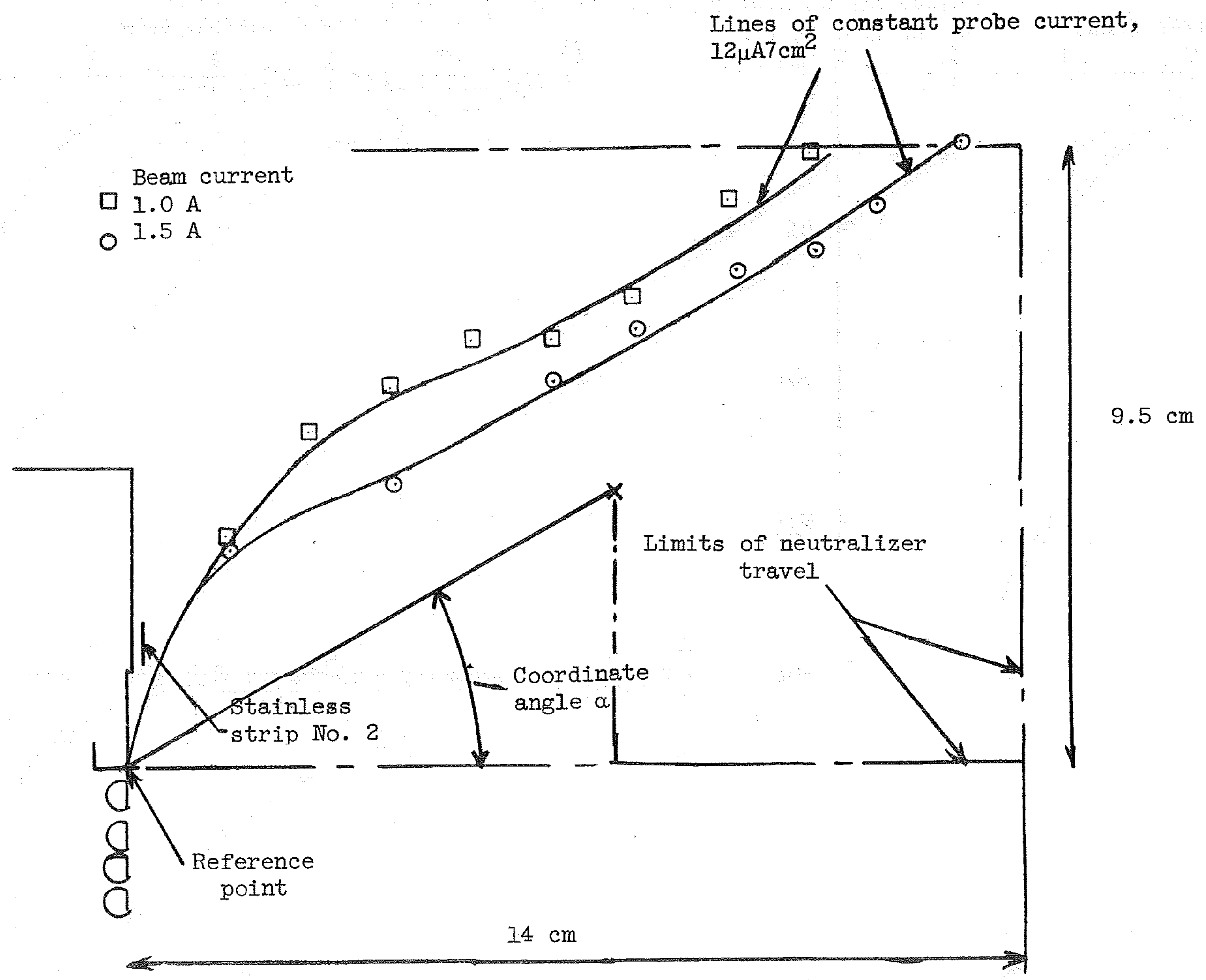


Figure 3. - Beam edge and area mapped by movable neutralizer and probe.

