Hollow Cathode Ignition and Life Model

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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 describe a detailed physical model of the cathode. Use of the model to characterize the expected life of the device was validated using published NASA data and internal L-3 ETI life test data.

Nomenclature

P_0 = barium pressure in tungsten pore at the burn front
P_s = barium pressure in tungsten pore at the emission surface
$\Omega(T)$ = time required to completely consume barium at temperature, T
G = surface deposition of barium integrated over time
θ = barium surface coverage
ϕ = work function
Γ = depth of the work function minimum
j = current density
i = emitted current

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 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 or orifice tip. Voltage is then applied to a close spaced Keeper prompting electron emission and subsequent ionization of xenon gas flowing through the cathode. The heaters are then de-activated and the 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 released from the thruster in order to balance the release of positive Xenon ions and maintaining charge neutrality in the thruster.

Several models of the behavior of the hollow cathode have been developed. In 1982 D.E. Siegfried [1] provided a detailed examination of the plasma physics processes within the hollow cathode during operation. Patterson and Jugroot [2], reported on an experimental and theoretical investigation into the discharge initiation of the T6 thruster hollow cathode. S. D. Kovaleski [3] developed a thermo-chemical model for the operation of a hollow cathode. The

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barium pressure in the pores was calculated and the loss of barium was associated with diffusion through the propellant and removal at the ends of the insert. Life was then determined by the consumption of barium.

More recently, Katz, et al. [4] have presented a model of hollow cathode operation and life limiting mechanisms. In this work the characteristics of the hollow cathode plasma during operation were modeled in detail. To determine life, the authors calculated the emission current at the beginning of life, including a Schottky correction factor. They then follow the work of Palluel and Shroff [5] to determine the barium consumption rate.

The station-keeping requirements of the XIPS 25 cm thruster, which entails daily ignition, suggests 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. A description of the processes leading to cathode ignition is central to this model.

Several life tests on hollow cathode assemblies have been performed [6-9]. These include a National Aeronautics and Space Administration (NASA) 28,000 hour test for the International Space Station (ISS) Plasma Contactor System and the L-3 Communications Electron Technologies Inc. (L-3 ETI) 13 cm thruster qualification test. More recently, life test of the NSTAR 30 cm thruster has been completed at the Jet Propulsion Laboratory (JPL). The L-3 ETI XIPS 25 cm thruster Life Test is nearing completion. The hollow cathode assemblies in each of these tests are similar and so can be used to benchmark the XIPS Cathode Ignition Model.

II. Cathode Ignition Model

A. Ignition and Aging

The standard ignition sequence for the 25 cm thruster begins with application of current to both the neutralizer and discharge cathode heaters. The heaters are coiled around the outside of the cathode tube, the end of which is the orifice tip. Both the cathode tube and tip (or orifice plate) are constructed of Moly-Rhenium. The hollow cathode insert is located inside the cathode tube. This insert consists of pressed, porous tungsten with the pores filled (impregnated) with a 4:1:1 stoichiometric mix of barium calcium aluminate.

Radiation shielding surrounds the heater/cathode tube and insert assembly and this is finally covered with a Keeper. A sketch of this configuration is shown in figure 1.

