Wall Material Selection Process for CAM200 Low Power Hall Thruster

IEPC-2015-103／ISTS-2015-b-103

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

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Low power Hall Effect Thrusters (HET) under 500 W are characterized by their low efficiency, low specific impulse and short lifetime relative to their higher power cousins. The CAMILA and Simplified-CAMILA Hall thrusters are an exception in that regard as their prototypes exhibited outstanding performance when operated at power levels ranging from 100 W to 300 W. In the process of developing a flight-qualified low power Hall thruster further investigations were performed on a Simplified CAMILA Development Model (DM), denoted CAM200-DM. The thruster was designed and manufactured by Rafael, and tested at the Asher Space Research Institute (ASRI). The present work describes the wall material selection process campaign of CAM200-DM that includes structural integrity validation, performance tests and discharge channel erosion measurements of three dielectric materials. Static, dynamic, sine and random vibration tests, as well as shock tests, were conducted for grade HP-BN, grade M26-BN and ZSBN discharge channel materials with a CAM200 Structural Model (SM). The thruster successfully passed all tests thus proving adequate structural integrity of both structural design and wall material. Performance tests were conducted at power levels in the range 100 W - 300 W. No significant difference in performance or erosion was observed when comparing the dielectric rings with different materials after 80 hours of operation. CAM200-DM exhibited exceptional performance when it generated, at 300 W, thrust above 16 mN, anode efficiency above 43% and specific impulse of above 1550 sec. During operation with ZSBN material rings the thruster exhibited unstable electrical behavior and therefore this material was ruled out. HP-BN rings experienced some geometry change after the short experimental campaign thus ruling out this material as well. The chosen dielectric material is grade M26-BN that performed flawlessly.

Nomenclature

Isp_a	=	Anode specific Impulse
P	=	Electrical Power
T	=	Thrust
η_a	=	Anode efficiency

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I. Introduction

Due to their small size micro-satellites (10-100 kg) are power limited and conventionally utilize chemical propulsion for their manuevering requirements. However, the use of high efficiency low power (<300W) electric propulsion with Hall Effect Thrusters (HET) can enhance micro-satellites' capabilities and allow them to perform a veriety of missions, particularly in Low Earth Orbits (LEO). In addition, thanks to the associated high specific impulse the use of low power HETs allows for propellant mass reduction, thus reducing the overall satellite mass. This, in turn, enables the enlargement of the mission payload if needed. Although HET technology carries these advantages at power levels of 50 W to 300 W HETs suffer from low efficiency and short operating lifetime relative to their higher power cousins[1,2].

The Coaxial Anode Magneto-Isolated Longitudinal Anode (CAMILA) HET confronts these weaknesses. The CAMILA HET has been developed and patented by Kapulkin et al[3] from the Asher Space Research Institute (ASRI) at the Technion, Israel institute of Technology. The CAMILA HET consists of an electrically floating gas distributer and a co-axial anode, where a longitudinal magnetic field is induced by designated anode coils and a radial magnetic field at the thruster's exit plane, which is induced by a conventional HET magnetic circuit[4]. This unique configuration enables almost a full ionization of the propellant in the anode cavity even at low mass flow rates[4,5]. Extensive experiments were conducted on CAMILA HET and on Simplified-CAMILA, which is a derivative of the basic CAMILA HET, yet without the added anodic axial magnetic field. During experimental tests conducted at ASRI, both configurations exhibited roughly the same performance of high efficiency and specific impulse at power levels of around 250 W[6].

In light of the above and because of its simpler and lighter mechanical structure, a feature which is relevant to system engineering considerations, it was decided to continue with the development of simplified CAMILA, now denoted CAM200. CAM200 is to be developed and qualified by Rafael to serve as efficient means of propulsion for power-limited micro-satellites.

Moreover, CAM200 is designated to compete for a place in the European-Israeli Micro-satellite Electric Propulsion System (MEPS) project[7]. The goal of MEPS, which is funded by European Space Agency (ESA) and the Israeli Space Agency (ISA), is to design, manufacture and qualify an electric propulsion system for micro-satellites. MEPS, which is planned to be qualified for space in three years, is a collaboration between RAFAEL and the Italian electric propulsion company, ALTA-SITAEL.

Figure 1. Picture of CAM200-DM.

