Ignition and Early Operating Characteristics of a Low-Current C12A7 Hollow Cathode

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Calcium aluminate electride 12CaO-7Al2O3:4e- (e.g., C12A7:e-) shows promise as a low temperature electron emitter for hollow cathodes in spacecraft electric propulsion, but the material's basic performance limits remain poorly understood, including an exact value for work function. As a supplement to a companion paper examining C12A7:e- emission in a planar close-spaced diode configuration in vacuum, this paper examines operation of C12A7:e- tubular inserts in the plasma environment of a gas-fed hollow cathode. The inserts are sized for a lanthanum hexaboride (LaB6) 20-ampere class cathode normally used in a Hall thruster, but are here operated at greatly reduced currents of 30-150 mA due to early experiences with insert overheating and degradation. Nevertheless, the low sustainable operating powers demonstrated in these low-current operating modes suggest that C12A7 cathodes merit further investigation and improved thermal and plasma design.

Nomenclature

Φ_W = work function

I. Introduction

Calcium aluminate electride 12CaO-7Al2O3:4e- (henceforth C12A7:e-) was discovered in 2003 and has received attention as a low temperature thermionic emitter in hollow cathodes for spacecraft electric propulsion since at least 2010. However, a wide range of work functions are reported for the material, and difficulty in fabricating the refractory ceramic material properly and poor repeatability/reliability in hollow cathode operation have hampered evaluation of the material's potential as a future competitor or replacement for current state of the art emitters such as barium oxide (BaO) impregnated tungsten or lanthanum hexaboride (LaB6).

C12A7:e- has been demonstrated to operate below 1000 C at emission current densities where traditional emitters BaO or LaB6 would operate above 1000 C or above 1500 C, respectively.[1] The material was also observed to ignite in a spark discharge at room temperature (i.e., without any external heating), though the long-term reliability and/or potential for emitter damage using this ignition mechanism is unknown. Nevertheless these results suggest a very low work function Φ_W for the material. However, the first reports of C12A7:e- measured $\Phi_W \sim 3.4$ eV using ultraviolet photoelectron spectroscopy (UPS) [2], higher than either BaO (2.1 eV) or LaB6 (2.6 eV). The low C12A7 cathode operating temperature and the heaterless ignition capability suggests a lower work function in practice than observed in typical UPS diagnostics.

C12A7:e- is attractive due to its low temperature and thus potential low power operation and its apparent resistance to poisoning by electron-attracting species such as oxygen and water. Low temperature operation, reported as low as ~700 C in Ref. [1] for low currents ~1-2 A, can significantly reduce radiative power losses

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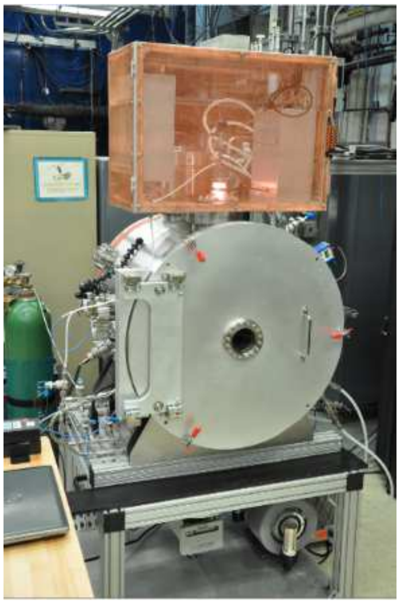
proportional to temperature T^4, as well as reducing conductive losses down the cathode axis directly proportional to T. Furthermore, reducing operating temperatures from the refractory range may also allow a range of new materials to be used with improved thermal characteristics and possibly allowing new fabrication techniques such as additive manufacturing. Finally, the material anecdotally appears more resistant to poisoning than BaO, though handling procedures and precautions are not yet firmly established. Nevertheless, the combination of potentially low operating power, easier fabrication and resistance to poisoning make C12A7:e- attractive as an enabling material for low-power electric propulsion systems as well as potentially attractive as an incremental improvement for higher power EP systems.

