Characterization of a High Current, Long Life Hollow Cathode

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Abstract: The advent of higher power spacecraft makes it is desirable to use higher power electric propulsion thrusters such as ion thrusters or Hall thrusters. Higher power thrusters require cathodes that are capable of producing higher currents. One application of these higher power spacecraft is deep-space missions that require tens of thousands of hours of operation. This paper presents the approach used to design a high current, long life hollow cathode assembly for that application, along with test results from the corresponding hollow cathode. The design approach used for the candidate hollow cathode was to reduce the temperature gradient in the insert, yielding a lower peak temperature and allowing current to be produced more uniformly along the insert. The lower temperatures result in a hollow cathode with increased life. The hollow cathode designed was successfully operated at currents from 10 to 60 A with flow rates of 5 to 19 sccm with a maximum orifice temperature measured of 1100 °C. Data including discharge voltage, keeper voltage, discharge current, flow rates, and orifice plate temperatures are presented.

Nomenclature

A	=	cross-sectional area of insert region
C	=	fit coefficient
d_i	=	insert inner diameter
e	=	elementary charge
Isp	=	specific impulse
J_{th}	=	current from thermionic emission
k_b	=	boltzmann's constant
k_{th}	=	thermal conductivity
K_{vl}	=	virtual thermal loss term
N	=	loss multiplier
Q	=	heat transfer rate
T	=	temperature
t	=	lifetime
V_a	=	energy of activation
x	=	position along cathode insert length
y	=	depth into insert of barium depletion
f_e	=	insert work function
$()_1$	=	reference cathode parameters
$()_2$	=	design cathode parameters
$()_{100\,\mu m}$	=	100 µm depth from insert surface
$()_{depth}$	=	depth from insert surface
$()_l$	=	minimum insert temperature
$()_{loss}$	=	thermal loss out of cathode insert region
$()_t$	=	peak insert temperature
$()_{vl}$	=	virtual loss parameters

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I. Introduction

Some electric propulsion systems that operate at higher power offer additional efficiencies and higher thrusting than the current state-of-the-art systems. Two types of higher power thrusters under development are the ion and Hall thrusters. These higher specific impulse and higher power thrusters will be key for planetary exploration and efficient cargo delivery to Mars.[1,2] NASA's Project Prometheus has been supporting the development of high specific impulse (Isp), high power ion thrusters (6000 to 8000 sec and 20 to 30 kW respectively) and Hall thrusters (2500 to 4000 sec and 20 to 50 kW respectively) for use with a nuclear powered spacecraft.[3,4,5] These thrusters would require 10 to 100 khrs of operation for the missions envisioned.[4] The longest ion thruster test to date was approximately 30 khrs at specific impulses up to 3100 seconds and powers up to 2.3 kW (1100 V beam voltage and 1.76 A beam current).[6] Missions such as these would also require a substantial increase in lifetime for Hall thrusters.[5]

A component that can limit the lifetime for these thrusters is the hollow cathode. Inert gas hollow cathodes have been operated for 28 khrs at a constant current and over 30 khrs at various currents.[7,6] Mercury ion thrusters and their hollow cathodes lasted from 13 khrs to over 26 khrs.[8,9,10] Previously developed hollow cathodes typically operated below 35 A. However, the higher power thrusters would require hollow cathodes that operated from 50 to 100 A. [11,12]

This paper will detail an approach for a higher current, longer life hollow cathode that can be applied regardless of required current along with test results from a cathode that was built to satisfy 50 A of discharge current for 100 khrs. Initially, a prediction of the hollow cathode insert lifetime will be presented that is primarily dependant on the temperature and thickness of an insert impregnated with a specific molar ratio of barium. Next, a model will be presented that predicts the insert temperatures based on the change in thermal conductivity in the insert region for a particular design. This model, along with the temperature requirement from the lifetime model, will be used to establish a long life design. A hollow cathode based on this design was built and tested. The purpose of the testing was to determine the operational temperatures of the cathode for comparison with the models, and also establish expected lifetime. Discharge voltages and cathode operational modes are presented for various cathode flow rates and currents, but these values are dependent on the cathode and anode configuration, so they are most relevant for establishing trends and confidence in the cathode design, whether for ion or Hall thrusters.

II. Cathode Lifetime Requirement

As previously mentioned, the lifetime required for these cathodes will have an upper bound of around 100 khrs. The life limiters for a hollow cathode include insert life, which is driven by impregnate depletion, sputtering wear to the orifice plate, orifice walls, and heater.[6] The orifice plate and heater are protected by a sacrificial keeper. The life of the keeper has been dramatically increased by changing from molybdenum to graphite which has a lower sputtering yield. The new keeper material then removes wear on the orifice plate and heater as life limiters. This leaves the cathode insert life as the primary life limiter and this will be the focus presented here. There are several factors that determine the life of an impregnated insert in the hollow cathode. They include the formation of tungstates, which bind up the barium and inhibit diffusion, and depletion of barium from within the insert.[13] Lifetime data has been compiled for planar impregnated cathodes used in vacuum tubes,[14] however, due to the different operating environments and mechanical designs (i.e. cylindrically enclosed vs. planar) it is unclear how well the planar vacuum data corresponds to the hollow cathode. The current hollow cathode life models are either based on prediction of chemical processes and vapor pressures,[15,16] or on lifetime data from planar impregnated cathodes operated in a vacuum tube.[17] The chemistry-based model is limited due to the complexity of the chemical processes in the insert and the planar cathode-based model is limited due to the difference in operating environments and physical construction of the hollow cathode. However, emitter temperature is the major factor for determining critical reactions and, therefore, the insert's lifetime. [13,18] Thus, first order estimates for hollow cathode emitter life can be obtained by using the known temperature and lifetime data from planar cathodes.