This paper presents an important segment of the CAM200 development program - the material selection process in which the most suitable discharge wall material is chosen. This development stage was conducted on a Development Model of CAM-200 (CAM200-DM).

II. CAM200 Thruster Description

CAM200-DM, shown in Figure 1, was developed at Rafael with the participation of ASRI, where the performance tests were conducted. The magnetic field pattern and the inner structure of the thruster are shown in Figure 2. One can observe that the discharge channel cavity is formed of a co-axial anode and ceramic dielectric rings attached to the anode. Also shown is the Gas Distributer (GD) which is gas-fed symmetrically through a xenon feed manifold. The GD is electrically isolated from the anode thus, it is electrically floating with respect to the Thruster Unit (TU). The design of CAM200 includes key dimensions, which are the same as that of the laboratory Simplified-CAMILA thruster.

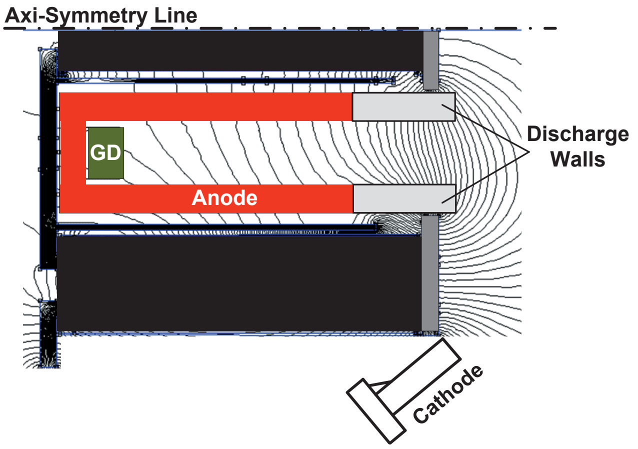

Figure 2. Two dimensional magnetic field pattern and thruster internal structure schematic of CAM200-DM.

III. Material Selection Test Campaign

Ceramics are the most commonly used materials in HETs due to their low erosion under ion bombardment, high temperature resistance and high secondary electron emission relative to other materials. On the other hand ceramic materials are brittle and therefore require suitable thruster structural design to prevent material cracking and fracturing. This is especially true during launch phase when the highest structural stresses are experienced by the propulsion system. Of the available ceramics Boron-Nitride (BN) based ceramic materials exhibit highest HET performance and are the natural candidates to be used in future HETs and specifically in CAM200.

The aim of the material selection program is to identify the most suitable discharge channel wall material that can satisfy both structural integrity requirements and exhibits highest performance, both in terms of thrust efficiency and low erosion. To do so three material candidates were examined: (1) High Purity BN (HP-BN) (2) M26-BN and (3) Zirconia-based BN (ZSBN). All materials and their key properties are presented in Table 1.

Property	HP-BN (High Purity)		M26-BN		ZSBN	
Crystalline Phase	Hex BN		BN-60%, SiO_2-40%		BN-45%, Zr_2O_3-45%	
Directionality	∥	⊥	∥	⊥	∥	⊥
Flexural Strength [MPa]	59	45	62	34	144	107
Thermal Conductivity (at 25°C) [W/mK]	27	29	11	29	24	34
Dielectric Strength [kV/mm]	>10		66		>9	

Table 1. Key properties of the three BN-based materials examined in the CAM200 material selection test plan

It can be seen that while pure hexagonal BN is a structurally weak ceramic material it has a relatively high thermal conductivity, an important feature that helps maintain low wall temperature thus reduce channel erosion[8]. Zirconia-based BN is the strongest material and has an excellent wear resistance yet it carries a possible drawback - the risk of increased electrical conductivity at temperatures over 300°C[9]. Since ZSBN contains a high fraction of zirconia (Zr_2O_3) it was acknowledged that there is the possibility that during HET operation the ZSBN ceramic wall will start conducting the electrons trapped in the acceleration and ionization regions and essentially short-circuiting the thruster. Still, due to the lack of existing literature on ZSBN electrical properties and its interaction with HET plasma it was decided to keep this material in the material selection program. Lastly, M26-BN is a common discharge channel wall material used in HETs[10] exhibits properties similar, yet not identical, to HP-BN and therefore is investigated as part of the test plan.

CAM200-DM ceramic wall material selection test program flow chart is presented in Figure 3.

