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INVESTIGATION OF THE EROSION CHARACTERISTICS OF A LABORATORY HALL THRUSTER

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ABSTRACT

The requirements of spacecraft propulsion systems for new mission profiles have increased beyond the existing level of Hall thruster technology. The range of desired power levels and operating conditions present a challenge for assessing operational lifetime for each case being considered. Therefore, an understanding of the discharge channel erosion processes that limit lifetime is desired. To investigate this, five grades of boron nitride (BN) ceramics were tested at NASA Glenn Research Center (GRC) with a 3-kilowatt (kW), stationary plasma thruster (SPT)-type laboratory Hall thruster. The ceramic discharge channels were tested for 200 hours each with the same thruster and at consistent discharge parameters. An additional test was conducted with a select grade of BN to examine the erosion rate of Hall thruster channel walls by varying the discharge power (at a fixed discharge voltage) and the applied magnetic field topography. A global erosion characteristic profile for the NASA-120M as a function of thruster discharge parameters is examined and the results are discussed.

INTRODUCTION

The requirements of spacecraft propulsion systems for potential new missions have increased beyond that of existing Hall thruster technology.[1,2] Hall thruster concepts that are being considered include multi-mode and high-power operation. The power levels and functionality of these new areas in Hall thruster technology present challenges with respect to quantifying thruster lifetime without performing expensive and time-consuming lifetime tests for each of the different cases being considered. Therefore, an understanding of the processes that limit lifetime is desired.

Erosion of a Hall thruster channel walls on a SPT or the guard rings on an anode layer thruster (TAL) is the primary operational life limiter for these engines. The erosion results from impingement of the propellant and is thought to be influenced by a thruster's physical parameters, applied magnetic field and power density.[3,4] Several experimental investigations have been conducted to evaluate the lifetime of Hall thrusters.[3–12] Analytic modeling techniques have been developed to help understand the experimental results and predict thruster lifetime.[13–16] These models predict the erosion rate as a function of ion current density at the surface of the exposed material and the volumetric sputtering coefficient (which is dependent on the ion's angle of incidence, average energy, charge state and wall material). The ion current density at the surface of the discharge chamber walls can be approximated by considering the physical and operating parameters of a Hall thruster

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and the influence of the wall material. The sputtering coefficient is typically determined empirically from lifetime tests of Hall thrusters or experimentally from a single energy ion beam sputtering apparatus. However, an ion beam sputtering apparatus does not capture the effects of a distribution of ion energies, various ion charge states and applied magnetic fields.

The erosion of both SPT- and TAL-type Hall thrusters has been quantified over a range of operational parameters during recent investigations at NASA GRC. The completion of the 1000-hour erosion test of the T-220 SPT-type thruster, operating at 500 volts (V) and 20 amps (A) discharge, indicated an estimated 4800-hour operational lifetime before the magnetic circuit would begin eroding.[9] The D-80 TAL-type thruster, operating at 700 V and 4 A discharge, indicated a substantial erosion through the outer guard ring between 600 and 900 hours.[10] The 1000-hour, T-220 test was conducted at the thruster's nominal operating parameters, whereas the D-80 investigated the effect of high discharge voltage operation on thruster lifetime.

Recent experiments at GRC investigated the effect of different grades of commercially available boron nitride (BN) on the erosion resistance of a Hall thruster's channel walls at a fixed operating condition. The influence of the operating condition on the erosion process was also examined. The experimental facilities, thruster and laser profilometery system used to map the erosion profiles are described below. The results of the BN material study and the influence of thruster operating conditions on erosion is presented and discussed.

EXPERIMENTAL APPARATUS

A. Vacuum Facilities

NASA GRC's Vacuum Facility 8 (VF-8; shown in Figure 1) is a 1.5-m diameter by 4.7-m long tank with a pumping speed in excess of 160,000 liters per second (air) produced by four 0.9-m diameter oil diffusion pumps. For this investigation VF-8 was used for the erosion characterization of various Hall thruster discharge chamber insulator materials.