The model used in this paper is based on a relationship outlined by Palluel and Shroff that is shown in Eq. (1).[18] This model examines the relationship between cathode lifetime and temperature. This model is developed based on data for impregnated planar cathodes that are used in the vacuum industry.

$$\ln(t) = C + \frac{eV_a}{k_b T} \tag{1}$$

Ref. 14 further elaborates on the model to determine the time to particular barium depletion depth on hollow cathode impregnated inserts. This relationship is given in Eq. (2) relating the time to a particular depletion depth to

the 100 µm depletion depth time. The relationship between the 100 µm depletion depth time and temperature following the relationship of Eq. (1) is given in Ref. 18.

$$t_{depth} = t_{100\mu m}\left(\frac{y_{depth}}{y_{100\mu m}}\right)^2 \tag{2}$$

While it is difficult to estimate the error using this model, it does provide a starting point for design.

While Eq. (2) will provide a life estimate to any depth, there is likely a depth where the barium will not be easily accessible. At the completion of the NSTAR ELT test (30+ khrs) both the neutralizer and discharge cathodes were still operational.[6] The measurements taken to determine barium depletion in that insert were only to a depth of 500 µm. The ELT results showed some barium depletion at a depth of 100 and 300 µm at the downstream end of the insert, but not at 500 µm. Based on those measurements, it would appear that barium is accessible to at least a 300 µm depth. Figure 1 shows the relationship between emitter temperature and lifetime for both the 300 µm and 500 µm barium depletion depths as derived from the model. In order to achieve a 100 khr lifetime the emitter must be between 1050 to 1100 °C. This is consistent with the recommended operating temperature of 950 to 1150 °C for a long life impregnated insert.[13]
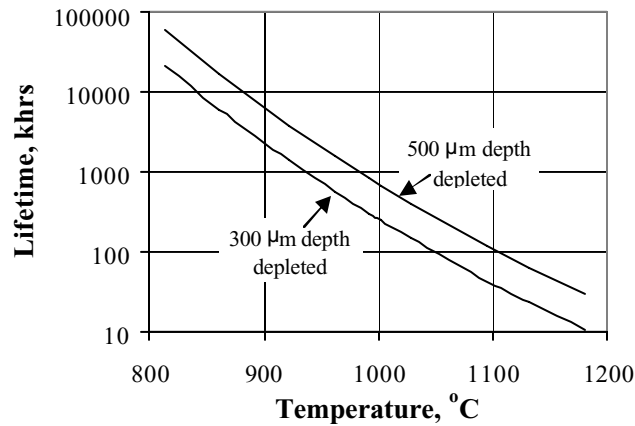

Figure 1. Graph showing lifetime estimate depending on depletion depth for an impregnated insert operating at various temperatures.

To further determine a usable depletion depth, the 0.6 cm outer diameter hollow cathode that was life-tested for 28 khrs[7] can be examined. A similar cathode had an insert peak temperature measured at 1180 °C.[19] In order for an insert with a peak temperature of 1180 °C to have a predicted lifetime of 30 khrs, Figure 1 shows the allowable barium depletion depth would be 500 µm.

This can also be examined from a slightly different approach. Eq.1 can also be used to compare similar cathodes when lifetime and temperature are known for one cathode and only temperature is known for a second cathode. To compare the two lifetimes based on different temperatures Eq. (1) can be rearranged to the ratio in Eq. (3).

$$\frac{t_2}{t_1} = \exp\left[\frac{eV_a}{k_b}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)\right] \tag{3}$$

Again using the data from the hollow cathode tested for 28,000 hours, a similar insert (V_a= 2.82 eV)[17] operating with a peak temperature of 1100 °C would last 104 khrs. Even though the results are based on the same model, this result gives validity to the design point of a maximum temperature of 1100 °C for the insert, which results in 100 khrs of operation.

