

High Current Hollow Cathodes for High Power Ion and Hall Thrusters

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Deep space missions continue to demand higher power ion thrusters and Hall thrusters capable of providing higher thrust and longer life. Depending on the thruster size, the hollow cathodes may be required to produce discharge currents in the 50 to 100 A range with lifetimes in excess of 10 years. A conventional 1.5 cm diameter hollow cathode with a barium-oxide impregnated insert has been operated at discharge currents of up to 50 A, but cathode life modeling indicates that achieving the required life is challenging. In addition, the gas purity requirements of dispenser cathodes are difficult and expensive to meet, complicating electric propulsion implementation. To increase the life capability at the desired discharge currents and ease the handling and gas purity requirements, a lanthanum hexaboride (LaB₆) hollow cathode has been developed. This cathode utilizes a LaB₆ insert in an all graphite hollow cathode structure with an integral graphite keeper. The LaB₆ cathode has been successfully operated at discharge currents of up to 60 A to date, which is the limit of the present discharge supply. While the LaB₆ cathode operates at a higher temperature than the conventional BaO cathode, LaB₆ offers the capability of long life and two orders of magnitude less sensitivity to propellant impurities and air exposure than conventional dispenser cathodes. The operating characteristics of the LaB₆ and dispenser cathodes and predictions of the cathode life are discussed.

Nomenclature

A	=	theoretical coefficient in the Richardson-Dushman thermionic emission equation
α	=	temperature coefficient of the material work function
e	=	charge
D	=	experimentally modified value of A
ϕ	=	work function
ϕ_0	=	temperature independent work function
k	=	Boltzman's constant
T	=	temperature

I. Introduction

NASA has spent the last 40 years developing barium-oxide impregnated dispenser cathodes for ion thrusters, Hall thrusters, microwave tubes, plasma contactors, and plasma neutralizers. However, there are over a hundred times more cathodes in space at this time that use lanthanum hexaboride (LaB₆) as the active electron emitter. Hundreds of Russian Hall thrusters have been flown over the last 20+ years with LaB₆ hollow cathodes¹. In addition, LaB₆ electron emitters are used extensively in university research devices and industrial applications such as plasma sources, ion sources, arc melters, optical coaters, ion-platers, scanning electron microscopes, and many others applications. The space heritage of lanthanum hexaboride is unquestionable, and the industrial experience in dealing with the higher operating temperatures and materials compatibility issues is extensive.

Typical conventional space hollow cathodes utilize a "Phillips Type-B" porous tungsten insert that is impregnated with an emissive mix of barium and calcium oxides and alumina². This configuration is often called a

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dispenser cathode because the tungsten matrix acts as a reservoir for the barium that is “dispensed” to activate the emitter surface. Chemical reactions at the surface or in the pores at high temperature evolve a barium oxide dipole attached to an active site on the tungsten substrate, which reduces the work function of the surface to about 2.05 eV at temperatures in excess of 1000 °C. Because chemistry is involved in the formation of the low work function surface, dispenser cathodes are subject to poisoning that can significantly increase the work function. Care must be taken in handling the inserts and in the vacuum conditions used during operation of these cathodes to avoid poisoning by impurities in the gas that produce unreliable emission and shorten the lifetime or even kill the cathode emission. One of the major drawbacks of using BaO dispenser cathodes in electric propulsion applications is the extremely high feed gas purity required, which has resulted in a special “propulsion-grade” xenon with 99.9995% purity to be required. Lanthanum hexaboride³, on the other hand, is a crystalline material made by press sintering LaB₆ powder into rods or plates and then machining the material to the desired shape. LaB₆ cathodes have a work function of about 2.67 eV depending on the surface stoichiometry, and will emit over 10 A/cm² at a temperature of 1650 °C. Since the bulk material is emitting, there is no chemistry involved in establishing the low work function surface and LaB₆ cathodes are insensitive to impurities and air exposures that would kill a BaO dispenser cathode. LaB₆ cathode can withstand gas-feed impurity levels two orders of magnitude higher than dispenser cathodes at the same emission current density. In addition, the cathode life is determined primarily by the low evaporation rate of the LaB₆ material at typical operating temperatures. The higher operating temperature of LaB₆ and the need to support and make electrical contact with LaB₆ with materials that inhibit boron diffusion at the operating temperatures has perhaps limited their use in the U.S. space program.