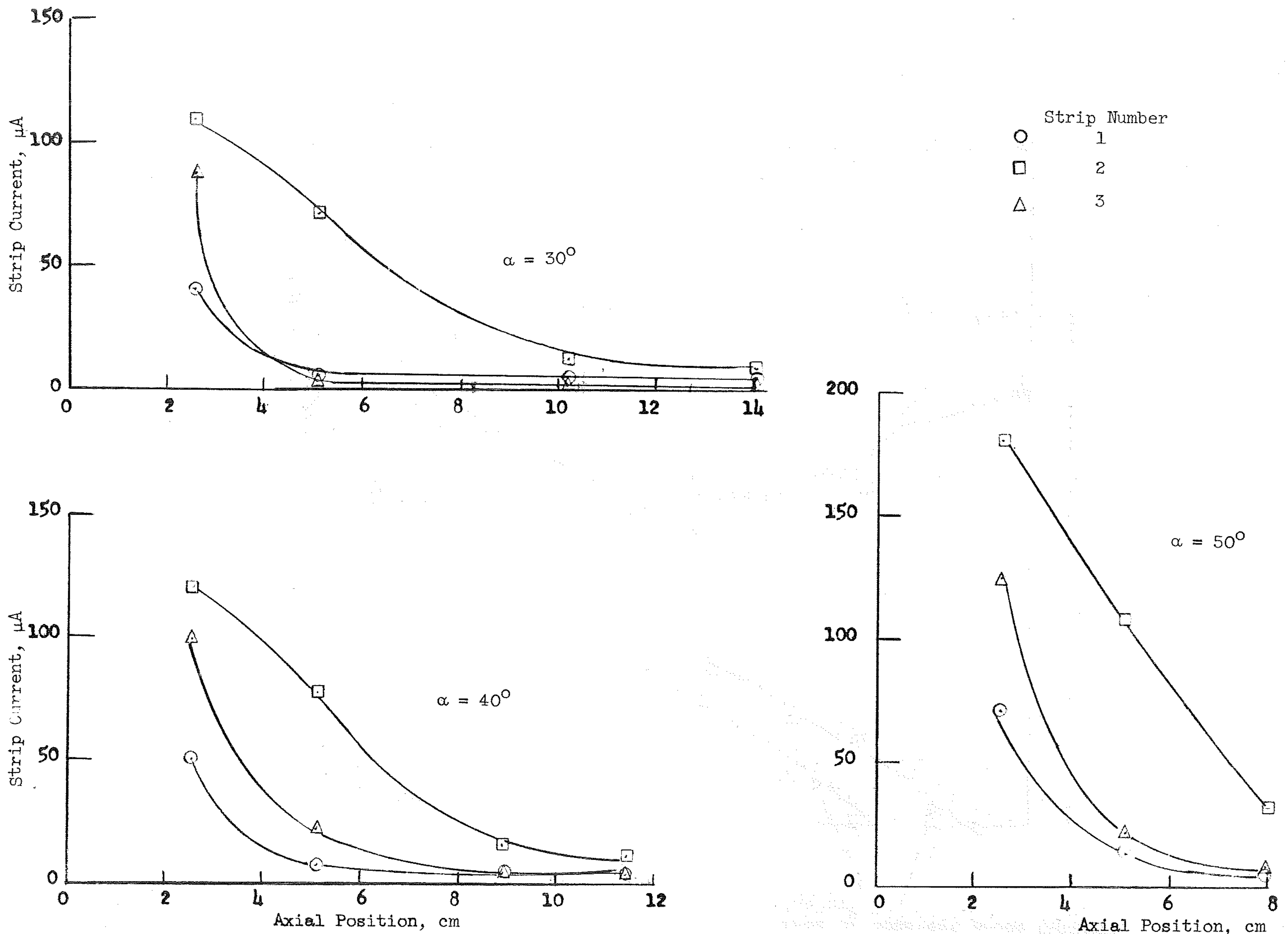


Figure 4. - Strip current as function of axial position for various coordinate angles.

