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SERT II: Durability of the Hollow Cathode and Future Applications of Hollow Cathodes

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The SERT II thruster uses mercury-vapor-fed hollow cathodes for both the main discharge chamber and for the neutralizer cathode. The design of these two nearly identical cathodes was determined by a previous development program. This paper presents the results of life testing seven main cathodes and six neutralizer cathodes in experimental thruster systems for periods up to 3438 hr. The main cathode emits 2 amp to the discharge chamber and has at this current, a maximum projected lifetime of 15,000 hr. When emission currents greater than 2.5 amp were drawn, the projected lifetime was sharply reduced. The neutralizer cathode injects 0.25 amp of electrons into the ion exhaust beam and has a maximum projected lifetime of 33,000 hr. A hollow cathode has been tested in a bell jar as a simulated neutralizer for more than 12,000 hr. Larger hollow cathodes developed for use in large thrusters emitted 10 to 20 amp and showed no wear after testing for 234 hr.

Introduction

A 15-CM-DIAM Kaufman thruster, using Hg propellant, will be used on the SERT II (Space Electric Rocket Test II) mission.[1] A development program was carried out at the NASA Lewis Research Center which specified the optimum experimental thruster components.[2–4] A part of that program consisted of endurance testing the final experimental thruster design for more than 2000 hr.

The experimental thruster was similar to the thruster system described in Ref. 5. The major difference was that the mercury vapor flow was not split between the cathode and discharge chamber. Instead two vaporizers were used—one for the hollow cathode and the other for the main discharge chamber. The experimental thruster also had the advantage of being easily modified for improvements or parts replacement.

This paper presents the endurance test results for the main discharge cathode and neutralizer cathode used in that program. Also discussed are two areas of concern relating to the plasma-bridge neutralizer. The paper also presents the results obtained with the SERT II and larger hollow cathodes when operated at higher emission currents.

Experimental Apparatus

A cross section sketch of the hollow cathode used for the SERT II experimental neutralizer and main thruster cathode is presented in Fig. 1 and is further described in Ref. 2. The main thruster cathodes and the neutralizer cathodes were

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identical in geometry with the exception of variances in the orifice diameters. The electrical system in Fig. 3 of Ref. 5 also applies to the experimental thruster.

Thrusters used for cathode and neutralizer endurance tests were operated at a constant ion-beam current and ion accelerating voltages. The majority of tests were conducted at a near constant discharge voltage of 36 v. The neutralizer could be biased negative with respect to facility ground when the thruster system common was grounded. When the entire thruster system was isolated from facility ground, the neutralizer system was connected to the thruster common.

Emission currents from cathodes tested in a belljar were collected with a flat metal anode. During thruster and bell jar tests of main cathodes, glass precision bore flow tubes were used to obtain time averaged liquid Hg flow rates for short periods of time—usually 6-min intervals. Data was recorded as the flow rate, and circuit voltages and currents were varied. The flow rates of endurance tests were also determined by weight measurements of the mercury reservoirs. The thruster and neutralizer cathodes were occasionally removed from the thruster and inspected for orifice wear.

Cathode Starting

Three criteria must be satisfied before a hollow cathode discharge will start.

The first requirement is sufficient thermionic emission. This emission is produced by heating the cathode to approximately 1400°K. Electron emission is enhanced at this low temperature by the presence of the BaO on the insert.

The second requirement is an accelerating field for the thermionic electrons. A starting potential of 300 v is placed on the keeper electrode to provide the field.

The third requirement is a sufficient neutral mercury density. Mercury is vaporized and the flow controlled by a heated porous plug in a liquid mercury supply line.

Thruster Cathode Tests

Seven thruster cathodes were tested for an accumulated total of 9263 hr. On several occasions during each duration test, the thruster was removed from vacuum and the cathode tip photographed and measured. Figure 2 is a plot of tip thickness in cm as a function of test time in hours for four of the thruster cathodes. The discharge voltage was either 36 or 43 v and the discharge currents varied from 1.9 to 2.2 amp. The cathode Hg flow rates varied between 0.035 and 0.067 equivalent amp. (An equivalent amp is equal to 6.24×10^{18} atoms/sec.)

