

An Evaluation of Hollow Cathode Scaling to Very Low Power and Flow Rate

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Abstract

As Hall and ion thrusters are scaled to power levels below 300 W to operate on small- and micro-satellites, hollow cathodes must be designed to accommodate the new operating regimes with efficient use of power and propellant. The conclusions of previous cathode scaling efforts by other authors are reviewed, and the importance of heat transfer and orifice processes are emphasized. Performance data for 3.2 mm orificed hollow cathodes are presented. Spot mode operation was achieved on Xe at the same equivalent mass flow rate as the SERT II ion thruster neutralizer. An insert with a diameter on the order of the orifice size was tested and required ten times the mass flow of the SERT II neutralizers to generate enough ions within the cavity for charge neutralization. Design considerations are discussed for improvement of the power and propellant consumption of the cathodes presented in this work.

Nomenclature

AR	= orifice to insert area ratio
d	= orifice diameter
D	= insert diameter
I	= current, A
J_o	= equivalent flow rate, A
l	= orifice length
L	= orifice plate to keeper gap length
W	= atomic mass, amu
	= cross-section, m ²

Introduction

The advent of small satellite constellations for cellular communications and their need for efficient propulsion has driven electric thruster design toward low power levels, typically 300 W or less. Candidate thrusters for these missions include resistojets, arcjets, ion thrusters, and Hall thrusters. Both ion and Hall thrusters use hollow cathodes, and scaling these thrusters to power levels below the kilowatt-class devices currently planned for use involves reduction in thruster component size. The 6.4 mm diameter cathodes currently employed in ion and Hall thrusters in the United States consume needlessly large fractions of the power and propellant for low power thrusters. Such thrusters will require between 0.2 and 1.5 A of current from their discharge cathode or neutralizer. Consequently, an investigation is underway to examine the scaling of hollow cathodes to minimize the consumption of power and propellant. This paper presents the initial

experimental investigation of 3.2 mm diameter orificed hollow cathodes and discusses the issues relevant to further reductions in cathode power and propellant consumption.

Orificed hollow cathodes generate a plasma within a cylindrical cavity by the thermionic emission of electrons from a low work function insert. The plasma then flows through an orifice and couples the cathode to the rest of the discharge. Since the plasma is largely confined within the hollow cavity and little power is required to sustain the thermionic emission relative to a more open geometry, this configuration permits low cathode fall voltages. Further, the plasma facilitates electron emission by neutralizing the effects of space charge. If the thermal flux of electrons from the orifice is sufficient to carry the discharge, the electric field between the keeper electrode or anode accelerates those electrons to maintain the current. This type of operation is called spot mode. As the mass flow rate decreases, the thermal flux becomes less than the discharge current, and additional ionization events must occur as the electrons traverse the gap between electrodes. This is termed plume mode operation. The ions created in the gap have some fraction of the cathode fall to accelerate them toward the cathode orifice plate which exhibits damage, presumably from ion sputtering, when operated in plume mode. Whether this erosion prohibits cathodes operating in plume mode from fulfilling mission requirements has yet to be

established. However, extended lifetime operation has been demonstrated to more than 25,000 hours¹ in spot mode which is consequently the preferred operating condition. As a result of these phenomena, cathode efficiency is dependent upon scaling of the flow rate necessary to maintain spot mode emission.

It is also necessary to reduce the power consumption of current generation 6.4 mm diameter cathodes. These cathodes typically operate at several tens of watts.² Power deposition to the cathode acts to maintain thermionic emission by balancing electron cooling, thermal conduction along the cathode tube, and radiative transfer to the surroundings. Clearly a reduced current requirement decreases the electron cooling. However, to minimize the heat loss due to conduction and radiation, geometric modification of the cathode becomes necessary. This forms the basis for the drive toward physically smaller cathodes than the 6.4 mm diameter cathodes currently in use.

This paper begins by reviewing the previous work performed in cathode scaling. The experimental apparatus is discussed, followed by a summary of the performance of the cathodes. The implications of these results on the design of even more efficient hollow cathodes is discussed, and finally, the conclusions are summarized.

