Barium Depletion in Hollow Cathode Emitters

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The effect of tungsten erosion, transport and redeposition on the operation of dispenser hollow cathodes was investigated in detailed examinations of the discharge cathode inserts from an 8200 hour and a 30,352 hour ion engine wear test. Erosion and subsequent redeposition of tungsten in the electron emission zone at the downstream end of the insert reduces the porosity of the tungsten matrix, preventing the flow of barium from the interior. This inhibits the interfacial reactions of the barium-calcium-aluminate impregnant with the tungsten in the pores. A numerical model of barium transport in the internal xenon discharge plasma shows that the barium required to reduce the work function in the emission zone can be supplied from upstream through the gas phase. Barium that flows out of the pores of the tungsten insert is rapidly ionized in the xenon discharge and pushed back to the emitter surface by the electric field and drag from the xenon ion flow. This barium ion flux is sufficient to maintain a barium surface coverage at the downstream end greater than 0.6, even if local barium production at that point is inhibited by tungsten deposits. The model also shows that the neutral barium pressure exceeds the equilibrium vapor pressure of the impregnant decomposition reaction over much of the insert length, so the reactions are suppressed. Only a small region upstream of the zone blocked by tungsten deposits is active and supplies the required barium. These results indicate that hollow cathode failure models based on barium depletion rates in vacuum dispenser cathodes are very conservative.

Nomenclature

\( E \) \hspace{1cm} \text{Electric field, V/m} \\
\( E_d \) \hspace{1cm} \text{Desorption energy, eV} \\
\( e \) \hspace{1cm} \text{Electron charge, C} \\
\( k \) \hspace{1cm} \text{Boltzmann's constant, J/K} \\
\( m_{Ba} \) \hspace{1cm} \text{Mass of barium, kg} \\
\( N_0 \) \hspace{1cm} \text{Number density of adsorption sites, m}^{-2} \\
\( n_{Ba} \) \hspace{1cm} \text{Number density of barium atoms, m}^{-3} \\
\( n_{Ba+} \) \hspace{1cm} \text{Number density of barium ions, m}^{-3} \\
\( \dot{n}_{Ba} \) \hspace{1cm} \text{Ba neutral loss rate by ionization, m}^{3}\text{s}^{-1} \\
\( \dot{n}_{Ba+} \) \hspace{1cm} \text{Ba ion production rate by ionization, m}^{3}\text{s}^{-1} \\
\( P_{Ba} \) \hspace{1cm} \text{Ba neutral pressure, Pa} \\
\( P_{Ba+} \) \hspace{1cm} \text{Ba ion pressure, Pa} \\
\( P_v \) \hspace{1cm} \text{Ba vapor pressure over reaction front, Pa}^2 \\
\( r \) \hspace{1cm} \text{Radial position coordinate, m} \\
\( T_c \) \hspace{1cm} \text{Emitter surface temperature, K} \\
\( T_e \) \hspace{1cm} \text{Electron temperature, K} \\
\( T_h \) \hspace{1cm} \text{Heavy particle temperature, K} \\
\( t \) \hspace{1cm} \text{Cathode operating time, hrs} \\
\( u_{t,Ba} \) \hspace{1cm} \text{Ba neutral thermal velocity, m/s} \\
\( u_{i,Ba} \) \hspace{1cm} \text{Ba ion thermal velocity, m/s} \\
\( u_{Xe} \) \hspace{1cm} \text{Xe neutral flow velocity, m/s} \\
\( u_{Xe+} \) \hspace{1cm} \text{Xe ion flow velocity, m/s} \\
\( z \) \hspace{1cm} \text{Axial position coordinate, m}

Greek Symbols

\( \Gamma_{Ba} \) \hspace{1cm} \text{Ba neutral flux, m}^2\text{s}^{-1} \\
\( \Gamma_{Ba+} \) \hspace{1cm} \text{Ba ion flux, m}^2\text{s}^{-1} \\
\( \Gamma_d \) \hspace{1cm} \text{Ba desorption rate, m}^2\text{s}^{-1} \\
\( \Gamma_s \) \hspace{1cm} \text{Ba supply rate, m}^2\text{s}^{-1} \\
\( \theta \) \hspace{1cm} \text{Ba surface coverage} \\
\( \lambda_{mfp} \) \hspace{1cm} \text{Mean free path for barium ionization, m} \\
\( \mu_{BaXe} \) \hspace{1cm} \text{Ba-Xe neutral collision frequency, s}^{-1} \\
\( \nu_{Ba} \) \hspace{1cm} \text{Ba ionization frequency, s}^{-1} \\
\( \nu_{BaXe} \) \hspace{1cm} \text{Ba-Xe neutral collision frequency, s}^{-1} \\
\( \nu_{BaXe+} \) \hspace{1cm} \text{Ba neutral-Xe ion collision frequency, s}^{-1}

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I. Introduction

State-of-the-art hollow cathodes consist of a porous tungsten tube (the insert), which is contained in a refractory metal cathode tube with an orifice plate on the downstream end. A small fraction of the thruster propellant is injected through the hollow cathode, and the orifice serves to increase the internal pressure in the insert region. Electron emission from the inner surface maintains an internal plasma which heats the insert to the required operating temperature and helps conduct the current into the main discharge. A heater surrounding the cathode is used to preheat it prior to ignition.

