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Thermal Characterization of a NASA 30-cm Ion Thruster Operated up to 5 kW

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THERMAL CHARACTERIZATION OF A NASA 30-CM ION THRUSTER OPERATED UP TO 5 KW

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ABSTRACT

A preliminary thermal characterization of a newly-fabricated NSTAR-derived test-bed thruster has recently been performed. The temperature behavior of the rare-earth magnets are reported because of their critical impact on thruster operation. The results obtained to date showed that the magnet temperatures did not exceed the stabilization limit during thruster operation up to 4.6 kW. Magnet temperature data were also obtained for two earlier NSTAR Engineering Model Thrusters and are discussed in this report. Comparison between these thrusters suggests that the test-bed engine in its present condition is able to operate safely at higher power because of the lower discharge losses over the entire operating power range of this engine. However, because of the 'burn-in' behavior of the NSTAR thruster, magnet temperatures are expected to increase as discharge losses increase with accumulated thruster operation. Consequently, a new engineering solution may be required to achieve 5 kW operation with acceptable margin.

INTRODUCTION

The benefits of high-specific impulse ion propulsion have been successfully demonstrated with the NSTAR (NASA Solar Electric Propulsion Technology Applications Readiness Program) ion thruster used on the Deep Space 1 (DS-1) spacecraft.[1] This ion thruster was designed to operate at a maximum input power and lifetime of 2.3 kW and 8,000 hours, respectively. The propulsion system has successfully met all of the performance requirements to date. Recent interest in interplanetary missions present propulsion requirements that can be addressed with ion thrusters operating at 3 to 5 kW input power. Consequently, a program was initiated at the NASA Glenn Research Center (GRC) to determine the capability of an NSTAR-class thruster to operate at these higher powers. One of the critical issues for successful long-life operation of the ion thruster is operating temperature. Thruster components that are expected to be significantly affected by increased operating temperatures include: 1) the rare-earth magnets used in the discharge chamber, 2) the discharge and neutralizer hollow cathodes, and 3) the propellant isolators. This report will focus on the magnet temperature behavior. The performance, as well as other operational aspects, of this engine has been reported elsewhere.[2,3]

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The rare-earth magnets used in the NSTAR thruster provide magnetic fields of sufficient strength for electron confinement within the discharge chamber, which is critical for efficient thruster operation. These magnets degrade rapidly at temperatures in excess of their thermal stabilization limit of 350 °C. Consequently, thruster operation is typically limited to temperatures below this thermal stabilization limit.

Rawlin et al. measured NSTAR thruster body and ancillary surface temperatures over the thruster power range of 0.5 to 2.3 kW.[4] Several thermocouples were mounted on the thruster and measurements were made once the engine thermally stabilized during characterization testing. Data were collected on a series of Engineering Model Thrusters (EMTs) developed during the engine design evolution to the flight system. Five engines were tested, including a flight-like pathfinder engine; the evolution of the thruster design is detailed in Ref. 4. These engines were typically installed in an enclosure that allowed the temperature of the ambient environment to be varied from -130 °C to 60 °C. This enclosure enabled the radiative characteristics of the ion engine to be investigated. The study of the thermal behavior was performed in part to understand how to minimize or eliminate the rejection of waste heat from the DS-1 ion engine to the spacecraft. The results of this study were used to establish the maximum magnet temperature allowed in the NSTAR thruster at 310 °C.[4] This NSTAR temperature limit subsequently established a safety margin of 40 °C with respect to the thermal stabilization limit.

As part of the development of a high-power ion thruster, an investigation is underway to characterize the thermal behavior of an NSTAR-derived ion thruster operated over an input power range of 0.5 to 5 kW. This engine will be referred to as the GRC test-bed thruster. The power range is 2x greater than that of the NSTAR engine, and consequently, would affect magnet temperatures.

Prior to testing of the GRC test-bed thruster, temperatures were measured on two NSTAR EMTs to determine their thermal behavior up to the thermal stabilization limit of the magnets. The results of these measurements will be included in this report.

Thruster surface temperatures were measured directly during performance testing. Additionally, temperatures on the hollow cathode surfaces were measured optically because of the difficulty with other temperature measurement approaches. This work is in progress, the results presented here are preliminary. This report consists of the following: 1) the methodology used for temperature measurements, 2) summary of the magnet temperature measurements of two EMTs (EMT 4 and EMT 3), 3) preliminary magnet temperature results obtained during thruster operation up to 4.6 kW, 4) a brief discussion on the quality of the temperature measurements, and 5) the relative differences in the results for all three engines.

TEST DESCRIPTION

Temperature Measurement Approach The thermal characterization of EMT 3 and 4 were performed in a similar fashion as the EMT characterization for the NSTAR ion thruster development program.[4] The procedure used for temperature measurement was to maintain the ion engine at a fixed condition until the temperatures stabilized. Stabilization in this investigation was defined as when a majority of the thermocouple readings changed by 3 °C or less during a 30 minute period. Temperatures were measured with and without beam extraction. For operation without beam extraction, the gas flows were adjusted to replicate the discharge power level (voltage changed while current remained constant) that existed with beam extraction. This approach was validated by measuring temperatures with and without beam extraction, wherever possible.

