Performance comparison of LaB6 and C12A7:e- emitters for space electric propulsion cathodes

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Abstract. This work, based on an EU-funded project, NEMESIS, is aiming at developing electride-based cathode technology which is compatible with all kinds of electric propulsion systems requiring neutralization. Its target is to demonstrate and validate the performance of a novel C12A7:e- electron emitter instead of traditional thermionic emitters such as lanthanum hexaboride, LaB6, or barium oxide, BaO. In this study, a fair comparison between LaB6 and C12A7:e- samples was performed both addressing pure material characterization parameters as well as comparing performance as cathodes under different architectures and operational conditions. In this case, a current/cathode power ratio around 3 mA/W was obtained when using the C12A7:e- sample in a plasma environment with Ar, which is approximately one order of magnitude higher compared to the LaB6 sample.

1. Introduction

Electric propulsion (EP) is an increasingly adopted technology for spacecraft propulsion in station keeping, orbit raising, or primary propulsion applications. EP systems use electrical and magnetic fields to change the velocity of a spacecraft. Most of these kinds of spacecraft propulsion systems work by electrically expelling propellant, reaction mass, at high speed. A common need for most of the EP thruster technologies is to operate a device for electron emission either for plasma generation or for charge neutralization of impellent positive ions [1–3]. Permanent research on new materials and architectures is mandatory to optimize efficiency of such devices in the extreme operation conditions and limited resources in space.

Traditional electron emitters used for EP in the space industry are lanthanum hexaboride, LaB6, and barium oxide, BaO, both requiring very high temperatures for operation, thus consuming large amounts of energy and producing huge thermal stress to EP thrusters and neutralizers and all surrounding subsystems, which drives to deterioration and reduction in components lifetime even when using expensive high thermally resistant materials.

In this paper are discussed the physical properties of the dodecacalcium hepta-aluminate (mayenite, 12CaO·7Al2O3, C12A7) based electrode, hereinafter referred to as C12A7:e- material. This novel material has excellent materials properties for thermionic devices for EP applications such as hollow cathodes or thermionic emitters [4]. Its properties are superior to those of conventional...
ceramics currently employed in EP neutralizer technology. It is anticipated that C12A7:e- neutralizer technology is a potential game changer widening the applicability of EP immensely by enabling new mission scenarios due to higher reliability, compatibility with alternative propellants, lower power consumption on satellite and less thermal load at low costs.

One objective of this work, based on the EU-funded project Novel Electride Material for Enhanced electrical propulsion Solutions (NEMESIS) [5], is to demonstrate and validate for the first time the application of a C12A7:e- electronegative emitter instead of traditional thermionic emitters such as LaB6 or BaO. As it is demonstrated, the performance of the electronegative material is superior to any other electron emitter due to its unique properties such as its chemical inertness, its low work function, a much lower operational temperature, and an improved lifetime. Due to the novel application and the low knowledge about the behavior of the material in a plasma environment, several devices with different cathode architectures were designed and tested before obtaining an optimize prototype able to operate with a LaB6 and a C12A7:e- sample.

In this work, we will first compare the results of C12A7:e- and LaB6 materials, in terms of thermionic emission, and then we will move to a real operation environment of both thermionic materials placed inside a cold cathode neutralizer prototype within a plasma environment.

2. C12A7:e- and LaB6 material thermionic emission parameter characterization

2.1. C12A7:e- and LaB6 comparison of thermionic emission in vacuum

As previously commented, the pure thermionic emission of a C12A7:e- sample and a LaB6 sample will be first compared in terms of the extracted current density as function of temperature and acceleration voltage.

