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INVESTIGATION OF HOLLOW CATHODE PERFORMANCE FOR 30-CM THRUSTERS

by Michael J. Mirtich
Lewis Research Center
Cleveland, Ohio 44135

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by Michael J. Mirtich
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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Abstract

A parametric investigation of 6.35 mm diameter mercury hollow cathodes was carried out in a bell jar. The parameters that were varied were the amount of initial emissive mix, the insert position, the emission current, the cathode temperature, the orifice diameter, and the mercury flow rate. Flow characteristic curves and performance as a function of time were obtained for the various cathodes of interest. Also presented are the results of a 3880 hr. life test of a main cathode run at 15 amps emission current with no noticeable changes in keeper and collector voltages.

Introduction

A program at Lewis Research Center is being carried out to develop thruster components. One aim of the program is to develop high performance, long life main cathode and neutralizer subsystems. To accomplish this objective, cathode parameters that can be varied include: orifice size, amount of emissive mix, insert position, emission current level, cathode temperature, and mercury flow rate.

Presented in this paper are the results of testing 6.35 mm diameter cathodes for use as both main cathodes and neutralizers. The cathodes were tested in bell jars, where the above mentioned parameters were varied. Of particular interest was performance as a function of time for a given cathode configuration. Thus, the time dependance of the characteristic curves, coupling voltage, keeper voltage, and temperature levels of cathodes are presented. Also presented are the results of a 3880-hour test of a cathode with a .75 mm orifice run at a 15 ampere emission level, with radiation shielding and a 1.27 cm rolled foil insert, coated with emissive mix, and recessed 1.91 cm from the cathode tip.

Apparatus and Procedure

Hollow Cathodes and Neutralizers

Hollow cathodes 6.35 mm in diameter and 5.72 cm long, made of tantalum tubing of wall thickness 0.38 mm had a 1.22 mm thick two percent thoriated tungsten disk electron beam welded to the tube. Holes were made in the thoriated tungsten tip by a controlled sandblasting technique that produced holes of desired diameter. The hole diameters in the cathodes ranged from 0.38 mm to 1.52 mm. Table I summarizes the various cathode configurations tested. Some cathodes tested had no inserts but a known amount of emissive mix was coated on the inside of the cathode and its tip. The emissive mix (R-500) was a barium carbonate and strontium carbonate mixture containing a nitrocellulose binder and suspended in a mixture of organic solvents. Cathode inserts were made of 0.012 mm thick tantalum foil 15 cm long and 1.27 cm wide, rolled into a coil, and dipped three times into the emissive mix. A flow passage of about 1.3 mm diameter existed along the center of the insert. The heaters used on the cathodes were tantalum wire enclosed in tantalum tubing and spot welded to the cathode. Radiation shielding made of seven layers of .015 mm thick tantalum foil was wrapped tightly around the heaters. Additional radiation shielding of the same type material enclosed the whole length of the cathode and formed two concentric cylinders. The cathodes were run in bell jars in a vertical position using a open loop wire keeper. The diameter of the keeper hole was 6.25 mm and the cathode to keeper spacing was 1.5 mm. For all cases tested the keeper current was 0.3 amperes. To simulate the thruster anode a 7.5 cm diameter Ta disk was placed 1.9 cm from the keeper. Thermocouples were used to measure cathode temperature at various locations along the cathode. Flow rates were measured using precision bore glass capillary flow tubes and time averaged liquid mercury flow rates were obtained for short periods of time.

Startup Procedure. The procedure used for starting the cathodes was to apply approximately 50 watts to the tip heater, 15 watts to the insert heater (if one were used) and 9 watts to the vaporizer heater. Once the desired temperature profile was attained, the keeper voltage was set at 300 volts and the collector voltage at 60 volts. After the discharge was initiated the flow was set to operate the cathode in the spot mode.

Vacuum Facilities. Tests on the cathodes were conducted in a 0.5 meter diameter bell jar. An oil diffusion pump, using a liquid nitrogen baffle, kept the bell jar pressure in the low 10^{-6} torr range. Mercury from the hollow cathodes was condensed on a liquid nitrogen cold trap.

Results and Discussion

Effect of Cathode Orifice on Performance of a Hollow Cathode

Figure 1(a) and 1(b) present collector and keeper voltages, respectively, as a function of mass flow rate for three cathodes with three different orifice diameters at several levels of collector current. The cathodes (1, 2, 3) (Table I) used to generate these curves were coated once on the inside of the cathode with emissive mix and the data was taken before the total run time on each cathode was 450 hours. From Figure 1(a), it can be seen that for each cathode, at a given emission current, there exists a region where the collector voltage is nearly independent of or increases slightly with mass flow. This region is usually called the spot mode. In the spot mode, the baseline collector voltage, for a given emission current, decreases as the orifice diameter increases. Also, with each of the cathodes tested, for a given orifice diameter, the baseline collector voltage decreased with increasing emission current. For the two largest orifice cathodes, the flow rate at which the transition from the spot to the plume mode occurred decreased with increasing emission current. The gradual transition to the plume mode observed by Rawlin and Pawlik[1] on SERT II neutralizers did not occur. Lowering the flow just slightly results in plume mode operation. This suggests that for a given cathode, there is a minimum emission current which must be drawn from the cathode in order to maintain spot mode operation and low mass flow rates. In turn, this minimum emission current increases with increasing orifice size. Fortunately, the expected lifetime of a hollow cathode also increases with increasing diameter at a given emission current (this will be discussed later).