839

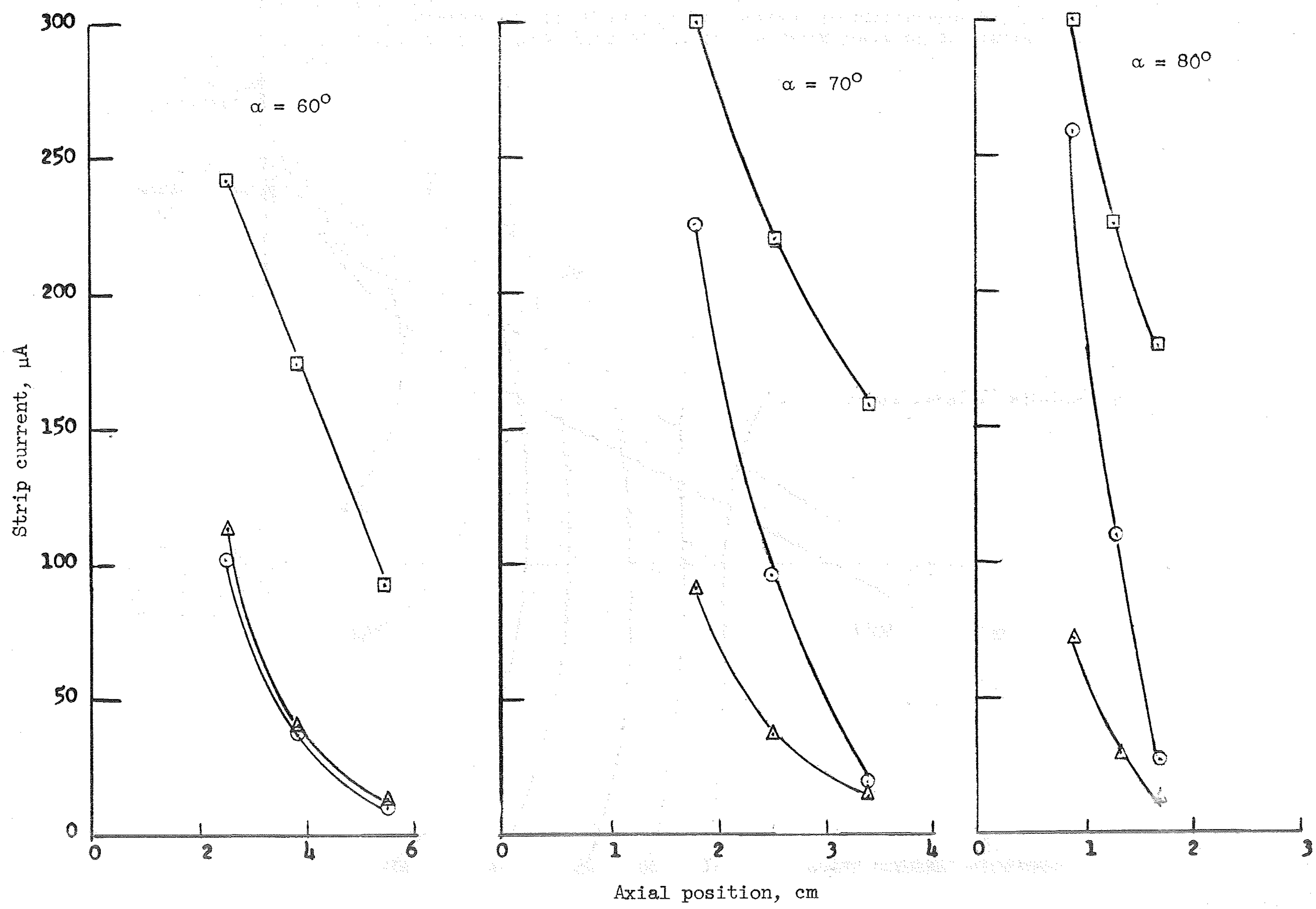


