JOURNAL OF PROPULSION AND POWER
Vol. 26, No. 1, January–February 2010

Ignition and Plume Characteristics of Low-Current Cerium and Lanthanum Hexaboride Hollow Cathodes

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DOI: 10.2514/1.41386

This research investigated cerium hexaboride (CeB_6) and lanthanum hexaboride (LaB_6) as emitters in 6.4-mm-diam hollow cathodes used for low-power electric propulsion applications. Each cathode's ignition performance and plume behavior is presented and discussed. Two identical cathodes, with the exception of the insert material, were assembled and integrated into a cylindrical anode configuration without an applied magnetic field. The experiments tested two orifice geometries and a wide range of xenon flow rates (1.5–4.5 sccm) and anode currents (2–6 A) for each cathode. Also investigated was cathode performance for these conditions with the keeper on and off. A langmuir probe collected plume data to include plasma densities, electron temperature, plasma potential, and floating potential. An oscilloscope monitored the voltage behavior of the keeper electrode and anode. Initially, both cathodes successfully started without excessive keeper voltages (<650 V), heating times (<15 min), or flow rates (<4.5 sccm). The LaB_6 cathode consistently started at these same conditions. However, the CeB_6 cathode demonstrated some degradation after time by requiring higher flow rates and a longer heating time to start. Both cathodes demonstrated ideal (spot mode) operation for flow rates as low as 1.5 sccm at anode currents as high as 5 A with no heater or keeper power.

Nomenclature

J_a = anode current, A
J_k = keeper current, A
j = current density, A/cm^2
k = Boltzmann's constant, J/K
q = charge of an electron, C
T = temperature, K
V_a = anode voltage potential, V
V_k = keeper voltage potential, V
φ = surface work function, eV

I. Introduction

RUSSIAN Hall thrusters have used lanthanum hexaboride (LaB_6) as an electron emitter in hollow cathodes for several decades [1]. It has a long, well-documented performance record for Russian electric propulsion applications and worldwide electron microscope applications [2,3]. The United States primarily uses porous tungsten emitters in hollow cathodes impregnated with a mixture of calcium, barium, and aluminum oxides. LaB_6 has a higher work function (2.67 eV), than most impregnated cathodes (2.0 eV).

Despite a higher work function, LaB_6 offers superior resistance to contamination from oxygen and water vapor over impregnated cathodes and does not require any special conditioning for electron emission [4]. The evaporation of LaB_6 is the only limit to the emitter's life, which is lower than the evaporation rate of the impregnate for porous tungsten emitters [5]. Previous research has shown that, under similar conditions, this increased life for LaB_6 emitters is an order of magnitude longer than for dispenser cathode inserts [6]. The work function of the LaB_6 emitter is not affected as the crystal evaporates, which also provides an advantage over impregnated cathodes.

For most of its history, LaB_6 has been a laboratory curiosity in the United States. Goebel et al. demonstrated its use as a hollow cathode emitter in 1979 [7]. This design required high discharge currents (∼100 A) to maintain the self-heating mode. Otherwise, a heater needed to be on for the LaB_6 emitter to maintain sufficient electron emission for the cathode to operate. Until 2005, in the United States, most LaB_6 hollow cathodes could not duplicate the performance of the impregnated cathodes. In 2005, Goebel and Katz [5] modified the LaB_6 cathode design to geometries very similar to impregnated cathodes. Upon doing so, the LaB_6 cathode was able to demonstrate operation from 10 to 100 A of discharge current without requiring heater operation or excessive flow rates and voltages [5]. In addition to poisoning resistance, LaB_6 further proved itself as a viable emitter for ion and Hall thrusters while demonstrating a low evaporation rate for high discharge currents and having a similar emission capability as impregnated cathodes. Three years later, Warner et al. demonstrated that the LaB_6 cathode could operate at discharge currents as low as 3.0 A without any heater or keeper power and maintain comparable flow rates and voltages to impregnated cathodes [8]. These investigations prove that LaB_6 has the potential for use as a high-current and moderately low-current electron emitter.