III. Background

A. Affect of Temperature Gradient on Peak Temperature of Hollow Cathode

The major requirements for an initial higher current, long life hollow cathode design are for a nominal current of 50 A with operation at or below 1100 °C. In order to design a hollow cathode that will operate with those requirements with a minimal insert diameter, it is essential that the entire insert largely contribute to the overall current emitted. The major mechanism for current production in the hollow cathode is thermionic emission. Since this emission is related to the exponential of the inverse of the temperature, the current that is emitted is very sensitive to its temperature. In previous hollow cathodes the temperature distribution along the length of the insert

varied by as much as 200 °C.[19] Figure 2 depicts this measured temperature profile for a cathode running at 12 A. Figure 3 shows the current density and percent of overall current produced along the length of an insert corresponding to the temperature distributions shown in Figure 2. It can be seen that for the 200 °C temperature profile, roughly 75% of the current is produced in the first third of the insert. While these profiles do not account for the current that is produced from the orifice or any plasma effects, they do demonstrate that by reducing the temperature gradient, the insert should more evenly produce the current necessary. Figures 2 and 3 also show the representative temperature profile and current production characteristics for a comparable cathode (i.e. same insert inner diameter), but with a temperature gradient of only 50 °C. It can be seen that the peak temperature is predicted to drop by about 73 °C and produce current densities on the order of 2:1 from front to back instead of over 20:1 for the previous profile. Using the relationship given in Eq. (2), an insert with a peak temperature reduced by 73 °C would yield a lifetime increase of 330 % of the original 28 khrs lifetime that was demonstrated.

The ability to decrease the peak temperature of an insert by decreasing the temperature gradient was demonstrated by Beattie.[20] For cathodes with comparable inner diameters and an emitted current of 16 A, one with approximately a 240 °C temperature gradient and peak temperature of 1140 °C was reduced to a peak temperature of 985 °C and a temperature gradient of 64 °C.
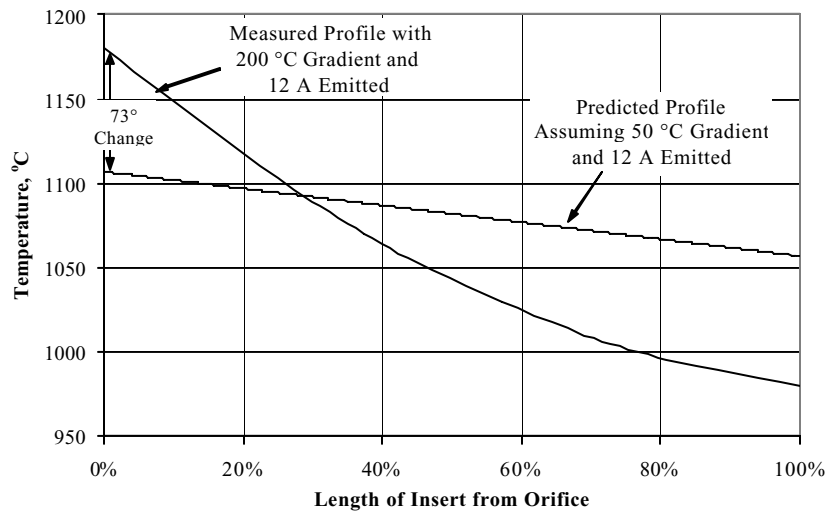

Figure 2. Hollow cathode insert temperatures as a function of length for 12 A of emission with differing temperature profiles.
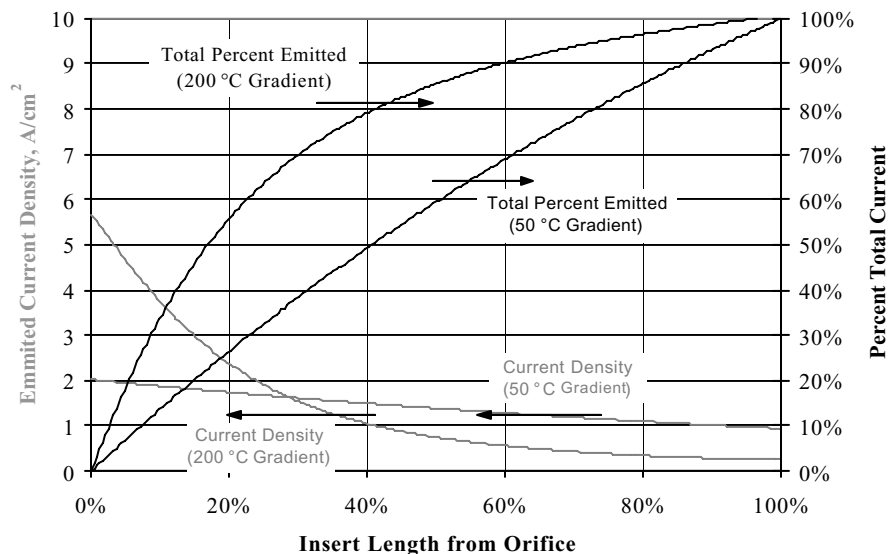

Figure 3. Current produced along the length of a hollow cathode insert for 12 A of emitted current with differing temperature profiles.