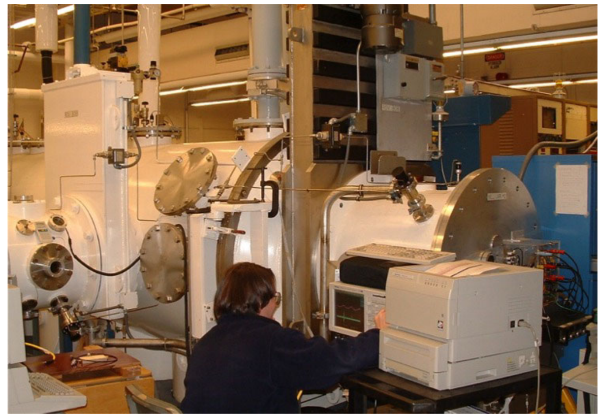

Figure 1. Vacuum Facility 8.

B. Hall Thruster

The experimental results presented in this paper were generated using a 3-kW-class, laboratory-model NASA-120M Hall thruster. This Hall thruster was developed as a test-bed for erosion research, capacitive discharge operation studies, and for investigation of the influence of channel parameters on the operation. The NASA-120M has an outer diameter of 120 mm and a hollow cathode located at the 12 o'clock position (Figure 2). The cathode was positioned at a 45-degree angle to the face of the thruster and the cathode orifice was located 12.7 mm downstream of the thruster exit plane and 22.5 mm above the outer wall of the discharge channel. The discharge chamber of the NASA-120M was composed of a primary BN channel, with replaceable inner and outer rings.

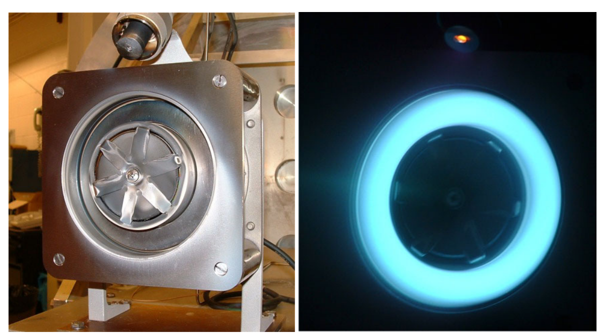

Figure 2. NASA-120M, a 3-kW-class, laboratory-model Hall thruster.

The NASA-120M performance characteristics are comparable to state-of-the-art Hall thrusters (500 V; 3.2 kW; total specific impulse = 2290 seconds; and total efficiency = 53%). Table 1 shows the measured performance characteristics of the NASA-120M for the two operating conditions used in this experiment. The cathode was operated at a mass flow rate of 0.85 mg/s throughout the testing.

Case	Voltage	Current	Power [kW]	Total Isp [sec]	Total Efficiency
(1)	300	5.5	1.65	1600	47%
(2)	300	4.3	1.3	1570	46%

Table 1. NASA-120M thruster performance.

C. Power, Mass Flow and Data Acquisition Systems

The NASA-120M was operated with a laboratory power console of commercially available power supplies. The discharge power supply is capable of producing a constant voltage output ranging from 0–600 V at current levels of 0–16 A. The power console contains auxiliary supplies for the electromagnetic coils and the hollow cathode. The xenon propellant was supplied to the anode and the cathode by commercially available mass flow controllers integrated into the laboratory feed system. The feed system was calibrated using a constant volume flow technique. A multiplexing digital voltmeter data acquisition system was used in conjunction with a personal computer (PC) to monitor the operating parameters of the Hall thruster system during the wear test. The PC and data acquisition system permitted unattended operation of the Hall thruster by monitoring upper and lower discharge current limits. If the thruster discharge current varied beyond the alarm limits, the PC acquisition system would signal a relay trip that would shut down the main discharge and mass flow system.

