Hollow Cathode Ignition Studies and Model Development

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ABSTRACT: The Hollow Cathode Assembly is a thermionic source of electrons critical to the operation of the L-3 ETI Xenon Ion Propulsion System (XIPS) thruster. There are two cathode subsystems on a XIPS thruster: the discharge cathode provides the current for the main discharge and the neutralizer cathode produces an electron stream to prevent the spacecraft from charging. There are two phases to the operation of the cathode: 1) a pre-heat phase during which an external heater prepares the cathode for ignition and 2) a self-heating phase that follows ignition. We will discuss experimental data related to the ignition processes for the hollow cathode. These included emission studies and Auger surface spectroscopy data. Based on these observations a detailed physical ignition model has been developed and benchmarked using available cathode and thruster life test data. The model will be outlined and its use in describing the expected ignition characteristics of the L-3 ETI 25 cm XIPS hollow cathode over life will be presented.

Nomenclature

P_0	=	barium pressure in tungsten pore at the burn front
P_s	=	barium pressure in tungsten pore at the emission surface
□(T)	=	time required to completely consume barium at temperature, T
□	=	barium surface coverage
□	=	work function
□	=	depth of the work function minimum
j	=	current density
i	=	emitted current
T	=	insert temperature at the emission surface: a function of length along the insert

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I. Introduction

Hollow cathodes are used in many applications including Ion thrusters, Hall thrusters and the Space Station plasma contactors. The Xenon Ion Propulsion System (XIPS) 25 cm thruster manufactured at L-3 Communications Electron Technologies, Inc (L-3 ETI) uses hollow cathodes in both the discharge and neutralizer cathode assemblies. An external heater is used to raise the temperature of the hollow cathode inserts to a level that allows barium to migrate onto the cathode tip. Voltage is then applied to a close spaced Keeper prompting electron emission and subsequent ionization of xenon gas flowing through the cathode. Following ignition the heaters are de-activated and plasma heating of the cathode insert allows an electron beam to be extracted. In the case of the discharge cathode, plasma electrons are accelerated into the discharge chamber, producing the discharge plasma. In the case of the neutralizer cathode, the electrons are emitted in order to balance the release of positive Xenon ions from the thruster and to maintain charge neutrality in the thruster.

Development of a physical model of the hollow cathode assists in making accurate assessments of performance and life and to guide design improvements. Several approaches have been reported [1-5]. The station-keeping requirements of the XIPS 25 cm thruster, which entails daily ignition, suggested a different approach to modeling the cathode life. This is based on the fact that a practical end of life occurs when the conditions required for cathode ignition can no longer be met. Ignition begins when electron emission from the cathode tip is adequate to form a plasma by ionizing the neutral xenon flowing through the cathode. The plasma allows the penetration of the electric field to the interior of the insert so that an electron beam can be extracted and the full cathode discharge is ignited. The model presented here deals with those processes that lead to emission from the cathode tip.

A description of this hollow cathode model was presented in an earlier paper [5]. Here we will provide experimental data that supports the proposed ignition mechanisms, a summary of the primary features of the model, and application of the model to specific test conditions. In the earlier application of the model [5], insert temperatures were based on available experimental data taken by J. Polk [6] at the Jet Propulsion Laboratory (JPL). These measurements were specifically taken using a cathode that did not include a Keeper and so did not represent the same conditions found in our earlier applications of the model. More recent measurements [7] provide insert temperatures with a Keeper and the temperature profiles for the cathode insert have been modified to reflect these data for the results presented here.

II. Experimental Evidence for the Hollow Cathode Ignition Processes

The model for ignition of the hollow cathode has been supported in a qualitative manner by several experiments. Additional detailed experiments are being planned that will provide more quantitative evidence for both the ignition and aging processes described in this model. In this section the available experimental evidence will be described.