This paper presents initial construction of a C12A7 cathode testbed to facilitate basic investigations into the material's plasma and thermal operating characteristics, with the aim of evaluating its potential to enable lower cathode power consumption. A large hollow cathode based on a Goebel design for use in Hall thrusters serves as a high temperature testbed[3], with identical copies of the cathode used for LaB6 and C12A7:e- operation. Material degradation observed at high temperature operation in this cathode motivated construction of a lower temperature "heatsink" configuration made of copper to better maintain a low operating temperature at the insert. The low thermal and electrical conductivity of the C12A7 material means that, in spite of its ability to emit electrons at a relatively low temperature, Ohmic heating due to current passing through the material can decompose the conductive phase and even heat it past its melting point.

II. Experimental Setup

A. Plasma Test Facility (PTF)



The Plasma Test Facility (PTF) is a cylindrical stainless steel vacuum chamber 39" long x 30" in diameter. A Varian TriScroll 600 dry scroll pump backs an Agilent Turbo-V 10001 Navigator turbopump mounted on top of the chamber with nominal 950 L/s pumping speed on air. A CTI Cryo-Torr 400 cryopump mounted on the bottom of the chamber provides an additional nominal 6000 L/s pumping speed on air. A Lesker 392 series hot ionization gauge monitors high vacuum pressure. The chamber reaches the high 10-7 Torr range in base pressure using the turbopump alone, and the low 10-8 Torr range using the cryopump. For cathode testing we use both the turbopump and cryopump, and based on a 5 sccm typical argon flowrate and an argon-corrected operating pressure of 1.5e-5 Torr we find an actual pumping speed of about 4000 L/s.

B. Shared High Temperature Cathode Testbed

We use a shared cathode testbed for most of our testing, based off a published design for a compact LaB6 hollow cathode by Goebel.[3] For our purposes we use a standard size tubular insert, 1" long x ¼" OD x 1/8" ID, regardless of the material being tested. Both the central cathode tube and the outer keeper are made of graphite, and a recently reported refractory heater (Ref. [4]) heats the end of the central tube until the tubular insert reaches thermionic emission.

A Keysight N5772A 600V 2.6A DC power supply supplies 600V to the keeper to ignite the discharge. A Keysight N5771A 300V, 5A DC power supply provides heater current. An Ohmite RKS1K0E 1 kΩ rheostat in series with the keeper discharge prevents excessive arcing and sparking during cathode ignition.