A possible alternative to LaB_6 is cerium hexaboride (CeB_6). It has a lower work function (2.5 eV) and evaporation rate than LaB_6 [9–11]. It has been used extensively in electron microscopes [3]. Wirz also investigated its use as an emitter for miniature ion thrusters [12]. The first to demonstrate CeB_6 as an electron emitter in a hollow cathode was Warner et al. in 2008 [8]. Using a cathode geometry identical to LaB_6, it was able to run at discharge currents as low as 1.5 A without heater or keeper power. This preliminary investigation provided the possibility that CeB_6 could offer an alternative to LaB_6, provided that it demonstrated the same resistance to poisoning and a lower evaporation rate.

Presented as Paper 1086 at the 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 7–10 January 2008; received 3 October 2008; revision received 5 October 2009; accepted for publication 27 October 2009.

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Because LaB_6 and CeB_6 have demonstrated the capability of operating in the low-current regime, an understanding of their performance as it relates to other cathodes is needed. The major questions addressed here are their ignition power requirements and how they compare to impregnated cathodes. The operating power requirements and plume characteristics are also studied. Other important considerations are the effects of poisoning and the projected lifetime of the insert materials. The plume characteristics and power requirements of these cathodes must be coupled with material behavior, a subject of another investigation completed within this research [13]. This information is critical to determining if LaB_6 or CeB_6 can provide an alternative to traditional U.S. cathodes.

II. Methodology

The facility used to test the hollow cathodes is capable of xenon pumping speeds of up to 16, 000 1/s [13]. An ExTorr® residual gas analyzer that recorded the total and partial pressures of the system while under high vacuum was able to detect elements and compounds ranging from 1 ro 100 AMU. The chamber is 2 m in diameter and 3 m long and constructed from 304L stainless steel. The chamber pressure was maintained at 8.67×10^{-4} Pa $\pm 5\%$ by bleeding in background neutral xenon as needed. Two precision MKS Instruments mass flow controllers calibrated for 0–10 sccm of xenon regulated the flow into each cathode. Grade 5 xenon (99.9995% pure) was used for all testing. The cathode was integrated into a triode configuration consisting of the cathode, the keeper electrode, and the anode to emulate the basic electrical circuit of a thruster; see Fig. 1. The stainless steel anode had a 5.0 cm diameter and 13 cm length. For both cathodes, the orifice of the keeper was aligned with the entrance plane of the cylindrical anode. No applied magnetic field was present.

The cathode was based on a design from previous research by Goebel et al. [14]. It has a molybdenum cathode tube with 12 wraps of an alumina-insulated tantalum-sheathed heater filament. This filament can provide over 140 W of power and operate at temperatures as high as 1800°C, much higher than required for these cathodes [8]. The filament was shielded with 13 layers of 0.127-mm-thick tantalum foil secured by one layer of 0.25 mm tantalum foil. The orifice plate of each cathode was constructed from tantalum. Each orifice plate was 0.25 mm thick and had a 1.0 mm unchamfered orifice. The aspect ratio of the cathode orifice was varied by adding or removing the plates. The LaB_6 cathode had two orifice depths tested (0.25 and 0.5 mm) whereas the CeB_6 had only one tested (0.5 mm). Other than the orifice plate, the insert material was the only variable.

Both cathodes' performances were studied for a range of xenon flow rates (1.5–4.5 sccm), anode currents (2–6 A), and keeper currents (0–1 A). A digitizing oscilloscope recorded anode and keeper voltages. Current was measured through calibrated shunt resistors. A SmartProbe® langmuir probe from Scientific Systems collected plasma densities and potentials. The probe tip diameter was 0.19 mm and its length was 2.41 mm. The cathode was mounted to a translating stage, allowing it to move relative to the probe to collect spatial data along the centerline. The resolution of the recording equipment was at least an order of magnitude smaller than statistical variations in the data captured for all cases. The data capture rates allowed for at least 200 points for each I–V curve and was repeated at each measurement location at least five times [13]. The bias error due to measurement resolution of the diagnostics and the analysis method are discussed further by Warner [13]. This error can be as high as 50% for langmuir probes [15]. The langmuir probe resolution for this research was 0.25 mV and 0.1 μA. The probe software employed the traditional Lamframboise method to determine plasma potential, electron temperature, and electron and ion currents. These values allow the determination of electron density consistently.

