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Model of Hollow Cathode Operation and Life Limiting Mechanisms

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Introduction

Hollow cathodes are a critical component of most electrostatic and Hall effect ion thrusters. Gridded ion thrusters such as the 30cm NSTAR thruster have two hollow cathodes. One hollow cathode provides electrons to ionize the propellant in the discharge chamber. The other provides electrons to neutralize the ion beam exterior to the engine.

The record life of a hollow cathode was the Space Station plasma contactor test run at NASA/GRC [1]. During this test, the cathode performance changed after 23,000 hours of operation, and the cathode finally failed to restart after 28,000 hours. This endurance is impressive, and exceeds almost all demands on a hollow cathode for solar electric propulsion missions. However, on missions to the outer planets, electric thrusters will be required to operate for more than 5 years. Because of this need, we have begun a systematic investigation to model the processes that can cause hollow cathode performance degradation and failure.

In the paper below we apply results from the extensive traveling wave tube vacuum barium impregnated cathode literature to the hollow cathodes used in ion thrusters. We show that the observed space station cathode life is in general agreement with published barium evaporation rates. While it may appear surprising that the hollow cathode design doesn't restrict the evaporation of barium, we show that in hollow cathodes barium is ionized immediately, and thus surface barium is not balanced by neutral vapor phase barium atoms.

This picture has immediate important consequences for assessing hollow cathode barium insert life. It suggests that every reduction in the insert operating temperature by about 40º C will extend the insert life by a factor of two, a well known rule of thumb for cathodes operating in vacuum. We discuss further measurements necessary to validate this conjecture for gas fed hollow cathodes.

Background

The Space Station hollow cathode plasma contactor test terminated when the hollow cathode fail to start and the tip temperature exceeded the pretest limit at 28,000 hours. The space station cathode tip temperature started at about 1200º C gradually dropped to about 1150º C and after 23,800 hrs, jumped to 1230º C, where it remained until the cathode wouldn't start after 28,000 hours. The jump in cathode starting voltage, and operating tip temperature after are both symptoms of a lack of free barium, in the insert. Free barium reduces the insert work function and also aids the in discharge initiation. In this paper we assume 23,800 hours as the time of effective depletion for this cathode.

Previous investigations of barium insert life in hollow cathodes focused on the reversible, equilibrium chemical reactions as barium oxide evaporates from the barium calcium aluminate mixture in a porous tungsten insert . The 1-D model of Kovaleski [2] includes the barium transport and diffusion in the hollow cathode xenon gas flow. The proposed loss mechanism was barium flow through the orifice. The loss rate was quite low, because the xenon gas velocity, approximately 4 m/s, was much slower than barium thermal velocity. Even with diffusion, the barium vapor pressure above the insert was sufficiently high to reduce the loss rate an order of magnitude compared with losses in a vacuum.

However, the space station hollow cathode experience is in better agreement with published depletion rates of barium cathodes operated in vacuum. An experimental study of barium impregnated cathode life in vacuum [3] showed the temperature dependence of barium depletion consistent with a 2.9eV heat of vaporization. A more recent study [4] showed that the same barium evaporation energy from 411 impregnates for a wide range of cathodes. They reviewed the literature and found the total variation from 2.8eV to 3.2eV, regardless of the matrix metal. The small variation of measured heat of evaporation, and its insensitivity to the matrix material, prompted us to apply the vacuum results to xenon gas fed hollow cathodes.

Application to the Space Station Hollow Cathode

In this paper we present a model of barium transport and loss in a typical electric propulsion hollow cathode that includes the effect of the insert region plasma.

Orifice Plasma Conditions

The current was 12 amperes during the space station hollow cathode test. This was the upper end of a large dynamic range, and the current density in the orifice was quite high. We have used a new 1-D, variable cross section model to determine the pressure and plasma density boundary conditions at the upstream end of the orifice. This model [5] extends the previous model of the insert region [6] to include charge exchange collisions, a radial density profile, and axial variation in all parameters. The model shows that the axial variation of ion currents to orifice walls is in agreement with published shapes of orifice erosion [7].