Cathode Scaling Background

Both 6.4 mm and 3.2 mm outer diameter hollow cathodes have been under investigation since the middle 1960's, although most of the recent work in the United States has focused on the 6.4 mm cathodes.^{2,3,4,5,6} The SERT II space test of mercury ion thrusters formed the basis for most of the hollow cathode work in the late 1960's and early 1970's in the U.S.^{3,7,8} One of the first attempts to develop a scaling law for orificed hollow cathodes was introduced by Kaufman.⁹ In this work, spot mode operation was observed provided that the ratio of the equivalent mass flow to the orifice diameter in a mercury hollow cathode exceeded an empirically determined constant:

$$\frac{J_o}{d} \quad 0.14 \text{ to } 0.40 \quad (1)$$

This equation gives a means by which to minimize the mass flow rate for a given cathode.

As inert gas thrusters began to be preferred, research on hollow cathodes also gradually moved toward use with the noble gases.^{2,5} Rehn and Kaufman¹⁰ expanded the dimensional analysis shown by Equation

1 to apply to inert gas hollow cathodes. A generalized criterion for spot mode operation that is dependent upon the propellant species was presented:

$$\frac{J_o \sqrt{W}}{d} \quad 13.9 \times 10^{-20} (\text{A}^{-\text{m}^2} \text{-amu}^{0.5} / \text{mm}) \quad (2)$$

The cross-section used in this analysis was the maximum value for the ionization of neutrals by electrons.¹⁰ In addition, some effort was made to correlate the coupling voltage and the electron emission to the propellant type. The voltage parameter scaled as the inverse of the ionization potential. Consequently, the discharge voltage and power were shown to increase with the propellant ionization potential. Geometric considerations were absent from the voltage parameter.

A more rigorous phenomenological model for orificed hollow cathode operation was introduced by Siegfried and Wilbur¹¹ in 1981, and then refined by the same authors in 1984.¹² This model examined the physics of the plasma within a mercury hollow cathode. While the model demonstrated qualitative agreement with experiments, little discussion was presented about using the model to scale the cathodes.

Work by Salhi and Turchi^{6,13,14} expanded on the phenomenological model of Siegfried and Wilbur to reduce the number of experimental inputs to the model and to include two dimensional variation in the heavy particle temperature. The model was used to establish some scaling relations for high current (greater than 20 A) cathodes. All of their results were in the limit of high power density where the dominant cooling mechanism was electron emission. Although this limit may be ill-matched to operation of low current cathodes, the trends predicted by this model are summarized here.

The maximum discharge current for a given cathode was shown to be proportional to the insert inner diameter;⁶ i.e.,

$$I \propto D \quad (3)$$

As the area ratio between the orifice and insert, $AR = (\psi_D)^2$, decreases, so does the maximum current that the cathode can carry. A smaller area ratio or a smaller insert diameter leads to a reduction in the cathode fall voltage for a given discharge current. This result shows that the smallest cathode capable of carrying a given current is also the most efficient since the power deposition is the smallest in this case. The model also predicted that larger cathodes tend to operate at low temperatures relative to small cathodes. These results provided insight into the

complex relationship between the orifice and insert diameters.

Modeling of the physical processes within the orifice has been comparatively less wide-spread. Mandell and Katz¹⁵ have developed a model describing the mechanism behind the transition from spot to plume mode based on a control volume approach in the orifice. This model treats the insert region as a plasma source. It balances ion production and loss, and energy within the orifice to determine electron temperature and number density given the discharge current and flow rate. The thermal flux of ions from the insert region is neglected. The model facilitates optimization of cathode geometry versus operating conditions, and illustrates that the ratio of the orifice length to diameter, l/d , should be optimized to provide a high gas utilization without driving up the cost of ion production. Both power consumption and gas utilization were found to scale with the ratio, l/d . Additionally the model provided an alternative method for determining the transition to plume mode by equating the thermal flux of electrons to the keeper with the discharge current. This condition defined the lower limit necessary for spot mode operation.

