# HOLLOW CATHODE CONDITIONING AND DISCHARGE INITIATION STUDIES [*]

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## Abstract

Hollow cathodes are used for a wide variety of applications, including challenging ones like plasma contactors for sounding rocket experiments. Existing hollow cathode designs cannot be started in the short amount of time available during sounding rocket flight, however, a fast-starting hollow cathode is being designed in Colorado State University to address this issue. In the framework of fast-staring cathode development, a study of cathode conditioning and activation was performed where desorption and outgassing of contaminants from a cathode during conditioning was studied. Cathode ignition times are correlated to no-flow (vacuum) emission levels, and a model that describes the vacuum electron emission from a cathode (that is coupled to a 3D thermal model) is presented and validated against experimental data.

## I. INTRODUCTION

Orificed, thermionic hollow cathodes have been developed and used for a wide variety of applications, including plasma electron supply for ion and Hall thrusters, plasma contactors for electromagnetic tethers, and for spacecraft charging control. Up to now many theoretical and experimental studies have been dedicated to understanding how these cathodes work and how their lifetime and reliability can be improved. The results to date allow optimization of a cathode design and prediction of cathode performance. However, little information is available concerning the process of the hollow cathode discharge initiation. In order to develop fast-starting cathodes, which are necessary, for example for sounding rocket experiments, a better understanding of the cathode activation process is required. It is also important to study and optimize the process of cathode conditioning, which precedes the cathode activation and typically takes several hours. In the framework of developing a fast-starting hollow cathode, a study of hollow cathode conditioning has been performed, which includes both temperature and contaminant desorption measurements. In addition, studies of hollow cathode emission characteristics under vacuum conditions have

been performed. Results of these tests are described herein along with measurements of the temperature of the cathode as a function of time and heater power. The data are used to verify a transient, 3D FEM thermal model and validate a coupled transient surface diffusion model that describes the migration and surface coverage fraction of low-work function material from the interior of the hollow cathode to the orifice barrel and to the exterior surface of the orifice plate of the cathode. Correlations are presented between the emission current onset and the ability to start the hollow cathode discharge once gas flow is initiated.

## II. CONDITIONING AND ACTIVATION STUDIES

The experiments on hollow cathodes described herein are performed in a cryopumped vacuum chamber. The operating pressure during no-gas-flow cathode experiments is in the high $10^{-7}$ Torr range. Temperatures at various locations on a hollow cathode under test are measured using type C and K thermocouples.

A typical hollow cathode is shown in Fig.1. A toroidally shaped electrode (keeper) is placed just downstream of the cathode, which is biased positive of the cathode. A 7-layer radiation shield formed from Ta foil wrapped around the heater reduces the amount of heat radiated from the cathode.



**Figure 1.**  Hollow cathode.

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Before a hollow cathode discharge can be initiated, it is necessary to prepare it for operation. This process is called conditioning and can take up to several hours for some cathodes. The purpose of conditioning is the safe removal of contaminants like water, oxygen, carbon dioxide, etc. from the low-work function insert, which is located within the hollow cathode near its downstream end. This goal is achieved by slowly increasing the cathode temperature using a heater while the cathode is held in a pristine vacuum environment. The slow ramping of temperature is necessary because, if the cathode is heated too quickly, the porous W insert could be "poisoned" by the out-gassing contaminants. The pristine vacuum environment is necessary to prevent undesirable (irreversible) chemical reactions (i.e., poisoning) that can occur in poor vacuum environments containing water vapor, oxygen, and carbon dioxide. The following conditioning sequence is used. First, the heater current is set to 2 A and then increased by 1 A every 5 minutes until a level of 6 A is reached. At this point, the heater current step size is reduced to 0.5 A, and two additional steps of 5-minute duration are performed at 6.5 and 7.0 A. It is noted that conditioning can be performed with or without gas flow through the cathode, and, typically, we perform the conditioning process without gas flow. A typical conditioning sequence is shown in Fig.2. The cathode tip temperature was measured during the conditioning using type C thermocouples and is shown in Fig. 3.
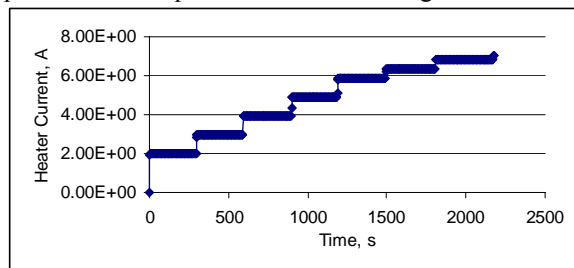


