JOURNAL OF PROPULSION AND POWER
Vol. 23, No. 3, May–June 2007

LaB_6 Hollow Cathodes for Ion and Hall Thrusters

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DOI: 10.2514/1.25475

Deep space missions and satellite station-keeping applications continue to demand higher power ion thrusters and Hall thrusters capable of providing high thrust and longer life. Depending on the thruster size, the hollow cathodes may be required to produce discharge currents in the 10–100 A range with lifetimes in excess of 10 years. A lanthanum hexaboride (LaB_6) hollow cathode has been developed for space applications to increase the current capability from the cathode and ease the handling and gas purity requirements. This cathode uses a LaB_6 insert in an all-graphite hollow cathode structure with an integral graphite keeper. Three different sizes of the LaB_6 cathode have been successfully operated at discharge currents of up to 100 A to date. Although the LaB_6 cathode insert operates at a higher temperature than the conventional BaO dispenser cathode, LaB_6 offers the capability of long life and orders of magnitude less sensitivity to propellant impurities and air exposure than conventional dispenser cathodes.

Nomenclature

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

I. Introduction

NASA and the commercial aerospace industry have spent the last 40 years developing, testing, and flying barium-oxide impregnated dispenser cathodes in ion thrusters, Hall thrusters, plasma contactors, and plasma neutralizers. However, over 100 Russian Hall thrusters have been flown over the last 35 years with lanthanum hexaboride (LaB_6) hollow cathodes [1,2]. In addition, LaB_6 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 other applications. The major reason for using LaB_6 cathodes, compared to conventional impregnated dispenser cathodes, is the incredible robustness, high-current density and long life exhibited by LaB_6 electron emitters. Lanthanum hexaboride cathodes are routinely used in all noble gases from helium to xenon, reactive gases including hydrogen and oxygen, and various other materials including liquid metals such as bismuth. The authors have successfully operated LaB_6 cathodes continuously at emission current densities exceeding 20 A/cm^2, in pure oxygen and nitrogen plasma discharges, and vented operating LaB_6 cathodes to water (from cooling lines breaking) and air without damaging the cathode. Although not used for space applications in the U.S., the space heritage of lanthanum hexaboride cathodes in Russian thrusters is considerable, and the industrial experience in dealing with the higher operating temperatures and materials compatibility issues is extensive. This provides an impetus for examining LaB_6 cathodes for space applications in the U.S.

Typical conventional space hollow cathodes use a porous tungsten insert that is impregnated with an emissive mix of barium and calcium oxides and alumina [3,4]. This configuration is called a dispenser cathode because the tungsten matrix acts as a reservoir for barium that is "dispensed" from the pores to activate the emitter surface. Chemical reactions in the pores or at the surface 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 2.06 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 and storage of these cathodes to avoid poisoning by water vapor and impurities in the gas that can shorten the lifetime or even prevent cathode emission. One of the major drawbacks of using BaO dispenser cathodes in electric propulsion applications is the extremely high feed gas purity presently specified by NASA and commercial ion thruster manufacturers to avoid these poisoning issues, which has resulted in a special "propulsion-grade" xenon with 99.9995% purity and extensive spacecraft feed system cleaning techniques to be required.

Lanthanum hexaboride [5], on the other hand, is a crystalline material made by press sintering LaB_6 powder into rods or plates and then machining the material to the desired shape. Polycrystalline LaB_6 cathodes have a work function of about 2.67 eV depending on the surface stoichiometry [6], and will emit over 10 A/cm^2 at a temperature of 1650°C. Because the bulk material is emitting, there is no chemistry involved in establishing the low work function surface and LaB_6 cathodes are insensitive to impurities and air exposures that would normally destroy a BaO dispenser cathode. In addition, the cathode life is determined primarily by the evaporation rate of the bulk LaB_6 material at typical operating temperatures [5,7]. The higher operating temperature of LaB_6 and the need to support and make electrical contact with LaB_6 with compatible materials has perhaps unjustly 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 for electric propulsion applications. Three different sizes of the basic cathode design have been built and tested to date to provide various current ranges and to fit into different thruster sizes. The design uses a LaB_6 insert in an all-graphite hollow cathode structure with an integral graphite keeper. The smaller version of this cathode has been

Presented as Paper 4239 at the 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Tucson, Arizona, 10–13 July 2005; received 28 May 2006; revision received 30 November 2006; accepted for publication 1 December 2006.

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operated in xenon from 7.5 to 60 A continuously, and the larger versions tested at discharge currents of up to 100 A. In this paper, the characteristics of lanthanum hexaboride and the hollow cathode using this material are described and compared to similar sized dispenser cathodes. In addition, first-order life estimates for the two types of cathodes are shown.

II. LaB_6 Characteristics

Lanthanum hexaboride was first developed as an electron emitter by Lafferty [5] in the 1950s. The thermionic emission of lanthanum-boron compounds as a function of the surface stoichiometry was extensively studied by several authors [6–9]. The first flight of Russian stationary plasma thruster (SPT) Hall thrusters [2] in 1971, and all subsequent flights, used lanthanum hexaboride cathodes. The first reported use of LaB_6 in the U.S. in a hollow cathode was by Goebel et al. [10] in 1978, and the development of a high-current LaB_6 cathode for plasma sources that dealt with supporting and making electrical contact with the material was described by Goebel et al. [11] in 1985. The lanthanum-boron system can consist of combinations of stable LaB_4, LaB_6, and LaB_9 compounds, with the surface color determined [8] by the dominate compound. The evolution of LaB_4 to LaB_9 compounds is caused either by preferential sputtering of the boron or lanthanum atoms at the near surface by energetic ion bombardment [8], or by preferential chemical reactions with the surface atoms [7]. Lanthanum-boride compounds, heated to in excess of 1000°C in vacuum, evaporate their components at a rate that produces a stable $LaB_{6.0}$ surface.