For the space station cathode, assuming an orifice temperature of 1200º C, the model predicts the insert region neutral xenon density of 5.4×10^{22} m^{-3} and a plasma density at end of the orifice of 3.4×10^{21} m^{-3}. About 0.1 amperes of ion flow upstream from the orifice into the insert region. We assume that the neutral gas density is fairly uniform throughout the insert region, but the plasma density drops rapidly away from the orifice.

Insert Region Plasma

If we assume constant neutral density, uniform electron temperature, the insert region plasma, including electron impact ionization of xenon atoms, and resonant charge exchange collisions between xenon ions and atoms can be modeled analytically.

With the assumption of quasi neutrality $n = n_i \approx n_e$, the local ionization rate links the steady state continuity equations for neutral xenon, xenon ions, and electrons.

$$\dot{n} - \nabla \bullet u_i n = 0$$
$$e\dot{n} + \nabla \bullet j_e = 0 ,$$

where e is the electron charge, n is the plasma number density, $j_e \equiv -e n u_e$ is the electron current, u is the axial speed (subscripts 0, i, e stand for neutral, ion and electron, respectively) and $\dot{n}$ is the ion generation rate

$$\dot{n} = 4\sigma(T_e)\, n_0\, n \sqrt{\frac{eT_e}{2\pi m_e}}$$

where m_e is the electron mass, n_0 is the neutral xenon number density, and $\sigma(T_e)$ is the impact ionization cross-section for xenon averaged over a Maxwellian distribution of electrons at temperature T_e (in eV) [6],

$$\sigma(T_e) \approx \left[3.97 + \left(0.643 T_e\right) - \left(0.0368 T_e^2\right)\right] Exp\left(\frac{-12.127}{T_e}\right) 10^{-20}$$

We assume that inertial terms are negligible in both the ion and electron momentum equations, an assumption supported by the calculations below. We also assume that the ion current is small compared with the electron current. The electron momentum equation takes the familiar form of a generalized Ohm's law, as does the ion momentum equation.

$$n(u_i - u_0) = -D_i \nabla n + n \mu_i \mathbf{E}$$
$$j_e = e D_e \nabla n + e n \mu_e \mathbf{E}$$

where for each species the diffusion coefficient, D, and the mobility, μ, are defined as

$$D_i = \tau_i \frac{kT_i}{M} \;,\; D_e = \tau_e \frac{kT_e}{m_e}$$

$$\mu_i = \tau_i \frac{e}{M} \;,\; \mu_e = \tau_e \frac{e}{m_e}$$

where τ is the collision time. By eliminating the axial electric field, $\mathbf{E}$, the ion momentum and electron momentum equations can be combined into a single equation

$$n(u_i - u_0) = -\left(D_i + \frac{\mu_i}{\mu_e} D_e\right)\nabla n + \frac{\mu_i}{\mu_e}\left(\frac{j_e}{e}\right)$$
$$= -D_a \nabla n + \frac{\mu_i}{\mu_e}\left(\frac{j_e}{e}\right)$$

where D_a is the ambipolar diffusion coefficient. While in the orifice the last term is non-negligible, in the insert region we neglect both it and the neutral drift velocity.

The ion mobility is limited by resonant charge exchange with neutral xenon. In the orifice the ion mean free path for charge exchange collisions is several microns. The ambipolar diffusion coefficient is

$$\tau_i = \frac{1}{\sigma_{CEX}\; n_0 u_{scat}}$$

$$D_a = \frac{1}{\sigma_{CEX}\; n_0} \frac{e}{M} \left(\frac{T_i + T_e}{u_{scat}}\right)$$

where σ_{CEX} is the xenon neutral-ion charge-exchange cross section and u_{scat} is an effective ion speed including drift and thermal velocities. For relatively slow diffusion, such as in the insert region, u_{scat} can be approximated by the ion thermal speed, u_{th}.