When the discharge current was 2.3 amp or less, the slopes or tip wear rates ranged between 6.6 and 15.0×10^{-6} cm/hr. When the discharge current was greater than 2.3 amp, the tip wear rates (not plotted in Fig. 2) ranged from 18 to 180×10^{-6} cm/hr. Figure 3 shows the tip wear rates, for the individual tests, as a function of the discharge current. The tip wear rates increase an order of magnitude by only doubling the discharge current. Cathode lifetimes are projected from

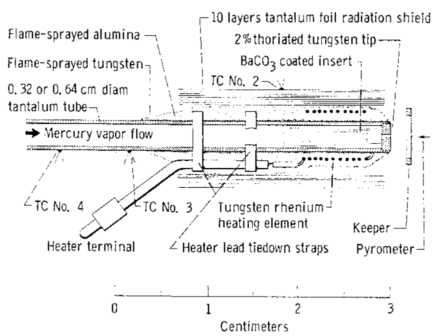

Fig. 1 Hollow cathode and keeper electrode.

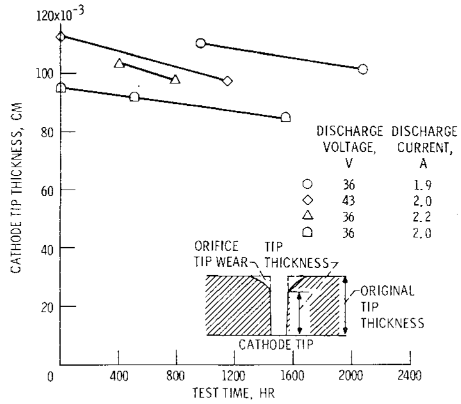

Fig. 2 Main cathode tip wear for near constant discharge voltage and current.

the tip wear rates assuming an initial tip thickness of 0.1 cm. The end of cathode life is defined as the time when the tip wear (assumed linear with time) reaches the upstream edge of the cathode hole, i.e., when the tip thickness denoted in Fig. 2 is equal to zero. The conclusions drawn from Fig. 3 are that for cathodes with a 0.1-cm-thick tip, lifetimes of 15,000 hr or more are possible for SERT II thruster cathodes if the discharge current is 2.0 amp and 6000 hr if the current is 2.5 amp. For these reasons, the SERT II discharge is current limited at 2.5 amp, with normal operation at less than 2.0 amp. The lifetime of the main cathode is not strongly dependent on hole wear or deposit buildup. The diameter of each main cathode orifice remained nearly constant for all endurance testing.

Neutralizer Cathode

Cathode Tip Wear

The final cathode design for the experimental SERT II plasma-bridge neutralizers is described in Ref. 2, and the neutralizer system is described in Ref. 5.

As mentioned previously, the neutralizer was operated in two ways. First, the thruster ground return and vacuum facility were electrically common while the neutralizer system was biased negatively so that the electrons were emitted into the ion beam. The neutralizer emission current was held at 0.25 amp (the value of the ion-beam current) by varying the neutralizer bias voltage. The mercury flow rate was varied to obtain the desired control point for the negative bias voltage, usually 15 to 20 v. In the second and preferred way, the entire thruster system and power supplies were electrically isolated from the vacuum facility. In this case the neutralizer emission current always followed any fluctuations in the beam current since all of the power supplies were connected to the same floating common. This common floating potential was

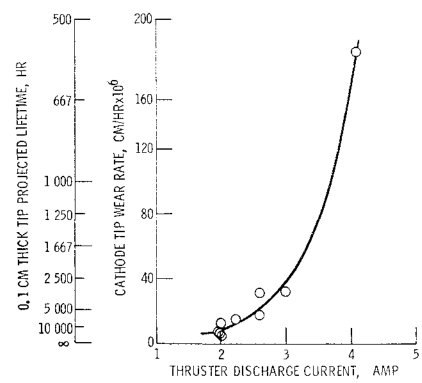

Fig. 3 Main cathode tip wear rate at various discharge currents.

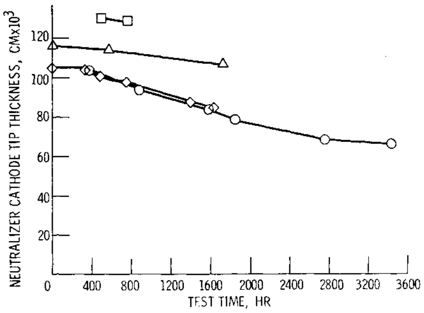

Fig. 4 Variation of neutralizer cathode tip wear with test time for four cathodes tested with a thruster.

the value necessary to couple the neutralizer electrons with the ion beam. A bank of thyratrons, set to fire if the thruster system floated off ground by more than 100 v, was used as a safety circuit.

