

Hollow Cathode Emission and Ignition Studies at L-3 ETI

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Abstract: The Hollow Cathode Assembly is a thermionic source of electrons critical to the operation of the L-3 Communications Electron Technologies Inc. (L-3 ETI) Xenon Ion Propulsion System (XIPS[®]) thruster. There are two cathode subsystems on these thrusters: the discharge cathode provides the current for the main discharge and the neutralizer cathode produces an electron stream that prevents the spacecraft from charging as it expels the positive beam ions. The 25 cm XIPS[®] serves both orbit-raising and station-keeping functions on the Boeing 702 communication satellite. For station-keeping the thruster is ignited daily and operated for approximately 1 hour. The ignition of the thruster is preceded by the ignition of both the discharge and neutralizer cathodes. An understanding of the cathode ignition processes is essential to ensure performance of the thruster over its mission life. The process of igniting each cathode begins by activating an external heater. This heater is coiled around the outside of the cathode tube that contains the hollow cathode insert. The insert is constructed of pressed, porous tungsten with the pores impregnated with barium:calcium:aluminate. As the temperature increases, 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 hollow core. Barium strikes all internal surfaces establishing the boundary condition for the diffusion of barium onto the outside of the orifice plate (or cathode tip). The surface coverage proceeds at a rate that is controlled by both the surface diffusion and desorption. A practical end of life for a hollow cathode occurs when the conditions required for cathode ignition can no longer be met. On-going efforts to understand details of the ignition processes of the hollow cathode are described. These include electron emission measurements over time during the pre-heat phase, ignition dependence on temperature and determination of the barium diffusion coefficient.

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Nomenclature

P_0	=	barium pressure in tungsten pore at the burn front
$\Omega(T)$	=	time required to completely consume barium at temperature, T
θ	=	barium surface coverage
ϕ	=	work function
Γ	=	depth of the work function minimum

I. Introduction

The hollow cathode is an essential component of the xenon ion thrusters manufactured at L-3 ETI. There are two cathode subsystems on these thrusters: the discharge cathode provides the current for the main discharge and the neutralizer cathode produces an electron stream that prevents the spacecraft from charging as it expels the positive beam ions. The main thruster product in the EP product line is the 25-cm XIPS[®] that has low (2 kW) and high (4.5 kW) power modes and is used for both orbit-raising and station-keeping functions on the Boeing 702 satellite. In this application 4 thrusters and 2 power supplies make up a single EP system on a satellite. To date, 52 25-cm thrusters have been placed in orbit and have accumulated more than 58,000 operational hours. An additional 16 thrusters are in spacecraft integration and 20 more are in production. The 25-cm XIPS[®] life test has recently been successfully completed [1]. Several aspects of the Cathode Assembly represent potential life limiting processes for the ion thruster including: erosion of the Cathode Orifice and Keeper [2], failure of the heater [3] and depletion of barium from the Cathode Insert.

A practical end of life for the cathode subsystem occurs when the conditions required for cathode ignition can no longer be met. This process of successful cathode ignition is of particular importance in the XIPS[®] thruster since, in the primary role of station-keeping, the cathodes need to be ignited every day. A detailed cathode ignition and life model has been developed at L-3 ETI [4] in an effort to better understand the ignition process, accurately predict cathode life, to guide design improvements and to discover improved operating conditions. A description of the processes leading to cathode ignition is central to this model.

The ignition of a XIPS[®] cathode begins with the activation of an external heater. 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

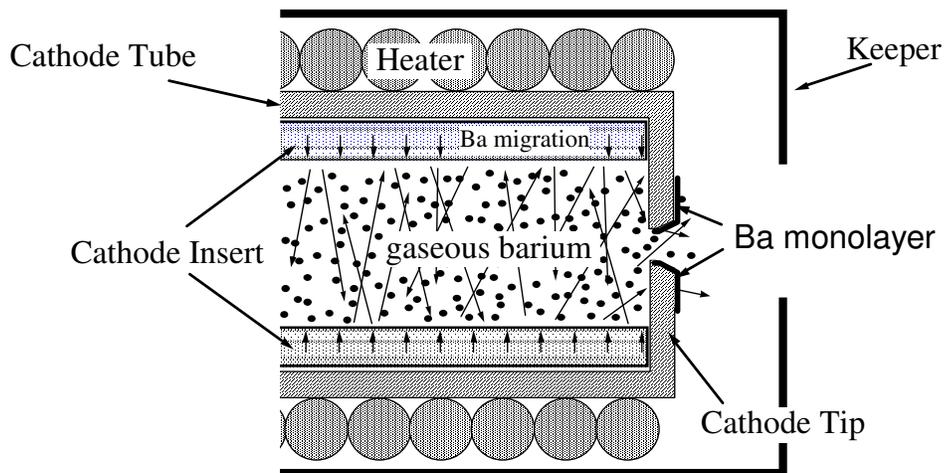


Figure 1. Illustration showing processes involved in cathode ignition model.

barium coverage on the inside of the orifice becomes the boundary condition for diffusion of barium onto the outside of the orifice plate. A schematic indicating the processes included in the model is shown in figure 1.

Barium coverage of the outer surface of the orifice plate proceeds at a rate that is controlled by both surface diffusion and desorption. 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.

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.

As the cathode insert ages, barium in the insert is consumed and the usable impregnant recedes deeper into the insert, creating a “burn front.” The rate at which the burn front moves depends on the operating temperature. Over time the barium migration length increases. This, in turn, decreases the inner core pressure and increases the time it takes to accumulate barium at the inner edge of the orifice hole. The concentration at the boundary diminishes, thereby reducing the emission current available for ignition.

II. Experimental Arrangement and Results

A. Experimental Set-up

The experiments reported in this paper were all performed in a Hollow Cathode Emission and Ignition Test Facility at L-3 ETI.

A schematic of the test facility is shown in figure 2. It consists of two basic components: a test chamber and a high vacuum region. An 8 inch cryo pump and a 350 l/s turbo pump comprise the primary vacuum pumps and are separated from the test area by a high vacuum valve. The test area simply consists of a pair of 10 inch vacuum tees with a 150 l/s turbo pump used to evacuate it prior to opening the high vacuum valve. The hollow cathode test devices are installed on one of the 10 inch flanges with all the electrical and gas feed-throughs connected on the same flange. A 4-ring anode is installed on the opposite flange and is used in establishing a plasma discharge following ignition of the cathode.

The plasma discharge is used to prepare the cathode emission surface prior to the emission tests.