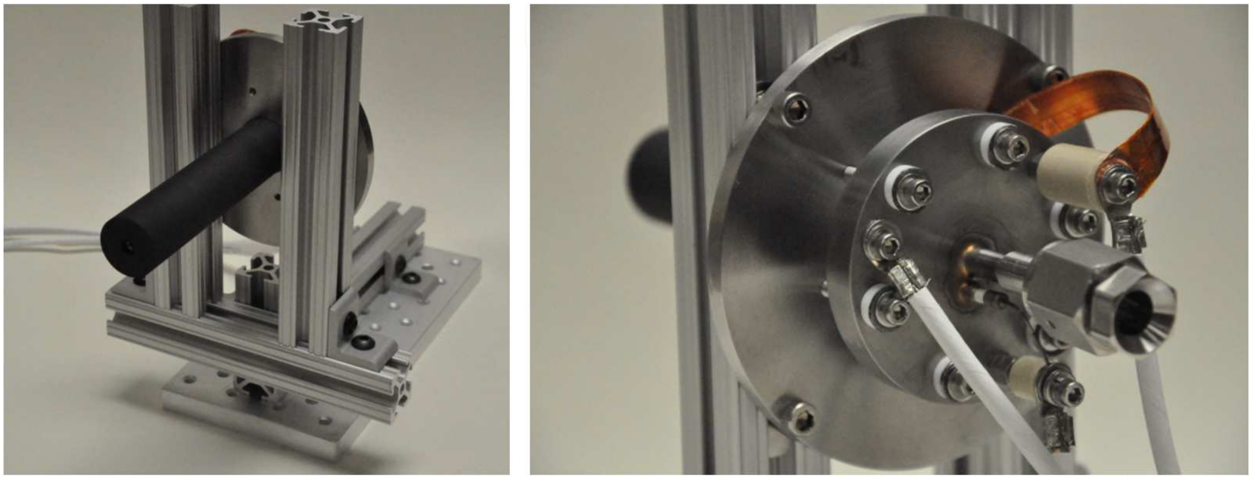


Figure 1: The high temperature hollow cathode testbed is shared between removable LaB6 and C12A7 inserts.

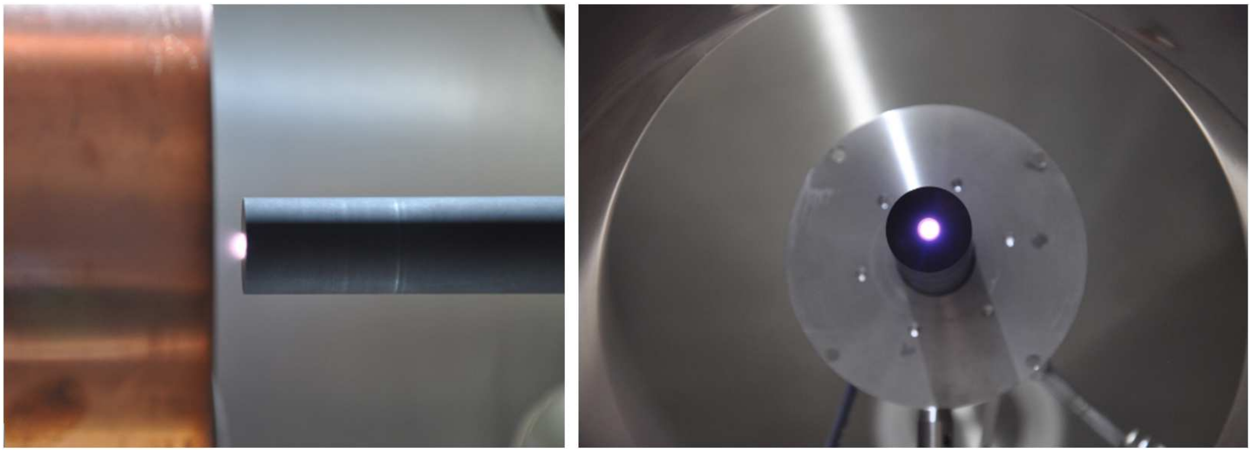


Figure 2: The high temperature testbed in operation with a C12A7 insert at the 150 mA and 5 sccm flowrate reported later in Figure 4.

C. Heatsink Cathode Configuration

Initial testing revealed that the C12A7 is prone to material degradation, likely due to overheating. The high temperature hollow cathode testbed above is designed for LaB6 emitter operating temperatures well over 1500 C and a result has a heavy focus on isolating heat at the cathode tip with minimal heat loss due to conduction or radiation. By contrast C12A7 melts at just over 1400 C and has been shown to degrade under exposure to temperatures above 1100 C over several hours.[5] This motivated the construction of a much simpler low temperature testbed designed to wick heat away from the insert.

The low temperature hollow cathode uses a 3/8" outer diameter x 1/16" thick copper tube approximately 3" long with a simple stainless steel Swagelok compression fitting to mount to the gas supply line. The keeper is a downstream copper foil tube. The low temperature cathode shares an identical heater with the high temperature unit, but requires slightly more heat applied to the insert to light due to the higher thermal conductivity of the copper tube than the graphite tube in the high temperature testbed. A thermocouple is mounted to the base of the copper tube on the compression fitting. The same power supplies and control software run both cathodes.