III. Experimental Results and Discussion

This section describes the results observed for the LaB_6 and CeB_6 cathodes. The ignition flow rates, voltages, and heating times are discussed. In addition, the operating characteristics of each cathode are also compared to determine which is superior.

A. Ignition Characteristics

The potential required to light impregnated cathodes is typically lower than LaB_6 cathodes due to their insert's lower work function. In addition, after the keeper starts, the heater is typically turned off. When the cathode performance degrades due to the insert being poisoned or the work function increasing over time, higher flow rates and more heater power are required to relight the cathode. Because of the higher work function of LaB_6, the first of the two cathodes tested, the initial ignition procedure began with slightly higher flow rates than the impregnated cathodes needed. The same heater power and keeper power were used throughout all ignition tests. For both the 0.5 and 0.25 aspect ratio cathodes, the following ignition procedures were used:

1) Pump propellant lines out to the bottle valve.
2) Set heater to 11.25 A until its voltage reaches 11 V (10 min).
3) Set flow to 4.5 sccm and run for 2.0 min.
4) Set keeper to 650 V and 1.0 A, and then turn on.

Without baking out the propellant lines to remove any trace amounts of water vapor, the LaB_6 cathode consistently started at the aforementioned conditions with no measurable degradation in performance. Neither residual gases nor orifice plate depth had an effect on the ignition characteristics. This behavior demonstrated the LaB_6 cathode's robust nature. Figure 2 is an image captured by a high-speed camera of the LaB_6 cathode at the moment of ignition. The keeper orifice is on the left of the frame, whereas the anode opening is on the right. The lines present in this image are luminous particles being ejected during the ignition event. This could be a potentially life-limiting mechanism of the cathode but is not discussed further in this paper.

Both cathodes underwent the same ignition procedure during preliminary tests, with only the higher aspect ratio orifice geometry

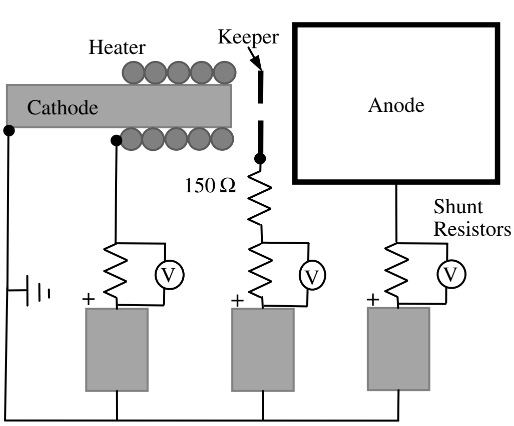

Fig. 1 Triode electrical circuit.

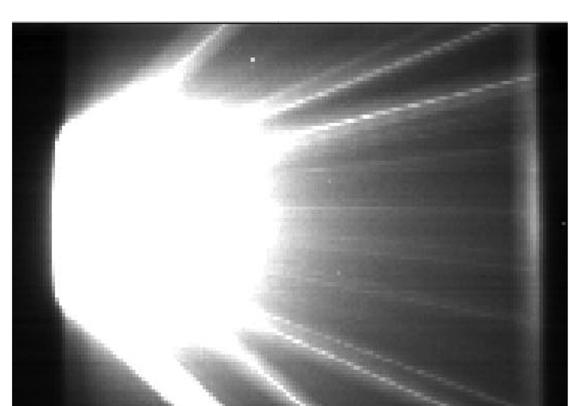

Fig. 2 LaB_6 cathode ignition.