B. Model to Predict Hollow Cathode Temperatures

The main approach to decreasing the temperature gradient along the insert is to increase the thermal conductivity in the insert region. It is important not to increase this conductivity outside of the region as to increase the thermal losses out of the cathode insert region. A simple model used for initial designing purposes was to consider that thermal conduction along the length of an insert is the major component to determining the temperature gradient along an insert. While there are other components that contribute to this gradient such as the emission of electrons and radiation, thermal conduction is the major driver.[21] The variation in temperature gradient in the insert region can be estimated by determining the ratio of heat transfer rates based on a change in thermal conduction in the insert region. This ratio is shown in Eq. (3).

$$\frac{Q_1}{Q_2} = \frac{k_{th1} A_1 \frac{dT_1}{dx_1}}{k_{th2} A_2 \frac{dT_2}{dx_2}} \cong \frac{k_{th1}}{k_{th2}} \frac{A_1}{A_2} \frac{\Delta T_1}{\Delta T_2} \frac{\Delta x_2}{\Delta x_1} \tag{3}$$

In order to estimate the change in heat transfer rates resulting from designs with different thermal losses out of the insert region, a virtual thermal conductive loss term is determined. This virtual term approximates all thermal losses out of a cathode as conductive. It is assumed that for a given cathode, the conduction term is constant and the loss is determined by the difference between the lowest temperature of the insert and some heat sink at very a low temperature at a fixed distance away. This concept is represented in Eq. (4) where K_{vl} is some conductive type term that represents thermal losses out of a cathode.

$$Q_1 = \left(k_{th1} A_1 \frac{dT_1}{dx_1} \right)_{insert} \cong \left(\frac{k_{thvl} A_{vl}}{\Delta x_{vl}} \Delta T_{vl} \right)_{loss} \cong K_{vl}\left(T_{l1} - 0\right) \tag{4}$$

For a cathode where there are no design changes to the cathode outside of the insert region, the ratio of heat transfer rates in Eq. (3) would be a ratio of the lowest insert temperatures since K_{vl} will be constant. However, a change external to the insert region, such as increasing the cathode tube diameter, can be approximated by a multiplier, N, as shown in Eq. (5).

$$\left(Q_2\right)_{loss} \cong NK_{vl}\left(T_{l2} - 0\right) \tag{5}$$

Then a comparison of heat transfer rates between a known cathode and temperature profile to a different design can be represented by taking the ratio of Eq. (4) over Eq. (5) to give Eq. (6).

$$\frac{Q_1}{Q_2} = \left(\frac{Q_1}{Q_2} \right)_{loss} \cong \frac{K_{vl}\left(T_{l1} - 0\right)}{NK_{vl}\left(T_{l2} - 0\right)} = \frac{T_{l1}}{NT_{l2}} \tag{6}$$

Eq. (6) can then be substituted in Eq. (1) resulting in Eq. (7).

$$\frac{k_{th1}}{k_{th2}} \frac{A_1}{A_2} \frac{\Delta T_1}{\Delta T_2} \frac{\Delta x_2}{\Delta x_1} = \frac{T_{l1}}{NT_{l2}} \tag{7}$$

Eq. (7) can then be rearranged to determine the ratio of the peak to minimum temperatures for the design as shown in Eq. (8).

$$\frac{T_{t2}}{T_{l2}} = 1 + \frac{k_{th1}}{k_{th2}} \frac{A_1}{A_2} \frac{N\Delta T_1}{T_{l1}} \frac{\Delta x_2}{\Delta x_1} \tag{8}$$

Once that ratio of peak to minimum temperatures is determined, a temperature profile similar to the one shown in Figure 2 is fit to this ratio and a corresponding emission current can be determined using the Richardson-Dushman's equation shown in Eq. (9).

$$\frac{J_{th}}{\pi d_i dx} = 120 T_{insert}^2 \exp\left(-\frac{e\phi_e}{k_b T_{insert}} \right) \tag{9}$$

The temperatures can then be iterated until the current produced using Eq. (9) matches the desired emission current. There are additional effects that are often considered when evaluating hollow cathode current emission including the Schottky effect that lowers the effective work function, the current from ion bombardment, electron backstreaming, and current from the orifice plate.[21] Based on measurements of a cathode with a segmented insert, it was assumed that roughly 10% of the discharge current comes from the orifice plate.[22] The contribution of ion current will be

ignored for this model as a second order effect, but it would effectively lower the amount of thermionic current for a given emitted current. The work function used varied with temperature, and was generated to provide a fit to the data in Figure 4. This work function fit, along with other published values used for the work function of these inserts, is shown in Figure 5. The slope for the work function used is steeper than the other slopes, but the overall values fall within the other published numbers. Since a fit was used for the work function to determine the insert temperatures, the Schottky effect is inherently accounted for. Using this approach, a set of peak temperatures versus currents were generated for the cathode with the measured insert temperatures.[19] This comparison is given in Figure 4 and demonstrates very good agreement with reasonable work functions.
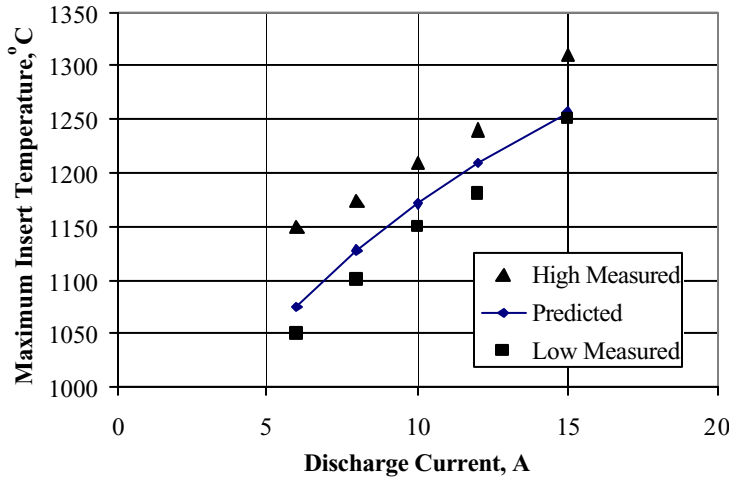

