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A HOLLOW CATHODE NEUTRALIZER FOR A 30-CM DIAMETER BOMBARDMENT THRUSTER

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Abstract

Recent improvements in overall thruster performance have imposed new constraints on neutralizer performance. The use of compensated grid extraction system requires a re-evaluation of neutralizer position. In addition a suitable control logic for the neutralizer has proven difficult. A series of tests were conducted to determine what effect neutralizer cathode geometry has on performance. The parameters investigated included orifice diameter and length, and cathode diameter. Similar tests investigated open and enclosed keeper geometries. Neutralizer position tests with compensated grids suggest positions ~10 cm from the accelerator and radially out of the beam envelope should result in satisfactory performance and long life. Finally operation at keeper currents of 1.5 amp has resulted in lower total neutralizer power, the elimination of tip heater power, and suitable closed loop control of the neutralizer vaporizer.

Introduction

Recent improvements in overall thruster performance[1,2] have imposed new constraints on neutralizer performance and operation. With the reduction of thruster discharge losses, the neutralizer power represents a larger fraction of the total power losses. Further, closed loop control of the neutralizer for most of the efficient operating conditions has proven difficult. Several variations of the hollow cathode neutralizer geometry and keeper geometry were made to determine their effect on neutralizer performance and control characteristics. These variations of geometry included cathode orifice length and diameter, cathode diameter, open and enclosed keeper geometries, methods of containing the emissive mix within the cathode. Also various modes of neutralizer operation, primarily involving keeper current level, were investigated.

Since the development of compensated grid extraction systems has significantly reduced beam divergence, it has become necessary to verify an acceptable neutralizer location.[3] The primary constraints on position are (1) the neutralizer not be subjected to significant sputtering damage due to primary ion bombardment and therefore must be located in a region of low ion current density; (2) the neutralizer performance must be acceptable, i.e., low mass flow rate and low neutralizer to beam coupling voltage; and (3) the neutralizer must not cause large charge exchange currents to the accelerator grid, especially in a small local area, which would cause significant grid erosion. A series of tests utilizing a movable planar beam probe and a movable neutralizer system to determine an acceptable neutralizer position with compensated optics are described.

Apparatus

Thruster Subsystem

A 30-cm diameter mercury bombardment thruster described in references 1, 4, and 5 was used for all tests. Two different sets of two-grid extraction system were used.[6] For set 1 (uncompensated), both the screen and accelerator grids had 1.27 mm (50 mil) holes which were chemically etched in the 0.38 mm (15 mil) molybdenum material. The grids were dished, as a set, to a depth of ~2.5 cm and mounted such that the direction of dish was away from the discharge. The grid gap was set for ~0.8 mm at room temperature. It is estimated in reference 6 that the on axis grid gap decreased to ~0.4 mm when the thruster was operating due to thermal expansion. Set 2 (compensated) had screen grid holes of 1.92 mm diameter and accelerator grid holes of 1.92 mm diameter. The accelerator grid was compensated to reduce thrust losses due to ion beam divergence (grid set E, ref. 2). The screen and accelerator grid thicknesses were 0.38 mm.

Neutralizer Subsystem

The baseline neutralizer subsystem used for all fixed location tests is described in references 3 and 5 and is shown in figure 1(a). The fixed neutralizer position used for these tests was 8.9 cm radially out from and 10.2 axially down from the accelerator reference (fig. 3) (the outermost row of accelerator grid holes) as described in reference 3. A total of six different neutralizer cathodes were tested and are detailed in table 1. Several keeper geometries were also tested and are detailed in table 2. These tests included both open and enclosed keeper designs. In the enclosed keeper tests, a boron-nitride and tantalum system was slipped over the neutralizer tip heater. The subsystem was unchanged in all other respects.

Three means of containing the barium carbonate emissive mix were used. The first method was deposition of the emissive mix on the inner walls of the cathode tube by means of a syringe. This included tests comparing cathodes 1, 2, 3, and 4 (table 1) and all keeper comparison tests.

The second method was to deposit the barium carbonate mix on a piece of 0.013 mm (1/2 mil) thick tantalum foil 4.4 cm by 10.2 cm (4.4 by 4 cm for the 3.2 cm o.d. cathode) by dipping the foil in the mixture. The foil was rolled into a 4.4 cm long cylinder and slid into the cathode tube to within 1.2 cm from the tip face. This located the edge just behind the neutralizer tip heater which was ~1.2 cm long.

The third method used barium carbonate impregnated inserts of two different designs. Figure 2 shows each of these designs, the only major difference being the propellant flow path.

Movable Neutralizer and Probe

The same movable carriage system was used for both movable neutralizer and beam probe tests (fig. 3). Both axial and radial movement (relating to thruster axis) was possible by use of two motor driven slides. The position was monitored by two, ten turn linear potentiometers.

The planar probe used for the probe tests was 1.6 diameter, mounted in a plane normal to the thruster axis. For the planar probe tests, a fixed neutralizer was used as shown in figure 3.

Accelerator Current Strips

For the movable neutralizer tests, the current to tantalum accelerator strips (fig. 3) was monitored. Each of these strips was ~5 cm^2 in area and were backed with a layer of insulating material to insulate them from the accelerator grid. Each strip was connected to accelerator potential through a 100 μA meter. Four strips were used; one on the molybdenum mounting ring at the point nearest the neutralizer (no. 1), the second was mounted on the curved grid surface but not on the hole pattern at the point nearest the neutralizer, the third and fourth steps were at similar locations 180° away from the neutralizer location.

Facility

All tests were conducted in a 1.2 m diameter bell jar on a 7.6 m diameter by 21.4 m long vacuum facility.(7) The thruster was extended into the main chamber of the tank approximately 1 m beyond the tank wall during thruster operation to minimize ion beam-facility interactions. Bell-jar pressure was typically 5×10^{-6} torr and main tank pressure 2×10^{-7} torr during thruster operation.

Procedure

Neutralizer Performance Tests

A minimum of 3 hours of thruster and neutralizer operation was generally required to ensure that the system was at thermal equilibrium. After this time, proportional controllers were used to vary the heater power of the main, cathode, and neutralizer propellant vaporizers to maintain a constant vaporizer temperature. Under equilibrium conditions, this resulted in constant propellant flow rates. The flow rates were determined by measuring the change in height of mercury in a precision bore glass capillary reservoir with time.

