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EFFECT OF POWER SUPPLY IMPEDANCE ON THE SERT II NEUTRALIZER

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ABSTRACT

The effect of neutralizer keeper power supply impedance on neutralizer performance was investigated with three basic keeper power supplies. Within limits, the required neutral flow rate decreased with increasing keeper supply capacitance (or decreasing inductance). The change in neutralizer performance reflected by the variation of power supply circuitry tested was such as to change the overall SERT II thruster efficiency by as much as 12 percent.

Coherent oscillations of frequencies between about 0.3×10^6 and 0.6×10^6 sec^{-1} were observed on several neutralizer parameters when the neutralizer power supply was capacitive in nature. These oscillations were not studied in detail in the present program.

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INTRODUCTION

The SERT II thruster system (ref. 1) utilizes a mercury plasma bridge neutralizer (ref. 2). Geometric details and some performance characteristics of the SERT II neutralizer system have been described (refs. 2 and 3). The mercury consumption of the neutralizer represents a loss in thruster system propellant utilization efficiency of between 4 and 6 percent (at the SERT II thruster design operating point). The power required for neutralizer operation (including beam coupling power) is about 3.5 percent of the total thruster operating power at 0.250 ampere beam current.

It was recently discovered, subsequent to the findings presented in references 2 and 3, that the impedance of the neutralizer keeper power supply can strongly affect neutralizer performance. The data presented herein show neutralizer performance as a function of neutralizer keeper power supply output impedance with several basic power supply systems. The trends and limits of neutralizer performance with keeper supply impedance are specified for a SERT II neutralizer system.

Research and development of a variety of electron-bombardment thruster systems and subsystems is being carried out by investigators at several locations (e.g., refs. 4, 5, 6 and 7). These efforts are being carried out with a number of different types of power supplies and associated filter networks. The preliminary data presented in this report indicate, however, that small variations in the filter networks, typical of power supplies used in experimental research, can strongly affect neutralizer performance.

In addition to performance considerations, some observations of oscillations of various neutralizer parameters are presented. These oscillations existed with all circuit types tested and were, in amplitude and form, sensitive to the neutralizer keeper power supply impedance. The possible source of these oscillations is discussed.

APPARATUS AND PROCEDURE

Thruster System

The thruster system was of the SERT II flight type design and identical to that described in reference 3. The electrical configuration utilized for all tests presented herein is shown in figure 1. For all tests the thruster system was isolated from ground by zener diodes which were selected to prevent the potential relative to ground from exceeding 100 volts. Since the thruster system has been previously described in detail and since this report is concerned only with neutralizer performance no further description of the thruster system will be presented.

Neutralizer System

The neutralizer system used was identical to that described in reference 3 with the exception that the flight type mercury reservoir was not utilized. The liquid mercury was supplied from a precision bore glass tube reservoir. Direct measurement of the mercury flow rate was obtained by monitoring the level of liquid mercury at frequent intervals. The flow rates presented are accurate to within 5 percent, based on the repeatability of flow measurements. The neutralizer is shown as it was installed on the thruster in figure 2. Mercury was vaporized at the porous tungsten plug and flowed to the cathode through a 0.25 cm inside diameter tantalum tube 10 cm in length. Details of construction of the neutralizer cathode were presented in reference 2 and are shown in figure 3. The cathode consisted of the 0.25 cm inside diameter tube capped off with a 0.1 cm thick 2 percent thoriated tungsten disk. An orifice about 0.025 cm in diameter was sandblasted into the thoriated tungsten disk. To assist in starting, a tantalum insert (fig. 3) coated with barium carbonate mixture was placed inside the cathode tube. The gaseous mercury was constrained to flow through the 0.05 cm inside diameter of the tantalum insert into a small cylindrical volume (about 0.15 cm long by 0.15 cm diameter) and thence through the orifice in the thoriated tungsten disk. The neutralizer keeper was fabricated of 0.05 cm thick tantalum sheet and was located 0.152 cm downstream of the cathode face.

Neutralizer Keeper Power Supplies

Three basic neutralizer keeper power supplies were utilized and are shown schematically in figure 4. Capacitors and inductors were also added to the three basic keeper power supplies for additional tests. In all cases the capacitors were added in parallel across the output of the keeper supply and the inductors were inserted in series with the positive leg of the keeper supply.

Power supply I (fig. 4(a)) was a part of a thruster power conditioning system used to test and evaluate SERT II prototype thruster systems. This basic power supply, with a 2 μF capacitor added across the output, was used to obtain the neutralizer performance data presented in figure 11 of reference 3. Reference 3 presented neutralizer performance of a SERT II flight type thruster system over an extensive range of neutralizer keeper voltages and thruster ion beam currents. The filter network of power supply I was arbitrary in that it was assembled prior to knowledge of the effect of keeper power supply impedance on neutralizer performance.

Power supply II (fig. 4(b)) was a part of a thruster power conditioning system used to test power conditioning concepts. This power supply was utilized for endurance tests 3 and 4 of reference 3 which specified the upper limits of neutralizer keeper voltage for the SERT II mission. The neutralizer keeper voltage set point could be continuously adjusted over the range of investigation (12 to 35 volts) with power supplies I and II.

Power supply III is part of a prototype SERT II neutralizer power conditioner. Both the neutralizer and thruster were operated with an experimental model SERT II power conditioner to obtain data with this third power supply. The neutralizer control was rather inflexible in that only two neutralizer keeper voltage set points were available per test.

The three basic keeper power supplies were similar in the following respect. Each supply provided (via an inductor or resistor in the primary) a volt-ampere characteristic which dropped from between about 300 to 400 volts at 0.005 A load to zero volts at about 0.200 A load. The power supply operation was thus very nearly at constant current in the range of intersection with the volt-ampere characteristic curve of the neutralizer keeper discharge. In all tests the neutralizer keeper voltage was held at the selected set point via a feedback loop with the neutralizer vaporizer heater.