Th procedure used for testing of the GRC test-bed thruster was similar to the aforementioned one, however, temperatures were measured before the thermal stabilization criterion was met to accommodate thruster performance testing. For this report, the recorded temperatures are reported along with error bars that represent the expected thermally stable temperatures.

Thruster Description. The NSTAR-derived GRC test-bed thruster and the NSTAR EMTs have been described in extensive detail elsewhere.[1,2,3,4] Briefly, the ion engine consists of a 30-cm diameter discharge chamber, which incorporates a permanent magnet ring-cusp configuration and two-grid ion optics. The discharge chamber is an aluminum cylinder with a conical section that eliminates the back-end corner, as shown in Figure 1. The magnets used are rare-earth magnets that have been thermally stabilized at 350 °C. The ring-cusp configuration consists of three rings: 1) the front ring, adjacent to the grid set, 2) the middle ring, at the junction of the cylindrical and conical body sections, and 3) the cathode ring, on the thruster back wall around the cathode assembly.

While the EMTs and GRC test-bed thruster designs are similar, differences in designs and operation may have significant thermal effects. These differences are summarized in Table 1.

Thruster operating procedures and results have been described elsewhere.[3]

Thruster Thermal Conditions. For the NSTAR EMTs, the entire engine was installed in a thermally isolated enclosure to more accurately represent the DS-1 spacecraft configuration. The enclosure is expected to increase all temperatures in the engine because it reduces the radiation losses from the thruster. The GRC test-bed thruster was tested without a thermal-isolation enclosure. This engine is only thermally isolated from its mounting supports. The GRC test-bed and EMT engines were also tested in different facilities as described below. However, the influence of the test facility on the thermal behavior of the thruster remains undetermined.

TEST SUPPORT EQUIPMENT

Test Facilities. For the NSTAR EMTs, the tests were conducted in a large space simulation chamber at NASA GRC. The facility, Vacuum Facility #5, is a steel tank that is 4.2 m diameter x 18.3 m long.[5] Facility pressures at 2.3 kW thruster power was nominally 2.0 x 10^{-3} Pa (1.0 x 10^{-5} torr) operating on 20-0.8 m diameter oil diffusion pumps. The thrusters were installed in the thermally isolating enclosure that extended into the tank during operation.

For the GRC test-bed thruster, the test facility, Vacuum Facility #11, consisted of an aluminum vacuum chamber that is approximately 2.2 m diameter x 7.9 m long. The chamber was equipped with 4-0.9 m diameter and 3-1.2 m diameter helium refrigerator cryo-pumps. It also included a turbo-molecular pump for evacuating elements not pumped by the cryo-pumps, such as helium. The total pumping speed of the facility was approximately 110,000 liters per second on xenon propellant. At the flow rate corresponding to operation at the maximum input power of 4.6 kW, the background pressure was 6.6×10^{-4} Pa (5.0×10^{-6} torr).

Power Supplies. Operation of the ion engines were conducted using two similar power consoles originally developed for the NASA 30-cm thruster.[6] The power console developed for NSTAR EMT testing was used for the EMTs' temperature characterization. This console was subsequently modified for testing the GRC test-bed thruster up to 5 kW. The thrusters use 4 power supplies for steady-state operation, and require 2 additional power supplies for start-up of the discharge and neutralizer cathodes**.**

Instrumentation. For NSTAR EMTs temperature characterization, EMT 3 and EMT 4 were outfitted with multiple Type K thermocouples, most of which were on the magnet ring surfaces on the discharge chamber exterior. Two or more thermocouples were attached at different positions around the thruster body for redundancy and to determine if any azimuthal asymmetry existed. Typically, the thermocouples were positioned 180° apart (top and bottom). For all thrusters, the thermocouples were electrically isolated from ground to ensure proper engine operation during beam extraction. Temperatures were displayed on digital meters.

For the GRC test-bed thruster, temperature measurements are being performed using three methods:

1) Thirty-four Type K thermocouples are attached at various surfaces on the thruster, including six on the magnet ring surfaces. The locations of the thermocouples attached at the magnet rings are shown in Figure 1.

2) A charged injection diode video camera records the optical emission from the GRC test-bed thruster surfaces. These measurements of light intensity from the operating thruster are converted to temperatures using a calibration with a tungsten filament lamp.

3) A disappearing filament oyrometer was used to measure temperatures on the discharge cathode and neutralizer cathode orifice and keeper plates.

While the latter two techniques are being used, the procedures require further refinement in order to gain a high degree of confidence in the temperature measurements. Therefore, temperatures reported herein are limited to the thermocouple data.