tested for the CeB_6 cathode. The operating conditions (voltage, discharge current, and flow rates) for the CeB_6 cathode were changed to investigate the validity of the reported lower work function. The lowest voltage required to start the CeB_6 cathode was 500 V at 1.0 A of keeper current, while maintaining heater power and flow at a constant level. After ignition, no heater power was required to maintain keeper-only operation. After further investigation, the actual power delivered during CeB_6 cathode ignition was 9.0 W more than the LaB_6 cathode received. Thus, the CeB_6 cathode's lower ignition voltage may have been attributed to not only a lower work function but also slightly more power from the heater. Nevertheless, the CeB_6 cathode's performance deteriorated with time. After the cathode was operated at a low discharge current and low flow rates, the cathode became progressively more difficult to start. The ignition voltage returned to 650 V, the flow rates increased to as high as 8.0 sccm, and the heating times reached up to 30 min. This behavior was indicative of poisoning and is a subject described in detail by Warner [13].

B. Operating Characteristics

The data presented in this section describe the performance of the LaB_6 and CeB_6 cathodes during operation. The performance focuses on stability in terms of spot and plume mode operation as well as specific plasma characteristics: plasma density, plasma potential, floating potential, and electron temperature. As a whole, both cathodes behaved very similarly and had comparable performances to an impregnated cathode.

1. LaB_6 *Cathode*

The operating points under investigation in this research were used to determine if the LaB_6 cathode was capable of sustaining a stable heater-free discharge at a low current. Preliminary findings presented by Warner et al. showed the LaB_6 cathode operating as low as 3.0 A at 1.5 sccm with the keeper electrode turned off [8]. For these tests, the anode voltage exceeded the power supply limit (60 V), not allowing the cathode to operate at any lower discharge currents without needing heater power to increase the insert temperature and lower the anode voltage. Further testing was completed with the anode opening coplanar with the keeper orifice. This reduced the voltage required to extract the electrons from the cathode and allowed it to operate as low as 1.4 A at 1.5 sccm with the keeper off. However, for the LaB_6 cathode to reach this discharge current, the orifice aspect ratio was reduced to 0.25, allowing the electric field to penetrate further upstream into the cathode and extract more plasma. Until this was done, the cathode's lower operating point with the aspect ratio 0.5 was 2.5 A at 1.5 sccm. For both of these conditions, the cathode operated in full spot mode, exhibiting no instabilities and maintaining low electron temperatures (<4.0 eV).

Of the two orifice aspect ratios tested on the LaB_6 cathode, the vast majority of their operating points were stable and in spot mode. A select few were in plume mode, having the typical large ac oscillations in the anode voltage and forming plasmoids in the near keeper region downstream of the cathode. The plume mode phenomenon is described in detail by other authors [16–18]. Table 1 and 2 summarize the operating points and the mode the LaB_6 cathode was in during testing for the 0.25 and 0.5 aspect ratios, respectively.

Most operating conditions showed the discharge plasma was monotonic and exhibited smooth stable dc characteristics. For the "intermediate" cases, the anode voltage had a very small ac component, but the discharge formed a plasmoid at the keeper exit. These dense plasma regions formed closer to the keeper under lower flow conditions, a behavior also observed by others [16]. For these experiments, a cathode was not considered to be in full plume mode unless a plasmoid and large instabilities were observed, thus the term intermediate. Neither the plume mode nor the intermediate mode formed under higher flow conditions. Whenever the flow rate decreased, and the anode current increased, the cathode's discharge became unstable. As previously stated, several cases were full plume mode whereas others were in a transitional, intermediate mode.

The only operating point that transitioned to full plume mode was when the probe came within 5.0 mm of the keeper orifice while it was off and the flow was 1.5 sccm with a 6.0 A anode current. The cathode did not transition back to spot mode until the probe was removed and the keeper electrode turned on. Plume mode appeared to be mitigated by keeper operation and higher flow rates, as also observed by others [19,20].

