# Design and Thermal Analysis of the Insert Region Heater of a Lanthanum Hexaboride Hollow Cathode

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***Abstract*—Several space electric propulsion devices, such as ion engines and Hall effect thrusters, use hollow cathodes as the electron sources for providing the necessary electrons for the ionization of the propellant and to neutralize the ion beam leaving the thruster. Most of the hollow cathodes used in space applications have used Barium-oxide impregnated Tungsten (BaO-W) inserts as the thermionic emission material due to its low work function. However, recent studies have shown the advantages of using Lanthanum-hexaboride ($LaB_6$) insert material as the thermionic emission source. However, due to its higher work function, the $LaB_6$ inserts have to be heated to a much higher temperature compared to the BaO-W inserts. In this paper, design and thermal analysis of the heater of a prototype hollow cathode with an $LaB_6$ insert as the thermionic emission material is presented. The built hollow cathode will be used as a neutralizer electron source for BURFIT-80, an 80 mm diameter laboratory RF ion thruster running on Xenon propellant.**

***Keywords*— hollow cathode; electric propulsion; thermionic emission; thermal modeling***

## I. Introduction

The hollow cathodes used in electric propulsion systems usually have a thin, long, hollow cylindrical conductor pipe in which an insert material with low work function is placed. Hollow cathodes operate based on a physical effect called *thermionic emission*. Thermionic emission is basically the release of electrons from an emitter material. The heating of the insert material causes increased electron emission from the surface to the hollow inner part of the cathode tube where a propellant flow is supplied. During steady state operation, the plasma generated inside the cathode tube provides a self-heating mechanism to keep the thermionic emission from the surface at a steady rate [1, 10, 11]. However, in order for the cathode discharge to begin, an external heating mechanism has to be used. This heater increases the temperature of the insert to the levels required for the desired current emission density from the insert surface. For starting the thermionic emission, the insert should be heated above 1600 $^{o}$C for $LaB_6$ inserts. However, for the same thermionic emission current density BaO-W inserts would have to be heated to a temperature of ~1100 $^{o}$C [3]. Therefore an external heater is required for the initial heating. Once the emitter reaches the required temperature for desired thermionic emission current density level, the heater is turned off. A schematic of a hollow cathode is shown in Fig. 1.

The thin, long tube where the insert is placed is called the *cathode tube*. The heater wires are placed around the cathode tube in the region of the insert material. The cathode tube has an opening called the orifice where the electron release to the region of interest takes place. Around the cathode tube a second conducting tube, called the *keeper*, is placed. Main function of the keeper is to accelerate electrons to initiate ionization. At first, plasma does not exist inside the cathode tube. Keeper creates an initial potential difference between the cathode tube and the exit of the whole system. By this way, electrons are accelerated so that electrons gain enough momentum to collide with neutral gas atoms in the environment and initiate ionization. After that, keeper regulates electron emission by maintaining an intermediate potential level between the plasma inside the cathode and the thruster plasma. Also, keeper protects the cathode from ion bombardment that may come from thruster plasma, because plasma inside the cathode has relatively lower potential. Hence keeper acts as a shield. However, this causes keeper to wear and this is one of the important factors that determine the cathode life [9].

Even though any low work function material could be used as the electron emitting insert, Barium Oxide impregnated Tungsten (BaO-W) and Lanthanum hexaboride ($LaB_6$) are the most commonly used thermionic emission materials in long life time hollow cathodes for use in electric propulsion applications. In 1950s, Lafferty investigated and developed Lanthanum hexaboride as an electron emitter [8,9]. Russians used a Hall thruster with a $LaB_6$ hollow cathode for the first flight of a stationary plasma thruster (SPT) in 1972 [7]. Russians have flown hundreds of thrusters with $LaB_6$ hollow cathodes since the early 1970s [8].