The most recent iteration on the phenomenological model was developed by Capacci, et al.¹⁶ This work builds on the work by Siegfried and Wilbur by including models of both the orifice region and the expansion toward the keeper. The voltage-current characteristics in this work accurately model the transition to plume mode operation, and the trends are in good qualitative agreement with experiment. The predictions of these models will be compared with the results of the current experimental investigation, and the consequences of these data for very low power and flow rate cathodes will be discussed.

Experimental Apparatus

All cathode tests were performed in port 2 of Tank 11 at the NASA Lewis Research Center. This port was isolated from the tank using a vacuum gate valve, and the vacuum was maintained using a cryopump. The base pressure in this tank was approximately 4×10^{-8} Torr, and the pressure in the vessel during testing ranged from 9×10^{-6} to 4.6×10^{-5} Torr on Xe. A flow system using a 0 to 5 sccm volume flowmeter and a needle valve supplied 99.999 percent Xe to the cathode with an accuracy of ± 0.1 sccm.

The experimental configuration is illustrated in Figure 1. A swaged heater was friction fit around the

outside of the cathode tubes. For these tests, only a molybdenum keeper was used to evaluate performance. Table 1 gives the area ratio and l/d . The two mechanically identical cathodes with BaO:CaO:Al₂O₃ impregnated porous tungsten inserts were tested and referred to as SC.001 and SC.002. Additionally, a cathode with a rolled-foil insert coated with R500 low work function compound was used to evaluate the effect of insert diameter on the performance. This was referred to as SC.002rfi since it was tested in the SC.002 tube prior to the tests with the porous tungsten insert. Consequently, the orifice geometry was identical to the other cathodes within the design tolerances. However, the insert diameter was on the order of the orifice diameter. This was accomplished by rolling a long piece of foil until a small inner diameter was achieved. The application of the R500 further reduced the insert inner diameter. This cathode had l/d and area ratios of 9 and approximately 1, respectively. The large area ratio made the orifice length, l , somewhat ambiguous.

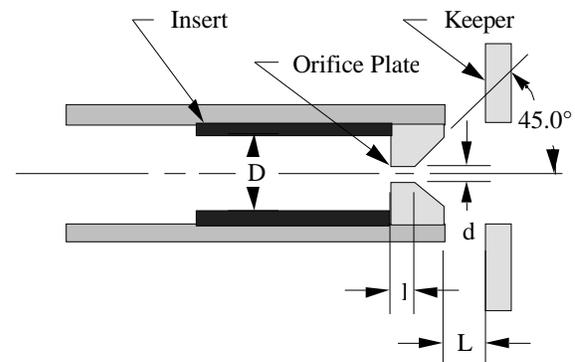


Fig. 1 - Schematic of the Hollow Cathode Experiments.

<i>Cathode</i>	l/d	$AR = (d/D)^2$
SC.001	9	0.01
SC.002	9	0.01
SC.002rfi	9	O(1.0)

Table 1. Cathode Parameters.

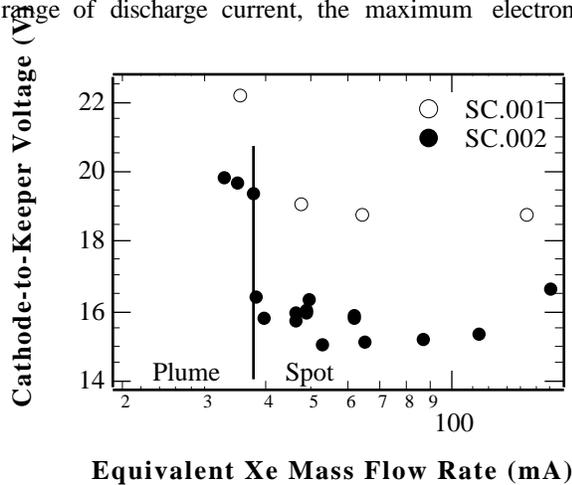
In each case, the cathodes were conditioned according to established space station plasma contactor procedures.¹⁷ The discharge and heater were supplied by DC power supplies. Current and voltage of both the discharge and the heater were monitored using digital multimeters. A disappearing filament pyrometer and a type R thermocouple were used to measure the external temperature of the cathode. The temperature data were taken to evaluate whether the cathode temperature at a given operating point was

sufficiently low to ensure a lifetime of several tens of thousands of hours.¹⁸ After an initial operating period of several hours, performance tests were conducted, and conditions were varied every fifteen minutes. A digital oscilloscope was used to observe fluctuations in the discharge voltage. Plume mode operation was evidenced by a sudden increase in the amplitude and frequency of the voltage oscillations.