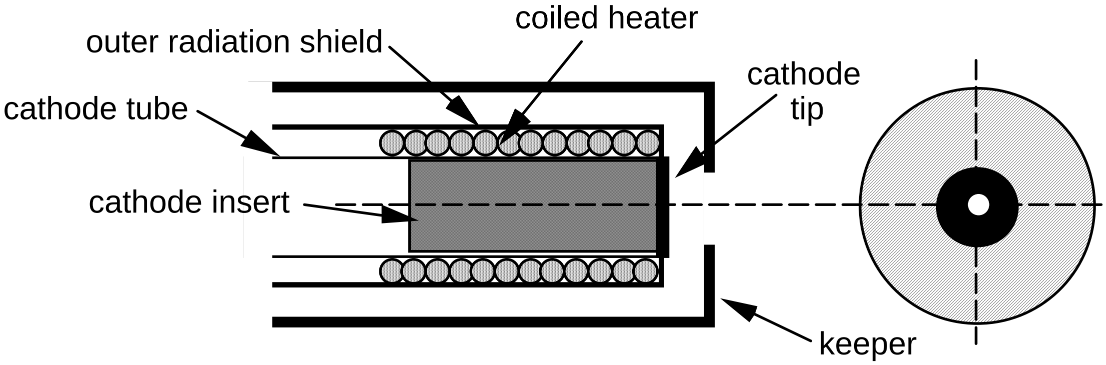

Figure 1. *A schematic showing the major features of the hollow cathode configuration used in the 25 cm XIPS thruster. Xenon gas flows through the center of the assembly.*

In the pre-heat stage, current is applied to the heater and the cathode tip temperature is eventually raised to ignition temperature in the vicinity of 1100 C.

As the temperature rises, barium is freed and flows 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 loss at both ends of the insert reduces the barium pressure in the inner core and thus the strike rate, increasing the time to cover the surfaces.

The barium then diffuses onto the outer surface of the orifice plate at a rate that is controlled by two parameters: the surface diffusion coefficient, D, and the desorption time, τ. These two parameters enter the model as a product, $D\tau$. 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 is consumed and the surface of the aluminate slowly progresses deeper into the insert, this is called the “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 in turn the emission current for ignition. Figure 2 provides a simplified picture of these phenomena.

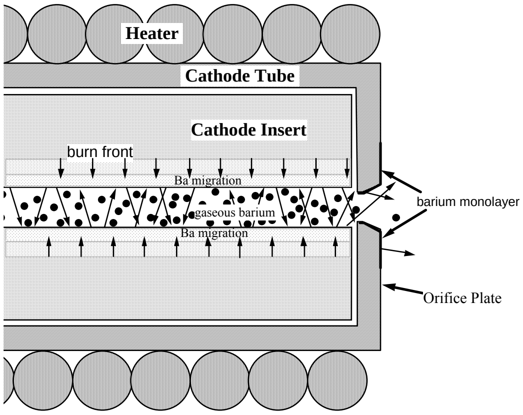

Figure 2. *A simplified schematic showing some features of barium migration that leads to ignition.*

B. Model Assumptions

The primary assumptions used in the Cathode Ignition Model are: 1) End of Life is determined by the inability to ignite the cathode, 2) a minimum power is required to ignite the plasma, 3) the barium-coated orifice is the only source of ignition electrons, 4) all surfaces exposed to the plasma are left in an atomically clean condition, and 5) plasma effects (erosion) are secondary in life determination

In addition to these assumptions there are additional simplifications used in the model. These are: 1) the cathode insert and the orifice tip temperatures are kept constant in time, 2) any barium gas leaving the cathode insert area is lost and 3) barium coverage can accumulate only to a monolayer.

Finally, estimates of the work function of the barium coated orifice plate and its temperature dependence are used in the model since experimental values were not available.

The first assumption distinguishes this model from several others, since end of life is not coincident with barium exhaustion. It is similar to one used in modeling the traveling wave tube (TWT) dispenser cathode. In the TWT dispenser cathode life model (DCLM), the end of life occurs when the “aging emission current” drops below the level that can be compensated or the tube drops out of specification for the mission. Similarly, for the ion thruster, as the hollow cathode ages the emission current will decline and when it falls below the level required for ignition, a “practical” end of life will have been reached regardless of how much barium remains. For the purpose of this study, an emission current of 100 μA with 100 V applied to the Keeper defines the minimum power level required for ignition. Ignition tests on 25 cm thrusters have been correlated with cathode emission tests and indicate that, at least in early life, this limit is reasonable.