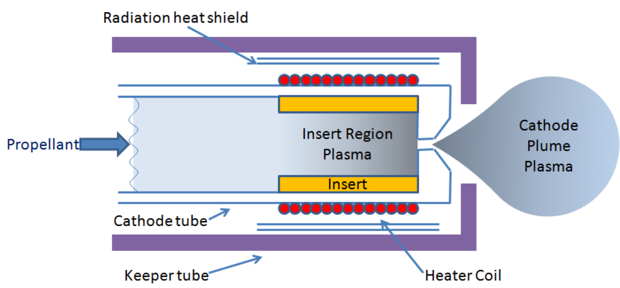


Fig. 1: Schematic of a hollow cathode

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In the United States, NASA have used Barium Oxide impregnated Tungsten (BaO-W) dispenser hollow cathodes from the 1960s [7, 8]. In the United States, Goebel reported the first time use of $LaB_6$ in a hollow cathode in 1978, and presented high current $LaB_6$ cathodes developed for plasma sources in 1985 [8]. Goebel and his collaborators have been continuing their research about the $LaB_6$ hollow cathodes [3,4,8]. Few other researchers have been following Goebel's studies in recent years. By following Goebel's research, Courtney [5] at MIT built and tested a small $LaB_6$ hollow cathode which had a discharge current under 2 Amperes. Similarly, Warner [2] at Air Force Institute of Technology studied hollow cathodes with $LaB_6$ and $CeB_6$ insert materials.

BaO-W and $LaB_6$ cathodes have been used as most common hollow cathode insert materials due to their low work functions. The work function of BaO-W is 2.06 eV at a temperature of around 1000 $^oC$ and the work function of $LaB_6$ is 2.67 eV around 1650 $^oC$. [8]. From the point of the cathode lifetime, $LaB_6$ cathodes have advantages as $LaB_6$ has a lower evaporation rate [4,8]. Moreover BaO-W cathodes are very sensitive impurity poisoning (water vapor, oxygen or other impurities in Xenon gas) at high temperatures and the poisoning can shorten the lifetime or even prevent the cathode emission [4,5]. For $LaB_6$ cathodes, special conditioning and storage procedures do not have to be followed and thus $LaB_6$ cathodes could be considered as more reliable than BaO-W cathodes [7].

A cut-off view of the preliminary design drawing of the hollow cathode that will be built at Bogazici University is presented in Fig. 2. The figure shows the components of the cathode: low work function insert, cathode tube, heater, keeper, spring and base parts. The insert should have sufficient surface area for the level of current for the operational conditions. In this project, the insert has a tubular shape with 2 mm inner diameter, 4 mm outer diameter and 10 mm length. Thus the surface area is 0.628 $cm^2$ and at a temperature of around 1650 $^oC$, the expected electron emission current would be 3 Amperes.

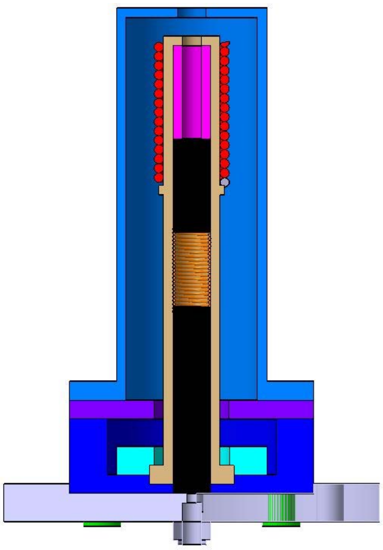

Fig. 2: Preliminary design of hollow cathode

This paper discusses three different heater designs for this $LaB_6$ hollow cathode. Several parameters are varied to obtain the better heater configuration. COMSOL, a finite element analysis program, is used for the thermal analysis of the three heater designs. COMSOL is a multi-physics solver program based on the balance equations for mass, momentum and energy, with an implicit scheme solving. By this design work and thermal modeling, discussions toward the manufacturing of the hollow cathode are provided. The results of this study are going to be used in deciding the design of the hollow cathode heater to be manufactured.

## II. The Theoretical Prediction

The basic operation mechanism of a hollow cathode is as follows: The insert ($LaB_6$) is heated by an external heater coil to an elevated temperature where sufficient electron emission per unit area is achieved. The electrons which are emitted from the insert hit Xenon gas and cause the Xenon neutral gas to be ionized. Then, with the application of an electric potential to the keeper electrode, which is placed external to the cathode electrode, ionized Xenon atoms will move out. The cathode insert can maintain its emission temperatures with the heat flux from the plasma to the insert surface. This is called the self-sustaining mode of operation. The heater is required only to provide the initial heating of the insert.