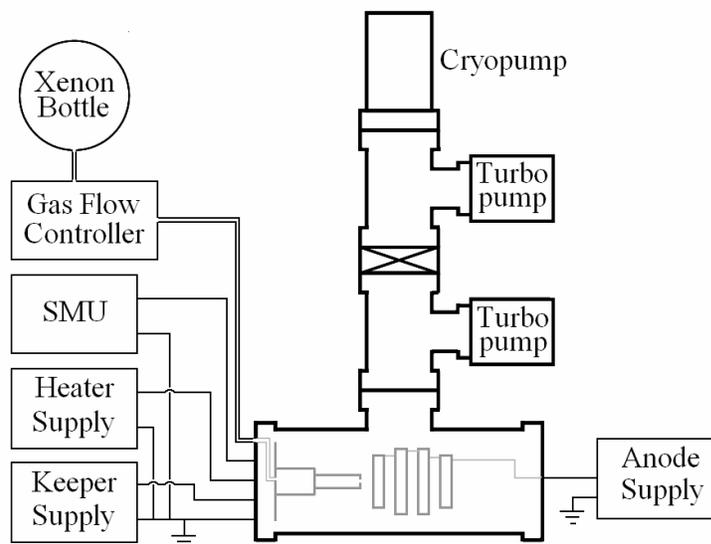


Figure 2. Schematic of the Hollow Cathode Emission and Ignition Test Facility

The cleaning of the emission surface by igniting a discharge plasma prior to emission testing was found to be very important in providing initial conditions that were as similar as possible for each test.

The cathode is ignited by first activating the external heater to the nominal current level and for the nominal pre-heat time period (typically 9 minutes). Voltage is then applied to the cathode Keeper, accelerating the emission electrons and ionizing the neutral xenon gas flowing through the cathode. The heater current is then turned off. Following ignition of the hollow cathode, the discharge is lit by applying a discharge voltage to the 4-ring anode. The anode rings are fitted with permanent magnets arranged to produce a cusp field typical of an ion thruster discharge chamber. The discharge is allowed to run for a set period using constant discharge parameters (flow, voltage and current). The discharge is then terminated and the cathode Keeper is run alone for a short period to allow the cathode tip to cool slightly before turning the Keeper off and shutting off the gas flow.

Ideally, all emitting surfaces are free of barium and in an equally well conditioned state following this cleaning procedure and prior to the emission test. Care was taken to keep the parameters used in these discharge plasma cleaning phases as similar as possible from test to test to avoid variation in initial conditions for the emission tests.

To perform an emission test the vacuum system pumps on the test chamber until a base pressure $<2 \times 10^{-9}$ torr is achieved. This base pressure is needed to reduce loss of emission due to poisoning effects caused by the accumulation of residual gases on the emission surfaces. This leads to poisoning effects that are particularly noticeable at lower operating temperatures. Between 4 to 12 hours were required after plasma cleaning to pump out the chamber.

Although the system is designed to test any XIPS[®] cathode assembly, only data from a 25 cm XIPS[®] discharge and a 25 cm XIPS[®] neutralizer cathode are presented in this paper. A schematic representation of a typical XIPS[®] cathode is shown in figure 3. Three electrical connections: the heater, Keeper and cathode ground connections are made to this cathode. The ground lead is connected to the chamber and is common to all power supplies.

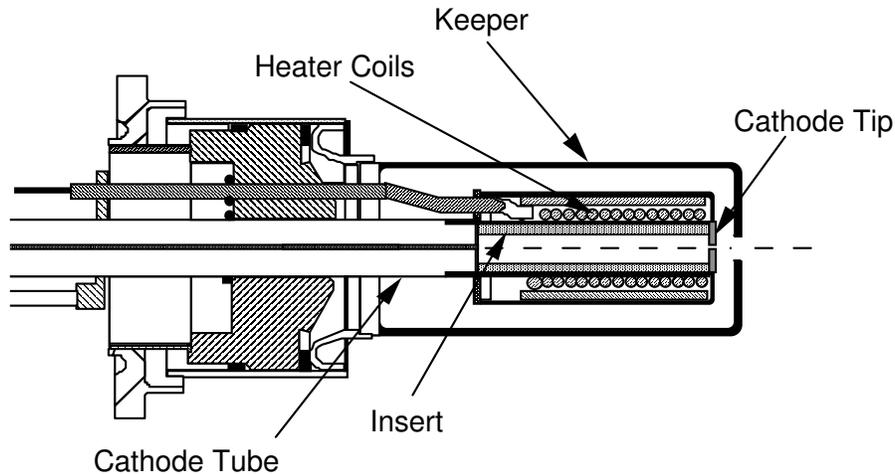


Figure 3. Schematic of a XIPS[®] Hollow Cathode

The discharge cathode used in these tests was flight-like and had been installed in a XIPS[®] thruster and then removed following the standard thruster acceptance testing and a small number of operating hours (<50) for ignition tests. The accumulated operating time on this cathode was less than 250 hours and approximately 25 ignition cycles. The pre-test history of the neutralizer cathode used in the emission testing reported in this paper was not known.

The 25 cm XIPS[®] neutralizer and discharge cathodes are virtually identical in design. The shape and the diameter of the hole in the cathode orifice plate is the only significant difference between these cathodes.

The emission tests were performed following the preparation processes described earlier. The cathode emission generally improved during the early stages of operation as the system cleaned up and the emission surfaces were conditioned. Because of this, tests were performed at fixed temperature until reasonably repeatable results were obtained. The emission tests were run using a Source Measurement Unit (SMU) to apply a fixed voltage to the cathode Keeper and measure the emitted current. In most cases the cathode orifice tip temperature was monitored

using an infra-red radiometer. This unit was calibrated against an optical pyrometer and corrected for window absorption and surface emissivity in order to obtain the true temperature of the cathode tip.

Typical emission testing began with the test article at ambient temperature and with the emission surfaces in an initially clean condition. The cathode heater was activated to a current value specified for the particular test. At the same time, the SMU was turned on to a specified applied voltage. The emitted current was measured approximately every ten seconds as the temperature of the cathode insert and the orifice plate increased.

The typical ignition time for the cathodes following activation is 9 minutes. The emission current was monitored over the first 10 minutes (600 seconds) following activation. A scan of the applied voltage was then performed while the emission current was measured. The voltage was scanned from 0 to 100 volts. In most tests, during this scan, the current was measured for both positive and negative polarities so that any non-thermionic component of current (leakage current, for example) could be detected and a precise measurement of the current emitted from the cathode could be made.