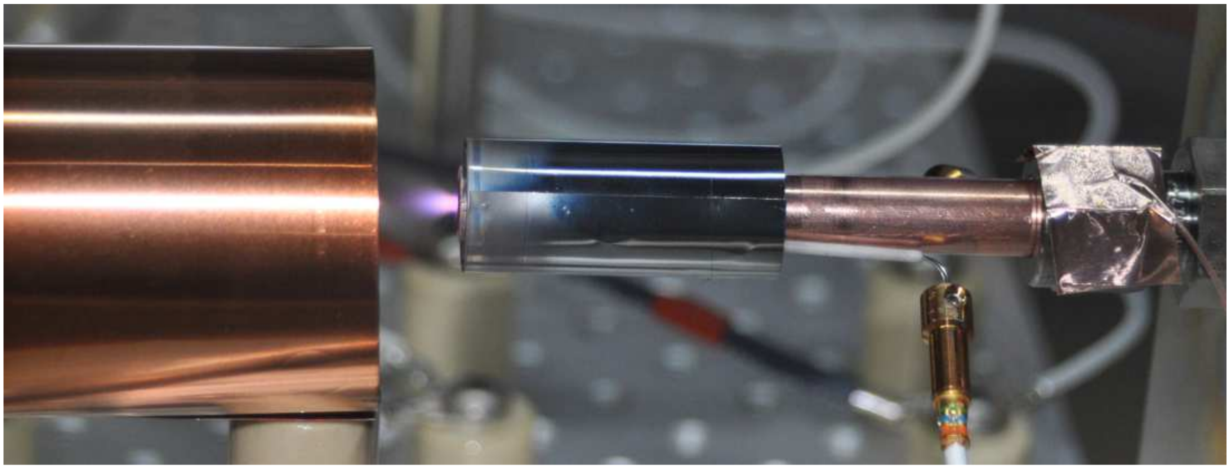


Figure 3: The heatsink cathode configuration uses an open copper tube with no orifice plate; the C12A7 insert is mounted flush with the tube face.

D. C12A7 Samples

The tube samples used in our testing were purchased via Dr. Martin Tajmar of Technische Universität Dresden and produced in collaboration between Dr. Tajmar and Fraunhofer IKTS. The material was formed initially from a rapidly quenched C12A7 melt, and the resulting glass was milled to powder, pressed into a green shape for machining into the tube form factor, then sintered in a reducing environment.

The naturally white calcium and aluminum oxides turn green when excess oxygen is removed in a reduction reaction, with darker shades of green indicating higher electron concentrations and thus more conductivity. However, while the samples are nominally conductive, surface 4-point conductivity measurements give typical sheet resistivities of several 10s-100s kΩ/sq. As a result Ohmic resistance during higher current operation is quite high, and we only report on operation up to 100-150 mA here to avoid degrading the samples.

III. Experimental Results

A. C12A7 Operation in the High Temperature Cathode Testbed

A successful ignition procedure for a C12A7 insert in the shared testbed was to apply 2.5 A heater current (about 33 W power) for 10 minutes with a typically 15-30 sccm gas flowrate. After 10 minutes, keeper voltage is applied at 600 V with a 50 mA current limit and a manual gas valve between the mass flow controller and cathode is closed until the line pressure reaches about 13 Torr. At that point the valve is opened again and the slug of gas enters the cathode and creates sufficiently high pressure for the gas to break down and ignite. Once the cathode ignites the flow is reduced to 5 sccm to maintain sufficiently low background pressure in our vacuum chamber to avoid inadvertent arcing in the chamber.