Six neutralizer cathodes were tested for a total of 9004 hr. Figure 4 is a plot of tip thickness at the orifice, as a function of test time for four neutralizer cathodes. The four shown have approximately the same slope or tip wear rate even though operating conditions were different. The thruster was either operated with a neutralizer bias of -15 v or permitted to float. The floating potential with respect to facility ground was -13 to -19 v. Hg flow rates varied from 0.007 to 0.031 equivalent amp. Keeper currents ranged from 0.090 to 0.230 amp and keeper voltages were 14 to 25 v. Also a variety of neutralizer keeper electrode and accelerator shield configurations were tested. Within these ranges of varying neutralizer parameters, the neutralizer cathode tip wear rates ranged between 3.0 and 20×10^{-6} cm/hr. These wear rates project lifetimes up to 33,000 hr for neutralizer cathodes (calculated in the same manner as for main cathodes).

The authors believe that neutralizer cathode orifices are sputtered by slow moving ions from the beam and plasma-bridge region. The energy of these ions is related to the coupling voltage between the neutralizer and ion beam. The coupling voltage is discussed further in a later section.

The minimum diameter of the neutralizer cathode orifice was observed to decrease with operating time. The effect of the diameter decrease was not noticeable in the neutralizer performance. After a 12,000-hr test (to be discussed later) the orifice minimum diameter decreased about 15% while the tip thickness decreased 30%. The greatest changes in orifice diameter occurred during the first 800 hr. The rate of diameter decrease then diminished and was consistent with lifetimes equal to or greater than those projected from tip thickness measurements.

Coupling Voltage

During the endurance tests, a movable, floating Langmuir probe was inserted into the ion beam. The active portion of the probe was a straight 0.008-cm-diam and 0.64-cm-long wire located perpendicular to the beam axis. The probe floating potential was assumed to be approximately equal to the beam plasma potential. The magnitude of the maximum beam plasma potential was always found to be between one and three times the magnitude of the thruster floating potential. Thus, the coupling voltage, defined as the sum of the maximum beam plasma potential and the magnitude of the negative thruster floating potential, was found to be between two and four times the thruster floating potential for those tests in which the beam plasma potential was not measured. Inasmuch as the beam potential decreases with increasing distance from the thruster, this assumed relation between thruster floating potential and coupling voltage would not be valid for facilities differing greatly in length from the one used for these tests (21 m long). Figure 5 shows the probe floating potential, the keeper potential and the thruster floating potential as a function of the neutralizer mercury flow rate. The beam and keeper currents were held constant. The magnitude of the thruster floating potential varies in consort with maximum floating potential of the beam probe. The keeper voltage monotonically decreases with increasing flow rate. The spot mode (high Hg flow) is characterized by only a small spot of visible plasma at the cathode orifice. The corresponding keeper voltage is low in magnitude (5 to 10 v). When the plume mode (low Hg flow) the plasma bridge is visible and extends like a plume from the neutralizer to the beam. The keeper voltage in the plume mode is large in magnitude (20 to 50 v).

Accelerator Groove Erosion

The early thruster tests demonstrated that slow ions in the region of the neutralizer were falling back to surfaces at the accelerator potential of -2000 v. Resulting damage was in the form of a groove, usually eight or ten accelerator holes long and about one hole diameter wide. Using sputtering yields for 2000 v Hg ions, normally incident on Mo, a calculation showed that an ion current of about 0.2 ma was required to do the observed damage. Operating a given thruster first with the plasma-bridge neutralizer, and then with tank neutralization (neutralizer discharge off), resulted in a decrease of accelerator impingement current of about 0.3 ma. This confirmed that the possible ion current from the neutralizer was the right order of magnitude to do the observed damage.

Since the neutralizer cathode location was fixed by design constraints, it was not varied in attempts to solve the problem. Instead, 25 different configurations of bolt-on shields near the accelerator and/or neutralizer, as well as neutralizer keeper variations, were tested, The results of varying the shield and keeper designs were as follows. First, the location of the groove on the accelerator could be moved back and forth by changing the shield position or shape. Second, the variations produced a range of accelerator wear rates which varied by a factor of 7. All of these rates, when projected, indicated that the accelerator would be worn through before the end of the six month mission.

The final shield design was chosen to give a minimum groove wear rate. For this design the groove was within the last three rows of accelerator holes. To further increase the lifetime, the accelerator thickness was doubled in this region. With the doubled thickness, the projected lifetime to wear through the accelerator was six months. Based on tests with other size thrusters, the authors believe that lower groove erosion should be obtainable by repositioning the neutralizer cathode. This possible solution could not be investigated within the hardware design constraints and time limits of the SERT II flight schedule.