The test program commences with X-ray computed tomography (CT) to verify initial ceramic wall structural integrity. Subsequently a set of environmental tests are applied to verify structural integrity under expected launch conditions. These include vibration and shock tests as well as frequency response test to measure the thruster's

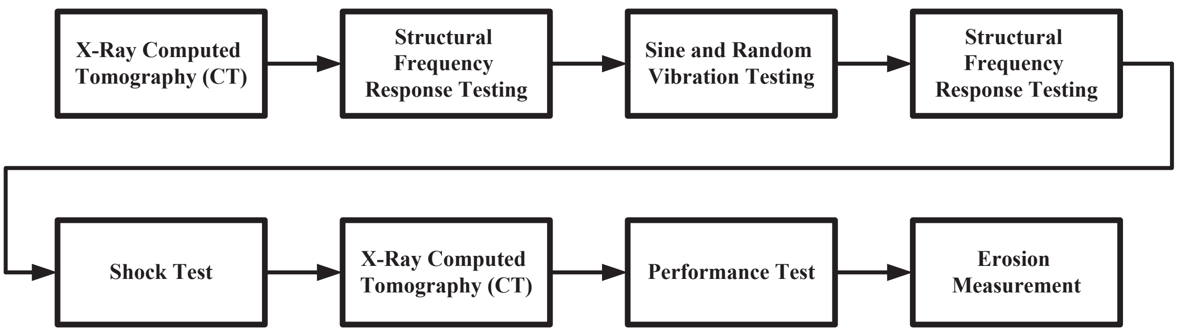

Figure 3. Ceramic wall material selection test program flow chart.

structural resonanse frequency. The vibration and shock tests conditions are described in the subsequent sections. Following the environmental tests an additional CT scan was performed to assure that no fractures were created during the tests. Finally, an 80 hours thruster firing test is conducted to characterize thruster's performance, compare between CAM200-DM operating under the same conditions with different ceramic wall materials and compare the the channel erosion of the different wall materials.

IV. Structural Integrity Tests

Modal analysis of CAM200 was performed using 'SolidWorks Simulation' final element software and was part of CAM200-DM design and fabrication process. To validate the design and mechanical integrity of CAM200-DM dynamic environment tests were performed on a Structural Model (SM) of the thruster. As a test case the dynamic environment specification requirements of the Venus satellite were implemented[11]. These requirements consider load amplifications on a small satellite due to launch loads such as those exerted on the satellite platform in various launchers. All tested vibration and shock tests correspond to estimated worst case scenario levels among all known commercial launchers. The tests included sine and random vibration and shock tests. Random vibration and shock test levels are presented in Figure 4 and in Table 2 respectively.

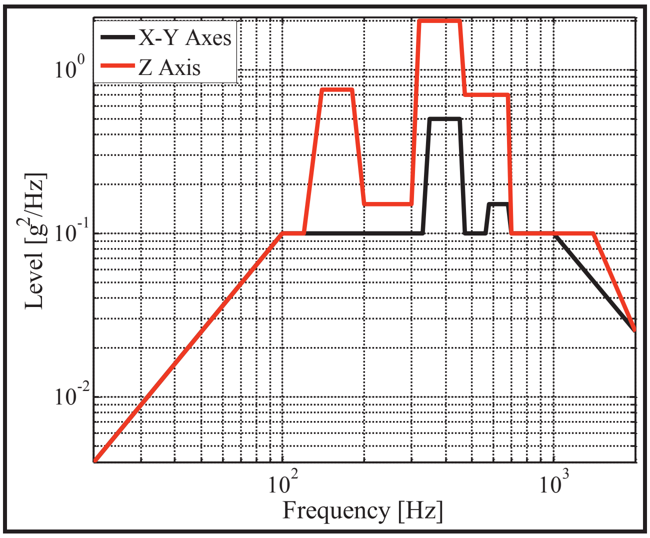

Figure 4. Vibration test levels performed on a structural model of CAM200 with all three types of wall channel materials.

Frequency [Hz]	Level [g]
100	150
2000	3000
10000	3000

Table 2. Shock test levels.

Figure 5 depicts the x-axis random vibrations test setup along with an illustration of the Hall thruster structural model.

All three material rings assembled in the SM successfully passed all the dynamic tests, therefore proving adequate structural integrity and paving the way for the next stage of the material selection program.