To take advantage of the reduced gas purity requirements and to provide high discharge currents with long life, a lanthanum hexaboride hollow cathode has been developed. This cathode utilizes a LaB₆ insert in an all graphite hollow cathode structure with an integral graphite keeper to produce discharge currents of up to 60 A to date, which is the limit of the present discharge supply. In this paper, the characteristics of lanthanum hexaboride and the hollow cathode utilizing this material are described.

II. LaB₆ Characteristics

Lanthanum hexaboride was first developed as an electron emitter by Lafferty³ in the 1950's. The thermionic emission of lanthanum-boron compounds as a function the surface stoichiometry was extensively studied by several authors^{4,6}. The first use of LaB₆ in a hollow cathode was reported by Goebel, et al.⁷ in 1978, and high current LaB₆ cathodes developed for plasma sources were described by Goebel, et al.⁸ in 1985. The lanthanum-boron system can consist of combinations of stable LaB₄, LaB₆, and LaB₉ compounds, with the surface color determined⁴ by the dominate compound. Lanthanum-boron heated to in excess of 1000 °C in good vacuum evaporates its components at a rate that produces a stable LaB₆ surface. The evolution of LaB₄ and LaB₉ compounds is caused either by preferential sputtering of the boron or lanthanum atoms at the near surface by energetic ion bombardment⁸, or by preferential chemical reactions with the surface atoms⁹.

Thermionic emission is well described by the Richardson-Dushman equation¹⁰:

$$J = A T^2 e^{\frac{-e\phi}{kT}} \quad (1)$$

where A is a universal constant with a value of 120 A/cm²°K², T is the temperature, e is the charge, k is Boltzman's constant and ϕ is the work function. Experimental investigations of the thermionic emission of different materials report values of A that vary considerably from the theoretical value. This has been handled by a temperature correction for the work function of the form¹¹

$$\phi = \phi_0 + \alpha T, \quad (2)$$

where ϕ_0 is the classically reported work function and α is an experimentally measured constant. This dependence can be inserted into Eq. 1 to give

$$J = A e^{\frac{-e\alpha}{k}} T^2 e^{\frac{-e\phi_0}{kT}} = D T^2 e^{\frac{-e\phi_0}{kT}}, \quad (3)$$

where D is the temperature-modified coefficient to the Richardson-Dushman equation.

Several different work functions have been reported in the literature for LaB₆. This is primarily due to varying use of A or D in Eq. 3, or due to different crystal orientation in single-crystal emitters used for some applications. For hollow cathode and large area emitter applications, the press-sintered LaB₆ material is polycrystalline and the

work function is an average over the different crystal orientations at the surface. Table 1 shows the work function and values of A and D for different electron emitter materials given in the literature. Amazingly, the actual emission current density of LaB₆ predicted by the different authors in Table 1 is within about 25% for the different values of A, D and ϕ used. The emission current density calculated from Eq. 3 for the materials in Table 1 are plotted in Figure 1 as a function of emitter temperature. We see that the LaB₆ operates at several hundred degrees higher temperature than the dispenser cathode for the same emission current density. The temperature is significantly lower than the typical refractory metal emitters used in some plasma discharges.

Table 1. Work function and Richardson coefficients for different cathode materials.