Figure 1(b) shows that keeper voltage decreased with the diameter of the orifice as was the case of the collector voltage. In contrast to collector voltage, however, the keeper voltage decreased with increasing emission current and was relatively insensitive to mass flow rate.

The general conclusion then, is that for neutralizer operation where low flows and less than 2 ampere emission are required it is desirable to have a small cathode orifice. Exact specifications depend on considerations such as control and lifetime[2]. However, for main cathode operation, where emission currents are on the order of 10 amperes and greater, the impact of flow rate through the cathode is less than for the neutralizer. Hence, larger orifice cathodes are desirable, but up to a limit depending on peak and throttling level desired. This is also necessary from the standpoint of main cathode lifetime.

Cathode Lifetime

Orifice Erosion. Cathode orifice erosion is of concern and variations in orifice dimension can be measured with the use of an elastic impression[3]. After setting, the material is flexible enough to be removed from the orifice without deforming the impression. A photomicrograph at 40X magnification was taken of each mold. Presented in Figure 2 are the orifice contours taken for different cathodes run at various emission current levels for different lengths of time. Details of operation are given in Table I. Figure 3 shows the orifice diameter as a function of time for the cathodes presented in Figure 2. From the figures it can be seen that cathode 2 with a 0.75 mm orifice run at 8 amps emission for as long as 1977 hours showed little or no wear of the downstream tip orifice. However, a similar cathode configuration (cathode 4) run at 15 amps emission showed significant wear in the first 200 hours after which the wear rate decreased and apparently the hole reached an equilibrium geometry. This geometry resembles a 0.75 mm orifice with a chamfered tip[4]. There is virtually no erosion of the 1.52 mm orifice when run at 15 amps emission. Even though this was the case, a 1.52 mm orifice diameter cathode probably isn't the best choice as a main cathode for a 30 cm thruster because of the high flow rate penalty associated with keeping this cathode in the spot mode at beam currents of 2 amps. A 0.38 mm orifice cathode (5) run at an emission current of 2 amps for 2784 hours showed negligible wear and appears to be acceptable for the neutralizer in 30 cm thrusters.

Depletion of Low Work Function Material. Two cathode tests were run at 8 amps emission specifically to determine the depletion rate of low work function material. The orifice diameter for both was 0.75 mm and was selected on the basis of the orifice erosion tests mentioned above. For cathode 6, 23 mg of emissive mix was coated all along the inside of the cathode including the inside of the tip. For cathode 7, only 1 drop (~ .1 mg) of emissive mix was dropped onto the inside of the tip. A tip heater power of 50 watts was applied throughout the test. The neutral flow rate, required to obtain spot mode operation, was maintained for each cathode. Plots of keeper and collector voltage as a function of time for each cathode are shown in Figure 4. The initial values of collector (~ 10 v) and keeper (~ 7 v) voltage were the same for both cathodes. The vertical arrows shown in the figure indicate restarts of each cathode. After each startup, the collector and keeper voltage were initially lower than the equilibrium value recorded prior to the cathode shut down. However, after a few hours of running, the pre-shut down voltage levels were again reached. The collector and keeper voltages for both cathodes increased at slightly different rates for both cathodes during the tests. This increase in keeper and collector voltages is probably due to depletion of emissive material as no change in physical dimension was observed for either cathode. Both tests were terminated when the cathodes wouldn't restart, at 1950 hrs. for cathode 6 and 1600 hrs. for cathode 7. After the tests the cathodes were inspected. It appeared that there was still emissive material on the inside of cathode 6, but at least 3 cm from the tip.

Another indication of emissive material depletion is the characteristic curves of the collector voltage vs. the neutral mass flow presented in Figure 5 for cathode 6. The curves were taken at different times during operation of the cathode. Initially the collector voltage baseline level in the spot mode was around 10.5 volts, and there was a smooth transition into the plume mode at around 100 milliamps equivalent flow. As depletion of emissive material takes place the collector voltage rose and the minimum flow necessary to keep the cathode in the spot mode increased. The smooth transition from the spot mode to the plume mode also disappeared, and only in the spot mode could the cathode provide enough electrons to satisfy the emission current level required.

The results of the tests seem to indicate that the initial amount of emissive material used in a cathode is not as important as its location. Cathode 7 (0.1 mg of emissive material) ran at a tip temperature of 1400° C. At this tip temperature one could expect the BaO in the emissive mix to disappear as the vapor pressure at this temperature is sufficiently high to evaporate the BaO within hours. Nevertheless, cathode 7 lasted 1600 hours.

Cathode 6 had 23 mg of emissive material coated along the inside of the cathode. It lasted longer than cathode 7, and there was still emissive material in the cathode, but it was so far from the tip that with only one tip heater it could no longer be heated to high enough temperatures such that a sufficient supply of Ba was available to initiate and sustain a discharge. It was thus felt that proper location of the low work function material was important, such that it was not overheated, but yet kept at a high enough temperature to activate the cathode tip. Hence a program was initiated to place emissive material on inserts and to recess the inserts from the cathode tip, allowing the emissive material to run at temperatures cooler than the cathode tip.