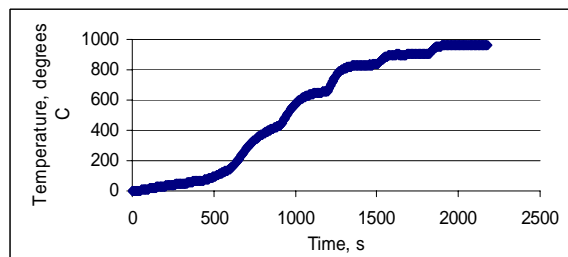**Figure 2** Hollow cathode conditioning: heater current vs. time



**Figure 3.** Hollow cathode conditioning: orifice plate temperature  vs. time

Outgassing was monitored using a Leybold TSP TR200 Residual Gas Anslyzer (RGA) during conditioning of the cathode (after it was exposed to atmosphere for an extended amount of time). Desorption of water, carbon dioxide and atomic oxygen data are shown on Fig. 4 (using the same time scale of Figs. 2 and 3). The most significant desorption occurs at 700-900 C. Haas [1]

observed desorption of these components at slightly lower temperatures for M cathodes. It is interesting to note that he also observed a single peak for water and multiple peaks for carbon dioxide.
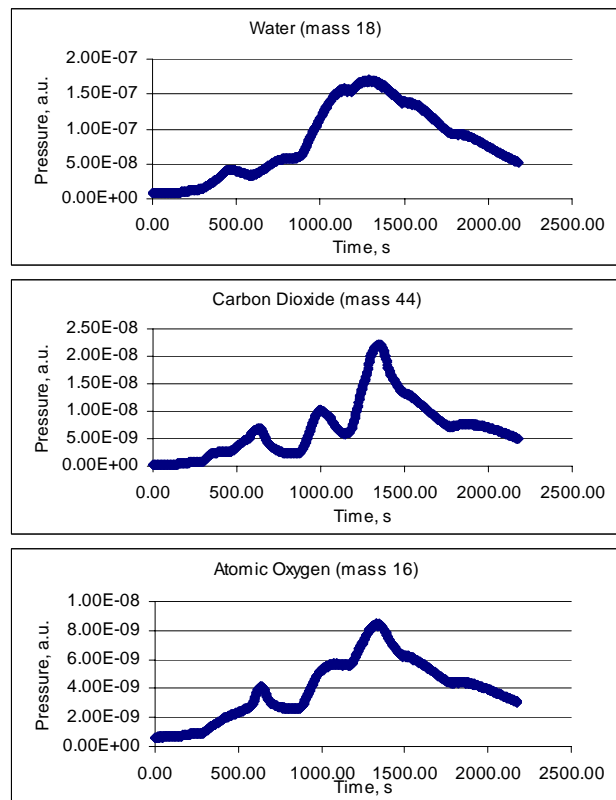


**Figure 4.**   Desorption of gases during conditioning

After conditioning is performed, the hollow cathode can be started (i.e., a plasma discharge can be established between the keeper and cathode). The minimum requirements to start the cathode include (1) temperature of approximately 1100 ºC, (2) gas flow in the range of 1-10 sccm, and (3) keeper potential biases in the range of 50V to 200V. A final requirement for starting is for the insert to coat the hollow cathode interior, orifice barrel and orifice plate exterior with a partial mono-layer of barium oxide. To check the condition of a cathode at a given point in its use history, the cathode heater is turned on (usually at a nominal level of 7 A) when the cathode is initially at room temperature.  The emission current profile is then recorded as the cathode heats up (with the keeper biased relative to the cathode set at +100 V). Typical data measured during a health check are shown in Fig. 5 (log-linear) for three different heater power levels, and, as expected, higher heater power levels cause emission to start sooner and reach higher saturation values. As noted above, the saturation value is dependent upon both the cathode temperature and the surface coverage fraction of barium oxide on the exterior of the cathode orifice plate.