Thermionic emission by these cathode materials is well described by the Richardson–Dushman equation [12]:

$$J = AT^2 e^{\frac{-e\phi}{kT}} \tag{1}$$

where A is a universal constant with a value of 120 $A/cm^2 \cdot K^2$. 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 form [13]

$$\phi = \phi_0 + \alpha T \tag{2}$$

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

$$J = Ae^{\frac{-e\alpha}{k}} T^2 e^{\frac{-e\phi_0}{kT}} = DT^2 e^{\frac{-e\phi_0}{kT}} \tag{3}$$

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

Several different work functions have been reported in the literature for LaB_6. This is primarily due to varying use of A or D in Eq. (3), variations in the surface stoichiometry [6], or due to different crystal orientations in single-crystal emitters used for some applications [9]. For hollow cathode and large area emitter applications, the press-sintered LaB_6 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. The emission current density calculated from Eq. (3) for the materials in Table 1 are plotted in Fig. 1 as a function of emitter temperature. Amazingly, the actual emission current density of LaB_6 predicted by the different authors in Table 1 is within about 25% for the different values of A, D, and ϕ used. We see that the LaB_6 operates at several hundred degrees higher temperature than the BaO-W dispenser cathode for the same emission current density. The LaB_6 temperature is also significantly lower than the typical refractory metal emitters used for filaments in some plasma discharges.

Table 1 Work function and Richardson coefficients for different cathode materials

	A	D	ϕ
BaO-W 411 (Cronin [3])	120		$1.67 + 2.82 \times 10^{-4}$ T
Bao-W 411 (Forrester [13])		1.5	1.56
LaB_6 (Lafferty [5])		29	2.66
LaB_6 (Jacobson and Storms [8])		110	2.87
LaB_6 (Storms and Mueller [6])	120		2.91
LaB_6 (Kohl [14])	120		$2.66 + 1.23 \times 10^{-4}$ T
Molybdenum (Kohl [14])		55	4.2
Tantalum (Kohl [14])		37	4.1
Tungsten (Kohl [14])		70	4.55

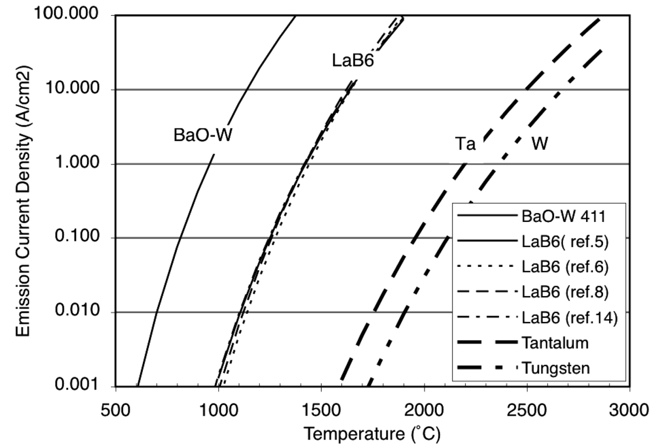

Fig. 1 Emission current density versus temperature.

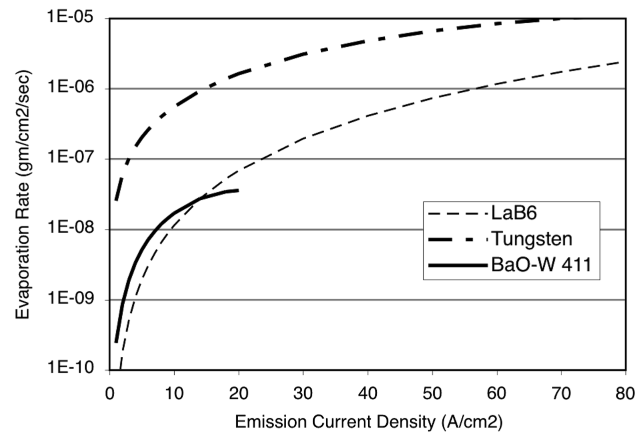

Fig. 2 Evaporation rate of LaB6 compared to tungsten and type-B dispenser cathodes.

Lanthanum hexaboride offers long lifetimes because the evaporation rate is significantly lower than for refractory metals. Figure 2 shows the evaporation rate of LaB_6 and tungsten as a function of the emission current density [14,15]. LaB_6 evaporation is more than 1 order of magnitude lower when compared to tungsten at the same emission current density. For comparison, the evaporation rate of BaO from a type-S 411 dispenser cathode [4] is also shown. In spite of operating at a significantly higher temperature, the LaB_6 has a lower evaporation rate than the impregnate material in dispenser cathodes until the emission current exceeds about 15 A/cm^2. This illustrates why the LaB_6 cathodes life is usually better because there is more material in the bulk LaB_6 than in the impregnated pores of dispenser cathodes, and the evaporation rate is lower or comparable up to about 20 A/cm^2.