Although the use of a double thickness accelerator was based on the time to wear through the accelerator, the end of

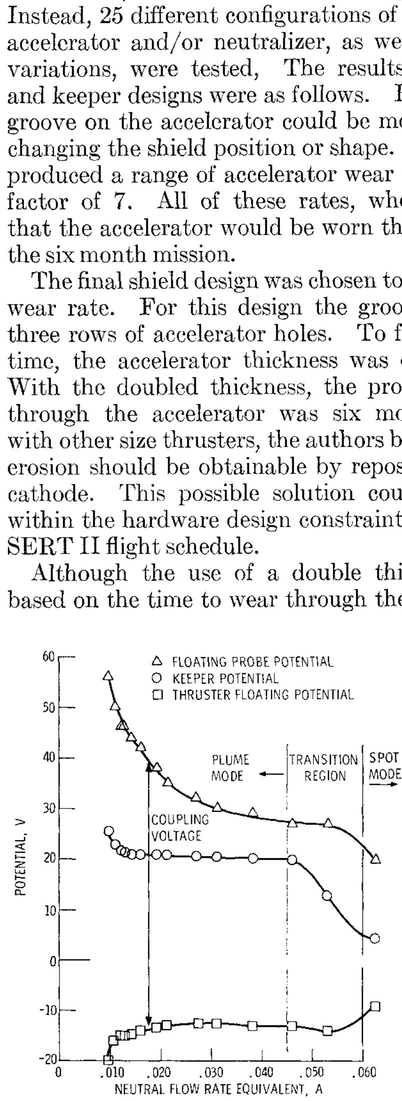

Fig. 5 Beam probe, keeper, and thruster floating potentials as a function of neutralizer flow rate. All potentials measured with respect to vacuum tank facility. Beam current = 0.25 amp and keeper current = 0.18 amp.

life of the thruster system is not necessarily that time. To really become a problem, the groove, in addition to wearing through the accelerator, must sufficiently increase in width to permit electron backstreaming. To investigate how wide a groove may be tolerated, a series of tests were conducted, using a SERT II experimental thruster with various grooves precut in the double accelerator grid. Over a range of normal SERT II operating voltages, electron backstreaming occurred only after a 3.5-cm × 1.1-cm groove was made in the accelerator electrode. The presence of this large opening did not affect neutralizer performance nor cause any noticeable direct ion impingement on the neutralizer. The accelerator "end of life" based on eroding a groove to a 1.1-cm width is triple the SERT II mission time.

Neutralizer Endurance Test

Shortly after the experimental thruster endurance tests were started (May 1967), an endurance test of a SERT II design neutralizer cathode was started in a bell jar. The cathode operated for 12,000 hr, emitting 0.25 amp to a collector plate. The cathode heater failed at 12,000 hr as a result of a laboratory power failure. Final analysis of this cathode has not been completed at the time of the writing.

There have been 13 interruptions to inspect the cathode orifice area and refill the Hg reservoir.

Figure 6 is a plot of tip thickness vs run time for the 12,000 hr. About one-third of the tip thickness at the orifice is worn away after 12,000 hr. The slope of the curve in Fig. 6 is nearly constant for the first 5000 hr and gives a projected lifetime of 20,000 hr. After 5000 hr the slope decreases. Based on the last 3000 hr of testing the projected lifetime (calculated in the same manner as for main cathodes) increases by more than an order of magnitude. The wear rate for this cathode is slightly less than that for a neutralizer cathode tested with a thruster. This may be because the average coupling voltage for the 12,000 test was 28 v as compared with 40 to 80 v during thruster operation.

Neutralizer Keeper Alignment

A series of tests were performed to observe the effects of neutralizer cathode-keeper axial asymmetries. These tests were done because seemingly identical flight-type neutralizers of another test program were requiring different mercury flow rates. One suspected difference was the axial asymmetry between the neutralizer cathode orifice and the keeper electrode. A flight-type neutralizer system was tested in a bell jar, the keeper being independently movable. Data was recorded at normal operating conditions. When the keeper hole center was offset from the cathode axis by one-fourth the keeper hole diameter, the keeper voltage decreased and the coupling voltage to a plate anode increased. Using SERT II control logic, the Hg flow was reduced to maintain a constant keeper voltage. When the Hg flow rate was reduced the coupling voltage increased further, enough to jeopardize the neutralizer cathode lifetime because of possible back-sputtering by Hg ions. This test was repeated with a SERT II flight-type thruster in an 8-m-long, 1.5-m-diam vacuum tank. A floating Langmuir probe was used to measure the beam plasma potential. Figure 7 shows the coupling voltage (the sum of the maximum beam plasma potential plus the magnitude of the thruster floating potential) as a function keeper voltage. The coupling voltage, at 21 v keeper voltage, is either about 30 or 85 v, depending on the axial symmetry of the cathode and keeper. Again the keeper hole center was offset from the neutralizer cathode orifice by one-fourth the keeper hole diameter.