A low emitter operating temperature is achieved by maintaining a layer of adsorbed oxygen and barium atoms that lowers the surface work function. In state-of-the-art impregnated cathodes Ba and BaO are supplied by barium calcium aluminate source material (the impregnant) incorporated in the pores of the tungsten. Gaseous Ba and BaO are released in interfacial reactions between the tungsten matrix and the impregnant, producing a temperature-dependent vapor pressure of these species inside the pores. The Ba and BaO then migrate to the surface by Knudsen flow and surface diffusion on the pore walls. In vacuum dispenser cathodes Ba adsorbates lost by evaporation are replenished by Ba and BaO through surface diffusion from the pores and most of the vapor flow from the pores is lost. In gas discharges, the vapor in the discharge may be transported back to the cathode surface, offering another path for replenishing Ba lost by desorption.

Near the surface, products of the impregnant reactions escape to the exterior through the pores, allowing the reactions to proceed to completion. Eventually, relatively stable tungststates are produced and production of volatile species in that region ceases. The reaction front proceeds into the insert as reactants nearer the surface are consumed and the porosity of the impregnant increases due to loss of volatile materials. The region behind the reaction front is depleted in barium and the depth of this depletion layer has been characterized in some cathode tests and is an indicator of remaining useful life.

Hollow cathodes are subject to a number of potential failure mechanisms. External erosion by high energy ions created downstream of the orifice has been observed in a number of tests and is the focus of experiments and modeling discussed elsewhere. Damage to the emitting surface due to poisoning by reactive gases or buildup of bulk tungstate layers due to reactive impurities is another potential failure mode. Insert life is ultimately limited by the barium supply in the impregnant. When the barium supply rate from the interior or from the gas phase drops below the rate at which adsorbed atoms are lost from the surface by desorption, the surface coverage drops and the work function rises. The cathode eventually becomes impossible to ignite or cannot be heated to the temperatures needed for the required electron current density.

Finally, tungsten transport has been observed in many extended hollow cathode tests. Impregnated cathode temperatures are not high enough to cause significant evaporation of the tungsten matrix, so these processes are undoubtedly due to formation and subsequent dissociation of volatile tungsten compounds. No failures have been attributed to this mechanism, but it could potentially lead to cathode failure. Reduction in the cathode orifice diameter by deposition of tungsten eroded from internal surfaces could increase the operating temperature or prevent cathode ignition, and deposits of tungsten on the emitter surface may limit barium flow through the tungsten matrix.

The lack of understanding of the chemical and mass transport processes in hollow cathodes has prevented development of useful models for these failure mechanisms. This paper attempts to answer two fundamental questions as a first step to developing the required insight. First, does the erosion, transport, and deposition of tungsten in the insert region affect hollow cathode function? Second, how does gas phase transport of barium affect the operation of the cathode? These two questions turned out to be intimately linked.
The first question has been approached by a detailed examination of the cathode inserts used in several long duration ion engine wear tests. The 8200 hour Life Demonstration Test (LDT) was performed with a 30-cm engineering model thruster similar to that flown on the Deep Space 1 (DS1) mission under the NASA Solar Electric Propulsion (SEP) Technology Applications Readiness (NSTAR) Program. A subsequent Extended Life Test (ELT) was performed with the DS1 flight spare NSTAR thruster, ultimately accumulating 30,352 hours of operation at several different throttle levels. Both tests were voluntarily terminated with the discharge and neutralizer cathodes exhibiting no evidence of performance degradation. The examination of these cathodes described here extends initial evaluations reported earlier and focused specifically on material transport. The objectives were to identify erosion and deposition sites and determine if these processes modified or have the potential to impact the function of the insert as an electron emitter.

The second question was addressed by developing a model of barium transport in the gas phase. This model leverages significant work done in modeling the internal xenon gas discharge. The objectives were to study how barium enters the discharge, flows through the plasma and is redeposited on the emitter surface, and how that affects the cathode work function.

II. Experimental Characterization of Barium Depletion

The discharge cathode in the LDT operated for a total of 8200 hours at a xenon flow rate of 3.7 sccm and a current that ranged from 13 to 15.2 A. Details of the post-test analyses of the insert and cathode assembly were reported previously. Here we summarize the key observations and report new measurements of the barium depletion depth as a function of position along the emitter.

Changes in the emitter geometry were characterized with laser profilometry and imaging in a scanning electron microscope (SEM). Figure (1) shows the surface profiles measured on the LDT insert and a control insert that had never been operated. The LDT discharge cathode profile exhibits erosion over 15 mm at the downstream end, with more severe erosion in the first 4-5 mm. Up to 100 µm of the tungsten matrix were lost at the tip.