Thermionic emission is the electron emission from a heated substance, such as the insert used in hollow cathodes. If a substance, like a thin Tungsten filament, is heated to a high temperature, some electrons acquire sufficient energy and then they are able to break away from the surface of the material. Thermionic emission by a material is described by Richardson-Dushman equation [6]:

$$J = AT^2 e^{-e\phi/kT} \quad (1)$$

where J is the thermionic emission current density, A is a universal constant 120 $A/cm^2K^2$, T is the surface temperature of the emitting substance in Kelvin, e is the electron charge, k is Boltzmann's constant and $\phi$ is the work function for the material [4].

Fig. 3 presents the temperature dependence of the electron emission current density for various low work function materials. As seen from the figure, the emission current density for $LaB_6$ would be significantly less than that of BaO-W for the same temperature. In order to reach an electron emission current density level of 8 $A/cm^2$, the $LaB_6$ insert should be heated to temperature of greater than 1600 $^oC$.

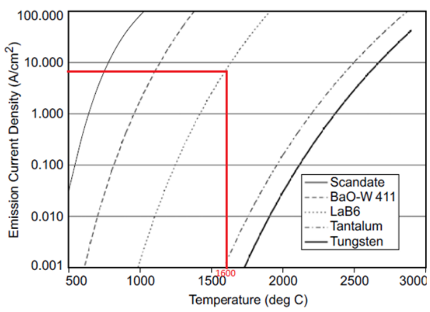


Fig. 3: Emission current density versus temperature for various cathode inset materials [4]

*A. Heater*

Normally hollow cathodes can provide self-heating to sustain the emission temperature. However for starting the thermionic emission, the insert should be heated above 1600 $^{o}$C for $LaB_6$ insert. Therefore an external heater is required for the initial heating. The high temperatures required for heating are typically supplied by refractory metals, like Tungsten and Tantalum, that can withstand very high temperatures [5].

Generally heaters are made by wrapping a wire around the cathode tube and then covering it by a foil. However this method has some disadvantages. Although it is the simplest method, this method may not be effective for heating the insert in small cathode tubes [5]. This method is weak about uniform, efficient heating of the insert [5]. Then as an alternative, a threaded ceramic tube which is wrapped by the wire is used as the heater for providing better surface contact between the heater assembly and the cathode tube compared with insulated wire [5]. Also a different heater design study is made in University of Michigan as shown in Fig. 4 [7]. Axial pattern is used instead of helical wire path to make the machining of the ceramic sleeve easier [7].

Fig. 4: Different heater design of University of Michigan [7]

In Goebel's experiment [4] a Tantalum heater wire was strung through alumina fish-spine beads and wrapped in a non-inductive coil around the hollow cathode tube. This heater can provide 250W of power to heat the cathode [4].

Like Goebel's heater, Warner, at Air Force Institute of Technology, used Tantalum as the heater material as shown in Fig. 5. The heater filament was a Tantalum sheathed alumina insulated wire. According to vendor data, these filaments operate as high as 1800°C [2]. 0.127 mm thick Tantalum wire was wrapped around the heater 12 times. Also there was an additional 0.254 mm thick piece of Tantalum foil for securing the thinner shielding and to keep it from un-winding [2].

In Dan Courtney's cathode work [5], initially commercially manufactured alumina beads were used; it was seen that that there would be a limited number of turns, ~3-4 turns, around emitting area and that would not provide uniform and efficient heating. Thus, as an alternative, threaded ceramic tube with wrapped Tantalum wire is considered. This configuration provides better surface contact and more turns per unit length. Instead of alumina, Boron Nitride was used as

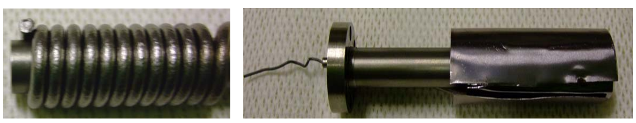

Fig. 5: Tantalum sheathed heater wire and foil shield [2]

ceramic material. Because at high temperatures a reaction occurs between alumina and Tantalum that causes severe degradation of the assembly and residues on the keeper and cathode housing [5]. Also, the heater size was decreased, from 3/8−24 thread on a 13.50mm long Boron Nitride tube with an OD of 9.0mm to a 5/16−24 thread on a 7.30mm outer diameter Boron Nitride tube. Thereby sufficient clearance was provided between the heater and radiation shield for the current to be returned via the outside of the heater [5].