$$u_{th} = \sqrt{\frac{eT_i}{M}} .$$

The collision time for electrons is given by

$$\tau_e = \frac{1}{\upsilon_{ei} + \upsilon_{en}}$$

where υ_{ei} is the electron-ion collision frequency and υ_{en} is the electron-neutral collision frequency. The electron-ion coulomb scattering from Reference [8] is

$$\upsilon_{ei} = 2.9x10^{-12} n\Lambda T_e^{-3/2}$$

$$\Lambda = 23 - \frac{1}{2} Ln\left(\frac{10^{-6} n}{T_e^3}\right)$$

and a numerical fit to the electron-neutral scattering cross section averaged over a Maxwellian electron distribution [9].

$$\upsilon_{en} = \sigma_{en}(T_e) n_0 \sqrt{\frac{eT_e}{m_e}}$$

$$\sigma_{en}(T_e) \approx 6.6x10^{-19} \frac{\left(\frac{T_e}{4} - 0.1\right)}{\left[1 + \left(\frac{T_e}{4}\right)^{1.6}\right]} .$$

Setting the diffusion loss rate equal to the ion production rate yields

$$-\nabla \bullet \left[D_a \nabla n\right] = \dot{n} .$$

Ignoring the axial and radial variations in electron temperature and neutral densities, we obtain

$$\frac{\partial^2 n}{\partial r^2} + \frac{1}{r}\frac{\partial n}{\partial r} + \frac{\partial^2 n}{\partial z^2} + C^2 n = 0$$

$$C^2 = \frac{n_0 \sigma(T_e)\sqrt{\frac{8eT_e}{\pi m_e}}}{D_a}$$

We can solve the diffusion equation analytically by separating variables

$$n = n(0) f(r) g(z)$$

$$\frac{1}{f}\frac{\partial^2 f}{\partial r^2} + \frac{1}{rf}\frac{\partial f}{\partial r} + C^2 + \alpha^2 = -\frac{1}{g}\frac{\partial^2 g}{\partial z^2} + \alpha^2 = 0$$

The solution is the product of a zero order Bessel function times an exponential

$$n(r,z) = n(0) J_0\left(\sqrt{C^2 + \alpha^2}\, r\right) e^{-\alpha z}$$

Previous investigations have reported an exponential fall of plasma density [10] , in agreement with above predicted behavior.

Assuming that the ion density goes to zero at the wall, we obtain

$$\sqrt{C^2 + \alpha^2} = \frac{\lambda_{01}}{R},$$

where λ_{01} is the first zero of the zero order Bessel function and R is the internal radius of the insert. Setting α = 0, this eigenvalue leads to the following equation that determines the maximum possible electron temperature:

$$\left(\frac{R}{\lambda_{01}}\right)^2 n_0 \sigma(T_e)\sqrt{\frac{8eT_e}{\pi m_e}} - D_a = 0$$

The electron temperature from this model agrees well with 1.1 eV measured by Malik, Montarde, and Haines [11] for the UK25 hollow cathode. For the space station hollow cathode, the predicted plasma temperature is slightly higher, 1.2 eV. The correction for finite α is less than one per cent.

The 1.2 eV plasma quickly ionizes any vapor phase barium atoms. Using plasma density from the orifice model, the ionization mean free path for a thermal barium atom is $4x10^{-5}$ m, much less than the insert inner diameter. The mobility of the barium ions is much greater than neutral barium atoms, and the predominate electric fields that pull electrons out of the cathode drive the barium upstream away from the orifice, the opposite direction than in the Kovaleski model [2]. This flow direction is consistent with reports of the presence of barium upstream of the cathode insert region. In what follows we assume that the evaporated barium atoms are ionized and transported upstream with negligible sticking time on the hot downstream regions of the insert.