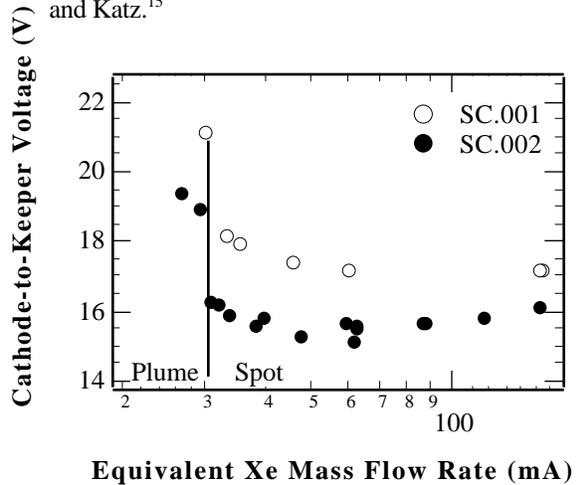
Experimental Results

Performance data for the porous tungsten insert cathodes, SC.001 and SC.002, are plotted in Figures 2a-d. Data were taken at 0.75, 1.00, 1.25, and 1.50 A. Operation was unstable below 0.75 A. Above 1.50 A, the cathode temperature became prohibitively high, and cathode lifetime would be compromised at the temperatures observed.¹⁸ In this range of discharge current, the maximum electron

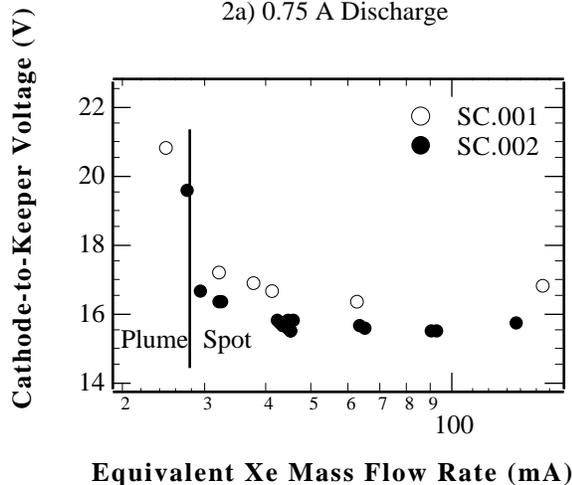
cooling was approximately 3.2 W, and the assumption of operation in the limit of high power density by Salhi and Turchi⁶ may be inaccurate for these cathodes. All of the characteristics show an abrupt transition to plume mode operation as the mass flow rate is decreased. In addition, model SC.002 operated at a consistently lower voltage than SC.001. This result was consistent with the fact that SC.002 maintained a higher temperature on the orifice plate, which resulted in increased thermionic current density and a reduction in the required voltage. The difference is thought to be due to variation in the keeper spacing. In addition, these cathodes operated at elevated voltages compared to data by Capacci, et al.¹⁶ Although dimensions were omitted from that report,¹⁶ operation at low voltages may be a manifestation of a small I/d ratio, as predicted by the model by Mandell and Katz.¹⁵