V. Performance Testing

A. Test Facility

Performance tests were conducted at the Asher Space Research Institute (ASRI) electric propulsion laboratory at the Technion (Figure 6). The test facility includes a 1.22m Ø × 2.7m stainless steel vacuum chamber with inner volume of approximately 3.2 m^3. The chamber is equipped with a 'RUTA WAU 501/D65B/A' forevacuum pump with pumping speed of 230 liter/s of air. Three 'Sumitomo' CP-22 cryopumps are located on the vacuum chamber's opposite end from the thruster. The combined measured pumping speed achieved is approximately 9,000 liter/s on xenon. The residual pressure of the vacuum chamber is lower than 9×10^{-8} Torr. During thruster operation at a total flow rate of 1.2 mg/s of xenon, chamber pressure was lower than 2×10^{-5} Torr.

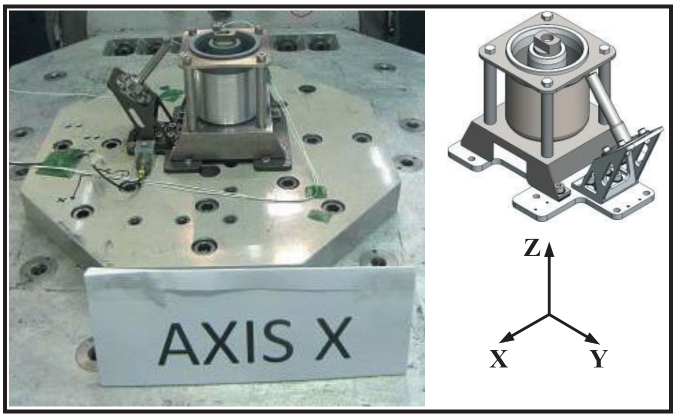

Figure 5. Left: CAM200 during random vibration test along the thruster's X-axis. Right: CAD model of CAM200 structural model.

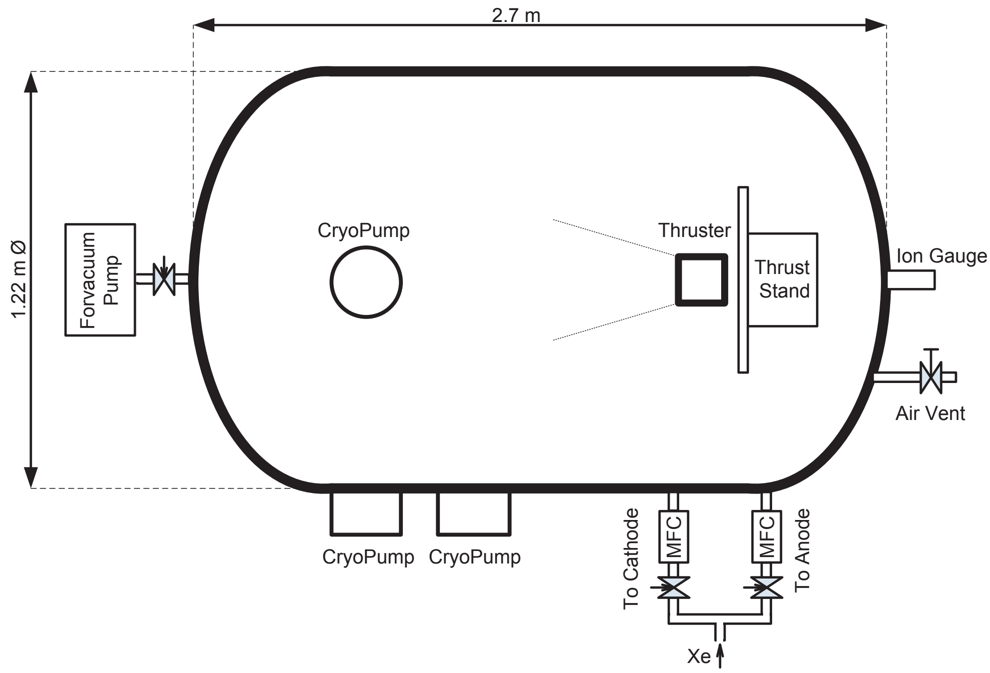

Figure 6. Schematic of the Asher Space Research Institute (ASRI) electric propulsion laboratory experimental facility (not to scale).