Added to the plume mode, this effort attempted to determine improved performance of this cathode by considering different orifice aspect ratios. The first measurements focused on plasma density, with higher plasma densities indicating a better performance. The plasma densities were slightly higher during some operating conditions for the cathode with the smaller orifice aspect ratio, as shown in Fig. 3. The other plasma parameters (electron temperature and plasma potential discussed further below) were very similar between the two aspect ratio configurations, however, and neither orifice geometry provided a considerable advantage over the other. In the end, the smaller aspect ratio only allowed the LaB_6 cathode to operate at a lower discharge current.

The results presented for the LaB_6 cathode demonstrate its feasibility as a low-current cathode emitter. Unlike some earlier hollow cathodes with a LaB_6 pellet, this design does not require continual heater operation to maintain a discharge. It also had a wide and stable operating regime and did not require excessive flow rates or potentials to sustain a spot mode discharge. Additionally, the cathode's performance did not degrade as testing progressed, confirmed by energy diffractive x-ray analysis [13]. After completing 52 h of LaB_6 cathode testing, the CeB_6 cathode underwent the same analysis and its results are presented next.

Table 1 LaB_6 cathode with 0.25 orifice aspect ratio

Flow rate, sccm	J_a, A	J_k, A	V_a, V	V_k, V	Mode
6	6	1	26.26	15.89	Spot
		0	25.57	N/A	Spot
	4	1	27.91	18.22	Spot
		0	27.72	N/A	Spot
	2	1	30.44	20.34	Spot
		0	31.18	N/A	Spot
4.5	6	1	26	16.22	Spot
		0	26.72	N/A	Spot
	4	1	27.43	17.83	Spot
		0	27.84	N/A	Spot
	2	1	30.23	20.63	Spot
		0	30.95	N/A	Spot
3	6	1	28.46	17.06	Spot
		0	29.36	N/A	Spot
	4	1	30.16	19.24	Spot
		0	30.89	N/A	Spot
	2	1	37.51	25.51	Spot
		0	39.18	N/A	Spot
1.5	6	1	32.17	19.48	Intermediate
		0	48.17	N/A	Plume w/probe
	4	1	31.62	21.31	Spot
		0	34.36	N/A	Spot
	2	1	38.89	25.46	Spot
		0	42.34	N/A	Spot

Table 2 LaB_6 cathode with 0.5 orifice aspect ratio

Flow rate, sccm	J_a, A	J_k, A	V_a, V	V_k, V	Mode
4.5	4	1	26.1	17.6	Spot
	2	1	32.4	23.6	Spot
3	6	1	27.78	25.15	Spot
		0	31.45	N/A	Spot
	4	1	28	18.4	Spot
	2	1	33.3	23.75	Spot
1.5	6	1	30.43	19.88	Intermediate
		0	34	N/A	Intermediate
	4	1	31.9	24.05	Spot
		0	35.24	N/A	Intermediate

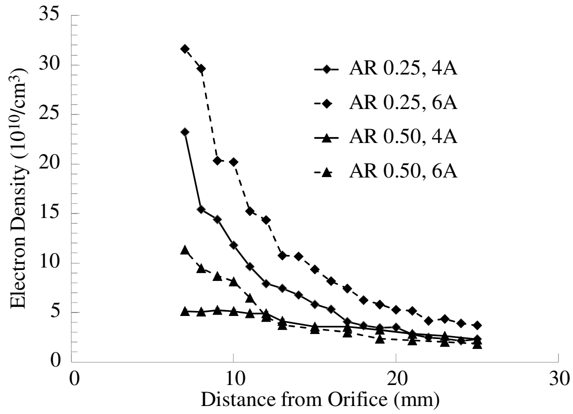

Fig. 3 Comparison of 0.5 and 0.25 aspect ratios for the LaB_6 cathode at 3 sccm along the centerline.