The desired temperature of the cathode at startup is approximately 1100 ºC and this temperature affects

electron emission capability and drives the production of the barium oxide coating. Therefore an understanding of the heat flow processes in the cathode is of great importance for the design of a fast-starting cathode. Figure 6 shows the temperature profiles of the cathode orifice plate during the no-flow electron emission tests corresponding to Fig. 5.
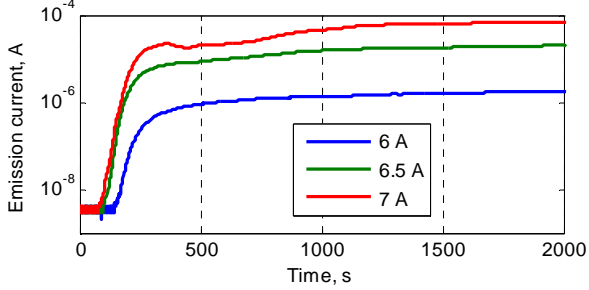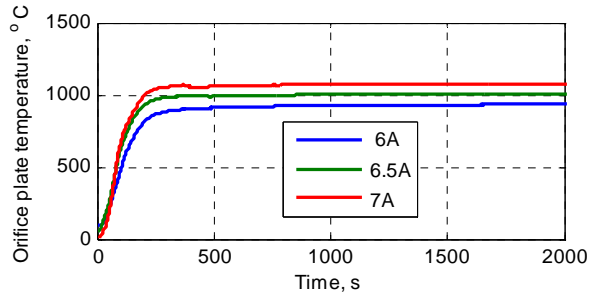


**Figure 5.** Emission current vs. time



**Figure 6.** Temperature vs. time

Two types of hollow cathode ignition tests were performed. During the first test, the heater was turned on at 7 A and a keeper bias of 50 V was applied. When the emission reached some particular value, a flow of xenon gas at 5 sccm was turned 'on'. If the cathode didn't start, the flow was turned 'off' and then turned back 'on' at a (pre-selected) higher vacuum emission level. These experiments demonstrated that the minimum, no-flow emission necessary to start the cathode with a given flow rate is 15 μA $\pm$3 μA. During the second test, the heater current, keeper bias, and flow were turned 'on' simultaneously and the emission current was recorded until the cathode discharge ignited. These experiments demonstrated that with gas flow, the emission current starts to increase earlier and increases more rapidly. As a result, the cathode can be started much faster. The correlation between the emission under no-flow conditions and with gas flow needs to be investigated further.

## III.    EMISSION AND THERMAL MODELING

The results presented in Figs. 5, 6, and 7 are used for verification of a computational model of the cathode start-up process. The model is based on the work of Tighe et al. [2], where the temporal surface diffusion characteristics of barium oxide are modeled along with the barium generation rate. The cathode start-up sequence begins with applying current to the heater that causes the cathode temperature to increase, eventually reaching approximately 1100 ºC. As the cathode heats up, barium evaporates from the cathode insert, creating a gas inside the cathode tube and covering the inner surfaces of the cathode. The barium deposited on the interior surface of the orifice plate and within the orifice barrel diffuses to the outer surface of the orifice plate, creating a low work function emitter. This process is described by the surface diffusion equation with a desorption term:

$$\frac{\partial \theta}{\partial t} = D\nabla^2\theta - E_0 \exp\left(-\beta E_d^{mono}\right)\theta^5 \qquad (1)$$

In Eq. (1), $D$ represents the surface diffusion coefficient, $\theta$ the surface coverage fraction, $t$ the time, $E_0=2.13*10^6\text{s}^{-1}$, $E_d^{mono}=2.06\text{eV}$ the activation energy for desorption, $\beta=1/kT$, and $T$ the orifice plate temperature. This form of the desorption term was proposed by Jensen et al. [3], and represents the best fit for the experimental data of Forman [4], that were used to determine the parameters $E_0$ and $E_d^{mono}$.

The boundary conditions for the surface diffusion equation are:

$$\theta = \theta_0, \qquad r=r_1 \qquad \theta = 0, \qquad r=\infty \qquad (2)$$

where $\theta_0$ is the surface coverage of the orifice barrel walls ($r=r_1$). The outer boundary of the solution domain was placed further from the orifice then the actual outer orifice plate boundary. This condition does not restrict the surface coverage on the outer boundary of the orifice plate, but instead reflects the fact that barium can diffuse from the orifice plate to the outer walls of the cathode. According to Longo [2], Forman [4], and Jensen [3], the coverage thickness is limited to a monolayer at a surface coverage fraction of 100%.

The surface coverage of the orifice barrel walls $\theta_0$ was chosen to fit the experimental data. It can be determined using the method proposed by Tighe [2], which also includes fitting parameters. Following Tighe [2], $\theta_0$ was assumed to be independent of time, and good agreement with experimental results shows that this is a valid assumption. The physical implication of this assumption is that the walls of the barrel are pre-covered with a partial monolayer of barium. The best fit $\theta_0$ value for the data presented here is about 0.3, which corresponds to the results of Jensen [3].