D. Laser Profilometry

The NASA GRC laser profilometry system was used during the T-220 and D-80 erosion investigations and is described in detail elsewhere.[9,10] The technique incorporates a cylindrical lens and laser to produce a plane of light perpendicular to the test sample surface of interest. The interaction of the laser light

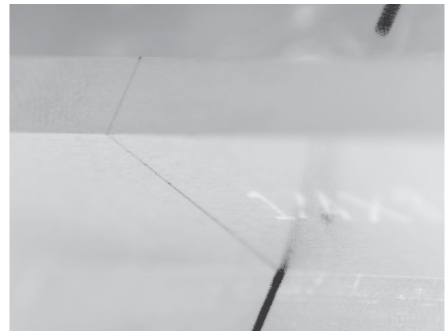

Figure 3. Sample image of a 0.25 in. x 0.75 in. gauge block that illustrates the laser profile of the surface.

on the surface of the sample forms a line that can be imaged by a CCD camera located at a different angle. A sample of an imaged profile of a 0.25 in. x 0.75 in. gauge block is shown in Figure 3. The laser, CCD camera and thruster are mounted on a rigid, optical aluminum frame. The thruster is affixed to a rotational stage and the laser adjusted such that the plane of light crosses the center of the thruster. The erosion profiles for the inner and outer walls of the discharge channel are typically mapped every one degree. The average error was less than 0.05 mm for both radial and axial directions. The error was determined by examining the distortion width of the imaged beam profiles of the reported erosion profiles in this paper. An illustration of the laser profilometry system is presented in Figure 4.

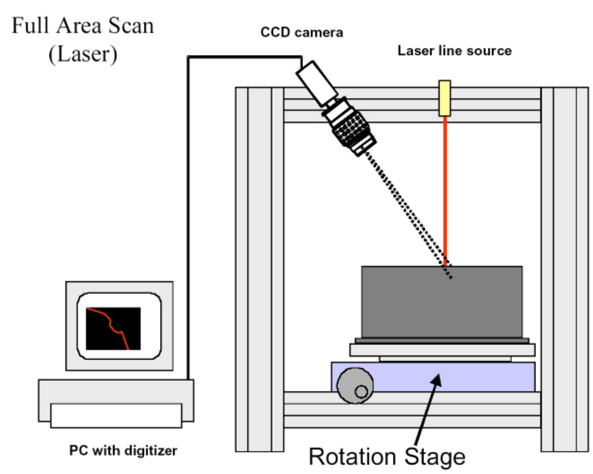

Figure 4. Laser Profilometry System.

RESULTS AND DISCUSSION

A. Erosion Measurements

Erosion measurements were made at the two different operating conditions shown in Table 1. The first operating condition was used for a material comparison study of five different grades of BN. This operating point was chosen for the stability of thruster operation and the ability to compare results with previous erosion measurements conducted on other thrusters. The second operating condition was used to investigate the role of the applied magnetic field on the erosion rate. The discharge voltage was held at 300 V. The mass flow rate was reduced and the magnetic field was re-optimized. These changes resulted in an approximately 20% decrease in the current and power densities at the second operating point.

The erosion profiles discussed below were generated at the 0 degree circumferential position, corresponding to the 12 o'clock position. There was an early indication of accelerated erosion at the cathode position as observed by Jacobson in the D-80 erosion study and Albarède in the cathode stream interaction study.[10,17] However, the periodic circumferential erosion pattern observed in the D-55 erosion investigations were not observed.[3] Figure 5 illustrates the circumferential dependence of the erosion after 200 hours of operation with the BN channel and Figure 6 demonstrates the asymmetric erosion near the cathode.

The observed erosion on the inner wall of the discharge channel at 0 degrees was greater than that at 180 degrees. This was observed with all materials investigated, although data for only one material is

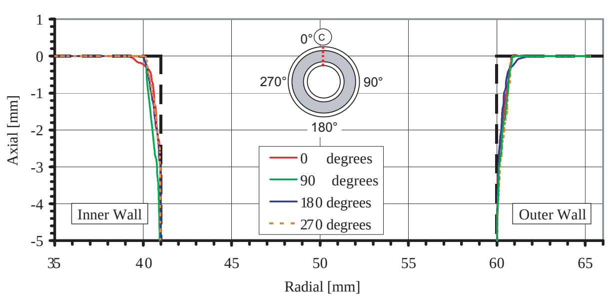

Figure 5. Comparison of the inner and outer wall erosion profiles at 90° intervals.

