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A 13 000-HOUR TEST OF A MERCURY HOLLOW CATHODE

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16. Abstract

A mercury-fed hollow cathode was tested for 12 979 hours in a bell jar at SERT II neutralizer operating conditions. The net electron current drawn to a collector was 0.25 ampere at average collector voltages between 21.8 and 36.7 volts. The mercury flow rate was varied from 5.6 to 30.8 equivalent milliamperes to give stable operation at the desired electrode voltages and currents. Variations with time in the neutralizer discharge characteristics were observed and hypothesized to be related to changes in the cathode orifice dimensions and the availability of electron emissive material. A facility failure caused abnormal test conditions for the last 876 hours and led to the cathode heater failure which concluded the test.

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A 13 000-HOUR TEST OF A MERCURY HOLLOW CATHODE

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SUMMARY

A mercury-fed hollow cathode nearly identical in design to the neutralizer of Space Electric Rocket Test II (SERT II), was endurance-tested in a bell jar for 12 979 hours. The test was conducted in 16 segments to permit periodic inspection of the cathode orifice and reliable mercury consumption measurements. The net electron current collected by an ion beam simulator was 0.25 ampere, the value of the SERT II ion beam current. The collector voltage varied between 21.8 and 36.7 volts, and the average mercury flow rate ranged between 5.6 and 30.8 equivalent milliamperes. The mercury flow rate and collector voltage required for stable operation at the fixed keeper and collector currents gradually decreased during the first 5300 hours of the test and increased over the last 7700 hours. The performance changes were correlated with gradual changes in both the cathode orifice dimensions and the availability of electron emission material. The orifice length, or tip thickness, decreased from about 1 to 0.665 millimeter during the test. The downstream orifice diameter increased from 0.348 to 0.554 millimeter as the tip thickness decreased, because the orifice diameter was larger within the bulk of the cathode tip than at either end. The upstream orifice diameter decreased from 0.214 to 0.173 millimeter because of a buildup of condensed sputtered cathode material. A vacuum-facility failure at 12 103 hours of operation caused abnormal test conditions during subsequent testing which finally led to the failure of the cathode tip heater.

INTRODUCTION

SERT II was launched on February 3, 1970 (ref. 1). The primary goal of SERT II was to operate one of the two onboard 15-centimeter-diameter ion thrusters for 6 months (4380 hr). The operation of any ion thruster in space requires a neutralizer in order to maintain spacecraft neutrality. One type of neutralizer which appeared to satisfy the efficiency, lifetime, and recycling requirements was the hollow-cathode neutralizer (refs. 2 to 5). This mercury discharge device uses low energy ions to form a plasma bridge to the ion beam for the neutralizing electrons. Thus, the neutralizer can be located so as to avoid direct impingement of high-energy beam ions and yet provide a low coupling voltage. Initial tests (ref. 4) had specified the basic neutralizer geometry and position on a SERT II thruster. Those tests also demonstrated that neutralizer operation on a thruster could be closely simulated in a bell jar.

Evaluation of this hollow-cathode neutralizer for use on the SERT II flight required operation for long periods of time. Areas of special concern were electrical performance variations and erosion of the cathode or keeper electrode. This report presents the results of an endurance test which was conducted in a bell jar to determine the long-term operational characteristics of the SERT II hollow-cathode neutralizer.

APPARATUS

Hollow-Cathode Neutralizer

A cross-section sketch of the hollow-cathode neutralizer used for the 13 000-hour endurance test is presented in figure 1. The cathode consisted of a 3.2-millimeter-diameter tantalum tube (0.38-mm-thick wall) with a 1-millimeter thick, 2-percent-by-weight thoriated (ThO_2) tungsten tip electron-beam welded to one end. The other end of the tube was connected to a supply of mercury vapor. A sandblaster which used a mixture of 27-micrometer-diameter aluminum oxide powder and air was utilized to cut an orifice in the center of the tungsten tip. The backspray of powder caused internal erosion of the orifice walls and produced a contoured hole that was larger in diameter within the tip than at either end, as shown in figure 1. A contoured hole of this shape is typical of all cathodes with small orifices made by this method. The initial upstream diameter of the test cathode orifice was 0.214 millimeter, while the downstream diameter was 0.348 millimeter.

An insert, which was used to improve starting and steady-state operation was placed inside the cathode tube, directly behind the cathode tip (ref. 4). The insert was a 0.013-millimeter-thick tantalum foil strip coated with approximately 10 milligrams of a barium carbonate and strontium carbonate mixture containing a nitrocellulose binder and suspended in a mixture of organic solvents. The foil strip was cut and rolled in a spiral such that a cavity, approximately 1.5 millimeter in diameter and 1.5 millimeter long, existed behind the cathode tip. A flowpassage, about 0.5 millimeter in diameter, also existed along the center of the insert. The insert was electrically connected to the tantalum tube with a 0.25-millimeter-thick tantalum wire.

The cathode was resistively heated with a tungsten-rhenium wire which was embedded between two layers of flame-sprayed alumina, as shown in figure 1. The cold resistance of the heater was 1.0 ohm, and the hot resistance was about 2.5 ohms. Ten layers of 0.013-millimeter-thick tantalum foil were wrapped around the cathode as a radiation heat shield.

The only differences between the test cathode and those used on the SERT II flight involved initial orifice dimensions and the cathode heater. The upstream orifice diameter was 0.25 millimeter for the flight neutralizer cathode. Also a layer of flame-sprayed tungsten was added as a corrosion barrier between the alumina and both the tantalum tubing and the radiation shield. A second heater lead tie-down strap was also added to the flight cathode.

A keeper electrode was used to start and maintain the discharge from the hollow cathode. The keeper used for the endurance test was a rectangular tantalum plate 7 centimeters long by 2.5 centimeters wide and 0.15 centimeter thick. A 0.45-centimeter-diameter hole in the keeper was positioned to be concentric with the cathode orifice. The cathode-to-keeper spacing was 0.15 centimeter. The electron beam was collected by a beam simulator electrode which used a dense mesh (5 percent open) tungsten screen held between two 2.5-centimeter by 3.2-centimeter tantalum plates, each having a 1.9-centimeter-diameter hole, as shown in figure 1. This electron collector was positioned 1.27 centimeters from the keeper electrode, was centered, and was perpendicular relative to the cathode axis.