	A	D	ϕ
BaO-W 411 (Cronin ¹²)	120		$1.67+2.82 \times 10^{-4} T$
BaO-W 411 (Forrester ¹¹)		1.5	1.56
LaB ₆ (Lafferty ³)		29	2.66
LaB ₆ (Jacobson and Storms ⁴)		110	2.87
LaB ₆ (Storms and Mueller ⁵)	120		2.91
LaB ₆ (Kohl ¹³)	120		$2.66+1.23 \times 10^{-4} T$
Molybdenum (Kohl ¹³)		55	4.2
Tantalum (Kohl ¹³)		37	4.1
Tungsten (Kohl ¹³)		70	4.55

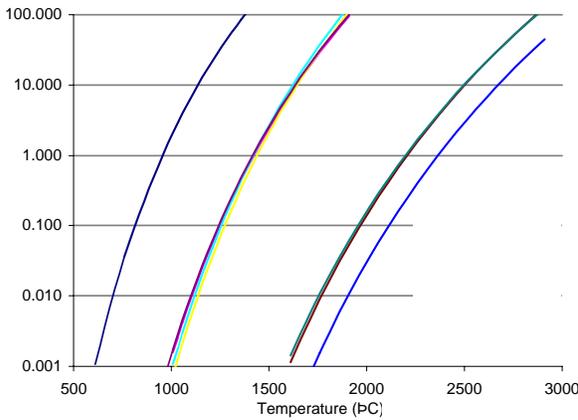


Figure 1. Emission current density versus temperature for different thermionic emitters.

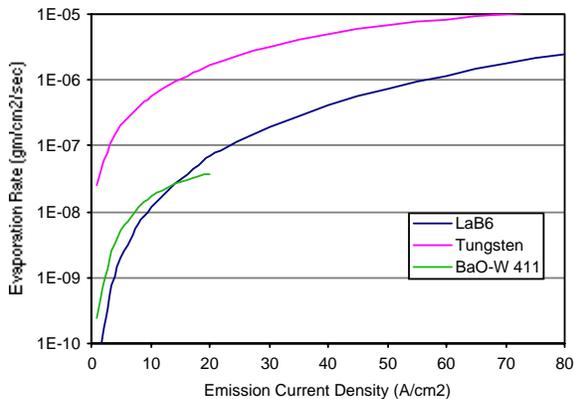


Figure 2. Evaporation rate of LaB₆ compared to tungsten and Type-B dispenser cathodes.

Lanthanum hexaboride offers long lifetimes because the evaporation rate is significantly lower than for refractory metals. Figure 2 shows the evaporation rate of LaB₆ and tungsten as a function of the emission current density¹⁴. LaB₆ evaporation is more than one order of magnitude lower when compared to tungsten at the same emission current density. For comparison, the evaporation rate of BaO from a Type-B 411 dispenser cathode¹² is also shown. In spite of operating at a significantly higher temperature, the LaB₆ has a lower evaporation rate until the emission current exceeds about 15 A/cm². While other considerations limit the current density of Type-B cathodes to less than about 20 A/cm², the life of the dispenser cathode is more complicated than just considering the evaporation rate due to the diffusion mechanism of the impregnate from the pores to the surface, as will be discussed later.

Several authors have investigated the poisoning of dispenser cathodes¹² and LaB₆ cathodes¹⁵. The most potent poisons for both cathode are oxygen and water, with other gases such as CO₂ and air causing poisoning at higher partial pressures. As mentioned previously, LaB₆ is insensitive to impurities that tend to limit the performance and life of barium dispenser cathodes. This is illustrated in Figure 3, where the fraction of the possible thermionic emission given by from Eq. 3 for a dispenser cathode and LaB₆ is plotted as a function of the partial pressure of oxygen and water for two different emitter temperatures. The curves for water poisoning of LaB₆ are off the graph to the right. We see that a partial pressure of oxygen below 10⁻⁶ Torr in the background or feed gas exposed to a dispenser cathode at temperatures of up to 1100 °C will cause