Lafferty pointed out in his original 1951 paper [5] that LaB_6 must be supported by materials that inhibit diffusion of boron into the support material, which would embrittle most of the contacting refractory metals that can be used at the higher operating temperatures of LaB_6 and lead to structural failure. In addition, the crystalline LaB_6 is susceptible to breakage from mechanical stress when clamped and from thermal shock. Several authors have supported LaB_6 with carbon [10], tantalum carbide [5,15], and

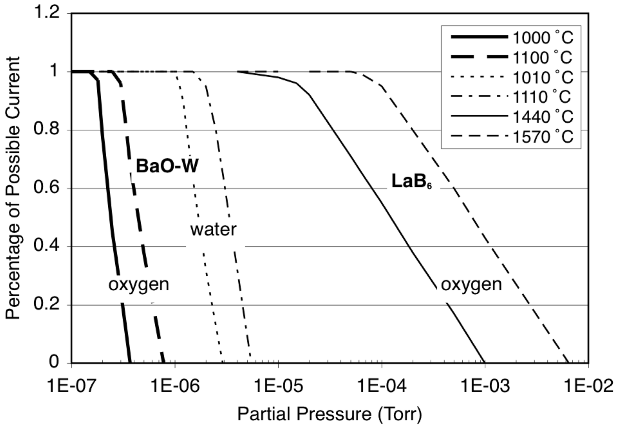

Fig. 3 Percentage of possible thermionic emission versus partial pressure of oxygen and water showing the poisoning of dispenser cathodes relative to LaB_6 cathodes.

rhenium [16] to avoid this problem, or constructed support structures with the interface material at lower temperatures [17]. Fine-grain graphite has a slightly larger coefficient of thermal expansion [14] than LaB_6 and provides good electrical contact and low stress support [10,11] without significant boron diffusion or boride formation. For this reason, the hollow cathodes described here use a graphite tube with a LaB_6 insert.

Comprehensive investigations into the poisoning of dispenser cathodes [18] and LaB_6 cathodes [19] have been published in the literature. The most potent poisons for both cathodes are oxygen and water, with other gases such as CO_2 and air causing poisoning at higher partial pressures. As mentioned previously, LaB_6 is significantly less sensitive to impurities that tend to limit the performance and life of the barium dispenser cathodes. This is illustrated in Fig. 3, where the fraction of the possible thermionic emission given by Eq. (3) for a dispenser cathode and LaB_6 is plotted as a function of the partial pressures of oxygen and water for two different emitter temperatures. The curve for water poisoning [19] of LaB_6 is off the graph to the right at much higher partial pressures. 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 vacuum electron emission. In a similar manner, water vapor at partial pressures below 10^{-5} torr will poison dispenser cathodes at temperatures below 1110°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, resulting in the high propulsion-grade purity mentioned previously.

In comparison, LaB_6 at 1570°C, where the electron emission current density is nearly the same as for the dispenser cathode at 1100°C, can withstand oxygen partial pressures up to 10^{-4} torr without degradation in the electron emission. This means that LaB_6 can tolerate 2 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 commercially available (≈99.99% purity) without affecting the LaB_6 electron emission or life. Lanthanum hexaboride cathodes also do not require any significant conditioning, activation, or purging procedures that are normally required by dispenser cathodes. This robustness makes the handling and processing of thrusters that use LaB_6 cathodes significantly easier than electric propulsion devices that use dispenser cathodes.

III. Experimental Configuration

Lanthanum hexaboride hollow cathodes for space applications can be configured in a geometry similar to conventional space dispenser hollow cathodes, which basically consists of an active thermionic insert placed inside a structural cathode tube wrapped by a heating element and heat shields. However, LaB_6 cathodes typically need more heater power to achieve the higher emission temperatures. BaO dispenser cathodes commonly use a coiled tantalum sheathed heater [20,21] that uses a magnesium-oxide powder insulation. This insulation material has a maximum operation temperature typically less than 1400°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 [21]. To first demonstrate the LaB_6 cathode performance, a tantalum heater wire was strung through alumina fish-spine beads and wrapped in a noninductive coil around the hollow cathode tube. Although only a laboratory tool, this heater could provide over 250 W of power to heat the cathode, and initial tests successfully used this heater. Subsequently, a tantalum sheathed heater that incorporated high-temperature alumina power insulation was procured [22] and used to heat the LaB_6 cathode. This geometry is common in industrial metal furnace heaters and can be found in the standard catalog of several companies. The heater catalogs indicate that the alumina insulation has a maximum temperature of about 1800°C, which is well in excess of the temperature required to start the LaB_6 cathode.

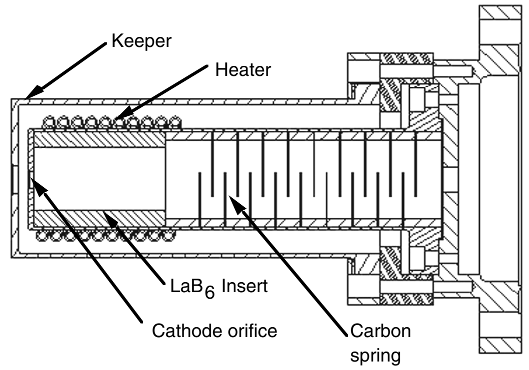

Fig. 4 Schematic representation of the 1.5-cm diam LaB_6 hollow cathode.