Recessed Inserts. The first test with a recessed insert had a 1.27 cm long insert recessed 3.45 cm from the tip in a cathode with a 0.38 mm tip orifice. Two C-A thermocouples were placed on the cathode, one at the cathode tip and the other over the insert. Upon applying 81 watts to the tip heater, the tip temperature went to 1100° C and the temperature over the insert to 600° C. After applying 300 volts to the keeper and 60 volts to the collector, the cathode wouldn't start (the Hg flow was around 200 ma). The insert was moved up, such that the forward end was located 2.86 cm from the tip. A two heater system was used for this cathode with one heater located over the insert and the second heater over the tip. With the tip temperature at 1100° C and the insert at 840° C, the cathode also would not start.

The first successful start of a recessed insert was a configuration where the insert coated with 69 mg of emissive material was at a position 1.9 cm from the tip. This cathode (8) configuration shown in Figure 6 had thermocouples located on the tip and 1.9 cm from the tip. The insert thermocouple just before the start up read 825° C and the thermocouple located on the tip 826° C. These temperatures were much lower than those attained in the unsuccessful start up attempts of the previous cathodes, where the inserts were recessed greater than 1.9 cm from the cathode tip. After start up, it was found that because of the radiation shielding the heaters could be turned off, the only effect being a 1 volt rise in keeper and collector voltage. This cathode was then run at 2 amps emission current for 1400 hours with 17 successful restarts at the same initial start up conditions. The keeper and collector voltages as a function of time are shown in Figure 6. Both the keeper and collector voltages rose between one and two volts over the test period but remained constant over the last half of the test. After testing in a bell jar cathode 8 was also run in a 30 cm thruster[5] as a neutralizer with a beam current of 2 amps. In the thruster test both the keeper and coupling voltages were 19 volts, for a keeper current of 500 ma and an equivalent flow of 84 ma. With this cathode as a neutralizer in the thruster, it was possible to reduce the Hg flow to 35 ma and still maintain a coupling voltage of 22 volts.

Another cathode test, cathode 5, was then performed which was identical to the previous test of cathode 8 except that: (1) the insert was pulled back 1.27 cm instead of 1.9 cm and (2) a single heater (Fig. 7) was used rather than a double heater. Cathode 5 ran for a total of 4300 hours at neutral flow rates of approximately 96 ma, and was restarted 17 times during this interval. Moving the insert to a position 1.27 cm from the orifice reduced the initial coupling and keeper voltages to 13 and 12 volts respectively. A history of the collector and keeper voltages and insert thermocouple temperature is shown in Figure 7. Initially the keeper and collector voltages were about the same value, however, after 1500 hours the collector voltage rose to 15.5 volts while the keeper voltage remained relatively stable at 12 volts. This cathode was removed from the bell jar after running 2600 hours and exposed to atmosphere for two months. The cathode was placed back in the bell jar by itself and run with no other cathode in the bell jar. This caused an increase in keeper voltage, but had no effect on the collector voltage. The test was terminated when a facility failure at 4300 hours caused the cathode tip to become detached from the rest of the cathode.

Figure 8 shows the effect of recessing a 1.27 cm long insert coated with emissive material on the baseline keeper and collector voltage for a 0.38 mm orifice cathode run at an emission current of 2 amps and 75 ma equivalent Hg flow. It can be seen that both the keeper and collector voltage increased with increased distance from the tip. This trend has been observed by Bechtel[6] in thrusters.

Since the results of the tests with cathodes run at 2 amps emission current indicated no change in performance for an insert recessed 1.9 cm from the tip, a 1.9 cm-recessed insert was placed in cathode 9 with a 0.76 mm orifice and run at 15 amps emission current. Cathode 9 used two heaters, one over the tip and a second heater over the insert, as shown in Figure 9. Radiation shielding consisting of two concentric cylinders of 0.015 mm Ta foil was placed around the entire cathode to allow passive operation of the heaters, and to simulate more closely the thermal environment of a cathode in a thruster[7]. To initiate a discharge the cathode was heated and the preheat temperature profile shown in Figure 10 was attained. The temperature of the cathode behind the insert heater was 910° C and the tip temperature 1100° C. Attempts to decrease these temperatures and initiate a discharge were unsuccessful. The temperature profile at 15 amps emission current, with no heaters on, is shown in Figure 10 by the triangular symbols. At this condition (with 190 ma equivalent flow) the tip temperature was 1450° C and the thermocouples upstream and downstream of the insert read 930° C and 1005° C respectively. This thermal condition did not vary throughout the 3800 hour duration of the test. Also shown in Figure 10, by the square symbols is the small rise in temperature along the cathode associated with applying 44 watts to the tip heater. It should be noted that there was a compression fitting between the cathode and the vaporizer, and hence the temperature profile here is dashed in the figure, since no thermocouples were employed in this region.

Presented in Figure 11 is a plot of the keeper and collector voltage for cathode 9 for a total test duration of 3880 hours. For the first 700 hours of the test, the cathode was run at an emission current of 8 amps, and 15 amps for the rest of the test. Resistance checks on the heaters, measured periodically throughout the test, indicated no noticeable changes in resistance. The neutral flow was maintained between 190 to 225 ma equivalent flow. The cathode was turned off at random during the test for periods ranging from one hour to ten days (after 2274 hours of running time had elapsed) when a mold was made of the orifice. (Note, that this exposure to atmosphere did not degrade the cathode.) The mold impression of the orifice is presented in Figure 2 and indicates little wear other than original chamfering which takes place in the first 700 hours for a cathode run at 15 amps emission (see Fig. 3). The characteristic curves taken periodically during the test indicated the base line keeper and collector voltages in the spot mode did not vary with mass flow. The base line collector voltage and keeper voltage started at 15 volts and 12 volts respectively. During restarts of the cathode these base line levels were reduced to about 9.5 volts and 7 volts respectively and as little as a few hours later rose to the equilibrium values of 15 volts for the collector and 12 volts for the keeper. The voltage levels remained relatively unchanged for a total test time of 3880 hours. Even though the cathode was running well at 3880 hours the test was terminated for inspection of the insert. Visual inspection and spectrographic analysis indicate that the front half of the insert was depleted of emissive material, while the rear half appeared to still have emissive material present. The insert itself was still ductile after 3880 hours.

