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# Performance Evaluation of the Prototype Model NEXT Ion Thruster

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## Abstract

The performance testing results of the first prototype model NEXT ion engine, PM1, are presented. The NEXT program has developed the next generation ion propulsion system to enhance and enable Discovery, New Frontiers, and Flagship-type NASA missions. The PM1 thruster exhibits operational behavior consistent with its predecessors, the engineering model thrusters, with substantial mass savings, enhanced thermal margins, and design improvements for environmental testing compliance. The dry mass of PM1 is 12.7 kg. Modifications made in the thruster design have resulted in improved performance and operating margins, as anticipated. PM1 beginning-of-life performance satisfies all of the electric propulsion thruster mission-derived technical requirements. It demonstrates a wide range of throttle-ability by processing input power levels from 0.5 to 6.9 kW. At 6.9 kW, the PM1 thruster demonstrates specific impulse of 4190 s, 237 mN of thrust, and a thrust efficiency of 0.71. The flat beam profile, flatness parameters vary from 0.66 at low-power to 0.88 at full-power, and advanced ion optics reduce localized accelerator grid erosion and increases margins for electron backstreaming, impingement-limited voltage, and screen grid ion transparency. The thruster throughput capability is predicted to exceed 750 kg of xenon, an equivalent of 36,500 hr of continuous operation at the full-power operating condition.

## Nomenclature

| | |
|---|---|
| $I_{SP}$ | specific impulse, s |
| $J_B$ | beam current, A |
| $J_{NK}$ | neutralizer keeper current, A |
| $m_C$ | discharge cathode flowrate, sccm |
| $m_M$ | discharge chamber main plenum flowrate, sccm |
| $m_N$ | neutralizer cathode flowrate, sccm |
| $P_{IN}$ | thruster input power, kW |
| $V_A$ | accelerator grid voltage, V |
| $V_B$ | beam power supply voltage, V |

## Introduction

The success of the Deep Space One mission, utilizing the NASA Solar Electric Propulsion Technology Applications Readiness (NSTAR) ion propulsion system, has secured the future of electric propulsion technology application in achieving and enhancing NASA's solar system exploration objectives in the 21st century (refs. 1 to 4). In 2002, NASA Glenn Research Center (GRC) was selected to lead the development of NASA's Evolutionary Xenon Thruster (NEXT) under the Next Generation Ion project. The NASA GRC-led NEXT team includes as partners the Jet Propulsion Laboratory, Aerojet—Redmond Operations, and L3 Electron Technologies (formerly Boeing Electron Dynamic Devices). The

NEXT project is tasked with development of the next-generation ion propulsion system. The NEXT Solar Electric Propulsion (SEP) system design enhances and enables Discovery, New Frontiers, and other exploration mission classes, including Mars sample return (refs. 5 and 6). The NEXT propulsion system is significantly more advanced than current state-of-the-art, NSTAR, ion thrusters and consists of a high-performance, 7-kW electric propulsion thruster (EPT); a lightweight, high-efficiency power processing unit (PPU); an advanced propellant management system (PMS); a lightweight thruster gimbal; and key elements of a digital control interface unit (DCIU) including software algorithms (refs. 7 and 8).

The NEXT system development Phase I effort, successfully completed in August 2003, included: building multiple engineering model (EM) thrusters; characterizing EM thruster performance; conducting a 2000-hr wear test; developing a breadboard PMS, a breadboard PPU, and a single-string DCIU simulator; and a breadboard system integration test of the entire NEXT system (refs. 9 to 11). After demonstrating component and system technology at a breadboard level, the NEXT Phase II activities include the development of flight-like engineering model components; performance, environmental, and integration testing; and thruster life assessment through both analysis and testing to validate the technology approach and hardware design (ref. 12). The hardware development activities for Phase II, initiated in October 2003, include prototype model (PM) thruster design, an EM PMS design, an EM PPU design, and a breadboard gimbal design (refs. 13 to 16).

The NEXT Phase II thruster effort, led by Aerojet, includes the design, development, manufacturing, and delivery of up to two PM NEXT thrusters for performance characterization, environmental qualification, and integration testing. The main philosophy of the PM thruster design is to incorporate lessons learned from NSTAR and NEXT EM thruster development efforts, while maintaining appropriate heritage and ensuring compatibility with all NEXT technical requirements and environments (ref. 17). Findings from Phase I testing and throttle table updates were incorporated into the PM design baseline. On January 19, 2006, the first PM thruster, designated PM1, was delivered to GRC by Aerojet. The PM1 performance acceptance test (PAT) was conducted at GRC to ensure compatibility with all the NEXT thruster requirements, demonstrate the manufacturing philosophy of the PM design, and provide PM thermal data for thermal modeling activities. This paper will discuss the PM1 PAT results with emphasis on compatibility with NEXT requirements, improvements relative to NEXT EM thrusters, and improvements relative to NSTAR through a comprehensive plan to address lessons learned.