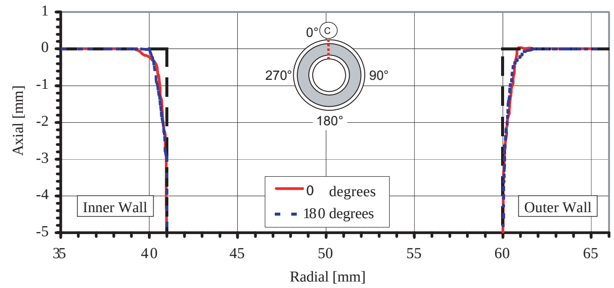

Figure 6. Comparison of the inner and outer wall erosion profiles at 0° and 180° intervals.

shown in Figure 6. The cause of this erosion is not clear, although it seems likely that it is related to the interaction of the discharge plasma with the propellant exhausted through the cathode. Errors in concentricity of the discharge channel and the magnetic circuit were discounted as a potential cause as this was verified before each of the six erosion tests.

B. Material Study

The initial goal of this investigation was to examine several grades of BN that are commercially available to evaluate the effects of each material on thruster lifetime and operation. The five BN materials used in this study are listed in Table 2.

Material	BN [%]	SiO_2 [%]	B_2O_3 [%]	Ca [%]	Other [%]
A	90	0.2	6	0.2	3.6
AX05	99	--	0.2	0.04	0.47
HP	92	0.1	0.3	3	4.6
M	40	60	--	--	--
M26	60	40	--	--	--

Table 2. BN material characteristics used in this investigation.

Each of the five material samples was machined from a cylindrical billet to the same initial dimensions and installed in the NASA-120M thruster prior to testing. Each sample was operated at 1.65 kW in VF-8 for approximately 200 hours. At the end of the five erosion tests the BN discharge channels were each placed in the laser profilometry system to map the erosion profiles.

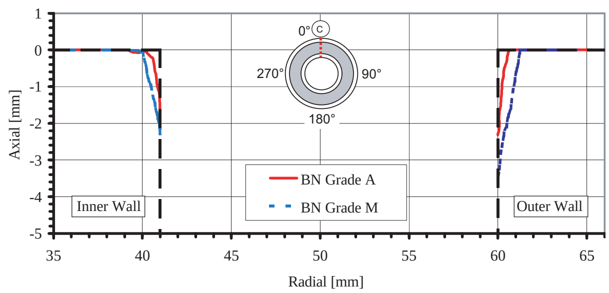

Figure 7. Comparisons of the BN samples that showed the most erosion (BN grade-M) and the least (BN grade-A).

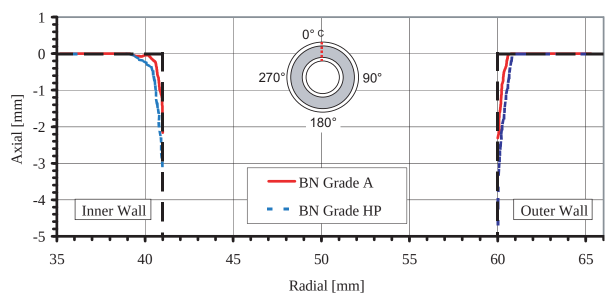

Figure 8. Comparison of grade-A and grade-HP BN erosion profiles.

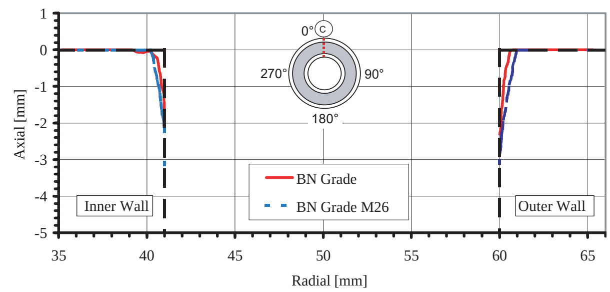

Figure 9. Comparison of grade-A and grade-M26 BN erosion profiles.