To check the base line keeper voltage and collector voltage as a function of insert position for a 6.35 mm cathode with a 0.75 mm orifice run at 15 amps emission, a 1.27 cm insert coated with emissive material was also placed in two identical positions, 1.27 cm from the tip, and right at the tip. These data are shown in Figure 12. For this cathode, run at 15 amps emission current, the base line keeper and collector voltages increase as the insert is recessed from the tip. This was also true for the 0.38 mm orifice cathode run at 2 amps emission current. However, the rate of voltage increase is not as great for the 0.75 mm cathode run at 15 amps (see Fig. 8).

A possible reason cathode 9 maintained voltage integrity is that the insert (i.e., emissive material) ran relatively cool, when compared to the other cathode insert configurations operated at emission current levels that result in tip temperatures of 1400° C. The temperature of the cathode on either side of the insert (as shown in Fig. 10) was 980° C and 1005° C respectively. Placing emissive material closer to the tip, as was the case of the 0.1 mg of emissive material deposited on the tip, allowed the emissive material to run too hot, and deplete at a rate too fast to allow restart reliability and long life time. Hence it would appear that the reason this cathode maintained integrity longer than any of the others tested was that the insert location was such that it wasn't hot enough to deplete the emissive material, but was close enough to the tip to initiate and maintain a discharge. However, cooling the cathode too much (i.e., by adding a radiation fin at the tip) may not by itself be the total solution to long lifetime. Preliminary data taken at Lewis but not presented here indicates that a 0.76 mm orifice cathode run at 12 amps emission current with a radiation fin is showing increases in collector and keeper voltages after 1000 hours of operation. The tip temperature of this cathode is 950° C and the temperature behind the heater and over the front of the insert is 860° C. These temperatures are considerably lower than those recorded over the insert on the cathode run at 15 amps for 3880 hours. The data shown in Figure 7 for the 0.38 mm orifice cathode run at 2 amps emission also shows degradation in performance, even though the cathode tip temperature ran below 900° C for most of the test and the temperature of the cathode over the insert 650° C. The difference in performance seems to be the fact that the 3880 hour cathode had a high tip temperature (1450° C) and a cool insert location. This combination may have led to long life time. The need of a high tip temperature is implied in the work of Fearn and Phillip[8], who showed it was possible to initiate a discharge in a cathode without emissive material providing the tip temperature was sufficiently high. Thus, it would seem that the combination of low work function material being present and kept cool in the cathode tube and a tip temperature sufficiently high to sustain the needs of the desired discharge current (but not high enough to physically degrade the cathode tip) may lead to prolonged cathode lifetimes. Detailed attempts to describe the physical mechanisms taking place in the recessed-insert-type cathode is beyond the scope of this paper, but merit investigation.

Conclusions

From the characteristic curves of voltage as a function of neutral mass flow, it was found that increasing the orifice diameter of a cathode operated in the spot mode decreases both the coupling and keeper voltages for the same emission current. A larger orifice cathode needs a higher neutral flow rate to maintain operation in the spot mode and higher emission currents are required for stable operation. For neutralizer operation it is desirable to have a small orifice cathode, since this cathode allows low flows on the order of 50 milliamps for low emission current levels of 2 amps.

Measurement of the wear of the cathode orifice indicate that there is little or no change in dimension for: a 0.38 mm orifice cathode run at 2 amps emission, a 0.75 mm orifice cathode run at 8 amps emission, and a 1.52 mm orifice cathode at a 15 amps emission current. A 0.75 mm orifice cathode, presently used at Lewis as the main cathode in a 30 cm thruster, showed initial chamfering of the orifice, but thereafter maintains physical integrity.

It was found possible to run a 0.75 mm orifice cathode with an initial amount of only 0.1 mg of emissive material for 1600 hours at 8 amps emission level. Tests using various amounts of emissive material on the inside of the cathode indicate the initial amount of emissive material is not so important as its location to provide cathode reliability and lifetime.

Recessing emissive material coated inserts caused an increase in base line keeper and collector voltages in the spot mode, but could reduce any changes in cathode performance levels with time. It was also found that proper radiation shielding of the cathode allowed passive operation of the cathode tip heater during normal operation, resulting in a power savings.

A 6.35 mm cathode with a 1.27 cm insert, recessed 1.9 cm from the tip showed no changes in base line keeper and collector voltage when run at 15 amps emission current for 3880 hours.

The results of the bell jar tests indicate that proper location of emissive material is important. It also seemed important that a combination of low work function material properly placed at a cool location in the cathode and a high tip temperature are desirable to insure cathode reliability and prolonged lifetime.