significant degradation in the electron emission. In a similar manner, water vapor at partial pressures below 10^{-5} Torr will poison dispenser cathodes at temperatures below $1110\text{ }^{\circ}\text{C}$. For typical pressures inside hollow cathodes of in excess of 1 Torr, this partial pressure then represents the best purity level that can be achieved by the gas suppliers. In comparison, LaB_6 at $1570\text{ }^{\circ}\text{C}$, where the electron emission current density is nearly the same as for the dispenser cathode at $1100\text{ }^{\circ}\text{C}$, can withstand oxygen partial pressures up to 10^{-4} Torr without degradation in the electron emission. This means that LaB_6 can tolerate two orders of magnitude higher impurity levels in the feed gas compared to dispenser cathodes. For the case of xenon ion thrusters, LaB_6 cathodes can tolerate the crudest grade of xenon available ($\approx 99.99\%$ purity) without affecting the LaB_6 electron emission or life.

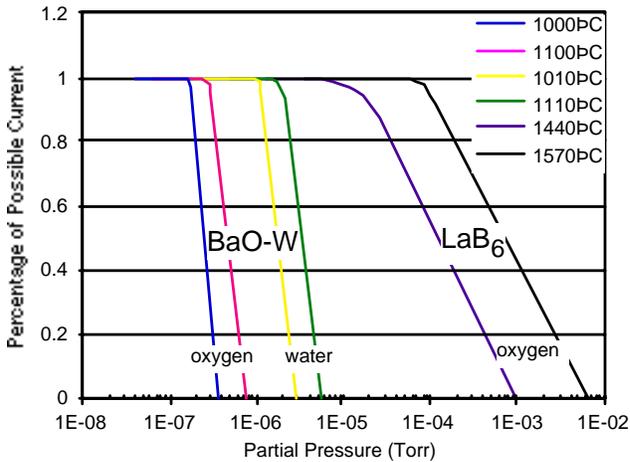


Figure 3. Percentage of possible thermionic emission versus partial pressure of oxygen and water showing the poisoning of dispenser cathodes relative to LaB_6 .

The insensitivity of LaB_6 to oxygen, water and air impurities extends beyond the partial pressures required in the feed gas system. LaB_6 cathodes do not require any significant conditioning or activation procedures that are required by dispenser cathodes. The authors have used LaB_6 cathodes to produce pure oxygen plasmas in background pressures of 10^{-3} Torr of oxygen. In this case, the operating temperature of the cathode had to be increased to just over $1600\text{ }^{\circ}\text{C}$ to avoid poisoning of the surface by the formation of lanthanum-oxide, consistent with Gallagher's results in Fig. 3. The authors have also exposed operating LaB_6 cathodes to atmospheric pressures of both air and water vapor. In both cases, the system was then pumped out, the heater turned back on and the cathodes started up normally. This incredible robustness makes handling and processing electric propulsion devices that use LaB_6 cathodes significantly easier than thrusters that use dispenser cathodes.

III. Experimental Configuration

The high current 1.5 cm diameter dispenser cathode developed for the NEXIS ion thruster has been previously described¹⁶⁻¹⁹. The cathode utilizes a standard 411 BaO impregnated insert with about a 0.75 mm wall thickness inserted into a Mo-Re tube with a tungsten orifice plate and a 2.5 mm cathode orifice diameter. A standard tantalum sheath heater wrapped around the cathode tube is used to pre-heat the cathode, and an input power of 115 W into the heater is typically required to light the discharge. The typical discharge voltage versus current performance of the cathode in an ion thruster simulator¹⁶ is shown in Figure 4. At low xenon flow rates of 4 sccm, the cathode reaches plume mode transition at about 30 A. Increasing the flow permits much higher discharge currents to be achieved. At 7 sccm flow, the cathode achieved the 50-A maximum of the power supply without any problem.