Figure 4. - Concluded

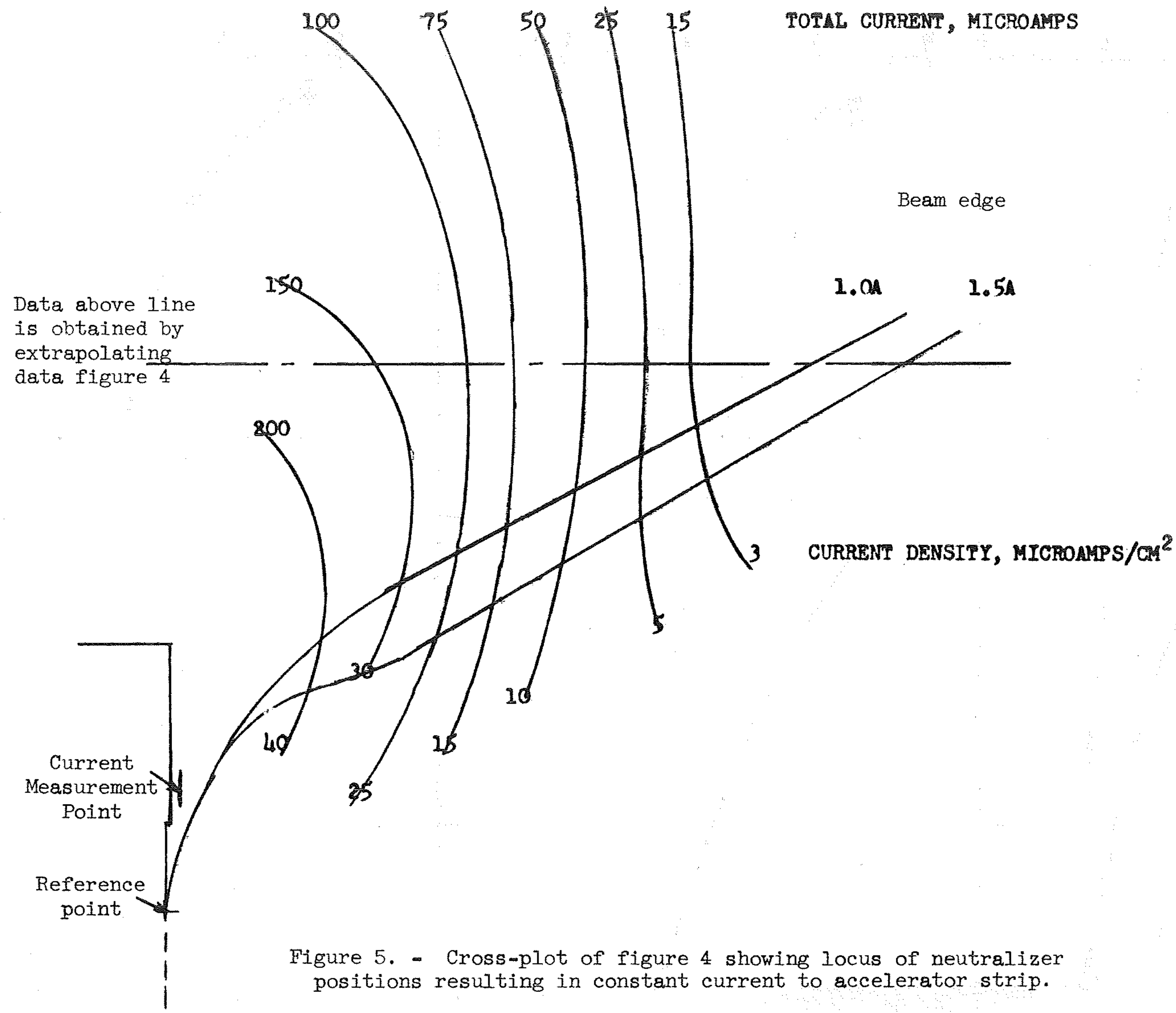