Once ignited the cathode insert is self-heated. While direct measurements have not fully characterized the processes following ignition, it is considered that a xenon plasma initially forms between the orifice plate and the keeper. This plasma extends into the hollow core of the cathode insert. Coupling of the electric field into this region drives the ionization electrons that ultimately provide the breakdown of the main discharge. The amount of current being extracted from the insert at this time strongly affects the temperature of the insert, and thus its life. The High Power Mode of the 25 cm XIPS thruster results in an insert temperature of ~1250 C near the tip; while in the Low Power Mode it is ~1100 C. The neutralizer operates at a slightly lower temperature than the discharge cathode. The temperature profile along the insert has been measured [13] and a simplification of the model is that this profile is usable under all conditions for all time. While temperatures across the insert may be higher during ignition, because of the greater time, it is the self-heated operation that contributes most significantly to the age of the insert.

The L-3 ETI 13 cm XIPS Thruster Life Test showed that operation in the plasma environment can have a substantial effect on the morphology of both the cathode emission surface (the inner-facing surface of the insert) and the orifice tip. More recently, data from the 25 cm XIPS and the 30 cm NSTAR Thruster Life Test indicate that the impact of the plasma environment may not be as significant. It would be expected that plasma-assisted reactions would have some effect on the long-term behavior of the insert and consequently its life. At this time, however, very little is understood about the precise consequences of these plasma-material interactions. In any case, the Cathode Ignition Model described here contains no physics associated with these phenomena.

C. Model Description and Equations

In order to determine the partial pressure of barium in the cathode, the pressure produced in the pores of the tungsten insert at the "burn front" is calculated. In an unused insert, the front is located at the surface of the inner diameter of the hollow insert. As the cathode ages the "burn front" migrates below the surface.

The migration of barium through the pores is characterized by Knudsen flow and is driven by the pressure. The pressure in the pore at the "burn front" is given by Rittner et al. [10]:

$$P_0 = 16.475\ e^{-\frac{21960}{T}} \qquad \text{eqn.1}$$

At the inward-facing surface the pressure will be reduced because of the pressure drop across the empty pores. This is given by:

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

In these expressions T (in Kelvin) is the operating temperature, t (in kilohours) is the time the cathode has operated with the insert (and orifice plate) at this temperature. Ω(T) is a function that represents the time required to completely exhaust all of the usable barium in the insert at temperature, T.

At t = 0, the impregnant fills the pores to the surface and eqn 2 reduces to $P_S = P_0$. When t = Ω(T), the pressure at the surface is 0. The temperature dependence of the Ω(T) function has been determined in life tests on TWT dispenser cathodes. The coefficient, discussed in the next section, has been determined from Hollow Cathode Life Test data.

$$\Omega(T) = 9.173 \cdot 10^{-3} e^{\frac{10924.6}{T}} \qquad \text{eqn. 3}$$

As the temperature of the insert rises, the partial pressure of barium increases. The surface pressure, however, is reduced by losses from the up-stream end of the insert and through the orifice at the tip so a reduction factor (the ratio of the loss area to the total area) is included in the model.

Barium evaporates from the surface and strikes all surfaces containing the volume. The number of atoms that strike is given by kinetic theory. The initial monolayer of barium adheres strongly to a properly conditioned surface. Due to its high vapor pressure, barium striking a surface covered with barium is rapidly desorbed. The model assumes that the surface coverage θ will be limited to a monolayer. With G, as the surface deposition (in monolayers) of barium integrated over time, this constraint is obtained by setting the surface coverage, θ,

$$\theta = \frac{G}{1+G} \qquad \text{eqn. 4}$$

These equations determine the arrival rate of barium on the boundary surfaces from which barium now diffuses onto the emission surface. This surface is the orifice plate. The generalized shape of the orifice surface and the plate are shown in figure 3. The conical portion is characteristic of the 25 cm discharge cathode and is not present in the neutralizer.

