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PARAMETRIC INVESTIGATION OF MERCURY HOLLOW CATHODE NEUTRALIZERS

by D. C. Byers and Aaron Snyder
Lewis Research Center
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TECHNICAL PAPER proposed for presentation at
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

A parametric investigation of mercury hollow cathode neutralizers for Kaufman ion thrusters was carried out in a bell jar over a range of collector (ion beam simulator) currents up to 2 A. The parameters investigated included mercury neutral flow rate, neutralizer cathode geometry, collector geometry and spacing, keeper power supply impedance, keeper current, keeper electrode geometry and spacing. Agreement was found between neutralizer operation in the bell jar and on an active thruster. The influence of the various parameters on neutralizer performance and control characteristics is discussed for three distinct modes of neutralizer operation.

Introduction

Hollow cathode neutralizers[1] appear to be suitable for use with thrusters which operate over a large range of ion beam currents.[2,3,4] Such neutralizers have been studied for a variety of specific thruster operating conditions.[5,6,7,8] Neutralizer optimization programs have been carried out or are in progress with 5, 15, and 30-centimeter-diameter thrusters.[2,3,4] It was found in these programs that the optimum neutralizer design was specific to the emission currents (equal to ion beam currents) and neutral flow rates at which the neutralizer was required to operate. Studies have been made of the effect of various neutralizer parameters[6,9] but in general most investigations have been concerned with a limited range of neutralizer operating conditions and/or a specific neutralizer configuration.

Important in evaluation of any hollow cathode neutralizer are the performance, control characteristics, and lifetime at the levels of emission current over which the neutralizer is required to operate.

The performance is defined in terms of the required neutral flow rates, operating voltages, and power levels. The neutral flow rate is charged directly against the overall thruster system propellant utilization efficiency and thus affects the thruster specific impulse. The operating voltages are directly related to neutralizer lifetime, thrust, and overall thruster system power efficiency.

Apart from performance considerations, the neutralizer system must be amenable to some type of control logic. Some parameters, such as coupling voltage, must generally be held or controlled within certain limits to avoid degradation of performance or lifetime.[5] To achieve control it is usual to sense the controlled parameter (or a parameter with a known relationship to it) and vary another parameter.

On the SERT II thruster, for example, the keeper voltage (which is proportional to coupling voltage) is sensed and controlled via a feedback loop with the neutralizer vaporizer.[2] The relationship between the controlled and control parameters must be known and of such a form as to allow a stable control loop logic.

This paper presents the results of a bell jar investigation of various hollow cathode neutralizers over a wide range of operating parameters. A comparison also was made between bell jar and thruster neutralizer operation. The collector current (corresponding to ion beam current) was varied from 0.030 to 2.0 A. Over this range of collector currents the effects of the following neutralizer parameters were studied: mercury neutral flow rate, neutralizer cathode geometry, collector (ion beam simulator) geometry and spacing, neutralizer keeper power supply impedance, neutralizer keeper current, geometry and spacing, and neutral flow rate introduction mode. The influence on both performance and control of these parameters is reported herein.

Apparatus and Procedure

Fig. 1 shows a sketch of the experimental setup used in the bell jar investigation. This arrangement is in many ways similar to that of reference 10. The neutralizer hollow cathodes were mounted at ground potential. The positively biased keeper electrode was mounted downstream of the cathode tip. A positively biased collector was positioned downstream of the keeper. The purpose of the collector was to simulate the ion beam of an operating thruster. An adjustable shaft could be connected to either the keeper or collector to allow movement of the keeper or the collector during testing.

The reservoir for the mercury was a precision bore glass tube which allowed measurement of the mercury flow rate. All flow rates quoted in this report were obtained via such measurements. The flow rate measurements were repeatable to an accuracy of 3 percent or better. The flow rate is expressed in terms of equivalent milliamperes of neutral flow and is so referred to throughout this report.

All tests were conducted in a 0.46 m diameter by 1.5 m high bell jar. Cryogenic pumping (LN_2) along with an oil diffusion pump enabled neutralizer testing to be conducted in the 3×10^{-6} to 7×10^{-6} torr pressure range.

Hollow Cathodes

Five hollow cathode neutralizers including one identical in design to the neutralizer used on the SERT II flight thruster were operated in the bell jar. Fig. 1 shows a cross section sketch of the SERT II type hollow cathode neutralizer. Reference 6 gives details of the fabrication of this cathode. Briefly, the neutralizer consists of a 2 percent thoriated tungsten disk welded to one end of a 3.2 mm outside diameter tantalum tube. A 0.25 mm diameter orifice is sandblasted into the thoriated tungsten tip. The upstream end of the tantalum tube is connected to the mercury vapor feed system. A rolled insert of barium carbonate coated tantalum foil is placed inside the tantalum tube directly behind the tip to assist in starting the discharge.

Four other neutralizer cathodes were tested. All were similar in construction to that shown in Fig. 1. Table I lists details of these cathodes which are denoted as A, B, C, and D in order of increasing tip orifice size. All were 6.3 mm outside diameter. The cathode tips were all about 1.5 mm thick, 2 percent thoriated tungsten disks. The orifice sizes of some of the cathode tips tapered slightly from a minimum at the upstream face to a maximum diameter at the downstream face. The minimum orifice sizes (listed in table I) ranged from the SERT II size of 0.25 mm diameter up to 0.69 mm diameter. A carbonate mixture, applied inside the tantalum tube near the tip, was used in place of the carbonate coated tantalum insert of the SERT II neutralizer to aid in starting cathodes A, B, C, and D. In addition, a slip-on heater was used for these four cathodes. The slip-on heaters required more power to operate than the SERT II tip heater.

Keeper Electrodes

A standard SERT II type keeper electrode was used with the five cathodes tested. This electrode was constructed of a 1.5 mm thick tantalum plate with a 4.5 mm diameter hole. The cathode to keeper spacing was set at 1.5 mm. Unless otherwise noted, this keeper was used for all tests.

Two additional keeper electrode designs were used to study the effects of keeper geometry. One electrode was similar to the SERT II keeper but had a smaller hole of 2.4 mm diameter. The other keeper was the enclosed type keeper which has been operated successfully at very low neutral flows.[3] The enclosed keeper design consisted of a procelain cylinder constructed to slip over the end of the 3.2 mm diameter cathode and project 1.5 mm beyond the tungsten tip. A tantalum cap, 2.5 mm thick, with a hole of 1.5 mm diameter was placed on the end of the porcelain insulator.

Collectors

The purpose of the collector was to simulate the beam potential of a thruster. Three types of collectors were used. One collector was a hybrid plate and screen. The hybrid collector was formed of dense mesh (5 percent open) tantalum screen 1.9-cm diameter set into a 2.54-cm by 3.18-cm rectangular tantalum plate. Unless otherwise noted, this collector was used throughout the tests. The other two collectors were made of stainless steel. One of these was formed of a 68 percent open area screen mounted on a 7.6 cm diameter support ring. The other collector was a solid 7.6-cm diameter plate.

Power Supplies

The keeper power supply was designed so that the output voltage dropped with increasing keeper current from the 300-volt starting level to the 0-50 volt operating region. The keeper power supply was equipped with a current limit control which allowed fine adjustments to be made in keeper current. The keeper power supply was operated with a capacitive, inductive, and resistive output circuit. As in Ref. 9, a capacitive circuit refers to one in which a capacitor was added in parallel across the supply output. An inductive circuit refers to one in which an inductor was added in series to the positive side of the power supply. A resistive circuit refers to one to which no impedance was added to the keeper power supply output.

The collector (beam simulator) power supply was a voltage unregulated direct current supply and was also equipped with a current limit control.

Results and Discussion

Before discussing the results, a brief review of neutralizer performance in an operating thruster will be presented. During thruster operation, the neutralizer cathode (and thruster) assumes an equilibrium potential negative with respect to the local ground. This is referred to as the floating potential in Refs. 2 and 11. Potentials in the exhaust ion beam rise to values above local ground. The beam potential varies axially and radially and has a maximum value on axis near the thuster[5]. The difference between the maximum beam potential and the neutralizer floating potential is called the coupling voltage[5]. Values of coupling voltage have been measured during some facility tests[6, 8], but are not generally available because measurement of the coupling voltage requires a probe in the beam plasma.

Due to the axial and radial variation of the beam potential, it would be difficult to simulate the potential distribution in bell jar tests. Instead, for simplicity, it was decided to use a single collector. The collector potentials used were in the range encountered in actual thruster operation.