SEM photomicrographs of the emitter surface show a combination of erosion and redeposition of tungsten at the downstream end. Photomicrograph F illustrates the appearance of the virgin porous tungsten structure from an unoperated insert. In comparison, the images from the LDT cathode reveal a dense growth of vapor-deposited tungsten crystals at the tip which covers the tungsten pores. Tungsten deposits are found in the surface pores over the rest of the eroded region, although it’s not clear from the SEM images if these deposits close off the surface as they appear to at the tip. The image at 10 mm shows a surface which is similar to that of an undisturbed insert. The erosion and subsequent redeposition of tungsten leads to a significant restructuring of the porous tungsten matrix at the downstream end.

The impact of this restructuring on the barium flow from the cathode interior is illustrated in Fig. (2). Figure (2a) is a composite photo constructed from SEM images of the LDT discharge cathode cross section showing the first 4.3 mm of the downstream end. The upper surface is the interior of the cylindrical insert, and the white line indicates the original surface, highlighting the erosion in the emission zone. The insert manufacturing process includes a weak etch after impregnation to remove impregnant from the surface and pores near the surface. The surface layer from which the impregnant has been removed is apparent in the photo as a region with dark pores. The porosity of the tungsten matrix is actually very uniform throughout the insert, but in this region the pores are emphasized because they are filled with potting material, which looks dark in the secondary electron imaging mode. The impregnant-free layer has been removed from the emitting zone by erosion.

Figure (2b) shows a barium element map constructed from energy dispersive spectroscopy (EDS) scans over the cross section pictured in Fig. (2a). As expected, the image is dark in the potting material around the insert and in the impregnant-free etched surface layer noted in Fig. (2a). The signal intensity is highest deep in the interior, where there is unreacted impregnant. The important feature in this image is the region with an intermediate signal strength, which indicates areas from which the barium has been depleted. This zone is found in the upper left, under the impregnant-free layer, in the upper right corner, the downstream face on the right side and along the bottom between the impregnant-free layer and the unreacted impregnant. However, this zone is not visible under the eroded zone in the upper right. Here the brightest zone extends
Figure 1. Profiles of the cathode emitter surface compared to an unused insert and photomicrographs showing the surface structure.
nearly to the surface.

Barium element maps, although giving an indication of depleted regions as in Fig. (2b), often do not have sufficiently high signal-to-noise ratio for quantitative measurements of the depletion depth as a function of position along the emitter. Quantitative measurements were obtained using EDS analysis of individual impregnant grains visible in the polished cross section of the emitter. Figure (3) shows an example of an area near the emitter surface. The open pores in the etched region are visible in the top half of the image. In the lower half, the pores are filled with impregnant material. The concentration of aluminum remains relatively constant over the insert interior because Al in the impregnant does not form volatile reaction products. It can therefore be used as an internal standard to determine relative concentrations of barium and calcium. Regions which are depleted in the volatile species Ba and Ca will have lower ratios of Ba or Ca peak area to Al peak area compared to those in regions with unreacted impregnant. The difference is quite obvious, as shown in Fig. (4). Regions in individual impregnant grains were identified on the SEM images and EDS spectra were obtained for those areas. Peak areas for the dominant Ba, Ca and Al lines in the spectra were calculated and used to form the ratios, which were then plotted as a function of the depth of the impregnant grain below the boundary defining the edge of the impregnated zone.
In this example, grains deeper than about 40 $\mu$m have Ba/Al ratios of about 2.5 and Ca/Al ratios of 0.29. Grains near the surface have corresponding ratios of 0.75 and zero, reflecting a loss of volatile Ba and Ca reaction products. In some locations, the Ca/Al ratios in the interior were as high as 0.6, perhaps reflecting a nonuniform distribution of free CaO. Examining individual grains at different depths provided a relatively well-defined boundary for the depleted zone. The majority of grains above the boundary exhibited barium and calcium depletion, although isolated exceptions were found, probably in locations which did not have interconnected pores forming a path to the surface.

The depletion depth measurements along the insert plotted in Fig. (5) are consistent with the qualitative picture from the barium element map in Fig. (2b). This plot also includes thickness measurements for the impregnant-free etched zone, which show the erosion at the downstream end. The zero line in this plot corresponds to the edge of the impregnated zone. Two notable features are apparent. First, the cathode suffered remarkably little barium loss in this test, with a maximum depleted depth of only 50 $\mu$m. Second, the barium loss is restricted to a fairly narrow region centered about 4 mm from the downstream end. As argued previously, the restructuring of the surface at the downstream end appears to reduce the effective porosity, preventing barium loss, and the partial pressure of barium in the discharge plasma is sufficiently high upstream that it inhibits the impregnant decomposition reactions. These observations were used to test the results of a model.
of barium transport in the hollow cathode.

III. A Model of Barium Depletion

The numerical model of barium transport in the hollow cathode discharge was used to calculate the net barium flow from the insert and the resulting depletion depth as a function of time to compare with the experimental results. The barium transport model has been described in detail previously, but we summarize the major features here briefly and describe improvements to the barium flux model and how the barium loss is integrated to determine depletion depths. The initial focus of the modeling is on barium because this is the dominant species produced by the insert. Barium transport is strongly influenced by the xenon plasma; the electron density and temperature control the ionization of barium, the electric field in the xenon plasma and collisions with xenon and xenon ions control the diffusion of barium. However, barium atom and ion densities are so low they do not significantly modify the charge density or temperature in what is primarily a xenon discharge. This allows us to separate the problem into two parts, and use the major species parameters predicted by a xenon discharge model as fixed quantities in the solution of the minor species transport equations.