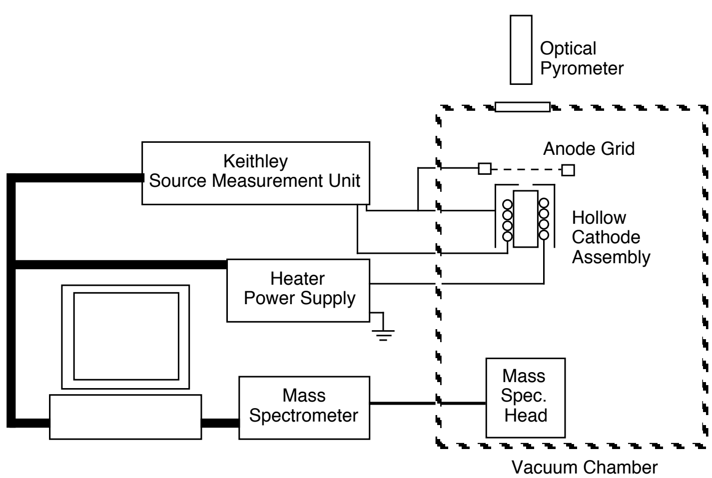

Figure 1. *Schematic of experimental arrangement to investigate hollow cathode emission.*

In a study to determine the work function of the hollow cathode insert, Longo [8] examined the emission from a hollow cathode as a function of accelerating voltage. These studies were performed in high vacuum, without gas flow. The voltage was stepped from 0 to 1100 volts, producing a Schottky plot. The data were then taken over a range of operating temperatures allowing the system to stabilize at the selected temperature. The set-up is shown in Figure 1.

Observations were inconsistent with electron emission coming from the cathode insert with a fixed area so a perveance study was performed to investigate the issue. This involved making emission measurements at low voltage to ensure that over the temperature range the emission remained in the space-charge limited regime [8]. In this regime, the emitted current is independent of temperature and depends linearly on $V^{3/2}$. The perveance is determined from the slope of this line and depends only on the geometry of the emission (the emitting area and the electrode separation). As can be seen in Figure 2, the slope, and so, the perveance, is observed to change significantly with temperature.

Modeling of the system suggested that the observed behavior could only be explained by an increase in emission area due to the diffusion of barium across the orifice plate with increasing temperature. The conclusion of this study was that ignition of the hollow cathode resulted from emission from the orifice plate and not the cathode insert.

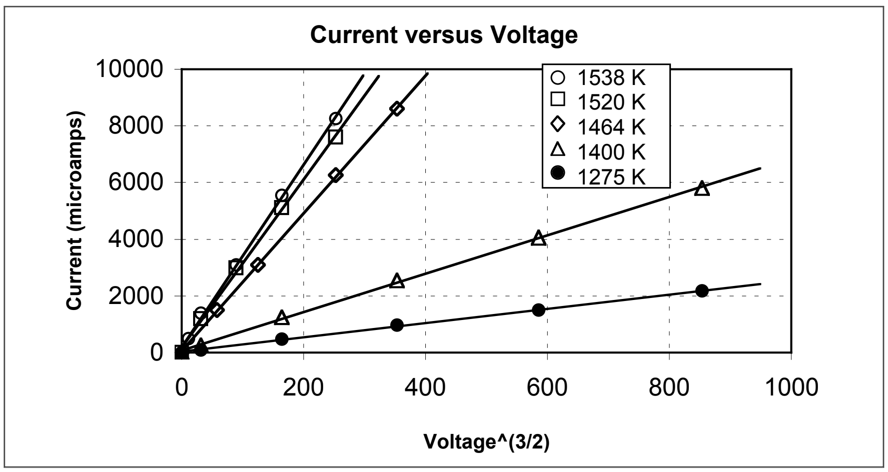

Figure 2. *Dependence of emitted current with voltage at different emitter temperatures. Space-charge limited behavior is indicated by the $V^{3/2}$ linear response and variation with temperature indicates perveance changes.*

Further testing, described below, involved placing a hollow cathode in the test chamber of an Auger Spectrometer. The results of these tests were reported by Hairapetian [9] and provide additional evidence that, prior to ignition, emission from the hollow cathode comes from the barium coated cathode tip. These tests were also performed without gas flow.

Following a standard cathode activation procedure the temperature of the cathode was raised to a maximum tip temperature of 1200 C. A surface layer of barium was then detected on the cathode tip, extending 0.010" out from the orifice. With continued heating of the cathode the barium coverage eventually extended 0.060" outward. The emission was monitored and found to increase with increased surface coverage. Furthermore, ion etching of the orifice plate resulted in an immediate and dramatic loss of emission which, with continued heated, recovered in under a minute. A final test was performed in which the emission from the hollow cathode was monitored. The orifice was plugged in situ and the emission fell slowly over several minutes as the barium desorbed from the surface. The emission recovered with the removal of the plug. This behavior supports the earlier conclusions indicating that barium migrates from the insert and onto the orifice plate resulting in electron emission.