SERT II Type Neutralizer Cathode

Three very distinct modes of operation existed with the SERT II type neutralizer cathode. Such modes were noted in Ref. 7 and were designated as plume, transition, and spot mode in Ref. 6. In general, the plume mode existed for collector currents less than about 0.5A. Above this level of collector current the neutralizer operated in either transition or spot mode. The effect of the various parameters on neutralizer performance was quite dependent on the mode of operation.

Variation of collector geometry and spacing. - A series of tests was carried out with a SERT II type neutralizer cathode and keeper and a number of collector geometries and keeper to collector spacing. These tests were made in order to relate bell jar and thruster operation.

Typical plots of the keeper and collector voltages (referenced to ground) as a function of neutral flow rate are shown in Fig. 2 for three collector geometries and two keeper to collector spacings. Also shown are values for the SERT II thruster system from Ref. 2. The values of keeper current and collector current (beam simulator current) were at the nominal SERT II values of 0.2 0.25 A, respectively, and the neutralizer operated in plume mode for all the data of Fig. 2.

The variation of keeper voltage with flow rate was quite similar to that of the SERT II thruster system. Fig. 2 shows that at a fixed neutral flow rate the keeper voltage was quite insensitive to both collector type and spacing. The keeper voltage was found to be sensitive to keeper-collector spacing only at spacings of less than about 0.6 cm. It may be that for these cases back reflection of neutrals from the collector was a factor.

It was noted for the SERT II thruster tests (ref. 2) that at a fixed neutral flow rate the keeper voltage increased as the ion beam current decreased. It was speculated in Ref. 2 that this could have been due to a contraction of the beam edge away from the neutralizer with a reduction in beam current. The data of Figs. 2(a) and 2(b) indicate, however, that increasing the beam coupling distance did not result in any variation of keeper voltage. This point is discussed further in the following section.

Figure 2 also shows that the collector voltage was very sensitive to both collector geometry and spacing. In general, the collector voltage increased with increasing collector open area and keeper-collector spacing. The strong effect on coupling voltage of neutralizer position relative to the ion beam has been observed in several investigations[6, 7, 8].

For purposes of simulated neutralizer operation, the collector voltage should probably be held at a value somewhere between two to four times the absolute value of thruster floating potential. This is based on the fact that with operating thrusters, the thruster coupling voltage is found to be from two to four times the absolute value of the thruster floating potential (ref. 5) referenced to ground. When compared to the SERT II floating voltage in Fig. 2, the collector voltages were in the right range for the hybrid and 68-percent open collectors at both keeper-collector spacings.

From Fig. 2 it is not completely clear which collector geometry-spacing configuration would best simulate the ion beam potential. Somewhat arbitrarily, the hybrid collector was selected for the balance of the data of this report and, unless otherwise stated, was located at a distance of 1.27 centimeters from the keeper. As will be seen later, many of the observed variations of neutralizer performance on a thruster were duplicated with this collector configuration. In addition, a hybrid collector, identical to the one of this paper, was the type used for the 10,800 hour neutralizer life test described in Ref. 5.

Effect of keeper power supply impedance. - Reference 9 noted that at SERT II operating conditions the variation in keeper voltage with neutral flow rate was strongly influenced by the impedance of the keeper power supply. The relationship between keeper power supply impedance and performance over an extended range of neutralizer operating parameters is presented in this section. All data of this section were taken with the neutralizer operating in the plume mode.

Figure 3 shows the variation of keeper and collector voltages with neutral flow rate for several keeper power supply impedances. Several thruster data points are included for comparison[2, 9]. Figure 3(a) shows that for all neutral flow rates tested the keeper voltage was higher for the inductive and resistive circuits than for the capacitive circuits. The shift was similar to that of Ref. 9. At neutral flow rates higher than about 35 mA the effect of impedance on keeper voltage was reduced. The collector voltage was sensitive to power supply impedance at neutral flow rates greater than about 25 mA. It is seen that variations in impedance changed both the level of collector voltage and the neutral flow rate at which the collector voltage was minimized.

The reason that keeper power supply impedance variations affected performance is believed related to the presence of oscillations in the voltages and currents of the keeper and collector discharges. These oscillations were investigated briefly in an attempt to relate the effect of impedance with the observed oscillation properties. For the conditions of Fig. 3(a) it was noted that, with a resistive circuit, as the neutral flow rate increased from 17 to 30 mA the oscillation frequency decreased from about 6 to 1×10^5 hertz. At about 35 mA neutral flow rate the frequency dropped sharply and the oscillation became very coherent. In general, the peak-to-peak amplitude of the oscillations decreased with inincreasing neutral flow rate.

The effect of impedance was also dependent on neutralizer keeper current. Figure 3(b) shows the variation of keeper and collector voltages with flow rate at conditions identical to Fig. 3(a) except that the current was reduced to 0.1 A. The effect of impedance on the keeper and collector voltages was noticeably reduced from the conditions of Fig. 3(a). This trend was found to hold over a range of keeper currents from about 0.05 to 0.4 A. Review of the oscillations indicated that the peak-to-peak amplitude of the oscillations decreased with decreasing keeper current. For example, at a keeper current of 0.2 A and a neutral flow of 15 mA the peak-to-peak amplitude of the oscillation of the keeper voltage was 55 V. At 0.1 A keeper current, other conditions being equal, no oscillation of keeper voltage could be detected.

The effect of impedance also was studied over a wide range of collector currents (0.05 to 0.5 A). Figure 4 shows the variation of the keeper and collector voltages with flow rate for a resistive (fig. 4(a)) and a capacitive (fig. 4(b)) circuit. With a resistive circuit the shapes of the curves of keeper and collector voltage versus neutral flow rate were dependent on the collector current. At low collector currents the voltages were rather insensitive to flow rate. It is also seen that at a given neutral flow rate the keeper voltage was not always a monotonic function of collector current. The collector voltage curves exhibited minima with the resistive keeper power supply. With the capacitive circuit, however, the keeper and collector voltages were monotonic functions of both neutral flow rate and collector current over the range tested. The use of the keeper power supply voltage to control neutral flow rate (as on the SERT II system) probably would be impossible with a resistive circuit at low levels of ion beam current. On the other hand, with a capacitive circuit such a control loop could be used over the range of collector currents tested (0.05 to 0.5 A).

A capacitive keeper circuit is superior to the resistive and inductive circuits on the basis of performance and/or control. The effect of impedance on lifetime, however, has not yet been demonstrated. In this investigation and in reference 9 it was found that the impedance type strongly affected the discharge oscillations. The use of inductive and capacitive keeper power supplies tended to hold the currents and voltages, respectively, constant. Both current and voltage may play a role in neutralizer lifetime[5]. At this writing, three SERT II neutralizer tests of the order of 4000 hours or greater have been conducted[11]. The keeper power supply for these tests was essentially capacitive. On the other hand, the 10,800 hour test reported in reference 5 was run with a supply which was not capacitive. Resolution of the influence of keeper impedance on lifetime requires further testing.

Fig. 4(b) can be used to compare neutralizer operation in a bell jar to that on a thruster. Data from the SERT II flight thruster is shown by solid symbols on Fig. 4(b). Fig. 4(b) shows that, at a given neutral flow rate, the keeper voltage increased monotonically with decreasing collector current. The sensitivity of keeper voltage to collector (or ion beam) current obtained in the bell jar study was about the same as that obtained on the SERT II flight thruster. The results of Fig. 4(b) then substantiate the conclusion, discussed previously, that the variation of keeper voltage with ion beam current on the SERT II thruster was not due to a shift in the effective coupling distance.

Fig. 4 also shows that the collector voltage increased monotonically with collector current. An increase of collector current from 0.075 to 0.25 A (fig. 4(b)) corresponded to an increase of collector voltage of about 22 V at a flow rate of 30 mA. A similar increase in ion beam current on the SERT II thruster[2] caused an increase in thruster floating voltage of only about 7 V. No beam potential measurements were made during the tests reported in reference 2. The variation of coupling voltage with beam current was then not known. If the coupling voltage remained at about two to four times the thruster floating potential the results of the bell jar tests are in reasonable agreement with the data of Ref. 2. On the other hand, comparison of Figs. 2 and 4 indicates that an increase of both collector current and collector spacing increases the collector voltage. It is possible that variation of the ion beam current of a thruster changes the effective coupling distance. Therefore the decrease of floating potential with decreasing beam current could be a result of the competing effects of increasing coupling distance and decreasing beam current.