Vacuum Facility

All tests were conducted in a 1.5 meter-diameter, 4.5 meter-long vacuum tank. The thruster was installed in a bell jar separated from the main tank by a 0.9 meter gate valve. Four 0.8 meter-diameter oil diffusion pumps were utilized along with cryogenic (LN_2) pumping. A similar vacuum facility is described in reference 8. All data presented herein were taken at bell jar pressures between 4 and 7×10^{-6} torr.

RESULTS

Effect of Keeper Power Supply Impedance on Neutralizer Performance

A number of tests were performed in which the neutralizer was operated with the three basic neutralizer keeper power supplies. The tests were performed with the same neutralizer-thruster system which was not removed from the test facility for the duration of the tests presented herein. Various impedances were added to each basic power supply. The performance of the neutralizer with basic power supplies I, II, and III (with various added impedances) is shown in figures 5(a), 5(b), and 5(c), respectively. The data with the three basic supplies were taken at values of total accelerating potential between 4900 and 5300 volts. Previous experience indicated that this variation of net extraction voltage would not significantly affect neutralizer performance.

Figure 5(a) presents the neutralizer keeper voltage and thruster floating potential as a function of neutralizer flow rate for power supply I. The impedances added to this supply ranged from a 2μF capacitor to a 35 mH inductor. Power supply I was also tested with the filter network (the capacitor, resistor, and inductor shown in figure 4(a)) removed. These data are presented as the solid data points in figure 5(a).

The shape of the curve of neutralizer keeper voltage as a function of neutralizer neutral flow rate remained similar for all power supplies tested. However, as the neutralizer keeper supply was made more inductive (or less capacitive) the neutral flow rate required for a given keeper voltage increased strongly. These two results were found for all three basic supplies tested. The observed oscillations on various neutralizer parameters also changed strongly with power supply circuitry and to a lesser extent with neutral flow rate. Discussion of the oscillations will be deferred to the DISCUSSION section.

Figure 5(b) shows the relationship between power supply impedance and neutralizer performance for power supply II. It is seen that the neutral flows were somewhat higher for supply II than supply I. The differences are greater than experimental inaccuracies and are probably attributable to the different thruster power conditioning systems used. Figure 5(b) also shows that the neutralizer performance does not indefinitely improve with added capacitance. Very little difference in performance was noted when the capacitance was increased from 3 to 30 μF.

Figure 5(c) shows the neutralizer performance with power supply III. The thruster as well as the neutralizer was operated with an experimental SERT II power conditioner for these data. The data with no impedance added was taken on two separate tests and adjustment of the two available keeper voltage set points was made between tests. No data are reported with capacitance added to this supply. Attempts to obtain data with a 0.5 μF capacitor led to strong interactions with the prototype conditioner. It is seen that with the experimental SERT II power conditioner (no added impedance) the neutral flow rate required to maintain a given keeper voltage was somewhat less than that reported in reference 3. The data shown by the dashed curve on figure 5(c), of reference 3, was taken with a SERT II flight thruster with power supply I with a 2 μF capacitor added.

Figure 5(c) shows that the neutralizer performance curve with the prototype conditioner (no added impedance) corresponded quite closely to that of power supply I with the filter network removed and a 3μF capacitor added (fig. 5(a)). Thus similar neutralizer performance was obtained with two different basic supplies with a considerably different degree of capacitance of the keeper supply output. Figure 5(c) also shows that the neutralizer performance was nearly identical with a 0.16 mH or with a 2.9 mH inductor added in series.

Many electrical and geometric factors can affect neutralizer performance (e.g., refs. 2 and 3). It is of interest to determine if the effect of neutralizer keeper impedance would act in an additive fashion with the effects of the electrical and geometric factors described in references 2 and 3. The effects would be expected to be additive if similar trends of neutralizer performance with electrical and geometric variations are found using different keeper supply impedances. One such factor, the effect of ion beam current on neutralizer performance, could be conveniently observed with two different neutralizer keeper power supplies. Figure 6 shows a plot of required neutral flow rate as a function of ion beam current for the data of reference 3 (supply I, 2 μF capacitor added) and supply III (no added impedance). Figure 6 shows that, although there was a difference in neutralizer performance with the two keeper supplies, the trend of required neutral flow rate as a function of ion beam current was very similar for both cases.

Oscillations of Various Neutralizer Parameters

Oscillations were observed by means of an oscilliscope on several neutralizer parameters with all supply combinations tested. The

Parameters observed were the neutralizer keeper voltage, V_{na}, and current J_{na}, the thruster floating potential, Vg, and the total neutralizer emission current, J_{ne}, (the sum of the keeper current and the net current emitted to the beam). The total neutralizer emission current, rather than the current emitted to the beam, was observed because the electrical junction (A on figure 1) was made internally in the various power supplies. The voltages were measured directly while the currents were determined by recording the voltage drops over the one ohm resistors R_1 and R_2 shown in figure 1.

Figures 7 and 8 show oscilliscope traces of various neutralizer parameters. These data were taken with basic power supply III with no impedance added (fig. 7) and with a 0.162 mH inductor added (fig. 8). The data of figures 7 and 8 are typical of all supply configurations tested with a capacitor or an inductor, respectively, as the final output impedance.

Figure 7(a) shows the oscillation of both the neutralizer keeper current and the total neutralizer emission current. The neutralizer keeper current exhibited a large coherent oscillation. This coherent oscillation occurred with all the capacitive circuits presented herein. The frequency was between 0.3×10^{6} and 0.65×10^{6} MHz for the range of circuits tested. With a given keeper supply circuit, the frequency decreased with decreasing keeper voltage (or increasing neutral flow rate). Some characteristics of the observed oscillations with power supplies I and II are given in Table I.

The oscillation of the total neutralizer emission current (fig. 7(a)) is in phase with and of very nearly the same amplitude as the oscillation of the neutralizer keeper current. As previously mentioned, the total emission current was the sum of the keeper current and the net current emitted from the neutralizer. It is evident, then, from figure 7(a) that the net electron current from the neutralizer is approximately constant.