## Test Article

The Next Generation Ion (NGI) solicitation, acknowledging that future exploration and inner solar system sample return missions will demand increased power range, throttle-ability, performance, and throughput at reduced specific mass, established a set of challenging mission requirements for the next generation of ion thrusters. An aggressive set of technical requirements for the NEXT thruster was established to meet these mission requirements. As shown in this paper, the NEXT PM design meets or exceeds these requirements providing a significant gain over the state-of-the-art NSTAR thruster. The NEXT thruster inherits the knowledge gained through the NSTAR thruster development and flight experience, while significantly increasing the thruster power level and improving key thruster performance parameters, as illustrated in table 1. All NEXT PM parameters, with the exception of throughput, have been demonstrated on PM1. Each thruster’s performance, illustrated in table 1, is from its respective throttle table developed under sample mission constraints. Additional capability is available, though at the expense of other thruster performance parameters such as service life, for many of the parameters. Further NEXT capability has been demonstrated through a study to assess extension of the existing NEXT throttle table to include high-thrust-to-power, demonstrated >13 kW, and high-thrust density, high-power operation, demonstrated up to 50 mN/kW at >2800 s specific impulse (ref. 18).

TABLE 1.—COMPARISON OF NSTAR FLIGHT THRUSTER (FT) AND NEXT PM ION THRUSTERS (REFS. 1 AND 19)

| Throttle table performance parameter | NSTAR FT | NEXT PM |
|---|---|---|
| Maximum input power, kW | 2.3 | 6.9 |
| Input power throttle range | 5:1 | 11:1 |
| Maximum specific impulse, sec | 3,185 | 4,190 |
| Thruster efficiency at full power, % | 62 | 71 |
| Propellant throughput, kg | 83 (design)—156 (qual) | >300 (design) |
| Specific mass, kg/kW | 3.6 | 1.86 |

TABLE 2.—NEXT PM THRUSTER DESIGN ATTRIBUTES

| | |
|---|---|
| Mass (excluding cabling), kg | 12.7±1 |
| Beam diameter, cm | 36 |
| External diameter, cm | [a]53.1, 58.0 |
| Total length, cm | [a]37.5, 43.4 |
| Gimbal attachment | 3-point, 120° separation |

[a]Including the neutralizer assembly

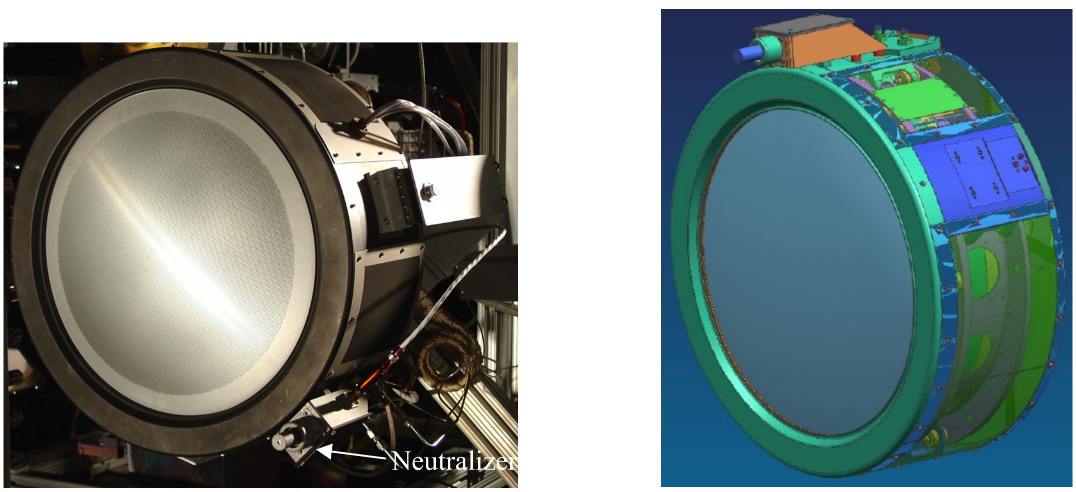


Figure 1.—NEXT PM1 in VF-6 at NASA GRC with thruster rotated 135° (left) and the NEXT PM CAD design (right).

A significant number of design changes were made from NSTAR, drawing heavily on the 40-plus years of ion thruster development at GRC, to achieve the advanced NEXT thruster requirements. The primary design changes include increased ion optics active area for higher-power operation, advanced ion optics design for greater throughput capability, an improved magnetic circuit that both reduces discharge losses and increases beam flatness, incorporation of compact propellant isolators, and utilization of higher-temperature stabilized rare-Earth magnets increasing the thermal margin enabling application to more extreme environments and allowing operation at higher powers (refs. 20 and 21). The PM thruster design includes significant enhancements over the EM thruster design including: innovative coatings to increase emissivity for enhanced thermal margin, more uniform ion optics apertures with much shallower cusps, masked ion optics to reduce edge-hole erosion, and graphite discharge cathode keeper to mitigate keeper erosion. A more detailed discussion of the PM thruster design drivers can be found in reference 22. The primary attributes of PM1 are identified in table 2. A photograph and assembly-level schematic of PM1 are shown in figure 1.