B. Steady-state Experiments

In a variation on the general experimental procedure described above, a single test was run with the discharge cathode in which the temperature of the cathode was simply scanned from low (~850 C) to high (~1250 C) allowing the emission to stabilize at each temperature. The test sequence was then reversed, reducing the cathode temperature from high to low values. Again the temperatures were held at each level until the emission current was observed to stabilize. This approach differs from the experimental procedure described earlier in that at each temperature level the initial conditions were not prepared to be the same. The initial conditions were effectively the final conditions from the previous temperature level. This precludes the ability to examine the emission behavior associated with the ignition process but, if adequate time is allowed for stability, does allow the steady-state conditions to be obtained. The raw data resulting from this test is shown in figure 4.

As indicated in figure 4, the total test time took longer than 3 days. It is clear from this data that the steady state conditions were achieved at most temperatures both while stepping the cathode temperature up and stepping it down. An exception to this is the initial test condition at 1095 C. Here, after a short, initially quite stable, period (with a small overshoot), the emission current began to rise and likely would have continued to increase had the temperature been held longer. The steady-state level at 1095 C, as indicated while stepping the temperature down, is noticeably higher. While the expected non-linear increase in emission with increasing temperature is observed, the observed overshoots and longer term variations in emission current reflect the changing balance between diffusion and evaporation processes at the various temperatures. In particular, the behavior at 1090 C suggests that in this temperature region the diffusion process becomes dominant resulting in a significant increase in emission area.

At the end of each test at the different temperature levels, a voltage sweep (as described earlier) from 0 to 100 V

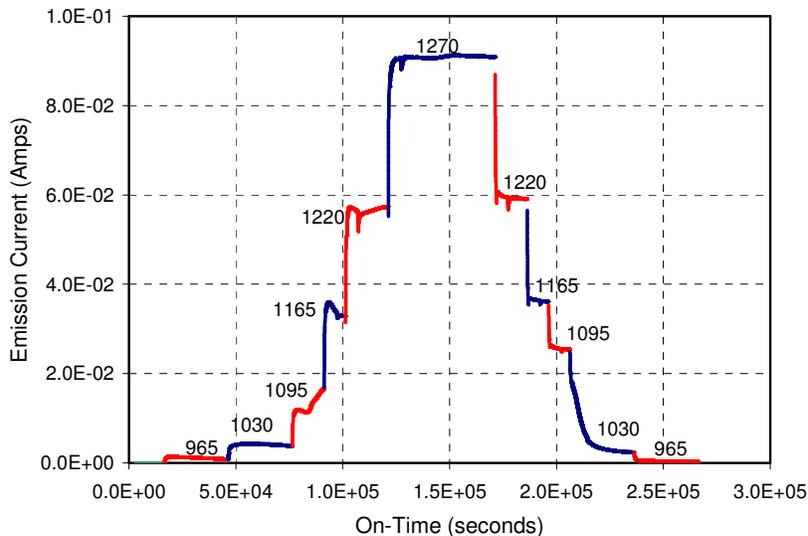


Figure 4. Steady-state testing of the XIPS[®] Discharge Cathode. Cathode tip temperature is first stepped up. Temperatures are based on calibration at the heater settings.

was performed. This data was examined in order to determine the conditions under which space-charge limited emission could be attained.

The Child-Langmuir law for emission in a parallel-plate diode, in the space-charge limit, can be written:

$$I = PV^{3/2} \quad \text{Eq 1}$$

where P is the perveance of the diode and is given by:

$$P = 2.33 \times 10^{-6} \frac{A}{d^2} \quad \text{Eq 2}$$

where A is the emission area and d is the cathode-to-anode spacing.

This can be readily solved for the area:

$$A = \frac{Pd^2}{2.33 \times 10^{-6}} = \frac{4.29 \times 10^5 Id^2}{V^{3/2}} \quad \text{Eq 3}$$

In figure 5, the emission is plotted against $V^{3/2}$ for each temperature step. In this case, the data obtained from the neutralizer cathode is shown because the data taken with the discharge cathode was slightly more limited. Basically identical behavior was seen with either cathode. If the cathode is emitting in the space-charge limit, the behavior is expected to be linear (with slope, P) and independent of temperature. It can be seen that this is not the case and only approaches it at the lowest voltage and the highest temperatures. This relationship is complicated by the fact that in this situation the diffusion and evaporation of barium from the cathode orifice plate will result in a different area at every temperature level.

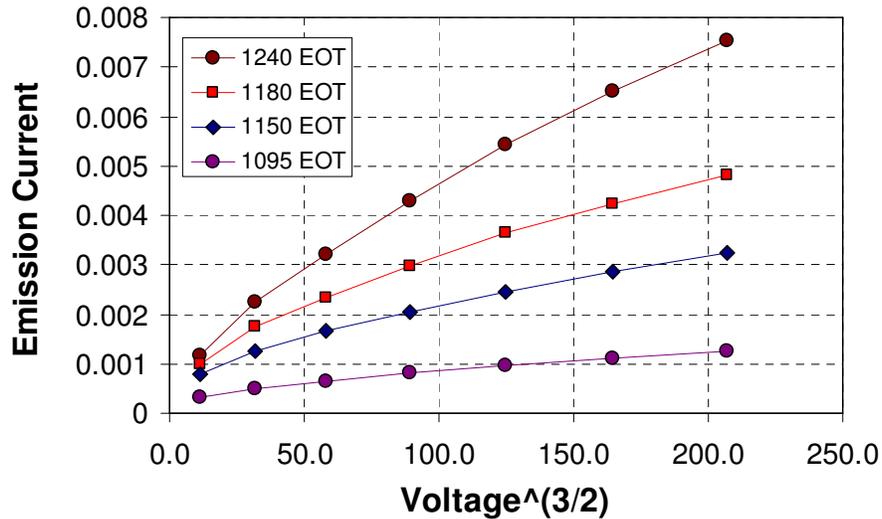


Figure 5. Family of emission curves for the XIPS[®] Neutralizer Cathode plotted against $V^{3/2}$ at different cathode tip temperatures under steady-state conditions.

To interpret this data, the assumption of space-charge limited emission at the lowest voltage level is made and the variation with temperature ascribed to changing area. The perveance (the slope at this voltage) can be plotted against $1/T$. The y-intercept will then represent the expected perveance at $1/T = 0$ or $T = \infty$. At infinite temperature, the emission is definitely space-charge limited and the emission area will be the total available area of the orifice plate. The area at any other temperature can then be determined by taking the ratio of the determined perveance to that obtained at infinite temperature.