The thruster discharge chamber operating parameters and flow rates were set to yield a 1.95 amp beam current at a typical net accelerating potential and accelerator potential of 950 volts and -550 volts, respectively. Thruster propellant utilization efficiencies were typically ≥0.85. A neutralizer vaporizer temperature was set and the flow rate measured over a period of 30 minutes or more after thermal equilibrium. The various changes in operating condition were then made at a constant mass flow rate.

Movable Neutralizer and Probe Tests

The movable neutralizer and beam probe tests were performed after the thruster system was at thermal equilibrium and operating on temperature controllers. The movable carriage was set at a fixed axial or radial location and then moved in the alternate direction. Neutralizer operating parameters were recorded at several positions and accelerator strip currents recorded on an x-y recorder as a function of axial location. The beam probe was biased to -30 volts and collected current recorded on an x-y recorder.

Results and Discussion

Effect of Neutralizer Cathode Geometry

The results of the six neutralizer cathode tests with an open loop keeper are detailed in table 1. In general, the neutralizer keeper current was varied from 0.3 to 1.3 amps at several different mass flow rates. The base line cathode (no. 1, table 1) operated at a keeper and coupling voltage between 13 to 15 volts at mass flow rates as low as 24 equivalent mA at tip heater powers of ~70 watts. However, the keeper voltage was somewhat insensitive to increases in mass flow rates up to the maximum flow tested of 41 equivalent mA at all keeper currents tested.

Cathodes 2, 3, and 4 were generally poorer in performance, primarily in the requirement for higher mass flow rates of 37 equivalent mA or more. In addition, cathodes 2 and 4, the large orifice diameter cathodes, generally operated at coupling voltages much in excess of 25 V, a level which begins to compromise expected neutralizer lifetime. In general, bell jar tests have indicated(8) that larger diameter orifice cathodes require higher operating voltages at low flow rates. Cathode 3 (smaller diameter, shorter length orifice) operated from 8 to 40 volts coupling depending on the keeper current, and required a minimum of 37 equivalent mA mass flow rate. The tip temperatures for cathodes 1 through 4 were typically 1300° C as measured by an optical pyrometer.

Cathode 5 was similar to the base line cathode except the upstream surface was beveled. This cathode performed comparably to the base line cathode. Mass flow rates were as low as 26 mA and tip temperatures as measured by thermocouple ranged from 950° to 1100° C.

Cathode 6 was tested in an attempt to lower the required tip heater power by decreasing the thermal conduction losses from those of the base line cathode. However, self-heating of this cathode raised the tip temperature to greater than 1300° C and the temperature over the insert to greater than 970° C. In addition, although mass flow rate requirements were generally low (~30 eq. mA), the operating stability was questionable. There was a greater tendency for the discharge to extinguish, especially during a high voltage recycle. The relation between keeper voltage and mass flow rate was strongly double-valued (both positive and negative slope portions existed for most voltages of interest), causing doubt about the controllability of such a geometry.

In general, several of the cathode geometries tested provided good overall performance, notably cathodes 1 (baseline cathode) and 5. Cathodes 2, 3, and 4 were slightly poorer in performance, specifically requiring higher mass flow rates.

Cathode 6 operated at considerably higher temperatures.

Effect of Neutralizer Keeper Geometry

The various keeper geometries tested and some performance characteristics are listed in table 2. Moving the open loop keeper further from the neutralizer cathode had little effect on neutralizer performance. Mass flow rates down to ~24 eq. mA at keeper and coupling voltages from 9 to 11 volts were possible for all keeper locations. Doubling the keeper thickness by adding an extra loop raised the minimum flow rate and keeper current requirements slightly (i.e., 29 eq. mA @ 1 to 2 amps, respectively).

The performance of the enclosed keepers was similar to that of the open keepers. The enclosed keeper geometry having the same keeper thickness, hole diameter, and gap as the base line open keeper yielded virtually the same keeper and coupling voltages and the same minimum mass flow rates. However, again no controllable voltage-mass flow relation was evidenced for this design. Decreasing the enclosed keeper diameter increased the minimum mass flow rate and keeper current requirements to ~48 eq. mA and 1.3 amps, respectively. Increasing the gap to 5.1 mm increased the minimum requirements to 48 eq. mA and ~1.2 amps.

In general, enclosed keeper geometries for high emission current neutralizers offer no performance advantages.

Method of Containing Emissive Mix

Three means of holding the barium carbonate emissive mix within the neutralizer cathode were tested as described in Procedure. Of the three types, the impregnated insert may offer greater reliability, repeatability, and convenience since it is commercially available. However, rolled inserts have proven lifetime for a variety of conditions.[10]

A comparison of these three insert types is presented in table 3. The data is for both high and low keeper current operation. Some temperature data were obtained using an optical pyrometer to measure brightness temperature while other data were obtained by more accurate thermocouple measurement. Some data was taken at both high keeper current and high tip heater power. Because of these differences, exact comparisons are difficult. But the data in table 3 shows similar performance for all three dispensing techniques tested. Operation at a high keeper current or at lower temperatures generally led to higher keeper voltages. The coupling voltages for all operating conditions of table 3 fall within a 5 volt range.

The one major difference in operation appears to be the temperature profile. Both impregnated insert cathodes operated at a lower tip temperature but higher insert temperature than the rolled insert cathode, resulting in a smaller thermal gradient along the cathode. Other preliminary tests have suggested that a steep temperature profile is more desirable from a start-up point of view. Also, any reduction in insert temperature could conceivably increase expected insert lifetime. Because of their greater fabrication reliability and repeatability with no degradation in short term performance, impregnated inserts offer an attractive alternative to hand-coated rolled foil inserts. However, at present, the long term reliability and performance of such inserts at the current levels of interest has not been demonstrated. They have been tested, however, for extended periods at lower current levels.[11]

Operation at High Keeper Current

Operating the neutralizer at keeper currents in excess of 1 amp has been suggested as a means of reducing mass flow rate requirements and improving control characteristics.[9] Figures 4 through 6 show data comparing high and low keeper current operation for several cathodes tested. Figure 4 shows performance curves at beam currents of 1.93 and 1.04 amps for the base line neutralizer and keeper geometry with a rolled tantalum foil insert. The tip temperature was held fixed at 1070° C by a tip heater power variation and curves generated for a keeper current (J_{NA}) of 0.69 and 1.56 amps at a beam current of 1.93 amps. There occurred a slight reduction in minimum mass flow rate required for stable operation at the higher keeper current. The neutralizer coupling voltage (V_G) level was a few tenths of a volt less at the higher keeper current but the neutralizer keeper voltage was slightly higher for the increased current. This is expected since the keeper voltage-current function has a positive slope for these mass flow rates. At low mass flow rates, the keeper voltage is more sensitive to changes in flow rate, resulting in a better control characteristic.