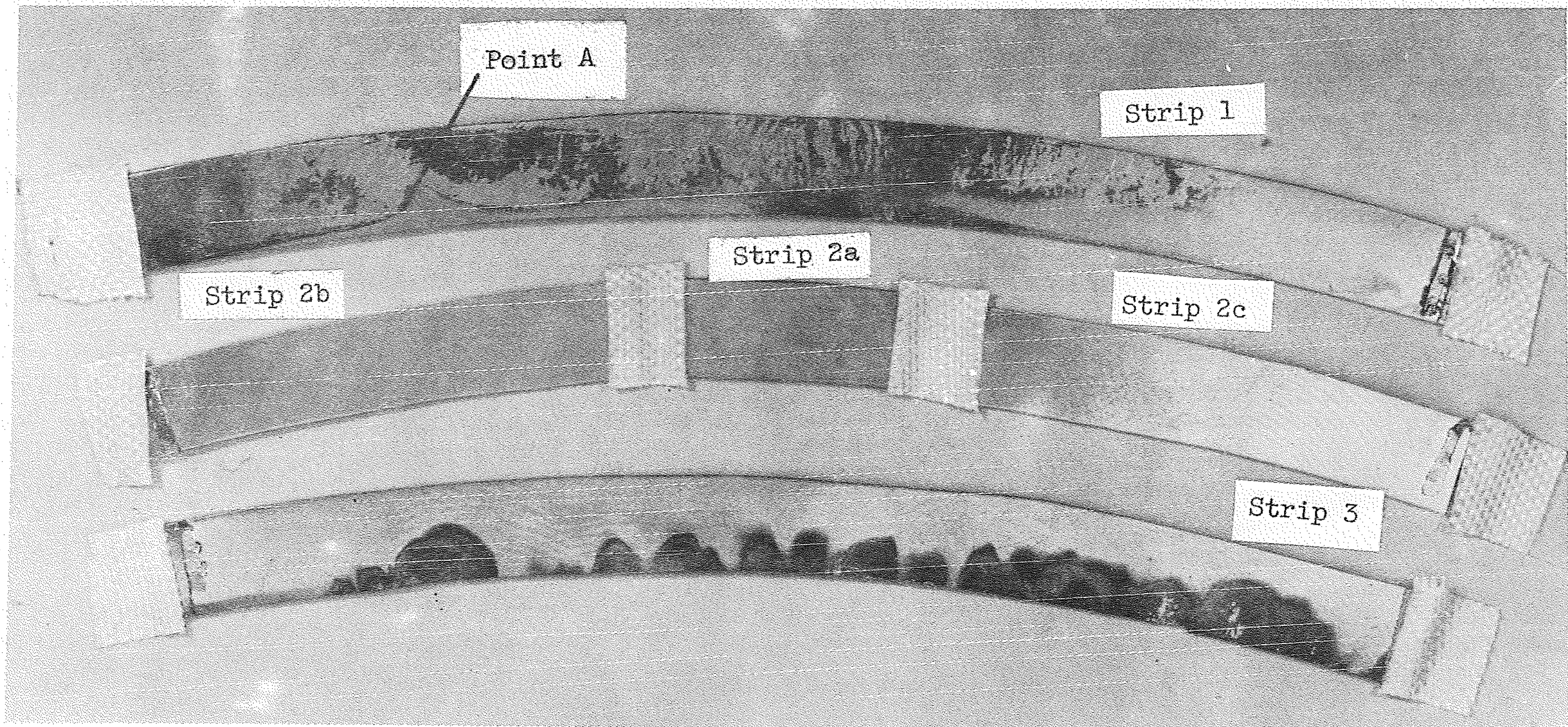