TEST RESULTS & DISCUSSION

For all of the engines investigated to date, the magnet temperatures as functions of discharge power, and, therefore, thruster power will be presented. In addition to the temperatures, the discharge losses were determined over the discharge and thruster power ranges. Discharge losses are defined as the discharge power divided by the beam current and represent the power required to generate the internal plasma from which the ion beam is extracted.

EMT Test Results. The EMT 4 engine was tested over the power range of 0.5 kW to approximately 2.7 kW. Several of the temperature measurements were obtained without beam extraction. The measured temperatures as functions of discharge power and thruster input power are shown in Figures 2 and 3, respectively. In each, the temperatures are shown for the front, middle, and cathode (back) magnet rings. The indicated temperatures are averages of all temperatures recorded on each ring. There were only small differences in measurements at different azimuthal positions, which is included in the indicated temperature reading uncertainty (error bars). Also included in the temperature uncertainty is the inherent thermocouple error of ≤ 1%.

The maximum temperature measured on EMT 4 was approximately 325 °C, which was recorded on the front magnet ring at a thruster power of 2.7 kW. The temperature behavior over the power range of 0.5 to 2.3 kW was similar to results obtained in Ref. 4.

EMT 3 was operated up to approximately 3.2 kW. Temperatures as functions of discharge and thruster power are shown in Figures 4 and 5, respectively. As can be seen, performance was similar to EMT 4. The most noteworthy difference was that while EMT 3 operated at slightly higher temperatures over the discharge power range, the discharge powers necessary to produce the required beam powers were lower. Consequently, the thruster power as a function of the discharge power was higher. The maximum magnet temperature measured on EMT 3 was approximately 330 °C on the front ring when the thruster power was at 3.1 kW, which is very similar to the maximum temperature on EMT 4 when operated at 2.7 kW.

While the magnet temperatures for both EMT 4 and EMT 3 exceeded the NSTAR temperature limit at thruster powers greater than 2.3 kW, the temperatures never reached the thermal stabilization limit of 350 °C. Consequently, no irreversible changes in the magnets were expected to occur nor were any apparent in subsequent thruster operation.

For both of the EMTs, the discharge losses decreased with increasing discharge (and therefor e thruster) power and reached a minimum value of approximately 200 W/A, both of which are consistent with previous testing. [7]

GRC Test-bed Thruster Results. Testing of the GRC test-bed thruster to date has focussed on performance characterization and plasma measurements.[2,3] Consequently, there has only been a limited opportunity for steady-state temperature measurements. In general, the thruster was maintained at each operating condition for approximately 30 minutes. Typical stabilization times for the data collected during EMT 4 and 3 testing was approximately 60 to 90 minutes. Based on the stabilization behavior of the measured temperatures on the EMT engines, it is estimated that the temperatures on the GRC test-bed thruster were within approximately 2 to 5 °C of their thermally stable point. The error bars for the temperatures shown in Figures 6 and 7 incorporated this stabilization error.

Testing was performed after the thruster had accumulated about 50 hours of total operating time. The engine was operated over the thruster power range of 0.5 to 4.6 kW. The magnet ring temperatures as functions of discharge and thruster power are shown in Figures 6 and 7, respectively. As with EMT 3, the temperatures are the average of all the temperatures recorded on the respective rings.

In general, the measured temperatures were lower than those in either of the EMT engines over the same discharge power range. As can be seen, the front ring was the hottest and was the only location where the NSTAR temperature limit was exceeded. This occurred at a discharge power of approximately 420 W and a thruster power of approximately 4 kW. However, there was no discernable change in subsequent thruster operation. The maximum temperature recorded for this thruster was approximately 335 °C at a thruster power of 4.6 kW.

The discharge losses as functions of the discharge and thruster powers are included in Figures 6 and 7. These losses were significantly lower than those measured with either EMT 3 or EMT 4. Consequently, lower discharge power was required to operate the engine at the thruster power set-points. The reduction in discharge power at a given thruster set-point resulted in lower magnet temperatures, allowing the engine to operate safely at higher power.

Even though the GRC test-bed thruster was operated up to higher thruster input powers, the magnet temperatures in this engine were similar to the EMT engines at the same discharge powers. This suggests the following: 1) that the discharge losses directly relate the discharge power to the thruster power (where beam power is fixed), and 2) that the design of the NSTAR-derived engine is a more significant factor in temperature determination than the thruster materials or the thermally isolating environment of the thruster.

One factor that is not apparent in the temperature data obtained to date is the effect of accumulated thruster operation on thruster performance and subsequently magnet temperatures. During a 8,200 wear test, the NSTAR thruster demonstrated a significant change in performance during the first 100+ hours of operation.[7] For discharge losses, this change results in a rapid increase to approximately 180 W/A. The discharge losses subsequently increased to approximately 200 W/A over the first 3,000 hours of testing. This 'burn-in' behavior appears to be intrinsic to the thruster design, as it has been observed on other operated devices, including EMTs 3 and 4.