Figure 4. Hollow cathode model compared to test peak insert temperatures for the 0.6 cm tube outer diameter hollow cathode.
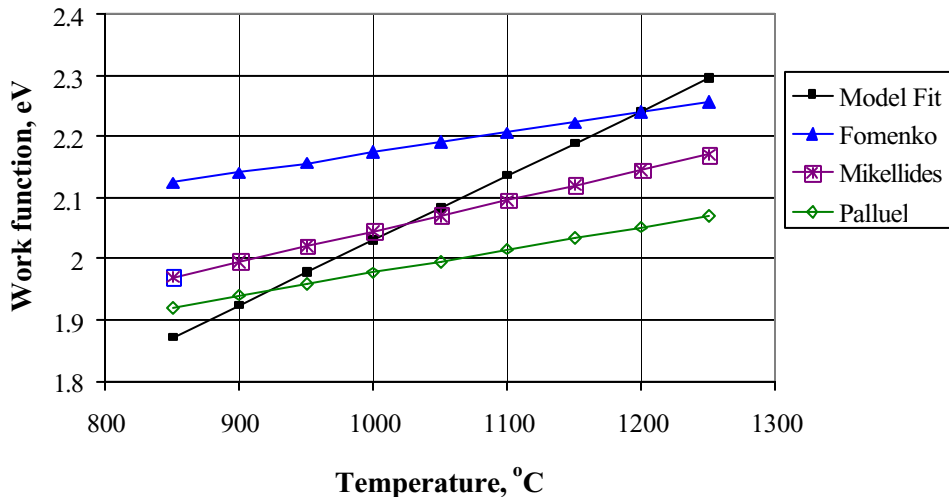

Figure 5. Work function used to fit temperature data compared to other published values [Fomenko[23], Palluel[18], Mikellides[24]].

C. Application of Model to Long Life, High Current Requirements

Several candidate geometries were implemented in the model. The goal of the cathode design was to operate with a peak insert temperature of 1100 °C while operating at a current of 50 A. Two approaches were used to minimize the temperature. The first was to allow sufficient thermal conduction through the insert region for significant emission contribution over the entire insert. A second simultaneous approach is to increase the inner radius of the insert creating a larger emission area and lowering the emitted current density required. However, allowing the inner diameter to increase unbounded would create a cathode much larger than practical and one that is

significantly larger, and perhaps different enough from existing experience that additional unforeseen issues could arise. Therefore, an additional requirement was to minimize the amount the cathode diameter could grow.

The model presented in the previous section was used for a variety of scenarios whereby the cathode insert inner diameter was increased to lower the emitted current density requirements, while the external diameter of the cathode tube was increased to provide sufficient thermal conduction along the insert region. It is important to note that for a given insert outer diameter, there is an optimal insert inner diameter such that the temperature is minimized. The minimal peak temperature is driven by a smaller inner diameter for increased thermal conduction, and is driven by a larger inner diameter to decrease the emitted current density. Also kept in mind were standard tube outer diameter sizes in order to facilitate standard gas feed system fittings. Figure 6 shows the predicted temperatures for the selected cathode design with a cathode tube outer diameter of 1.9 cm and an insert thickness in excess of 1 mm. The N thermal losses multiplicative number is estimated relative to the 0.6 cm outer diameter cathode. The 0.6 cm cathode provided the baseline internal temperature measurements for the model. A rough approximation would put the loss multiplier N between 2 to 3 times the 0.6 cm cathode thermal losses. However, without a comprehensive study, a better estimate of losses cannot be determined.
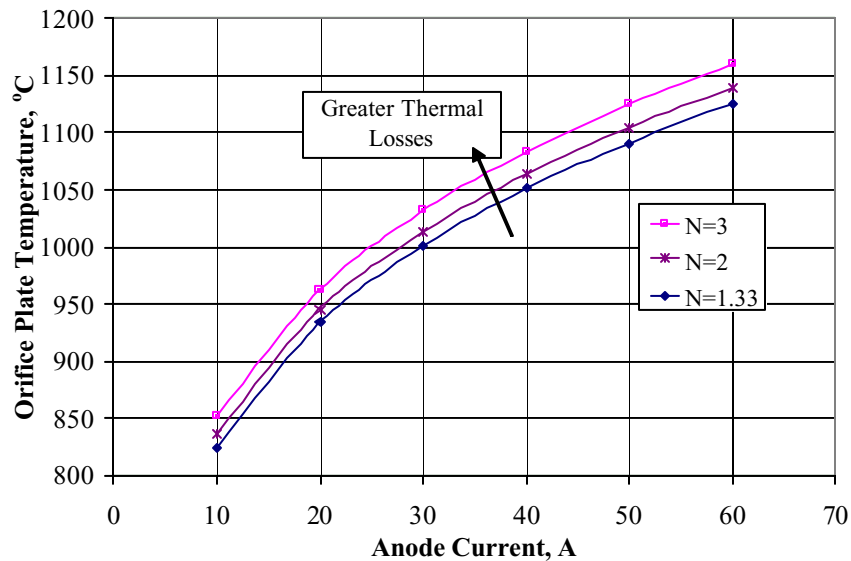