Lanthanum hexaboride hollow cathodes⁷ have a similar geometry as conventional dispenser hollow cathodes, but

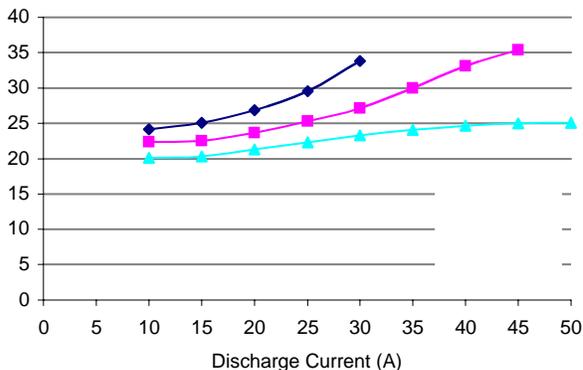


Figure 4. Discharge voltage versus current for the NEXIS 1.5 cm dispenser cathode for various xenon gas flow rates.

require more heater power to achieve the higher emission temperatures and require controlled interface materials to the LaB_6 insert. BaO dispenser cathodes commonly use a coiled tantalum sheathed heater that utilizes magnesium-oxide powder insulation. This material has a maximum operation temperature typically less than $1400\text{ }^{\circ}\text{C}$, at which chemical reactions between the oxide insulation and the heater electrode or sheath material cause a reduction in the resistance and ultimately failure of the heater. To first demonstrate the LaB_6 cathode performance, a tantalum heater wire was strung through alumina fish-spine beads and wrapped in a non-inductive coil around the hollow cathode tube. While not flight worthy, this heater could provide up to 200 W of power to heat the cathode.

Subsequently, a tantalum sheathed heater that incorporated high temperature alumina power insulation was procured and used to heat the LaB₆ cathode. This geometry common in industrial metal furnace heaters and can be found in the standard catalog of several companies²⁰. The catalogs indicate a maximum temperature of 1800 °C, which is well in excess of the temperature required to start the LaB₆ cathode.

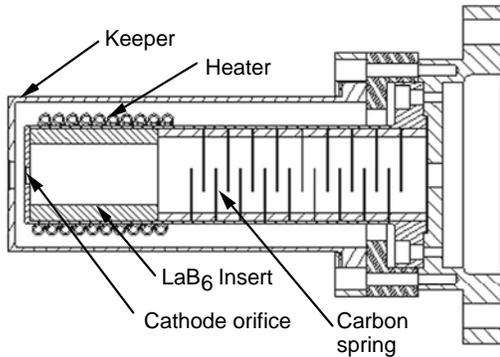


Figure 5. Schematic representation of LaB₆ hollow cathode.



Figure 6. End view of the LaB₆ hollow cathode with the beaded heater mounted to the gas feed system and test fixture.



Figure 7. Photograph of the LaB₆ hollow cathode with the sheathed heater mounted on the test fixture.

Contact with the LaB₆ insert at temperature can only be made with materials that inhibit boron diffusion from the crystal lattice into the support material^{7,8}. Typical materials reported in the literature are tantalum-carbide, rhenium and carbon. We utilize carbon because it has a similar coefficient of thermal expansion¹⁶ as LaB₆, and fabricate the entire hollow cathode tube out of a single piece of Poco graphite in which the insert is slipped. The keeper electrode used to start the discharge is also fabricated from Poco graphite. Figure 5 shows a schematic cross section of the LaB₆ cathode. The cathode tube has an outside diameter of 1.5 cm, and the LaB₆ insert has a wall thickness of about 0.3-cm and a length of 2.5 cm. This creates an active emitting area inside the cathode of about 5 cm², which according to Fig. 1 can produce emission currents of 50 A at temperatures of about 1650 °C. The insert is held in place by a slotted carbon spring that pushes the insert against the orifice plate. The all carbon geometry eliminates the materials compatibility issues with LaB₆ and makes the cathode electrodes robust against sputtering in xenon discharges. The carbon cathode tube and the carbon keeper are bolted to support and insulating flanges which are attached to the gas feed system and the power supply electrical leads. Figure 6 shows a photograph of the 1.5-cm LaB₆ cathode with the beaded heater arrangement under several layers of heat shielding and mounted into the test fixture. Figure 7 shows a similar photograph of the 1.5 cm LaB₆ cathode with the alumina-insulated sheathed heater and heat shielding.