Effect of keeper current. - The keeper and collector voltages are presented in Fig. 5 as a function of flow rate for a number of keeper currents with a capacitive (0.33 uf) keeper power supply circuit. For reference, data from the SERT II flight thruster is included on Fig. 5(a).

Fig. 5(a) shows that at a given neutral flow rate, the keeper voltage increased with increasing keeper current. To maintain a fixed keeper voltage, the required neutral flow rate increases with keeper current. It is seen from Fig. 5(a) that the data of SERT II is in the same range as that of this program.

It is also important to note that the shape of the curve of keeper voltage versus flow rate changed with keeper current. In application, if the keeper current is expected to vary with mission time (as is the case with the SERT II flight), attention must be paid to the variation in performance and control loop characteristics that might be experienced.

Fig. 5(b) shows that the collector voltage was not a monotonic function of keeper current. Over the range tested the maximum collector voltage was obtained at a keeper current of from 0.20 to 0.25 A.

Effect of keeper spacing and geometry. - The effects of keeper spacing and geometry were tested over a range of neutral flow rates and collector currents. The three keeper geometries tested were described in the Apparatus section. All data in this section were taken with a capacitive (1.08 uf) keeper power supply and a keeper current of 0.2 A.

Fig. 6 presents the variation of keeper and collector voltages with keeper spacing with the SERT II type keeper. The neutral flow rate was varied between 14 and 89 mA. The collector current was 0.25 A for these data. At low neutral flow rates a shallow minimum existed in both the keeper and collector voltages. As the flow rate increased, the voltages became somewhat less sensitive to spacing but generally increased at the larger spacings. The neutralizer was in the transition mode at the neutral flow rate of 89 mA. In this mode the keeper voltage was very insensitive to spacing. The collector voltage was also insensitive to distance except at the largest spacings.

The variation of the voltages with keeper spacing was also tested over a range of collector currents from 0.030 to 0.40 A with the SERT II type keeper. The general trends were similar to those shown on Fig. 6. As the collector current increased, however, the value of keeper spacing at the minimum keeper voltage decreased. For example, at collector currents of 0.03 and 0.25 A, the minimum keeper voltage (at a neutral flow of 18 mA) occurred at keeper spacings of 2.5 and 1.2 mm, respectively. In addition, at a constant neutral flow rate, the voltages became more sensitive to spacings as the collector current increased. At a neutral flow rate of 24 mA, an increase in keeper spacing from 0.51 to 2.53 mm caused an increase in collector voltage of 1.1 and 12.3 V for beam currents of 0.030 and 0.40 A, respectively.

The effect of keeper spacing was also tested with the 2.4 mm inside diameter hole keeper. The hole diameter is one-half that of the SERT II type keeper. Fig. 7 shows the variation of the voltages with keeper spacing at a neutral flow rate of 24 mA for three values of collector current. With this particular keeper geometry, exact measurement of the keeper spacing during operation was not possible. The values of spacing shown are, however, accurate to within about 0.15 mm. In comparison with the SERT II type keeper, which was set at a spacing of 1.5 mm, the minimum measured voltages occurred at smaller spacings. It is also seen that at 0.25 A collector current, the collector voltage was more sensitive to keeper spacing than for the SERT II type keeper (fig. 6).

Comparison of Figs. 6 and 7 and other data indicated that at a given neutral flow rate and collector current the reduction in keeper hole size caused an increase in collector voltage and a decrease in keeper voltage. For example, at a flow rate of 18 mA and a collector current of 0.25 A the values of the keeper and collector voltages were 27.4 and 34.8 V for the SERT II keeper and 17.5 and 38 V for the smaller hole size keeper.

The final keeper design tested was an enclosed keeper that was similar to one tested on a 5-centimeter thruster[3]. The diameter of the keeper hole for this test, however, was double that of the enclosed keeper of Ref. 3 (0.76 mm). Some results obtained with the enclosed keeper are presented in table II along with data points taken with the previously described keeper types.

A comparison of single operating points of Ref. 3 and this experiment is presented on lines 1 and 2 of table II. The keeper voltage and thruster floating potential were found to be very sensitive to neutralizer cathode heater power in Ref. 3. The neutralizer heater power was about 9 w for the two cases compared (lines 1 and 2, table II). It is seen that the keeper and collector voltages for the enclosed keeper of Ref. 3 were lower and higher, respectively, than for the enclosed keeper (larger keeper hole) of this experiment.

As pointed out in Ref. 3, the most noteworthy feature of the enclosed keeper is that very low neutral flow rates may be obtained. On the other hand, in the simulation tests the coupling voltage was found to be very sensitive to collector current. When the collector current was increased to 0.06 A (line 3, table II) at constant neutral flow rate, the collector voltage increased by more than a factor of four. This effect was anticipated because of the reduced keeper hole size.

Shown in table II (lines 4, 5, and 6) are data for the three types of keepers used herein. These data were taken at constant neutral flow rate (24 mA), collector current (0.25 A), and keeper current (0.20 A). From table II and other data some general conclusions were drawn. At a fixed keeper-cathode spacing, the effect of reduction of the open area (keeper hole size) between the cathode and the collector generally reduced the keeper voltage and increased the collector voltage. Reduction of the open area also allowed operation at lower neutral flow rates but caused an increase in the sensitivity of the collector voltage to collector current which could limit the range of collector current at which the neutralizer could be operated.

Selection of an optimum keeper design will then depend on the constraints placed on coupling voltage and neutral flow rate. In general, however, the data indicate that as a thruster ion beam current level increases, the keeper design should become more open for overall optimum design. The sensitivity of the neutralizer performance to keeper spacing does indicate, in addition, the prudence of selection of a keeper design which guarantees fixed spacing. The enclosed keeper concept, with hole size selected for the particular application would appear to answer this criterion.

Variation of collector current. - Thrusters are currently being investigated that operate at ion beam currents of about 1.5 A (refs. 12 and 13). For this reason the range of collector currents were varied up to that value. Fig. 8 shows the variation of keeper and collector voltages as a function of collector current at a neutral flow rate of 32 mA. A SERT II type keeper was used for all the data of this section.

Fig. 8 shows that the neutralizer operated in two modes for the range of parameters shown. At collector currents, generally less than about 0.5 A the neutralizer operated in the plume mode. At higher collector currents the neutralizer would switch to the transition mode. The level of collector current at which the transition occurred decreased with increasing keeper current. The plume and transition modes were separated by a large range of collector current. Even with the current limited power supplies used, the neutralizer would not operate in the region of collector currents between the plume and transition modes. In Fig. 8 the regions of collector current over which the neutralizer would not operate are shown by dashed lines.

The performance shown in Fig. 8 was typical over the range of neutral flow rates from about 30 to 90 mA. The former flow was the lowest at which 1.5-A collector current could be obtained at the 65-V limit of the collector power supply.

Operation in transition and spot modes. - It was seen in Fig. 8 that above about 0.5 A collector current the neutralizer ran in the transition mode (fig. 8). At neutral flow rates higher than that of Fig. 8 the neutralizer also ran in spot mode. If a SERT II type neutralizer were to be operated on a thruster system at currents in excess of 0.5 A, the neutralizer would probably operate in either transition or spot mode. Fig. 9 presents the voltages as a function of neutral flow rate at a collector current of 1.5 A. The data were taken at a constant keeper current (0.2 A) and compared for three collector spacings. For comparison some data points from a 30-centimeter thruster are presented from a companion paper.[12] The neutralizer cathode and keeper used in Ref. 12 were essentially identical to the SERT II type.

The neutralizer was in the transition mode, for most of the data of Fig. 9. In this mode the collector voltage varied smoothly with flow rate and spacing while the keeper voltage was insensitive to these variables. For the 9.5 mm spacing, however, at high flow the neutralizer switched to spot mode. In this mode neither the collector nor keeper voltage was significantly affected by neutral flow rate.

The data of this program agreed with the data of Ref. 12 (30-cm thruster) only in the spot mode. While not certain, it is estimated from the results in Fig. 9 that the effective coupling distance on thruster of Ref. 12 is of the order of 1 centimeter or less. It was noted in that program that the ion beam divergence was such as to impinge directly on the neutralizer at an ion current of 1.5 A.