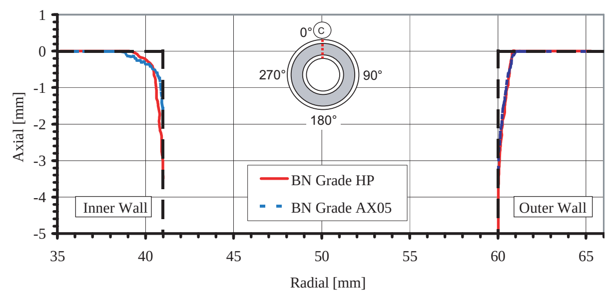

Figure 10. Comparisons of the two high purity grades of BN (AX05 with 99% BN and HP with 92% BN).

Several observations were made during the evaluation of the BN discharge channel samples. The least amount of erosion did not occur with the two highest purity BN samples (AX05 or HP), as suggested by Garnier et al., but with grade-A BN.[18] The most erosion occurred with the grade-M material, which had the lowest fraction of BN. A comparison of the BN samples with the most and least amount of eroded material is shown in Figure 7.

The presence of B_2O_3 could have been responsible for the reduced erosion of the grade A material relative to the two higher purity BN samples (AXO5 and HP). The trace amounts of impurities found in the HP grade of BN (Ca for example) did not improve the material's resistance to erosion, as can be seen in Figure 8, which is a comparison of the grade-A BN with a 6% concentration of B_2O_3 and grade-HP BN (the next highest concentration of B_2O_3). The additional SiO_2 found in grades M and M26 did not offer any benefit, as can be seen in Figure 9, which is a comparison of the grade-A BN with a 6% concentration of B_2O_3 and grade-M26 with a 60% concentration of BN and 40% of SiO_2.

While it is difficult to assess how the differences in material composition affected the erosion rate, it was clear from these data, as can be seen from Figures 7 and 8, that the addition of components other than BN did not improve erosion resistance with the exception of B_2O_3. And while the results suggest that the addition of B_2O_3 to a Hall thruster's discharge channel may slightly improve the channel's resistance to erosion, neither the mechanism for this observed improvement, nor the optimal percentage of B_2O_3 component was determined in this study. These data also show that increasing the concentration of BN generally improved erosion resistance, as illustrated in Figures 7 and 9.

A comparison of the erosion observed using the two highest purity grades of BN is presented in Figure 10. The wall erosion patterns for the AX05 and HP samples are nearly identical, with only a slight

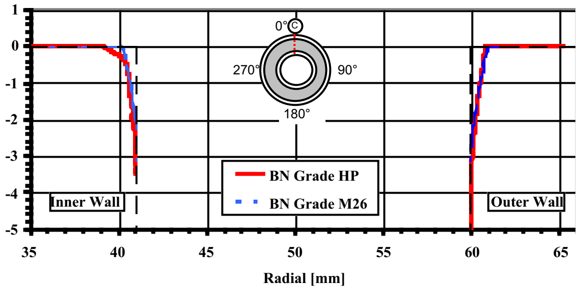

Figure 11. Comparison of grade-M26 and grade-HP BN erosion profiles.

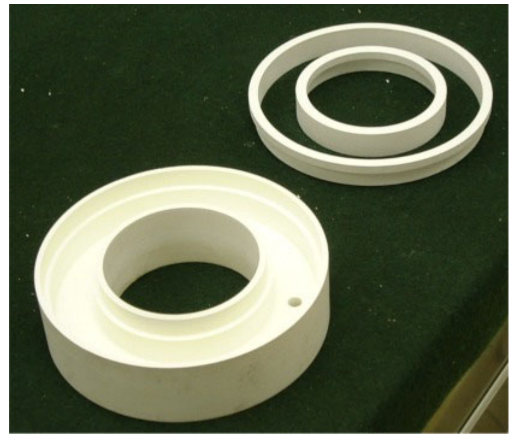

Figure 12. The NASA-120M replaceable segmented discharge channel.

difference in the measured erosion profile along the inner wall. This slight difference makes it unclear whether the addition of a small percentage of Ca or other impurities has any perceptible effect.