IV. LaB₆ Cathode Performance

The LaB₆ hollow cathode was installed in a vacuum system with 1500 l/sec xenon pumping speed from two cryo-pumps, and coupled to a cylindrical water-cooled copper anode. Figure 8 shows the discharge voltage versus discharge current measured with 5 sccm xenon gas flow for various orifice sizes in the cathode and keeper electrodes. The keeper was continuously biased during operation and the keeper current regulated to 2 A by the keeper power supply. The cathode was observed to enter plume mode (large AC discharge and keeper voltage oscillations) at discharge voltages above about 30 V and currents above 30 A. Increasing the cathode orifice size by 30% from orifice #1 to orifice #2 did not change the discharge parameters of the plume mode transition significantly. However, increasing the keeper orifice diameter by only 17% from #1 to #2 eliminates the plume mode transition at discharge currents up to and exceeding 50 A.

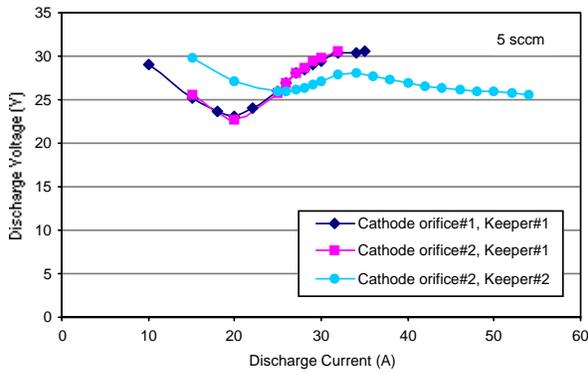


Figure 8. Discharge voltage versus current at 5 sccm xenon flow for various orifice sizes.

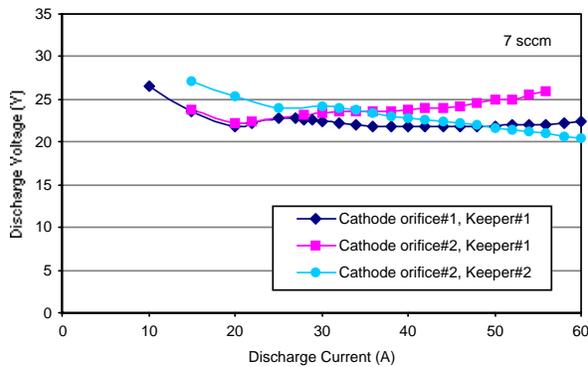


Figure 9. Discharge voltage versus current at 7 sccm of xenon gas flow for various orifice sizes.

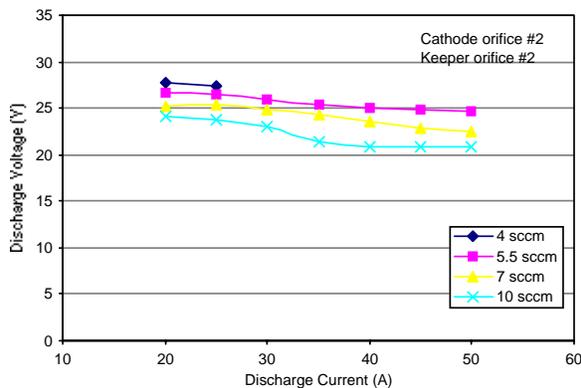


Figure 10. Discharge voltage versus current for various flow rates with the largest cathode and keeper orifices.

projected life. We see that the 1.5 cm diameter LaB₆ cathode is projected provide up to 100 kHrs of life at discharges up to 50 A. This is comparable to the projected NEXIS dispenser cathode life for insert thicknesses of 1.5 to 2 mm. Higher discharge currents result in lower projected lifetimes, although several years of operation (>30 kHrs) are still possible at 100 A.