The data of Fig. 9 suggest that the neutralizer control loop used on the SERT II thruster could not be used at the high ion beam currents of the 30-centimeter-thruster system since the keeper voltage is quite insensitive to neutral flow rate. The thruster floating potential (or in space, a spacecraft potential with respect to local ground) could possibly be used for closed loop vaporizer control if the neutralizer is operated in the transition mode. When the neutralizer operates in spot mode, it is unlikely that either keeper voltage or thruster floating potential could be used in a closed loop vaporizer neutralizer control logic.

Variable Neutralizer Cathode Geometry

Four neutralizer cathodes, other than the SERT II geometry, were tested. Geometric details of these cathodes were presented in table I. It was of interest to test other cathodes with increased orifice diameters, for two reasons: (1) The SERT II neutralizer cathode was not stable over the full range of collector currents of interest (Fig. 8) and (2) The results of Refs. 12 and 13 indicate improved lifetime by use of increased cathode orifice diameter. A SERT II type keeper at a distance of approximately 1.5 mm from the cathode face was used for all the data of this section. As these cathodes had no insert, a triple carbonate mixture was applied to each cathode to insure repeatable starting. After one application the neutralizers started in a repeatable fashion over the duration of testing (of order one week).

Fig. 10 presents the variation of keeper and collector voltages as a function of collector current for the four larger diameter cathodes. The keeper current was 0.2 A for the data of Fig. 10, and the neutral flow rate was 43 mA.

Fig. 10 shows that cathode B, C, and D were stable over the range of collector currents up to 1.5 A. Cathode A, with orifice dimensions nearly identical to the SERT II cathode, exhibited an instability similar to that of the SERT II cathode (Fig. 8). Fig. 10 also shows that the collector voltage, at a given collector current was not a monotonic function of orifice diameter.

Data of the type shown in Fig. 10 were taken over a range of keeper currents and neutral flow rates from 0.1 to 0.7 A and 35 to 94 mA, respectively. Over this range of keeper currents, the results were similar to those of Fig. 10. Cathodes B, C, and D provided stable operation for collector currents up to 1.5 A while cathode A was generally unstable at collector currents greater than about 0.5 A.

The effect of keeper current on keeper voltage was about the same at large collector currents (> 0.5 A) as at low collector currents. In general, the keeper voltage rose monotonically with keeper current. The collector voltage, however, generally exhibited a minimum at a keeper current of about 0.4 A in some contrast to the data of Fig. 5.

Over the range of neutral flows tested the neutralizer also operated in a fashion similar to that shown in Fig. 10. The lowest flow rate tested (35 mA) was the minimum at which 1.5 A collector current could be obtained due to the voltage limit (~ 65 v) of the collector power supply.

The effect of keeper power supply impedance was tested with cathodes B, C, and D at levels of collector current greater than 0.5 A. The keeper supply impedance had little effect on neutralizer performance when the neutralizer was operated in the transition mode. This is probably due to the fact that, as pointed out in Ref. 6, keeper discharge oscillations are strongly reduced in the transition mode compared to the plume mode. When the neutralizer was in the plume mode, the effect of keeper supply impedance with the large orifice cathodes was similar to that with the SERT II cathode. For example, at a collector current and neutral flow rate of 0.25 A and 43 mA, respectively, the keeper voltage dropped about 2 volts when the keeper circuit was changed from resistive to capacitive (1.08 uf).

Fig. 11 shows the variation of keeper and collector voltages as a function of neutral flow rate at a collector current of 1.5 A. For reference, data with the SERT II type cathode is included. Cathode A is not shown because it would not operate at 1.5 A collector current. Fig 11 shows that at a fixed neutral flow rate, the collector voltage was similar for all cathode types tested.

The shapes of the curves of collector voltage versus flow rate on Fig. 11 indicate that the thruster floating potential, or some beam potentials possibly could be used in a closed loop control of the neutralizer at high levels of ion beam current. However, as indicated in Fig. 9, for the SERT II type neutralizer, care would have to be taken to insure that the effective coupling distance on the thruster was such as to avoid spot mode operation.

External Flow Addition

In several tests mercury vapor was introduced downstream of the keeper. This was done to see if the keeper voltage could be made sensitive to neutral flow rate at values of collector current in excess of 0.5 A. If the keeper voltage were sensitive to neutral flow, a control loop such as that used on SERT II possibly could be used at high ion beam currents.

The experimental setup is shown in the sketch on

Fig. 12. Cathode C (table I) was used with a SERT II type keeper. Neutral flow was introduced both through the main cathode and perpendicular to the cathode axis downstream of the keeper by use of an auxiliary vaporizer. The auxiliary vaporizer and main cathode were both at ground potential. To avoid thermal feedback difficulties, a 0.63 centimeter long tantalum sleeve was slipped over the auxiliary vaporizer. For some tests a reflector, shown in the sketch on Fig. 12, was used. Typically, a normal operating point was obtained with flow through the main cathode only. The auxiliary vaporizer was then turned on to determine the effect of the added neutral flow.

At some value of auxiliary flow, dependent on the collector and keeper currents of the normal discharge, a bright discharge would seat on the exit of the tantalum tube. The auxiliary neutral flow rate had negligible effect on the normal discharge until the discharge at the tantalum tube appeared. At this point the main neutralizer cathode flow could be reduced.

Fig. 12 shows the variation of the keeper and collector voltages as a function of the total (main cathode plus auxiliary) neutral flow rate. Solid data were obtained with main cathode flow only. The data of Fig. 12 with the two vaporizers were taken with the bright discharge seated on the tantalum tube.

Of most interest on Fig. 12 are the data at a total neutral flow of about 74 mA. Although the total flow was constant the flow through the main cathode differed by about a factor of two for the single and two vaporizer systems. It is seen that little difference in keeper voltage existed for the single and double vaporizer systems indicating that the auxiliary flow was ineffectual. At a cathode neutral flow rate slightly less than 38 mA, the keeper discharge became unstable for the double vaporizer system. It should also be added that the discharge on the tantalum tube was rather unstable and strongly interacted with the collector current. No significant variation in performance was noted when the reflector was used. The data indicate that variation of neutral flow introduction may not provide an improved neutralizer control loop characteristic.

Summary of Results

Tests were first carried out to compare neutralizer operation in a bell jar to that on a thruster. A collector (ion beam simulator) geometry and spacing were selected which provided agreement between neutralizer performance in the bell jar and on the SERT II thruster system. A parametric investigation of the effects of several neutralizer operating parameters on performance was then carried out with several neutralizer cathodes. The tests were made over a range of ion beam simulator currents up to two amperes.

The neutralizer was found to operate in three distinct modes of operation, previously identified as the plume, transition, and spot modes. In general, the neutralizer operated in the plume mode at collector currents less than about 0.5 A and in the transition or spot mode at larger collector currents.

A capacitive keeper power supply impedance was found to be desirable for neutralizers operating in the plume mode. At collector currents greater than about 0.5 A (transition and spot modes) the keeper supply impedance had little effect on neutralizer performance.

The effects of keeper geometry and spacing were studied and it was found that low neutral flows could be obtained with enclosed keepers, in agreement with previous results. On the other hand, minimum collector voltages were obtained with open keeper designs. Selection of an optimum keeper shape depends on the range of ion beam currents at which a thruster is to be operated.

The keeper current was varied and found to affect the required neutral flow rate and the slope of the curve of the keeper voltage as a function of neutral flow rate. In addition, the level of keeper current also influenced the relationship between keeper supply impedance and neutralizer performance.

Neutralizer performance was investigated with five different neutralizer cathodes. One was of the SERT II type. The other four had double tube diameter and orifice diameters ranging from equal to 2.5 times that of the SERT II neutralizer. The SERT II neutralizer was found to be unstable in a range of collector (ion beam) currents of interest for 30-cm-diameter thrusters. Use of cathodes of larger orifice diameter allowed stable operation at 2 A collector current. Efforts to improve the control characteristic of the neutralizer at high levels of collector current by use of a two-vaporizer system were ineffectual.