In a first experiment, run by Justus-Liebig-University of Giessen, the setup is an anode-cathode configuration where the distance between them is 2 mm. The sample was heated by a heater underneath the cathode, and the cathode is negatively biased to accelerate the emitted electrons towards the anode. In addition, the sample temperature is measured by a thermal imaging camera. During the initial tests performed using medium electron concentration samples of C12A7:e- (N0 ≈ 10^20 cm^-3), the extracted current density was similar for both emitters at medium temperatures, around 600 °C, when biasing with 1000 V (see Table 1).

| Emitter  | Temperature (ºC) | Current density (nA/cm^2) |
|----------|------------------|---------------------------|
| C12A7:e- | 607              | 106                       |
| LaB6     | 603              | 104                       |

To verify the current emission values, further tests were performed at Exotrail premises with a different setup and prototype. The experimental setup includes the use of a vacuum chamber, a test hardware in which a sample is placed, a power supply and sourcemeter for voltage and current control, thermocouples and software for data acquisition. The vacuum chamber is equipped with a rough pump and a turbopump with a pressure during test in the range of 1·10^-6 to 8·10^-8 mbar. Regarding the setup, it includes a pyrolytic boron nitride heater, a boron nitride insulator and a tantalum foil as cathode and anode terminal. The distance between cathode and anode is 4.1 mm, similar value compared to the first experiment. In this prototype, the temperature is monitored by two thermocouples.

To assure a correct measurement of the current, a procedure was developed in order to allow the proper outgassing at different temperatures before acquiring the data. In addition, the leak current of the system, without samples, was measured and subtracted from the current-voltage curves recorded at different sample temperatures.
Figure 1 shows the outcome of the comparison tests on thermionic current emission measured with C12A7:e- and with LaB$_6$ emitter materials at different temperatures and acceleration voltages. As seen in Figure 1, the emission current extracted from the C12A7:e- sample is higher than that of the LaB$_6$ one. For example, at about 900°C, the extracted electron currents of the C12A7:e- and the LaB$_6$ samples are 0.1 mA and 0.01 mA, respectively.

![Graphs showing emission current vs. temperature and voltage for C12A7:e- and LaB$_6$ samples.](image)

**Figure 1.** Emission current extracted from C12A7:e- (top) and LaB$_6$ (bottom) 8 mm diameter disc samples
2.2. C12A7:e- and LaB6 performance comparison in a plasma discharge cathode

In this section, we will describe the comparison tests of both materials as emitter in a plasma discharge cathode neutralizer. For this purpose, we will use one-inch diameter discs with 2 mm thickness of each material as emitter, placed within a prototype heater less neutralizer described hereafter. In this case, the cathode is based on a heater less neutralizer working at low temperatures, approximately below 300ºC, and therefore reducing the power consumption compared with the previous prototype setups described in section 2.1. A conceptual scheme and a description of the main characteristics of the cathode are represented in Figure 2, and the results of performance test under different operation conditions are presented below.

As a brief description, it is necessary to use a negatively bias power supply for the cathode (V_c) while the keeper is grounded. As it can be seen in Figure 2, the noble gas is introduced in the gap space between the keeper structure and the cathode, being the keeper totally isolated from the cathode. In addition, a positively bias power supply, hereinafter named as V_a (anode), is also necessary. This metallic anode, located at approximately 40 mm, will collect the electron current emission from the cathode.

![Figure 2. Scheme of the heater less neutralizer used for performance tests](image)

### Table 2. Vacuum chamber and control equipment characteristics

| Vacuum chamber          |
|-------------------------|
| Size: 300x300x350 mm    |
| Pump: Turbo molecular pump Edwards EXT255H |
| The pump: Alcatel |
| Vacuum level up to 10^{-7} Torr |
| Connectivity of up to 9 thermocouples |

| Control equipment               |
|---------------------------------|
| Pico-amperemeter (Keithley DDM 6500) |
| DB9 connector for 9 analog signals |
| Two current sources (100 A, 22.3 A) |
| High voltage power supply 300 V |

### Table 3. Performance test conditions

| Size sample                     | 25.4 mm diameter and 2 mm thickness |
|---------------------------------|------------------------------------|
| Cathode voltage (V_c)           | 150-300 V                           |
| Gas                             | Ar and Xe: from 1 to 50 sccm mass gas flow |
| Thermocouple                    | Type K connected at the base of the sample |
The performance measurement tests presented hereafter were obtained with the same vacuum chamber, and test set-up cathode prototype configuration, described in Tables 2 and 3. As it will be presented in the following figures, the anode current \( I_a \) was obtained as a function of the anode voltage \( V_a \), gas flow and cathode power \( P_c \) parameters.