To extend the life of the cathode in this discharge current range, a 2-cm diameter cathode has been designed and fabricated. Figure 12 shows the calculated life for the 2-cm diameter for the LaB₆ cathode with a 2 mm thick insert and a 2-cm diameter dispenser cathode with two insert thicknesses. In this case, both cathode designs provide over

Increasing the gas flow rate to 7 sccm, shown in Figure 9, eliminates the plume mode transition for all the orifice diameters at discharge currents up to 57 A. Again, increasing the keeper orifice diameter by 17% permitted operation at the highest current at this flow, which was limited to 60 A by the existing power supply. The discharge operation was very stable with well less than 1 V oscillation in the discharge voltage.

Figure 10 shows the discharge behavior of the cathode with the largest orifices as a function of the gas flow. As is typical with hollow cathodes, increasing the gas flow rate decreases the discharge voltage and increases the peak current capability before the transition into plume-mode. In this case, plume mode transition was only encountered at 4 sccm at less than 25 A of discharge current. At xenon gas flow rates of 5.5 sccm and above, the cathode produced the full 50 A test criterion without problem.

The current available from this cathode was limited only by the existing discharge power supply. As mentioned above, this LaB₆ insert has an inside surface area of about 5 cm², and so produces about 50 A of emission at 1650 °C. Thermionic emission of about 20 A/cm² is possible from LaB₆ at temperatures of only about 1700 °C, which is easily obtainable from this material⁸.

V. Discussion

The 1.5 cm diameter LaB₆ cathode discussed here has a lifetime limited only by the evaporation rate of the insert. Interestingly, as the insert evaporates the inner diameter increases and the surface area enlarges. This causes the required current density and temperature to decrease, which reduces the evaporation rate of the insert. The life of the LaB₆ cathode is calculated taking this change in the emission area with time into account, and is shown in Figure 11 as a function of the discharge current. Also shown for comparison is the insert life calculated¹⁷ for the same size 1.5-cm conventional dispenser hollow cathode used in the NEXIS ion thruster¹⁸, but with several different insert thicknesses. The calculations assume that nearly all of the impregnate and the LaB₆ material is exhausted, and so represent an upper limit on the

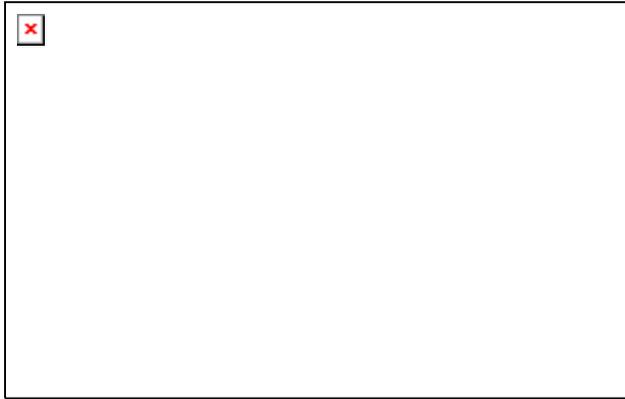


Figure 11. Calculated cathode lifetime in kWhrs versus the discharge current for the 1.5 cm diameter LaB₆ cathode and the 1.5 cm diameter NEXIS cathode with different insert thicknesses.

orifice plate due to barium that has diffused out of the orifice



Figure 12. Calculated cathode lifetime in kWhrs versus the discharge current for the 2 cm diameter LaB₆ cathode and a 2 cm diameter NEXIS cathode with different insert thicknesses.

through the potential drop in the hollow cathode. Figure 13 shows the plasma potential profile inside the hollow cathode measured by a fast scanning probe¹⁹. The potential drop in the hollow cathode plasma is about 10 V, which is less than the 12 V measured¹⁹ for the NEXIS dispenser cathode. This is primarily attributed to the slightly smaller inside diameter of the LaB₆ cathode compared to the NEXIS cathode insert, which reduces the radial voltage drop from the plasma axis to the insert wall. This is the same effect found for the NSTAR 1/4" cathode, where the internal voltage drop is typically found to be only about 6 V.