As mentioned above, the structural cathode tube in contact with the LaB_6 insert is made of graphite because it has a similar coefficient of thermal expansion [16,23] as LaB_6, and fabrication of the entire hollow cathode tube out of a single piece of Poco graphite is straightforward. The keeper electrode used to start the discharge is also fabricated from Poco graphite. Figure 4 shows a schematic cross section of the LaB_6 cathode with a 1.5-cm outside diameter (O.D.) graphite tube. The cathode tube has a wall thickness of 0.1 cm, and the LaB_6 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 cm^2, which according to Fig. 1 can produce emission currents of 100 A at temperatures of about 1700°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 LaB_6 and makes the cathode electrodes robust against ion sputtering in xenon discharges due to the low

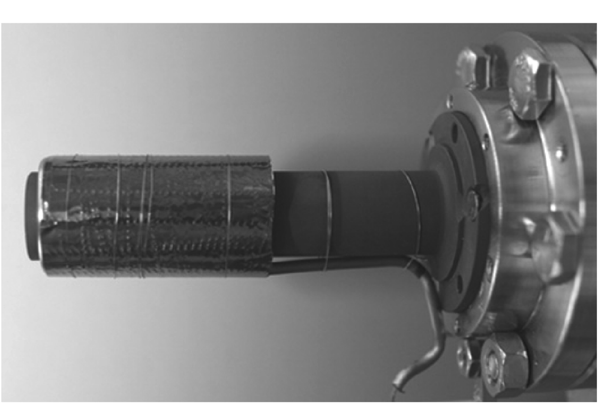

Fig. 5 Photograph of the 1.5-cm LaB_6 hollow cathode with the sheathed heater mounted on the test fixture.

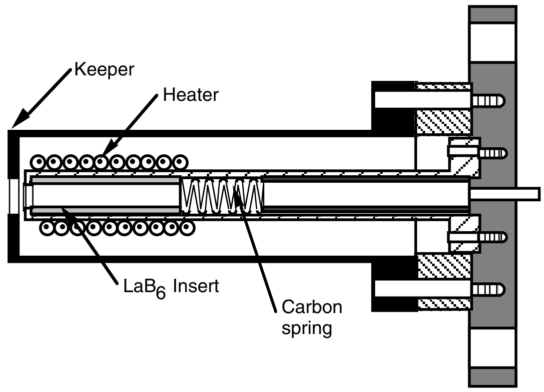

Fig. 6 Compact version of the LaB_6 cathode with a 0.8-cm diam graphite cathode tube and a 0.38-cm diam insert I.D.

erosion yield [24] compared to the refractory metals used in conventional cathodes. The carbon cathode tube and the carbon keeper are bolted to support and insulating flanges that are attached to the gas feed system and the power supply electrical leads. Figure 5 shows a photograph of the 1.5-cm LaB_6 cathode mounted on the test fixture with the alumina-insulated Ta-sheathed heater and heat shielding around the cathode tube.

Two additional cathode sizes were also fabricated from this basic design. First, a larger diameter cathode with more insert surface area was designed to provide higher discharge currents. This cathode features a 2-cm diam graphite cathode tube with the same tube wall and insert thicknesses as the 1.5 cm cathode. The mounting and spring geometry are also the same as the 1.5 cm cathode. In addition, a smaller cathode with a cathode tube O.D. of 0.8 cm was fabricated. A schematic cross section of the 0.8 cm cathode is shown in Fig. 6. This cathode is intended to run in smaller thrusters and operates at lower discharge currents, and so features a longer, thinner cathode tube to minimize heat conduction from the insert to the base and extra heat shielding around the insert region. The insert in the 0.8 cm cathode has an inside diameter (I.D.) of 0.38 cm, identical to the cathode. All of the cathodes used cathode orifice diameters of 0.38 cm and keeper orifice diameters of 0.64 cm. In the case of the 0.8 cm cathode, the orifice and insert I.D. were the same. Discharge current and voltage changes in the larger cathodes with several different cathode orifices and keeper orifices were previously reported [25].

All three cathodes were operated in the Jet Propulsion Laboratory (JPL) cathode test facility [26]. The experimental configuration is illustrated in Fig. 7. The cathodes were installed in a 1-m diam by 2-m-long vacuum system with 1250 l/s xenon pumping speed from two cryopumps, and mounted on a scanning probe assembly used to measure the density, temperature, and potential inside the hollow cathode in the insert region [27]. A solenoid coil is positioned around the keeper electrode to provide an adjustable axial magnetic field at the cathode exit. The anode consists of a water-cooled cone connected directly to a straight cylindrical section to simulate an ion thruster discharge chamber. Rings of permanent magnets are attached to the outside of the anode to provide some magnetic confinement of the plasma electrons to improve the ionization efficiency in the anode region. This produces discharge voltages in the 20–30 V range, depending on the current and gas flow rate, which is characteristic of thruster discharges. Several scanning probes are mounted in the chamber to provide plasma profiles in the anode region, which are not reported here. A complete description of the facility is available in [26,27].

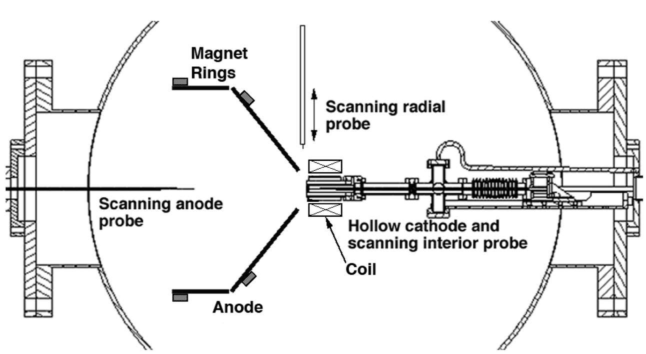

Fig. 7 Cathode test facility showing centrally mounted LaB_6 cathode, magnet rings, and anode arrangement.