After ignition, we expected a slow reduction in the keeper voltage at a constant current, based on observations by Rand that a C12A7 hollow cathode slowly settled in to a steady operating temperature a few hundred degrees below the initial ignition temperature.[1] This would manifest as a reduced keeper voltage in our telemetry since maintaining a lower operating temperature would require less power from plasma self-heating. Instead, we observed a keeper voltage increase during overnight testing from about 140 to 180 V (Figure 4) at a discharge current of 150 mA.

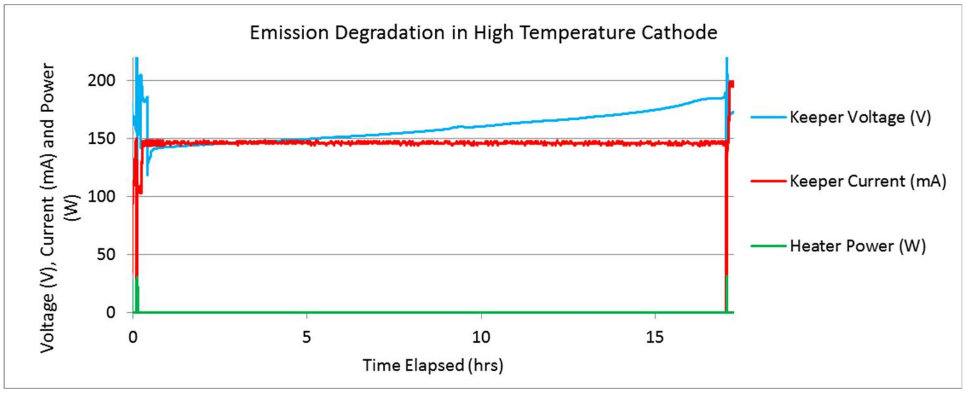


Figure 4: Keeper current and voltage during an overnight test of a C12A7 insert in the high temperature cathode testbed. The keeper voltage climbs steadily throughout the night at a constant current setting.

Additionally, upon removing the insert from the cathode we found that it had shattered and begun to decompose during operation. The insert was partially wrapped in a band of copper foil to make better thermal contact with the graphite tube, and that foil was all that held the insert together when it was removed. The insert had begun to visibly change color, indicating either oxygen uptake or loss of the C12A7 phase, and sputtering or melting of copper onto the orifice plate is evident.

Figure 5: The C12A7 insert from the high temperature testing fractured and visibly degraded during the test. The piece at far right is the cathode orifice plate.

B. C12A7 Operation in Heatsink Cathode Configuration

Ignition in the heatsink cathode followed a similar procedure to the high temperature cathode case, requiring only a slightly higher 2.75 A heater current for ignition, or about 37 W. To avoid overheating, after first ignition the heater power was reduced to 2.5 A from 2.75 A and the keeper current was reduced from 50 mA to 30 mA. At this point the insert was glowing very slightly red on the forward surface, which was visible given the lack of an orifice plate. Under these conditions we allowed the cathode to settle in over 8 hours with a high gas flow of about 30 sccm.

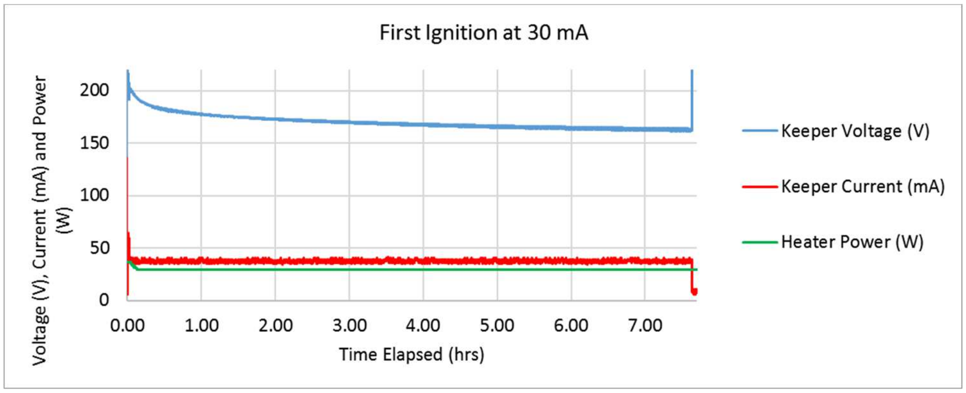


Figure 6: Telemetry after first lighting of a C12A7 insert in the heatsink cathode configuration. Keeper voltage leveled out after nearly 8 hours, and then the test was terminated.