The source of mercury vapor was a resistively heated, cylindrical, stainless-steel reservoir partly filled with liquid mercury (ref. 4). The liquid mercury temperature was monitored with an iron-Constantan thermocouple on the outside of the reservoir wall.

Electrical Arrangement

A schematic of the experimental neutralizer electrical system is shown in figure 2. For the first 4300 hours of the test, the cathode tip and the mercury reservoir were heated with separate 60-hertz, alternating-current power supplies. For the last 8700 hours, both heaters were connected in series to simulate SERT II neutralizer operation. An 11-ohm resistor was placed in parallel with the tip heater to keep the heater current at approximately the same value as had been used in the previous portion of the test. A 300-volt, 500-milliampere, direct-current power supply was used for the keeper and collector electrodes. Variable ballast resistors were used to separately control the current to each electrode. No series inductance or shunt capacitance was added at the power supply output.

The ac current and voltage meters used were accurate to 3 percent, while the dc meters were accurate to 1 percent and were calibrated several times during the test.

The reservoir thermocouple output was monitored with a self-compensating dial indicator which provided temperatures accurate to ±2 K.

Vacuum Facility

The experiment was contained within a 46-centimeter-diameter glass bell jar. An oil diffusion pump equipped with a liquid-nitrogen cold baffle along with a liquid-nitrogen-cooled target near the cathode maintained the bell jar pressure at less than 1×10^{-5} torr throughout the endurance test.

EXPERIMENTAL PROCEDURE

Cathode Tip Examination

Before and after each segment of the 13 000-hour test, the cathode tip was inspected with a microscope to document any cathode erosion. The microscope was equipped with a calibrated vertical vernier, such that by focusing on the upstream and then the downstream orifice edges, a measurement of the tip thickness at the orifice was obtained. The initial cathode tip thickness was not measured but was specified to be 1 millimeter. Tip thickness measurements were accurate to within 0.003 millimeter. A camera was mounted on the microscope to enable 73-power photographs of the orifice to be taken. From these photomicrographs, measurements of the upstream and downstream orifice diameters were made. As the initial orifice was not exactly circular, the maximum downstream orifice diameter was always measured. Orifice-diameter measurements were also estimated to be accurate to within 0.003 centimeter.

Mercury Flow Rates

The mercury reservoir was weighed before and after each test segment to determine the time average rate of mercury consumption. Less accurate but instantaneous indications of the flow rate could be obtained from a curve of flow rate as a function of reservoir temperature, compiled from previous runs. Mercury flow rates are expressed in equivalent milliamperes where 7.5 milligrams per hour of mercury flow is equivalent to 1 milliampere of singly-charged mercury ions.

Cathode Starting

Three conditions had to be satisfied before the hollow-cathode discharge would start:

The first requirement was sufficient thermionic emission. This emission, experimentally found to be approximately 50 microamperes, was produced by heating the cathode to 1300 K, as measured with an optical pyrometer. Electron emission is enhanced at this temperature by the presence of the emissive oxides on the insert.

The second requirement was an accelerating field for the thermionic electrons. A starting potential of 300 volts was applied to the keeper electrode to provide the field.

The third requirement was a sufficient neutral mercury density. Mercury was vaporized and the vapor pressure controlled by raising or lowering the mercury reservoir temperature.

Under normal starting conditions, 300 volts was applied to the keeper as on the SERT II thruster. The cathode tip and mercury reservoir were then heated with a maximum of 34 watts, which resulted in a reservoir temperature of about 480 K. When the electron emission current increased to about 50 microamperes and the mercury flow rate was approximately 25 equivalent milliamperes, the cathode discharge usually started. At this indicated flow rate, the pressure inside the cathode, assumed equal to that of the reservoir, was estimated from the reservoir temperature to be about 2700 newtons per square meter (20 torr).

A trade-off could be made among the three conditions needed for starting. With excess mercury flow and electron emission, the discharge could be started with a keeper voltage of only 20 to 30 volts. With low thermionic emission ($<10\ \mu A$) a discharge would not start until the neutral flow rate was about five times normal.

Steady-State Operation

Once the neutralizer discharge was started, the keeper and collector currents were set at 0.2 and 0.25 ampere, respectively. The mercury flow rate was then usually reduced and held constant at the lowest flow rate yielding stable operation with a collector voltage of 35 volts or less.

For the first 6000 hours of the test, data were taken at 4-hour intervals during every workday. The neutralizer was allowed to run unattended over the weekends and was found to operate stably with almost no change in operating conditions over this period.

For the last 7000 hours, data were usually taken only at the start and end of each workday. After recording the data, the operator would make any adjustments necessary to maintain the parameters at the desired values.

The test was usually interrupted at approximately 1000-hour intervals for cathode inspection. The irregular times of several segments were caused by the need for mercury reservoir refill or facility maintenance. To end a segment of the test, the cathode and vaporizer heater currents were reduced to zero. As the mercury flow decreased, the keeper and collector voltages increased. The dc power supply was turned off when either the keeper or collector voltage reached 100 volts, and the system was then allowed to cool to room temperature. The neutralizer cathode and mercury reservoir were removed from the bell jar and exposed to atmosphere.

The cathode was detached from the reservoir and photomicrographs were taken. The mercury reservoir was weighed, refilled, and then reweighed. The parts were reassembled and installed in the bell jar for further testing.

RESULTS AND DISCUSSION

This section will discuss the selection of the endurance test conditions, a time history of the electric and geometric parameters, and the possible causes of the time variation of the test conditions.