IV. LaB_6 Cathode Performance

After installation in the test facility, the system was pumped down into the 10^{-6} torr range and the cathode heater turned on for 5–10 min. The cathode discharge was then started by initiated the xenon gas flow through the cathode, applying 150 V to the keeper electrode and turning on the anode power supply. Once the anode discharge current exceeded about 10 A, the keeper power supply was turned off and the keeper was allowed to float. Figure 8 shows the discharge voltage versus discharge current measured for all three cathodes in the same test configuration at 9 sccm (standard cubic centimeters per minute) xenon flow. The two larger cathodes had essentially identical discharge performance characteristics and were tested at currents up to 100 A. A reduction in the cathode gas flow to 7 sccm limited the discharge current to about 60 A, above which significant discharge voltage oscillations were observed. At discharge currents below 20 A, the discharge voltage was observed to increase slightly and the larger cathodes tended to cool off and stop operating at currents below 10 A. This is because the self-heating mechanism in the hollow cathode depends on the discharge current level, and the

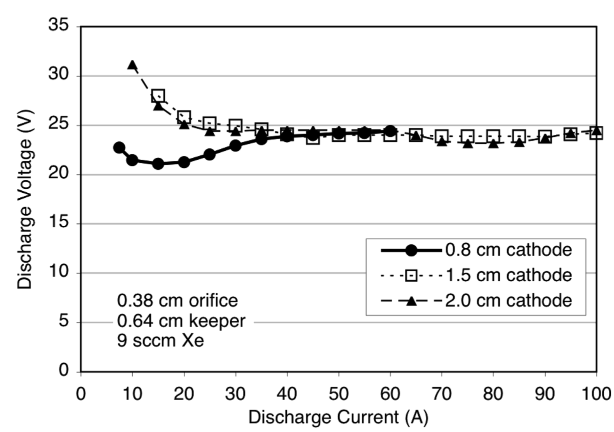

Fig. 8 Discharge current and voltage for three LaB_6 cathodes at 9 sccm xenon gas flow.

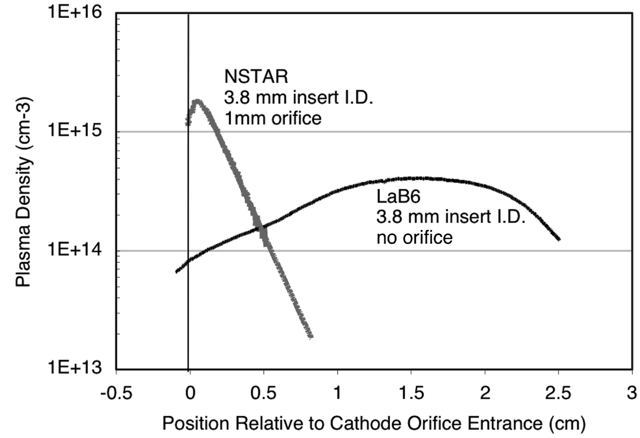

Fig. 9 Plasma density comparison in the insert region for the NSTAR and LaB_6 hollow cathodes at the TH15 throttle point of 13 A discharge current.

lower current levels provided insufficient heating in these cathodes to maintain the insert temperature. In this case, the voltage drop in the cathode plasma increases to provide sufficient heating, which increases the measured discharge voltage.

The smaller 0.8 cm cathode was operated from a discharge current of about 7–60 A. As shown in Fig. 8, the discharge voltage did not in this case increase until the discharge current fell below 10 A. This occurs because this cathode is designed with the longer graphite tube to reduce heat loss to the mounting structure, and the smaller cathode size reduces the radiation heat loss area, making it easier for the self-heating mechanism to maintain the insert temperature at low currents. Because the insert interior surface area is 3 cm^2, this insert is capable of emitting 20 A/cm^2 for a total of 60 A of emission current at a temperature of 1700°C. These emission current densities and discharge currents are routinely achieved with LaB_6 cathodes [10,11]. Likewise, the 1.5-cm diam cathode has 5 cm^2 of exposed insert area, and so is capable of producing the measured 100 A of discharge current at this same emission current density and temperature. The 2-cm diam cathode has 10 cm^2 of insert area and is capable of 200 A of emission. Power supply limitations precluded testing to currents above 100 A.

To understand the electron emission processes of the LaB_6 insert in these hollow cathodes, plasma density profiles were taken by the interior scanning probe and compared to that obtained with a conventional dispenser cathode. Figure 9 shows the plasma density profile at 13 A and 3.7 sccm of xenon flow obtained with the 0.8-cm diam LaB_6 cathode (with no orifice) and with the NSTAR dispenser cathode [26] with a 1-mm diam orifice. The insert I.D. and length are identical in these two cathodes. The small orifice in the NSTAR cathode increases the pressure in the insert region, which pushes the plasma close to the orifice plate [28] and limits the contact length with the insert. In this case, only the first few millimeters of the insert are emitting current [28], and most of the power is deposited near the orifice creating a large temperature gradient along the insert [29], which further limits the electron emission away from the orifice. In contrast, the plasma profile in the LaB_6 cathode is very broad, and the plasma is in contact with the entire insert length. In addition, the plasma density is sufficient all along the insert length to avoid space-charge limitations on the emitted electron current density well in excess of 20 A/cm^2. Therefore, the insert is operating in the thermally limited emission regime and the emission will be fairly uniform along the insert length if the temperature is constant. Increases in discharge current and gas flow rate tend to push the plasma density peak toward the orifice, further flattening the profile. Because the plasma is in contact with the entire insert and LaB_6 has a good thermal conductivity [14], the temperature variation along the insert is small and the emission fairly uniform. Similar broad density profiles were observed with the 1.5 cm cathode at discharge currents up to about 40 A, indicating that the plasma is in good contact with the entire insert length. Higher discharge currents than this tended to melt the probe, but the trend of the plasma being in contact with essentially the entire insert length did not change significantly as the current increased.