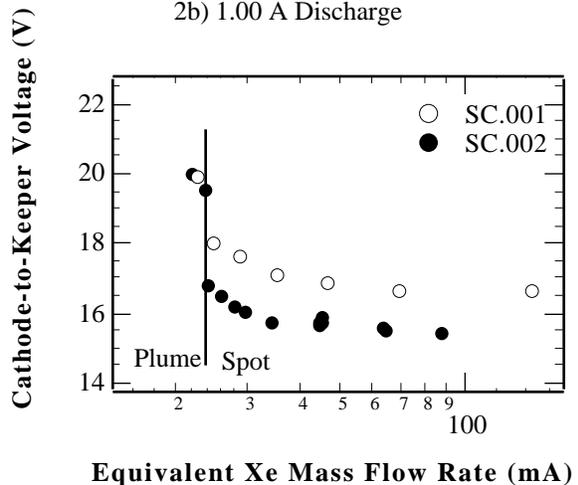
2a) 0.75 A Discharge



2b) 1.00 A Discharge



2c) 1.25 A Discharge



2d) 1.50 A Discharge

Fig. 2 - Performance Characteristics of the Cathodes with Impregnated Porous Tungsten Inserts.

The voltage-equivalent flow rate characteristics for SC.001 and SC.002rfi are plotted in Figure 3 to compare with the mercury hollow cathode neutralizer on the SERT II ion thruster.⁷ The total emission current of the SERT II cathode was 0.45 A. By scaling the orifice according to Equation 2, SC.001 operated in spot mode over the same equivalent mass flows as the SERT II cathode. Further reduction in orifice diameter should permit spot mode operation to even lower mass flow rates, although the operating regimes of these designs will be more restricted.

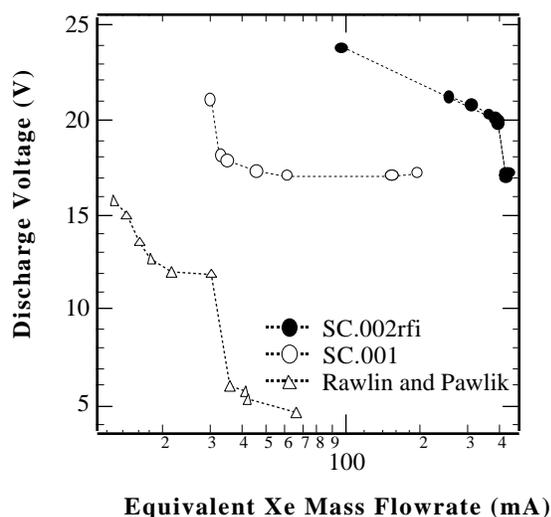


Fig. 3 - Comparison of Xe Cathodes at 1 A with Two Different Insert Geometries and a Hg Cathode at 0.45 A from Rawlin and Pawlik.⁷

Figure 4 illustrates the minimum flow rate necessary to maintain spot mode emission at a given discharge current. Equation 2 predicts an equivalent mass flow of about 30 mA, independent of the discharge current. However, as Figure 4 shows, in actuality the equivalent mass flow for spot mode emission was dependent upon the discharge current. Power deposition to the cathode increased with current. This resulted in an increase in cathode temperature and thermionic electron emission. Consequently, the increased thermionic current density within the cavity produced a more highly ionized plasma which could sustain the spot mode emission at reduced mass flow rates.

The results of the tests with SC.002rfi are presented here as a limiting case of insert geometry. Figure 3 depicts the limited spot mode regime for this cathode.

The rolled foil insert cathode required more than an order of magnitude more propellant than SC.001 or SC.002 to maintain spot mode emission. The model by Mandell and Katz¹⁵ neglects the particular physics of the insert region, and the results obtained with SC.002rfi clearly illustrate the necessity for inclusion of the insert processes in modeling. With the small insert diameter, an increase in neutral density was necessary to ensure that the thermionic electrons generated a plasma sufficiently dense to carry the current. This limits the effectiveness of scaling the insert diameter much below that of the porous tungsten inserts. Additionally, multichannel hollow cathodes, which have been found to operate at lower mass flow rates than single channel cathodes,¹⁹ may be impractical for application to low power thrusters since the channel geometry would be similar to the SC.002rfi insert.