Similar results were found at a beam current of 1.04 amps (fig. 4(b)). At the lower beam current, stable neutralizer operation was difficult at any keeper current less than 0.9 amp. But the increase in keeper current from 0.93 to 1.53 amps again resulted in an increased sensitivity of keeper voltage to mass flow. The fact that the tip temperature was slightly less at the lower keeper current (1032° C against 1070° C) possibly could have caused a slight increase in the neutralizer keeper voltage characteristic, but this effect was probably minimal.

Figure 5 shows similar results for a base line neutralizer and keeper using an impregnated insert with a peripheral flow path (fig. 2(b)). The minimum mass flow rate requirements were reduced by 10 eq. mA and the slope of the control characteristic improved when the keeper current was increased. A similar test using the inverted orifice cathode (table 1) yielded almost identical results (fig. 6). These data indicate that operating a neutralizer at different levels of neutralizer keeper current while maintaining near constant temperatures does not significantly effect coupling voltage. Increasing the temperature at a fixed keeper current does reduce the coupling voltage by a few tenths of a volt.

However, increasing the keeper current at a constant temperature does increase the keeper voltage, but also yields a much more suitable control characteristic. An increase in temperature at the higher keeper current reduced the keeper voltage only at the very low mass flow rates and lessened the characteristic's slope slightly. Thus the improvement in controllability is almost entirely due to the increase in keeper current.

This increase in keeper current and voltage does represent an increase in power, typically less than 5 watts. This increase is probably more than offset by the elimination of heater power for most thermal configurations. The elimination of tip heater power for steady state operation allows the heater to be operated in a passive mode. This should greatly increase the reliability and lifetime of this component as well as afford a significant power saving. Table 4 summarizes the total neutralizer accountable powers for both high and low keeper current operation. For these particular geometries, operation at high keeper current results in power savings of 50 watts or more.

In addition, operating at high keeper currents provides better control at both high and low beam currents without significantly increasing coupling voltages.

Neutralizer Position

The major considerations which govern neutralizer position are primary ion beam current density striking the neutralizer, neutralizer caused charge exchange current striking the accelerator grid, and neutralizer performance. The first two considerations primarily effect neutralizer and accelerator grid lifetime.

Tests to determine an acceptable neutralizer performance with glass coated accelerator grids are described in reference 3. Similar tests have indicated these results to be valid for standard uncompensated grids. The tests described here are to verify an acceptable neutralizer position for compensated grids which provide a less divergent beam.

A planar probe was used to determine the beam profile near the grid system for both uncompensated and compensated grid systems. A map of this region showing lines of constant current density for two grid sets is shown in figure 7. (See fig. 3 for reference locations.) The beam envelope is considerably more compact for the compensated grids. At an axial location of 10 cm the 500 μA constant current line is ~6 cm closer to the thruster axis for the compensated grids. At the neutralizer position of 9.0 cm axial by 10.2 cm radial determined by tests of reference 3, the probe current is reduced by more than a factor of three for the compensated case. This, of course, should greatly reduce primary ion erosion rate of the neutralizer.

Figure 7 also shows the neutralizer to beam coupling voltage at various locations in the same region at a neutralizer mass flow rate of ~40 eq. mA for the compensated case (locations indicated in figure). The beam current was typically 1.95 A. As expected the coupling voltage increased as the neutralizer was moved axially toward lines of smaller current density. The same effect occurred when the neutralizer was moved radially outward to regions of lower current density at axial locations greater than 8 cm. At closer axial positions the coupling voltage near a constant current line of 100 μA, decreased slightly as the neutralizer was moved radially further out. The keeper voltage was relatively constant, varying only from 16.6 to 17.0 volts. Thus, any location within the region shown in figure 7 should yield acceptable performance.

The effect of neutralizer operation on accelerator grid current was determined in the manner described in reference 3. A plot of collector strip current as a function of neutralizer axial location for a given radial location is shown in figure 8. Note that the current collected by the strip located on the grid away from the neutralizer (no. 3), and, to a lesser extent, the strip located on the ring away from the neutralizer (no. 4) are relatively weak functions of neutralizer axial location. The strongest dependence on axial location occurs for the strip located on the ring near the neutralizer (no. 1).

The analysis of the data as regards expected accelerator grid wear is based on the assumption that the base level current collected by the strips when the neutralizer was positioned at large axial locations is primarily due to thruster rather than neutralizer operation, and cannot be significantly reduced by moving the neutralizer further from the grid.

A family of curves similar to those of figure 8 were used to generate figure 9. This figure shows lines of neutralizer position resulting in a fixed strip current increase above the base level current. This increase represents the current to the strips which can be eliminated by a variation of neutralizer position. Extended tests and wear measurements described in reference 3 suggest a current of 5 μA to a 5 cm^2 strip should result in grid lifetimes of order 10^4 hours for thin (typically 0.015 in.) accelerator grids. Figure 9(a) shows that the strip current is actually less than 3 μA on the grid surface for axial locations greater than 10 cm and any radial location. The current to the strips located on the mounting ring are somewhat higher, but since the ring is approximately 20 times thicker than the grid, these current levels should still be acceptable.

Figure 9(b) shows an even greater degree of flexibility in selecting a neutralizer location when using 5 μA as the maximum allowable current. In this case, the neutralizer can be located as close as ~7.5 cm from the grid.

In general, it appears that a minimum axial distance of 8 to 10 cm from the accelerator grid at the worst radial location should provide adequate lifetime probability with compensated grids without significantly affecting performance. The actual radial location is primarily a function of the beam profile.

Conclusion

Tests conducted indicated that of the several neutralizer cathode designs tested, none significantly improved performance over that of the base line cathode design. The base line design was a 6.3 mm cathode diameter with an orifice dimension of 0.38 mm diam. by 1.22 mm. long. Further variations of the open loop keeper distance from the cathode face indicated no change in performance. The use of an enclosed keeper design with a high current neutralizer has an adverse effect on performance.

Several methods of containing the emissive mix were tested. Coating a piece of Ta foil proved to be a reasonably reliable method. Barium impregnated inserts were also used. The performance with these inserts was typically the same as for the rolled Ta foil inserts. The difference in thermal loading did seem to raise the temperatures on the cathode tube above the insert, however. No conclusions regarding long term performance of these inserts at high emission currents can be drawn at present.