Pressure is measured using an 'Ionivac' sensor, model ITR90 from 'Leybold', located behind the thruster. The 'Ionivac' pressure gauge is calibrated by the manufacturer and has a declared precision of 15%. A commercial 0÷1.96 mg/s flow controller, model M100b from MKS, controls xenon flow rate to the thruster's gas distributor. Similarly, a 0÷0.98 mg/s flow controller controls flow rate to the cathode which set to 0.15 mg/s during all tests. The mass flow controllers are calibrated by the manufacturer, with a declared precession of 1% of full scale. The thrust stand used is a feedback-controlled inverted pendulum type, manufactured for ASRI by PLATAR LTD, Moscow, Russia. It is capable of thrust measurements in the range 1÷200 mN. Measurement accuracies, as declared and verified by the manufacturer, are ±3.5% between 5÷10 mN and ±3% between 10÷20 mN. During tests the thrust stand is calibrated using weights once in every two hours.

The experiments were conducted on CAM200-DM, using a low-current heaterless hollow cathode procured from Kharkiv Aviation Institute (KhAI) of Kharkiv, Ukraine. A dedicated Ignition Block (I/B) supplies the high voltage pulse necessary to ignite the cathode as well as the keeper holding voltage required to sustain emitter-keeper plasma after cathode discharge is set. The thruster discharge voltage is supplied by the main P/S that connects between the anode and cathode. Two power supplies feed current to the magnetic circuit; one to the outer coils assembly and the other to the centeral coil. This arrangement enables small magnetic field pattern adjustments during tests in case unexpected thruster behavior is encountered. The thruster electrical setup schematic is depicted in Figure 7.

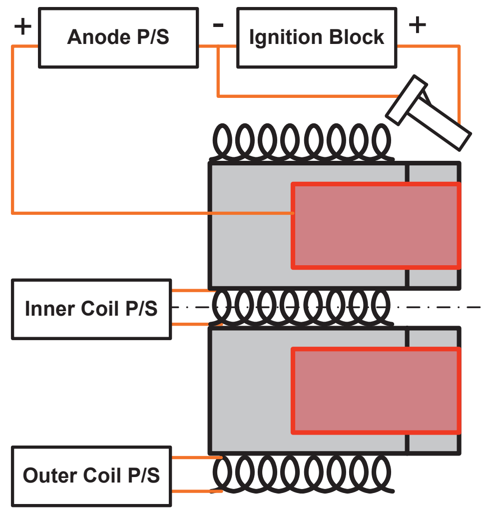

Figure 7. Left: CAM200-DM electrical experimentation scheme.

B. Operation Test Plan

The wall material selection criteria is based on (a) performance (b) erosion level and (c) material dimensional stability. For each material examined the test plan commenced with 15 hours performance investigation at three power levels, 100 W, 200 W and 300 W, followed by 50 hours of operation at 200 W and concluded with a second performance investigation at the above three power levels. The entire operation duration for each wall material was 80 hours. After thruster operation concluded, for each wall material test run, the discharge channel rings were visually examined and material erosion measured for comparison.

To measure discharge rings erosion their profiles were scanned prior and post operation. Scanning was performed with a FARO-GAGE-1001-0411, four arms, 3D measuring system with a measurement resolution of 0.02 mm. Although Hall thruster erosion is usually not significant after less than 100 hours of operation thanks to the high accuracy of the measurement equipment minor variations in erosion should be possible to detect. Moreover, wall erosion is expected to be significantly larger in low-power Hall thrusters in general, and at the thruster's beginning of life[12,13] in particular, which is the case of the CAM200-DM performance testing.

C. Test Results and Discussion

The first discharge wall material to be tested was ZSBN. Soon after ignition it was found that the ZSBN discharge rings became electrically conductive to a detrimental level. This behavior manifested by a sharp increase in discharge current accompanied by a visual change in the shape of the main discharge plasma at the channel exit plane. The thruster eventually shut down spontaniously. Therefore, it was concluded that thruster operation with ZSBN discharge rings could not be properly executed and the material was disqualified. Subsequently the discharge rings were replaced with HP-BN discharge rings followed by M26-BN rings. A picture of CAM200-DM during operation is shown in Figure 8(d).