Figure 7(b) shows the neutralizer keeper current and voltage. It is seen that the neutralizer keeper voltage oscillated at the same frequency as the keeper current and approximately 180 degrees out of phase with it. The peak-to-peak amplitude of the oscillation of the neutralizer keeper voltage decreased with increasing capacitance, as might be expected. The thruster floating potential oscillated with the same frequency (with a peak-to-peak amplitude of about 4 volts) as the other parameters and for the sake of brevity is not shown.

Figure 8 shows the effect of added inductance (0.162 mH) on the same parameters shown in figure 7. Figure 8(a) shows both the keeper and net emitted currents. It is seen that the addition of inductance damped the oscillation of the currents, as might be expected. Figure 8(b) shows the keeper current and voltage. The addition of inductance caused a peak-to-peak noise in the neutralizer keeper voltage of about 36 volts. The data of figure 8(b) are typical of all supplies tested with an inductor as the final impedance. The amplitude of the noise of the keeper voltage increased with inductance. For example, the peak-to-peak noise amplitude of the keeper voltage with power supply III with 2.8 mH added inductance was about 48 volts.

The oscillations were also noted in the preheat phase of thruster operation. During the preheat phase the ion beam current is zero and the neutralizer keeper discharge arc is lit with no net emission from the neutralizer. The oscillations in neutralizer keeper current and voltage were (for power supply III with no added impedance) approximately the same as those observed during normal thruster operation.

DISCUSSION

Overall Thruster Efficiency

The data of figure 5 will be discussed in terms of the effect on the SERT II thruster efficiency represented by the variation of neutralizer performance. The total neutral flow of the SERT II thruster system (including that required for the neutralizer) is about 320 ma of equivalent flow. The overall propellant utilization efficiency of the SERT II thruster system then changes by about one percent with a 3 millampere equivalent change of neutralizer neutral flow rate. The flow variation shown on figure 5(a) represents about 8 percent of the overall propellant requirements of the SERT II thruster system at a neutralizer keeper voltage of 29 volts. The range of neutral flows would reflect a variation in total propellant requirement of nearly 12 percent at a keeper voltage of 22 volts.

The thruster floating potential, V_g, with respect to the building ground increased (became less negative) in figure 5(a) with increasing neutral flow rate but did not vary strongly with circuit impedance. The decrease of floating potential with decreasing flow rate corresponds to an increase in coupling power and, hence, represents an increased power loss. The coupling power is the product of the ion beam current and the sum of the absolute value of the floating potential and beam potential. The coupling potential (based on probe floating potential measurements) was found to be between 2 and 4 times the absolute value of the thruster floating potential over a large range of conditions (ref. 2). The 6-volt variation in absolute value of floating potential shown on figure 5(a) then corresponds to a possible 24 volt increase in coupling voltage or a power increase of about 6 watts. This power is less than one percent of the total SERT II nominal operating power (850 W).

The range of variation of propellant requirements with keeper voltage shown on figures 5(b) and 5(c) is somewhat smaller than that shown on figure 5(a). It is not known if this is due solely to the differences in the basic keeper power supplies or if it arises, in part, from the fact that different thruster power conditioners were utilized with each basic keeper power supply. The high voltage ripple of the net accelerating potential supply was considerably different for the thruster power conditioners used with basic power supplies I and III. Both high voltage supplies produced a nominal voltage of +3300 volts. The one used with basic power supply I, though, had a 1600 volt peak-to-peak ripple while the other used with basic power supply III had a 200 volt peak-to-peak ripple.

It was seen that the neutralizer performance with power supply I with a 3 μF capacitor added (fig. 5(a)) was similar to that with power supply III which had a 0.33 μF capacitor as its final impedance (fig. 5(c)).

It was also seen from figure 5(a) that the neutralizer performance was sensitive to variation of capacitance in the range 0.33 to 3 μF capacitance. The similarity of neutralizer performance with the large difference in final output capacitance might be due to the difference in the ripple of the net accelerating potential supplies utilized with basic power supplies I and III.

The data of figure 5(b) indicated that the neutralizer performance became insensitive to increases in capacitance. Figure 5(c) indicated, on the other hand, that the decrease of neutralizer performance with added inductance might hold only over limited range of inductance. It is not known if the limits of the relationship between impedance and neutralizer performance suggested by figures 5(b) and 5(c) are general or specific to the particular electrical and geometrical neutralizer-thruster systems tested.

The trends of the results presented herein are, however, probably applicable to other thruster types which utilize mercury-hollow cathode neutralizers. It is likely that the relative effects of neutralizer keeper supply impedance on overall thruster performance would increase as the thruster beam power decreases from those of the SERT II configuration.

Possible Sources of Oscillations

Exact identification of the source of the oscillations would have required a more detailed investigation than covered by this report. It is of interest, however, to discuss the oscillations in terms of the available data. The presence of the oscillations does not depend on an interaction between the neutralizer system and the ion beam since the oscillations in keeper current and voltage existed during preheat with no ion beam present.

Figure 7 showed that the keeper voltage oscillated at the same frequency as the keeper current but was approximately 180 degrees out of phase. This behavior indicates that the impedance of the keeper discharge plasma changed with the observed frequency. The fact is suggestive that some mechanism existed which led to periodic plasma density variation of the keeper discharge plasma. Variation of the discharge plasma density would vary the impedance and the space charge properties of the keeper discharge. If the basic mechanism which gives rise to the oscillation produces a periodic variation of available electrons, the number of ions available (by ionization) would also vary. The ion density in the neutralizer keeper discharge is also of importance to the stability (ref. 9) of the discharge in that, if insufficient ions are available, the electron flow will tend to become space charge limited (i.e. decrease from its normal value). In a case of larger oscillations the discharge may go completely out and thruster operation would be stopped.

The basic oscillation producing mechanism could exist either inside the neutralizer cathode and/or in the arc between the cathode and the keeper. Some mechanisms have been reported which gave rise to oscillations of the order of the observed frequencies. Plasma oscillations have been observed in mercury discharges which have been ascribed to ion acoustic waves (ref. 10). Reference 11 also proposed a "continuity oscillation" which could cause periodic oscillations.