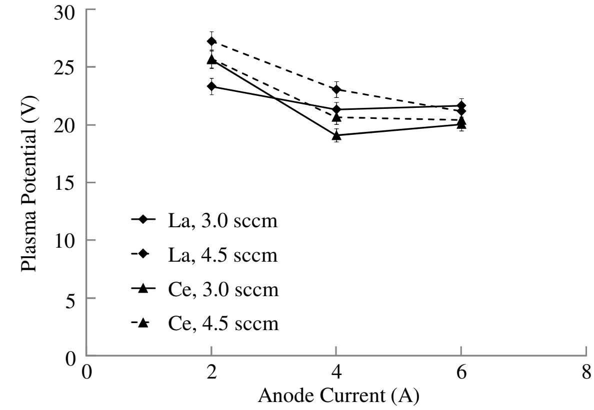

Fig. 4 Comparison of LaB_6 and CeB_6 cathode plasma potential with keeper on, 0.5 aspect ratio.

2. CeB_6 *Cathode*

The CeB_6 cathode performance was very similar to that of the LaB_6 cathode. It had similar plume mode operating conditions and did not exhibit appreciably higher plasma densities or distinctly different plasma potentials or electron temperatures. Table 3 summarizes its behavior for one orifice aspect ratio, 0.5. Just like the LaB_6 cathode, plume mode was characterized by large (>5.0 V), high-frequency (>50 kHz) ac oscillations in the anode potential, coupled with a plasmoid forming at the exit of the cathode keeper. The lower operating point of the CeB_6 cathode was 1.5 A with no heater or keeper power at 1.5 sccm, nearly the same as the LaB_6 cathode with the 0.25 aspect ratio. Initially, this result was attributed to the lower work function of the insert, but after further experimentation, proved not to be the case. The CeB_6 cathode's performance degraded as it succumbed to poisoning from trace amounts of oxygen and water vapor, raising its work function and increasing the cathode's lower current limit.

As for plasma characteristics, Fig. 4 gives a comparison of the typical average plasma potential observed between the LaB_6 and CeB_6 cathodes for an orifice aspect ratio of 0.5. Overall, the plasma potential of both cathodes was within a reasonable hollow cathode range and was comparable to impregnated cathodes [5]. The same could be stated about the average floating potential; see Fig. 5. The measured floating potential fluctuations are related to the temporal oscillations in the plasmoid as well as the strong spatial gradients in the plasma density. These oscillations are likely to produce larger measurement variations, as seen in Figs. 4 and 5. Gobel et al. introduced a theory suggesting oscillating plasma in that region can be linked to keeper erosion [14].

Table 3 CeB_6 cathode with 0.5 orifice aspect ratio

Mass flow, sccm	J_a, A	J_k, A	V_a, V	V_k, V	Mode
4.5	6	0	23.6	N/A	Spot
	4	1	23.43	17.12	Spot
		0	23.59	N/A	Spot
	2	1	23.54	22.62	Spot
		0	32.85	N/A	Spot
3	6	1	25.95	16.45	Spot
		0	25.09	N/A	Spot
	4	1	27.9	18.18	Spot
		0	29.28	N/A	Spot
	2	1	25.9	25.6	Spot
		0	32.47	N/A	Spot
1.5	6	1	42.9	18.53	Plume
		0	43.09	N/A	Plume
	4	1	27.89	N/A	Intermediate
		0	31.19	N/A	Intermediate
	2	1	30.68	27.89	Spot
		0	36.36	N/A	Spot

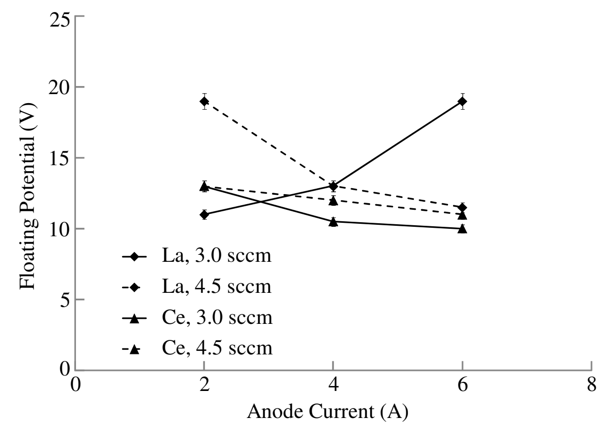

Fig. 5 Comparison of LaB_6 and CeB_6 cathode floating potential with keeper on, 0.5 aspect ratio.