The performance of CAM200-EM, in terms of specific impulse, thrust and anode efficiency, assembled with HP-BN and M26-BN discharge ring are presented in Figure 8(a)-(c). It can be observed from the figure that at all presented anode power both discharge ring types manifested comparable performance within errorbars. Therefore, there is no particular reason to prefer one material over the other based on thruster performance.

It can also be observed from the figure that at low power of 100 W CAM200-DM generates thrust higher than 5

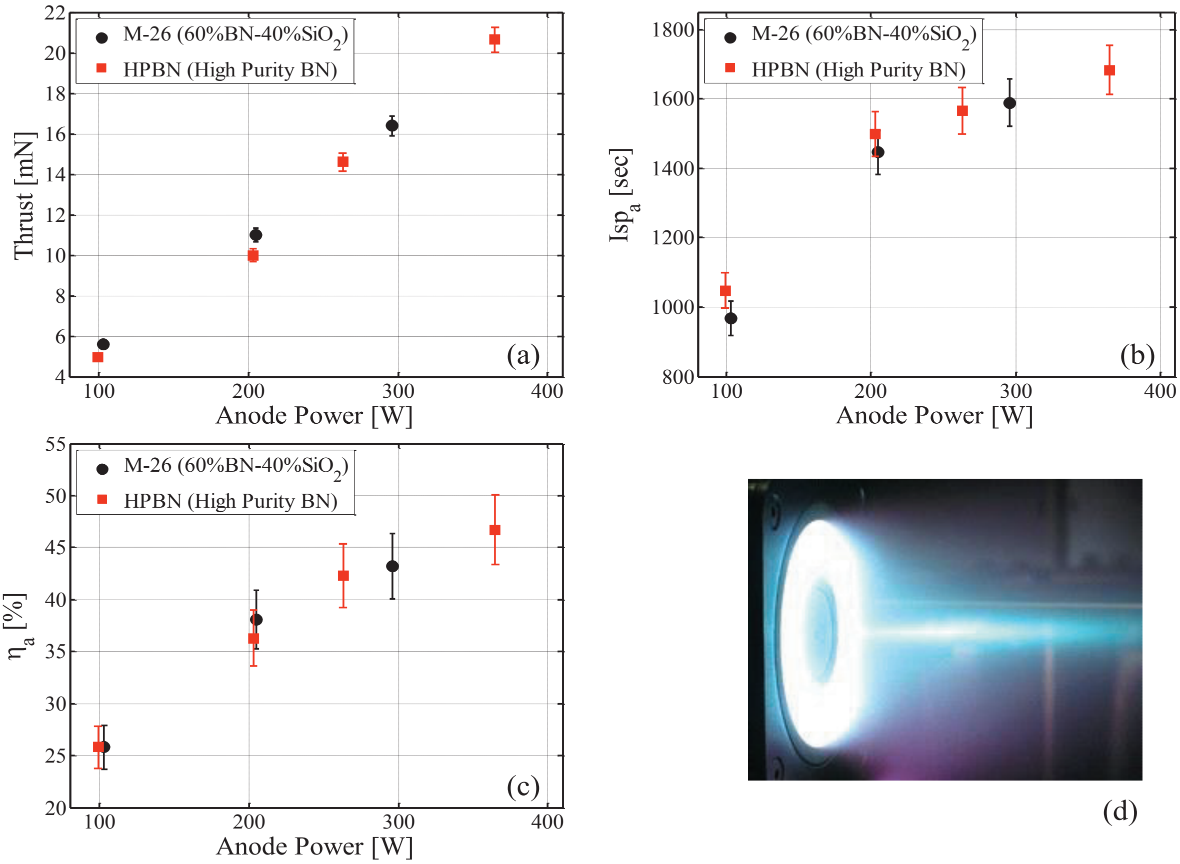

Figure 8. Measured performance of CAM200-DM. (a) Thrust, (b) Specific Impulse, (c) Anode Efficiency and (d) Picture of CAM200-DM during operating.

mN, specific impulse around 1000 sec and anode efficiency higher than 25%. Additionally, at higher power levels of about 300 W CAM200-DM generates thrust higher than 16 mN, specific impulse around 1600 sec and anode efficiency higher than 42%. All performance results are quite satisfactory and clearly indicate on the advantage of using the CAM200 Hall thruster at low power under 300 W.