Finally, measurements were made of electron emission from a specially prepared hollow cathode where the insert had been electrically isolated from the rest of the cathode [9]. This allowed bias voltages to be applied that could identify if the insert was the source of emission electrons. It was found that emission from the hollow cathode did not originate from the insert but, most likely, from the orifice plate.

The evidence provided by these experiments supports the basic ignition process described in this model, that is; as the cathode is heated, barium migrates from the insert to the orifice plate providing a low work function emitter that then provides the current required to initiate a plasma discharge.

III. Cathode Ignition Model

A. Overview

As reported earlier [5], the standard ignition sequence for the 25 cm thruster begins with application of current to both the neutralizer and discharge cathode heaters. The heater is coiled around the outside of the cathode tube, the downstream end of which is the cathode tip (or orifice plate). The hollow cathode insert is located inside the cathode tube. The insert is constructed of pressed, porous tungsten with the pores filled (impregnated) with a 4:1:1 mix of barium:calcium:aluminate. Radiation shielding surrounds the heater/cathode tube and insert assembly that is finally covered with a Keeper electrode.

As the temperature rises in the pre-heat phase, barium is freed and migrates through the porous tungsten matrix to the inward facing surface (the inner diameter of the insert.) Here the barium evaporates, creating a gas of neutral barium atoms in the inner core. Barium strikes all internal surfaces at a rate that depends on the pressure. The barium coverage on the inside of the orifice becomes the boundary condition for diffusion of barium onto the outside of the orifice plate.

Barium coverage of the outer surface of the orifice plate proceeds at a rate that is controlled by both the surface diffusion coefficient and the desorption time. The formation of a barium monolayer on the orifice plate provides a low work function emitter that produces the source of ionization electrons for ignition.

As the cathode insert ages, barium in the insert is consumed and the surface of the aluminate slowly recedes deeper into the insert, creating a “burn front”. The rate at which the burn front moves depends on the operating temperature, and with time the barium migration length increases. This, in turn, decreases the inner core pressure and the time it takes to accumulate barium at the inner edge of the orifice hole, diminishing the boundary concentration for diffusion and thereby reducing the emission current available for ignition. Figure 2 shows a simplified picture of these phenomena.

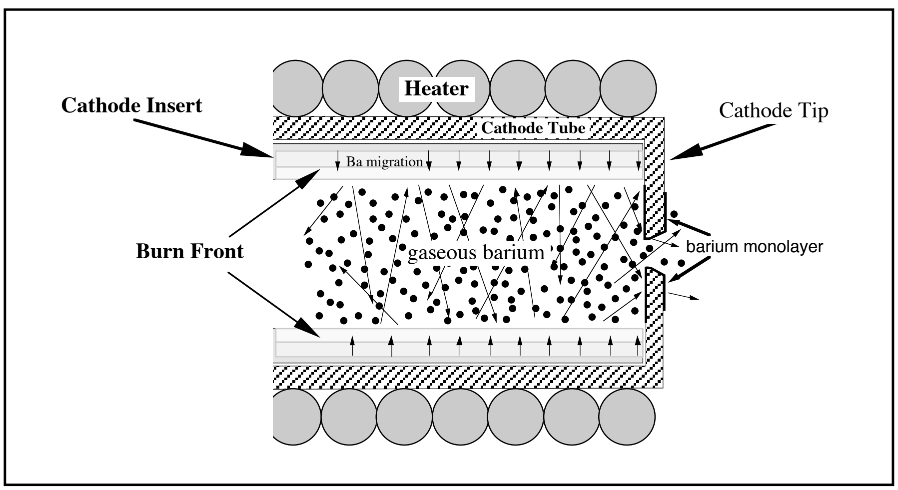

Figure 2. *A simplified schematic showing some features of barium migration that leads to ignition.*

B. Basic Equations

The primary assumptions and simplifications used in the Cathode Ignition Model have been previously described [5]. The most important of these are: 1) all surfaces exposed to the plasma are left in an atomically clean condition once the plasma is turned off, 2) plasma effects on the surfaces are not addressed, 3) the spatial and temporal profiles for the insert and orifice tip temperatures do not change with age except when different operating conditions (such as thruster power level) are being modeled, and 4) barium coverage is limited to a monolayer. Finally, estimates are used of the work function of the barium coated orifice plate and its temperature dependence since experimental values are not available.