V. Discussion

A. Cathode Life

It is useful to discuss the expected life of LaB_6 hollow cathodes. The life of a LaB_6 cathode in vacuum is determined [5,7,14,15,17] by the evaporation rate of the material and the size of the cathode. In plasma discharges, sputtering of the LaB_6 surface can also impact the life [11]. However, as in a dispenser hollow cathode, the plasma potential is very low in the insert region and the bombardment energy of xenon ions hitting the surface is typically less than 20 V, which virtually eliminates sputtering of the cathode surface. The low plasma potential inside the LaB_6 cathodes is shown in Fig. 10, where the potential on axis in the insert region is measured by the scanning probes for two discharge cases for two of the cathodes. The potential on axis remained well below 20 V for all the cases we investigated and tends to decrease as the discharge current and flow rate increases. This is consistent with the self-heating mechanism of the hollow cathode in that less potential drop is required to heat the cathode as the discharge current increases. Because the potential inside hollow cathodes is so low, we can neglect the ion sputtering and estimate the cathode life based on evaporation. It is assumed that the evaporated material leaves the cathode and does not recycle to renew the insert surface, which will provide a lower estimate of the insert life than might actually exist. Interestingly, as the insert evaporates the inner diameter increases and the surface area enlarges. This causes the required current density and temperature to decrease at a given discharge current, which reduces the evaporation rate of the insert.

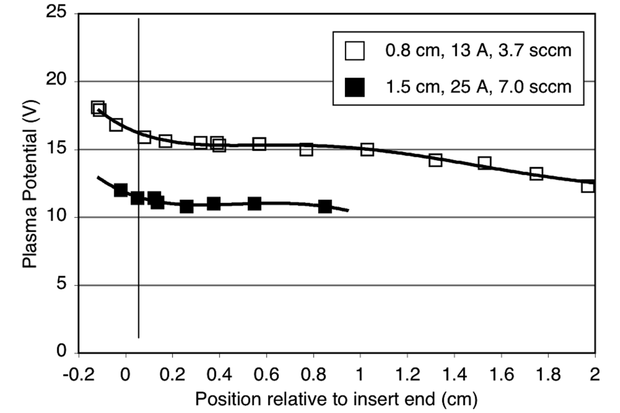

Fig. 10 Plasma potential measured on axis inside two of LaB_6 hollow cathodes relative to the orifice upstream entrance for two discharge conditions.

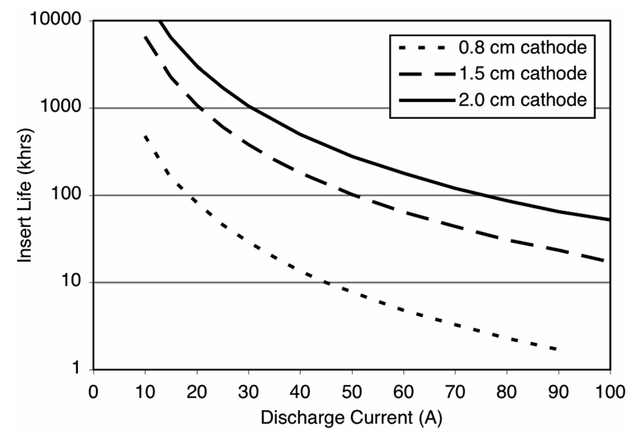

Fig. 11 Calculated cathode lifetime in thousands of hours versus the discharge current for three different cathode diameters presented here.

The life of the LaB_6 insert for the three different cathode sizes described here versus discharge current was calculated based on the evaporation rate at the temperature required to produce the discharge current in the thermally limited regime observed here. Assuming that 90% of the insert can be evaporated, the cathode life is shown in Fig. 11 as a function of the discharge current. Lifetimes of tens of thousands of hours are possible, and the larger cathodes naturally tend to have longer life. Although other mechanisms, such as temperature variations along the insert or LaB_6 surface removal or material buildup due to impurities in the gas, can potentially reduce the life, redeposition of the evaporated LaB_6 material will tend to extend the cathode life. Therefore, these life estimates are mostly valid relative to each other, and the actual life of the cathode can be considered to be on the order of the values calculated in Fig. 11.

To obtain an idea of the life of a LaB_6 cathode relative to a conventional dispenser cathode, the predictions from a dispenser cathode life model [30] applied to the NSTAR cathode are compared to the 0.8 cm cathode life predictions in Fig. 12. These two cathodes have similar insert diameters and lengths and so a direct comparison is reasonable. The dispenser cathode calculation assumes that barium evaporation from the insert surface causes depletion of nearly all of

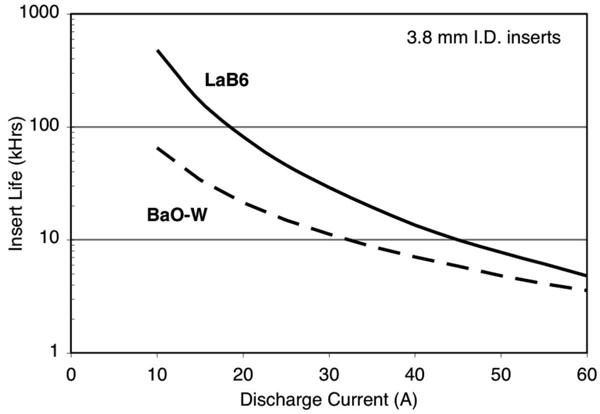

Fig. 12 Comparison of the calculated cathode lifetime versus the discharge current for the 0.8 cm O.D. LaB_6 cathode and the NSTAR dispenser cathode.