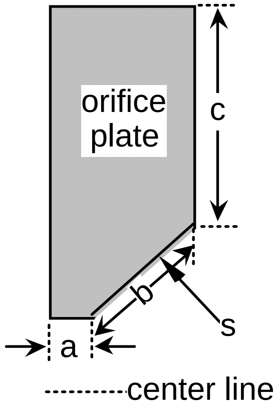

Figure 3. *A "generalized" half section of the orifice plate showing the inside surface of the orifice consisting of a flat section,* a, *a conical section,* b, *and the flat face section,* c. *The location represents the leading edge of the barium monolayer.*

The diffusion equation for the surface diffusion of barium is modified to include a term for barium desorption, the diffusion equation is

$$D\nabla^2\theta = \frac{\partial\theta}{\partial t} + \frac{\theta}{\tau} \qquad \text{eqn. 6}$$

The two solutions, flat and conical regions, must be patched together.

With the surface coverage of barium now determined, 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:

$$\phi(\theta) = 4.3\left(\frac{4.3\Gamma}{2.49}\right)^{\frac{\Gamma\theta}{1-\Gamma}} + 2.49\left(1 - \left(\frac{4.3\Gamma}{2.49}\right)^{\frac{\theta}{1-\Gamma}}\right) \qquad \text{eqn. 7}$$

Emission current will be generated from all coated surfaces so that:

$$i = i_{cone} + i_{flat} \qquad \text{eqn. 8}$$

where the individual components will produce current according to the surface coverage and the Richardson-Dushman equation with the Schottky term. So we have,

$$i_{cone} = 2\pi \int_{s_0}^{s_1} j(\phi(\theta_{cone}(r,t)) \ r \ dr \qquad \text{eqn. 9 - a}$$

and

$$i_{flat} = 2\pi \int_{s_1}^{s_2} j(\phi(\theta_{flat}(r,t)) \ r \ dr \qquad \text{eqn 9 - b}$$

with

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

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. The ability to reach the required current can then be evaluated as a function of age. In effect there are two time scales in the model. The aging time at a fixed operating temperature and the ignition time or the time required to reach the emission level required for ignition. By defining the constraints on ignition, an effective End of Life (EOL) can be determined.

III. Model Verification using Hollow Cathode Life Tests

A. NASA SSC Insert

To calibrate the model we use the NASA SSC Hollow Cathode Life Test data [6, 7], and the self-heating insert temperature profile measured experimentally at JPL [13].

This Life Test used a diode configuration in which an anode was placed 6 cm away from 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. This point in the life test was preceded by the first regeneration of the cryopumps. The tip temperature increased by ~80 C (from ~1250 to ~1330 C) at this point. 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 useful benchmark to define the Ω(T) function with the caveats that 1) test conditions may have influenced the end of life condition (cryopump regeneration) and 2) the ignition sequence used in this test configuration differs somewhat from that used in this model.

The ignition voltage, shown in figure 4, was calculated from the model from the following considerations. It is assumed that the minimum power required to ignite the plasma does not change over the life of the insert. At the beginning of life this power is determined from the current emitted and the applied voltage. The current was then calculated from the model using the heater time to reach ignition and the voltage between the tip and anode, and by adjusting the coefficient in the Ω(T) function, the desorption time, and the diffusion length.

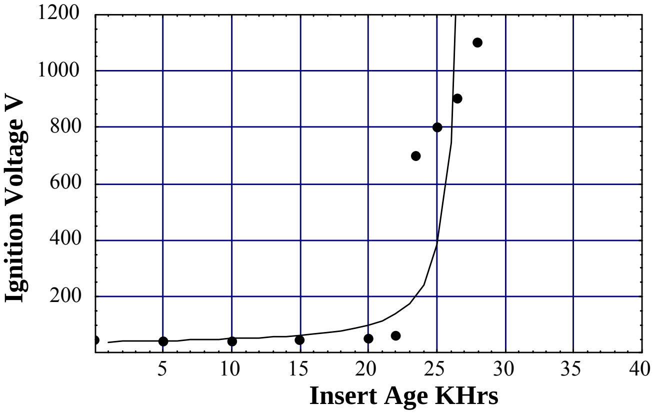

Figure 4. *Ignition voltage as a function of age. Data points are from reference [9].*