The calculation of the emission area for the discharge cathode, using the approach described above, is presented in figure 6. One factor that would influence this result is that electrons from the cathode insert will contribute to the

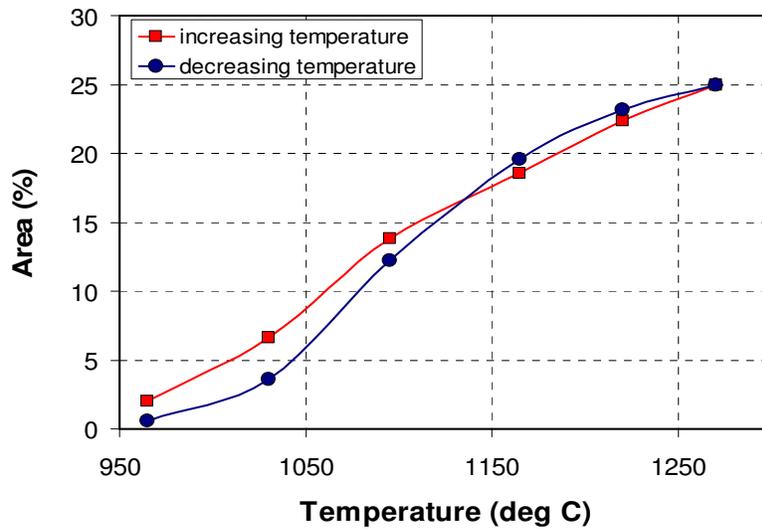


Figure 6. Emission Area as a percentage of the area of the orifice plate for the XIPS[®] Discharge Cathode as a function of cathode tip temperature under steady-state conditions.

total emission current since there is significant field penetration through the orifice. This would result in an overestimate of the emission area. The impact of this will be the subject of future investigations.

Figure 6 shows the rise in area as the temperature increases. The most significant change occurs from 1050 C and 1100 C. At higher temperatures the surface coverage appears to be saturating at ~25%. The behavior suggests that, at low temperature, evaporation of the barium is small and the emission increases as the barium slowly diffuses over the surface. At higher temperatures there is rapid diffusion and the surface coverage becomes significant. At still higher temperatures, evaporation increases and begins to balance the diffusion process so the coverage increases more slowly. To a small degree, as the cathode temperature is decreased, barium remains in place resulting in a small amount of hysteresis.

A similar calculation was performed using the 25 cm XIPS[®] neutralizer cathode. As previously indicated, this test article lacks a detailed pre-test history. It is possible that this history could be reflected in these results.

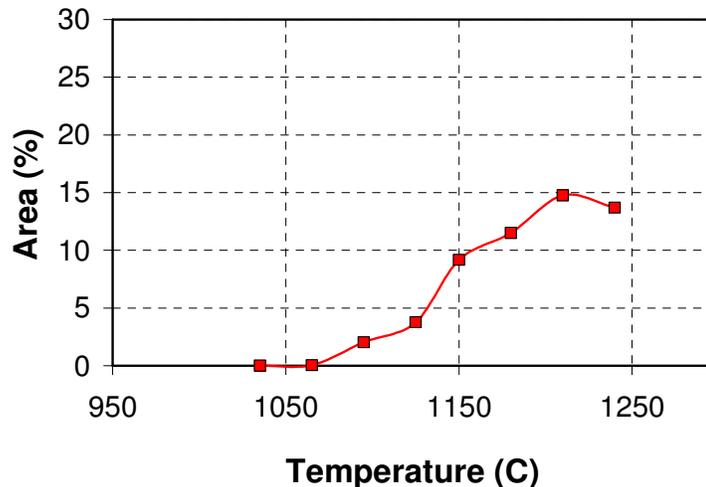


Figure 7. Emission Area for the XIPS[®] Neutralizer Cathode as a function of cathode tip temperature under steady-state conditions. Area is shown as a percentage of total cathode orifice plate.

Nevertheless, these and other results from this test article will be reported here with the understanding that detailed conclusions cannot be drawn until the tests are repeated with a flight-like test article.

The standard experimental approach, described earlier, was taken with the neutralizer cathode. The surfaces were cleaned prior to each change in temperature. The emission during the initial ignition phase was obtained and then the test continued until the emission reached steady-state. The test time at each temperature was approximately 1 day.

The steady-state emission area calculations are presented in figure 7. Compared to the discharge cathode the maximum coverage is lower, reaching a maximum of only 15%. Because of the smaller hole size in the neutralizer cathode plate, there is no electric field penetration into the insert region and this may be a factor resulting in the slightly different behavior of the 2 cathodes. At the highest temperature there is a small reduction in emission area that may be due to an increase of evaporation over diffusion at this temperature. Aside from the reduced coverage, the overall behavior of the 2 cathodes is similar.

C. Emission during cathode ignition phase

Figure 8 shows a family of curves representing the thermionic emission for the 25 cm XIPS[®] discharge cathode during the start-up phase that ends with the ignition of the cathode. This period may also be referred to as the ignition phase. These data serve two purposes: to determine the diffusion rates with the cathode model and to determine the emission current required to ignite the cathode. We will discuss the results from the cathode model in section III. A discussion of the ignition requirements will be given in the next section.

The observed emission curves for the discharge cathode are governed by the temperature and the emission area.

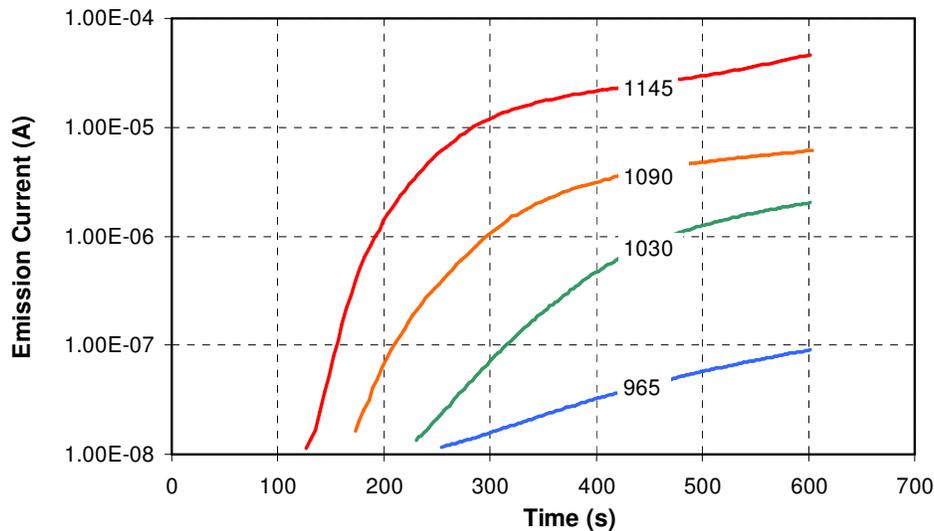


Figure 8 XIPS[®] discharge cathode emission current profiles during first 10 minutes following activation of the cathode heater.