After the surface coverage is determined, the work function $\varphi$ over the exterior of the orifice plate can be determined using the equation derived by Longo [5]:

$$\varphi(\theta) = \varphi_W \left(\frac{\Gamma \varphi_W}{\varphi_{Ba}}\right)^{\frac{\Gamma\theta}{1-\Gamma}} + \varphi_{Ba}\left[1 - \left(\frac{\Gamma \varphi_W}{\varphi_{Ba}}\right)^{\frac{\theta}{1-\Gamma}}\right] \qquad (3)$$

In Eq. (2), $\Gamma$ represents the parameter that determines the minimum work function at monolayer coverage determined from Longo's data [5], $\varphi_W$ the tungsten work function and $\varphi_{Ba}$ the barium work function.

Now we can calculate the emission current density $j$ using the Richardson-Dushman equation combined with the Schottky term.

$$j = AT^2 e^{-\frac{q\varphi(\theta)}{kT}} e^{\frac{0.44}{T}\sqrt{\frac{V}{d}}} \tag{4}$$

In Eq. (3), T represents the temperature of emitting surface (orifice plate), k the Boltzmann constant, V the bias voltage between the cathode and the keeper electrode, and d the distance between the cathode and the keeper electrode. This equation describes the field-enhanced, thermal emission from the exterior surface of the orifice plate. Integrating the current density over the orifice plate surface we obtain the emission current:

$$i = 2\pi \int_{r_1}^{r_2} j(\varphi) r \, dr \tag{5}$$

At the present time, the emission current behavior is being estimated using the experimentally measured orifice plate temperature. A thermal model was also developed (see discussion below) and validated, and temperatures calculated from the thermal model can be used in place of the measured temperature profile. The emission current profiles calculated using the model described above and the experimentally measured emission current are presented in Fig. 7, where good agreement is observed.
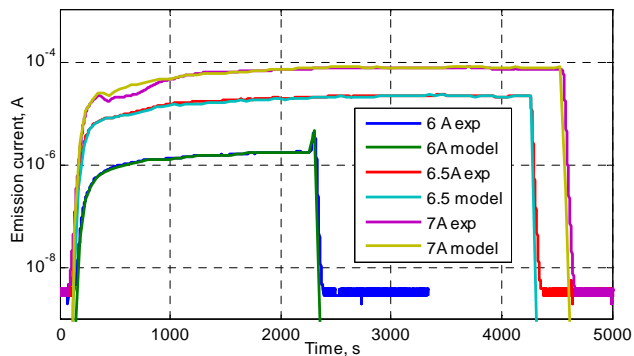


**Figure 7.** Comparison of calculated and measured emission current

A 3-D, transient thermal model of a hollow cathode was assembled using ePhysics™ software from Ansoft. Both conduction and radiation processes are included along with a temporal description of the power delivered to the heater. A calculated temperature distribution is shown in Fig. 8 for a heater current of 7 A. The cathode/heater coil region is shown with a transparent radiation shield to display more information. Experimental measurements of the temperature in different locations on the cathode were used to calibrate the model.

## IV. SUMMARY AND SUGGESTIONS FOR FUTURE WORK

Our paper presents data on cathode conditioning and activation. The conditioning study included measurements of cathode temperature measurements and out-gassing. Temperature and emission profiles at different heater current levels were also reported where strong dependence of emission onset and saturation on temperature was observed. Comparisons between the temporal behavior of the no-flow emission current and a model of this process suggest that pre-coverage of the orifice barrel region occurs. Cathode ignition tests were also discussed where 15 μA or greater levels were found to ensure discharge ignition at 50 V biases.
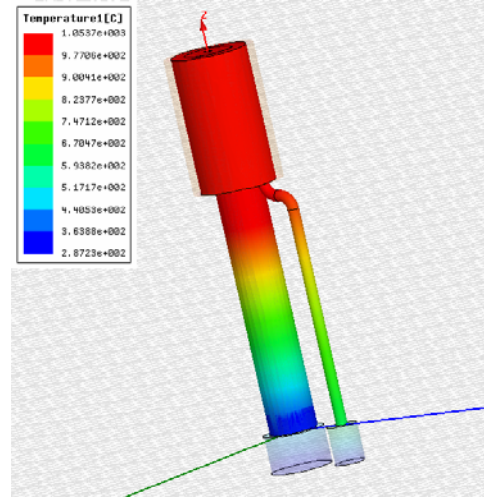


**Figure 8.** Calculated temperature distribution for a heater current of 7 A.

## V. ACKNOWLEDGEMENTS

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