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Cathode	Cathode outside diameter, mm	Upstream orifice diameter, mm	Downstream orifice diameter, mm
SERT II	3.2	0.25	0.25
A	6.3	.25	.25
B	6.3	.41	.41
C	6.3	.53	.56
D	6.3	.69	.76

TABLE 1 GEOMETRY OF THE VARIOUS CATHODES TESTED

Number	Keeper type	Keeper hole diameter, mm	Keeper voltage, V	Keeper current, A	Collector voltage, V	Collector current, A	Mercury flow rate, mA
1	Enc.(3)	0.76	15.5	0.250	22.0[a]	0.030	2.3
2	Enc.	1.52	20.7	.250	16.8	.030	2
3	Enc.	1.52	18.9	.250	77.8	.060	2
4	Enc.	1.52	11.0	.200	42.5	.250	24
5	Open	2.38	19.0	.200	47.2	.250	24
6	Open(2)	4.77	21.5	.200	25.5[a]	.250	24

TABLE 2 VARIATION OF NEUTRALIZER PARAMETERS WITH KEEPER GEOMETRY. Cathode to keeper spacing, 1.5 mm

(a) Thruster floating potential

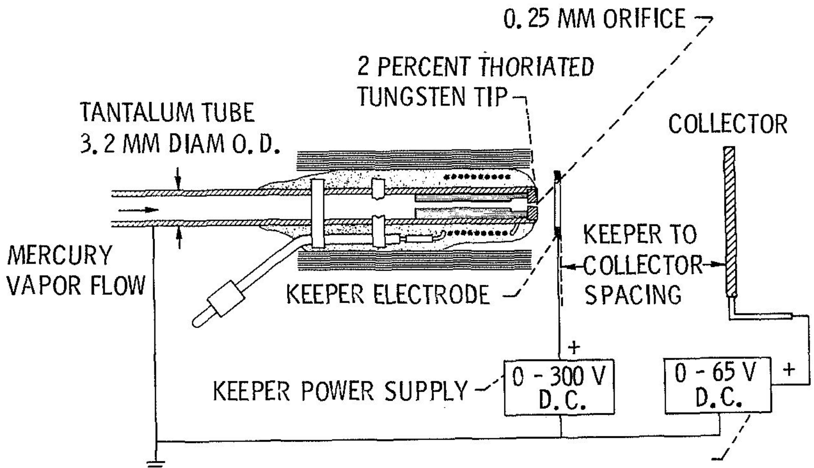


Figure 1. - Experimental setup with SERT II hollow cathode neutralizer.

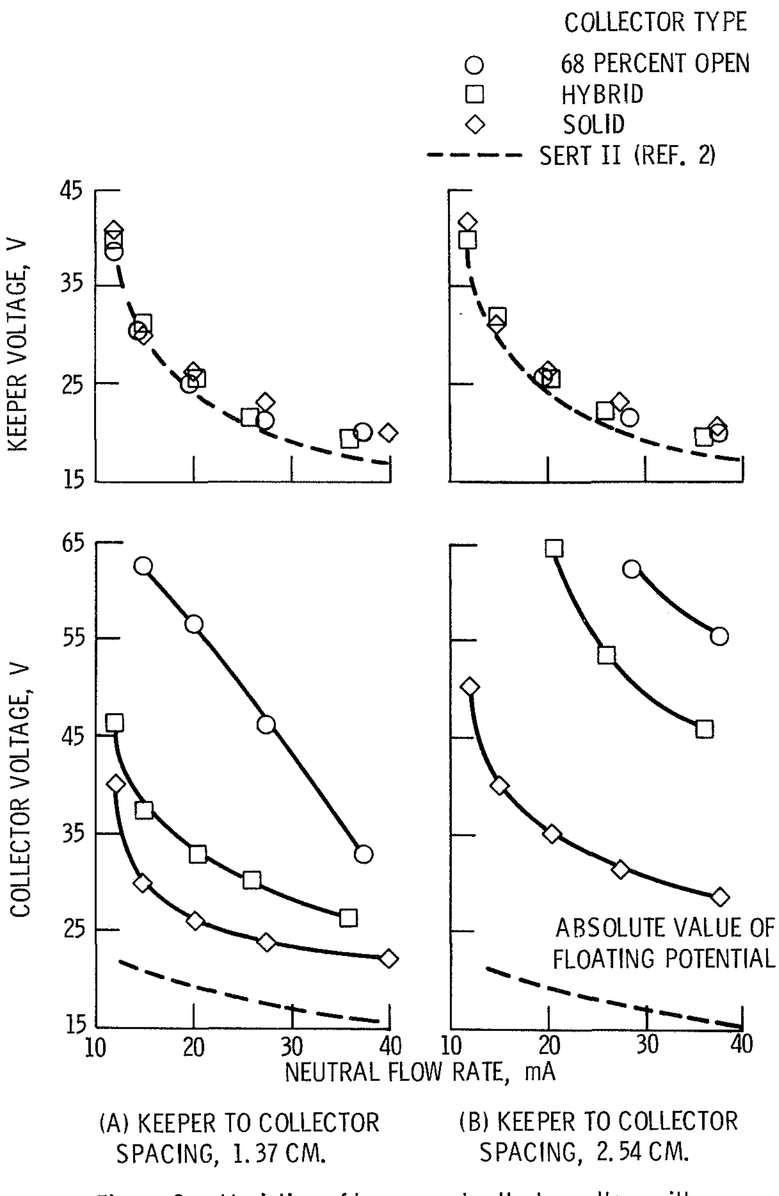


Figure 2. - Variation of keeper and collector voltage with neutral flow rate for various collector geometries at two keeper to collector spacings. Keeper current, 0.20 A; collector current, 0.250 A.

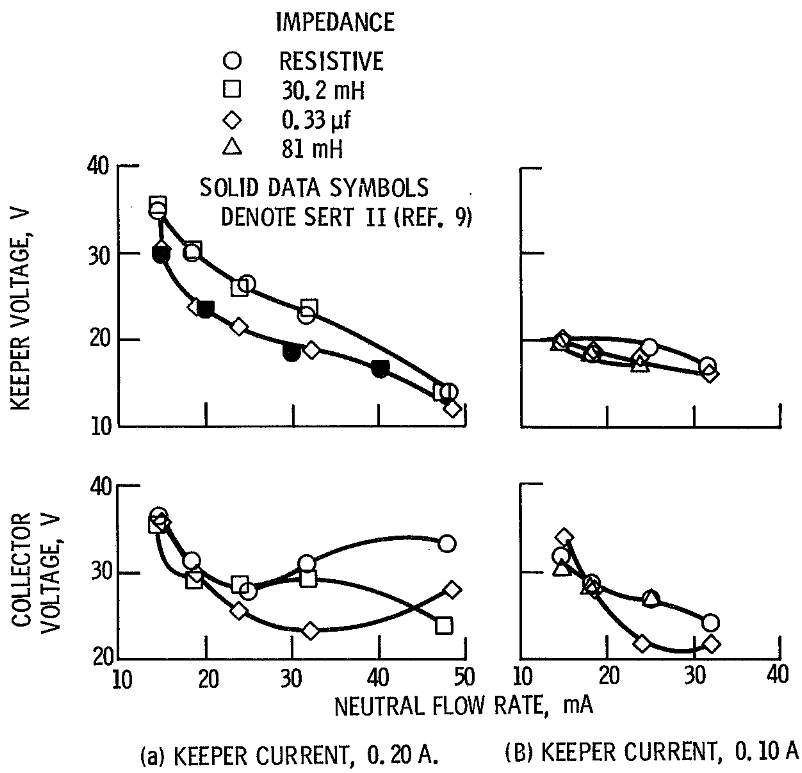


Figure 3. - Variation of keeper and collector voltages with neutral flow rate for various keeper supply impedances and keeper currents. Collector current, 0.250 A.