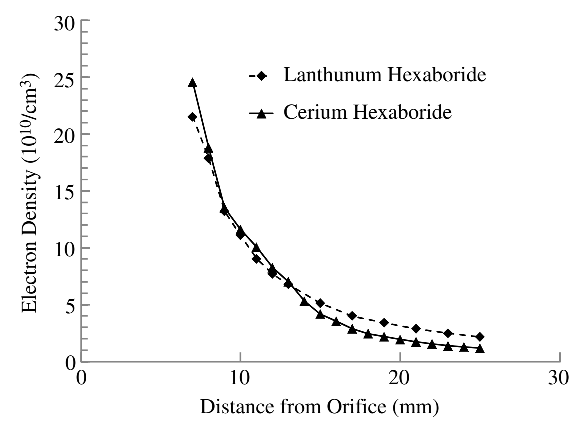

Fig. 6 Comparison of LaB_6 and CeB_6 cathode electron density with keeper off, 4.5 sccm, anode current 4.0 A.

The electron temperatures ranged between 1.5 and 3.0 eV for all test conditions. In Fig. 6, the plasma densities of the CeB_6 and LaB_6 cathodes were also comparable to impregnated cathodes and were not considerably different from each other. The data for Figs. 4 and 5 were taken along the centerline from 5.0 to 25 mm distance from the orifice plate. Values have been averaged over these measurements to show relative trends and these figures include errors represented by one standard deviation of these data [13]. These results suggest that the different cathode insert materials perform very similarly.

IV. Conclusions

Overall, both cathodes successfully demonstrated their ability to operate in the low-current regime. The CeB_6 initially had superior performance traits, but with time, its performance degraded and was surpassed by the LaB_6 cathode. With poisoning set aside, the cathodes had similar spot and plume mode operating regimes and similar plasma characteristics. They both demonstrated a wide, stable operating regime at reasonably low flow (<3.0 sccm). This proves the similarity between LaB_6 and CeB_6 in terms of electron emission, but does not definitively support CeB_6 as a possible alternative to LaB_6. Warner et al. discussed the poisoning effects and why they were different between the LaB_6 and CeB_6 cathode [8].

The tests do provide evidence to suggest LaB_6 as an alternative to impregnated tungsten inserts for low-current applications. These tests show LaB_6 has the ability to operate at a low discharge current in self-heating mode. Excessive flow rates were not required for low-current, spot mode operation. A very simple 15–20 min ignition procedure consistently worked for the LaB_6 cathode without requiring excessive flow rates or voltages to ignite. With this data, the LaB_6 cathode proved itself the superior electron emitter to CeB_6 and as a possible alternative to impregnated tungsten inserts.

Acknowledgments

Michael Huggins of the U.S. Air Force Research Laboratory at Edwards Air Force Base, California, graciously sponsored this work. The authors would like to thank Dan Goebel for providing the cathode design and for his technical assistance. The authors also thank John Williams for his technical advice throughout the course of this research and Glen Perrum for diagnostic support.

References

[1] Milosevic, N. D., Vukovic, G. S., Pavicic, D. Z., and Maglic, K. D., “Thermal Properties of Tantalum Between 300 K and 2300 K,” *International Journal of Thermophysics*, Vol. 20, No. 4, 1999, pp. 1129–1136.
doi:10.1023/A:1022659005050

[2] Wolski, W., “Pressed Boride Cathodes,” NASA TM-77821, Washington, D.C., June 1985.

[3] Davis, P. R., Swanson, L. W., Hutta, J. J., and Jones, D. L., “Fabrication and Characterization of Rare Earth Hexaboride Single-Crystal Materials,” *Journal of Material Science and Technology (Sofia)*, Vol. 21, March 1986, pp. 825–836.