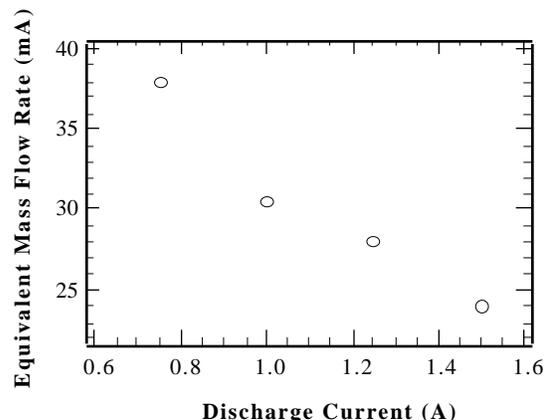


Fig. 4 - Flow rates Required to Maintain Spot-Mode Emission.

Further Scaling Considerations

The cathodes, SC.001 and SC.002, would consume about 1 kg of Xe during 8000 hours of operation. While the cathodes have demonstrated operation at very low flow rates, other researchers have produced cathodes capable of operating at lower power.^{16,20} These designs reflect careful minimization of heat conduction away from the cathode. In both flow rate and power consumption, the improvements are likely to be of the order of micrograms per second and Watts, respectively. In order to reduce substantially the mass penalty associated with cathode mass flow, a cathode that operates without propellant, such as a field emitter array cathode,²¹ would be necessary. Given the relative gap in demonstrated lifetimes between hollow cathodes and field emitter array

cathodes, further reduction in hollow cathode scale appears to be the best near term solution for low power thrusters. Some theoretical and practical scaling considerations are discussed below.

Scaling Theory

Since the model by Salhi and Turchi⁶ assumes high power density operation, its results were only expected to yield qualitative agreements with the trends observed in the operation of SC.001 and SC.002. Further reductions in the size of hollow cathode orifices will also reduce both the area ratio AR and the operating regime. Equation 2 indicates that the minimum mass flow rate for spot mode emission scales with orifice diameter, and further mass flow savings can be expected by reducing the orifice size. Given the effectiveness of SC.001 and SC.002 to operate at low mass flow rate, the ratio l/d may be reduced to yield lower discharge voltages. The work by Capacci et al.¹⁶ illustrates the importance of thermal modeling for low power cathodes. In order to generate a more accurate picture of the operating regime of cathodes, future theoretical design should include the two dimensional considerations in the insert region presented by Salhi,¹⁴ the orifice physics, and a thorough heat transfer analysis of the cathode.

Mechanical Scaling Considerations

The primary considerations in the fabrication of small hollow cathodes are the orifice and insert dimensions. Currently, the orifice plate is machined on a lathe. The orifice has a practical limit of approximately 0.08 mm based on the l/d of about 5 necessary for machining. EDM may create orifice diameters down to 0.025 mm, although the geometry of the orifice would vary greatly from unit to unit.²² The insert has similar physical constraints. The porous tungsten plug is formed by sintering, and then the emissive mix is impregnated in the voids in the tungsten plug. While small channels can be created during sintering, clearing the channels of the emissive mixture may be prohibitive.²² Additionally, small channels are more susceptible to blockage by material erosion or swelling of the insert.²³ Current fabrication techniques offer modest reductions in cathode scale.

Conclusions

The initial results of an investigation into low consumption hollow cathodes was presented. Previous efforts to develop scaling relationships for hollow cathodes were discussed. While the phenomenological models offered the greatest predictive flexibility, the empirical transition to spot

mode criterion¹⁰ accurately predicted the flow rate necessary to maintain spot mode emission. The performance of 3.2 mm orificed hollow cathodes was presented, and spot mode operation at equivalent flow rates comparable to the SERT II neutralizer was obtained. A cathode with an insert diameter on the order of the orifice diameter required nearly an order of magnitude more propellant to maintain spot mode emission than the small area ratio cathodes, illustrating the difficulty in greatly reducing the insert diameter.

Recommendations for further reductions in cathode flow rate and power consumption were presented. An orifice diameter of 0.08 mm with an l/d ratio of five or less appears to be the practical limit for orifice geometry. This would yield a low flow rate, low voltage cathode with a limited current operating regime, since the operating temperature increases with decreasing orifice size for a given discharge. New fabrication and assembly procedures will have to be developed in order to reduce substantially the size of hollow cathodes.

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