The PM thruster design philosophy has been to meet the NEXT project technical requirements while improving manufacturability and reducing mass (ref. 22). The PM design seeks to maintain heritage for life critical components while addressing NSTAR lessons learned. One of the hard-learned lessons of NSTAR was the need for closer collaboration between NASA GRC and the prime contractor, in this case Aerojet, which was addressed from the beginning of the PM design and build. The PM design has improved upon the EM thruster design with emphasis on survival of environmental conditions such as launch load and vibration requirements as well as thermal environments. Improved manufacturability was addressed by changing the design and manufacturing processes to make parts more repeatable and less dependent on the skill of the individual.

## Test Support Hardware

The following section provides a brief description of the test support hardware employed during the PM1 PAT. Prior to PM1 delivery, a comprehensive investigation of thermal, electrical, and plasma interactions between a cluster of 3+1 NEXT EM thrusters was conducted (refs. 23 to 25). The multi-thruster array test utilized an extensive array of diagnostics and test support hardware that remained place. PM1 replaced one of the EM thrusters in the array and, as such, PM1 is shown in test photographs integrated into the multi-thruster array setup. A more detailed description of the multi-thruster test array hardware and diagnostic items can be found in references 23 to 25. PM1 is shown operating in the multi-thruster array in figure 2.

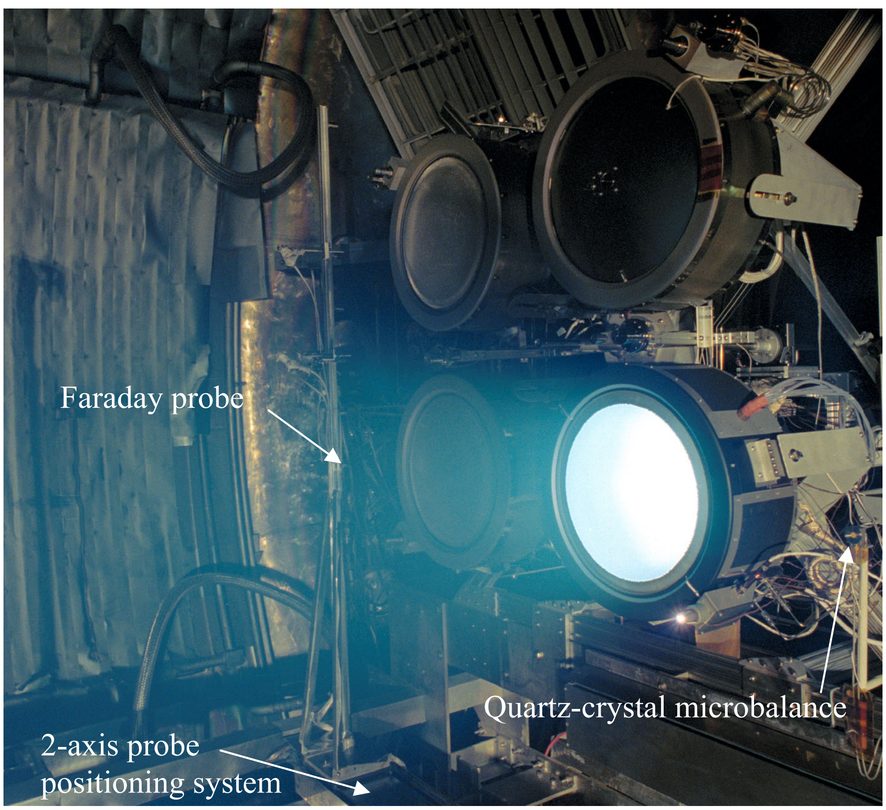


Figure 2.—NEXT PM1 thruster mounted on the multi-thruster array shown operating during performance acceptance testing.

### Power Console and Gas Feed System

A power console, similar to that described in reference 26, supplies power to PM1. The power console allows for thruster input powers up to 10 kW with beam power supply voltages up to 2000 V. The power console utilizes commercially available power supplies and integrated recycle logic circuitry. A high-purity xenon feed system (XFS) delivers propellant to the discharge cathode, neutralizer cathode, and discharge chamber main plenum through individual mass flow controllers. Each of the mass flow controllers are calibrated using a control volume technique prior to thruster operation.

### Vacuum Facility

The PM1 PAT was conducted in Vacuum Facility 6 (VF-6) at NASA GRC. The 7.6 m diameter by 22.9 m long facility is evacuated with 12 cryogenic pumps. Facility pressure is monitored via two ionization gages, a nude ion gauge located ~0.5 m below the ion engine and a wall-mounted gauge on the facility located ~3.2 m downstream of the thruster. Facility base pressures, corrected for xenon, with all cryo-pumps operational is $<1\times10^{-7}$ Torr. On xenon, the facility pumping speed is ~400 kL/s. Facility background pressures, corrected for xenon, during testing are $7\times10^{-7}$ to $1.5\times10^{-6}$ Torr. All interior surfaces downstream of the thruster are lined with flexible carbon material to reduce the amount of facility material back-sputtered onto the thruster.