the barium impregnate at the end of life in the NSTAR dispenser cathode at the measured [31] insert temperature and temperature gradient. This provides an upper limit to the dispenser cathode life if other mechanisms such as poisoning or degrading the work function impurity buildup plugging the pores actually causes the cathode life limits. Likewise, recycling of the barium will extend the dispenser cathode life, so uncertainties in the dispenser cathode life estimates by this model have the same uncertainties due to impurities and redeposition that are found for the LaB_6 life model (although LaB_6 is less likely to be affected by impurities). Therefore we will show a direct comparison of calculated life versus discharge current and realize that the curves will likely shift together vertically due to impurity or redeposition issues. We see that the LaB_6 cathode life is projected to exceed the dispenser cathode life by nearly an order of magnitude at the nominal NSTAR full power currents of less than 15 A. Assuming that the NSTAR cathode can produce higher discharge currents, the LaB_6 cathode life is projected to exceed the NSTAR over the full current range demonstrated by this cathode. As seen in Fig. 11, the larger LaB_6 cathodes will have even longer lifetimes, and their life significantly exceeds that projected for the NEXIS 1.5-cm diam dispenser cathode [30] that is designed to operate up to about 35 A.

B. Cathode Heating and Startup

Because the LaB_6 cathode operates at several hundred degrees higher temperature than the dispenser cathode, 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 cathode heater, which requires multiple wraps of thermal insulation outside the heater coils to minimize the amount of power required to start the cathode. Initially, the 1.5 cm cathode required 234 W of heater power to ignite. The heat shielding on the outside of the heater was improved and elongated to better shield the graphite tube, and the required heater power for ignition dropped to about 160 W. The 0.8 cm cathode was designed with the longer cathode tube and heat shield and also included more layers of heat shielding to reduce the required heater power to 125 W.

Dispenser cathode discharges start by vacuum thermionic emission from the front of the cathode orifice plate [32] due to barium that has diffused out of the orifice 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 the keeper gap provides plasma that flows into the orifice, couples to the insert region, and starts the plasma discharge. The LaB_6 cathode, in comparison, does not have a mechanism for the orifice plate to become emitting. However, the relatively large orifice diameter (or lack of an orifice) used in high-current hollow cathodes permits a small amount of electric field to penetrate the insert region and extract electrons. Ignition of the discharge by coupling directly from the insert to the keeper and anode was readily achieved through the relatively large orifices (0.18–0.4 cm diam) tested with these cathodes. The observed discharge current increased in direct proportion to the external heater power until the discharge self-heating became significant.

Once the discharge has started, the heating of the insert is achieved by the discharge current flowing through the potential drop in the hollow cathode. Higher discharge currents tend to reduce the potential drop in the cathode, which was shown in Fig. 10 and calculated from a series of performance measurements on the LaB_6 cathode in the ion thruster simulator [33]. This work showed that the 0.8 cm LaB_6 cathode provided comparable performance as the NSTAR dispenser cathode in terms of the number of ions produced in the thruster when the discharge current exceeded about 10 A. Below this current, the discharge voltage and internal voltage drop in the LaB_6 cathode was observed to increase, which degrades the performance. In general, LaB_6 cathodes work as well in the plasma discharges provided that the current was sufficient to enable efficient self-heating.

VI. Conclusions

Three high-current hollow cathodes have been fabricated and tested for high power ion thruster and Hall thruster applications. The new 1.5-cm LaB_6 cathode demonstrated stable discharge currents up to 100 A to date. For applications that need discharge currents in the range of 10–60 A, the 0.8 cm cathode designed without an orifice runs stably and appears to perform comparably to dispenser cathodes in terms of voltage drop and plasma generation. A 2-cm LaB_6 cathode was also designed and run in our test facilities at discharge currents up to 100 A, and discharge currents of up to 200 A appear possible with this cathode. The 2-cm cathode was also run successfully on a Hall thruster [34] at discharge currents up to 40 A, and demonstrated low coupling voltages at the nominal flows in the thruster. Operation at discharge currents below about 10 A appears problematic for the sizes of LaB_6 cathodes investigated here, although smaller cathodes could be fabricated to run at low current. The LaB_6 hollow cathode is very simple to operate, with no conditioning or activation procedures required, and has the promise of less sensitivity to the propellant gas impurity levels and long lifetimes.

Acknowledgment

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

[1] Arkhopov, B. A., and Kozubsky, K. N., "The Development of the Cathode Compensators for Stationary Plasma Thrusters in the USSR," IEPC Paper 91-023, 1991.

[2] Kim, V., "Electric Propulsion Activity in Russia," IEPC Paper 2001-005, 2001.

[3] Levi, R., "Improved Impregnated Cathode," *Journal of Applied Physics*, Vol. 26, No. 3, March 1955, p. 639.

[4] Cronin, J. L., "Modern Dispenser Cathodes," *IEE Proceedings*, Vol. 128, No. 1, Feb. 1981, pp. 19–32.

[5] Lafferty, J. M., "Boride Cathodes," *Journal of Applied Physics*, Vol. 22, No. 3, March 1951, pp. 299–309.

[6] Storms, E., and Mueller, B., "A Study of Surface Stoichiometry and Thermionic Emission Using LaB_6, *Journal of Applied Physics*, Vol. 50, No. 5, May 1979, pp. 3691–3698.