The following day we reduced the gas flow to 5 sccm, which is more appropriate for our chamber given its limited pumping speed, and increased current to 100 mA while removing external heater power. With the reduction from 30 to 5 sccm the plasma retreated into the insert, and the insert was no longer visibly glowing after external heating was removed. The steady state operating power for the cathode at this condition was 18 W, or about half of the required power to light the cathode. It is not clear if this new voltage settling period reflected some further improvement of the emitter material, or if the discharge simply moved to a new axial location in the insert and repeated whatever phenomenon took place during the earlier discharge at 30 mA.

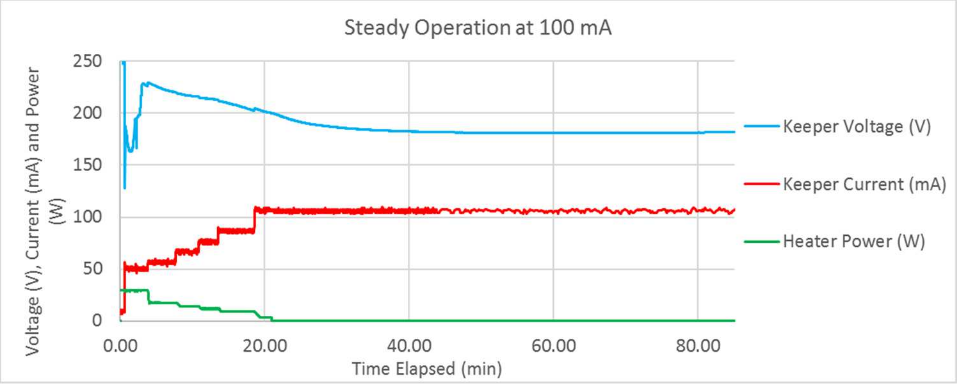


Figure 7: During subsequent testing at 100 mA, the keeper voltage settled in at 180 V over a little more than an hour. This discharge was self-sustaining after heater power was cut at 20 minutes.

IV. Discussion

Our C12A7 hollow cathode testing to date has been at very low currents to avoid insert overheating, which appears to be caused by a combination of the high bulk resistivity of the material and high local current densities when ramping up to ampere-class currents. Estimating the performance limits of a C12A7 cathode is difficult from the data presented so far due to the lack of detail for a thermal model. Only rough estimates are currently available for insert temperature, emission area, and what fraction of the discharge current is due to electron vs. ion current.

Nevertheless, we can make some qualitative estimates of the effective work function given observed temperatures and global emission levels from the insert. Based on the barely visible red glow of the cathode insert after turning off the plasma during operation at 100 mA, and the approximate total internal area of the insert, about 2.5 cm^2, we can estimate a minimum effective current density for the insert depending on the level of backstreaming ion current as 20-40 mA/cm^2. The current is likely localized over a smaller region of the insert and operating at a higher temperature (possibly glowing but not visibly from outside the cathode), but this sets a useful operating range. From the plot of typical emission current densities vs. temperature for various emitters Figure 8 this places the heatsink cathode configuration in a relatively small region between LaB6 and BaO.