Both of these parameters increase with time but at different rates. The temperature profiles are shown in figure 9. At lower temperature the emission curves rise more slowly than the temperature while, at the higher temperatures, the rate of increase of the emission curves is comparable to or slightly faster than the temperature.

The temperature indicated in figure 9 was taken with an infrared radiometer with fast time resolution and calibrated with optical pyrometer readings that were corrected for window absorption and surface emissivity. Modeling of this data proved challenging. Results are presented in the following section.

Rubin and Williams [5] have recently reported on a similar study. This work focused on gas evolution during cathode conditioning as well as the requirements for ignition and efforts to provide a faster ignition process. Cathode emission testing was performed and produced results that are very similar to those presented here for the discharge cathode.

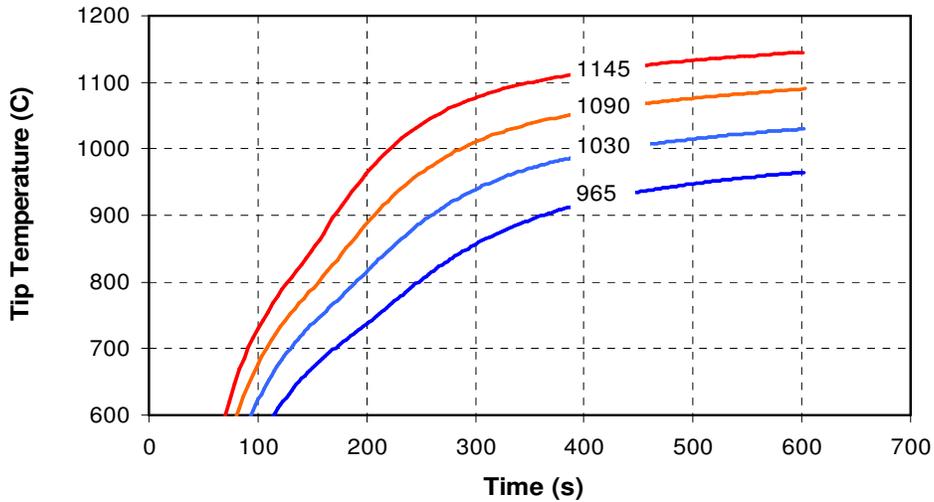


Figure 9 Temperature profiles associated with emission curves in figure 8.

Similar test data for the emission current for the 25 cm XIPS[®] neutralizer cathode is shown in figure 10. A temperature dependent dip in emission is observed in this cathode. This distinctive feature was not detected with the discharge cathode. The onset of the dip occurs sooner and the recovery is faster at high temperature than at lower temperatures. The precise cause of this phenomenon is not yet understood and tests are being prepared to investigate it. One possibility is that a gaseous poisoning agent (O₂, CO, CO₂) may be present in this cathode. A poison could be released as the temperature increases and thereby reduce the emission. With further increase in temperature the emission would recover as the impact of the poison diminishes. This could occur either because the quantity of poison or the attachment of poison is reduced. However, a Residual Gas Analyzer (RGA) was used during these tests and no poisons were detected. Furthermore, the cathodes were carefully out-gassed and conditioned prior to operation. Because of this, another possibility is being considered in which the boundary conditions driving the barium coverage have a time dependency that imposes the observed oscillation on the emission. Initial modeling

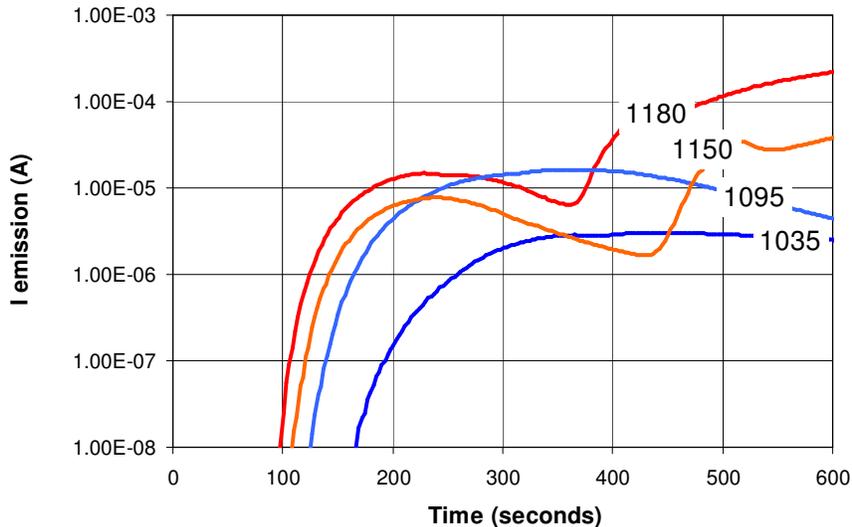


Figure 10. XIPS[®] neutralizer cathode emission current profiles during first 10 minutes following activation of the cathode heater. Cathode ignition takes place at the 540 s (9 min) point.

suggests that, with contributions of emission from the orifice walls and the insert region, such a modulation may be possible. The dimensions of the orifice would affect the degree of this modulation and may explain the observed differences between the neutralizer and discharge cathode. Further investigation will be needed to resolve this issue but, at this stage, the impact on ignition appears insignificant since, at nominal operating temperatures, the emission has basically returned to expected values before ignition is attempted.

Following the same procedure as outlined for the steady-state emission data, the emission area coverage at the 600 s point (approximately the time of ignition) was calculated for both the discharge and the neutralizer cathode. Results are shown in figure 11. The data is presented on a log-linear plot and demonstrates the exponential increase in emission area with temperature. The surface coverage of the cathodes is very small even at the typical ignition temperatures of 1150 C. The dependence of surface coverage on temperature of the neutralizer and the discharge cathode is very similar except that the magnitude of the emission area is larger for discharge cathode as indicated by the observed offset in figure 11. As with the steady-state results discussed earlier, this may be due to the contribution of additional emission from the insert region of the discharge cathode or the possibly less than ideal condition of the neutralizer cathode.