[7] Storms, E., and Mueller, B., "Phase Relationship, Vaporization and Thermodynamic Properties of the Lanthanum-Boron System," *Journal of Chemical Physics*, Vol. 82, No. 1, Jan. 1978, pp. 51–59.

[8] Jacobson, D., and Storms, E. K., "Work Function Measurement of Lanthanum-Boron Compounds," *IEEE Transactions on Plasma Science*, Vol. 6, No. 2, June 1978, pp. 191–199.

[9] Pelletier, J., and Pomot, C., "Work Function of Sintered Lanthanum Hexaboride," *Applied Physics Letters*, Vol. 34, No. 4, Feb. 1979, pp. 249–251.

[10] Goebel, D. M., Crow, J. T., and Forrester, A. T., "Lanthanum

Hexaboride Hollow Cathode for Dense Plasma Production," *Review of Scientific Instruments*, Vol. 49, No. 4, April 1978, pp. 469–472.
[11] Goebel, D. M., Hirooka, Y., and Sketchley, T., "Large Area Lanthanum Hexaboride Electron Emitter," *Review of Scientific Instruments*, Vol. 56, No. 9, Sept. 1985, pp. 1717–1722.
[12] Richardson, O. W., "Electron Theory of Matter," *Phillips Magazine*, Vol. 23, 1912, pp. 594–627.
[13] Forrester, A. T., *Large Ion Beams*, Wiley–Interscience, New York, 1988.
[14] Kohl, W. H., *Handbook of Materials and Techniques for Vacuum Devices*, Reinhold, New York, 1967.
[15] Leung, K. N., Pincosy, P. A., and Ehlers, K. W., "Directly Heated Lanthanum Hexaboride Filaments," *Review of Scientific Instruments*, Vol. 55, No. 7, July 1984, pp. 1064–1068.
[16] Favreau, L. J., "Cataphoretic Coating Lanthanum Boride on Rhenium Filaments," *Review of Scientific Instruments*, Vol. 36, No. 6, June 1965, pp. 856–857.
[17] Boers, A. N., "Electron Gun Using Long-Life Lanthanum Hexaboride Cathode," *Journal of Applied Physics*, Vol. 38, No. 4, 1967, pp. 1991–1992.
[18] Cronin, J. L., "Practical Aspects of Modern Dispenser Cathodes," *Microwave Journal*, Sept. 1979.
[19] Gallagher, H. E., "Poisoning of LaB_6 Cathodes," *Journal of Applied Physics*, Vol. 40, No. 1, Jan. 1969, pp. 44–51.
[20] Soulas, G. C., "Status of Hollow Cathode Heater Development for the Space Station Plasma Contactor," AIAA Paper 1994-3309, 1994.
[21] Tighe, W. G., Freick, K., and Chien, K. R. "Performance Evaluation and Life Test of the XIPS Hollow Cathode Heater," AIAA Paper 2005-4066, 2005.
[22] Catalog item from Idaho Labs, Idaho Falls, ID.
[23] Chen, C.-H., Aizawa, T., Iyi, N., Sato, A., and Otani, S., "Structural Refinement and Thermal Expansion of Hexaborides," *Journal of Alloys and Compounds*, Vol. 366, No. 1–2, 2004, pp. L6–L8.
[24] Doerner, R., White, D., and Goebel, D. M., "Sputtering Yield Measurements During Low Energy Xenon Plasma Bombardment," *Journal of Applied Physics*, Vol. 93, No. 9, May 2003, pp. 5816–5823.
[25] Goebel, D. M., and Watkins, R., "LaB_6 Hollow Cathodes for Ion and Hall Thrusters," AIAA Paper 2005-4239, 2005.
[26] Goebel, D. M., Jameson, K., Watkins, R., and Katz, I., "Hollow Cathode and Keeper-Region Plasma Measurements Using Ultra-Fast Miniature Scanning Probes," AIAA Paper 2004-3430, 2004.
[27] Jameson, K., Goebel, D. M., and Watkins, R., "Hollow Cathode and Keeper-Region Plasma Measurements," AIAA Paper 2005-3667, 2005.
[28] Mikellades, I., Katz, I., Goebel, D. M., and Jameson, K. K. "Plasma Processes Inside Orificed Hollow Cathodes," *Physics of Plasmas*, Vol. 13, No. 6, 2006, p. 063504.
[29] Mikellides, I., Katz, I., and Goebel, D. M., "Numerical Simulation of the Hollow Cathode Discharge Plasma Dynamics," IEPC Paper 2005-200, 2005.
[30] Goebel, D. M., Katz, I., Polk, J. E., Mikellides, I. G., Jameson, K. K., Liu T., and Dougherty, R., "Extending Hollow Cathode Life for Electric Propulsion in Long-Term Missions," AIAA Paper 2004-5911, 2004.
[31] Polk, J., Grubisic, A., Taheri, N., Goebel, D. M., Downey, R., and Hornbeck, S., "Emitter Temperature Distribution in the NSTAR Discharge Hollow Cathode," AIAA Paper 2005-4398, 2005.
[32] Tighe, W., Chien, K., Goebel, D. M., and Longo, R., "Hollow Cathode Ignition and Life Model," AIAA Paper 2005-3666, 2005.
[33] Polk, J. E., Goebel, D. M., and Jameson, K. K., "Advanced Long-life Hollow Cathode Development at JPL," AIAA Paper 2006-5150, 2006.
[34] Hofer, R. R., Johnson, L. K., Goebel, D. M., and Fitzgerald, D. J., "Effects of an Internally-Mounted Cathode on Hall Thruster Plume Properties," AIAA Paper 2006-4482, 2006.

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