The frequencies predicted by the phenomena presented in references 10 and 11 are both proportional to the square root of the plasma number density. In addition the frequency predicted by reference 11 is proportional to the square root of the neutral number density. The data of table I shows that the frequency, for the two circuits shown, decreased slowly with increasing flow rate. The flow rate and keeper voltage could not be independently varied, however, and the frequency change may be related to the change in keeper voltage. Unfortunately the data are not extensive enough to define the cause of the oscillations.

CONCLUDING REMARKS

It was found that the impedance of the neutralizer power supply could strongly affect neutralizer performance tested. For the power supplies tested the required neutral flow rates at a fixed keeper voltage decreased with increasing capacitance (or decreasing inductance). The change of neutralizer performance reflected by the variation of power supplies tested was such as to change the overall SERT II efficiency 8 and 12 percent at keeper set point voltages of 29 and 22 volts, respectively.

Coherent oscillations of frequencies between about 0.3×10^6 to 0.65×10^6 Hz were observed on several neutralizer parameters when the neutralizer power supply was capacitive in nature. The oscillations were not studied further in this program.

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TABLE I. - OBSERVED FREQUENCIES

Ion beam current, 0.25 A; keeper current, 0.2 A

Neutralizer keeper voltage, V_{na} V	Neutral flow rate, $\dot{m}$ mA	Observed frequency, f MHz
36.2	1.1	0.526
21.8	14.6	0.464
18.3	30.8	0.384

(a) Modified Power Supply I (no filter network) 3 μF capacitor added

Neutralizer keeper voltage, V_{na} V	Neutral flow rate, $\dot{m}$ mA	Observed frequency, f, MHz
37.5	15.8	0.50
30.4	17.4	0.487
26.9	19.5	0.453
21.8	26.2	0.417
19.9	31.8	0.385

(b) Power Supply II, no added impedance

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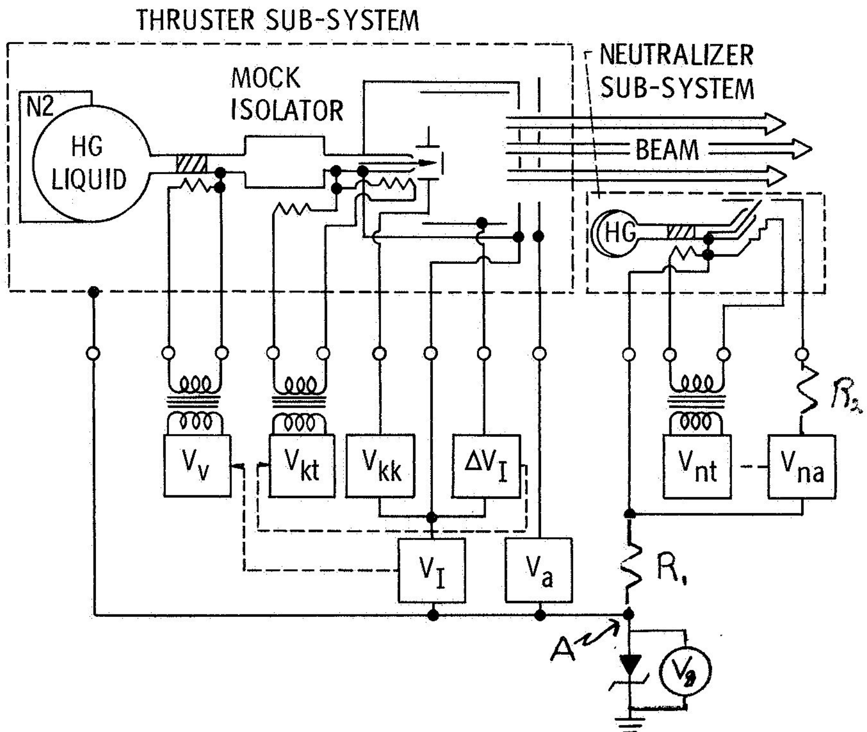


Figure 1 - Electrical schematic of SERT II thruster.

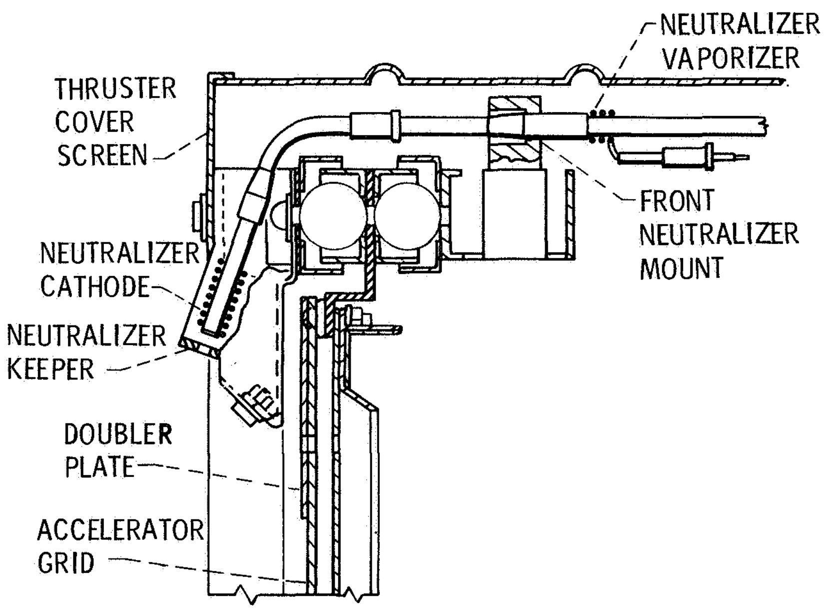


Figure 2.- Cross-sectioned view of neutralizer subsystem.