It was observed that cold start ignitions present instabilities for both materials before reaching 200 °C. To solve this issue a warmup procedure was applied from room temperature till reaching close to 250 °C. This process was initially carried out by means of a heater, but finally it was replaced by an Ar bombardment with a mass flow of 50 sccm for 5 min. Once the system is ignited and thermal stabilized, we obtained a stable operation mode of the cathode without instabilities using a mass flow of 0.9 sccm Xe and 1.5 sccm of Ar.

In Figure 3 we can observe that anode currents and performance ratios are significantly higher for C12A7:e- electride than for LaB₆ when using 1.5 and 10 sccm of Ar. For example, when applying 30 W and using 1.5 sccm of Ar for C12A7:e-, we obtained around 20 mA anode current with the anode grounded, and a current of around 100 mA when applying an anode voltage of 20 V. A similar performance was observed with a mass flow of 10 sccm of Ar where the current obtained for the electride sample achieved a value of 150 mA at 30 V of anode voltage.

In Figure 4 we can see the results of the anode I/V characterization curves for 10, 20, and 30 W cathode power levels, for 0.9 and 5 sccm mass flow of Xe. The LaB₆ sample was not characterized when using 0.9 sccm mass flow of Xe since it was not possible to reach a stable operation of the cold cathode below 5 sccm, being this another advantage of the C12A7:e- sample.
Figure 4. I/V characterization curves of C12A7:e- and LaB₆ in a cold cathode at 0.9 (left) and 5 sccm (right) Xe mass flow for different cathode powers.

As it can be observed in Figure 4, the LaB₆ needs a minimum of 15 W cathode power while the C12A7:e- electride sample is able to operate using 12 W of cathode power. It can also be seen that, both for 20 and for 30 W, the anode current is clearly higher with electride sample. We can also observe a current saturation at low anode voltages, 10 to 15 V, in the case of the LaB₆ curves.

In addition, Table 4 is showing a summary of the performance of the heater less neutralizer, with a C12A7:e- and a LaB₆ sample, working at different Xe and Ar mass flow with 30 W cathode power (P_c) and 20 V of anode voltage. As it can be observed, C12A7:e- shows a clear superiority with both Ar and Xe and, above all, a better stability of the anode current was observed with lower mass flows and power cathode (P_c).

Table 4. Performance comparison test results in a cold cathode neutralizer working at low temperature

|       | I_a (mA) | I_a/P_c (mA/W) |
|-------|----------|----------------|
| C12A7:e- |          |                |
| Ar 1.5 sccm | 99.6     | 3.32           |
| Ar 10 sccm  | 110.0    | 3.36           |
| LaB₆   |          |                |
| Ar 1.5 sccm | 5.4      | 0.18           |
| Ar 10 sccm  | 20.5     | 0.68           |
| C12A7:e- |          |                |
| Xe 0.9 sccm | 26.0     | 0.86           |
| Xe 5 sccm  | 31.9     | 1.06           |
| LaB₆   |          |                |
| Xe 0.9 sccm | N.A.     | N.A.           |
| Xe 5 sccm  | 5.8      | 0.19           |

As the results indicate the I_a/P_c ratio obtained for the C12A7:e- sample are around 3.3 mA/W with Ar and 1 mA/W with Xe, confirming the great possibilities of C12A7:e- material for designing cold cathodes in neutralizers operating at temperatures below 250 °C.
3. Conclusions
One of the conclusions of this work is that LaB$_6$ will perform similar to C12A7:e- in devices working purely based on temperature induced electron emission. C12A7:e- starts thermionic current emission at lower temperatures than LaB$_6$. However, current intensity emission from C12A7:e- is similar due to the low A constant in Richardson-Dushman equation.

Regarding the operation in a plasma environment with low temperatures, around 250 ºC, a higher performance of the C12A7:e- sample was observed. In this case, a performance ratio of 3.3 mA/W was measured when using Ar and 30 W of power cathode for the C12A7:e- sample. Further performance improvements under test could even improve these performance ratios.

Additional performance comparisons are expected on other neutralizer devices under development, like the hollow cathode neutralizer designed at JLU Giessen. A higher C12A7:e- performance observed in the here described cold cathode neutralizer is also expected in these hollow cathode neutralizers presently under tests.

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