III.A. Barium Transport Equations

The barium flow in the insert plasma is modeled using the species momentum and continuity equations assuming that viscous and magnetic field effects are negligible, that the phenomena of interest are sufficiently slow, i.e. there are no high frequency phenomena and fluid acceleration is small compared to the force terms, and that collisions between barium ions and other minor species (such as barium) are sufficiently rare that they can be neglected. The barium ion flux can then be written as the sum of four terms,

$$\Gamma_{Ba^+} = n_{Ba^+} u_{Ba^+} = -\nabla P_{Ba^+} + n_{Ba^+} \left( \frac{1}{1 + \nu_{Ba^+Xe} / \nu_{Ba^+Xe^+}} \right) u_{Xe^+} + \frac{\nu_{Ba^+Xe^+} / \nu_{Ba^+Xe}}{\nu_{Ba^+Xe} / \nu_{Ba^+Xe^+}} u_{Xe} + \frac{en_{Ba^+}}{\nu_{Ba^+Xe} / \nu_{Ba^+Xe^+}} u_{Xe}$$

(1)

The first two terms represent ion flux driven by pressure gradient and electrostatic forces. The third term is the flux driven by drag due to collisions with xenon ions and the fourth is the flux due to drag from collisions with xenon neutrals. Previously the xenon neutrals were assumed to have negligible flow velocities. In the results presented here, xenon neutral velocities calculated in the xenon discharge model were used in the barium simulation. The collision frequency terms are cast in the form of ratios to the dominant interaction, coulomb collisions between xenon and barium ions. The electron drag term can be neglected because of the small electron-to-heavy particle mass ratio. The same approach yields the flux of barium neutrals,

$$\Gamma_{Ba} = n_{Ba} u_{Ba} = -\nabla P_{Ba} + n_{Ba} \left( \frac{\nu_{BaXe} / \nu_{BaXe^+}}{1 + \nu_{BaXe} / \nu_{BaXe^+}} \right) u_{Xe^+} + n_{Ba} \left( \frac{\nu_{BaXe^+} / \nu_{BaXe}}{1 + \nu_{BaXe^+} / \nu_{BaXe}} \right) u_{Xe}$$

(2)

The ion-ion collision frequency that appears in these equations is given by the standard coulomb frequency, and the neutral-barium-xenon collision frequency is expressed in terms of a constant scattering cross-section $\sigma_D = 40 \text{Å}^2$ based on diffusion measurements for barium in xenon. Barium ion-xenon neutral and barium neutral-xenon ion collisions are assumed to have the same cross section.

The continuity equations for barium ions and neutrals can be expressed in terms of these fluxes,

$$\frac{\partial n_{Ba^+}}{\partial t} + \nabla \cdot \Gamma_{Ba^+} = \dot{n}_{Ba^+}$$

$$\frac{\partial n_{Ba}}{\partial t} + \nabla \cdot \Gamma_{Ba} = \dot{n}_{Ba} = -\dot{n}_{Ba^+}$$

(3)

where $\dot{n}_{Ba^+}$ is the rate at which barium ions are created by ionization of barium neutrals and $\dot{n}_{Ba}$ is the rate at which neutrals are consumed by ionization reactions. The ionization rate is given by the product of the
The barium transport model depends on a number of xenon plasma parameters, including the xenon ion and atom densities and heavy particle temperature, which appear in the collision frequencies, the electron density and temperature, which determine the barium ionization rate, and the xenon neutral and ion velocity and electric field, which appear in the force terms of the momentum equations. These quantities are taken from a separate simulation$^{17}$ of the xenon plasma and are assumed to be independent of the dynamics of the barium plasma.

The xenon plasma code was modified to solve a discretized form of Eqs. (3) on the 2D axisymmetric computational domain and mesh shown in Fig. (6). This region encompasses the insert plasma at the downstream end of the emitter in the hollow cathode. The barium ion and neutral densities were initially assumed to be a uniform low value, and the continuity equations were then time-marched until the densities and fluxes achieved steady state values.

### Boundary Conditions

The simulation domain is bounded by the 5 surfaces shown in Fig. (6), including the centerline, the entrance to the cathode orifice, the upstream face of the orifice plate, the emitter surface and the upstream inlet to the cathode. Ion and neutral fluxes through these surfaces are specified as boundary conditions. The centerline is a symmetry boundary, so the ion and neutral fluxes are set equal to zero.