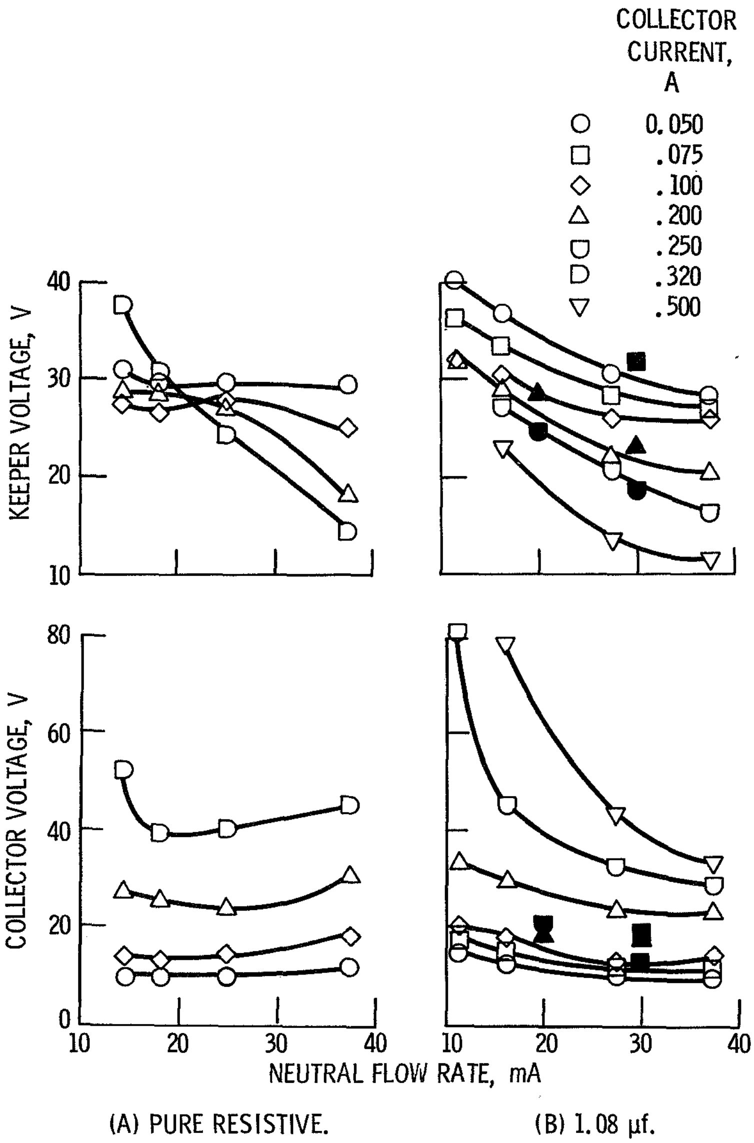


Figure 4. - Variation of keeper and collector voltages with neutral flow rate for various collector currents and keeper power supply impedences. Keeper current, 0.20 A.

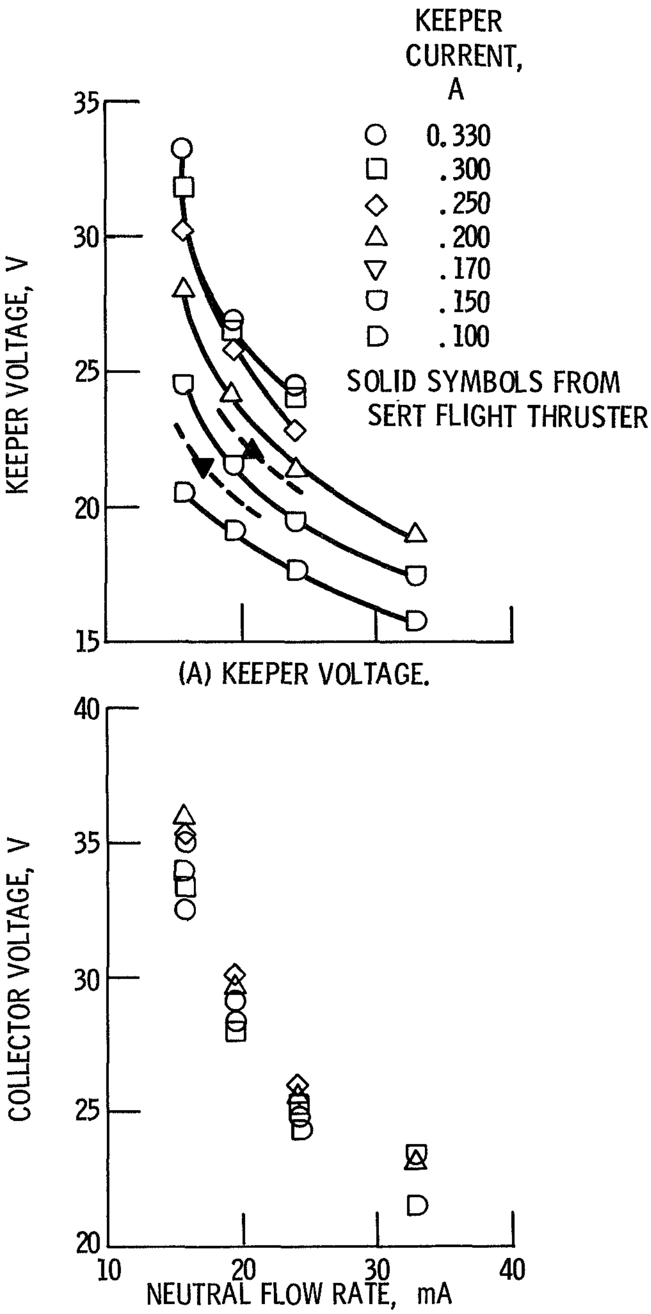
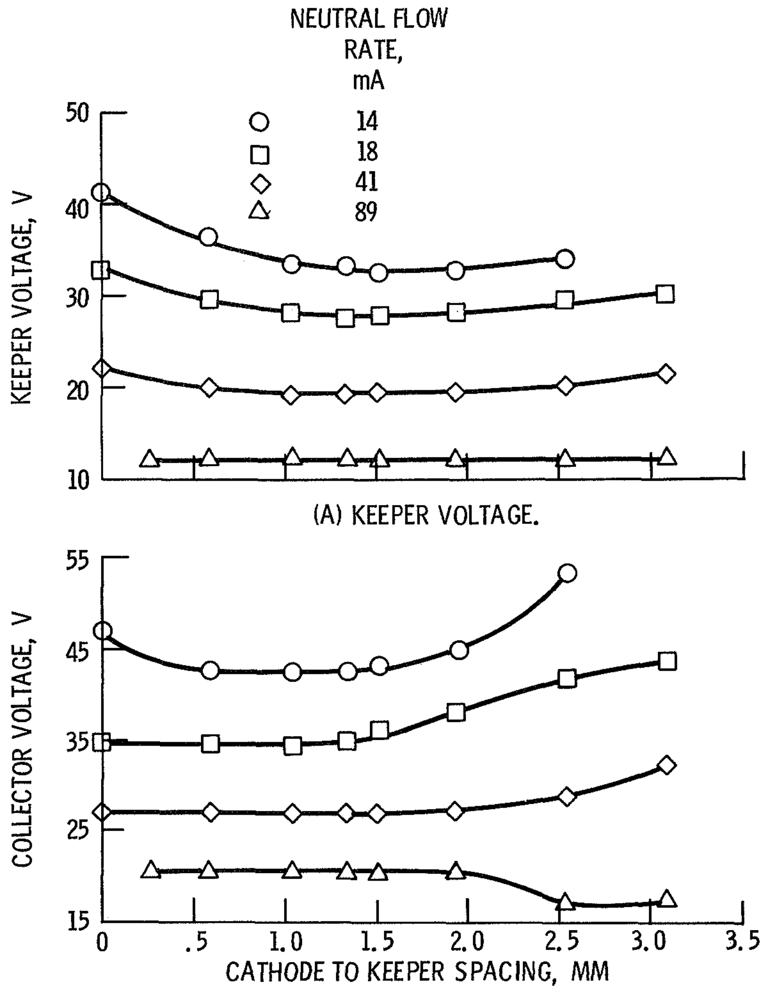


Figure 5. - Variation of keeper and collector voltages with neutral flow rate for various keeper currents. Collector current, 0.250 A; capacitive keeper power supply circuit, (0.33 μf).



(B) COLLECTOR VOLTAGE.

Figure 6. - Variation of keeper and collector voltages with cathode to keeper spacing at various neutral flow rates. Keeper current, 0.20 A; collector current, 0.250 A; capacitive keeper supply circuit, 1.08 µf.