The measurements made to date on the GRC test-bed engine have all been within the first 50 hours of accumulated operation, when the discharge losses are expected to be low. A characterization of temperature behavior of the GRC test-bed thruster should be performed after a few hundred hours or more of accumulated operation. Based on a linear extrapolation of the temperature behavior shown in Figure 6 and assuming a nominal discharge loss of 200 W/A, then it is estimated that the front ring magnets may get as hot as 380 °C ± 10 °C at 4.6 kW thruster power. This incorporates the conservative estimation that the temperatures continue to scale linearly with discharge power. Consequently, the current rare-earth magnets are not expected to be compatible with 5 kW operation.

In order to achieve higher power operation without jeopardizing the magnets, and maintain a margin between operating temperature and the thermal stabilization limit of the magnets, changes to the thruster will be required. One approach is to modify the thruster design to reduce magnet temperatures. These modifications are expected to require substantial changes to the thruster, and consequently break the current heritage with the NSTAR engine. Alternatively, recently developed rare-earth magnet with a higher thermal stabilization temperature (> 500 °C) could provide the necessary margin, as well as accommodate the impact of increasing discharge losses during thruster "burn-in," without modification of the NSTAR thruster design.

CONCLUDING REMARKS

The GRC test-bed thruster has been successfully operated up to approximately 4.6 kW without exceeding the magnet temperature stabilization limit. From the temperature measurements obtained to date, it was concluded that:

1. The magnet temperatures in the GRC test-bed and EMT engines were approximately the same over the same discharge power range. This strongly suggests that the NSTAR-derived thruster geometry is a more significant factor in temperature determination than the materials or the thermally isolating environment.
2. Magnet temperatures as a function of the thruster power are strongly related to thruster discharge losses.

The GRC test-bed engine is compatible with operation up to 5 kW at the beginning of life. However, because of the 'burn-in' behavior of the NSTAR thruster, the magnet temperatures are expected to increase as the discharge losses increase with accumulated thruster operation. Based on past behavior of the NSTAR thrusters, the magnet temperatures were conservatively estimated to reach a maximum of approximately 380 °C once test-bed thruster performance has stabilized, which exceeds the magnet stabilization temperature limit. Therefore, modifications to the thruster design are required to enable successful operation up to a thruster power of 5 kW.

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[7] Polk, J.E., Anderson, J.R., Brophy, J.R., Rawlin. V.K., Patterson, M.J., Sovey, J., and Hamley, J., "An Overview of the Results from an 8200 Hour Wear Test of the NSTAR Ion Thruster," AIAA Paper 99-2446, 35th Joint Propulsion Conference, Los Angeles, CA, June 1999.

Table 1. Comparison of EMT and GRC test-bed thruster thermal factors.

Engine ID	EMT 3	EMT 4	GRC test-bed
Description			
Thermal isolation of engine from facility?	Yes	Yes	No
Discharge chamber material	Al/Ti	Ti	Al
Wire mesh throughout discharge chamber?	Yes	Yes	Yes
Discharge chamber interior grit-blasted for emissivity control?	Yes	Yes	Yes
Lightening holes on magnet retaining rings?	Yes	Yes	Yes
Temperatures measured without beam extraction?	Partial	No	No

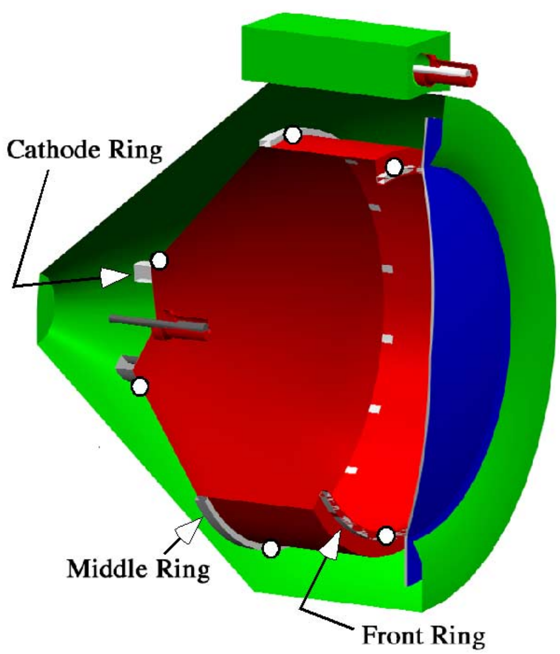

Figure 1. Schematic of NSTAR-derived thruster configuration. The white dots indicate the positions of the thermocouples used for magnet temperature measurements.