As stated earlier, the initial phases of cathode ignition are determined by the ability to diffuse barium onto the face of the cathode orifice plate. This migration of barium from the insert begins with the chemical release of free barium from the impregnant through chemical reactions with the porous tungsten matrix and is characterized as Knudsen flow driven by the pressure of barium in the pores. This pressure was determined by Rittner et al. [10] and is given by:

$$P_0 = 16.475\ e^{-\frac{21960}{T}} \qquad (1)$$

Barium is released into the hollow cathode at the inward-facing surface. As it is consumed a burn front is created and the pressure at this surface is reduced by the pressure drop across the empty pores. With time, t, the pressure in the pore will drop linearly with $t^{1/2}$[10]. The surface pressure can then be described by:

$$P_S = P_0\left(1 - \sqrt{\frac{t}{\Omega(T)}}\right) \qquad (2)$$

The Omega function, $\Omega(T)$, represents the time required to completely exhaust all of the usable barium in the insert at temperature, T. The temperature dependence of this function will follow an Arrhenius relationship with an activation energy. Detailed testing of identical cathode materials used in traveling wave tubes (TWTs) has determined this activation energy and the Omega function can be defined as:

$$\Omega(T) = C \cdot e^{\frac{10924.6}{T}} \qquad (3)$$

The coefficient, C, depends on the amount of barium available and will be determined from Hollow Cathode Life Test data discussed later in this paper.

Barium evaporates from this inner insert surface and strikes all surfaces containing the volume. A monolayer is formed at a rate given by kinetic theory. The deposition of barium determines the boundary condition for diffusion, and the surface coverage, θ, will be determined by the processes of deposition, diffusion and desorption.

In this model, ignition is characterized by emission from the cathode tip. This will be determined by barium diffusion onto and evaporation from the tip. The diffusion equation, including desorption characterized by the time constant τ, is:

$$D\nabla^2\theta = \frac{\partial\theta}{\partial t} + \frac{\theta}{\tau} \qquad (4)$$

The surface coverage, θ, depends on the geometry of the surfaces. For the discharge cathode this includes conical and flat sections and the final solution is made up of contributions from these regions. With the surface coverage of barium determined by the solution to Eq. 4, the emission current can be calculated from the work function of this surface. The equation describing this work function is taken from the work of Longo [11, 12] and is given by:

$$\phi(\theta) = 4.3\left(\frac{4.3}{2.49}\right)^{-\frac{\theta}{\theta_m}} + 2.49\left[1 - \left(\frac{4.3}{2.49}\right)^{\frac{\theta}{\theta_m}}\right] \qquad (5)$$

where the individual components will produce current, *i*, according to the surface coverage

$$i = 2\pi\int_{s_0}^{s} j(\phi(\theta(r,t)))\ r\ dr \qquad (6)$$

where the current density, j, is determined from the Richardson-Dushman equation given by,

$$j = A\,T^2 e^{\frac{-q\phi(\Omega)}{kT}}\, e^{\frac{0.44}{T}\sqrt{\frac{V}{d}}} \qquad (7)$$

These equations constitute the entire ignition model and provide the capability of describing the time dependence of the emission from the orifice tip to the Keeper during ignition. In effect there are two time scales in the model: the aging time of the insert at the operating temperature and the time required to reach the emission level needed for ignition. By defining the requirements for ignition, an effective time to End of Life (EOL) can be determined.

IV. Application of the Model to Hollow Cathode Life Tests

A. NASA SSC Insert

This cathode model was calibrated against the NASA SSC Hollow Cathode Life Test data [13,14], and the self-heating insert temperature profile measured experimentally at JPL [6]. These temperature data were measured specifically for this cathode geometry. The results provided here are very similar to those previously reported [5] with the exception that a different approach has been taken to more accurately fit the Omega function through the ignition process.