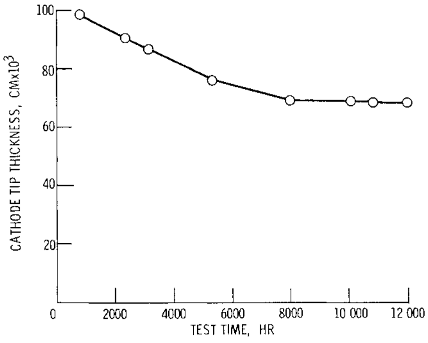

Fig. 6 Neutralizer cathode tip wear for 12,000 hr simulated operation in a bell jar. Collector current = 0.25 amp.

	KEEPER POTENTIAL, V	THRUSTER FLOATING POTENTIAL, V	BEAM POTENTIAL, V	NEUTRAL FLOW RATE EQUIV., A
○ SYMMETRIC	18.5	-10.1	15.0	0.061
	20.8	-10.6	17.9	.038
	22.0	-13.2	29.4	.018
□ ASYMMETRIC	17.7	-10.7	19.5	0.051
	19.3	-16.0	31.4	.018
	20.7	-28.5	50.0	.011

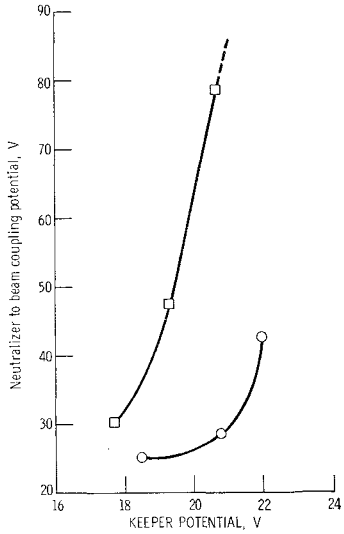

Fig. 7 Neutralizer coupling potential variation with keeper misalignment on flight-type thruster. Beam current = 0.25 amp and neutralizer keeper current = 0.20 amp, probe on beam axis.

High Current Cathodes

A 30-cm-diam mercury bombardment thruster, producing a 1.5-amp beam current has been tested.[6] The cathode initially used in this thruster was a SERT II hollow cathode operated at 5 to 20 amp of discharge chamber current. At these high-discharge currents, the SERT II cathodes had drastic orifice damage (apparently due to local melting). The orifice diameter increased to approximately four times the original diameter of 0.019 cm in several hours of testing. A SERT II type cathode was also tested in a bell jar, emitting to a metal plate collector, with nearly the same results after only 3 hr. The only power provided to this cathode was the discharge power which produced the self-heating. Ions formed in the discharge fall back to the cathode and are neutralized. The authors believe that it is this ion back flow that causes the major part of the self-heating. Since the melting type of damage occurred only when tip temperatures were extremely high, an effort was made to redesign the cathode to keep the cathode orifice area cooler. It was thought that the cathode orifice could be kept cooler by either using a larger diameter cathode tube, or by increasing the area of the orifice hole. Some of the results of bell jar tests, using two diameter cathode tubes and several sizes of orifices including multiple orifices, are shown in Fig. 8.

	TUBE DIAMETER CM	ORIFICE DIAMETER $\times 10^3$ CM	TIP THICKNESS, $\times 10^3$ CM	COLLECTOR VOLTAGE, V	NEUTRAL FLOW RATE, AMP
□	0.32	55	100	10	0.10
△	0.64	75	50	9	0.30
◇	.64	100	50	10	.23

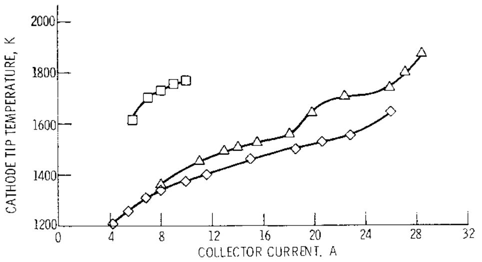

Fig. 8 Cathode tip temperatures for various size hollow cathodes; no heater power used.

The cathode tip temperature for all cathodes increased with an increase in emission current. The level of tip temperature was lower for the larger (0.64 cm) diameter cathodes. The larger diameter cathode with the larger hole diameter resulted in the lowest tip temperature. Multiple hole cathodes offered no consistent reduction in operating temperature. In addition, the multiple hole cathode discharges were unstable, and it was difficult to maintain a discharge simultaneously in all of the holes.

Five single-hole cathodes have been tested in a bell jar between 75 and 234 hr at high levels of emission current. Four tests were conducted at 10 amp emission, whereas the last was at 20 amp emission. In none of the tests was there any visible or measurable damage to the cathode tip.