In this manner, the Ω(T) function was determined to be:

$$\Omega(T) = 9.173 \cdot 10^{-3} e^{\frac{10924.6}{T}} \qquad \text{eqn 10}$$

Figure 5, represents ten sections along the length of the cathode insert. This representation may be thought of as the upper half of a length-wise cross-section of the hollow cylindrical insert. The temperature profile shown in the center row is determined from the JPL data. The top row is the normalized length from the up-stream to the down-stream end of the insert. 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 16.1 Khrs, and the plasma will have to reach deeper into the insert for emission. Complete exhaustion of the barium in the insert would occur in 57 Khrs. However this "maximum life" is not attainable since, if the system ever shuts down, restart would be impossible.

Up-Stream End **Down-Stream End**

Distance	0.0	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	1486	1516	1548
Ω(KHrs)		57	51	45	39	34	30	26	22	19	16.1

Figure 5. Insert profile for the SSC unit.

B. ELT NSTAR (Extended Life Test)

To check the Ω(T) function derived from the SSC data, NASA ELT NSTAR test results were modeled. This JPL Life Test of the Deep Space 1 Flight Spare Ion Engine [8] 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 1.

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 1. *Throttle settings for the NSTAR life tests.*

Assuming the same insert temperature profile, as for the SSC, the temperature at each throttle setting can be determined. The model can be used to mimic the varying conditions associated with each throttle setting. For the purpose of demonstration, however, results are shown in figure 6 assuming that the entire test was run at a single setting. In the bottom of figure 6, the calculated values of Ω at the highest throttle setting (TH15) are given for each section of the insert. In the middle row, values calculated for the final throttle condition (TH5) are shown. In some sense these operating conditions bound the expected performance. The darkened segments in this figure indicate that at the end of the life test period (30,000 hours) these insert regions would be exhausted of usable barium.

Up-Stream End **Down-Stream End**

Distance	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Ω(KHrs): Last throttle		136	123	110	98	86	75	65	56	48	40.7
Hi-throttle		47	42	37	32	28	24	21	18	15	13.1

Figure 6. *Insert profile for the NSTAR life test.*

Although these results do not completely validate the model, it does provide some credibility and confidence since it indicates that the cathode insert should contain adequate barium to continue to operate beyond the termination of the Life Test.

C. ETI L-3 13 cm XIPS Thruster Life Test

As an additional check on the model, data was used from the L-3 ETI 13 cm XIPS Thruster Life Test [9]. The dimensions of the cathode assembly (insert size, orifice dimensions, keeper spacing) were input into the model. The geometry here is similar to the L-3 ETI 25 cm XIPS cathode but differs somewhat from the NASA design. The Life Test was voluntarily terminated after ~21,000 hours and ~3,400 cycles. While neither the neutralizer nor the discharge cathode experienced any issue associated with ignition, there was substantial ion erosion of the discharge cathode orifice plate and degradation of the insert.

To validate that the model would predict that adequate barium would remain to provide ignition, at the termination of the Life Test, the model was run with cathode temperatures consistent with nominal operating conditions. The results shown in figure 7 assumed continuous operation for both the discharge and neutralizer cathodes.

DISCHARGE CATHODE

Up-Stream End **Down-Stream End**

Distance	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Temperature (K)	1241	1254	1269	1285	1303	1323	1344	1368	1393	1420	1448
Ω(KHrs)	61	56	50	45	40	35	31	32	23	20	17.3

NEUTRALIZER CATHODE

Up-Stream End **Down-Stream End**

Distance	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Temperature (K)	1219	1234	1245	1260	1277	1296	1317	1339	1363	1388	1436
Ω(KHrs)	72	64	59	54	48	42	37	32	28	24	18.5

Figure 7. *ETI L-3 13 cm, insert profile for both the discharge and neutralizer cathodes at nominal operation.*

It is clear from these results that, at the time the test was voluntarily terminated, neither cathode would be expected to have reached a condition that would result in ignition problems.