References

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Table I

Summary of Cathode Configurations Tested

CATHODE NUMBER	ORIFICE DIAMETER, CM	EMISSIVE MATERIAL	INSERT POSITION, DISTANCE RECESSED FROM TIP, CM	NUMBER OF HEATERS	EMISSION CURRENT, AMPERES	TOTAL HOURS
1	.38	coated, inside of tip	-	1, tip	2	1000
2	.75	coated, inside of tip	-	1, tip	8	1000
3	1.52	coated, inside of tip	-	1, tip	15	1000
4	.75	coated, inside of tip	-	1, tip	15	1200
5	.38	insert, 69 mg	1.27 cm	1, tip	2	4300
6	.75	coated, 23 mg on inside of cathode	-	1, tip	8	1950
7	.75	coated, .1 mg on inside of tip	-	1, tip	8	1600
8	.38	insert, 69 mg	1.9 cm	2, (1 over insert) (1, tip)	2	1400
9	.75	insert, 69 mg	1.9 cm	2, (1 over insert) (1, tip)	15	3880

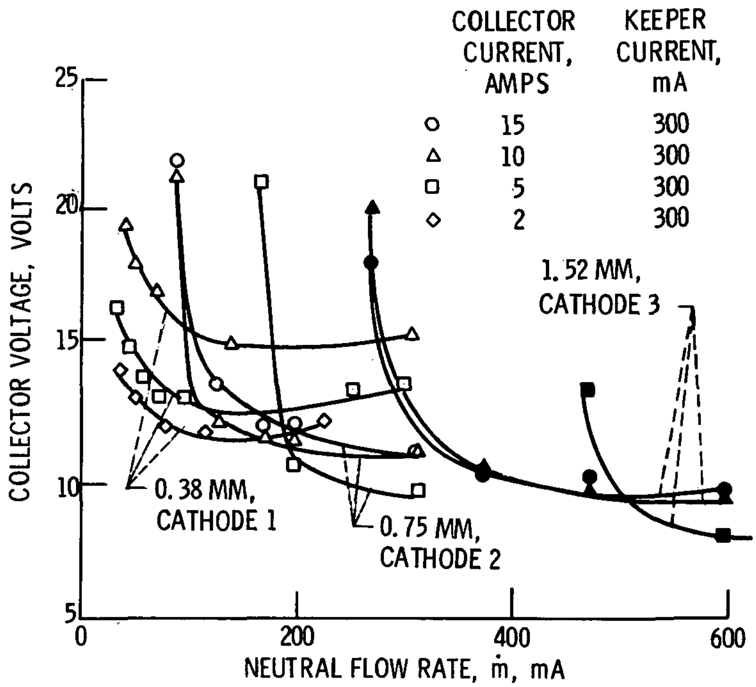

Figure 1(a). - Variation of collector voltage with neutral flow rate at different emission current levels for various orifice size cathodes.

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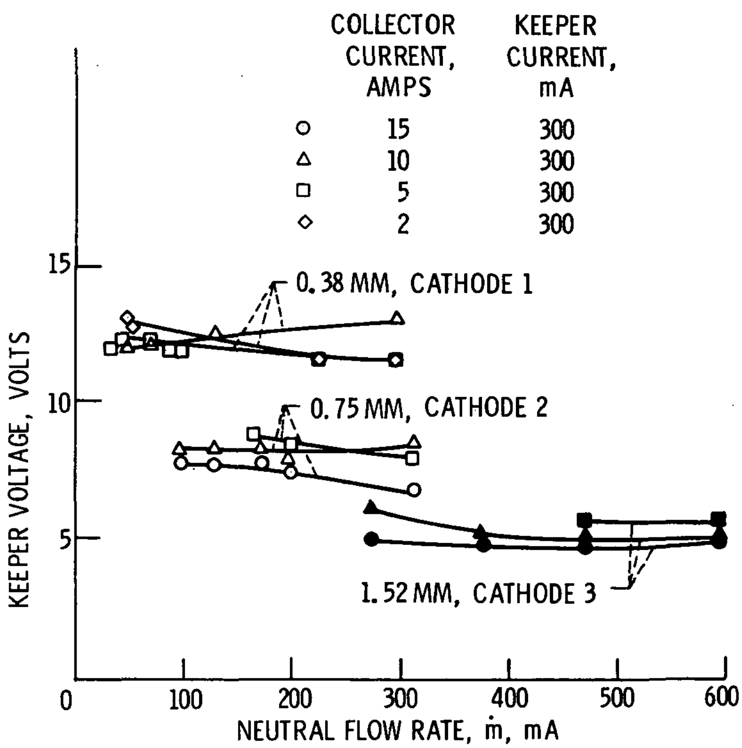

Figure 1(b). - Variation of keeper voltage with neutral flow rate at different emission current levels for various orifice size cathodes.