Selection of Test Conditions

The net emission current drawn from the neutralizer to the collector was held constant at 0.25 ampere - the value of the SERT II ion-beam current. The choice of the collector voltage was based on previous experimental results. A neutralizer operating on a thruster experienced severe orifice erosion when the neutralizer was biased 30 volts negative with respect to ground (ref. 6). The coupling voltage for that test was indicated to be greater than 35 volts. Subsequent neutralizer tests at reduced coupling voltages of 30 to 35 volts gave acceptable orifice erosion rates. Therefore, 35 volts was chosen as the maximum allowable collector voltage for the bell-jar endurance test.

The keeper current was held constant at 0.20 ampere for the entire test with the exception of test segment 1, where it was 0.16 ampere. At the start of test segment 2, it was found that the collector voltage was minimized when the keeper current was adjusted to 0.2 ampere. Reference 4 has shown this to be true when a similar neutralizer was tested on a thruster. For the endurance test, the keeper voltage was always found to be less than the collector voltage and was, therefore, allowed to vary with test time. Subject to the above constraints of keeper and collector voltages and currents, the mercury flow rate was always reduced to the lowest possible value compatible with stable neutralizer operation.

Test Results

Figure 3 graphically presents the variation with test time of the indicated mercury flow rate, the electrode voltages, and the cathode orifice dimensions. The average values of those parameters and the cathode tip heater currents and orifice wear rates for each test segment are given in table I. Figure 3 shows that the endurance test, excluding test segment 11, was characterized by three different regions of operation. They occurred during the intervals from the start of the test to about 5300 hours, from 5300 hours to 12 100 hours and from 12 100 hours to the end of the test.

During the first eight test segments (5300 hr), as the flow rate was adjusted to satisfy the test criteria, the maximum collector voltage at which stable operation could be obtained decreased. The indicated flow rate also decreased and then increased slightly at the end of test segment 8. During that interval, the orifice length decreased at a nearly constant rate, while the downstream orifice diameter increased initially at a fixed rate and then began to approach a constant value. The upstream orifice diameter decreased at a uniformly low rate. From test segments 9 to 14 (5300 to 12 100 hr), excluding the anomalous conditions of test segment 11, the flow rate and collector voltage both increased. During that time, the downstream orifice diameter remained nearly constant, and the orifice length decreased to a nearly constant value also. The upstream orifice diameter continued to decrease at nearly the same low rate. Test segment 14 ended with a facility failure which caused abnormal operation in subsequent test segments.

Figure 4 shows characteristic curves of the electrode voltage as a function of mercury flow rate obtained at three different times during the test. Figure 4(a) taken at 360 hours shows that there are three modes of operation (refs. 4 and 6). These are the "plume" mode, at low flow rates; the "transition" mode, at intermediate flow rates; and the "spot" mode, at high flow rates. With the exception of test segment 11, the entire 13 000-hour test was conducted in the "plume" mode. In this mode, both the keeper and collector voltages decrease monotonically with increasing mercury flow rate for a fixed cathode geometry. It has been noted that both the operating points at which mode changes occur and the shape of the characteristic curve depend on electrode currents and spacings and cathode orifice geometry (refs. 7 and 8). Details of the hollow-cathode operation throughout the endurance test are presented below.

During the first three test segments (1774 hr), it was found that the flow rate could be continuously decreased from 15.5 to 6.5 milliamperes while still maintaining a collector voltage of less than 35 volts. For segments 4 to 8 (3500 hr), the flow rate was nearly constant, with an average value of 6.3 milliamperes, while the collector voltage decreased from 25.5 to 21.8 volts. During these first eight segments, the keeper voltage fluctuated between 13.5 and 18.8 volts. Figure 4(b) shows the characteristic curve taken at the start of segment 4 (1780 hr). This curve was typical for segments 4 to 8. Comparison of figures 4(a) and (b) shows that between test hours 360 and 1780 the collector voltage, at a given flow rate in the plume mode, had decreased. Figure 4(b) also shows that at the maximum allowable collector voltage of 35 volts, operation was on the vertical portion of the characteristic curve, where a small decrease in flow rate would cause the collector voltage to rise rapidly over 35 volts. Therefore, to satisfy the stability constraint, the flow rate was increased slightly, and the collector voltage decreased to an average value of 22.4 volts for test segments 4 to 8.

Throughout the first eight test segments (5300 hr), the cathode orifice dimensions changed at near-constant rates, as shown in figure 3. The orifice length decreased from about 1 to 0.762 millimeter. The downstream orifice diameter increased from 0.348 to 0.452 millimeter, while the upstream diameter decreased from 0.214 to 0.183 millimeter.

As stated earlier, the mercury-reservoir and cathode-tip heaters were connected in series at the start of test segment 8. In this arrangement, any increase in the required mercury flow rate would be accompanied by an increase in the cathode tip temperature. Also, at the normal starting flow rate of approximately 25 milliamperes, the cathode tip brightness temperature was now 1500 K, or 200 K hotter than that of earlier test segments. This condition of elevated temperature occurred for less than 1 hour at the start of subsequent test segments, but nevertheless was a deviation from the earlier starting procedure.

During test segment 9, the maximum stable collector voltage increased from 23 to 27 volts, while the minimum allowable flow rate had to be increased from 7.4 to 8.1 milliamperes. This trend of rising maximum stable collector voltage and the corresponding flow rate continued to segment 14, not considering the anomalous conditions during test segment 11. The keeper voltage fluctuated between 14.3 and 20.2 volts for segments 9 to 14. Figure 4(c) shows the characteristic curves at 10 000 hours. The minimum flow rate for which the collector voltage equaled 35 volts had increased from 5 milliamperes at 1780 hours to 11 milliamperes at 10 000 hours. On the other hand, over that time period the relation between flow rate and voltage had not changed significantly for the "transition" and "spot" modes.

An accidental misalinement between the cathode orifice and the hole in the keeper electrode caused the abnormal test conditions for segment 11. The spacing between them was correct, but they were eccentric by approximately one-fourth the keeper hole diameter, or about 1.1 millimeter. This misalinement caused the average collector voltage for the test segment to be 32 volts even though the flow rate was 27.5 milliamperes and operation was in the "transition" mode. This type of keeper misalinement has been discussed in detail in reference 6. The problem was corrected at the start of segment 12, and normal operation was restored.