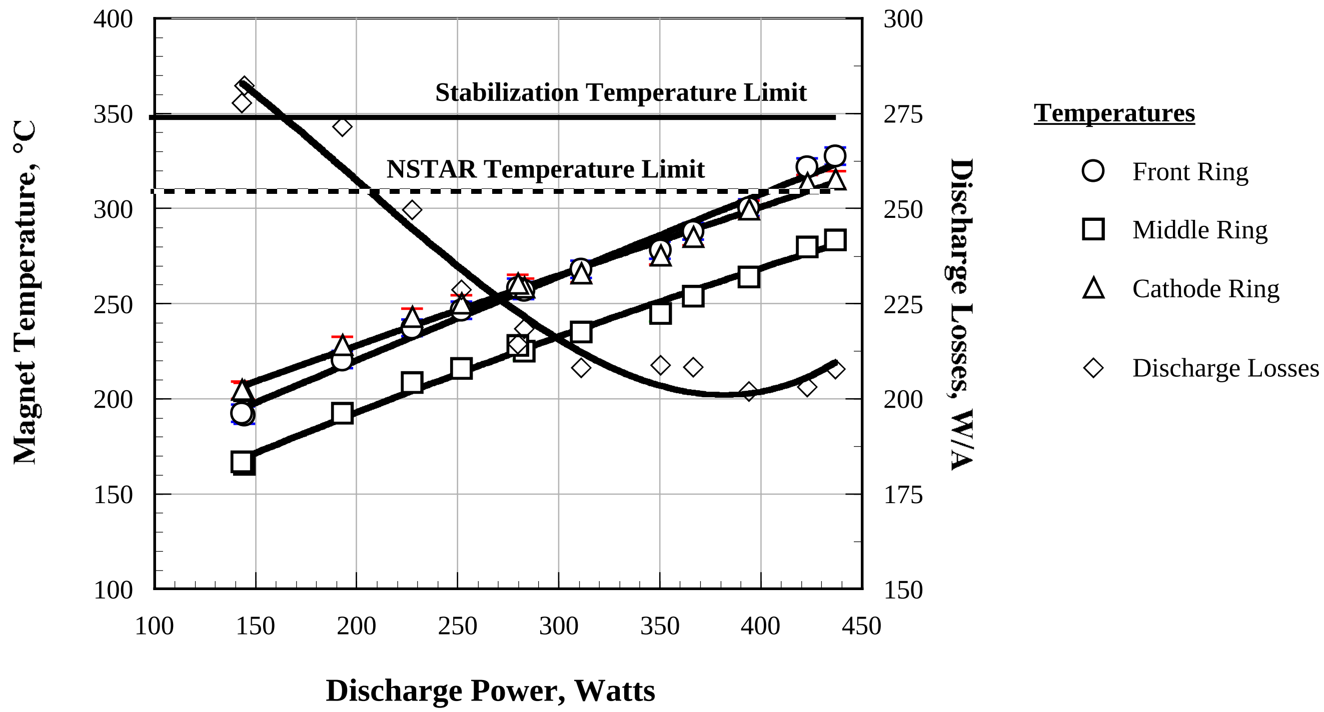

Figure 2 Magnet ring temperatures and discharge losses measured on the NSTAR EMT 4 as functions of discharge power within the thruster.