Cathode Heat Balance

The cathode heat balance measurements and calculations have been done on the larger (0.64-cm-diam) cathode because this cathode is the size believed necessary for the larger emission currents of a 30-cm-diam thruster.[6] The 0.32-cm-diam cathodes used on the SERT II thruster system have a projected lifetime of at least 10,000 hr and are of less interest for study. The neutralizer of SERT II will probably be used directly for the larger beam currents of the 30-cm thruster, and should operate well at the higher levels (1.5 vs 0.25 amp) of emission.

A 0.64-cm-diam cathode instrumented with thermocouples was placed in a bell jar and heated without a discharge. One thermocouple was on the heat shield for radiation and two were on the tube to measure the conduction. The mercury vaporizer was also heated to produce the same vaporizer temperature and mercury flow to the cathode as existed when there was a discharge. The cathode heater power was varied from 8 to 45 w resulting in cathode temperatures ranging from 600° to 1400°K.

The vaporizer power was adjusted to hold a constant vaporizer temperature. The tip temperature was measured with an optical pyrometer.

The temperature measurements at a heater power of 30 w were used to estimate the amounts of heat lost from various parts of the cathode. The tube losses including conduction and radiation from the short tube length between the end of the shielding and thermocouple 3 was 11 w. The radiation from the tip face was 3 w. The total loss to the thermocouples was calculated to be 3 w. The sensible heat in the Hg vapor flow was less than 0.1 w. The sum of all these calculated heat losses is 28 w, which is in close agreement with the input power of 30 w.

The same 0.64-cm-diam cathode was then used to produce a discharge in the same bell jar. The mercury flow was held constant at the previous flow and the discharge was lit to the keeper and anode. To maintain a stable discharge at lower discharge currents a keeper current of about 0.5 amp was necessary. The keeper voltage was 1 to 2 v lower than the collector voltage. When the cathode heater was turned off, the cathode self-heating was sufficient to maintain the discharge. The level of the discharge current was varied by changing the collector potential. As the discharge current increased the temperature of the cathode increased.

The amount of self-heating power was deduced by combining the results of heating the cathode by the two different methods and eliminating the temperature. If it is assumed that the same amount of self-heating power and cathode-heater power is required to produce a given temperature reading, the value of the self-heating power can be determined. One advantage of this comparative procedure is the insensitivity of the result to temperature measuring errors. The comparative procedure was repeated for all thermocouple positions because it was not immediately obvious which thermocouple could best be used as a reference. Results are plotted in Fig. 9. Values of self-heating power range from 8 to 48 w over a discharge current range of 1 to 8 amp.

As can be seen from Fig. 9 different values of self-heating power were obtained for different measuring locations. Differences in heat flux are expected because the heater and the plasma add heat at different locations. The discharge, as plotted in Fig. 9, changed from the plume mode (Ref. 7) at currents below 2 amp to the spot mode at currents above 3 amp.

The slope of the curves of Fig. 9 is of interest because the slope is the quantity of self-heating energy per electron in the discharge. At 1 amp of emission, the slope (extrapolated back to the origin) is 8 ev/electron. The slopes have values of 2 to 5 ev/electron at higher values of discharge currents. The fraction of discharge current due to ion back flow may be estimated with the following equation:

$$P = J_+(V_i + V_s) - J\Phi_0$$

where P = self-heating cathode power, w; J_+ = ion current back to cathode, amp; V_i = first ionization potential, 10.4 v; V_s = cathode sheath drop, 2 to 11 v[7,8]; J = total discharge current, amp; Φ_0 = cathode work function, 2 to 4.5 v.

From Fig. 9 the value of P is 8 w for a J of 1 amp. If a value of 11 v is used for V_s, the ion current J_+ is about half the total discharge current. If a value of 2 v is used for V_s, the ion current is about equal to the discharge current. At higher values of discharge current, 10 amp, a similar calculation using a 30 w (3 ev/electron) self-heating power predicts that the fraction of ion current is only a fourth to a half of the total current. Any value of cathode self-heating due to excited neutrals releasing energy at the cathode walls would reduce the above calculated values of ion current fraction. The method used herein to measure cathode self-heating can-

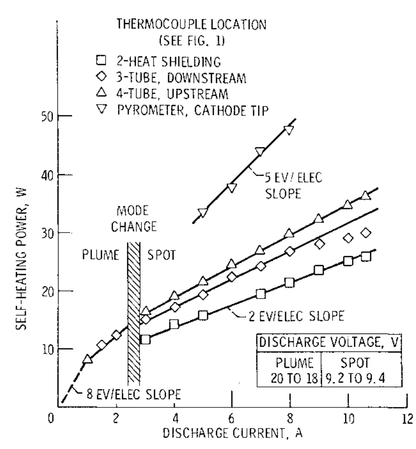

Fig. 9 Self-heating of a 0.64-cm-diam hollow cathode.

not resolve what part might be due to ion bombardment or to excited neutrals.