It was found that performance and the control characteristics of the base line and other neutralizers were significantly improved by operating at high keeper currents. A minor reduction in flow rate requirements was noted for some configurations. The major advantage however was a large power savings resulting from the self-heating at higher keeper currents and the resulting elimination of tip heater power. In addition, the neutralizer keeper voltage became much more sensitive to mass flow rate, providing for a more stable control characteristic. The coupling voltage was not significantly affected.

Finally tests with a movable beam probe and movable neutralizer and compensated grid extraction system indicate that a neutralizer position of 8 to 10.0 cm downstream from the last row of accelerator grid holes and radially out of the primary ion beam should result in minimal wear of the neutralizer by the primary ion beam, also neutralizer caused charge exchange current striking the accelerator grid was reduced. Positioning the neutralizer downstream had no adverse effect on neutralizer performance.

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Table 1 Summary of cathodes tested

Cathode number	Orifice diam., mm	Orifice length, mm	Cathode o.d., cm	Wall thickness, mm	Comments
1	0.38	1.22	6.3	0.51	Base line cathode
2	0.76	1.22	6.3	0.51	Minimum mass flow, 66 eq. mA Minimum keeper current, 1.2 A
3	0.38	0.25	6.3	0.51	Minimum mass flow, 37 eq. mA Minimum keeper current, 0.7 A
4	0.76	0.25	6.3	0.51	Minimum mass flow, 40 eq. mA Coupling voltage > 25 V
5	0.38	0.6	6.3	0.51	45° chamfer on upstream surface to depth of 0.6 mm - base line performance
6	0.38	0.38	3.2	0.43	High self-heating temperatures

Table 2 Summary of keeper geometries tested

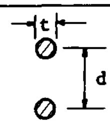
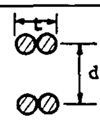
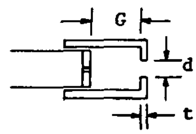
Type	Keeper thickness t, mm	Keeper diam. d, mm	Keeper to cathode gap G, mm	Minimum mass flow, eq. mA	Minimum keeper current, amps	Cross section
Open	1.5	6.3	1.5	24	<0.3	
Open	1.5	6.3	2.5	24	<0.3	Same
Open	1.5	6.3	5.1	24	<0.3	Same
Open	3.0	6.3	1.5	29	1.2	
Enclosed	1.5	6.3	1.5	27	0.3	
Enclosed	1.5	3.2	1.5	48	1.3	Same
Enclosed	1.5	6.3	5.1	48	1.2	Same

Table 3 Comparison of barium container (insert) types tested

[Beam current, 1.95 amp]

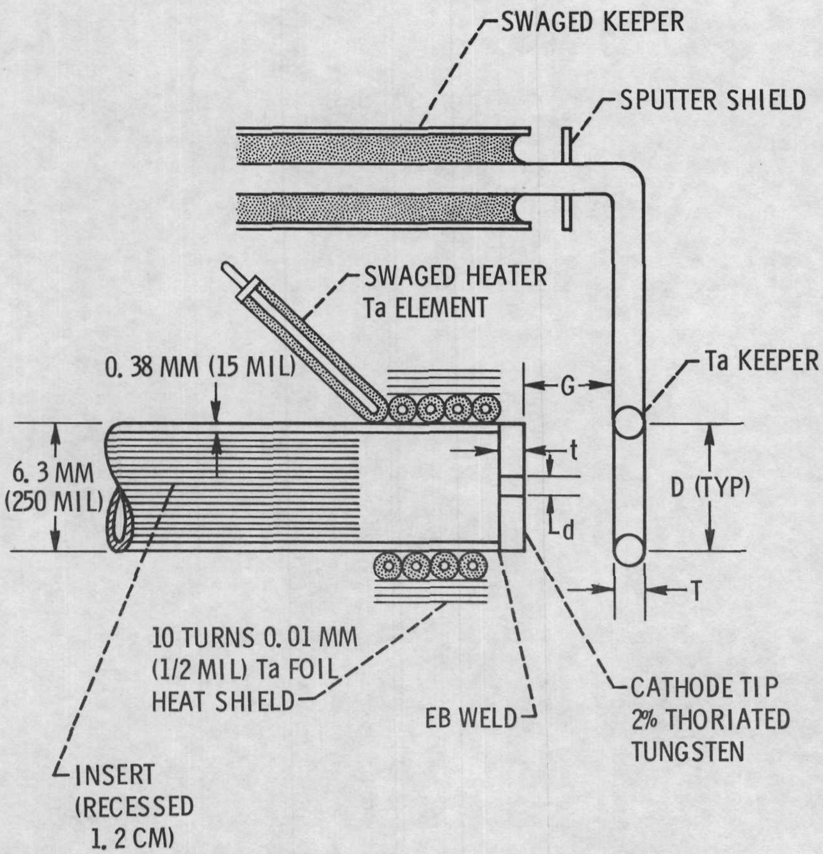
Insert type	Keeper voltage, V	Keeper current, A	Coupling voltage, V	Mass flow, eq. mA	Tip temp., °C	Temperature over insert, °C	Tip heater power, W
Low neutralizer keeper current							
Syringe	9.6	0.69	9.7	28	1320*	---	78
Syringe	10.9	0.58	11.1	36	1335*	---	88
Syringe	10.7	0.56	10.9	26	1335*	---	88
Rolled Ta	11.8	0.58	11.1	33	1238	612	72
Impregnated (edge)	11.1	0.68	10.2	36	1077	850	72
High neutralizer keeper current							
Syringe	12.1	1.48	11.3	36	>1335*	---	88
Syringe	12.2	1.48	11.1	26	>1335*	---	88
Rolled Ta	15.7	1.59	12.6	30	1132	677	0
Impregnated (edge)	14.4 12.7	1.55 1.55	11.7 10.8	25 35	1070 1070	822 822	56 56
Impregnated (concentric)	17.1 15.7	1.58 1.59	13.9 14.4	30 22	1032 995	740 732	0 0

*Measured with optical pyrometer.