The SSC Life Test used a diode configuration, with an anode placed 6 cm in front of the cathode. The cathode itself had no Keeper. The cathode discharge was ignited on 22 occasions followed by various segments of continuous operation. Ignition voltages were very stable over the first 23,000 hours of operation at which point they rose dramatically and the cathode tip temperature increased by ~80 C (from ~1250 to ~1330 C). This change was preceded by the first regeneration of the cryopumps. At ~28,000 hours the cathode failed to ignite with an applied voltage of >1000 V. This marked the end of the test. The test data provides a benchmark to define the Ω(T) function with the caveat that some of the test conditions may have influenced the end of life condition (e.g. the cryopump regeneration).

The Omega function coefficient, C, in Eq. 3 was adjusted in the model until the voltage behavior observed in the life test was reproduced. The voltage required to ignite the neutral xenon gas was determined by calculating the emitted current from the model and a calculation of the ionization rate using available Xe ionization cross-section data [15]. The results are shown in Figure 4. The very sharp rise in voltage observed in the test is also seen in the model predictions. The voltage rise appears as sharp as it does in part because of the long time scale of the plot. Early life would have an over-abundance of barium and voltage for ignition remained constant and low. Only toward the end of life does barium delivery become a problem and then changes to the ignition voltage will occur very rapidly. Because of concerns with changing test conditions, the first data point following the cryopump generation was ignored.

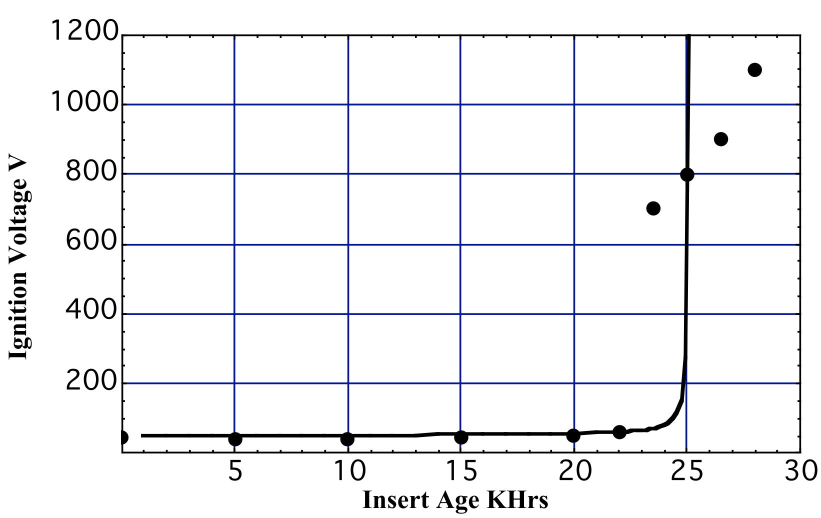

Figure 4. *Ignition voltage as a function of age. Data points are from reference [13].*

Using this procedure, equation (3) can now be written as:

$$\Omega(T) = 7.797 \cdot 10^{-3} e^{\frac{10924.6}{T}} \qquad (7)$$

Table 1, represents ten equally spaced segments along the length of the cathode insert. This representation may be visualized as the upper half of a length-wise cross-section of the hollow cylindrical insert. The top row is the normalized length from the up-stream to the down-stream end of the insert. The temperature profile shown in the center row is determined from the JPL data. The lower row is the time to usable barium exhaustion at each temperature. The model shows that for an insert run continuously, the down-stream end will exhaust first, at 9.0 Khrs, and the plasma will have to reach deeper into the insert for emission. Complete exhaustion of the barium in the insert occurs in 30 Khrs.

	Up-Stream End									**Down-Stream End**
Distance	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Temperature (K)	1323	1341	1361	1382	1406	1431	1457	1586	1516	1548
Ω (KHrs)	30.0	26.8	23.8	21.0	18.4	16.1	14.0	12.1	10.5	9.0

Table 1. *Insert profile for the SSC unit. At 30,000 hours the front half of the insert is completely depleted of usable barium.*

The SSC Hollow Cathode Life Test data has provided the means needed to obtain the coefficient in the Omega function. The depletion of barium indicated by the model shows that the ignition of the cathode remains unaffected until ~70% of the insert has had the usable barium completely consumed.