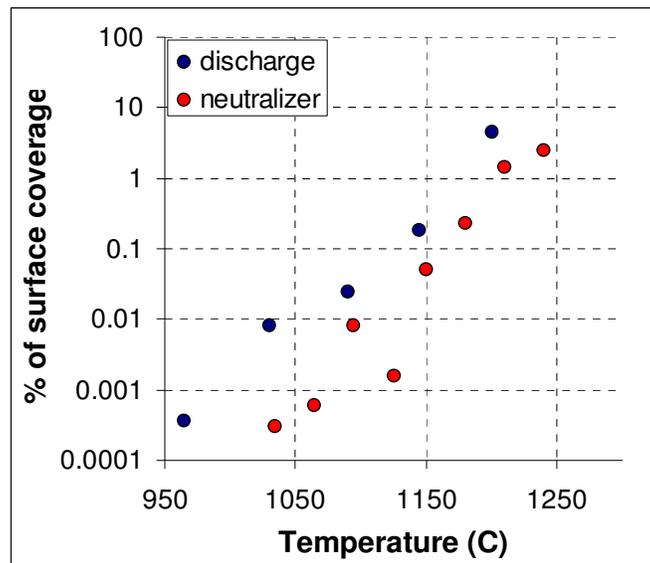


Figure 11. % of surface coverage at the time of ignition for both the discharge and neutralizer cathodes

D. Ignition Studies

Ignition of both neutralizer and discharge cathodes were studied. Temperature dependence of the ignition voltage and the impact of small quantities of cathode poisons and additional pre-heating of the cathode on ignition time were limited to the neutralizer cathode. In this paper, only results from the neutralizer cathode study will be presented.

The study was performed by first setting the cathode gas flow to 2 sccm. This is slightly higher than the nominal value of 1.6 sccm for the 25 cm XIPS© thruster operation. The work of Rubin and Williams [5] showed a dependence of gas flow on the ignition process, presumably because of higher ionization rates at higher pressure in the ignition region of the cathode. No impact on ignition was observed at the flow rates used here.

With the cathode at room temperature, the heater is activated at a pre-set current level for the nominal ignition period of 9 minutes. Ignition was then initiated by applying a Keeper voltage with programmed limits of 100 V and 1 A. Ignition occurs when, as the voltage is ramped up, the extracted emission current produces adequate ionization to result in plasma formation and extraction of the 1 A of Keeper current from the cathode insert. A digital oscilloscope was used to monitor the voltage profile and identify the voltage at the time of ignition.

The main discharge was then ignited by applying voltage to the 4-ring anode and this was allowed to run for 30 minutes. As with the emission study, this allowed plasma cleaning of the emission surfaces and provided similar initial conditions for each of the tests.

The cathode was then allowed to cool for 4 hours and the test was repeated with a new heater current setting

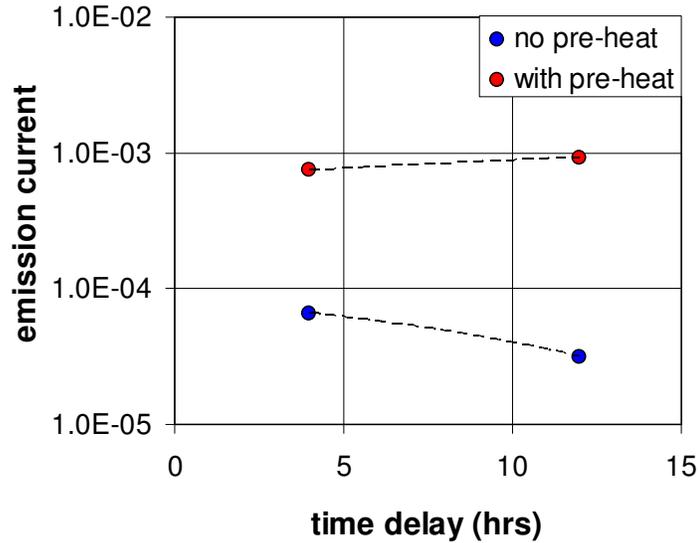


Figure 12. The effect of extended delay (12 hours versus 4 hours) on cathode emission current with and without a 4 hour pre-heat phase at low heater current. Data were taken under steady-state conditions and low cathode temperature.

thereby providing a new cathode temperature at the time of ignition. Ignition voltage as a function of cathode temperature could then be determined.

Ignition testing was also performed using a 4 hour, low temperature “maintenance” phase. For this phase the cathode heater was on with very low current producing a cathode temperature of ~400 °C. These tests were included because during emission testing with the neutralizer cathode it was observed that extended delays between tests resulted in a noticeable reduction in the emitted current. This effect was of concern since, during station-keeping operation, a XIPS[®] thruster remains in an “off” condition for more than 20 hours prior to ignition. In orbit, the thruster is effectively dormant in the atmosphere surrounding the satellite and may accumulate poisons prior to ignition. In these tests the cathode was left dormant in the test chamber for 4 – 12 hours at a pressure of 10^{-8} – 10^{-9} torr. It was hoped that maintenance of a low temperature on the cathode emission surfaces would discourage the accumulation of poisons.

The impact of a 12 hour delay with and without pre-heat during steady-state on cathode emission at 1060 °C is shown in figure 12. The data presented here was taken with a cathode tip temperature of 1060 °C which is below nominal for ignition. Extending the delay between tests from 4 hours to 12 hours resulted in a drop of ~4x in emission current in steady-state and as much as 10x during the ignition phase. As would be expected, the reduction in emission current was considerably less at higher cathode tip temperatures. As can be seen in figure 12, using the 4 hour pre-heat (or maintenance) phase described above, the drop in emission current was reduced, particularly in the steady-state condition. More importantly, the pre-heat provided a dramatic increase in emission current at these temperatures both during the ignition phase and in steady-state. Increases of as much as 100x during the ignition phase and 10x during steady state were observed.

The dependence of temperature on ignition voltage and the effect of the 4 hour pre-heat on this dependence can be seen in figure 13. Without pre-heat, ignition voltage dependence on the cathode tip temperature was as expected – increasing non-linearly as the temperature is dropped. The required ignition voltage was slightly higher than expected for a healthy cathode and this again placed some suspicion on the test article. The presence of the 4-hour pre-heat phase allowed ignition at dramatically lower cathode tip temperature. Above 1150 °C the 4 hour pre-heat had no effect but below this temperature the pre-heat phase allowed nominal ignitions at temperatures 200 °C below that available without a pre-heat.