Table 4 Summary of neutralizer powers at high and low keeper current base line cathode and keeper

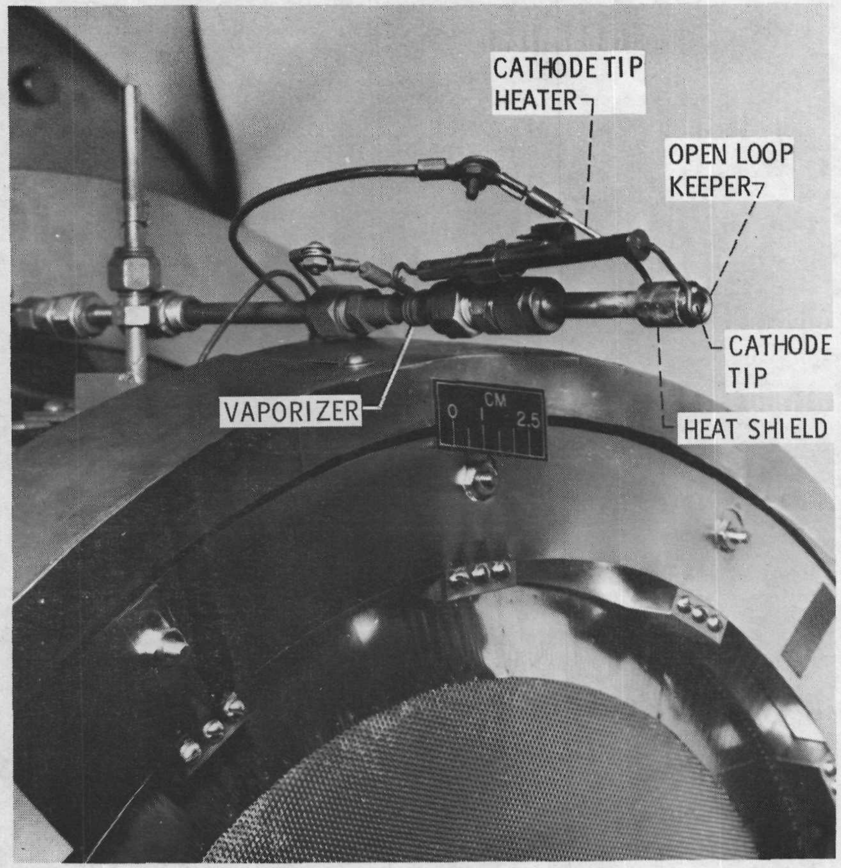
[Beam current, ~1.9 A]

	Rolled Ta insert		Impregnated insert
Keeper current	0.69 A	1.55 A	1.6 A
Keeper voltage	11.8 V	15.8 V	15.75 V
Keeper power	8.1 W	24.4 W	25.2 W
Coupling power	22.0 W	23.2 W	26.5 W
Tip heater power	72.1 W	0	0
Total power	102.2 W	47.6 W	51.7 W
Tip temperature	1070° C	1158° C	1032° C
Mass flow rate	28 eq. mA	30 eq. mA	30 eq. mA



(a) SKETCH OF CATHODE AND KEEPER.

Figure 1. - Neutralizer subsystem.



(b) SYSTEM MOUNTED ON THRUSTER.

Figure 1. - Concluded.

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(a) CONCENTRIC FLOW PATH.

(b) PERIPHERAL FLOW PATH.

Figure 2. - Sketch of impregnated inserts tested.