To find the exponential coefficient, α, of the insert plasma decay, we balance the measured hollow cathode input power with the ionization losses in the insert. The Space Station test cathode operated at 12 Amperes and 12.5 volts [1]. From our 1-D model, we find that about 67 watts were dissipated in the orifice by Ohmic heating which not only heated the orifice plate, but also generated and heated the plasma that left the cathode. The power that traverses the cathode sheath is the total discharge power minus the power dissipated in the cathode aperture:

$$I = 12\,\mathrm{A}$$

$$V = 12.5\ \mathrm{V}$$

$$I\ V = 150\,\mathrm{W}$$

$$I\,\phi_{sheath} = 150 - 67 = 83\,\mathrm{W}$$

$$\phi_{sheath} = 6.9\ \mathrm{V}$$

This leaves a maximum of 6.9 V for the sheath potential, neglecting any resistive drop in the insert region. The sheath current consists of electrons and ions. The power that the electrons gain from the sheath goes into ionization and electron convection. The energy imparted in the ionization collision is sum of the ionization potential (12.1 eV) and the secondary electron kinetic energy (≈2 eV) that is convected away.

$$I = I_e + I_i$$

$$\begin{aligned} I_e\,\phi_{sheath} &= 12.1\ I_i + \tfrac{5}{2} I\ T_e \\ &= 12.1(12 - I_e) + 37 \end{aligned}$$

Solving for the ion and electron current through the sheath at 12 A of discharge current, we find that

$$I_e = 9.6\ \mathrm{A}$$

$$I_i = 2.4\ \mathrm{A}$$

Analytically, the insert ion current generation is equal to the integral of the ion generation rate over the insert volume.

$$\begin{aligned} I_i &= \int \dot{n}\,dV \\ &= 2\pi \iint 4\sigma(T_e) n_0 n_e(r,z) \sqrt{\frac{eT_e}{2\pi m_e}}\, r\,dr\,dz \end{aligned}$$

Applying the analytical solution for the electron density derived earlier, we can rewrite ion current generation in terms of the average radial density and solve for the ion current.

$$\begin{aligned} \bar{n} &= \frac{\int_0^R n(0,0) J_0\left(\frac{\lambda_{01}}{R} r\right) 2\pi r\,dr}{\pi R^2} \\ &= n(0,0)\left[\frac{2J_1(\lambda_{01})}{\lambda_{01}}\right] \end{aligned}$$

$$I_i = \frac{\pi R^2}{\alpha} 4\sigma(T_e) n_0 \bar{n} \sqrt{\frac{eT_e}{2\pi m_e}}$$

For the peak density, n(0,0), we use the upstream orifice plasma density from the 1-D orifice code. Solving this equation for α, we find the plasma falls off upstream on a scale length of 0.7 cm, roughly consistent with the measurements of insert surface change reported by Sarver-Verhey [1].