The location of the self-heating is deduced to be the region of the tip, because the tip temperature is hotter when self-heated than when heated by the same amount of cathode heater power. The self-heating power will produce temperature gradients in the cathode. Taking as an example a 2-amp discharge, the amount of self-heating (from Fig. 9) is 12 w. This heat flow will produce a calculated temperature difference of 47°K from the center of the tip to the outer edge. However, as the heat flows into the tube, it will produce a tube gradient of 530°K/cm. A small tip temperature variation of about 50°K, which is insignificant when compared to the 1500°K average tip temperature, was observed in pyrometer readings. The tube gradient was not measured, but in an early design, the tube near the tip had considerable corrosion damage, indicative of excessive temperature in this region. A cure used was a corrosion barrier of W between the Al_2O_3 insulation. A future solution might be to use a thicker-walled tube to reduce the tube gradient. This solution would both ease the corrosion problem and possibly extend the tip lifetime by a reduction of the cathode tip temperature.

Electron Emission

The mechanism of electron emission from a hollow cathode has been widely discussed but without universal agreement.[9] For the hollow cathode of the type presented in this paper, several mechanisms exist for producing electron emission and these will be discussed below.

There is thermionic electron emission that starts the discharge. This starting emission is low and much less than a space-charge-limited electron flow from the tip face to the keeper. The insert and other areas inside the hollow cathode may be activated and, although possibly capable of producing the operating levels of emission, may lack a way to overcome local space charge. Once the discharge lights, there are enough ions formed to overcome electron space charge effects. The electrons are emitted and conducted by the plasma out the cathode orifice. The inside surface areas stay activated because the ion bombardment energy (2 to 11 v) is less than the sputtering threshold of about 20 v. In addition, evaporation losses of activator are minimized by the confining geometry of the hollow cathode and insert.

Electron emission may also be produced by field emission at a cathode spot.[10,11] The high fields of 10^6 v/cm necessary to produce field emission may be present at the cathode surface. Such fields could be formed by a cathode sheath drop of 2 to 11 v and a sheath thickness of 10^{-6} cm. This sheath thickness was estimated by solving Childs law for an ion flow of 1 amp to the cathode for an area of 4×10^{-3} cm^2. The area represents about one-tenth of the inside surface area of the cathode. Analytical determination of an exact cathode spot size is beyond the scope of this paper and from self-heating measurements the ion back flow may be 1 amp for a 2-amp or greater discharge. The foregoing example serves to illustrate though that a spot size would not have to be too small to produce a high electric field. Any smaller spot size would increase the ion current density, reduce the sheath, and increase the field even further. A lower limit of spot size is determined by the ability of the cathode surface to conduct heat away without melting. Assuming an infinite tantalum slab at 1400°K (cathode insert) and an ion energy release of 15 w at the cathode spot requires a spot area of 2×10^{-5} cm^2 to produce a surface spot temperature of 3000°K. If such a cathode spot size and temperature existed, direct thermionic emission of sufficient magnitude is possible.

Some of the discharge electrons are produced as secondary electrons from ionization collision reactions. For every secondary electron which reaches the anode, an ion is formed which falls back to the cathode. The fraction of the total discharge current which is made up of this ion current is limited by the cathode self-heating, as previously noted, to a maximum value of 0.8 for a 1-amp discharge and to less than 0.5 at levels above 3 amp. The predicted values of ion back flow current will be reduced by whatever fraction of self-heating is caused by excited neutrals.

The authors believe that the actual cathode emission may be a combination of all three methods discussed, direct thermionic emission from activated surfaces, field emission at a cathode spot, and ion back flow to the cathode. Because hollow cathodes that successfully produce a discharge have been made without inserts or activators, it would seem that direct thermionic emission is a minor part of the total current when the total current is low. At the higher discharge currents of 10 to 20 amp, however, where the cathode is becoming very hot due to self-heating, thermionic emission could be producing more electrons. This conclusion is supported by the observation that the ratio of ion back flow to electron current is being reduced at the high discharge currents. If the limited ion back flow current is subtracted, the balance of emission must be produced by some field enhanced or spot emission.