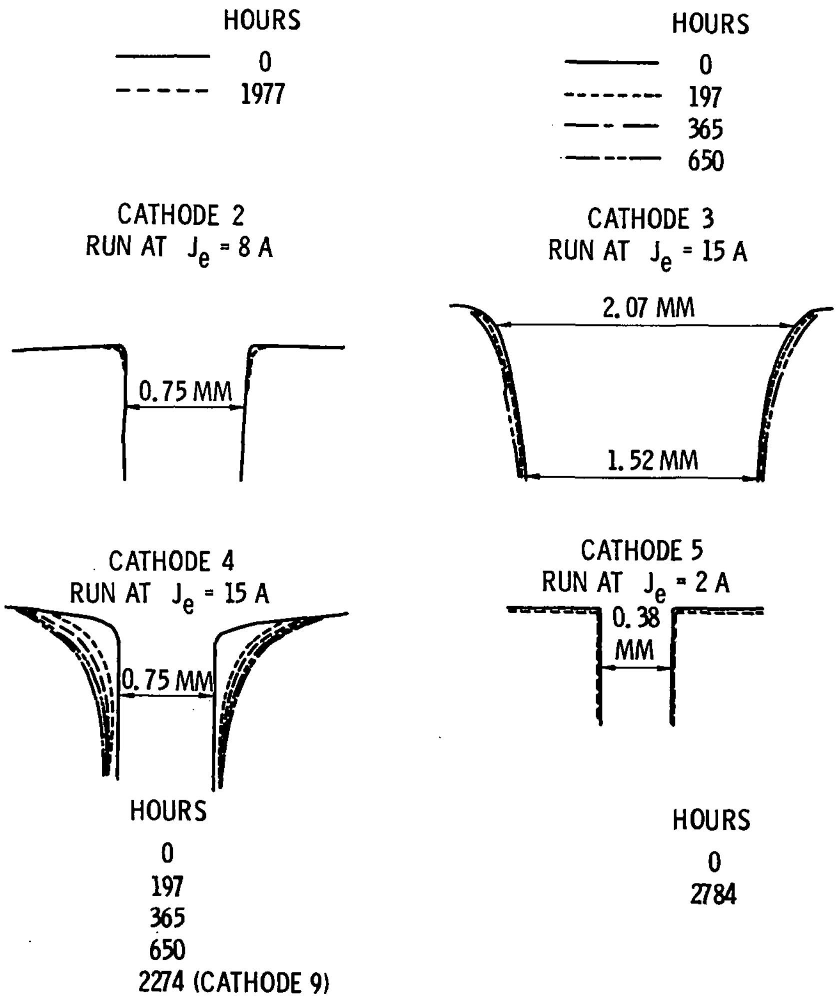

Figure 2. - Orifice contours taken for different cathodes. 40 X Magnification.

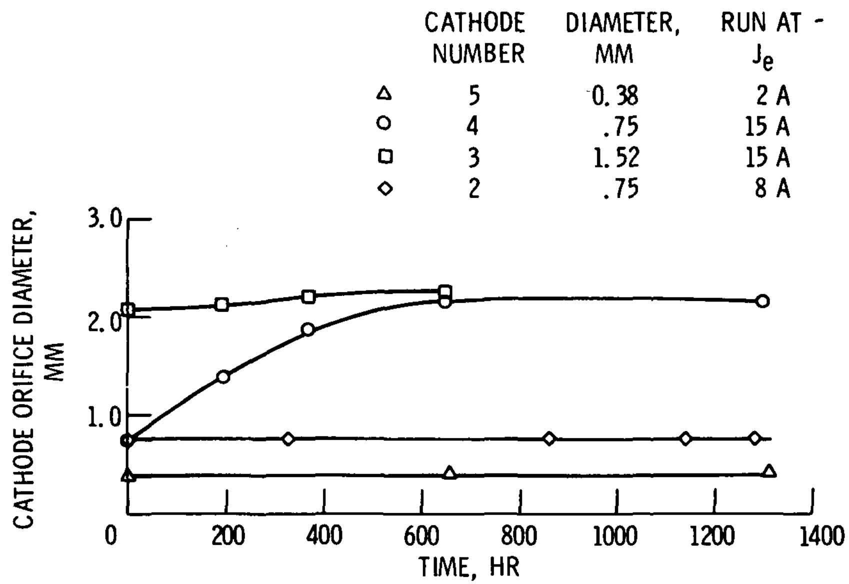

Figure 3. - Cathode orifice diameter as a function of time for different cathodes run at various emission current levels for different lengths of time.

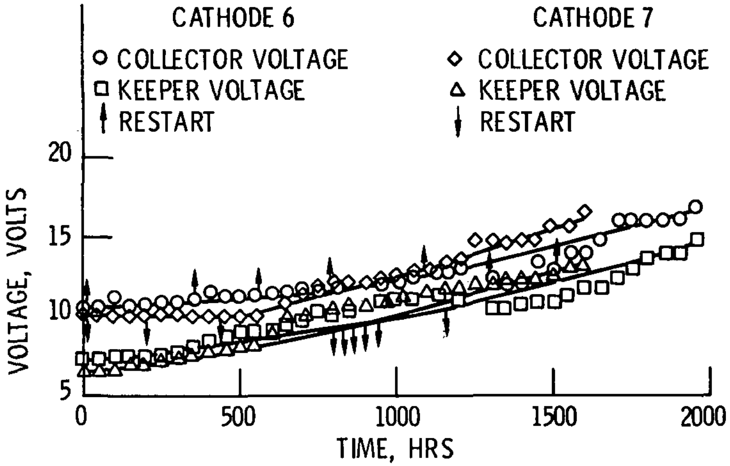

Figure 4. - Keeper and collector voltages as a function of time for cathodes 6 and 7.