Facility back-sputtered material deposition is monitored throughout performance testing using a quartz-crystal microbalance mounted in the thruster exit plane ~0.5 m from the thruster. The PM1 thruster may be subjected to wear testing, as such, the thruster is maintained in a condition such that it is life-test worthy. An effort was made to minimize the amount of back-sputtered material during performance acceptance and subsequent environmental testing. The back-sputter rate at the thruster in VF-6 is ~1.2 μm/khr when PM1 is operating at full-power.

### Thruster Telemetry and Ion Beam Diagnostics

The PM thruster currents and voltages are measured via calibrated multimeters and recorded. Facility pressures and individual mass flows to the engine are also recorded. PM1 is outfitted with a number of thermocouples to assist in the thermal model validation efforts. The placement of these thermocouples and thermal data can be found in reference 27.

A planar, 1-cm$^2$ circular, molybdenum Faraday probe is used to measure ion beam profiles. The probe is fixed at the thruster centerline in the vertical direction mounted on a two-axis probe motion system for measuring the ion beam current densities. To measure the ion beam current density profiles, the probe is biased –30 V with respect to ground potential to repel electrons and radially swept through the beam while measuring the collected current to the probe. Radial beam current density profiles are taken at 3 axial locations to determine beam divergence half-angle. Probe sweeps are conducted at axial locations of 45, 173, and 345 mm from the maximum dome height of the accelerator grid.

## Performance Test Operating Conditions

The NEXT thruster is designed for robotic exploration of the solar system using electrical power requiring throttle-ability. The entire NEXT throttle table, found in table A1 located in the appendix, is based upon a subset of possible mission needs requiring a throttling range of 0.5 to 6.9 kW. The PM1 PAT conditions consist of a subset of the NEXT engine throttle table shown in table 3. Performance testing is conducted at several of the power levels in the NEXT throttling table encapsulating the following operating conditions the highest power and highest wear, the most demanding thermal load, the lowest power, and a number of intermediate conditions. The main-to-discharge cathode flow split selection results in a 23.5 to 27.0 V discharge voltage. Thruster performance testing includes measuring engine operating parameters and determining engine performance; component performance assessments

TABLE 3.—NEXT PM1 PERFORMANCE ACCEPTANCE TEST OPERATING CONDITION INPUT PARAMETERS

| $P_{IN}$, kW[a] | $J_B$, A | $V_B$, V | $V_A$, V | $m_M$, sccm | $m_C$, sccm | $m_N$, sccm | $J_{NK}$, A |
|---|---|---|---|---|---|---|---|
| 6.86 | 3.53 | 1800 | –210 | 49.6 | 4.87 | 4.01 | 3.00 |
| 4.70 | 3.53 | 1180 | –200 | 49.6 | 4.87 | 4.01 | 3.00 |
| 3.99 | 2.00 | 1800 | –210 | 25.8 | 3.87 | 2.50 | 3.00 |
| 2.75 | 2.00 | 1180 | –200 | 25.8 | 3.87 | 2.50 | 3.00 |
| 2.46 | 1.20 | 1800 | –210 | 14.2 | 3.57 | 3.00 | 3.00 |
| 1.71 | 1.20 | 1180 | –200 | 14.2 | 3.57 | 3.00 | 3.00 |
| 1.13 | 1.20 | 679 | –115 | 14.2 | 3.57 | 3.00 | 3.00 |
| 0.545 | 1.00 | 275 | –500 | 12.3 | 3.52 | 3.00 | 3.00 |

[a]Nominal values

of the discharge chamber, ion optics, and neutralizer; and beam profile and divergence measurements. Discharge chamber performance is assessed by measuring discharge losses as a function of discharge propellant utilization efficiency at fixed discharge voltages to ensure operation on the "knee" of the curve. Ion optics performance includes electron backstreaming and perveance margins, but does not include screen grid ion transparency measurements because the screen grid is hardwired to discharge cathode common potential at the thruster. Neutralizer performance is determined by measuring neutralizer keeper voltage mean value and peak-to-peak fluctuations as a function of neutralizer flow. The latter indicates the point of transition from spot to plume mode operation.

## Performance Test Results and Discussion

The thruster performance results are discussed in the following sections. PM1 performance is compared to the NEXT EPT requirements and to the performance of EM thrusters that are closest in terms of configuration to the PM design. The closest EM thrusters to PM1 are the EM3 thruster, utilized in the ongoing NEXT long-duration test (LDT), and the EM4 thruster utilized in the NEXT multi-thruster array testing (MTAT) (refs. 23 and 28). Both of these EM thrusters utilize 36 cm diameter active area ion optics with the EM3 thruster outfitted with a PM ion optics set. The EM3 thruster is also outfitted with a graphite discharge cathode keeper similar to that employed on PM1. Comparison to EM1, the thruster used in the NEXT 2,000 h wear test, is also made where appropriate.