Figure 11 illustrates that the erosion profiles of the M26 and HP grades of BN were the most similar of the five materials investigated. The M-26 grade material is most similar to the material used in Russian flight thrusters. From a performance standpoint, the HP grade BN, which has been used in the construction of other thrusters, has been shown to have no significant disadvantages with respect to performance relative to M-26.[19] However, the HP grade BN material does cost less than the M26 material. Other material properties that may further differentiate the suitability of these materials for operational use—such as mechanical strength, thermal conductivity, and resistance to thermal shock—were not considered as part of this investigation.

C. Operating Condition Study

The second part of the investigation was to examine how operating conditions influence discharge channel erosion. The approach used was to reduce the anode mass flow rate and re-optimize the applied magnetic field. The discharge voltage was held constant. Therefore, any changes in the erosion profiles could be attributed to changes in density or applied magnetic field. The resulting operating power was 1.35 kW in comparison to the 1.65 kW used for the material investigation.

For this portion of the investigation the discharge chamber of the NASA-120M was modified to accommodate replaceable segments for the inner and outer channel walls, as seen in Figure 12. This modification expedited fabrication of new test specimens and reduced test sample cost. The axial length of the segments were chosen such that the interface of the base BN channel and each segment would not interfere with the operation and erosion characteristics of the thruster. This length was determined from the results of the initial study. The HP grade of BN was chosen for this stage of the investigation due to its favorable cost and its similarity to M26 with respect to erosion and operating characteristics. This was desirable because, as noted, M26 has been used successfully by Russian Hall thrusters on orbit for decades.

The circumferential erosion asymmetry with respect to the cathode previously shown in Figures 5 and 6 was observed during this test segment as well. The erosion profiles for the 1.3-kW and 1.6-kW power levels on HP-grade BN are presented in Figure 13.

The erosion profiles show the inner wall erosion increased while the outer erosion decreased at the new operating point. It was expected that the overall erosion would decrease with a reduction in anode mass flow rate. However, as indicated in Figure 13, the erosion of the inner wall increased. In order to investigate this result, the magnetic field topography for each of these two cases was considered because electric field lines, which in turn are responsible for ion trajectories, are approximated by the equi-potentials of the applied magnetic field topography.[20–22] A comparison of the magnetic field topographies for each of the two operating points is

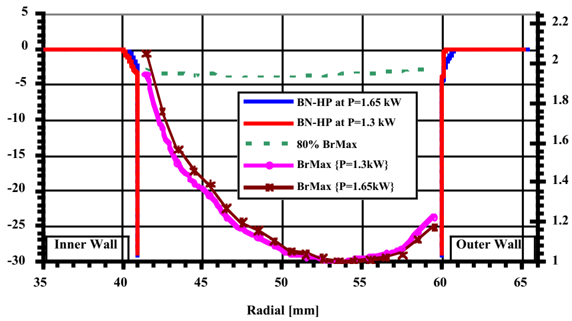

Figure 13. Comparison of the 1.35 kW and 1.6 kW erosion results, normalized radial magnetic field magnitudes versus radial position information, and the location corresponding to a radial magnetic field strength that is 80% of the maximum.

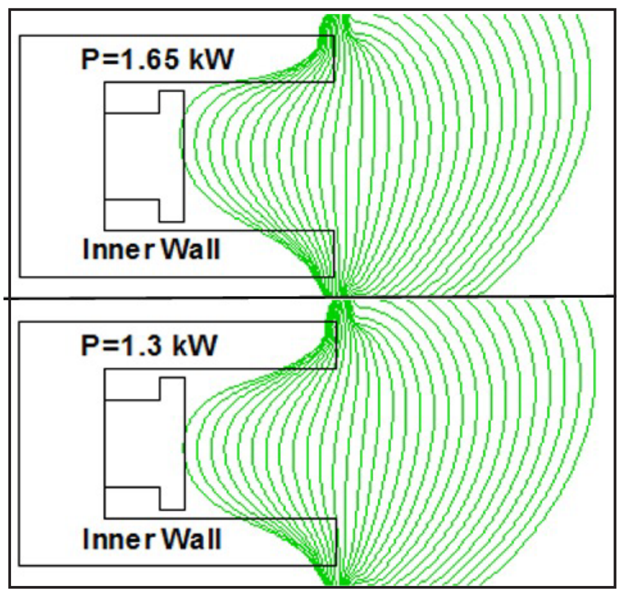

Figure 14. The optimized magnetic field topographies for the 1.65-kW and 1.3-kW operating cases discussed in this work.

illustrated in Figure 14. The field topographies were generated using a 3D magnetostatic solver that has been benchmarked with several thruster designs with an accuracy of 10% or less.