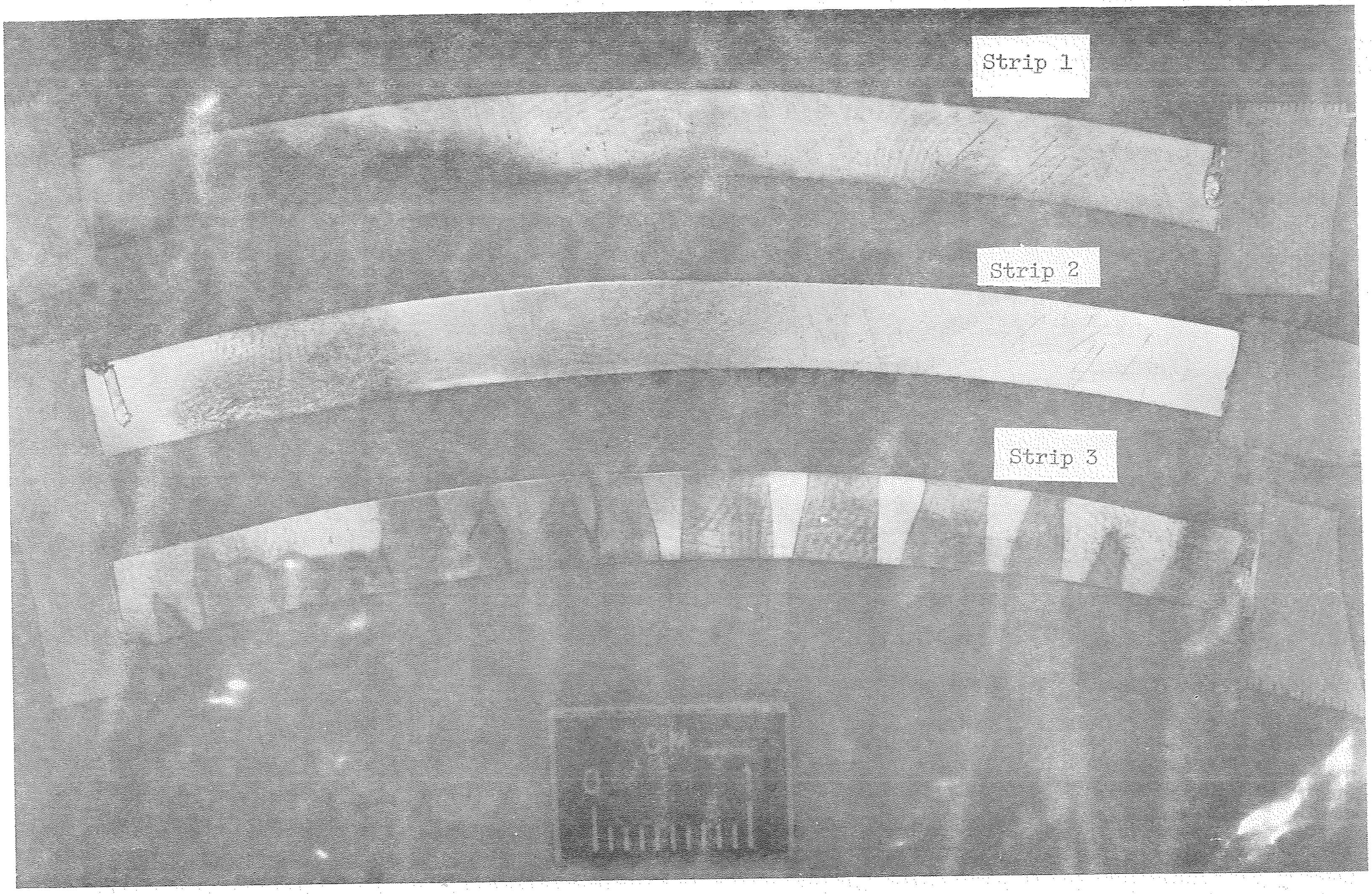