The source of barium is flow from the interior of the emitter through the reaction products in the pores of the tungsten matrix. The rate at which barium is dispensed depends on three main parameters: insert temperature $T_c$, barium partial pressure in the insert plasma $P_{Ba}$ and the depth of the reaction front $e$, which varies with time. The impregnant decomposition reaction is assumed to be strongly diffusion-limited, so the barium pressure at the reaction front is very close to the equilibrium pressure of barium over the reactants, which is a function of the insert temperature. The diffusive flow or Knudsen flow through the pores and reaction products in the insert is driven by the difference in the pressure at the reaction front and the barium partial pressure at the insert surface. Finally, the reaction front recedes into the insert as the barium is consumed, so the flow resistance increases with time.
The supply rate of barium from the emitter in previous publications, was based on measurements of the barium flux from S-type cathodes in vacuum early in life (with a total operating time \( t_{\text{ref}} \) on the order of 10 hours) scaled by the square root of the operating time. This approach suffered from the uncertainty in the reference time \( t_{\text{ref}} \) and because it did not give an explicit dependence on depth of the reaction front. The results presented here are based on an improved barium flux model which uses depletion depth measurements from dispenser cathodes operating in vacuum. The depletion depths \( e \) measured on a number of pellet-shaped dispenser cathodes operated at four different temperatures for various times are plotted in Fig. (7). These cathodes employed the same impregnant as our hollow cathodes, but the tungsten matrix had a porosity of 0.185. The brightness temperatures reported by Roquais were converted to true temperatures using data from Malter. These data are well-represented by linear fits of the form \( \ln(e) = \ln(A) + \frac{1}{2} \ln(t) \), yielding the square root dependence of depletion depth on time observed by others:

\[
e = A t^{1/2}.
\]  

A plot of \( \ln(A^2) \) as a function of inverse true temperature also reveals a linear dependence, as shown in Fig. (8). This gives an Arrhenius-type relationship for the square of the depletion factor \( A \),

\[
A^2(T_c) = 3.749 \times 10^{11} \exp(-3.17 e/kT_c).
\]

Differentiating eqn. (4) with respect to time yields the rate at which the reaction front receded into the interior in Roquais’ experiments,

\[
\frac{d}{dt} \left( \frac{de}{R} \right) = \frac{A^2}{2e} \cdot \frac{\tau \rho \beta \Pi_R}{m_{\text{imp}}} \cdot \frac{(de)}{dt} = \frac{\tau \rho \beta \Pi_R}{m_{\text{imp}}} \left( \frac{A^2}{2e} \right).
\]

The corresponding barium flux can be written as

\[
\Gamma_{Ba,e,R} = \frac{\tau \rho \beta \Pi_R}{m_{\text{imp}}} \cdot \left( \frac{de}{dt} \right) = \frac{\tau \rho \beta \Pi_R}{m_{\text{imp}}} \left( \frac{A^2}{2e} \right).
\]

Figure 7. Measurements of depletion depth as a function of time and temperature for pellet-shaped cathodes operated in vacuum.

Figure 8. Variation of the depletion factor plotted as \( \ln A^2 \) with inverse temperature.
Assuming barium is transported by vapor flow through the pores, the flux can also be modeled in terms of the pressure gradient driving the flow,

\[ \Gamma_{e,R}^{Ba} = \frac{4}{3\Pi(2\pi m_B kT_e)^{1/2}} \left( \frac{dP_{Ba}}{dx} \right) = \frac{4}{3\Pi(2\pi m_B kT_e)^{1/2}} \left( \frac{P_e}{e} \right). \]  

In the second expression, the pressure gradient is approximated by the vapor pressure over the reaction products divided by the depth of the reaction front, assuming that the barium partial pressure outside the insert is zero. The barium flux from the cathode interior can be similarly expressed as

\[ \Gamma_{e}^{Ba} = \frac{4}{3\Pi(2\pi m_B kT_e)^{1/2}} \left( \frac{P_e - P_{Ba}}{e} \right) = \Gamma_{e,R}^{Ba} C_{\Pi} \left( \frac{P_e - P_{Ba}}{e} \right), \]  

where the factor \( C_{\Pi} = \frac{R_e \Pi_e}{R \Pi_e} \) corrects the flux for the change in flow restriction due to the difference in tungsten porosity of the hollow cathode inserts compared to those used by Roquais. Data from vacuum cathodes with different tungsten porosities indicate that \( C_{\Pi} = 1.2 \) for the porosity of the hollow cathode inserts. In the hollow cathode the pressure gradient is approximated by the difference in internal pressure \( P_i \) and external pressure \( P_{Ba} \) divided by the flow path length \( e \).