### Overall Engine Performance

The mission-derived EPT performance technical requirements and the results of the PM1 performance acceptance test are listed with comparison conditions shaded in tables 4 and 5, respectively. The beam divergence thrust correction factor for thrust calculations and the total doubly-to-singly-charged ion current ratio range from 0.96 to 0.98 and 0.037 to 0.060, respectively, based upon reference 29. Ingested mass flow due to facility background pressure is included in the total mass flow rate to the engine for determining thrust efficiency, specific impulse, and discharge performance (ref. 30). PM1 performance meets or outperforms all of the mission-derived EPT technical requirements for the operating conditions investigated. PM1 performance is consistent with the EM thrusters (refs. 23, 28, 31, and 32). Specific impulse varies from 1400 s at low-power (0.55 kW) to the maximum of 4310 s at an intermediate power level (4.0 kW) with 4190 s demonstrated at full-power (6.9 kW). PM1 thrust is calculated to be 25.5 mN at low-power and 237 mN at full-power, satisfying the BOL requirements. Thrust efficiencies range from 0.32 at low-power to 0.71 at full-power demonstrating compliance with the NEXT EPT requirements.

TABLE 4.—BEGINNING-OF-LIFE NEXT THROTTLE TABLE REQUIREMENTS (REF. 33)

| $P_{IN}$, BOL, kW | $V_B$, V | Thrust efficiency, BOL | Thrust, mN | $I_{SP}$, s |
|---|---|---|---|---|
| 6.86 | 1800 | 0.71 | 236 | 4190 |
| 6.05 | 1570 | 0.70 | 221 | 3910 |
| 5.46 | 1400 | 0.69 | 208 | 3690 |
| 4.71 | 1180 | 0.68 | 192 | 3390 |
| 3.22 | 1020 | 0.65 | 137 | 3130 |
| 2.44 | 1800 | 0.65 | 80.2 | 4000 |
| 2.16 | 1570 | 0.63 | 74.9 | 3730 |
| 1.96 | 1400 | 0.62 | 70.7 | 3530 |
| 1.70 | 1180 | 0.61 | 65.0 | 3240 |
| 1.52 | 1020 | 0.59 | 60.4 | 3010 |
| 1.42 | 936 | 0.58 | 57.8 | 2880 |
| 0.665 | 300 | 0.37 | 31.8 | 1590 |
| 0.538 | 275 | 0.32 | 25.5 | 1400 |

TABLE 5.—NEXT PM1 PERFORMANCE ACCEPTANCE TEST RESULTS IN VF-6

| $P_{IN}$, kW | $J_B$, A | $V_B$, V | Discharge losses, W/A | Thrust efficiency | Thrust[a], mN | $I_{SP}$, s |
|---|---|---|---|---|---|---|
| 6.86 | 3.53 | 1800 | 127 | 0.71 | 237 | 4190 |
| 4.70 | 3.53 | 1180 | 138 | 0.68 | 192 | 3400 |
| 3.99 | 2.00 | 1800 | 162 | 0.71 | 134 | 4310 |
| 2.75 | 2.00 | 1180 | 170 | 0.68 | 108 | 3490 |
| 2.46 | 1.20 | 1800 | 197 | 0.64 | 80.4 | 4000 |
| 1.71 | 1.20 | 1180 | 204 | 0.61 | 65.1 | 3240 |
| 1.13 | 1.20 | 679 | 223 | 0.52 | 49.2 | 2450 |
| 0.545 | 1.00 | 275 | 222 | 0.32 | 25.5 | 1400 |

[a]Calculated thrust

## Discharge Chamber

Discharge losses, shown in figure 3, for PM1 are lowest at the full-power operating point and highest at the low-power operating conditions. Discharge losses generally decrease with increasing total voltage, which is the sum of the absolute values of the beam and accelerator power supply voltage. This is largely due to the increasing screen grid ion transparency at higher total voltages. To reduce discharge cathode assembly and screen grid erosion rates, thruster discharge voltages are kept below 30 V. Discharge voltages ranged from 24.6 to 26.1 V at high and low power, respectively. The power-processing unit is capable of supply discharge voltage up to 35 V at the lowest input bus voltage of 80 V. The service life requirement combined with the desire to operate at high discharge propellant efficiencies determines, for a given discharge chamber and cathode design, the discharge flow rates and currents for a given operating condition. Comparison of PM1 with EM discharge losses can be made with equivalent mass flow rates. The PM1 discharge is shown to have higher discharge losses by up to 10 W/A compared to EM thrusters for certain operating conditions. Several minor design changes were made to the PM thruster discharge cathode relative to the EM discharge cathode. These changes altered the conducted heat lost from the discharge cathode assembly requiring higher discharge power to achieve the desired beam current. Differences in the construction of the discharge chamber may have also contributed to the higher PM discharge losses.