Figure 5. - Cross-plot of figure 4 showing locus of neutralizer positions resulting in constant current to accelerator strip.



a) Test 1

Figure 6. - Accelerator strips after tests



b) Test 2

Figure 6. - Concluded

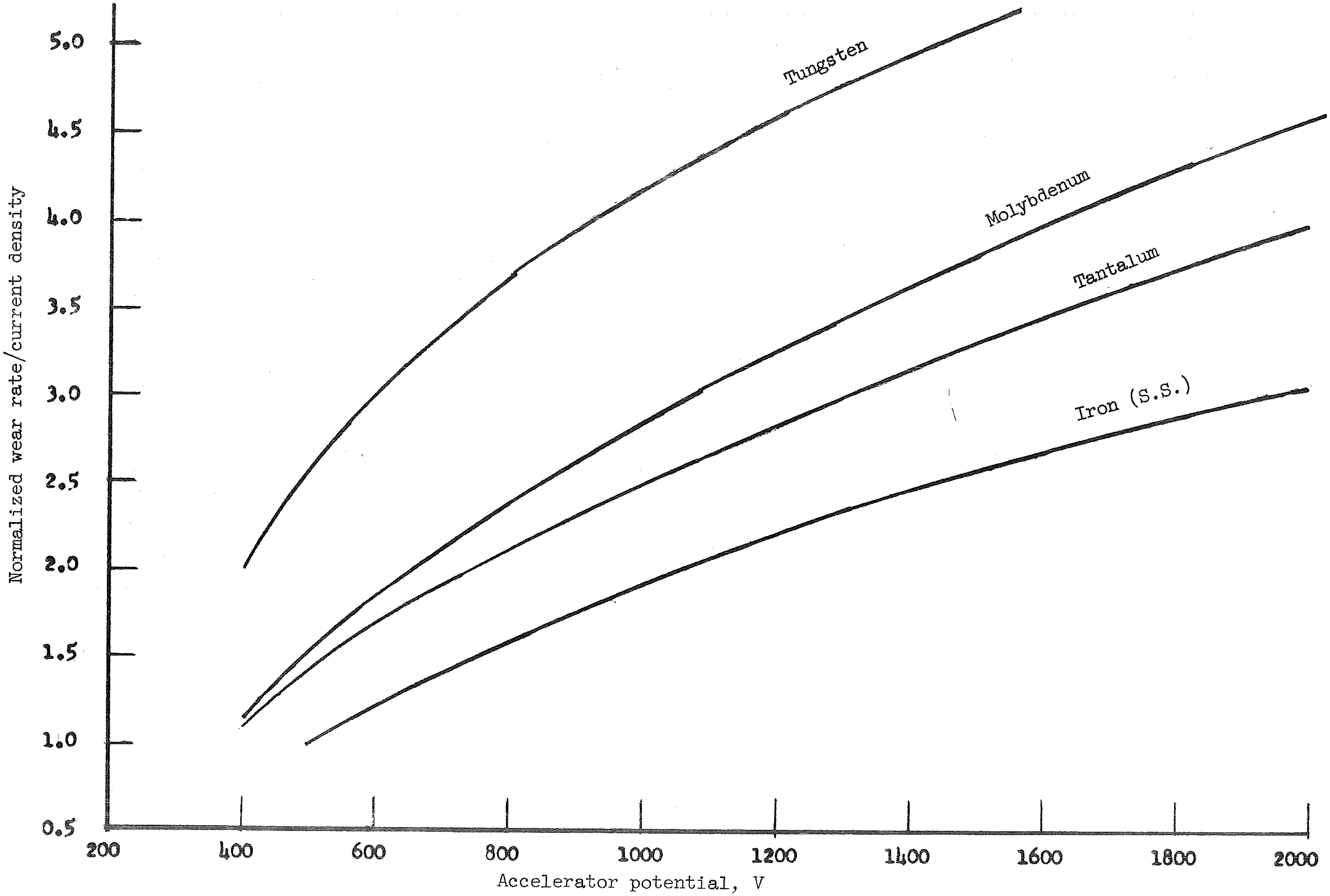


Figure 7.- Normalized wear rate/current density constant for various materials and voltages. Normalized to unity for iron at 500 volts.