The magnetic field of the 1.65-kW operating point is shifted towards the outer wall upstream of the area where the erosion occurred. The magnetic field of the 1.3-kW operating point was more symmetric than the 1.65-kW case and was closer to the shape of an ideal plasma lens.[19,23] However, the differences in the magnetic field topographies occurred in regions where there was little or no erosion.

Rather than the magnetic field topographies being responsible for the observed erosion profiles, the radial magnetic field magnitudes in the vicinity of the walls was considered. The normalized radial magnetic field strengths, as a function of radial position from the inner wall to the outer wall, are shown in Figure 13. The radial field magnitudes are normalized to the minimum radial field across the channel, which subsequently occurred at the same radial position. The erosion was minimized where the radial magnetic field strength along the wall was maximized. Similar results were observed during an accelerated guard ring erosion test on a TAL Hall thruster by Marrese et al.[3] It was discovered that due to the particular design of the magnetic circuit of the D-55 thruster, there were regions of lower radial magnetic fields that occurred between electromagnetic coils. These regions of decreased magnetic field corresponded with the region of greater erosion.

The location at which the radial magnetic field strength dropped to 80% of the maximum value was also calculated from the magnetic field topographies obtained for each operating condition. This location, also shown in Figure 13, corresponded to the most upstream location where measureable erosion was observed. The ionization region of a Hall thruster has also been shown to occur at approximately 80% of the maximum of the radial magnetic field.[24,25]

SUMMARY

Methods for predicting Hall thruster erosion, as a function of physical parameters and operating conditions would be valuable for assessing a particular design during the development stages. To this end, the erosion characteristics of the NASA-120 Hall thruster was investigated. The erosion characterization examined five different grades of boron nitride at a fixed operating condition to understand how material can enhance the erosion resistance. The study found that the grade-A BN with a 6% concentration of B_2O_3 demonstrated the highest resistance to erosion and that grade-M, with only 40% of BN, had the most amount of eroded material. The material study also indicated that the M26 grade of BN and grade-HP had comparable erosion profiles. The circumferential asymmetry of the channel erosion that has been reported previously in the literature was observed. [10,17]

The second portion of this investigation involved changing the NASA-120M operating set point for a given grade of BN. This was accomplished by varying the thruster's discharge current at a fixed discharge voltage. The applied magnetic field was re-optimized. The results of this experiment indicated a relationship between the radial magnetic field strength near the channel walls and the amount of eroded material. The inner wall erosion increased with the drop of the magnetic field, while the outer wall erosion decreased with an increase in the magnetic field in the region of the outer wall between the two operating conditions. Internal and near-field plasma property measurements need to be conducted before further conclusions can be drawn on the data presented in this work.

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The requirements of spacecraft propulsion systems for new mission profiles have increased beyond the existing level of Hall thruster technology. The range of desired power levels and operating conditions present a challenge for assessing operational lifetime for each case being considered. Therefore, an understanding of the discharge channel erosion processes that limit lifetime is desired. To investigate this, five grades of boron nitride (BN) ceramics were tested at NASA Glenn Research Center (GRC) with a 3-kilowatt (kW), stationary plasma thruster (SPT)-type laboratory Hall thruster. The ceramic discharge channels were tested for 200 hours each with the same thruster and at consistent discharge parameters. An additional test was conducted with a select grade of BN to examine the erosion rate of Hall thruster channel walls by varying the discharge power (at a fixed discharge voltage) and the applied magnetic field topography. A global erosion characteristic profile for the NASA-120M as a function of thruster discharge parameters is examined and the results are discussed.

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