B. ELT NSTAR (Extended Life Test)

This JPL Life Test of the Deep Space 1 Flight Spare Ion Engine [16] was operated for more than 30,000 hours and then terminated voluntarily. The thruster performed nominally prior to termination. Post-test destructive physical analysis (DPA) found the discharge keeper to be severely eroded. In spite of this there was no noticeable change in the cathode ignition characteristics over its life. There was little indication of plasma erosion of either the orifice plate or the cathode insert.

The ELT NSTAR life test was run at different throttle settings as shown in Table 2.

throttle	**Power (kW)**	**Accumulated (hrs)**	**Discharge current (A)**
TH12	1.96	500	9.9
TH15	2.33	4800	13.5
TH8	1.46	10500	7.6
TH15	2.33	15500	13.5
TH0	0.52	21500	4.9
TH15	2.33	25500	13.5
TH5	1.12	30000	6.3

Table 2. *Throttle settings for the NSTAR life tests.*

Earlier attempts to model the NSTAR ELT assumed that the insert temperature profile was the same as that used for the SSC geometry. In this section the modeling effort is repeated but now using the new temperature measurements for the correct NSTAR geometry. The temperature profiles data used in this modeling effort are shown in Figure 5.

In addition, the model has been modified to allow the depletion of the cathode to be determined for the operating time at each throttle level using the insert temperature in Figure 5. Basically the condition of the insert at the end of the run at a specified throttle level is brought forward as an initial condition for the next throttle level. The model was run in a manner identical to the actual test with the results shown below in Table 3. In this table, the amount of useful barium remaining can be tracked at each stage of testing.

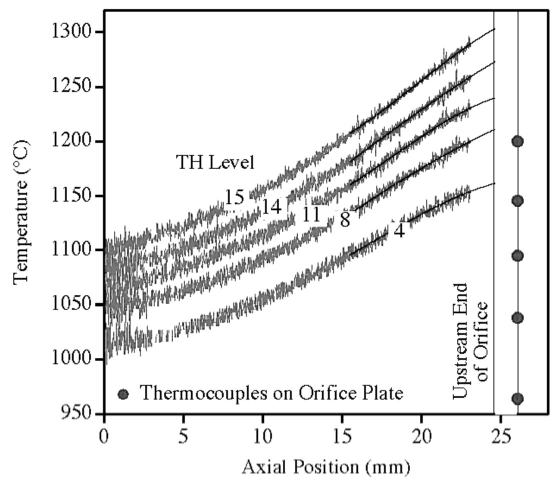

Figure 5. *Temperature profiles of the hollow cathode insert for the NSTAR ELT throttle levels. Cathode configuration includes a Keeper. Orifice plate temperatures are indicated. (from J. Polk et al. [7])*

Throttle	Temp(K)	Hrs		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
TH12	1504.6	500		99.0	99.0	98.9	98.7	98.5	98.3	98.0	97.8	97.5	97.2
TH15	1551.9	4300		89.2	88.3	86.9	84.9	82.3	79.0	75.1	70.7	65.9	60.9
TH8	1466.8	5700		80.8	79.3	77.1	73.9	69.8	65.0	59.6	53.8	47.9	42.6
TH15	1551.9	5000		71.5	69.3	66.1	61.7	56.2	49.9	42.9	35.9	29.1	21.1
TH0	1398.2	6000		66.5	64.2	60.6	55.8	50.0	43.5	36.7	29.9	23.7	18.4
TH15	1551.9	4000		60.4	57.7	53.8	48.6	42.4	35.7	28.8	22.2	16.6	12.1
TH5	1439.5	4500		56.5	53.7	49.7	44.3	38.1	31.4	24.8	18.8	13.7	9.8

Table 3. *Insert profile evolution for the NSTAR life test. Throttle level and measured tip temperature are shown on the left. Percentage of useful barium remaining in each segment from the downstream (segment 10) to the upstream side (segment 1) are tabulated on the right side.*

At the end of the Life Test the model predicts that ~10% of the usable barium would still remain in the first segment of the downstream end of the insert. However, it appears from this modeling run, when compared to the SSC result, that at 30,000 hours the amount of usable barium remaining upstream from the first cell is more than adequate for nominal ignition, in agreement with the Life Test observation.