Cathode Photographic Data

A 0.64-cm-diam cathode was used to establish a discharge to a flat place anode. The discharge was operated in either a spot mode (5.6 amp, 11.2 v, and 0.100 amp equivalent Hg flow) or the plume mode (5.6 amp, 33 v, and 0.031 amp equivalent Hg flow). A Fastex camera was positioned to obtain a head-on view of the cathode orifice. A special microscope lens was used to obtain magnifications that would resolve spot sizes of 2×10^{-3} cm. The camera was first used to photograph the spot mode. No spot nor discharge irregularities were noted for any framing rate from 1000 to 4000 frames/sec (16mm film). The framing method was then discontinued in favor of the continuous slit method. Photographs using a 0.0075-cm slit were taken of both the spot and plume modes. The spot mode produced a continuous light source. There was no evidence of any kind either of motion in the discharge or of a cathode spot rotating around the orifice. If an oscillation or rotary motion were occurring, its frequency had to exceed 2.7 MHz to be undetected. There was a slight luminosity gradient that was brighter at the edges of the cathode orifice and less intense at the center. This same luminosity gradient was also noted in the plume mode streak pictures. In all cases of observation, either visual or photographic, the intensity of the discharge was great enough to obliterate any detail of the insert or the walls of the cathode orifice.

When operating in the plume mode the streak pictures showed periodic and random changes in light intensity across the entire slit. There was no indication of any rotating or traveling cathode spot. The periodic frequency, which was much more evident during projection, was 75 KHz. The random luminosity changes which were superimposed on the periodic changes had band widths or lifetimes 2 to 4 times longer than the periodic changes. Typical random bands appeared in groups of two. The first band was higher than average luminosity and the second band was lower than average luminosity. At no time was there a complete absence of luminosity or complete interruption of the discharge.

If an acoustical velocity is calculated for mercury vapor at 1500°K and if this velocity is divided by twice the periodic frequency, a characteristic length of 0.2 cm is found. This length is close enough to dimensions inside the cathode that possibly the periodic oscillation is driven by an acoustical resonance. The absence of the oscillation in the spot mode may be explained by the thinness of the cathode sheath. A thin sheath could penetrate inside and act as an acoustical baffle that damps out oscillations or prevents resonating waves. Visual observations of a hollow cathode plume discharge indicate a conical-shaped intensely luminous area or "seed" that protrudes about 0.1 cm from the end of the orifice. When a cathode is in the spot mode this "seed" is absent and there is only an over-all brightness in the orifice.

The long term life of a hollow cathode, used either as a main or neutralizer cathode, has been shown to depend primarily on the wear of the front edge of the orifice. The photographic absence of any arc spot in this area tends to rule out arc spot or local evaporation theories. Either the photographic technique had insignificant sensitivity (felt to be unlikely) to show the cathode spot, or the wear is occurring from ion bombardment.

Concluding Remarks

Hollow cathodes, operated as main discharge cathodes, were tested in SERT II experimental thrusters for periods up to 2067 hr. To achieve long lifetime the cathode operating temperature which is a function of the discharge current, must remain low (1400°K). The discharge voltage must also be kept low enough to reduce sputtering damage. The upper limit for discharge voltage has not yet been firmly established. Based on the tests reported herein a safe voltage is 35 v.

Neutralizer cathodes were tested with an operating thruster for periods up to 3438 hr. For a neutralizer cathode to achieve long lifetime the coupling voltage to a beam must be kept low to prevent ion sputtering. This can be done by controlling the neutralizer flow rate to hold a constant neutralizer keeper voltage and thus hold a constant coupling voltage. Asymmetry of the keeper was found to be undesirable. Although it reduced the required flow rate for a given keeper voltage, it also resulted in a higher coupling voltage with a consequent lower projected cathode lifetime. A hollow cathode, tested as a simulated neutralizer in a bell jar, has operated for 12,000 hr.

Cathode self-heating power was measured and found to increase the cathode temperature as the discharge current was increased. Lower cathode temperatures at a given discharge current could be obtained by using larger diameter cathodes with larger orifice diameters. The ratio of the self-heating power to the discharge current decreased from about 8 ev/electron at low-discharge currents to about 3 ev/electron at higher discharge currents. This ratio indicates that more than half of the discharge current could be carried by ions in low current discharges, while less than one-fourth is carried by ions in high current discharges.

At the high-discharge currents the local cathode temperature may be hot enough to supply nearly all of the required current by thermionic electrons.

Although uncertainties exist in the theory of operation of this relatively new type of hollow cathode, a development program has produced cathodes with a projected lifetime of at least 10,000 hr for the SERT II thruster system. In addition, a larger hollow cathode has been developed that can produce an order of magnitude more emission for larger size mercury bombardment thrusters.

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