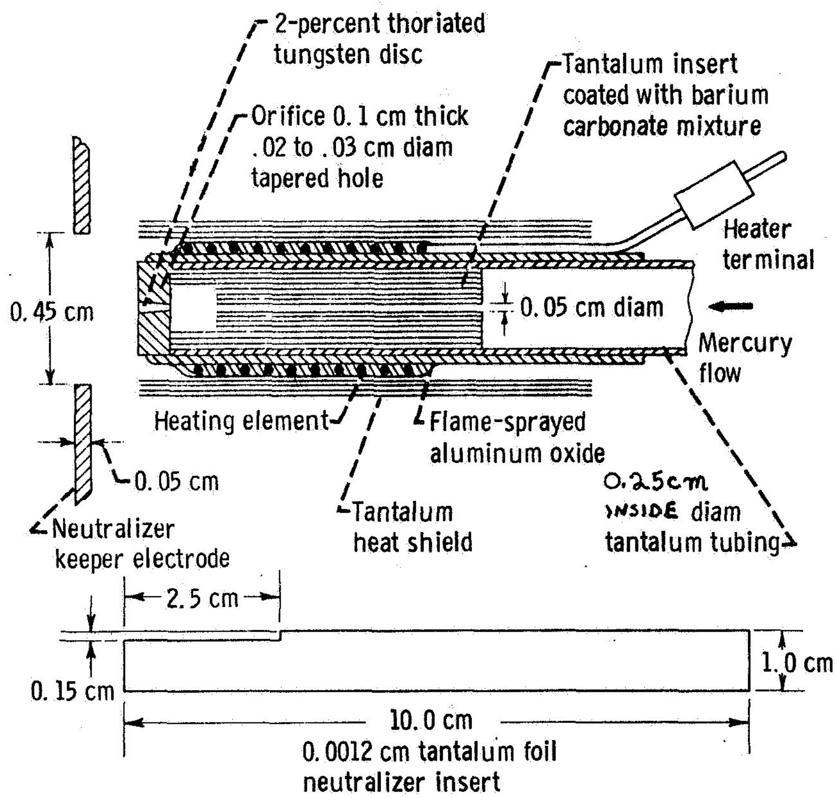
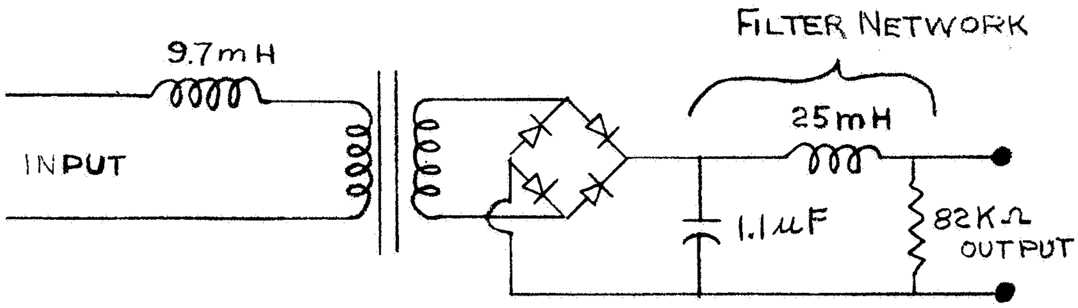
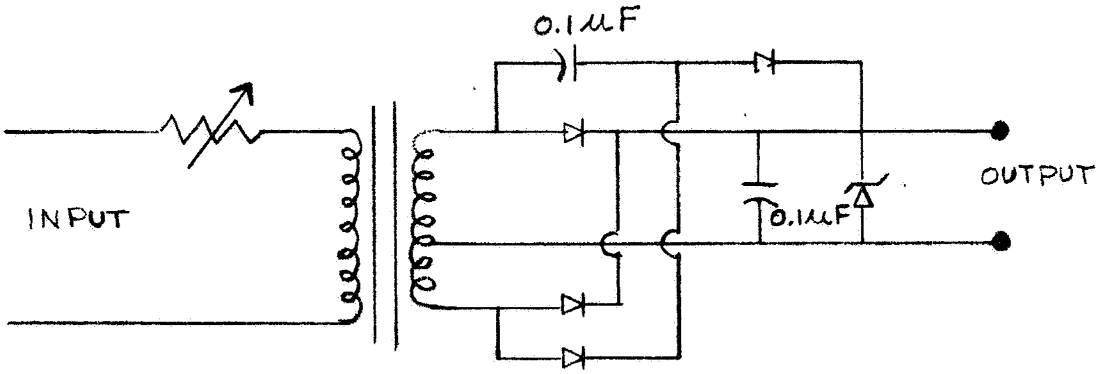


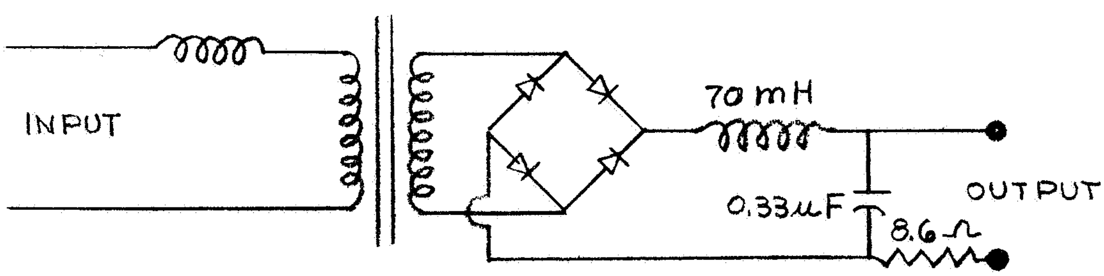
Figure 3 - Plasma-bridge neutralizer cathode construction.