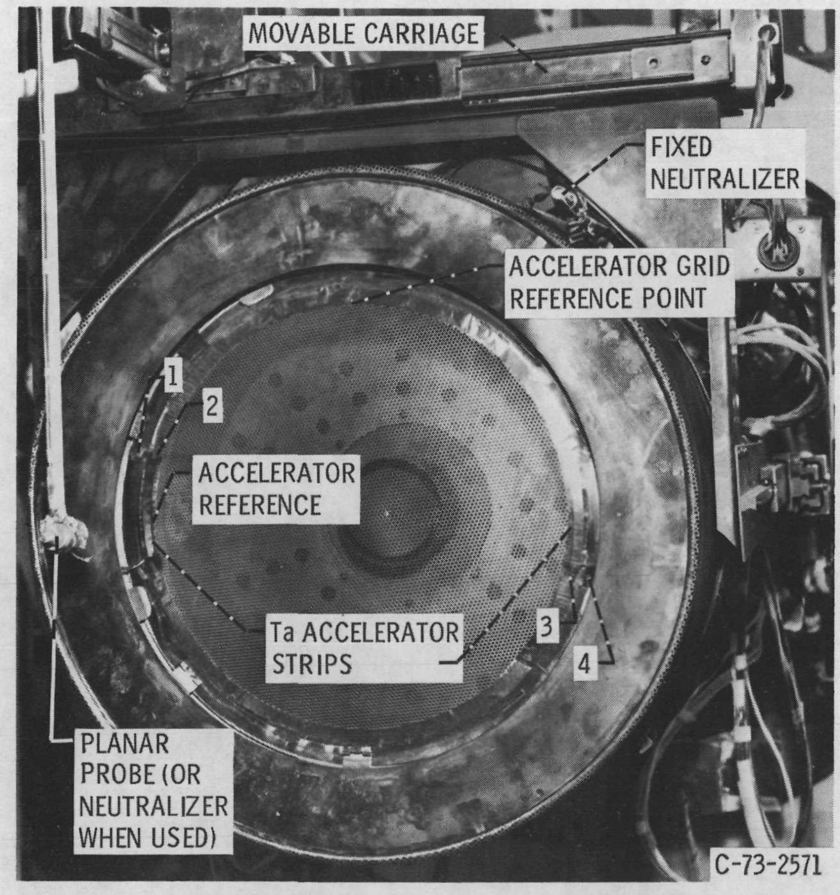
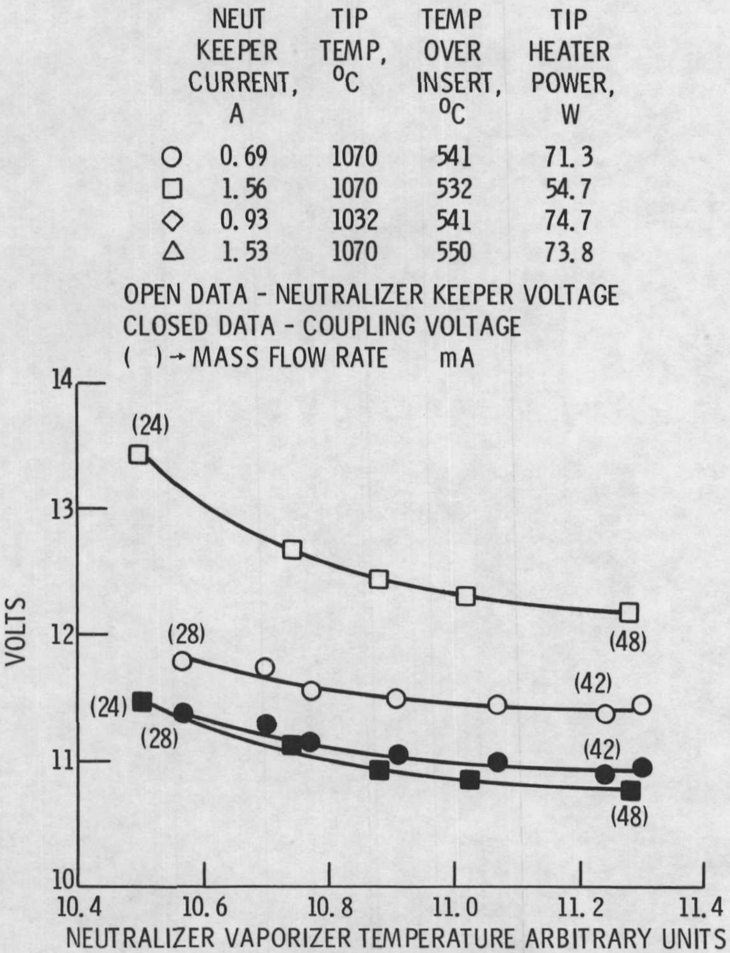
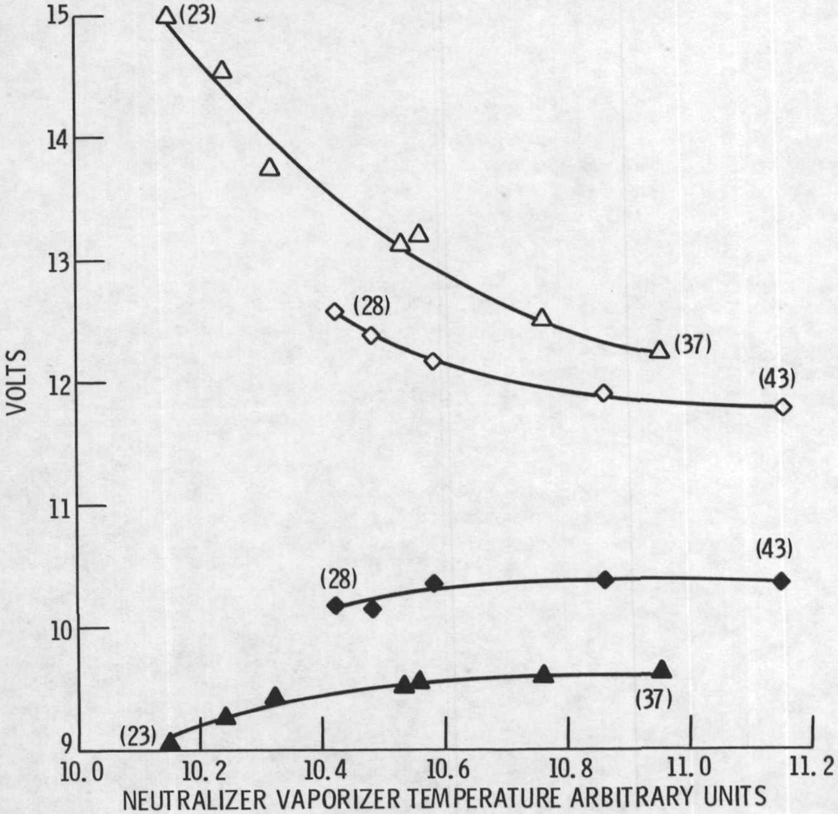


Figure 3. - Thruster with movable carriage mounted.



(a) BEAM CURRENT 1.93 A.

Figure 4. - Neutralizer performance at high and low keeper current. Net accelerating potential 1000 V, accelerator potential 640 V, rolled Ta insert.



(b) BEAM CURRENT 1.04 A.

Figure 4. - Concluded.

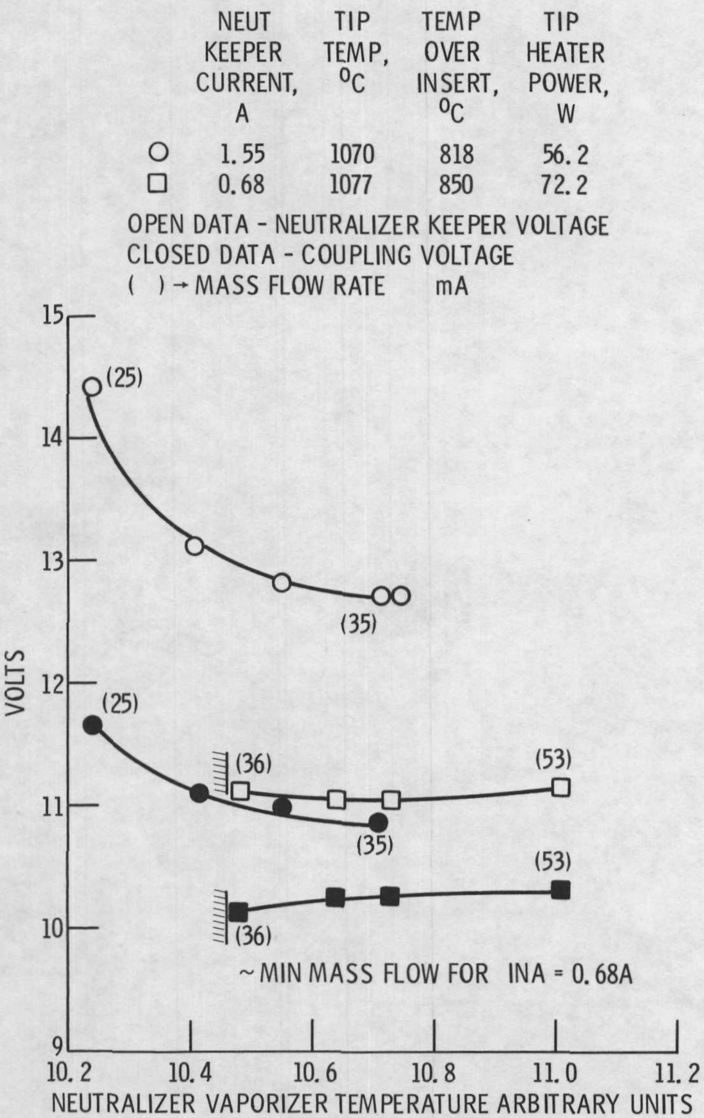


Figure 5. - Neutralizer performance at high and low keeper current beam current 1.93 A, net accelerating potential 950 V, accelerator potential 610 V, impregnated insert with peripheral flow path.