A DPA of the NSTAR ELT discharge cathode was performed [17]. Measurements of the barium/tungsten ratios were made both axially and radially across the insert and compared to an unused insert. Along the length of the insert, the ratio indicated barium depletion only over the first few centimeters from the downstream end. Radially the depletion depth did not appear to go beyond 0.3 – 0.5 cm from the inner wall. Surface depletion over the first 0.5 cm of the downstream end was estimated to be 66%. While the values provided in this analysis are not in direct agreement with those predicted by the model, it should be kept in mind that the measurements do not represent the amount of usable barium remaining but is complicated by the presence of barium tied up in tungstate formation. The general qualitative behavior is consistent with the modeling results.

C. ETI L-3 25 cm Ignition Profiles

The primary purpose for developing this cathode ignition model was to evaluate the expected performance of the cathode used in the L-3 ETI 25 cm XIPS thruster. In order to determine and develop confidence in the □(□) function, the previous analyses were performed. Using the □(□) function, an effective life of the system can now be determined. The effective life is, by definition, the age at which a normal re-start is impossible. For the purpose of the 25 cm the ignition could be defined by the operational constraints placed on the thruster. Among other factors, these include a minimum current required to achieve ignition and a maximum time interval available to successfully ignite the thruster. As previously noted, the effective end of life will occur before all the usable barium has been exhausted.

The results in section A and B were presented in terms of the usable barium exhaustion time and the percentage of remaining usable barium. In this section emission curves at ignition will be shown as the cathode ages. This makes use of the full capabilities of the model in determining the current emitted from the orifice plate to the keeper and tracking this behavior as the insert ages. The model requires a profile of the insert temperature as a function of time as the heater is activated. As with the NSTAR ELT simulation, the temperature profile of the insert during thruster operation had, in our previous efforts [5], been based on measurements that were inappropriate for our cathode configuration.

Also, as was done with the NSTAR throttle settings, the High and Low Power Operation were simulated in a manner consistent with actual test conditions of the 25 cm Thruster Life Test. An ~3000 hour High Power Operation period was run followed by Low Power Operation, effectively, until the end of life. The results of this calculation are shown in Figure 6.

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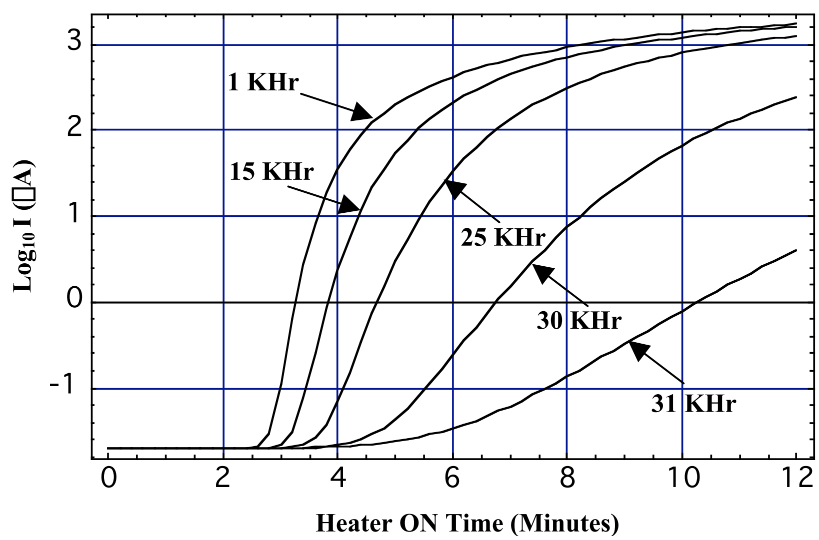

Figure 6. *Predicted aging of the emission curve for the 25 cm XIPS thruster discharge cathode. The time indicated is at Low Power and follows a period of 3000 hours at High Power.*