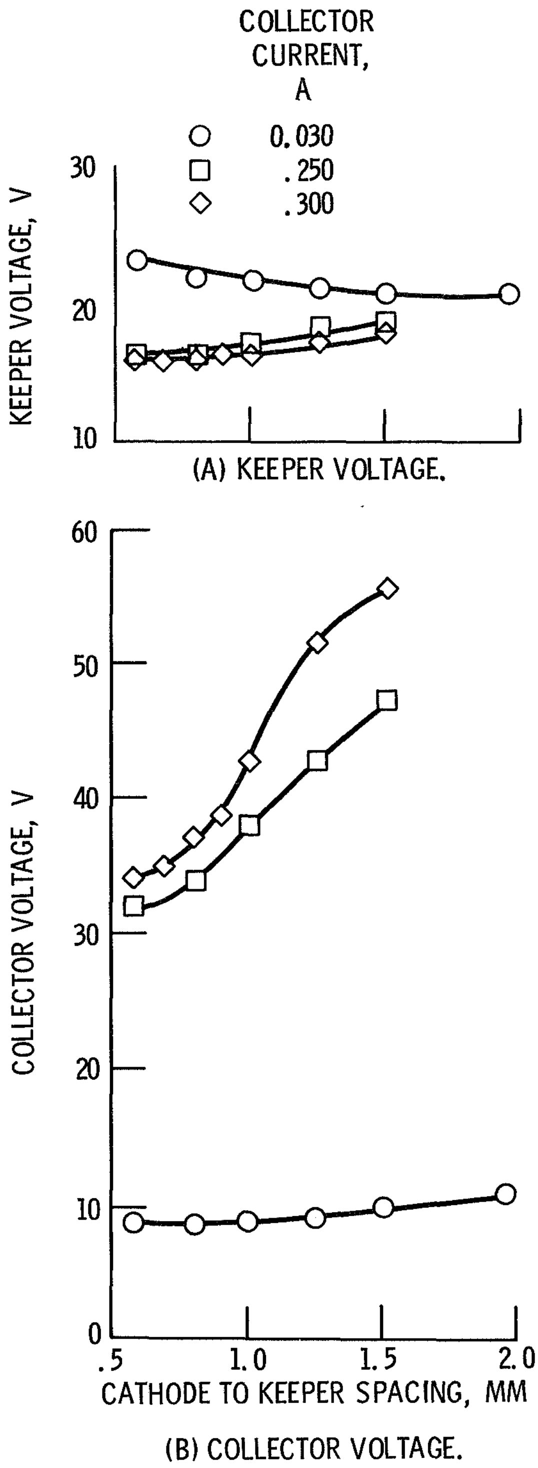


Figure 7. - Variation of keeper and collector voltages with cathode to keeper spacing for three collector currents. Keeper current, 0.20 A; neutral flow rate, 24 mA; keeper hole diameter, 2.5 MM.

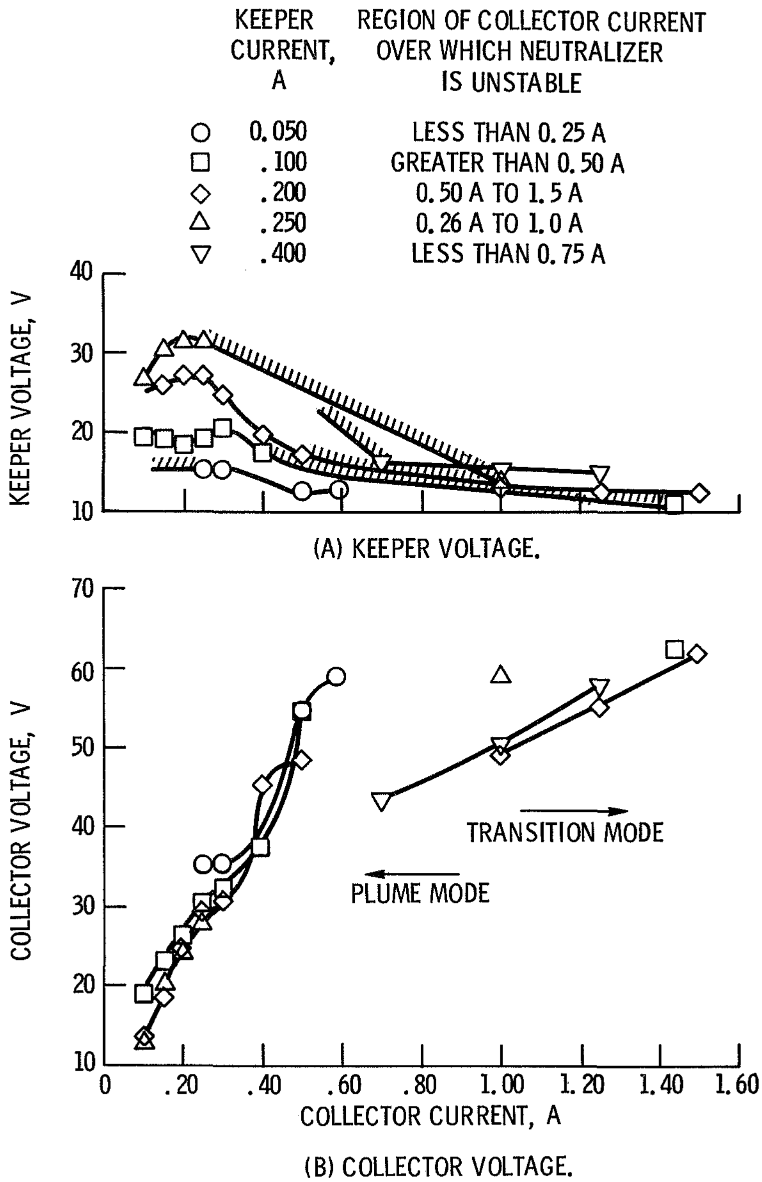


Figure 8. - Variation of keeper and collector voltages with collector current at several valves of keeper current. Neutral flow rate, 32 mA, resistive keeper power supply circuit.

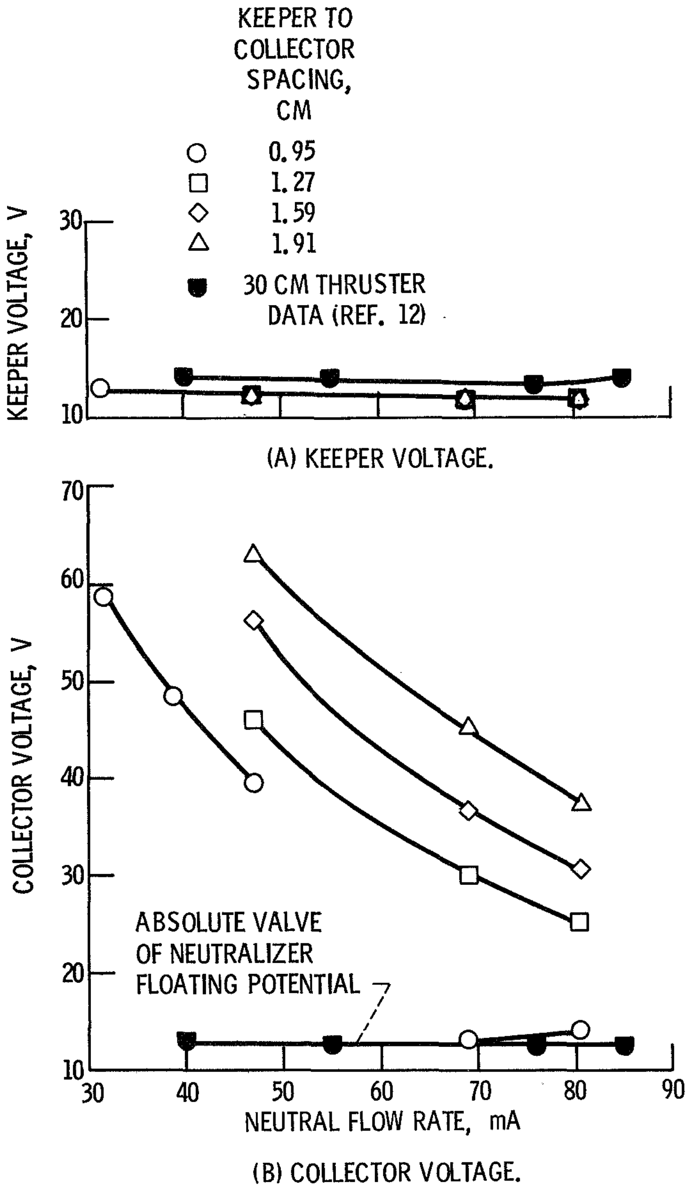


Figure 9. - Variation of keeper and collector voltages with neutral flow rate for various keeper to collector spacings. Keeper current, 0.20 A; collector current, 1.5 A; resistive keeper power supply circuit.