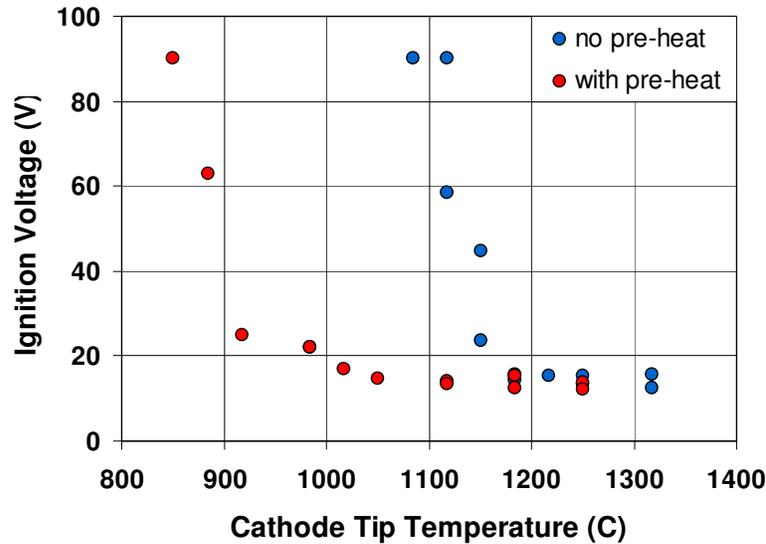


Figure 13. Effect of 4 hour preheat phase at low heater current on ignition voltage as a function of cathode tip temperature for XIPS[®] neutralizer cathode

By comparing the emission current at the temperature and voltage values obtained in the ignition study (see figure 13), an estimate can be made of the emission current required to ignite the cathode. By taking the average over all test temperatures and conditions, a value of $21 \pm 10 \mu\text{A}$ was obtained. This is in good agreement with the value of $15 \pm 3 \mu\text{A}$ reported by Rubin and Williams [5].

Attempts to provide a full explanation of the effects observed following the 4 hour pre-heat or “maintenance” phase have not yet been successful. Several contributing factors may be involved including: reduction of poisons on the emission surfaces of the cathode, preparation of the emission surfaces with barium coverage prior to beginning the ignition sequence and the reduced time to temperature during the ignition sequence resulting from having a warmed cathode at start-up. Nonetheless, the effects may be beneficial under conditions where the ignition process has become challenging. Such a scenario could occur toward the end of life or following an unexpected event on orbit.

The contribution of reduced time to temperature during the ignition sequence can be seen in, in part, in figure 14. Here, following the pre-heat phase, the emission rises rapidly reaching levels above $1 \times 10^{-5} \text{ A}$ (approximately the level required for ignition) in less than 90 seconds. Without the pre-heat, ignition at this temperature is clearly marginal. Although not shown here, the rapid rise in emission basically follows the rapid rise in cathode tip temperature. The dramatic increase in emission level is more likely to be associated with the change in initial conditions associated with barium coverage.

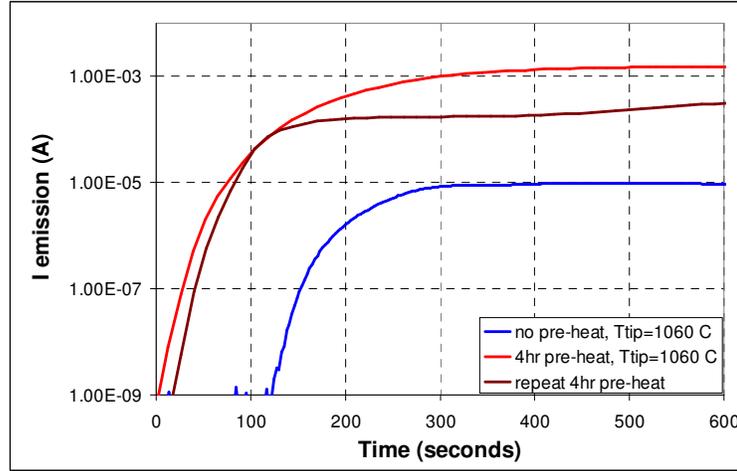


Figure 14. Effect of 4 hour preheat phase on emission current during ignition phase

Adding a 4 hour pre-heat to the ignition process may raise concerns for the heater life. Results from a detailed investigation outlining the effect of time at temperature on the life of the heater [3] indicate that the impact on the heater is negligible at these heater currents and temperatures. Further investigation of this phenomena is being planned with the intent of providing a procedure for igniting hollow cathodes rapidly and under challenging conditions.

III. Model Overview and Results

The primary assumptions and simplifications used in the Cathode Ignition Model have been previously described [4]. The most important of these are: 1) a minimum current is required to ignite the plasma, 2) all surfaces exposed to the plasma are left in an atomically clean condition, 3) plasma effects (erosion) are secondary in life determination, 4) the insert and orifice tip temperatures are kept constant in time, and 5) barium coverage is limited 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.

As stated earlier, the ignition of the cathode is determined by the ability to diffuse barium onto the face of the orifice. 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. [6] and is given by:

$$P_0 = 16.475 e^{-\frac{21960}{T}} \quad \text{Eq.4}$$

Barium is released at the inward-facing surface and as barium is consumed a burn front is created. The pressure at this surface is reduced by the pressure drop across the empty pores and changes with time as barium is consumed. The pressure is given by:

$$P_s = P_0 \left(1 - \sqrt{\frac{t}{\Omega(T)}} \right) \quad \text{Eq.5}$$

$\Omega(T)$ represents the time required to completely exhaust all of the usable barium in the insert at temperature, T, and has been defined in this model to be:

$$\Omega(T) = 9.173 \cdot 10^{-3} e^{\frac{10924.6}{T}} \quad \text{Eq. 6}$$

Barium evaporates from this surface, striking all surfaces containing the volume. A monolayer is formed at a rate given by kinetic theory. The deposition of barium determines the boundary conditions 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 downstream face of the orifice plate. This is dependent on the diffusion of barium onto this surface. The diffusion equation, including desorption is:

$$D\nabla^2 \theta = \frac{\partial \theta}{\partial t} + \frac{\theta}{\tau} \quad \text{Eq. 7}$$

The solution to the surface coverage equation depends on the geometry of the orifice. 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, 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 [7, 8] and is given by:

$$\phi(\theta) = 4.3 \left(\frac{4.3\Gamma}{2.49} \right)^{\frac{\Gamma\theta}{1-\Gamma}} + 2.49 \left(1 - \left(\frac{4.3\Gamma}{2.49} \right)^{\frac{\theta}{1-\Gamma}} \right) \quad \text{Eq. 8}$$

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

So finally we have,

$$i = 2\pi \int_{s_0}^s j(\phi(\theta(r,t))) r dr \quad \text{Eq. 9}$$

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.