For segments 9 to 13, the orifice length decreased from 0.762 to 0.690 millimeter, while the downstream orifice diameter increased from 0.452 to 0.463 millimeter. However, as shown in figure 3, the rate of change of those two dimensions decreased to nearly zero. The upstream orifice diameter continued to decrease at about the same low rate as for the entire test, changing from 0.183 to 0.168 millimeter during test segments 9 to 13.

Test segment 14 was terminated at 12 103 hours by a laboratory wide power interruption which resulted in a shutdown of the mechanical pumps and allowed the diffusion pump oil vapors to coat the hot neutralizer tip as the bell jar pressure rapidly increased to 1 atmosphere. Upon removal of the neutralizer, the tip was found to be covered with a green coating, possibly tungsten trioxide. When detached from the mercury reservoir for microscopic inspection, the neutralizer orifice was noted to be closed with the green coating. The hole was partially cleared with a tantalum wire, photomicrographed, and reinstalled for further testing.

It was impossible to obtain accurate measurements of the orifice length and upstream diameter at the end of segment 14 because of the green coating. The downstream orifice diameter had decreased slightly to 0.468 millimeter.

Test segment 15 was started by slowly heating the neutralizer tip and mercury reservoir to 1500 and 480 K, respectively, to evaporate the remaining green coating. When the keeper discharge would not start, the tip was removed from vacuum. No visible coating remained. The tip was then painted externally with the barium-strontium carbonate mixture used for coating the inserts. When reinstalled, the discharge started normally, but the flow rate required to keep the collector voltage at about 32.5 volts increased from 16.8 to 26.4 milliamperes. The keeper voltage was also higher than expected at 30 volts. It was obvious that the cathode had been severely affected by the shutdown during test segment 14. Inspection of the cathode orifice after only 463 hours of operation revealed that the rate of change of the downstream orifice diameter was nearly three times any previous rate. Also, the orifice length and upstream diameter had increased from the start of segment 14, perhaps from cleaning the blocked orifice or from the events which occurred at the end of segment 14.

An increased cathode temperature of 1600 K was required to start the discharge for test segment 16. Performance was similar to that of segment 15 in that the initial flow rate was 16 milliamperes and increased to 27 milliamperes to keep the collector voltage at about 35 volts. Again, the rate of change of the downstream orifice diameter was high, while that of the upstream orifice diameter was normal. The rate of erosion of the orifice length was greater than any rate previously observed.

While attempting to restart the discharge for further testing of the neutralizer, it was noted that again there was no observed thermionic emission at the normal input power of 34 watts. The neutralizer and mercury reservoir heater powers were then increased as at the start of segment 16, and the cathode heater developed an open circuit under these abnormal conditions. The heater operated for 12 979 hours at approximately 15 watts and had been cycled to atmosphere 16 times. Since normal discharge operation was not restored during the last 876 hours of the test, further testing of the hollow cathode neutralizer was discontinued.

Analysis of the Time Variation of Performance

This section will discuss those neutralizer parameters believed to be the primary factors which determined the observed variations in the steady-state neutralizer performance.

Cathode orifice dimensions. - Figure 3 showed how the orifice dimensions varied over the test period. Figure 5(a) is a 100-power photomicrograph of a cross-sectioned unused cathode orifice. The orifice shape is typical of those used in the SERT II program and in this 13 000-hour test. As stated in the APPARATUS section, the contoured orifice was made with an abrasive sandblaster. This process always resulted in a hole which was larger in diameter inside the bulk of the cathode tip than at either end. The maximum diameter of about 0.4 millimeter was located about one-third of the tip thickness from the downstream face of the cathode tip. Note that if the downstream face of the cathode tip were worn away, the downstream orifice diameter would naturally increase until the maximum diameter of the orifice was reached. Figure 5(b) is a 100-power photomicrograph of the cross-sectioned 13 000-hour test cathode. The surface shown is displaced approximately 0.03 millimeter from the cathode orifice axis, which makes the diameters measured from this photomicrograph slightly smaller than those listed in table I. Figure 5(b) shows that the downstream face of the cathode was worn away, thereby reducing the orifice length.

Figure 6 is a composite drawing of cathode orifice outlines from figure 5(b) and table I. The dots mark the locations of the edge of the orifice at the conclusions of the test segments indicated by the numbers. The solid line is the outline of the cathode orifice traced from figure 5(b). The downstream face of the cathode tip was continuously bombarded by ions formed in the discharge. With collector voltages less than 35 volts, little erosion was expected, since the "sputtering threshold" for mercury ions on tungsten, given in reference 9, is 25 volts. However, in reference 8, where an identical cathode was tested at similar conditions, it was found that the electrode voltages oscillated with peak amplitudes often twice the dc meter value. Therefore, ions could have been formed with energies as high as 60 volts in the 13 000-hour test and could have caused the observed erosion. In addition, doubly charged mercury ions could be formed which would cause even more sputtering damage.

Figure 5(b) also shows a thin layer of small-grain tungsten along most of the orifice length, which accounts for the decrease in the upstream orifice diameter observed during the test. The large elongated grains which make up the bulk of the cathode tips shown in figure 5 are typical of the original condition of the cathode material. Inspection of the cross-sectioned cathode tip with an electron scanning microscope indicated that no thoria was present in the region of the small grains. The small-grained layer was, therefore, not the same as the parent tip material. Since there was a direct line of sight from the downstream edge of the orifice to the upstream region of the orifice, it is probable that some of the sputtered tungsten atoms condensed on the orifice walls. As the orifice length decreased because of ion bombardment, the condensed tungsten layer as well as the parent tip material would be removed, as shown in figure 5(b). Deposition of sputtered cathode material has been observed in other long-term tests with cathodes of this type. The endurance test of the 5-centimeter ion thruster reported in reference 10 was recently terminated at 9700 hours. Erosion of the hollow-cathode neutralizer used in that test was similar to that reported herein for the 13 000-hour cathode. Condensed tungsten, free of thoria, was found on the upstream side of the enclosed keeper cap. (Information obtained through private communication with Wayne R. Hudson of the NASA Lewis Research Center.)