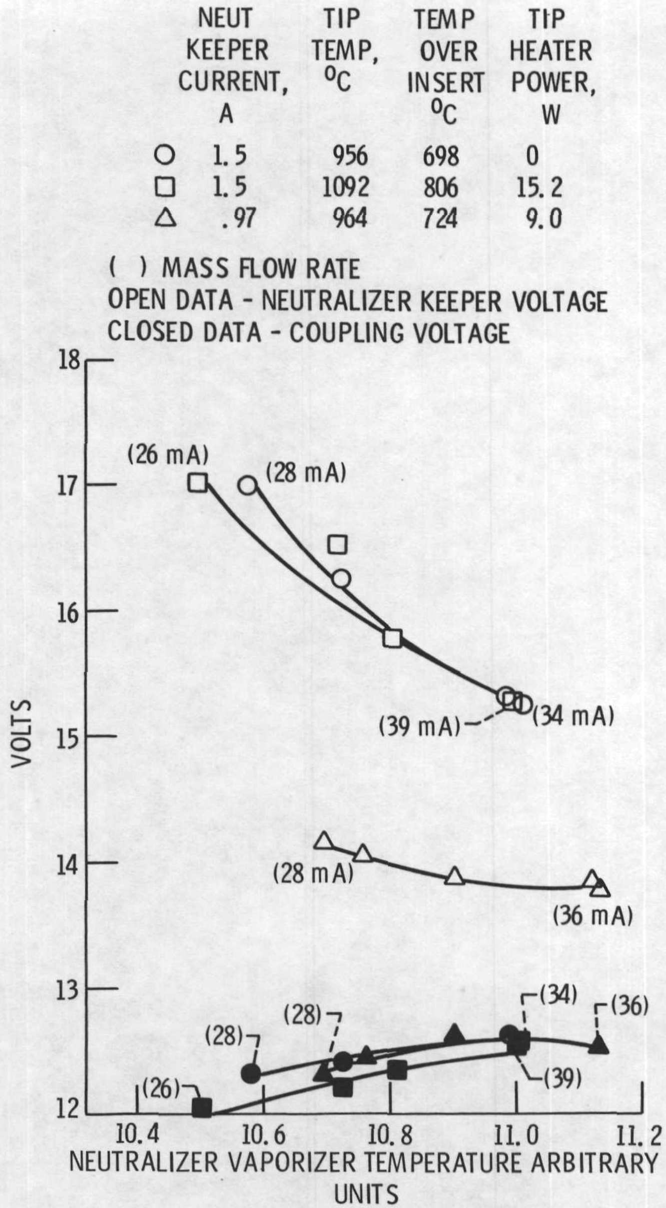


Figure 6. - Performance of inverted orifice neutralizer (5 Table I) beam current 1.9 A, net accelerating potential 980 V-accelerator potential 820 V - rolled Ta foil insert.

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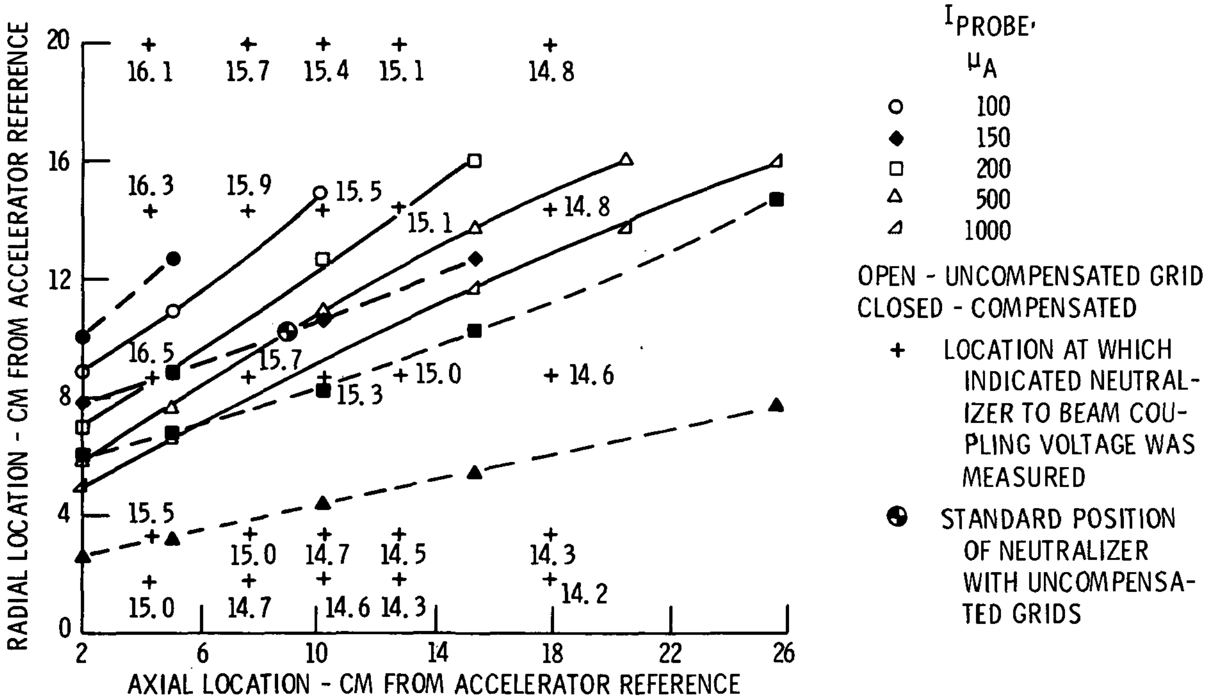


Figure 7. - Map of downstream area; neutralizer propellant flow rate ≅ 40 mA; probe area 2 cm^2; range of neutralizer keeper voltages 16.6 to 17.0 volts; keeper current 1.55A; tip power 0 watts.