(a) CIRCUIT OF SUPPLY I

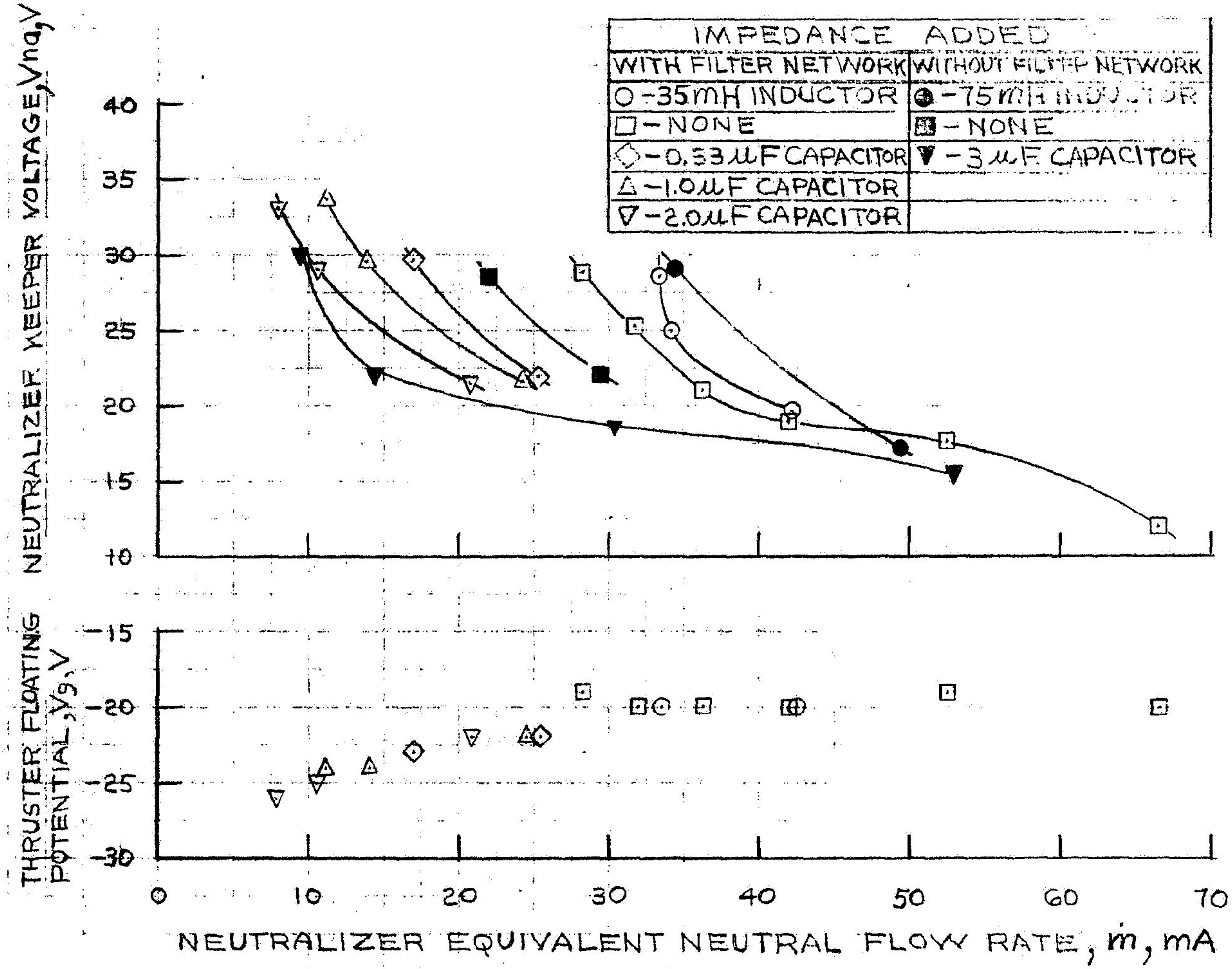


(b) CIRCUIT OF SUPPLY II



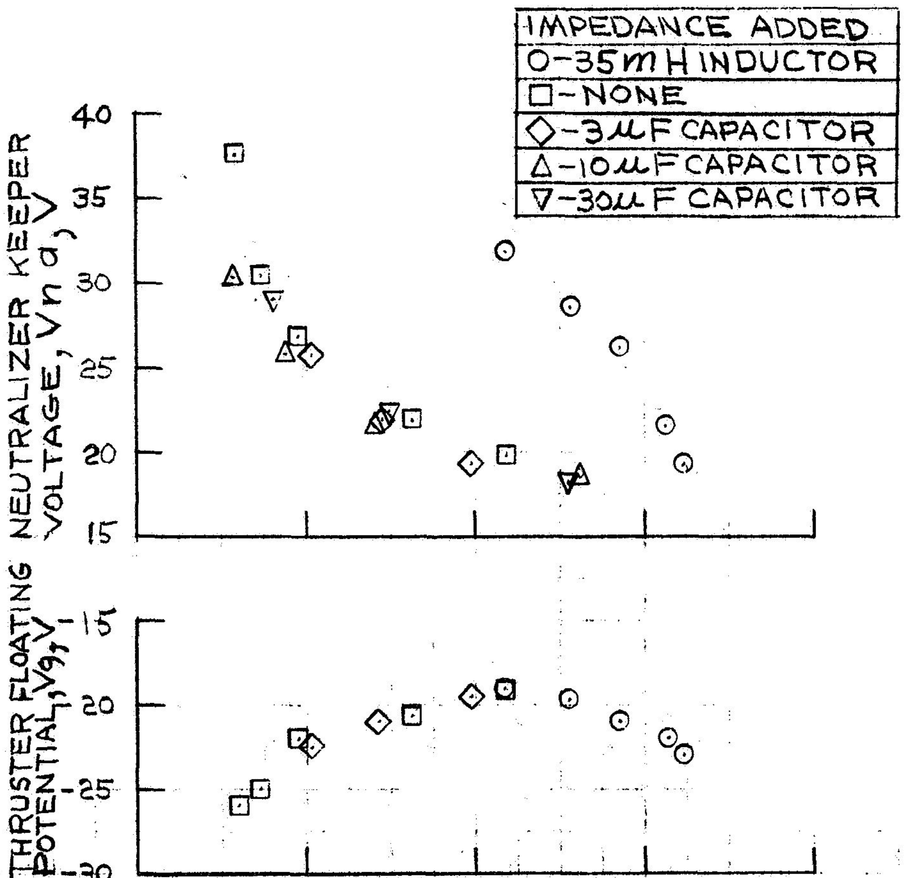
(c) CIRCUIT OF SUPPLY III

FIGURE 4 - CIRCUITS OF BASIC NEUTRALIZER KEEPER POWER SUPPLIES UTILIZED

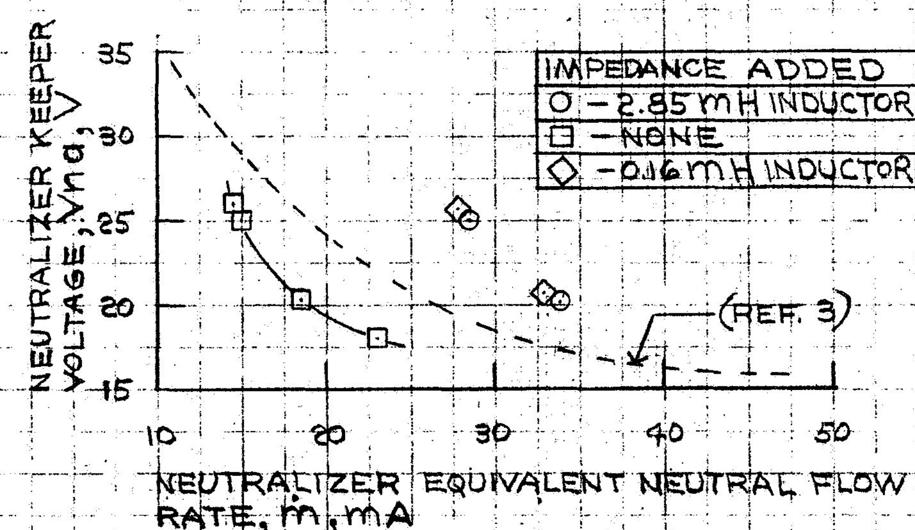


(A) POWER SUPPLY I

Figure 5 — Effect of neutralizer keeper power supply impedance on neutralizer performance.