Such redistribution of cathode material is not unique to the 13 000-hour test. In reference 4, a cross-sectioned molybdenum cathode tested for only 333 hours under similar conditions showed evidence of a decreasing orifice diameter. The metal appeared to have flowed from the downstream orifice edge inward to close the hole. Again, in reference 6, a neutralizer tested with an operating thruster for only 416 hours experienced severe sputtering damage and finally stopped operating because of a completely closed orifice. Examination of the photomicrographs of these two cross-sectioned cathodes also indicated small-grain structure where metal had apparently been removed from the downstream orifice edge and then was condensed on the orifice walls.

The rate at which the orifice length decreased was nearly constant at 5×10^{-5} millimeter per hour for the first 8 test segments (5300 hr). The rate at which the upstream orifice diameter decreased was uniformly low during most of the 12 979-hour test. It is quite likely that the early shifts in the characteristic curves, as indicated in figures 4(a) and (b), were caused by the changing cathode orifice dimensions. Since operation of the neutralizer was in the region of gas flow between viscous and free molecular flow where the discharge particles make an appreciable number of collisions with the orifice walls as well as with each other, changes in the orifice dimensions would very likely affect the plasma properties. As shown in figure 3, both the orifice length and the downstream diameter showed little further change in the 6800-hour interval of test segments 9 to 14. While there is no known reason for the reduced erosion rates in the latter portion of the test, it is possible that if the plasma properties were altered by the earlier orifice erosion, the amplitude of the discharge oscillations may have been reduced, leading to lower bombarding ion energies and reduced sputtering damage. The observed increases in the flow rate and collector voltage for the latter period were probably not due to the corresponding small changes in cathode orifice dimensions.

Oxide-coated insert. - At the end of the test, the insert was removed for inspection, and it was found that the upstream half of the insert was ductile and had some oxide coating remaining. The downstream half of the insert was brittle and appeared to have undergone some sputtering damage. Also, there was no visible oxide coating remaining. No attempts were made to directly measure the dispensation of the electron emissive material from the insert. As long as the cathode discharge could be initiated at the start of each test segment, it was assumed that the insert was functioning properly and that sufficient emission material was available from the insert. The presence of a low work function surface is required for efficient neutralizer operation. Reference 6 reported an example in which the mercury flow rate required to maintain a constant coupling voltage had to be increased 70 percent when the oxide coated insert became electrically disconnected from the cathode. The flow rate decreased to near normal when the wire attached to the insert was reconnected to the cathode tube. Those results imply that there may be discharge attachment to the insert.

An abrupt change occurred in the performance of the cathode after the catastrophic ending of segment 14 at 12 103 hours of the test. When the hot cathode was covered with diffusion-pump oil and quickly exposed to atmosphere, the oxide present was probably coated or "poisoned" so that it could no longer supply emissive material required for further starting and operation. At the start of segment 15, there was no observed thermionic emission - one of the requirements for normal starting. After the downstream face of the cathode had been coated with the mixture of barium carbonate and strontium carbonate, the cathode lit easily, but operation was still abnormal. This fact supports the conclusion that normal operation was dependent on a properly located, low-work-function surface. It is also possible that evaporation or chemical reaction caused the gradual depletion of the emissive material from the insert which resulted in the gradual degradation of the hollow-cathode performance indicated by the rising collector voltage and flow rate shown in figure 3. Reference 11 has shown that similar cathodes tested as thruster main cathodes at emission currents of 7 to 10 amperes also had performance degradation over a period of only several hundred hours. Those changes were attributed to a high evaporation rate of the barium oxide due to elevated cathode temperatures.

CONCLUSIONS

A mercury-fed hollow-cathode-neutralizer nearly identical to the ones used on the flight of SERT II was tested in a bell jar at SERT II conditions for 12 979 hours. The downstream face of the cathode tip was sputtered during the test, thereby causing the orifice length to decrease from about 1 to 0.665 millimeter. The sputtering erosion can be attributed to discharge ions which may have obtained energies as high as 60 volts from discharge voltage oscillations. The orifice diameter was initially larger in the bulk of the cathode tip than it was at either end. As the orifice length decreased, a larger downstream orifice diameter was exposed, which resulted in an increase from 0.348 to 0.554 millimeter in this diameter during the test. The rates of change of the orifice length and downstream diameter were nearly constant during the early portion of the test, and both decreased substantially after 8000 and 4300 hours of testing, respectively. Some of the tungsten sputtered from the downstream face of the cathode tip was deposited, at a uniform rate, on the upstream walls of the orifice, and this caused the upstream orifice diameter to decrease from 0.214 to 0.173 millimeter. There was no visible sputtering damage to the upstream portion of the orifice nor to the upstream face of the cathode tip, but the downstream end of the insert did show evidence of some sputtering erosion. The downstream half of the insert was void of any emissive material and was brittle, while the upstream half had some emissive material remaining and was ductile. The observed variations with time of the neutralizer characteristic curves of electrode voltage as a function of mercury flow rate during the first 5300 hours of test are believed to have been caused principally by the gradual changes in the cathode orifice dimensions. The cathode did function for 12 979 hours, during which time it was exposed to atmosphere on 16 occasions. A facility failure caused abnormal test conditions for the last 876 hours and led to the cathode heater failure which concluded the test.