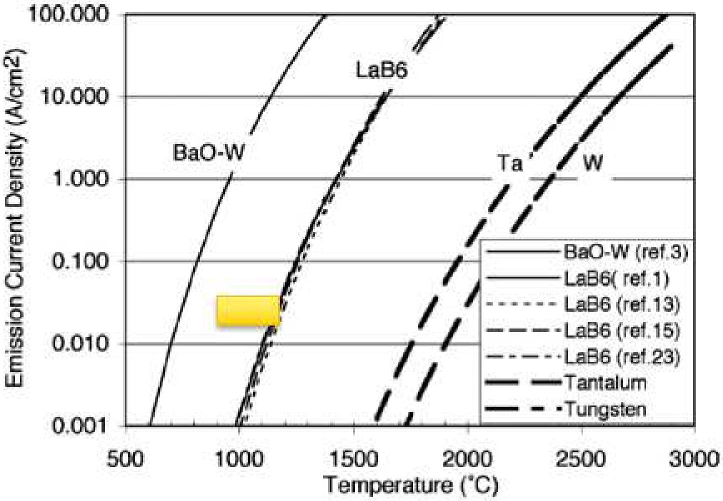


Figure 8: The estimated performance of the C12A7 insert at 100 mA in the heatsink configuration lies near the yellow box on this plot of state of the art hollow cathode emitter performance from Goebel.[3]

Estimating a material work function indirectly from hollow cathode operation is not precise; the region outlined in Figure 8 spans hundreds of degrees Celsius and a wide range of current densities. A companion paper to this one describes efforts to measure thermionic emission from planar C12A7 emitters in a close-spaced diode configuration.[6] Nevertheless, these rough global estimates as well as comparisons with LaB6 operation in the shared high temperature hollow cathode testbed indicate lower C12A7 operating temperatures than LaB6. LaB6 ignition in the shared cathode testbed requires 5.25 A heater current, or about 200 W heating power, while the C12A7 insert required just over 30 W and was typically barely visibly red hot when ready to ignite. Steady state LaB6 operation usually requires at least 5 amperes of discharge current or the insert will wink out due to insufficient heating, with typical total discharge powers of 100-150 W. By comparison the C12A7 insert in the high temperature shared testbed operated (albeit under degrading conditions) at 150 mA for several hours at powers ranging from 21-27 W. In the heatsink cathode configuration, the insert operated stably for an hour at even lower power, just 18 W.

V. Conclusions

We have reported on initial operating characteristics of 1/8" ID (3mm) tubular C12A7 inserts in two hollow cathode configurations. We were able to successfully light the cathode in both configurations with heater powers of about 35 W, keeper voltages of 600 V and the aid of a gas pulse to provide a momentary high pressure gas breakdown before steady state operation at 5 sccm. In the first configuration, a shared testbed initially designed for LaB6 inserts, the C12A7 insert degraded at 150 mA over 16 hours after ignition from 140 V to 180 V on the keeper. This degradation was likely due to overheating and upon inspection the insert was broken, likely due to thermal stress, as well as visibly discolored indicating oxidation or C12A7 phase decomposition. This steady state operating power of 21-27 W is far lower than the typically 100-150 W

In the second configuration, a copper barrel designed to wick heat away from the C12A7 insert, the cathode settled in at 30 mA over 8 hours after initial ignition from over 200 V to 160 V on the keeper, with about 30 W heater power continuously applied. Subsequently the cathode operated at 100 mA over an hour at a relatively steady 180 V on the keeper with no heater power, operating purely in a self-heating mode. This corresponds to a steady state operating power of 18 W.

The insert from the second configuration remains operational and will be taken to higher current operation in upcoming testing, in conjunction with internal Langmuir probing to monitor the plasma conditions in the orifice to gauge emission uniformity. If possible the cathode will also be outfitted with additional thermocouples to present a clearer thermal picture of the cathode system. Despite the low operating currents tested to date, the results support reports in the literature that C12A7 may be at least as strong an electron emitter as LaB6 at moderate temperatures <1000 C, with a minimum emission in the tens of mA/cm^2 range at a temperature producing minimal visible red-hot glow.

References

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