Ion beam current, J_B, 0.25 A; Total extraction voltage, $V_I + |V_A|$, [illegible]; Neutralizer keeper current, J_{na}, 0.20 A



(B) POWER SUPPLY II



(C) POWER SUPPLY III

Figure 5 - CONCLUDED

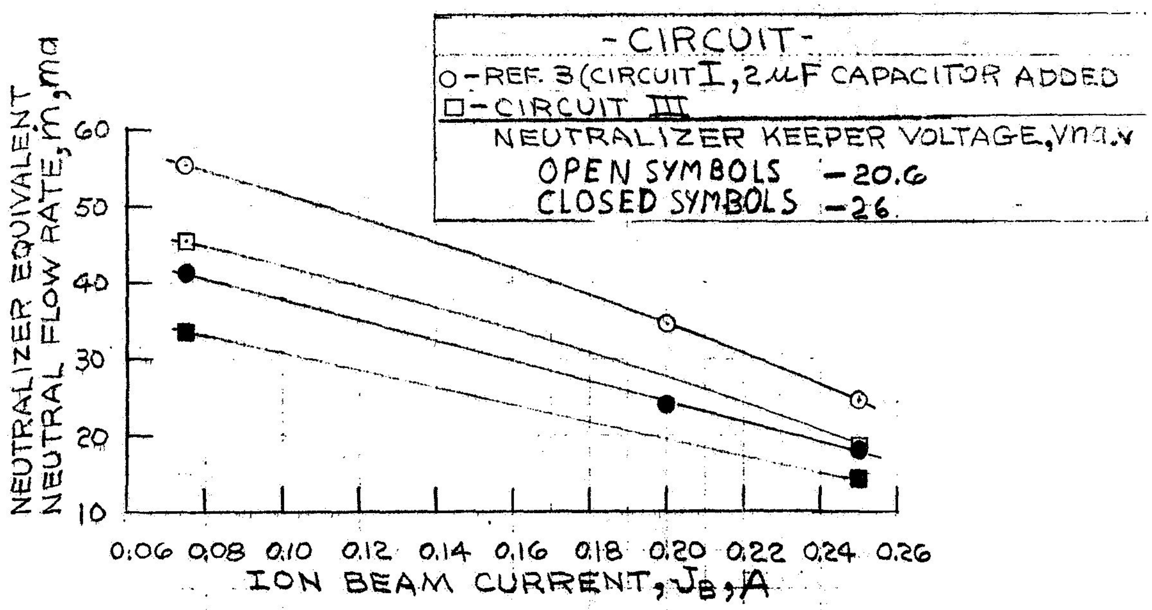
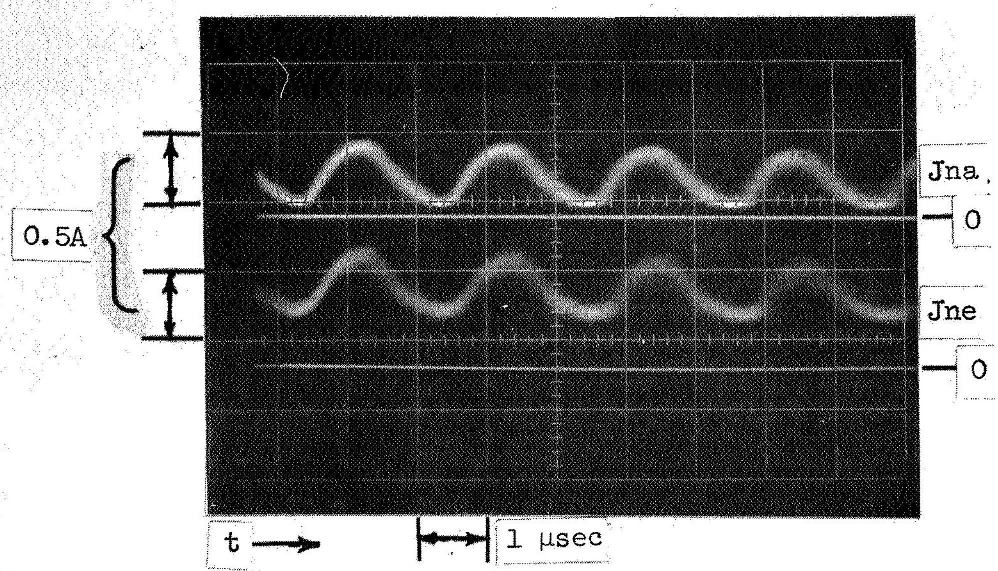
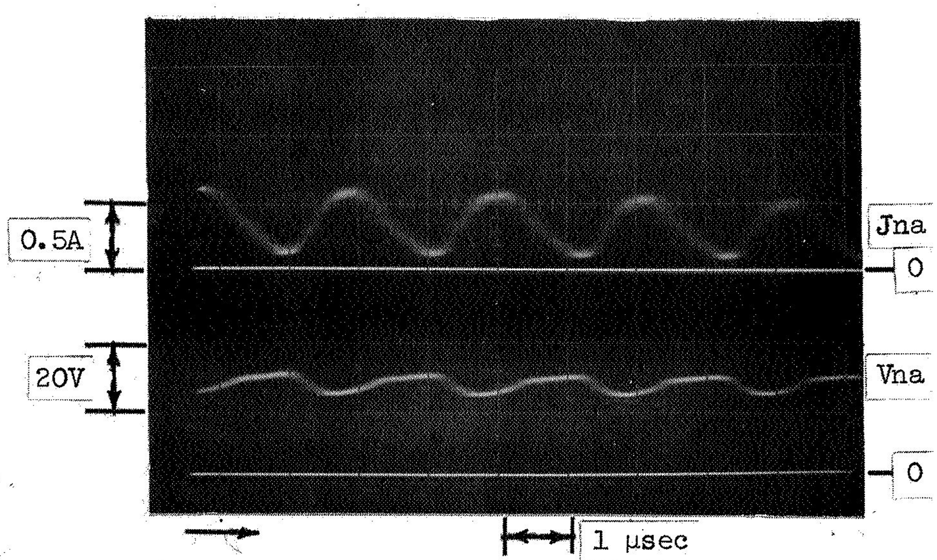