Figure 6. Peak insert temperature model predictions for candidate high current, long life hollow cathode are depicted with differing amount of thermal losses for a variety of emitted currents.

IV. High Current Cathode Test

A. Test Setup

Figure 7. Pretest photograph taken of the lab model hollow cathode assembly with graphite keeper.

A laboratory model (LM) version of the hollow cathode was designed to operate at the temperatures shown in Figure 6 and was fabricated with a graphite keeper. This cathode tube diameter facilitates a large emission area on the insert to reduce the current density required from the insert. The impregnated insert wall thickness is in excess of 1 mm to facilitate thermal conduction along its length and provide ample amounts of barium for the life of the insert. This cathode is shown assembled in Figure 7.

The cathode was installed in the NASA Glenn Research Center Vacuum Facility 61 (VF61). This vacuum facility has two ports that are configured for hollow cathode testing. The two ports are 0.33 m in diameter and 0.41 m long. The overall facility is 1.0 m diameter by 1.5 m long. VF61's pumping speed is 13,000 l/s with xenon. The base pressure is 5.3×10^{-7} Pa. This facility has been used for extensive

7

hollow cathode testing in the past including the space station hollow cathode.[25]

Figure 8 shows the setup for the hollow cathode in a vacuum facility port. A cylindrical anode was used to allow the current to attach radially and the neutral gas to flow unimpeded downstream. The anode had a diameter of 0.25 m and was constructed of molybdenum, since large anode temperatures were expected. Two thermocouples were placed on the anode to monitor its temperature. Additional thermocouples were located on the cathode orifice plate weld, immediately behind the insulator on the cathode tube and also on the keeper cylindrical wall immediately behind its face. The power supply used for discharge could provide a 100 A current at 40 V. A flow controller capable of flow rates up to 100 sccm was used to regulate the flow of xenon to the cathode. The cathode keeper collected no current and its potential was allowed to float. The potential was monitored to determine when the cathode transitioned into plume mode for this configuration. All NASA GRC procedures were followed for storing, conditioning, and igniting the cathode.[26]
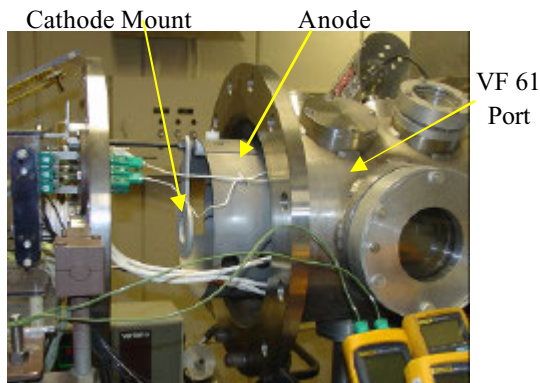

Figure 8.   Picture showing VF61 port 1 test setup.

Figure 9.   Picture taken of a LM hollow cathode discharge.

B. Test Results

The hollow cathode was operated at discharge currents from 10 to 60 A with xenon flowrates of 5 to 19 sccm. Figure 9 shows the high current discharge from the LM hollow cathode. The hollow cathode required approximately 25 hours of operation to condition itself, during which the cathode orifice plate temperatures decreased by ~100 °C. Initially, the orifice plate will not have any barium on its surface and the barium in the insert will be migrating to its surface. This type of lowering in temperature over the first tens of hours of operation is typical in these cathodes and is also seen in the results from the 28 khr cathode.[7] A comparison of predicted temperatures and test temperatures after conditioning is shown in Figure 10.