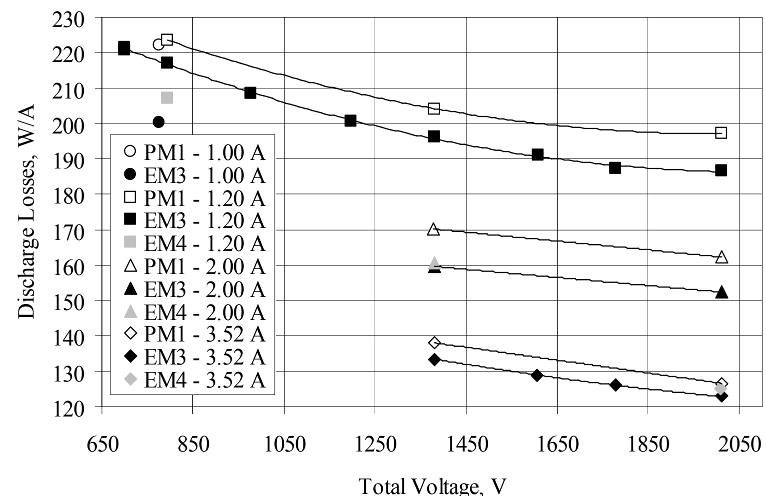


Figure 3.—Discharge losses as a function of total voltage for PM1, EM3, and EM4 at various beam currents.

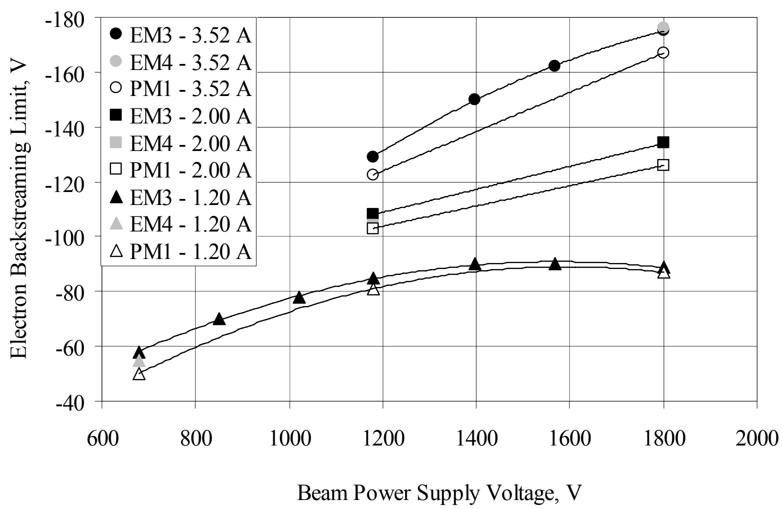


Figure 4.—Electron backstreaming limit as a function of beam power supply voltage at various beam currents for PM1, EM3, and EM4.

## Ion Optics Performance

The electron backstreaming limit is the highest accelerator voltage, i.e., lowest in magnitude, which will prevent ambient plasma electrons from backstreaming through the ion optics. The electron backstreaming limit is determined by lowering the magnitude of the accelerator grid voltage until the indicated beam current increases by 1 mA. Figure 4 shows the electron backstreaming limit as a function of beam power supply voltage at various beam currents for PM1, EM3, and EM4. PM1 electron backstreaming limit demonstrates higher margin compared to both of the EM thrusters with 36 cm diameter active area optics. The slightly larger backstreaming margin of PM1 compared to EM3, both PM ion optics, is due to slightly smaller accelerator apertures for PM1 compared to EM3, a result of the fabrication process (ref. 31). The minimum backstreaming margin for PM1 is 43 V occurring at the full-power point. The PM ion optics design demonstrates higher electron backstreaming margins compared to EM thruster ion optics due to their thicker accelerator grid and higher uniformity during manufacturing (refs. 22 and 34). Electron backstreaming margin will decrease with thruster operation due to enlargement of the accelerator grid apertures due to sputter erosion processes.

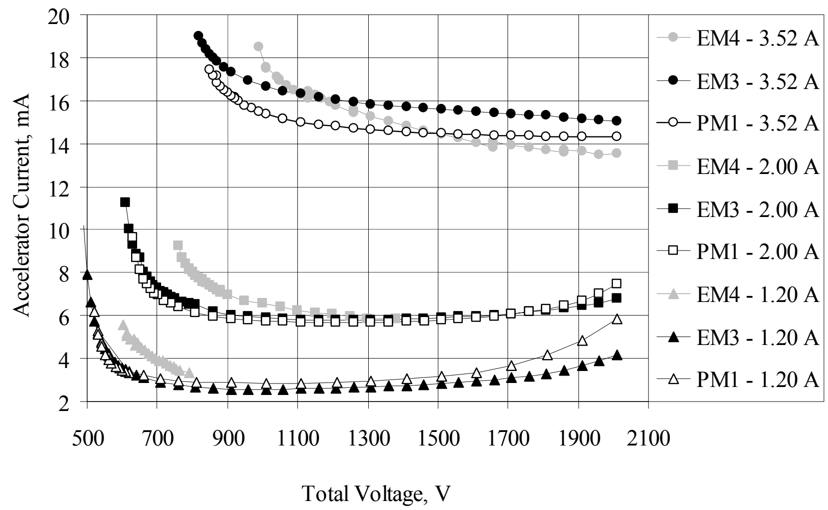


Figure 5.—Accelerator current as a function of total voltage for various beam currents for PM1, EM3, and EM4.