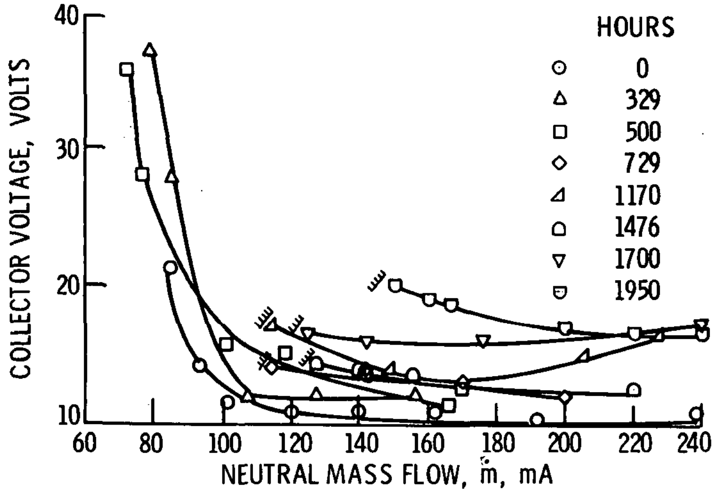

Figure 5. - Variation of collector voltage with neutral flow taken at various times for cathode 6.

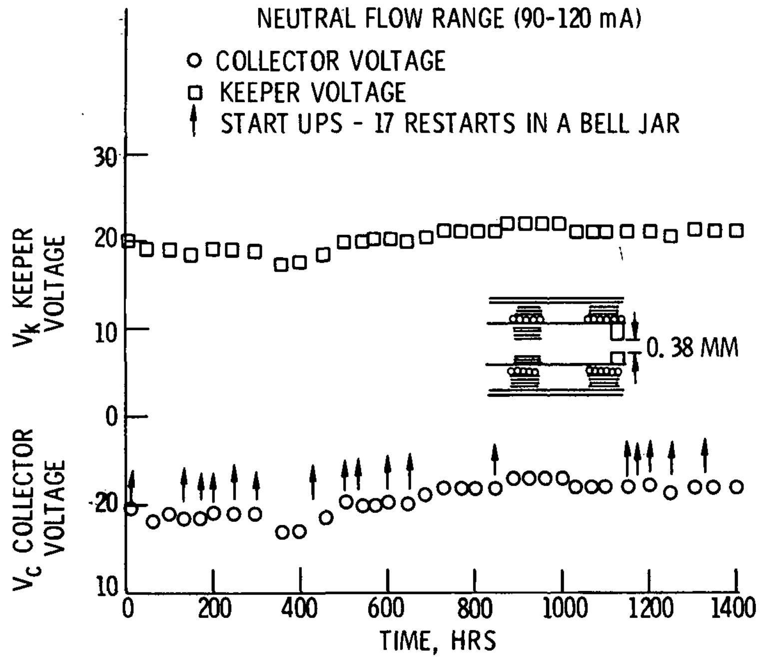

Figure 6. - Keeper and collector voltages as a function of time for cathode 8.

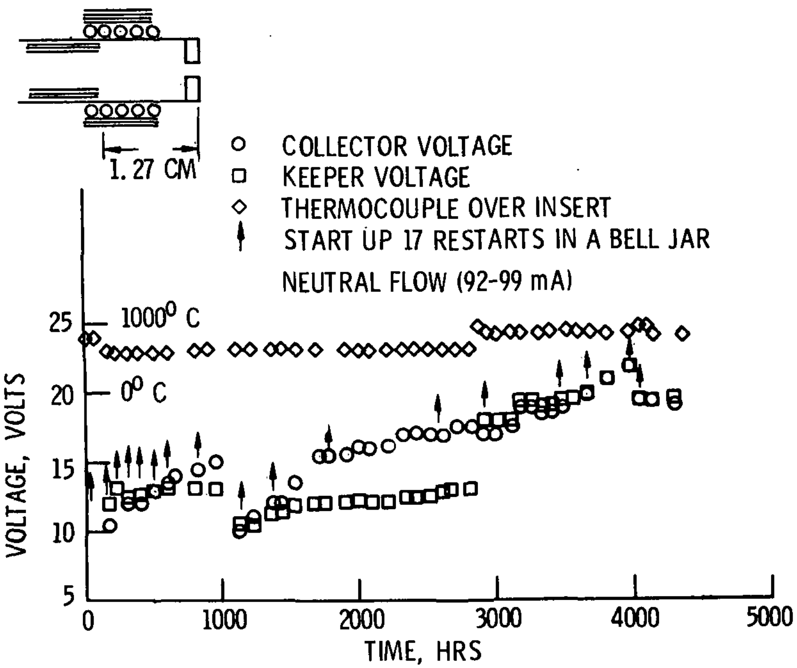

Figure 7. - Collector and keeper voltages as a function of time for cathode 5.

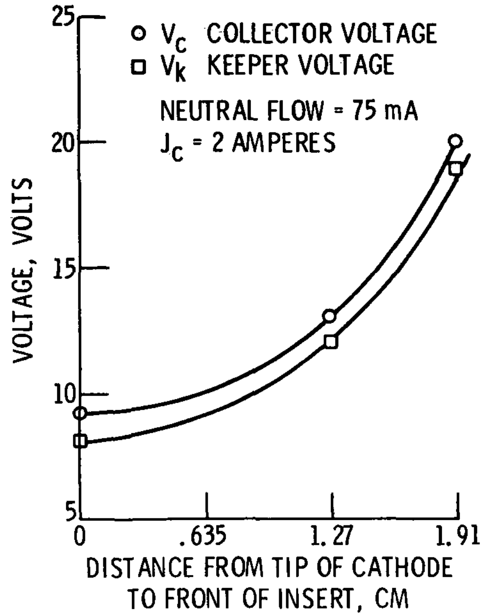

Figure 8. - Effect of insert position on baseline keeper and collector voltages for a 0.38 mm orifice cathode run at 2 amperes emission current.