It can be seen that the insert temperature in Figure 10 predicted is up to 150 °C hotter than the measured orifice plate temperatures. Either the model is overpredicting the insert temperatures or the insert is operating hotter than the orifice temperature. Temperature measurements of an insert as seen in the smaller cathode showed that the orifice plate could operate up to 100 °C cooler than the insert.[19] Either way, it is very likely that the model is the upper bound of the temperature in the insert and the lifetime below 50 A could be well in excess of 100 khrs. If orifice temperatures are fairly close to the insert temperatures then this cathode insert could exhibit a lifetime on the order of 100 khrs at currents up to 60 A. It will be valuable in future work to measure the insert temperatures for comparison to the model and a further assessment of life. The model predicts the trend of how the temperature changes quite well.
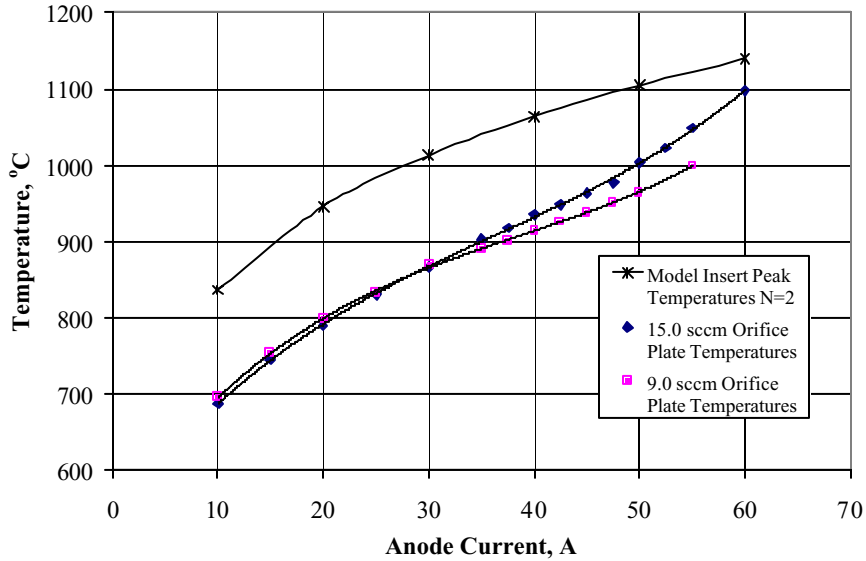
Figure 10.   Graph showing cathode orifice plate temperature for varying anode currents.

While the anode voltages can vary based on the location and design of the anode, the discharge voltages are a useful parameter to evaluate cathode operation. The keeper voltages and discharge voltages are shown in Figure 11 for cathode flow rates of 9 and 15 sccm. Hollow cathodes can operate in either spot or plume mode, with spot mode typified by a very bright spot downstream of the orifice and keeper voltage transients below 5 V peak-to-peak. When cathodes transition into plume mode, the keeper transient voltages shift above 5 V peak-to-peak and the spot becomes more diffuse with a hazy plume becoming more prominent. It should be noted that this hollow cathode would exhibit spot to plume mode type transition in the discharge chamber of an ion thruster because of the presence of a magnetic field and differing anode geometry. However, the discharge voltages are still very useful to establish trends and characterization of the cathode on a component level. As shown in Figure 11, the hollow cathode tested transitioned into plume mode for current above 40 to 45 A at 9 sccm. With a flow rate of 15 sccm the cathode operates entirely in spot mode for currents up to 60 A. The discharge voltage also varies only a few volts for the 15 sccm flow rate.
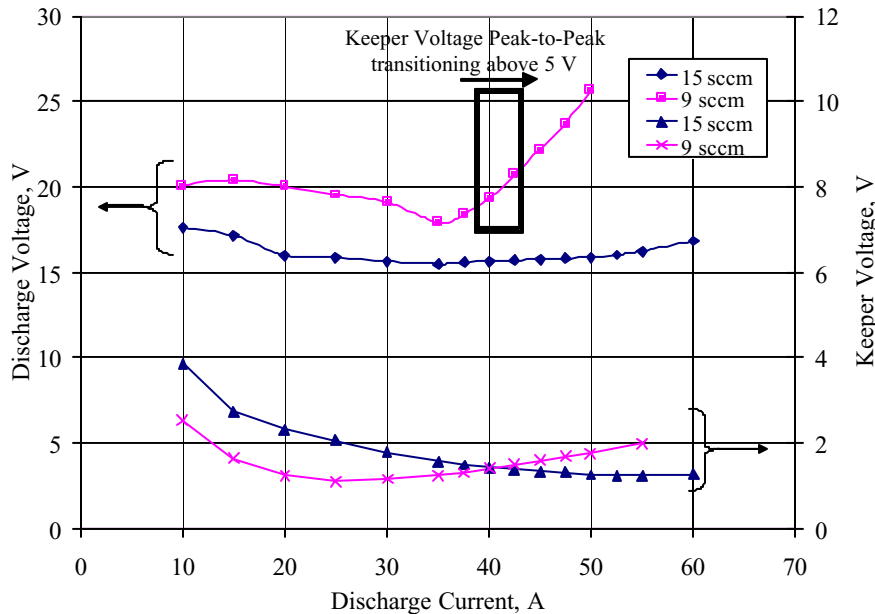

Figure 11.   Graph showing discharge and keeper voltages for varying discharge currents.