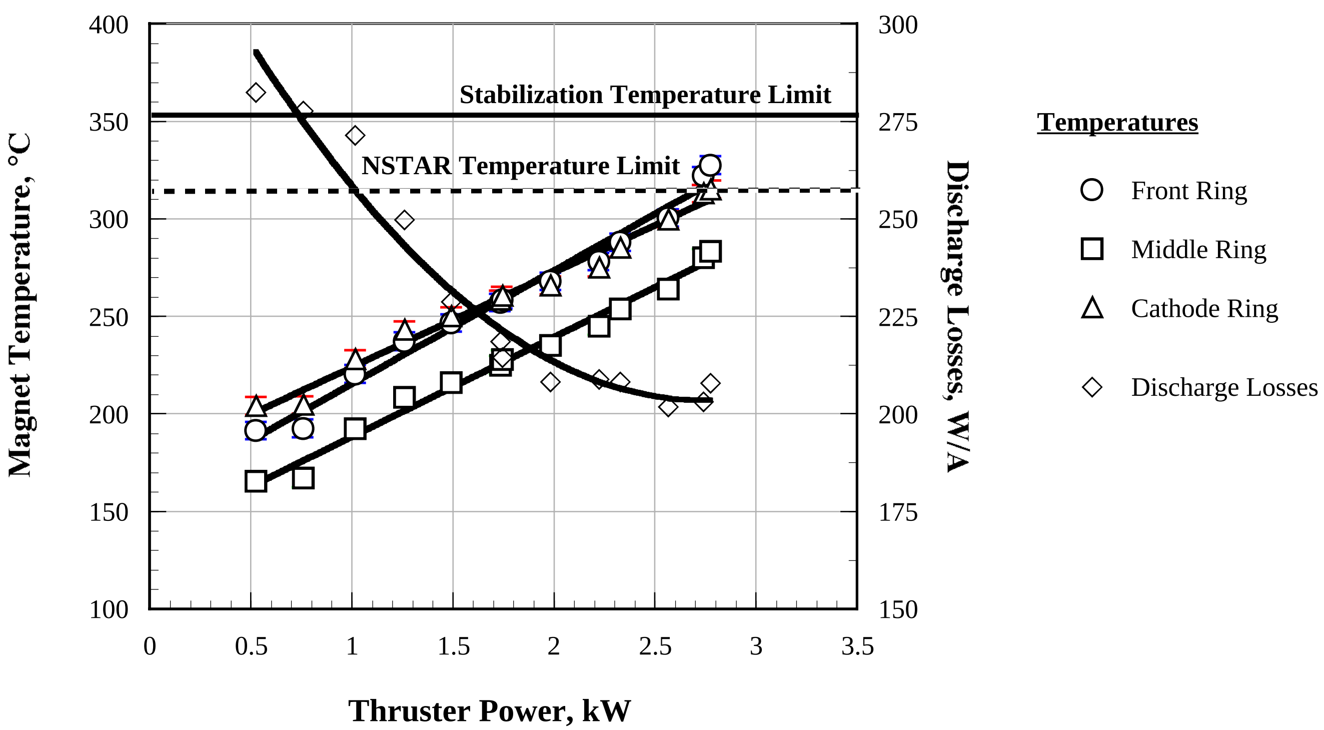

Figure 3 Magnet ring temperatures and discharge losses measured on the NSTAR EMT 4 as functions of thruster input power.

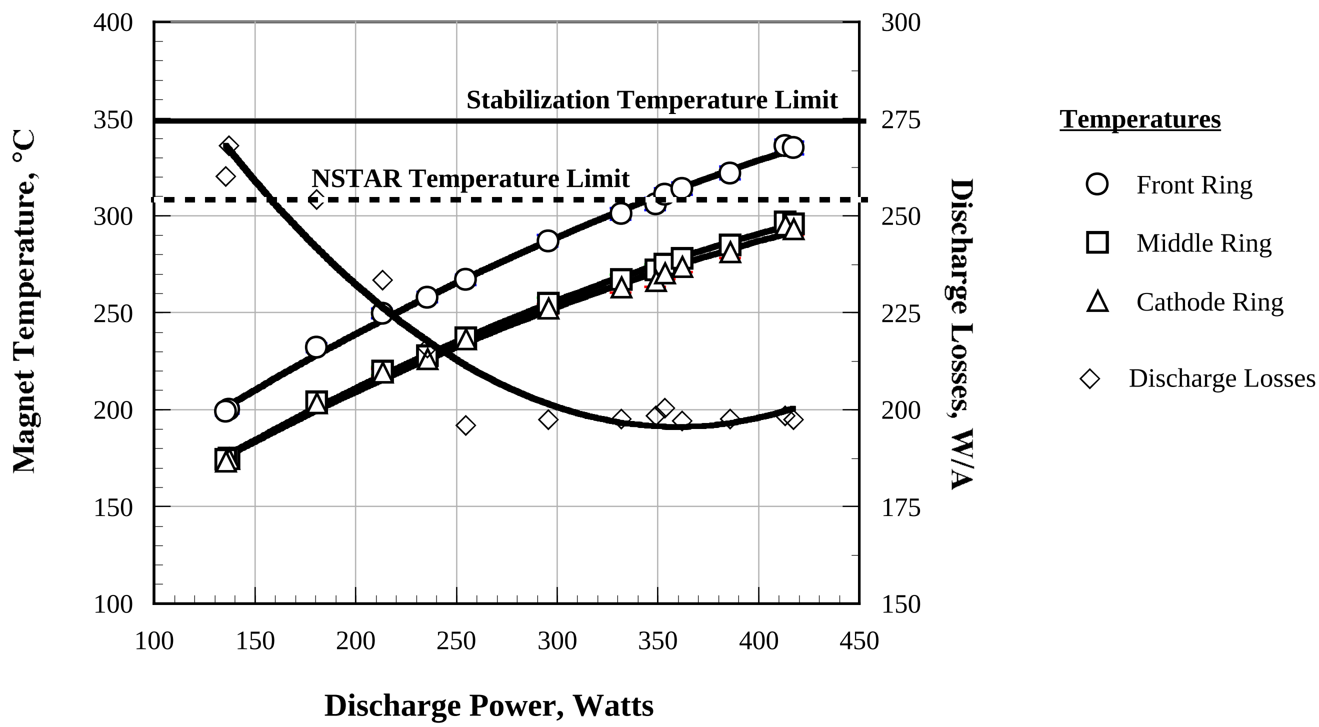

Figure 4 Magnet ring temperatures and discharge losses measured on the NSTAR EMT 3 as functions of discharge power within the thruster.