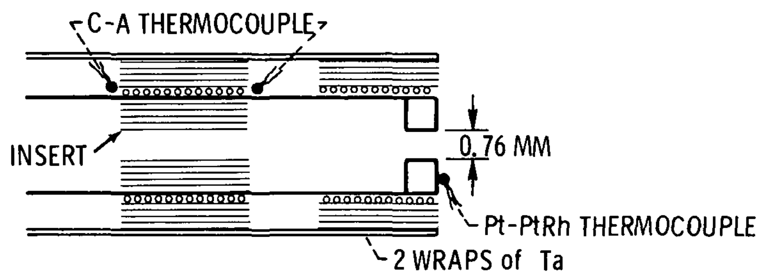

Figure 9. - Configuration of cathode 9.

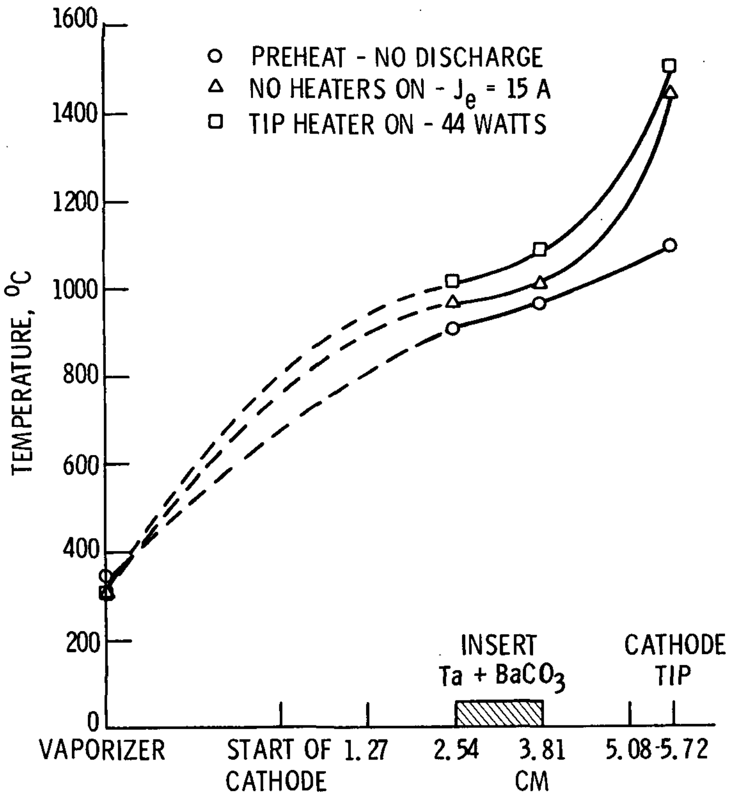

Figure 10. - Cathode temperature profile.

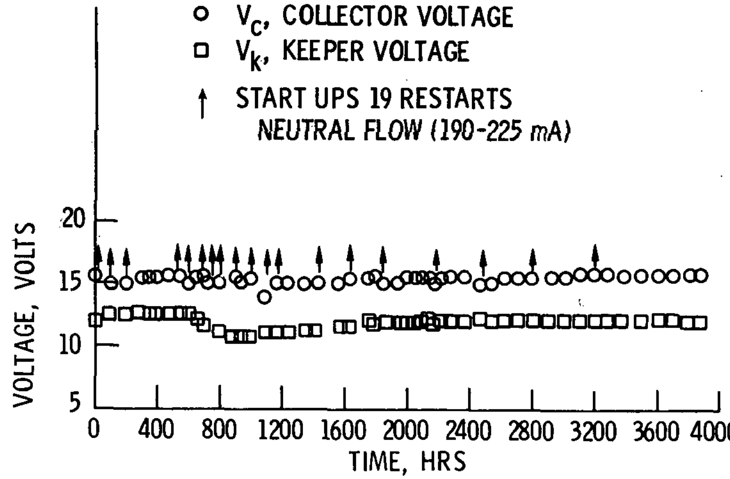

Figure 11. - Keeper and collector voltage as a function of time for cathode 9.

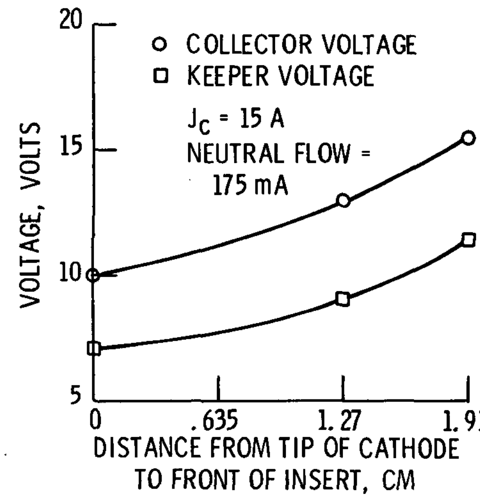

Figure 12. - Effect of insert position on baseline keeper and collector voltage for a 0.75 mm orifice cathode run at 15 amperes emission current.