Figure 12 shows how the orifice plate temperatures vary with cathode xenon flow rate. This data was taken prior to cathode conditioning, so the temperatures will vary a bit from the temperatures shown in Figure 10. Even though

9

the temperatures are higher, the trends they demonstrate are still valid. It can be seen that in Figure 10, the temperatures vary minimally between 9 and 15 sccm below 35 A and show divergence at higher currents just as shown in Figure 12. At higher currents and lower flow rates the cathode was transitioning into plume mode where peak-to-peak keeper voltages above 5 V where seen. This transition is also seen in Figure 12 by the orifice plate temperatures quickly increasing with lower flow rates.

Figure 13 shows how the discharge voltage changed with flow rate, and corresponds to the same data shown in Figure 12. The discharge voltages at higher flow rates were fairly similar, with the 10 A emission exhibiting a slightly higher discharge voltage. The discharge voltage increased with all currents tested as the flow rates were decreased. For currents above 20 A, a significant increase in discharge voltage is seen for low flow rates. This is also an indication of plume mode operation. It can be seen that as the current increases a higher minimal flow rate is required to establish spot mode operation.
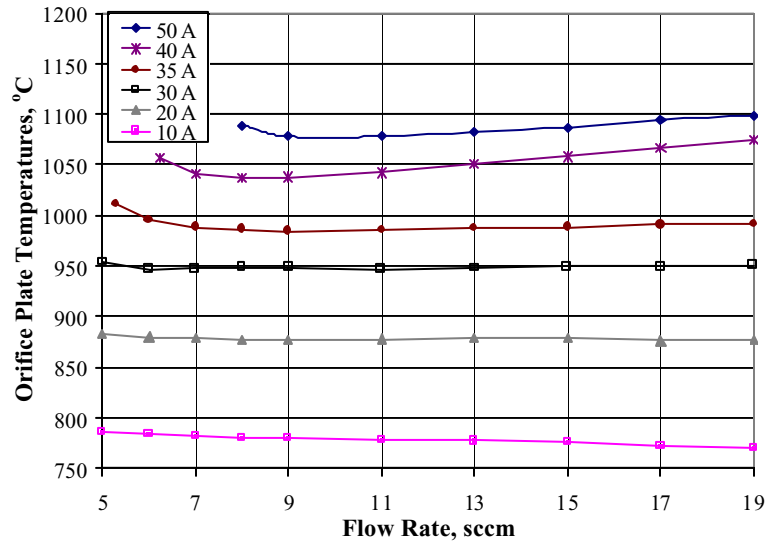

Figure 12.   A graph that shows how the of orifice plate temperatures varies with cathode flow rates.
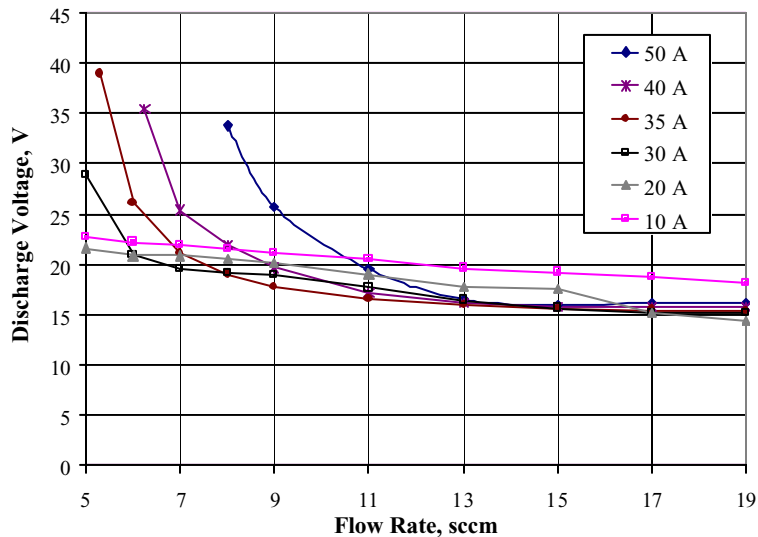

Figure 13.   A graph that shows how the discharge voltages vary with cathode flow rate.

V. Conclusion

An approach has been outlined for long life, higher current hollow cathodes. A relationship between the insert temperature and lifetime is approximated to establish design requirements. A model was developed to predict peak insert temperatures for various currents using a known temperature profile as a baseline. Predictions of new temperature profiles were based on the change in thermal conductivity in the insert region and thermionic emission

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necessary for a given discharge current. The approach presented to minimize the peak insert temperature was mainly a twofold approach. First, increasing the thermal conductivity along the insert region length reduced the temperature gradient and lowered the peak temperature. Second, the insert inner diameter was increased to provide additional area for emission and, thereby, lowering the maximum current density required. However, the overall diameter of the cathode was minimized to prevent the cathode from becoming extraneously large. Based on this approach, a 50 A nominal hollow cathode with a predicted minimum lifetime of 100 khrs was fabricated. This cathode was tested for flow rates from 5 to 19 sccm and discharge currents ranging from 10 to 60 A. The maximum orifice plate temperature measured for currents up to 60 A was 1100 °C and is consistent with a long life of 100 khrs of operation.

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