Lewis Research Center,
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TABLE I. - TEST-SEGMENT SUMMARY

Test segment	Segment time, hr	Total test time, hr	Average flow rate, equiv. mA	Cathode heater current, A	Average keeper voltage, V	Average collector voltage, V	Tip thickness, mm	Downstream orifice diameter, mm	Upstream orifice diameter, mm	Tip-thickness wear rate, nm/hr	Downstream orifice diameter wear rate, nm/hr	Upstream orifice diameter wear rate, nm/hr
0	0	0	----	---	----	----	(a)	0.348	0.214	--	---	--
1	355	355	14.8	2.4	14.0	28.5	(a)	.361	.208	--	37	17
2	440	795	11.7	2.4	16.0	29.0	0.983	.361	.208	--	0	0
3	979	1 774	7.4	2.4	16.0	28.6	.932	.394	.198	52	34	10
4	583	2 357	5.7	2.4	18.5	24.0	.904	.414	.196	48	34	3
5	835	3 192	5.6	2.4	18.0	22.3	.868	.437	.191	43	28	6
6	208	3 400	5.8	2.4	17.5	22.5	(a)	(a)	(a)	--	---	--
7	895	4 295	6.4	2.4	17.0	21.8	.811	.447	.191	52	9	0
8	977	5 272	7.1	2.3	18.2	22.0	.762	.452	.183	50	5	8
9	1246	6 518	7.6	2.3	18.5	25.0	.724	.452	.180	31	0	2
10	1536	8 054	10.0	2.5	16.5	27.5	.693	.457	.175	20	3	3
11	1042	9 096	27.5	2.8	12.5	32.0	(a)	.463	.170	--	6	4
12	1111	10 207	12.9	2.6	16.0	28.0	.693	.463	.170	0	0	0
13	775	10 982	12.5	2.4	17.0	30.0	.688	.463	.168	6	0	3
14	1121	12 103	12.5	2.4	20.2	34.0	(b)	.468	(b)	--	4	--
15	463	12 566	21.6	2.7	30.0	32.5	.693	.518	.175	--	108	--
16	413	12 979	19.3	2.7	29.3	35.0	.665	.554	.173	68	87	5

[a]Data not taken.
[b]Questionable accuracy.

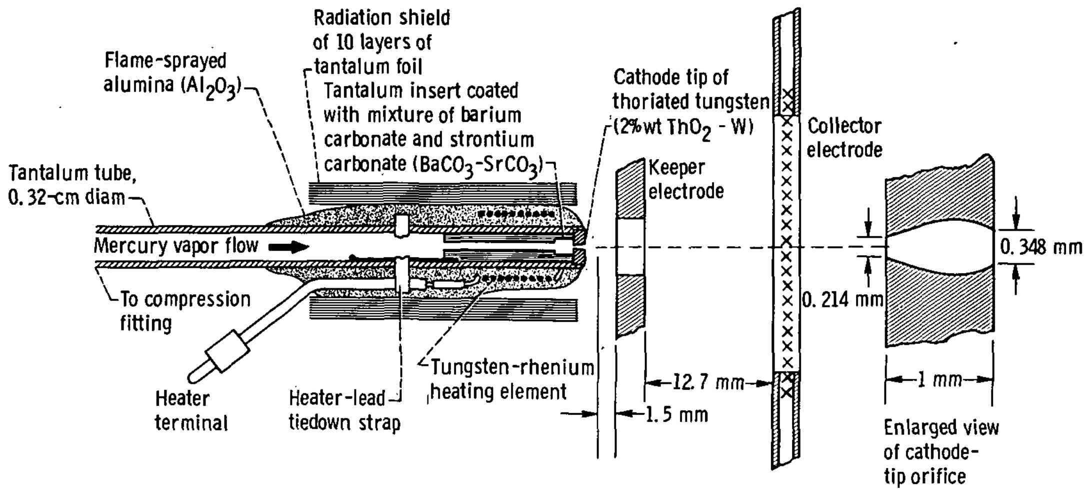


Figure 1. - Hollow-cathode neutralizer used for endurance test.

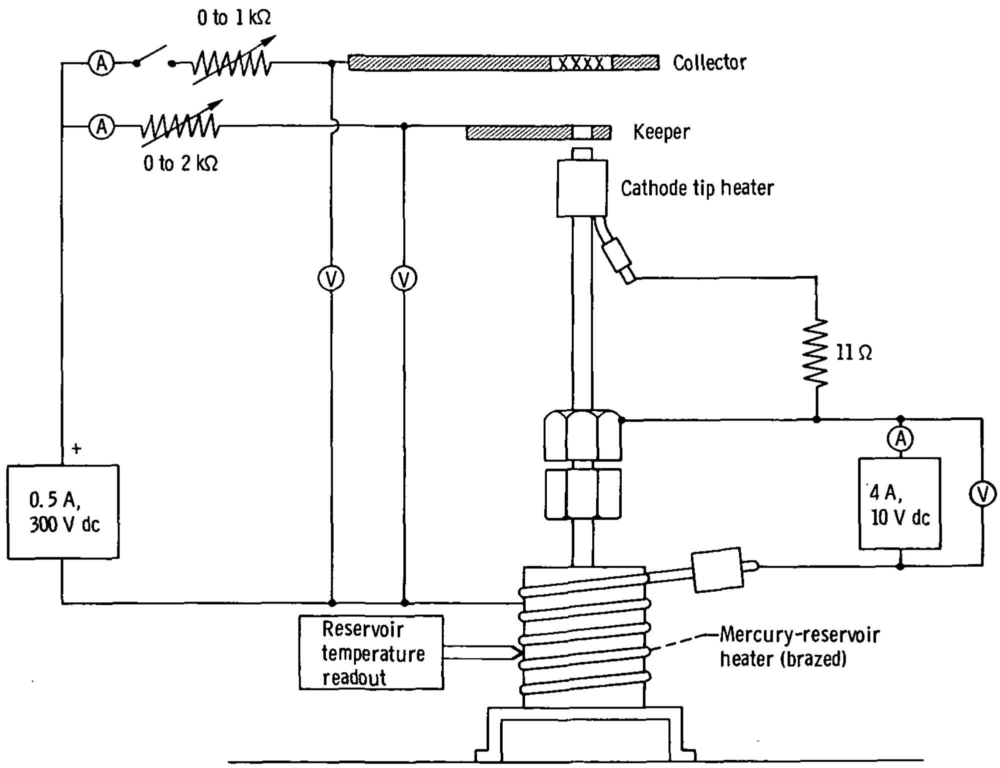


Figure 2. - Schematic diagram of the neutralizer endurance-test electrical system.