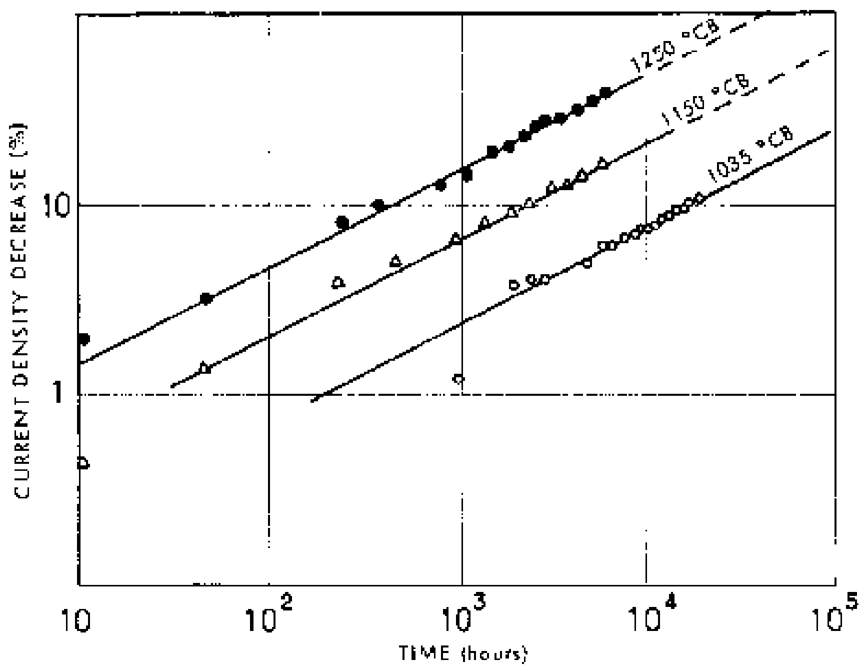

Figure 1. Decrease in saturation emission current with time for different cathode temperatures. Figure from Palluel and Shroff [3].

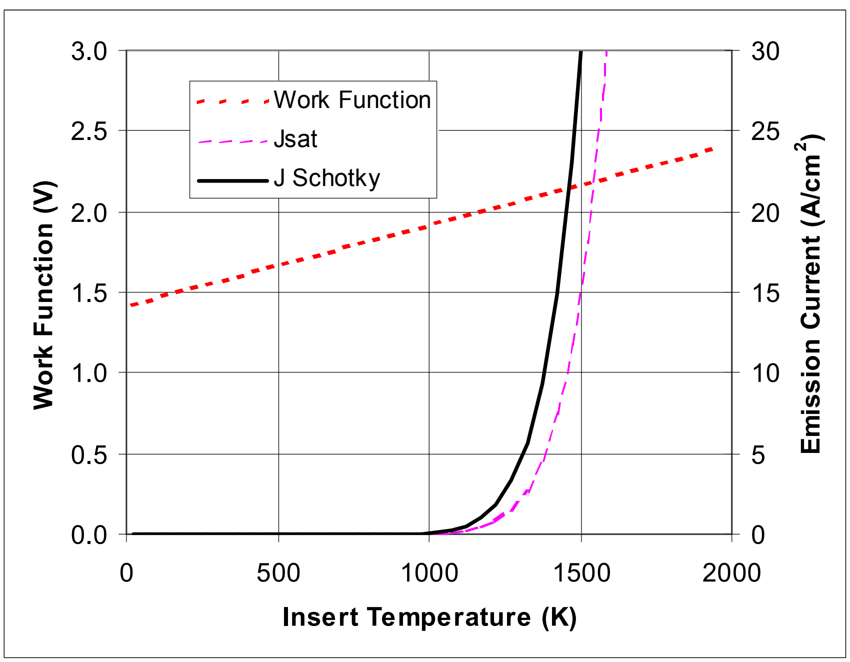

Figure 2. Work function and saturation emission currents with and without the Schotky electric field enhancement term.