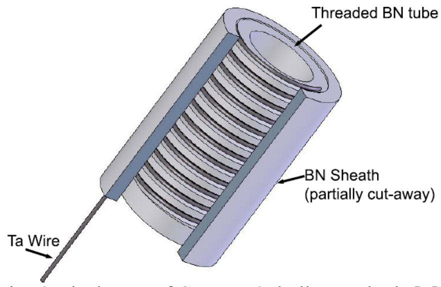


Fig. 6: The heater of Courtney's hollow cathode [5]

The heater wire was designed as 1 mm thick Tantalum wire making 15 turns around the tube. Although Tungsten is commonly used, Tantalum was selected as the heating element due to its combination of high resistivity and less brittle behavior at high temperatures [5]. A Tantalum sheet is used as a refractory material to prevent the radiative heat loss and aid maintaining the self-heating of the hollow cathode. The heater is approximately 15 mm long, 5 mm longer than the insert. This is enough for covering the insert region and heating it.

## III. DESIGN AND THERMAL MODELING OF THE CATHODE HEATER

In this study, three different heater designs have been considered. These designs, shown in Fig. 7, are inspired by the several other works mentioned in the literature as discussed in the previous section. The considered heater designs will be called as design A, design B and design C. In design A, the heater wire is assumed to be a 1 mm thick insulated Tantalum wire making 15 turns around the tube. The heater is assumed to be approximately 15 mm long (5 mm longer than the insert). In design B, a Boron Nitrite ceramic tube with helical shaped grooves placed on the cathode tube in the insert region. A bare Tungsten wire is assumed to be wound inside these grooves. This shape will provide a more uniform heating of the insert as well as allowing a more compact wounding of the wire. In design C, similar to design B, a Boron Nitride ceramic tube is placed around the cathode tube, but this time vertical grooves, instead of the helical shaped, are machined on the ceramic. Again, a bare Tungsten wire provides the resistive heating. A cylindrical Tantalum sheet, placed around the cathode tube and the heater coils, is used as a refractory material to prevent the radiative heat loss and aid maintaining the self-heating of the hollow cathode. The cylindrical Tantalum sheet radiates heat back into the system so that the generated heat is encapsulated and higher temperature values are achieved.

In designs B and C it is assumed that Boron Nitride ceramic will be used for the heater. However, Boron Nitrite might decompose in vacuum (~$10^{-6}$ Torr) at very high temperatures [12], thus this must be taken as a factor. Alumina or other high temperature ceramics could also be considered for this purpose.

COMSOL, a FEM (Finite Element Model) software, is used to analyze the heating time and the uniformity of the heating for these three different designs. The 3-D drawings of the designs are created in CATIA, software for creating technical drawings, and then imported into COMSOL. For the analysis, appropriate material properties are entered into COMSOL, and the tetrahedral mesh for the thermal analysis is generated.

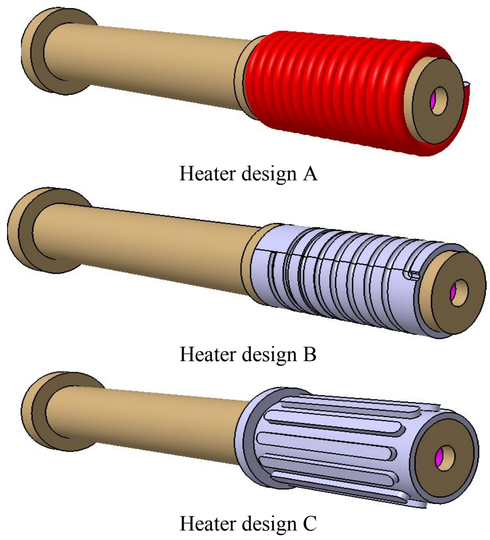


Fig. 7: Heater designs for the hollow cathode

Even though, it was possible to create the tetrahedral mesh for the designs A and B which have helical shaped wiring structures (as seen in Fig. 8 for design A), there were difficulties in obtaining the thermal analysis results. Thus, in the thermal analysis part, the helical shaped coil structure of the designs A and B are modified and the analysis was carried out with ring shaped coils of equivalent number and length.

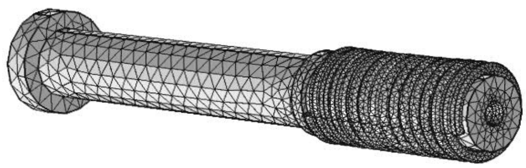

Fig. 8: The mesh generated by COMSOL for the heater design A

### *A. The Heat Transfer Model*

The designs elaborated in this work is supported by heat transfer simulations. The aim is that the hallow cathode reaches a steady state in which the temperature distribution of the cathode insert surface is above the desired temperature for the thermionic emission current density levels required.