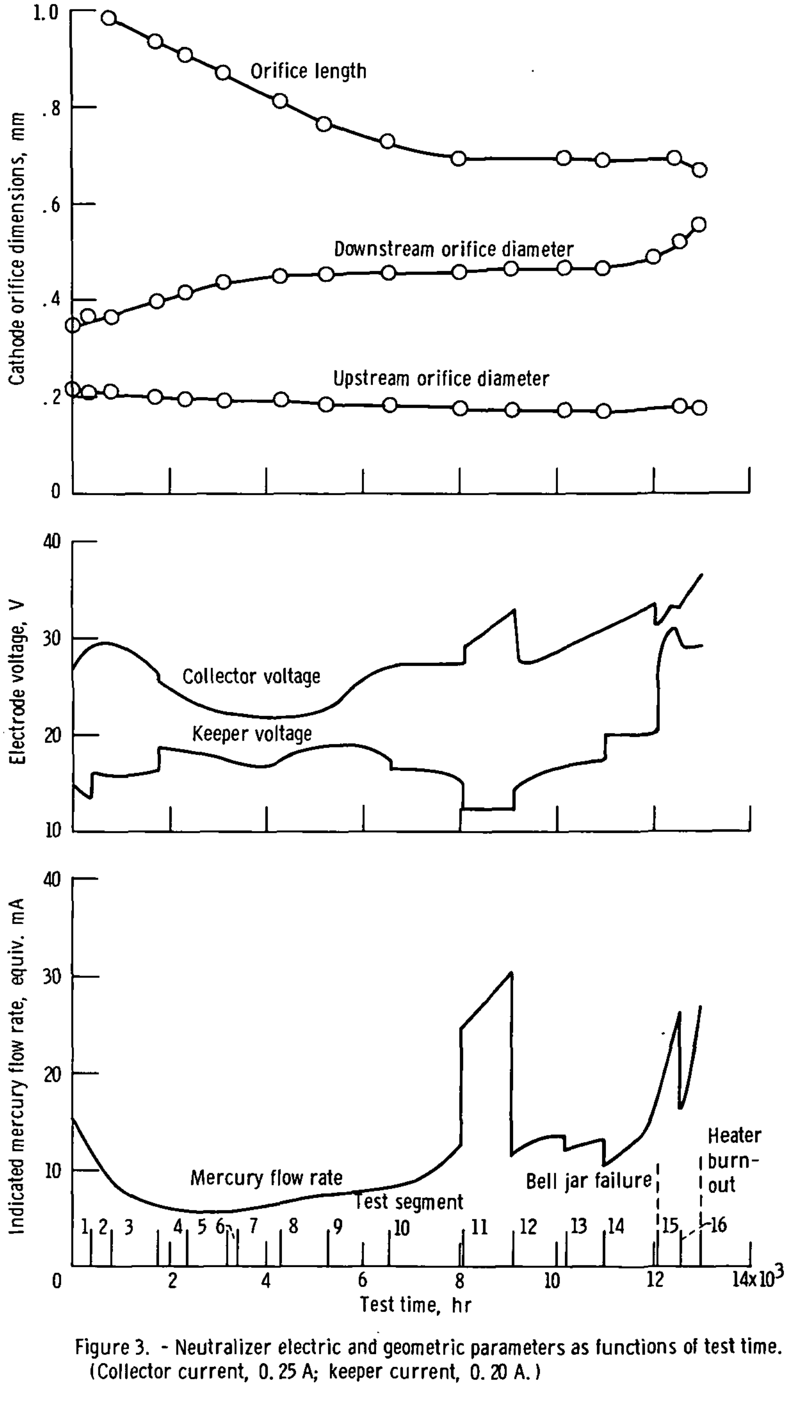


Figure 3. - Neutralizer electric and geometric parameters as functions of test time. (Collector current, 0.25 A; keeper current, 0.20 A.)