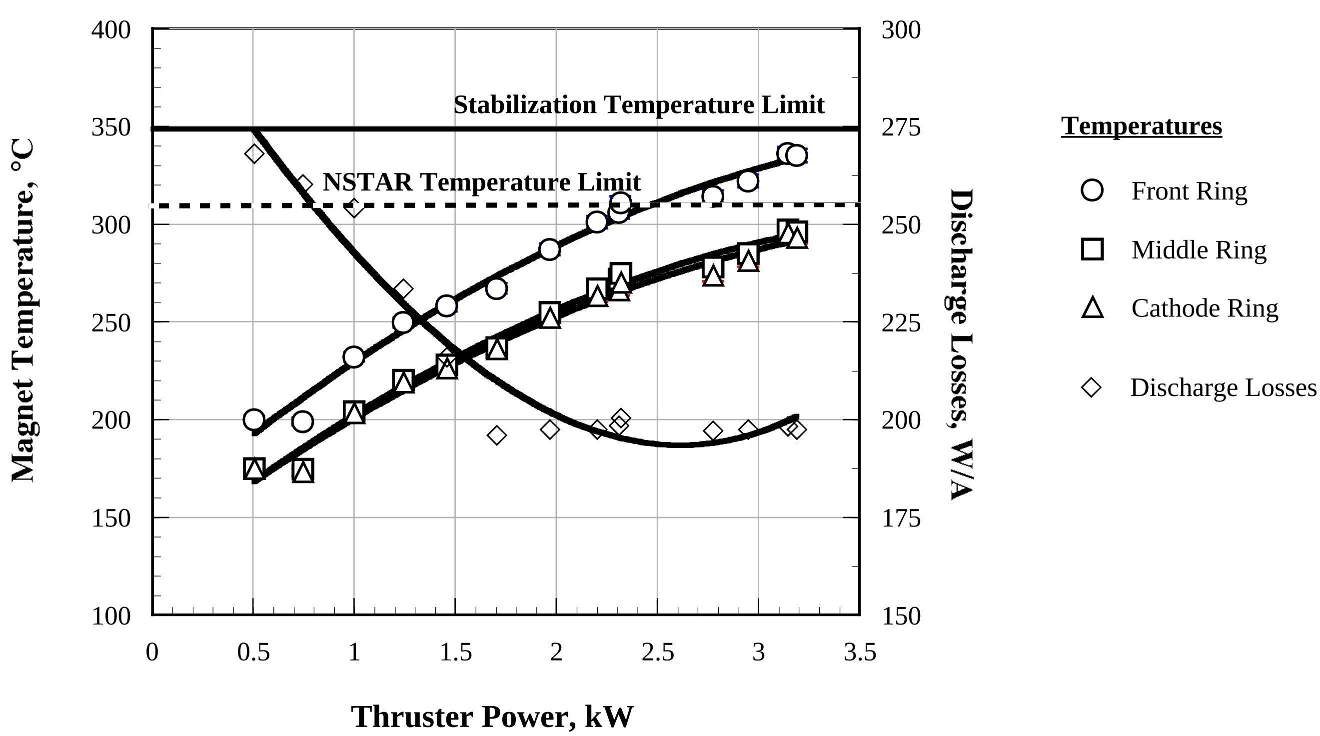

Figure 5 Magnet ring temperatures and discharge losses measured on the NSTAR EMT 3 as functions of thruster input power.