The flux from the emitter as a function of cathode temperature and depth of the reaction front (depletion depth) is modeled in the code in terms of material properties, Roquais' data on depletion rates over long periods of time, the vapor pressure associated with the dominant Ba-forming reaction, and the Ba partial pressure in the insert plasma,

\[ \Gamma_{e}^{Ba}(T_e, e) = \frac{\tau \rho \beta \Pi R}{m_{imp}} C_{\Pi} \left( \frac{A^2}{2e} \right) \left( \frac{P_e - P_{Ba}}{P_e} \right). \]

As eqn. (12) shows, \( A^2 \) is exponentially dependent on temperature. The vapor pressure also varies exponentially with temperature, and in this model is given by the equilibrium pressure \( P_e \) in Torr for the impregnant decomposition reaction proposed by Rittner,

\[ \log P_e = 8.56 - 20360/T_e. \]

In cases for which the ambient barium pressure exceeds the equilibrium pressure, the reaction is assumed to cease. The temperature distribution measured along the axis of an emitter with the same geometry and operating conditions as the NSTAR LDT cathode was used in the simulations. The barium partial pressure in the insert plasma near the emitter surface is calculated as part of the barium plasma solution. The fraction of the pores filled with impregnate \( \tau \) is assumed to be 1. The fraction of impregnate mass that can be lost in the form of barium, \( \beta = 0.39 \), is based on Lipelles’ and Kan’s thermochemical model of 411 impregnant. The remaining 60% of the barium is locked up in monobarium aluminate and various tungstates, which are stable reaction products. The fraction of barium remaining in the measurements discussed in the experimental section was about 0.3 (based on comparing the Ba/Al ratios in the depleted regions with those in the unreacted regions). The EDS measurements were probably dominated by the signal in the interior of the impregnant-filled pores, which might be primarily monobarium aluminate (with a barium content equal to 1/4 the original value). The tungstates are probably concentrated along the walls of the pores where the BaO released in impregnant decomposition reacts with the tungsten.

Barium neutrals and ions also flow back to the insert surface. Ions enter the sheath at the Bohm velocity \( u_B = \sqrt{kT_e/m_B} \) and the ion flux is \( \Gamma_{Ba}^+ = n_{Ba^+} u_B \). However, the cathode temperatures are too high for barium to accumulate in thick layers on the surface (the evaporation rate for bulk barium at these temperatures exceeds the ion and neutral fluxes by many orders of magnitude), so we assume that the surface has a steady state, submonolayer coverage of barium adsorbed on oxygen on tungsten. In steady state, there is no net total barium flux to the surface. The neutral flux to the surface is balanced by the desorption of neutrals, and ions that strike the surface return to the plasma as neutral barium atoms, so there is a net neutral flow (in addition to the neutral flow from insert interior) which is equal in magnitude to the ion flow. This assumption is consistent with the observations from long duration tests that barium does not accumulate on the downstream surfaces of the inserts.

The orifice plate upstream face was also assumed to have a steady-state, submonolayer coverage with a net neutral flow from the surface equal to the impinging ion flux. Neutrals were assumed to flow out of the
cathode orifice with their thermal velocity. Ions were assumed to have the same velocity at this point as the xenon ions. In practice, there are very few barium ions or neutrals in this region, so the results are not sensitive to these assumptions. The upstream boundary is the only major sink for barium. Ions and neutrals were assumed to flow out this surface with their thermal velocities and condense on cooler surfaces upstream, as observed experimentally.  

III.C. The Xenon and Barium Plasma Solutions

The results of the xenon plasma simulation for the NSTAR cathode at a discharge current of 13.3 A and a xenon flow rate of 3.7 sccm are displayed in Fig. (9). Figure (9a) shows the neutral flow field. Because of the small orifice, the neutral density is relatively high ($\sim 10^{22}$ m$^{-3}$). The density drops rapidly in a small region near the orifice because of flow out of the cathode and consumption of neutrals in the strong ionization zone at the downstream end of the insert. The streamlines reveal two sources of neutral gas; the upstream inlet and the return flow of ions neutralized on the walls. The streamlines from both sources converge on the orifice.

Figures (9b) and (9c) illustrate the electron current transport and resultant plasma heating. The streamlines represent the electron current. As Fig. (9c) shows, the emitter temperature is strongly peaked at the downstream end and electron emission is confined to a region about 4 mm long near the orifice plate. The streamlines show that the electron flow converges on the orifice and resistive heating from the high current density results in a peak in the electron temperature of about 1.85 eV in the orifice. Further upstream the plasma potential is low and electrons can penetrate from the plasma to the insert surface, resulting in net electron flow to the insert.

The plasma density distribution and resulting ion flow are shown in Fig. (9d). The high electron temperature near the orifice leads to a peak plasma density of $\sim 10^{21}$ m$^{-3}$ at the downstream end of the insert. Ions created in this ionization zone flow out radially and upstream, as shown by the ion current streamlines. Xenon ions created here are neutralized on the walls and return to the discharge as neutrals, as shown by the neutral flow streamlines in Fig. (9a).

The barium plasma simulation results are shown in Fig. (10). The mean free path for barium atom ionization $\lambda_{mfp}^{iz} = u_{r,Ba}/\nu_{iz}^{Ba}$ based on the barium atom thermal velocity $u_{r,Ba} = (8kT_h/\pi m_{Ba})^{1/2}$ and the ionization frequency was calculated using the electron density and temperature profiles and is plotted in Fig. (10a). The mean free path for ionization upstream of the dense plasma region is on the order of meters, but drops to less than 0.1 mm near the orifice. Barium atoms that drift into the dense xenon plasma have a high probability of being ionized.