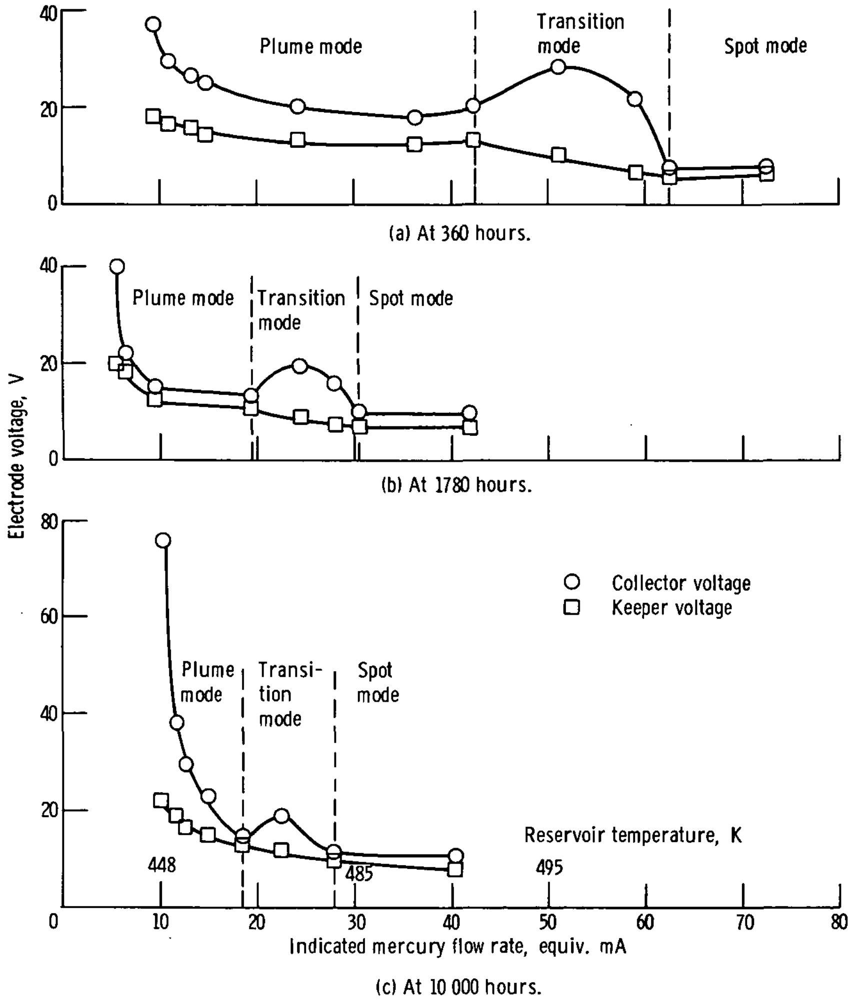
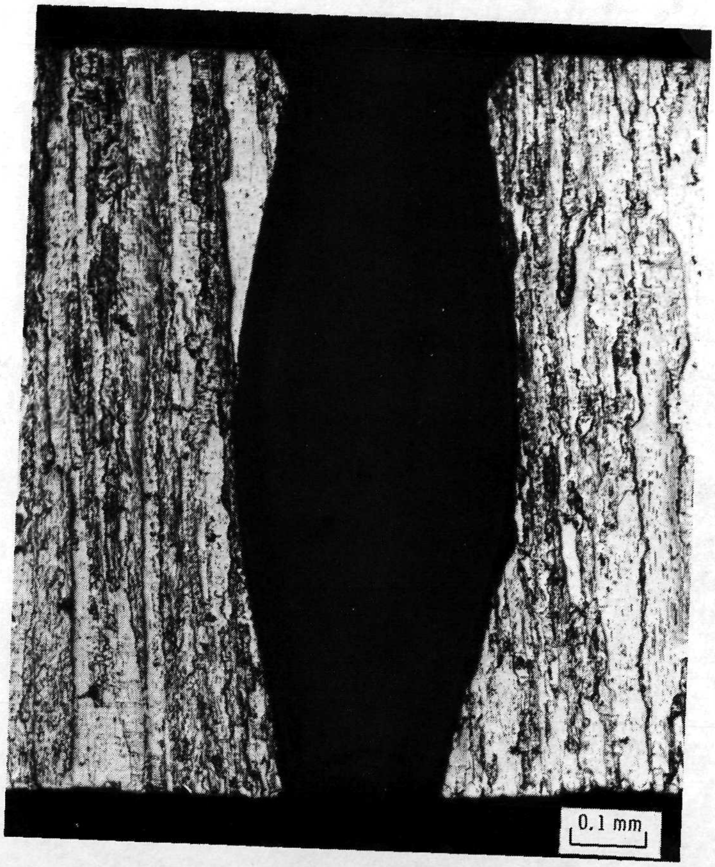
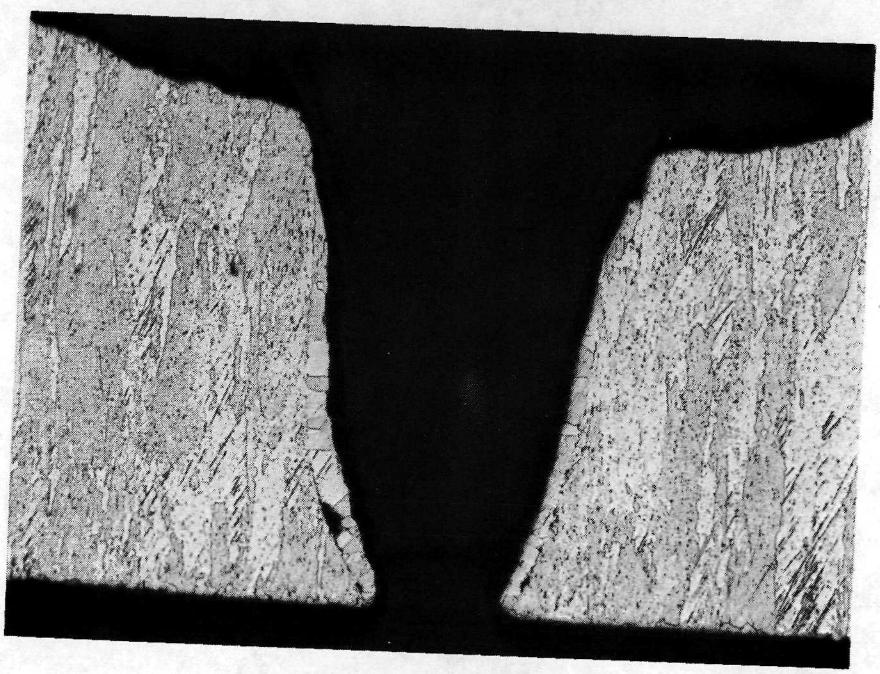


Figure 4. - Keeper and collector voltages as functions of mercury flow rate for three test times. (Collector current, 0.25 A; keeper current, 0.20 A.)



(a) Unused cathode.



(b) Endurance-tested cathode.

Figure 5. - Cross-sectioned cathode tips.

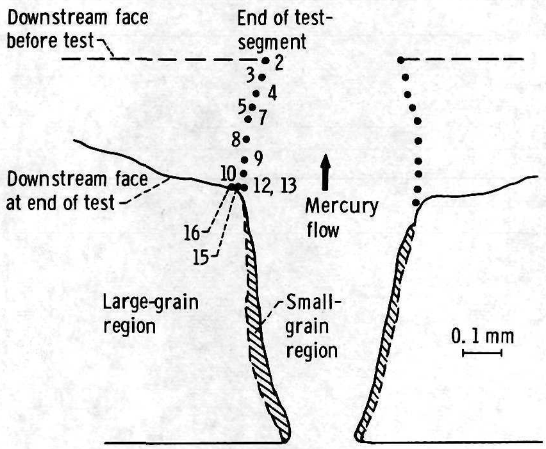


Figure 6. - Sketch of cathode-orifice erosion during endurance test. (Sketch based on data of fig. 5(b) and table I.)

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