The coil wrapped around the graphite cathode tube is heated up with the current passing through its windings due to the Joule heating. In the thermal analysis, it is assumed that the heater coils consume a total power of 107 W. It is thought that a current of 7 Amperes at ~15.3 Volts will be provided to the heater coils by an external power supply. This value is adapted from the experimental observation of the highest power delivered to the heater, before the initiation of the discharge, for the heating of Busek BHC-1500 hollow cathode.

In the analysis, it is assumed that the cathode loses heat by conduction to its base that is assumed to be kept at constant temperature of 300 K, and by radiation. Since the cathode testing (and real life operation) will be conducted in vacuum environment; the convective heat loss from the outside of the cathode is neglected. Although there will be a purging of the propellant gas (Xenon) inside the cathode tube during the initial heating of the insert region, it is calculated that the convective heat transfer due to the inner flow will be small compared to the conduction and the radiative heat losses. Thus, only conduction heat loss to the base and radiative heat loss to the outside are considered. A simple depiction of these heat losses are presented in Fig. 9.

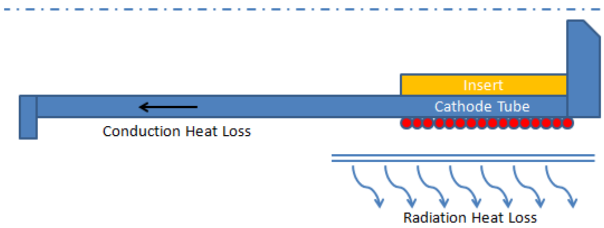


Fig. 9: A depiction of the heat losses for the hollow cathode

#### *1) 2D Results*

Prior to the 3D modeling, the hallow cathode heater is represented with an axisymmetric 2D domain. The mesh of the section of the model with coils is presented in Fig. 10.

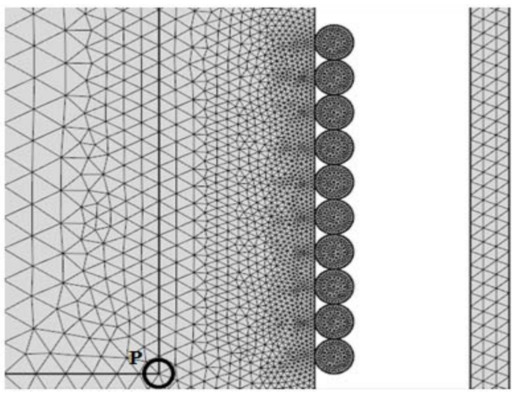


Fig. 10: The mesh generated by COMSOL for the axisymmetric cathode heater model. The point "P" is the corner node whose temperature evaluation is monitored.

The simulation results indicate that the hollow cathode heater reaches steady state after around 1500 s. The temperature at point "P", which is indicated in Fig. 10, is monitored with time and the temperature curve is plotted in Fig. 11. For the case where cathode is assumed to be floating, the steady state temperature of this point is approximately 2000 K.

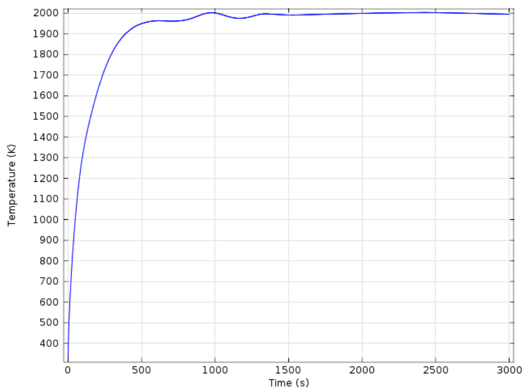

Fig. 11: The temperature vs. time plot of the point P

The temperature distribution on the whole model shows the similar tendency and convergence behavior. The steady state contour plot of the whole assembly is presented in Fig. 12. In this test case, it is assumed that the cathode is floating in space and not attached to any fixed temperature structure.