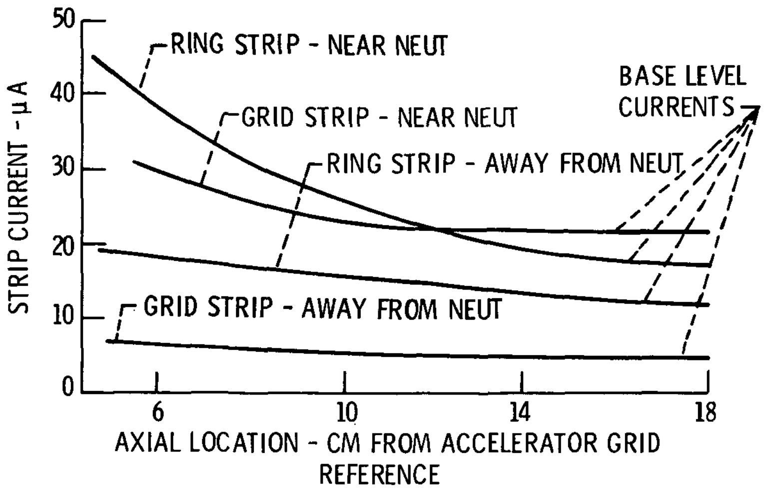
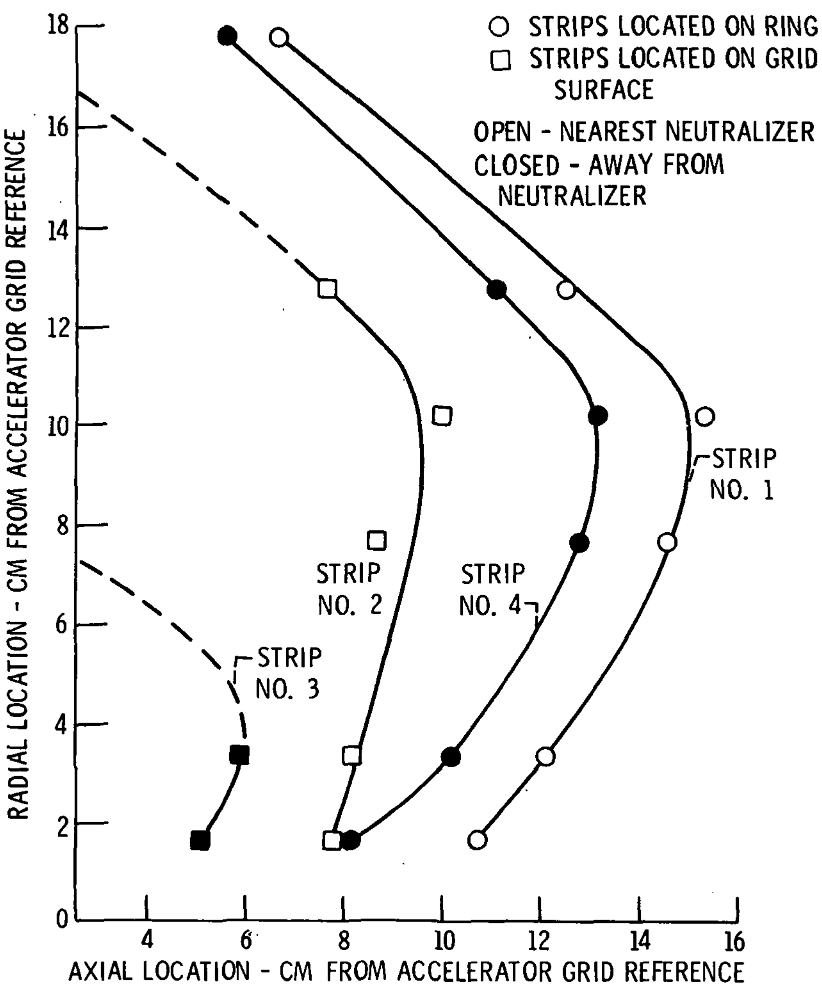
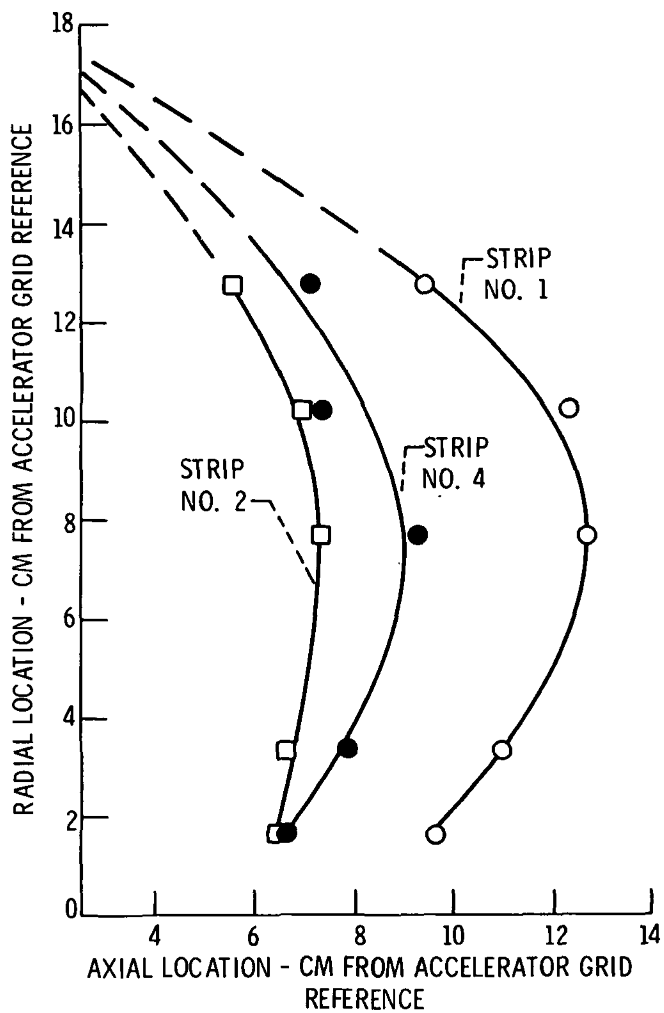


Figure 8. - Current to each of 4 accelerator strips; radial location = 7.6 cm; beam current 1.9A; neutralizer mass flow rate ≅ 40 mA.



(a) STRIP CURRENT 3μ A.

Figure 9. - Locus of neutralizer positions resulting in a constant current to each of the four accelerator strips. Beam current 1.9 amps - neutralizer mass flow rate ~ 40 mA.



(b) STRIP CURRENT 5μA.

Figure 9. - Concluded.