After thruster operation was concluded the thruster was taken out of the vacuum chamber and discharge rings visually examined. After taking out the thruster with the HP-BN discharge rings it was noticed that the rings shrunk in size and is not pressure-locked as it was prior to thruster operation. Albeit the reduction in HP-BN ceramic channel geometry similar behavior was not observed for the case of M26-BN discharge channel rings. Be that as it may the ceramic discharge channel looked sound and without any visible damage.

It is speculated that the change in HP-BN dimensions during thruster operation can be attributed to the sintering process of the ceramic. It is possible that the combination of temperatures of over 300°C and the pressure exerted by the thruster mechanical configuration led to ceramic material density increase. It was decided to investigate this behavior in more detail in the 'Erosion Measurement' phase where more accurate dimensional analysis is conducted.

D. Relative Erosion Estimation

According to the test plan after the thruster was disassembled and discharge ceramic rings taken out their dimensions were measured. The purpose of the measurements is to examine possible differences in erosion between the thruster with two discharge channel materials - HP-BN and M26-BN.

The dimensional measurements are presented in Figure 9. It can be seen from the figure that both channel type materials were eroded more on the inner discharge ring, close to the thruster center, than on the outer discharge ring. The highest erosion measured is about 0.5 mm on the inner discharge ring at the thruster exit plane. It should be noted that erosion rate in Hall thrusters is highly non-linear[13-15] and diminished significantly during the thruster lifetime. It can also be observed from the erosion measurement results that the HP-BN channel experienced erosion similar to the M26-BN discharge channel. Therefore no obvious advantage in erosion-resistance ability can be attributed to any one of the tested materials.

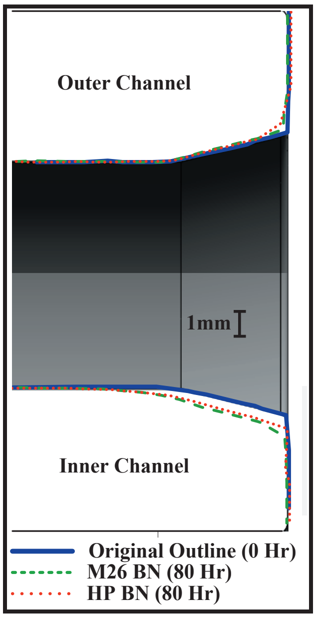

Figure 9. Ceramic channel dimensions for HP-BN and M26-BN ceramic channel materials before and after thruster operation.

The most important finding detected during the channel dimension examination was a minor dimension reduction in the HP-BN discharge rings of the order of ~0.1 mm. Due to the small dimensional change it is hard to discern it in the corresponding figure. Simply put, the discharge channel rings experienced a minor shrinkage that made them loose within the thruster configuration. This phenomenon is not surprising as it was previously observed in Hall thruster discharge channel materials[16] when using HP-BN purchased from the same vendor. It was also found in the same research that M26-BN discharge channel materials do not shrink at temperatures under 1000°C such as in the CAM200 Hall thruster.

Due to the fact that future acceptance test procedures, on future CAM200 thrusters, will include a short thruster operation segment similar phenomenon is expected if the thruster is to be used with HP-BN. Discharge channel shrinkage prior to launch is unacceptable because of possible jilts that might occur to the ceramic channel. For this reason, and because both HP-BN and M26-BN materials exhibited similar performance, it was decided to disqualify the HP-BN material.

The material chosen for the CAM200 Hall thruster is M26-BN which is also the material used in other conventional Hall thrusters.

VI. Conclusion

The material selection program of CAM200 was concluded. The program included a structural integrity test, performance test and erosion test. Three discharge channel materials were examined - HP-BN, M26-BN and ZSBN.

All three discharge channel materials were tested and approved for high launching loads, therefore validating both the thruster structural configuration and discharge ring materials.

Thruster performance was tested with all three discharge channel materials. During this test the ZSBN-made discharge channel rings became electrically conductive to a detrimental level. For this reason ZSBN was disqualified and performance tests continued only with HP-BN and M26-BN channel materials. Thruster performance with HP-BN and M26-BN rings was similar without any obvious advantage to neither of them.

Erosion measurements were performed on the discharge rings after 80 hours of thruster operation and showed no significant difference in erosion between the two materials. On the other hand a slight reduction in dimensions was observed in the HP-BN rings that made them loose within the thruster configuration. To avoid any possible future complications it was decided to continue with the M26-BN material.

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