Figure (10b) shows the neutral barium flow field. The barium neutral density peaks at $\sim 10^{17}$ m$^{-3}$ near the emitter surface at a point 0.5-0.6 cm upstream of the orifice plate and in the corner between the emitter and the orifice plate. The density decreases by up to two orders of magnitude at the upstream end of the insert and drops to near zero in the ionization zone near the orifice. All barium neutrals ultimately originate in the insert. Barium ions are neutralized on the walls and return to the interior as neutrals, providing a second source of neutral gas. There are two sinks for barium neutral gas—the cold surfaces upstream of the emitter where barium condenses and the ionization zone where neutrals are consumed in ionizing reactions. The neutral density is so low near the orifice that the neutral loss rate through the orifice is negligible.

Two separatrices are apparent in the flow streamlines plotted in Fig. (10b). The upstream separatrix at an axial location of 0.8-1.1 cm divides the neutral flow upstream from the neutral flow into the ionization zone. The downstream separatrix divides the flow of neutrals from the insert and the flow of neutrals from the orifice plate. The streamlines also reflect the force balance that results in the steady state neutral density distribution. Xenon ion drag forces are at least two orders of magnitude lower than neutral drag and pressure forces over the entire flow field, so the barium neutral pressure force is balanced by the neutral xenon drag force, $\nabla P_{Ba} = \nu_{Ba,Xe} \mu_{Ba,Xe} (\mathbf{u}_{Ba} - \mathbf{u}_{Xe})$. The steep pressure gradient at the edge of the ionization zone downstream is sustained by a high neutral barium diffusion velocity $\mathbf{U}_{Ba} = (\mathbf{u}_{Ba} - \mathbf{u}_{Xe})$ and the resulting neutral xenon drag force. At the upstream end, the barium diffusion velocity exceeds the neutral xenon flow velocity, resulting in barium flow upstream. In an intermediate region where the neutral barium pressure gradient is lower, the neutral barium diffusion velocity required to generate a drag force that balances the
Figure 9. Xenon plasma solution for the NSTAR discharge hollow cathode at the full power operating point.

(a) Xenon neutral density contours, \(n_{Xe}/10^{21} \text{ (m}^3\text{)}\) and neutral flux streamlines.

(b) Electron temperature contours (eV) and electron current streamlines.

(c) Emitter temperature profile and electron emission current density.

(d) Plasma density, \(n_e/10^{19} \text{ (m}^3\text{)}\) and ion current streamlines.
pressure force is lower than the xenon flow velocity and the barium flow reverses direction. Between 0.8 and 1.3 cm at the points where the flow streamlines change direction, the axial barium diffusion velocity is equal to the axial neutral xenon flow velocity of 2-6 m/s.

The barium ion density and flow streamlines are shown in Fig. (10c). The barium ion density is near zero inside the dense xenon plasma near the orifice and peaks in a relatively thin ionization front surrounding that zone. As Figures (10a) and (10b) indicate, neutral barium flowing toward the intense xenon plasma is ionized at the periphery. The barium ion streamlines show that the ions generated in the ionization zone flow outward and ultimately strike the emitter or the orifice plate, where they are neutralized and re-emitted as barium atoms. The steady state barium ion density distribution is the result of a more complex balance of forces. The high density xenon plasma near the orifice has a very low barium ion density because neutrals are ionized before they penetrate very far and the resulting ions are pushed outward by the electric field. In the region immediately outside the high density xenon plasma the electric field force is balanced by the barium ion pressure, xenon ion drag and xenon neutral drag in approximately equal proportions. Where the barium ion density starts to drop beyond that, the pressure force becomes negligible and the electrostatic force is balanced by ion and neutral drag. At the upstream end of the insert, the xenon ion density drops and the ion drag force becomes negligible. In this region neutral drag alone resists the electric field force,
although the barium ion density is very low here because most of the ions have been driven to the emitter upstream of that due to strong radial electric fields near the wall.

III.D. Time Dependent Simulation of Barium Depletion

We assume that the depletion depth changes slowly in time and that the internal distribution of barium moves through a series of quasi-steady states, which allows the use of the steady state plasma model to calculate the barium fluxes from the insert. The depletion calculation starts by specifying the initial depletion depth along the insert \( e_0(z) \), which represents the flow resistance associated with the porous tungsten structure in the etched region. The pores in the tungsten are much larger than the pores in the impregnant reaction products, so presumably this flow resistance is relatively low. The initial depth was typically assumed to be 2 \( \mu \)m, although the final results are not particularly sensitive to this choice.

Next, a steady state simulation of the barium plasma in the insert was performed using eqn. (10) as the depletion depth-dependent emitter flux boundary condition. The velocity of the reaction front into the hollow cathode insert was then integrated to calculate a new profile for the depletion depth. The reaction front velocity is given by

\[
\frac{de}{dt}_{hc} = \frac{\Pi R}{\Pi_{hc}} C_H A^2 \left( \frac{P_v - P_{Ba}}{P_v} \right),
\]

(12)

assuming one dimensional diffusion of barium from the interior. Integrating this expression yields the new depletion depth at a given \( z \) location along the insert,

\[
e_{i+1}(z) = \left[ \frac{\Pi R}{\Pi_{hc}} C_H A^2 \left( \frac{P_v - P_{Ba}}{P_v} \right) \Delta t + e_i^2(z) \right]^{1/2}
\]

(13)

This assumes that the barium partial pressure \( P_{Ba} \) does not change significantly of the time \( \Delta t \). Figure (11) shows the change in the peak barium pressure near the emitter surface over the course of the simulation. Time steps varying from 50 to 1000 hours were chosen to minimize the discretization error. The calculation was then repeated using the new values for the depletion depth profile until a total of 8000 hours had been accumulated.