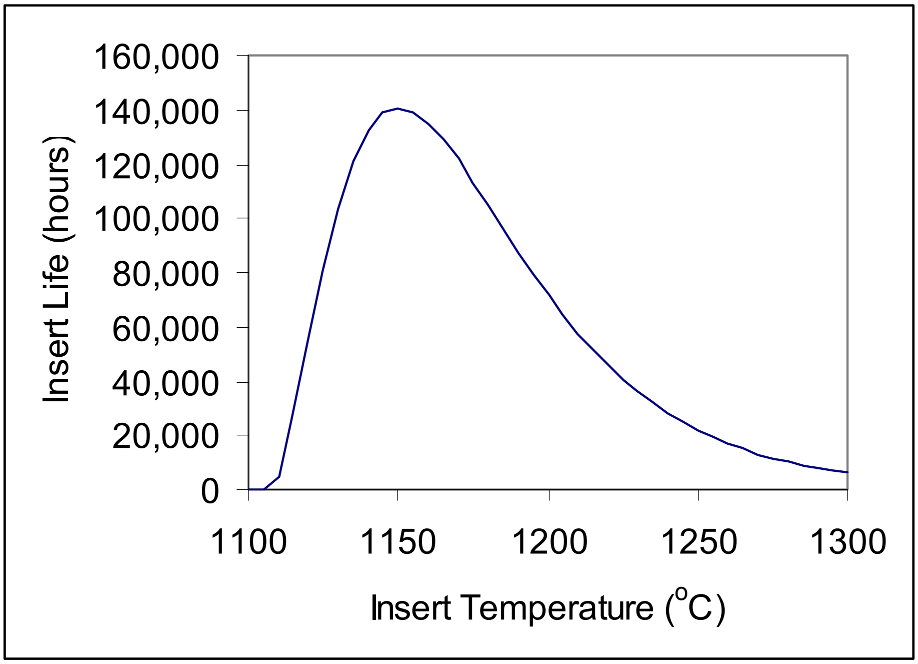

Figure 3. Expected insert life for the space station cathode as a function of insert temperature

Insert life

Palluel and Shroff [3] measured decrease in insert emission in vacuum as a function of time and temperature (see Fig. 1). They found that the temperature dependence was consistent with the 2.9eV heat of vaporization, and that the rate varied as the square root of time, consistent with Knudsen diffusion through the pores. As barium evaporates, the emission current density that the cathode can support decreases, presumably due to reduced surface coverage.

Following Palluel and Shroff, we have calculated the saturated emission current density at the beginning of life, shown in Figure 2, and have included a Schotky correction using the ion current and plasma length scale calculated above. At 1250º C (1523 K), the Schotky field enhanced saturated electron current density that the cathode could emit is about 35 A/cm^2, while the calculation above indicates that the cathode was drawing less than 10 A/cm^2 of electron current from the emitting surface.

In Figure 3 we plot the time that the space station cathode could support the discharge current as a function of the insert temperature based on the Palluel and Shroff vacuum data. At an internal insert temperature of about 1250º C, the Schotky enhanced emission current density would have dropped below the operating cathode current after about 20,000 hours. This would require an increase in insert temperature at that point to maintain the discharge current, which is consistent with the experimental results reported by Sarver-Verhey.

This insert temperature, 1250ºC, is about 70ºC greater than the cathode tip temperatures as reported by Sarver-Verhey, and within the range of temperatures measured by various means during the test. As long as the current density that the surface can emit is well in excess of the emission current required to support the discharge, the expected insert life would double for every 40ºC decrease in operating temperature. As seen in Fig.3, dropping the insert temperature 100˚C to about 1150˚C would have increased the cathode lifetime in this test to in excess of 100,000 hours while maintaining the discharge current. This insert temperature reduction could have been achieved by simple geometry and flow changes in the hollow cathode.

Conclusion

The fundamental result of this analysis is that during the 28,000 hour life test, the space station hollow cathode insert was operating at a temperature far in excess of the minimum necessary to support the emission current density. This caused excessive evaporation of barium from the insert, which was transported upstream away from the plasma to regions where emission can not occur due to space charge effects. Consequently, after a sufficient time the cathode could not support the discharge current required due to barium depletion in the plasma contact area of the insert.

Modifying the cathode to operate at a lower insert temperature would have resulted in a significantly longer life. We are certain that this is not surprising information to the test designers. The contactor cathode was designed for a large dynamic range in discharge current, and the test was conducted at the highest end of that range. Under less demanding conditions, at lower currents or with a cathode design change, the life would have been much greater. The hollow cathodes used in the NSTAR thruster are of similar design, but operate at lower temperatures. In the NSTAR Extended Life Test [12], these cathodes continue to operate stably and with reproducible emission performance for over 27,000 hours, with no change in starting voltage.

The model presented is empirical in nature. Direct measurements of insert operating temperatures are needed on future tests, as are measurements of barium depletion as a function of time. If the assumption is borne out that impregnate life in gas fed hollow cathodes is similar to that in vacuum cathodes at the same temperature, the ion thruster community will benefit from the extensive literature of vacuum cathode life test data and models.

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