The power deposited in the cathode during the self-heating mode can be estimated to first order to be the discharge current times the plasma potential drop inside the insert region. The NSTAR cathode in the high current mode then drops about 78 W in the cathode, while the 1.5 cm diameter cathodes drop on the order of 250 W in the cathode. This is the source of the power that keeps the LaB₆ cathode at emission temperature. The NEXIS cathode drops nearly 300 W at 25 A of discharge current, which is even higher. However, this cathode is not as well heat shielded as the LaB₆ cathode, and probably requires more self-heating power to maintain its temperature.

250 kWhrs of life at 50 A, and over 100 kWhrs of life at 75 A of discharge current. The LaB₆ cathode, of course, provides this life with the much high tolerance to feed gas impurities as discussed in Section II.

The LaB₆ cathode operates at several hundred degrees higher temperature than the dispenser cathode, and an effort was made to understand the starting mechanism and how the emitter temperature is produced during self-heated operation. Of primary importance is proper heat shielding of the heater, which requires multiple wraps of thermal insulation outside the heater coils to minimize the amount of heater power needed to start the cathode. Dispenser cathode discharges start by vacuum thermionic emission from the front of the cathode and activated the surface. This process requires time for the diffusion and surface chemistry to activate the surface and initiate emission. At a sufficient emission current, the ionization of the gas in the cathode to keeper gap provides plasma into the orifice and starts the discharge. The LaB₆ cathode, in comparison, does not have a mechanism for the orifice plate to become emitting. However, the relatively large orifice diameter used in high current hollow cathodes permits a small amount of electric field to penetrate the insert region and extract electrons. The discharge current increases in direct proportion to the externally heated insert temperature until the discharge heating becomes significant. The discharge couples directly from the insert to the keeper and anode.

Once the discharge has started, the heating of the insert is achieved by the discharge current flowing

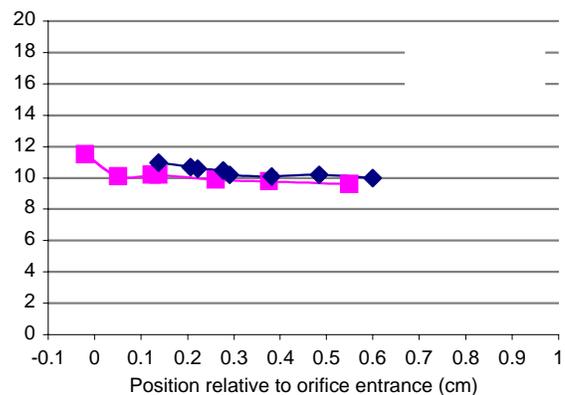


Figure 11. Plasma potential measured on axis inside the hollow cathode relative to the orifice upstream entrance for two gas flows at 25 A discharge current.

VI. Conclusion

Two high current hollow cathodes have been fabricated and tested for high power ion thruster and Hall thruster applications. The 1.5 cm NEXIS hollow cathode demonstrated stable discharge operation at currents up to 50 A. The new LaB₆ cathode demonstrated stable discharge currents of up to 60 A, which was the limit of the existing power supply. The successful procurement of a new higher temperature sheathed heater for this cathode makes fabrication for the cathode assembly similar to conventional dispenser hollow cathodes. The LaB₆ emitter is very simple to operate, with no conditioning or activation procedures required. In the near future we plan to run the 1.5 cm LaB₆ cathode at up to 100 A, and start testing the 2 cm cathode.

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