The results for the nominal temperature profile are plotted in Figures (12) - (14). The calculated neutral barium partial pressure near the emitter is compared to the equilibrium barium pressure over the reaction zone in Fig. (12). The equilibrium vapor pressure profile follows the cathode temperature profile, increasing monotonically in the downstream direction. The axial neutral pressure distribution first rises in the downstream direction, then drops where the electron density and temperature peak, due to ionization. Although barium flow from the emitter is set to zero over 2.5 mm at the downstream end of the insert, the neutral pressure rises again near the orifice plate in a small recirculation zone that is generated in the corner. The ambient barium pressure initially exceeds the equilibrium vapor pressure over much of the insert length, suppressing the reactions in the interior of the porous tungsten dispenser.

The decrease in neutral barium pressure with time apparent in Fig. (12) is due to a reduction in the barium flux from the interior, as shown in Fig. (13). The flux is initially peaked in the region between 1.5 and 1.75 cm. The distribution broadens with time as the neutral barium pressure falls below the equilibrium vapor pressure over the reaction front. By the end of the 8000 hour period, the flux is relatively uniform over the surface.
Figure 12. Equilibrium barium pressure over the reaction zone and profiles of the barium partial pressure in the insert plasma over the course of the simulation for the nominal temperature profile.

The recession of the reaction front into the interior with time is displayed in Fig. (14). Barium depletion is initially restricted to the narrow region between 1.5 and 1.75 cm, but as more of the surface starts to emit barium, this profile also broadens. The maximum depth predicted for these conditions after 8000 hours of operation is about 200 µm just upstream of the region over which barium emission is set to zero.

IV. Comparison of Experimental and Simulation Results

The simulation results are compared with the measured depletion depths in Fig. (15). Equation (13) becomes exact when the barium partial pressure is set equal to zero, and the resulting depletion depth corresponding to operation in vacuum is plotted as the lower dashed line in Fig. (15). These values are much larger than the measured values, highlighting the importance of the finite barium pressure in the discharge plasma in suppressing depletion.

Figure 13. Variation in the profile of barium flux from the emitter due to depletion over time for the nominal temperature profile.

Figure 14. Depletion depth as a function of time for the nominal temperature profile.
The intermediate curve represents the results using the nominal temperature profile. It reproduces qualitatively the shape of the measured curve, with a peak in depletion upstream of the region with no barium emission and lower values where the barium plasma pressure suppresses reactions. The magnitude of the depletion depth is larger than the measured values by a factor of up to 4.

V. Conclusions

The insert analyses and modeling resulted in three main conclusions that have significant implications for hollow cathode lifetime. First, tungsten erosion and subsequent redeposition in the emission zone result in the formation of a dense tungsten shell with reduced porosity. This deposit inhibits barium flow from the interior and therefore suppresses the reaction, resulting in very little barium depletion under the primary electron emission zone. Despite this, hollow cathodes appear to function correctly for very long lifetimes.

The barium transport model shows that barium in the downstream region can be very effectively supplied through the gas phase and will maintain adequate surface coverage in the emission zone for lifetimes on the order of those achieved in long duration tests. The key difference between hollow cathode gas discharges and vacuum dispenser cathodes is that hollow cathodes make much more efficient use of the barium supplied by the insert. Neutral barium from the insert is ionized in the intense xenon plasma, and the combination of the electric field and the drag from the xenon ion flow results in a high barium ion flux to the emitter surface. The ions are neutralized on the surface and return to the discharge to be ionized again. Because the upstream boundary is the only effective sink for barium (except under conditions in which barium can accumulate on the cathode surface; in the presence of oxidizing impurities for instance) a high barium partial pressure builds up at the downstream end.

The high barium partial pressure appears to suppress impregnant reduction reactions over most of the insert length. Barium is evidently supplied only from a narrow region where ionization reduces the neutral density below the equilibrium vapor pressure. This result is the most surprising, and perhaps the most uncertain because it relies on the relative values of thermochemical properties which are not well known. A careful examination of the depletion profile along hollow cathodes from long duration wear tests could help confirm this conclusion. This is another example of self-regulation in hollow cathodes—the barium production rate increases until the pressure builds up sufficiently to suppress reactions over some length of the insert. This suggests that barium located upstream of the electron emission site is not wasted, but is critical to the operation of the discharge through gas phase resupply and, in fact, much of this supply is saved until it is needed. These improvements in understanding of barium transport processes indicate that models of cathode failure due to barium depletion that are based on vacuum dispenser cathode data are likely to be extremely conservative.

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