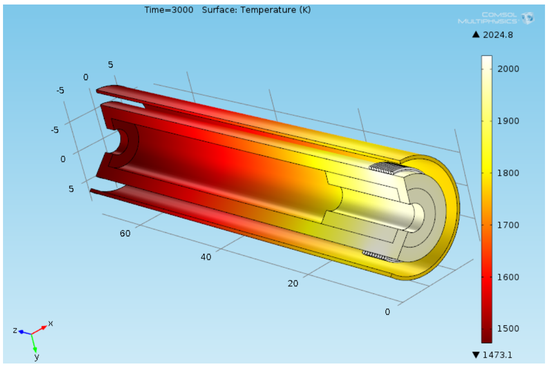

Fig. 12: The 3D surface plot of the temperature distribution. The minimum value of the temperature is 1473.1 K, whereas the maximum temperature is 2024.8 K.

*2) 3D Modeling Results*

The time variation of the temperature for the cathode is modeled until a steady state temperature distribution is obtained. Fig. 13 shows the comparison of the time variation of the insert surface temperature for all three heater designs.

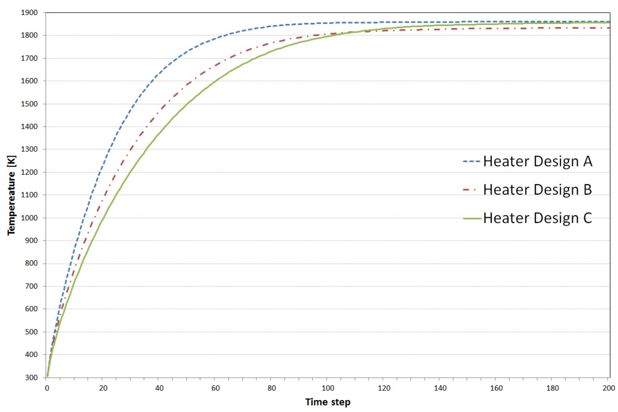


Fig. 13: Comparison of the transient temperature for the three designs

As seen in this figure, design A reaches the steady state temperature faster that the other two designs. This is expected, since in design A, the heater coils are in direct contact with the graphite cathode tube. The helical shaped design of the heater B allows a faster heating of the insert surface in comparison to the axial wiring scheme of the heater design C. As expected, in all cases a similar steady state temperate distribution is observed.

Fig. 14 shows the center axis slice contour plots of the steady state temperature distribution for the three cases. The similar structure of the temperature distribution is seen in the presented plots.

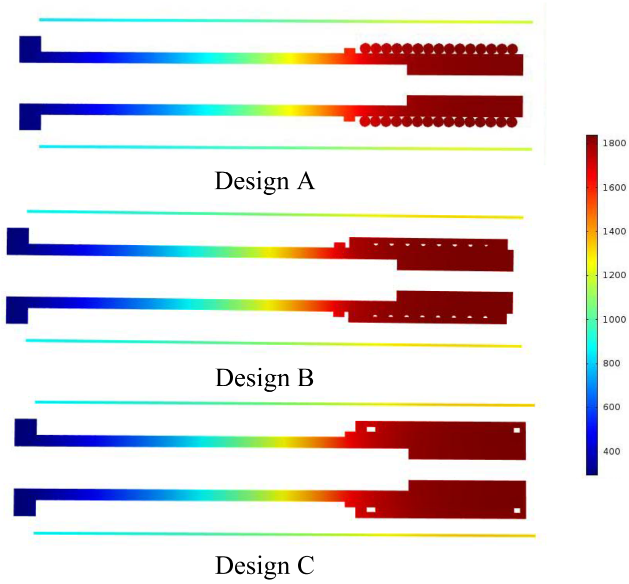


Fig. 14: Contour plots of the steady state temperature distribution for the hollow cathode heater designs

## IV. CONCLUSION

Ion engines and Hall effect thrusters that are used for certain propulsive applications of spacecraft and satellites need devices called hollow cathodes for the delivery of the electrons needed for their operation. Most of the hollow cathodes used in space applications have used Barium-oxide impregnated Tungsten (BaO-W) inserts as the thermionic emission material due to its low work function. However, recent studies have shown the advantages of using Lanthanum-hexaboride ($LaB_6$) insert material as the thermionic emission source. Due to its higher work function, the $LaB_6$ inserts have to be heated to a much higher temperature compared to the BaO-W inserts. In this study three different heater designs and related thermal analysis work are presented for a hollow cathode with $LaB_6$ insert. The study shows that the designs affect the time required for the low-work-function insert material to be heated to the desired temperatures for the desired thermonic emission current density levels.

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