[4] Gallagher, H. E., “Poisoning of LaB_6 Cathodes,” *Journal of Applied Physics*, Vol. 40, No. 1, Jan. 1969, pp. 44–50.
doi:10.1063/1.1657092

[5] Goebel, D. M., and Katz, I. C., *Fundamentals of Electric Propulsion: Ion and Hall Thrusters*, Wiley, New York, 2008.

[6] Goebel, D. M., Katz, I., Mikellides, Y., and Polk, J., “Extending Hollow Cathode Life for Deep Space Missions,” AIAA Paper 2004-5911, Sept. 2004.

[7] Goebel, D. M., Crow, J. T., and Forrester, A. T., “LaB_6 Hollow Cathode for Dense Plasma Production,” *Review of Scientific Instruments*, Vol. 49, No. 4, April 1978, pp. 469–473.
doi:10.1063/1.1135436

[8] Warner, D. J., Branam, R. D., Hargus, W. A., and Goebel, D. M., “Low Current Cerium Hexaboride and Lanthanum Hexaboride Hollow Cathodes,” AIAA Paper 2008-1086, Jan. 2008.

[9] Christman, L. A., Schwind, G. A., and Swanson, L. W., “A Comparison of CeB_6 and LaB_6 Thermionic Cathodes,” *49th Annual Meeting of the Electron Microscopy Society of America*, Aug. 1991, pp. 346–361.

[10] Swanson, L. W., and Mcneely, D. R., “Work Functions of the (001) Face of the Hexaborides of Ba, La, Ce, and Sm,” *Journal of Surface Science and Technology* Vol. 83, 1979 pp. 11–28.
doi:10.1016/0039-6028(79)90477-1

[11] Davis, P. R., Gesley, M. A., Schwind, G. A., Swanson, L. W., and Hutta, J. J., “Comparison of Thermionic Cathode Parameters of Low Index Single Crystal Faces of LaB_6, CeB_6, and PrB_6,” *Applied Surface Science*, Vol. 37, No. 4, Aug. 1989, pp. 381–394.
doi:10.1016/0169-4332(89)90499-6

[12] Wirz, R., “Discharge Plasma Processes of Ring Cusp Ion Thrusters,” Ph.D. Dissertation, California Inst. of Technology, Pasadena, CA, April 2005.

[13] Warner, D., “Advanced Cathode for Next Generation Electric Propulsion Technology,” M.S. Thesis, U.S. Air Force Inst. of Technology, Wright–Patterson Air Force Base, March 2008.

[14] Goebel, D. M., Watkins, R. M., and Jameson, K. K., “LaB_6 Hollow Cathodes for Ion and Hall Thrusters,” *Journal of Propulsion and Power*, Vol. 23, No. 3, 2007, pp. 552–558.
doi:10.2514/1.25475

[15] Tuszewski, M., and Tobin, J. A., “The Accuracy of Langmuir Probe Ion Density Measurements in Low-Frequency RF Discharges,” *Plasma Sources Science and Technology* , Vol. 5, 1996, pp. 640–647.
doi:10.1088/0963-0252/5/4/005

[16] Martin, R. M., and Williams, J. D., “Direct Measurements Nearby a Hollow Cathode Using a High Speed Electrostatic Probe,” AIAA Paper 2006-4820, July 2006.

[17] Mandell, M. J., and Katz, I., “Theory of Hollow Cathode Operation in Spot and Plume Modes,” AIAA Paper 94-3134, June 1994.

[18] Goebel, D. M., Jameson, K., Katz, I., and Mikellides, I. G., “Energetic Ion Production and Keeper Erosion in Hollow Cathode Discharges,” *29th International Electric Propulsion Conference*, IEPC Paper 2005-266, Nov. 2005.

[19] Kamhawi, H., “Development of a Hollow Cathode Assembly for the High Voltage Hall Accelerator,” AIAA Paper 2007-5172, July 2007.

[20] Domonkos, M. T., “Evaluation of Low-Current Orificed Hollow Cathodes,” Ph.D. Dissertation, Univ. of Michigan, Ann Arbor, M, June 1999.

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