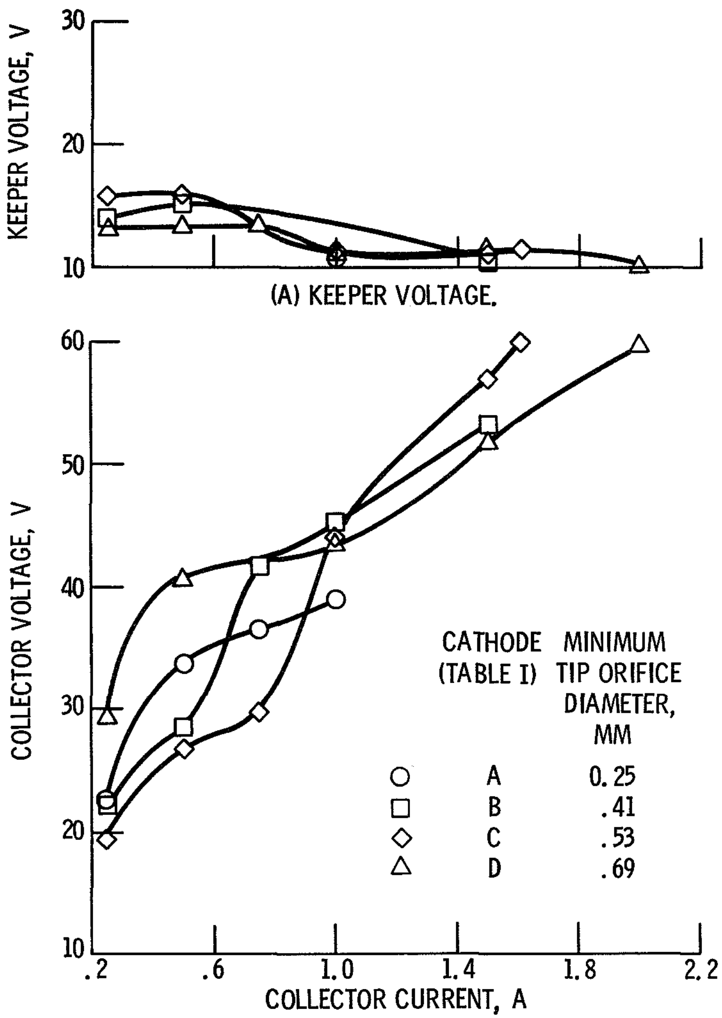


Figure 10. - Variation of keeper and collector voltages with collector current. Keeper current, 0.20 A; neutral flow rate, 43 mA; resistive keeper power supply circuit.

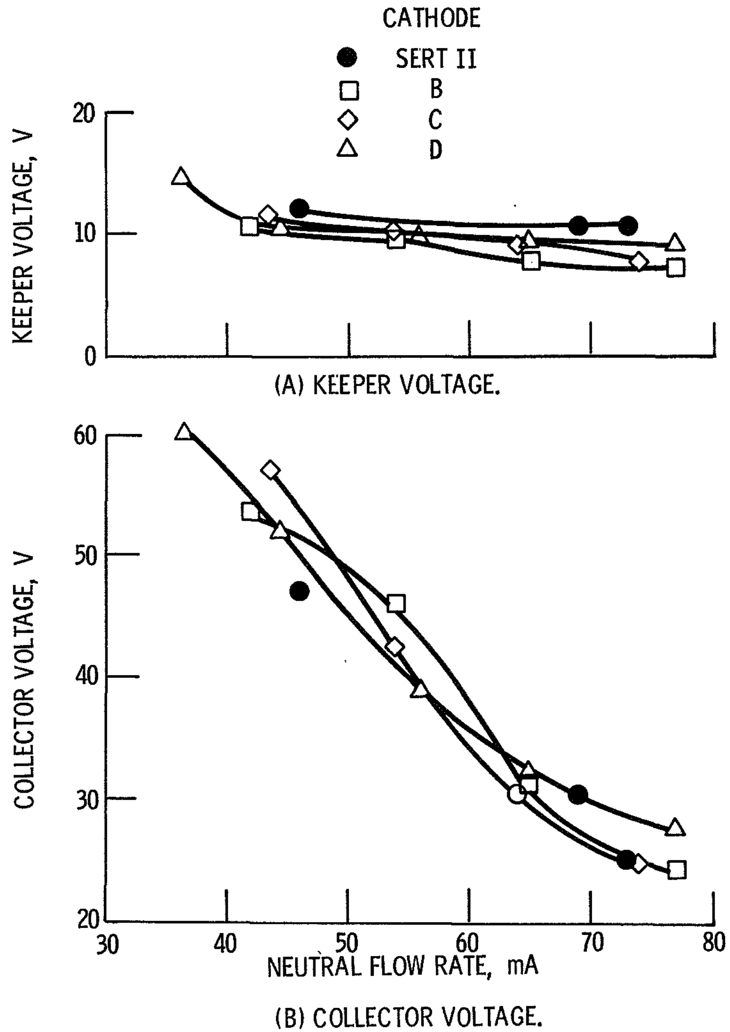


Figure 11. - Variation of keeper and collector voltage with neutral flow rate for various cathodes. Keeper current, 0.20 A; collector current, 1.5 A; resistive keeper power supply circuit.

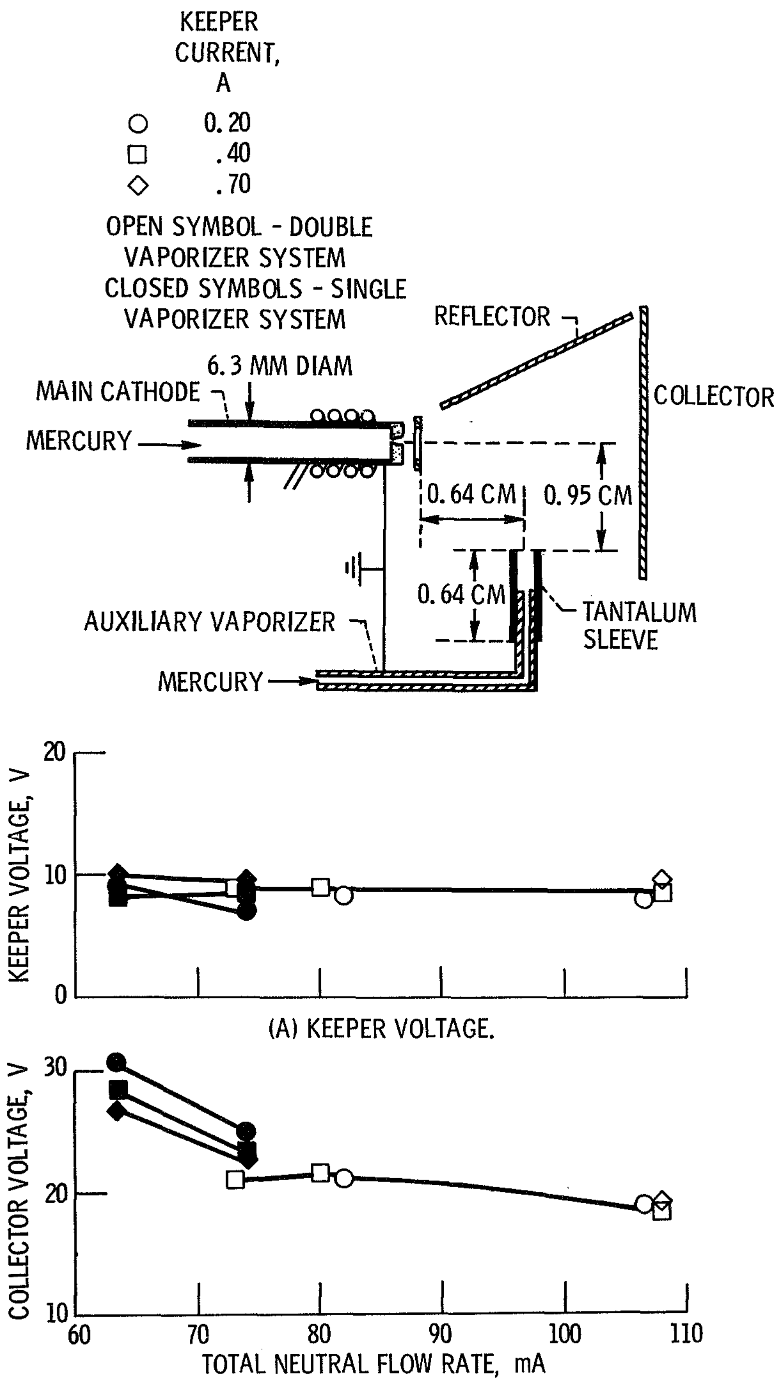


Figure 12. - Variation of keeper and collector voltages with total neutral flow rate for the double vaporizer system and single vaporizer at various keeper currents. Cathode C; collector current, 1.5 A; resistive keeper power supply circuit, 38 mA flow through main cathode for two vaporizer system.