As seen in Figure 6, the heater time increases as the cathode ages and changes dramatically towards the end of life as the aging process accelerates. The effective end of life occurs when the current available in the maximum allowable time period is below that required for ignition. From the SSC data, the rate of ionization was calculated when the voltage began to rise sharply and was defined as the rate that is critical for ignition. This value was then imposed on the 25 cm XIPS cathode and a critical current was calculated. This ignition current was found to be ~2 □A. Due to the differences in the geometry of the two cathodes, specifically the presence of a Keeper in the 25 cm XIPS cathode, the current needed for ignition would be expected to be higher. A more practical value, based on emission test data, is between 10 and 100 □A. As the cathode insert ages, a longer heater ON time is required to attain the necessary emission current. This model then shows that at ~15 Khrs the thruster will not start with a 4 minute, 40 volt condition. Supporting this result, it was observed that at ~10 KHrs into the L-3 ETI 25 cm XIPS Thruster Life Test the ignition time had to be extended from 4 to 8 minutes to ensure a low voltage ignition.

Table 4 shows the distribution of usable barium at the time steps shown in Figure 6. Consistent with the observed depletion of barium in the SSC model runs, changes to the ignition requirements do not become significant until more than 50% of the insert has been completely depleted of barium.

	0.1	.02	.03	.04	.05	.06	.07	.08	.09	1.0
1 KHrs	97.6	97.5	97.3	97.0	96.6	96.1	95.5	94.8	94.0	93.1
10 KHrs	81.6	80.5	78.9	76.7	73.8	70.1	65.8	60.8	54.9	48.5
15 KHrs	71.1	69.4	66.6	62.6	57.2	50.2	40.8	27.3	0	0
20 KHrs	58.8	56.0	51.3	44.2	33.3	10.8	0	0	0	0
25 KHrs	43.1	38.2	28.8	0	0	0	0	0	0	0
30 KHrs	16.1	0	0	0	0	0	0	0	0	0
31 KHrs	0	0	0	0	0	0	0	0	0	0

Table 4. *Insert profile evolution for the L-3 ETI XIPS 25 cm cathode for the same conditions used in Figure 6. Percentage of useful barium remaining in each segment is tabulated for the indicated operating time at Low Power.*

The results of this model indicate that the ignition of the 25 cm cathode should remain stable providing effective life well in excess of mission requirements (~13,000 hours of Low power after the High power stage). There may, however, be life-limiting agents not included in the model that determine the final cathode life.

V. Conclusion

The model presented here determines an effective end of life for a hollow cathode based on the inability to restart the unit after a shutdown. The proposed mechanism for ignition depends on the diffusion of barium onto the cathode orifice plate. During ignition the cathode insert represents a barium source and the release of barium from the insert is described in the model by processes that are similar to those developed at L-3 ETI for Traveling Wave Tube cathodes. As the cathode ages with thruster operation, the barium burn front retracts from the surface of the hollow insert inner diameter. The time required to deposit and then to diffuse barium onto the ignition surfaces increases so that the conditions for ignition take longer to be reached. The model requires descriptions of the geometry of the insert, cathode tube and orifice plate as well as the operational requirements for ignition.

Benchmarking the model with available cathode life test data, the model has been used to determine the expected time required to deplete the usable barium along the cathode insert and compare these calculations with the results of both the NSTAR ELT thruster Life Test. The Cathode Ignition Model provided a good representation of this test. Finally the model was used to describe the emission curves at ignition for the L-3 ETI 25 cm XIPS cathode and track these curves as the insert aged. The results indicate that the ability to ignite the cathode should remain stable well beyond the present mission requirements.

The work presented here should be considered as an initial step to understanding the ignition processes and effective End of Life of the Hollow Cathode. Several parameters in the model were based on limited data and several assumptions. There is a need for additional experimentation to provide direct measurements to validate the model. A hollow cathode test facility is presently being planned at L-3 ETI for this purpose.

This model ignores plasma-material interactions that are often clearly visible upon examination of used inserts. The justification for this approach are: 1) the plasma-material interaction does not close up the pores, if anything the erosion enhances the surface porosity on the I.D. of the insert, and 2) the chemical reactions that are responsible for freeing barium in the insert take place deep in the insert and are shielded from the plasma. Nevertheless, the robustness of the hollow cathode to harsh environments may impact performance in a manner not captured by this model and, ultimately, may represent the limiting factor in determining life.

Acknowledgments

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