Figure 15 shows the results of fitting the model to the emission data from the flight-like XIPS[®] 25 cm discharge cathode shown in figure 8.

At the higher temperatures the model is pessimistic, showing a calculated current smaller than the data. At lower temperatures the model is optimistic producing a higher current than actual. The middle temperature $T = 1090^\circ\text{C}$ produces a reasonable fit. The fit was performed using all the emission data at all temperatures: (1145, 1090, 1030, 965) °C with the same set of parameters. That is to say, the parameters of the model were not varied for each individual temperature run.

Setting $\Gamma = 1.2$, the fit produces a minimum work function of 2.5 eV.

During the ignition phase the cathode spends a long time at very low temperatures and evaporation is ignored. The diffusion coefficient, D_0 , is given through the equation:

$$D(T) = D_0 e^{\frac{-q\epsilon}{kT}} \quad \text{Eq. 10}$$

and the fit results in a value of $D_0 = (5.3 \pm 2.5) \times 10^{-4} \text{ m}^2/\text{s}$ and $\epsilon = 4.1 \pm 0.3 \text{ eV}$ for the activation energy.

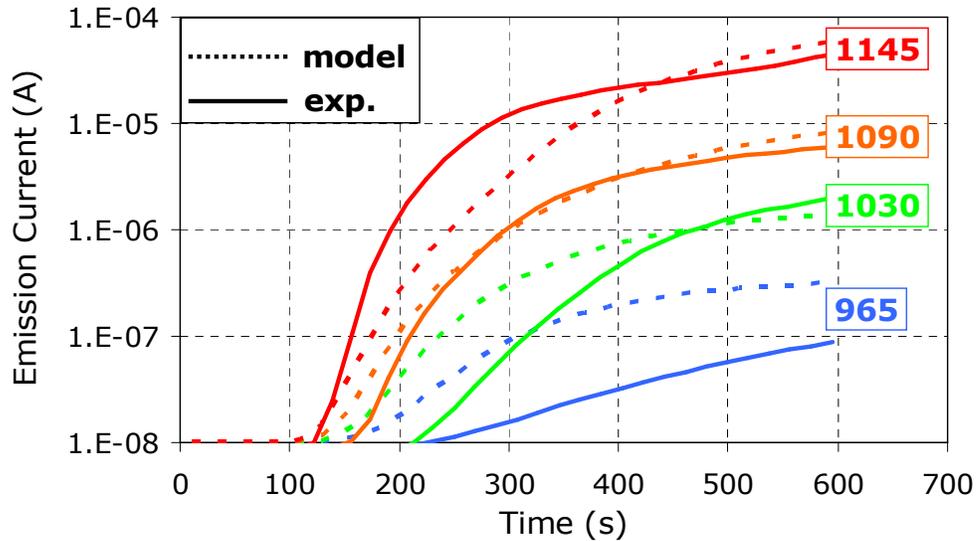


Figure 15. Example of model fit to discharge cathode emission data. Cathode tip temperature at ignition was 1090 C

Fitting the emission area with the model during steady-state generates a coefficient that represents the product of diffusion and desorption (evaporation). Having determined the diffusion coefficient, the desorption time can then be determined from the steady-state emission data.

The desorption time is the saturated area divided by the diffusion constant, this gives

$$\tau(T) = 1.96 \times 10^{-10} e^{\frac{67098}{T}} e^{-\frac{1.67 \times 10^7}{T^2}} \quad \text{Eq. 11}$$

Although not presented here, a similar fit was performed to the neutralizer data which resulted in a diffusion coefficient that was identical.

IV. Conclusions

A Hollow Cathode Emission and Ignition Test Facility has been developed at L-3 Electron Technologies Incorporated (L-3 ETI). The facility has been used to perform studies of emission and ignition using both the 25 cm XIPS[®] thruster discharge and neutralizer cathodes. Perhaps the most important aspect of this testing was the need to provide initial conditions that are consistent from test to test so that repeatable results can be obtained and appropriate conclusions can be drawn.

Steady-state conditions for emission over a wide range of cathode temperatures were obtained and estimates of the surface coverage of the orifice plate of the cathode were determined. These data reflected the changing balance between diffusion and evaporation processes as a function of temperature. Emission from the orifice plate showed a strong dependence on temperature indicating, at the lowest applied voltages, a changing area of emission. Estimates of the emission area were made and showed that diffusion increased between 1050 C and 1100 C and began to saturate at higher temperature. In steady-state the discharge cathode saturated at ~25% of the total orifice plate area while the neutralizer was limited to ~15%. The increased area for the discharge cathode was likely due to contributions to the current from the cathode insert region resulting from penetration of the electric field through the larger aperture of this cathode.

Emission data during the ignition phase of these cathodes were also obtained as a function of cathode temperature. The data was used in determining the diffusion rate with the cathode model and to determine the emission current required to ignite the cathode. The discharge cathode emission data was smooth and behaved in an expected manner. The neutralizer cathode showed a distinct feature: a dip in emission with a dependence on temperature. Proposed mechanisms driving this phenomenon are being investigated. Calculations of the emission area showed that there was an exponential increase in area associated with the temperature. The emission area at the time of ignition was very small, less than 0.1%, at typical ignition temperatures.

Ignition tests demonstrated the strong dependence of ignition voltage on cathode tip temperature. The emission current at the time of ignition was determined by examining the emission data (under “no flow” conditions) at the same temperature and voltage values. An emission current of $21 \pm 10 \mu\text{A}$ was found to be needed to provide ignition. Attempts to ignite at lower than nominal cathode temperatures ($<1100 \text{ C}$) were dramatically affected by keeping the cathode warm prior to ignition. The benefits of using a 4-hour pre-heat at very low heater current were significant and may prove beneficial under end of life conditions.

Attempts to fit the emission current with the cathode model were satisfactory though not as exact as was hoped for. It is not clear at this time if the issue lies with the model or the experiment. Fits with the model generated a diffusion coefficient of $(5.3 \pm 2.5) \times 10^{-4} \text{ m}^2/\text{s}$

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