D. 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 $\Omega(T)$ function, the three previous analyses were described in terms of the usable barium exhaustion time. Using this $\Omega(T)$ function, the 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.

In presenting the results of the model, the emission curves at ignition are 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. It is assumed that this profile remains unchanged with time.

Setting temperatures typical of High Power Operation for the discharge and the neutralizer cathode, the results of this calculation for the discharge cathode are shown in figure 8 and for the neutralizer in figure 9. The rate at which the insert temperature rises during ignition was obtained from a direct measure of this profile early in life.

As the cathode insert ages, a longer heater on-time is required to attain the necessary emission. The change in heater time increases 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 normal ignition.

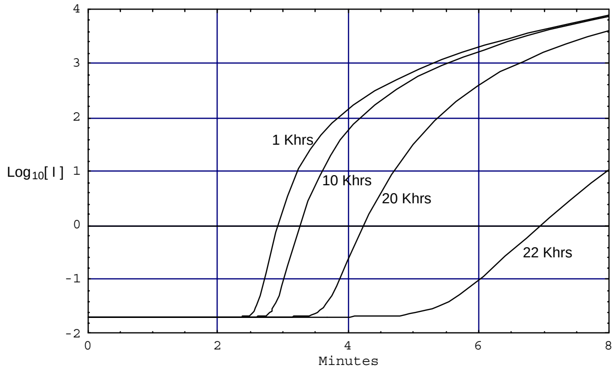

Figure 8. *Predicted aging of the emission curve for the 25 cm XIPS thruster discharge cathode. The temperature simulated High Power Operation.*

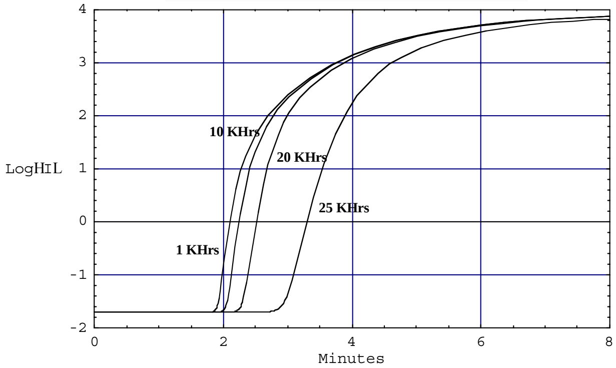

Figure 9. *Predicted aging of the emission curve for the 25 cm XIPS thruster neutralizer cathode. The temperature simulated High Power Operation.*

Results for the discharge cathode during Low Power Operation are shown in figure 10. Because of the lower operating temperature the expected life under these conditions is significantly longer.

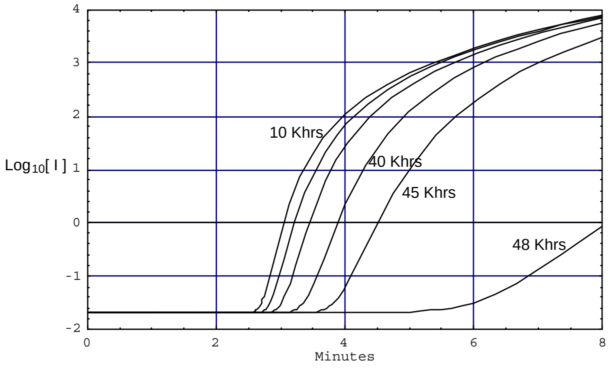

Figure 10. *Predicted aging of the emission curve for the 25 cm XIPS thruster discharge cathode. The temperature simulated Low Power Operation*

The results of this model indicate that, even under high power operating conditions, the ignition characteristics of the cathode should remain stable and the effective life should exceed 20,000 hours. There may, however, be life limiting agents not included in the model so that the predictions may be optimistic.

IV. Conclusion

The model presented here determines an effective end of life for a hollow cathode based on the inability to re-start 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 and the L-3 ETI 13 cm XIPS Life Test. The Cathode Ignition Model provided a good representation of these tests. 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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