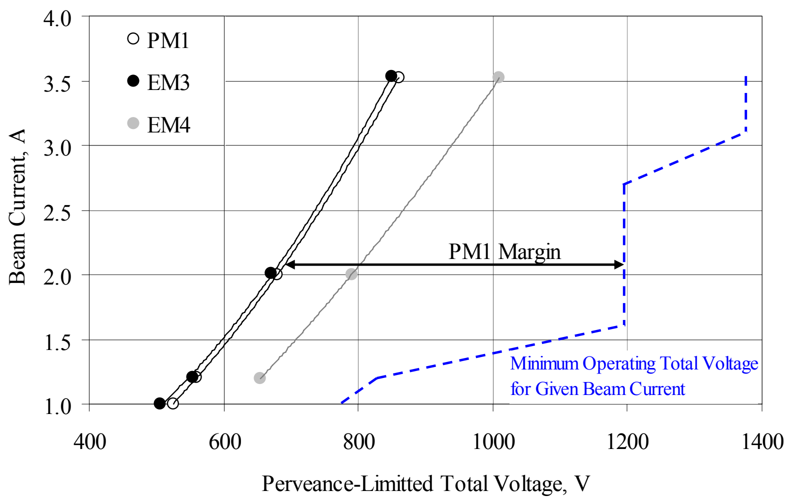


Figure 6.—Beam current as a function of impingement-limited total voltage for PM1, EM3, and EM4.

The impingement-limited total voltage is a measure of the current extraction capability of the ion optics and therefore a measure of perveance. Impingement-limited total voltages are determined from plots of accelerator current as a function of total voltage and defined as the total voltage where the slope is –0.02 mA/V; consistent with the NSTAR criterion. Figure 5 illustrates perveance data taken for PM1, EM3, and EM4 thrusters. The accelerator currents for EM4 are larger than both PM1 and EM3 for low total voltages due to smaller EM ion optics apertures compared to PM optics in the high current density regions (ref. 35). The EM optics are also more variable resulting in the more rapid increase in accelerator current as total voltage is decreased for higher beam currents. PM1 accelerator currents are higher than those of EM3 for conditions that simultaneously include both low beam currents and high total voltages due to over-focusing caused by slightly smaller accelerator apertures that were mostly located at the outer radius on the PM1 optics set compared to the EM3 PM optics set. At higher beam currents, PM1 exhibits lower accelerator currents due to the increased pumping speed in the facility tested.

Figure 6 shows beam current as a function of impingement-limited total voltage for PM1, EM3, and EM4 as well as the lowest throttle table total voltage for each beam current in table 3. The PM ion optics have demonstrated substantial perveance margin, i.e., the difference between the impingement-limited total voltage and the lowest total voltage set point for a given beam current. The lowest perveance margin is for the lowest beam current and is ~250 V. The perveance limit will increase, i.e., the margin will increase, as accelerator grid apertures enlarge from direct impingement and sputter erosion. The impingement-limited total voltages of PM1 and EM3 are similar confirming improved manufacturing uniformity in the PM ion optics for the majority of the high current density regions. The EM4 impingement-limited total voltages are greater than those of PM1 or EM3, i.e., they have a lower perveance margin. This behavior is expected as the 36 cm diameter optics on EM4 are an EM optics set with smaller accelerator aperture diameters in the bulk of the beam current density profile.

## Radial Beam Current Density Profiles

Radial beam current density profiles are used to determine radial current density distributions, peak current densities, and beam flatness parameters. No attempt was made to repel charge-exchange ions from the probe or to account for secondary electron emission due to ion bombardment. Assuming azimuthal symmetry, the radial beam current density profiles can be integrated yielding beam currents 2 to 10 percent higher than the measured beam current owing primarily to the factors mentioned above and errors discussed in references 36 and 37.

Figure 7 illustrates sample radial beam current density profiles for PM1 for three operating conditions taken at the closest axial location, 45 mm. The maximum beam current density is 3.94 mA/cm$^2$ at full power. The PM1 ion beam flatness parameter, the ratio of average-to-peak ion current density, ranges from 0.66 to 0.88 at lowest and highest input power levels, respectively. NEXT beam flatness parameters are 65 to 85 percent higher than those of the NSTAR thruster for the same average ion current densities (refs. 36 and 38). The improved NEXT beam flatness has the following advantages over the NSTAR thruster: increased electron backstreaming margin, increased ion optics perveance, increased screen grid ion transparency, and reduced accelerator aperture enlargement near centerline of the optics and therefore increased accelerator grid service life. Comparison of the peak beam current densities for PM1 and the EM thrusters is shown in figure 8. Lower total voltage conditions for a given beam current require larger discharge current due to the reduced ion transparency resulting in higher peak beam current density and slightly reduced flatness parameters. The peak beam current density for PM1 agrees well with the EM3 and EM1 thrusters. Divergence of the PM1 ion beam, defined as the half-angle containing 95 percent of the beam, represents a thrust loss and has been included in the thrust calculation. The measured beam divergence and thrust correction factors for beam divergence are listed in table 6 for PM1 over the operating conditions investigated.