FIGURE 6 - EFFECT OF ION BEAM CURRENT ON NEUTRALIZER EQUIVALENT NEUTRAL FLOW RATE

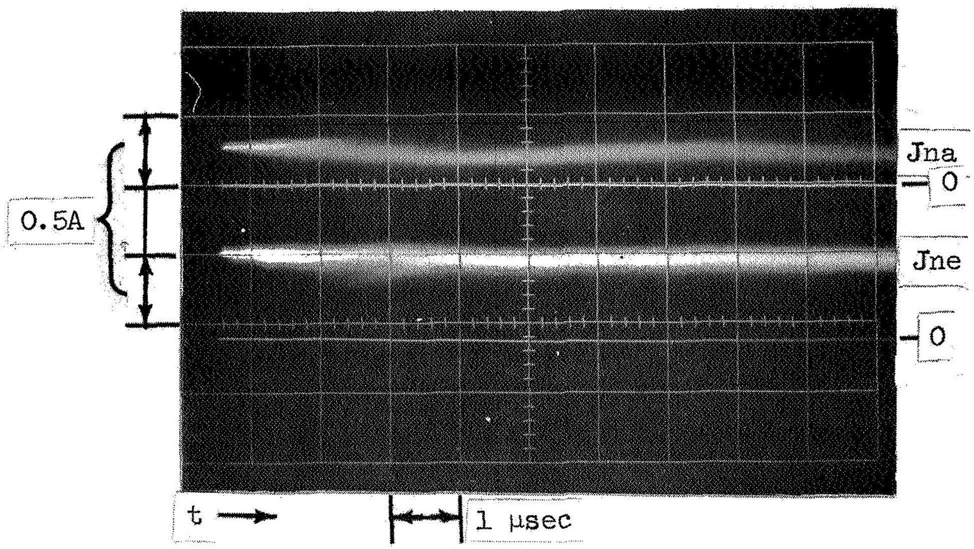


(a) Neutralizer keeper, Jna and total emission, Jne, currents.

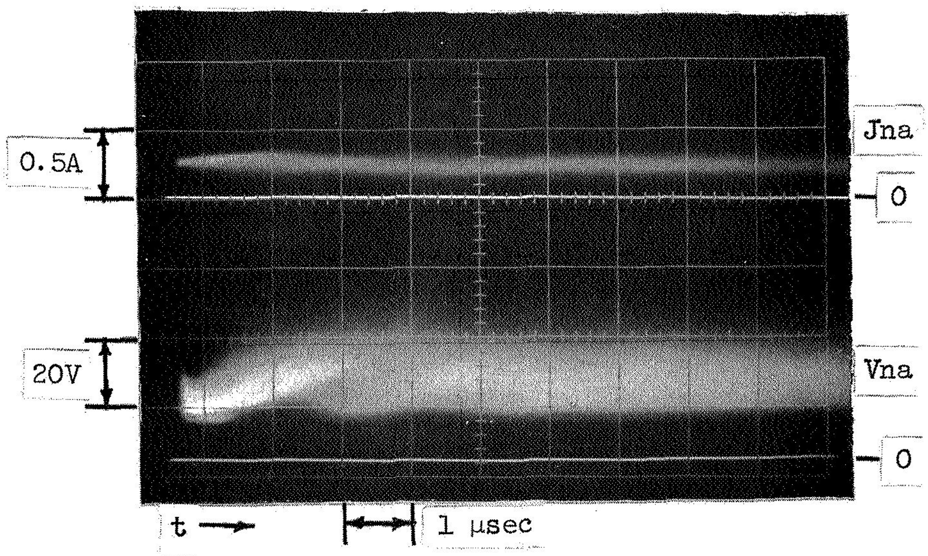


(b) Neutralizer keeper current and voltage.

Figure 7. - Oscilloscope traces of various neutralizer parameters. Basic circuit III.



(a) Neutralize keeper, Jna, and total emission, Jne, currents.



(b) Neutralizer keeper current and voltage.

Figure 8. - Oscilloscope traces of various neutralizer parameters. Basic circuit III, 0.162 m H inductor added.