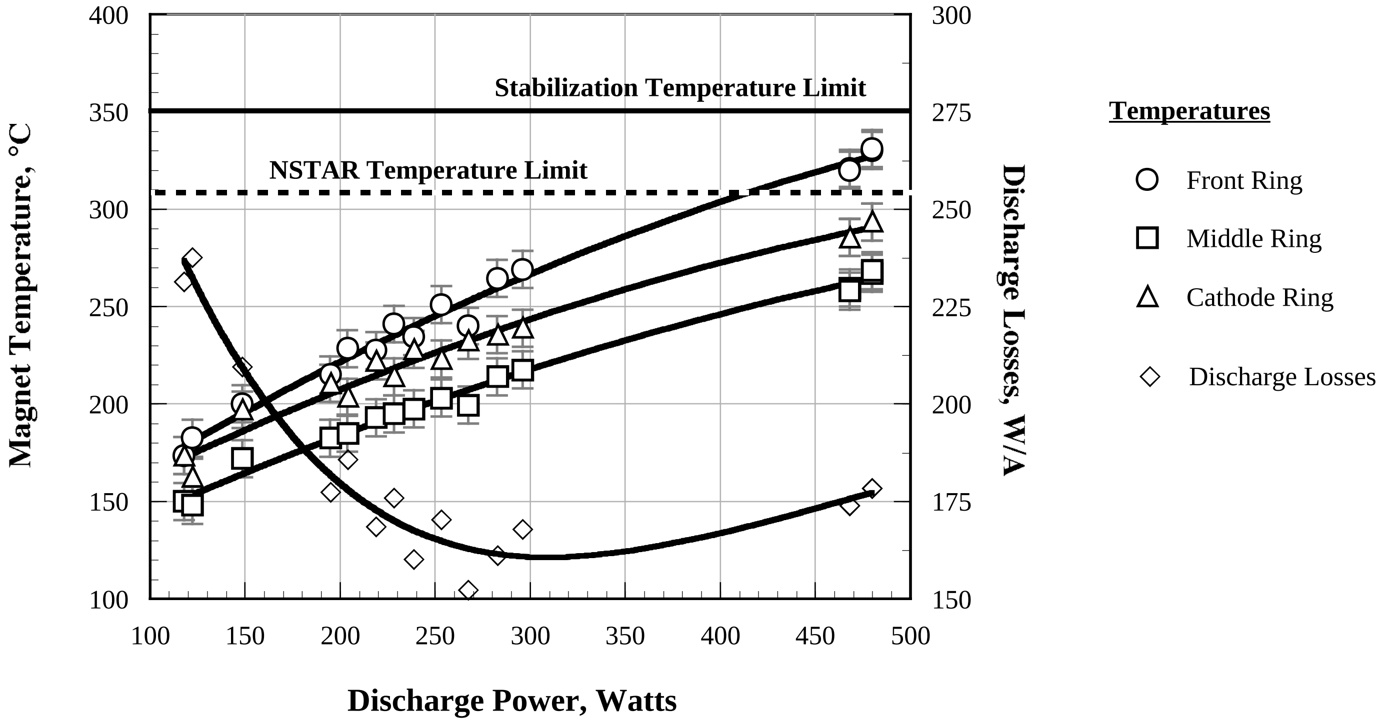

Figure 6 Magnet ring temperatures and discharge losses measured on the GRC test-bed thruster as functions of discharge power within the thruster.

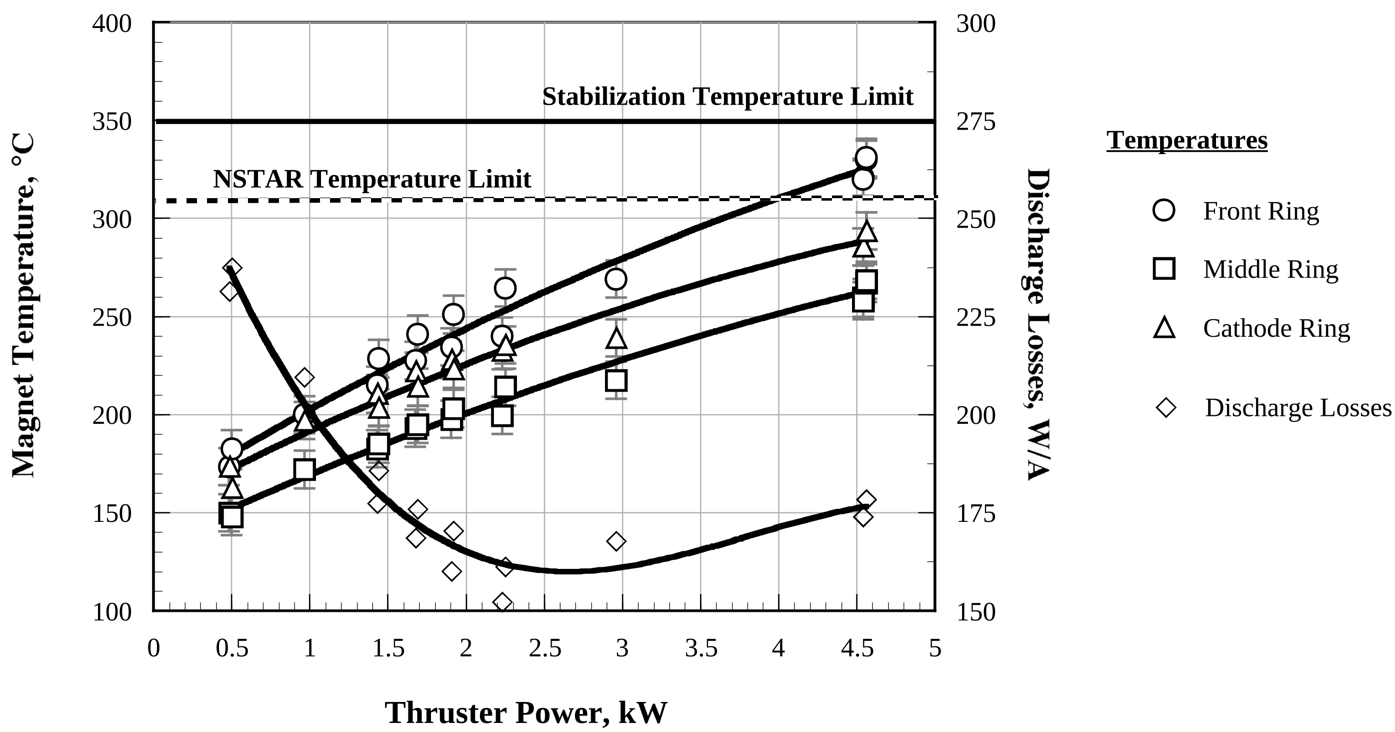

Figure 7 Magnet ring temperatures and discharge losses measured on the GRC test-bed thruster as functions of thruster input power.

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13. ABSTRACT ***(Maximum 200 words)***
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