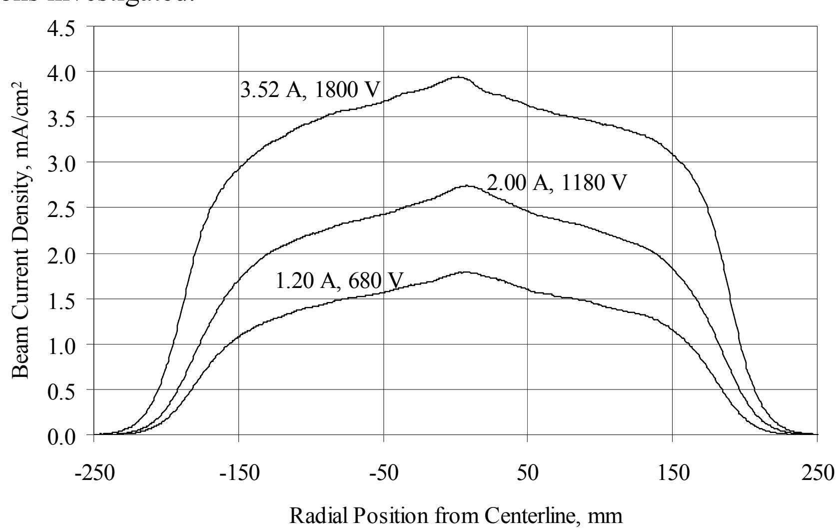


Figure 7.—Radial beam current density profiles for probe sweeps 45-mm downstream of PM1 ion optics.

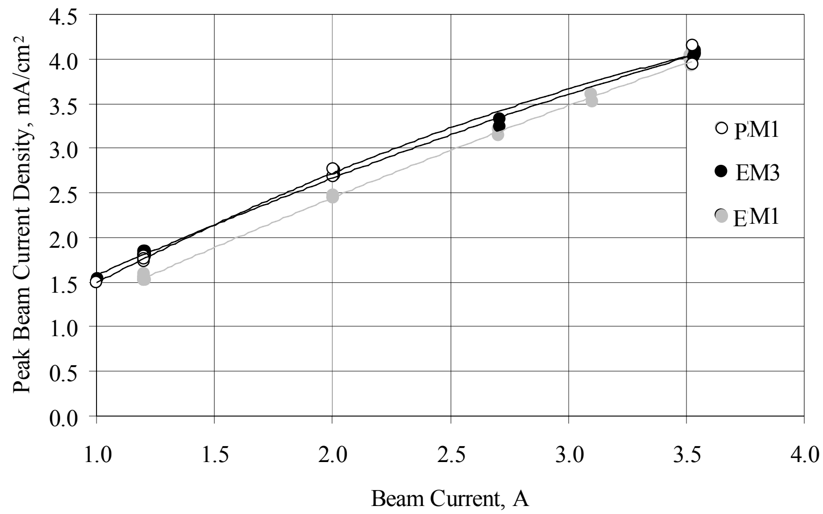


Figure 8.—Peak beam current density at a distance of 45-mm downstream of optics for PM1, EM3, and EM1.

TABLE 6.—NEXT PM1 BEAM DIVERGENCE HALF-ANGLES AND BEAM DIVERGENCE THRUST CORRECTION FACTORS

| $P_{IN}$, kW | $J_B$, A | $V_B$, V | $V_A$, V | Divergence half-angle at 95 percent of beam current, degrees | Thrust correction factor for beam divergence |
|---|---|---|---|---|---|
| 6.86 | 3.53 | 1800 | –210 | 27 | 0.97 |
| 4.70 | 3.53 | 1180 | –200 | 22 | 0.98 |
| 3.99 | 2.00 | 1800 | –210 | 27 | 0.97 |
| 2.75 | 2.00 | 1180 | –200 | 26 | 0.97 |
| 2.46 | 1.20 | 1800 | –210 | 26 | 0.97 |
| 1.71 | 1.20 | 1180 | –200 | 25 | 0.98 |
| 1.13 | 1.20 | 679 | –115 | 21 | 0.98 |
| 0.545 | 1.00 | 275 | –500 | 30 | 0.96 |

## Neutralizer Cathode

The neutralizer is characterized by the steady-state neutralizer keeper voltage and measuring the neutralizer flow at which transition between spot and plume modes of operation occurs. Over the conditions investigated, the neutralizer keeper voltage ranged from 12 to15 V from high to low power, respectively. The low neutralizer keeper voltage reduces the erosion rate, thereby extending service life, and is within the defined output capability of the PPU (refs. 13 and 39). Plume mode operation is characterized by high voltage and current fluctuations, which can limit the life of a cathode. The transition to plume mode, incorporating some margin, is defined when the peak-to-peak of the ac component of the neutralizer keeper voltage reaches or exceeds 5 V. During the characterization of the EM thrusters at low beam currents, neutralizer flow margin was only a few tenths of a sccm. Since the coupling voltage was low in magnitude, the neutralizer-to-keeper gap was increased on the PM design thereby increasing the flow margin at a modest expense to the coupling voltage. Figure 9 shows the improved margin the PM1 neutralizer exhibits over the EM thrusters at low beam currents due to a larger neutralizer cathode-to-keeper gap. Coupling voltage as a function of beam current is illustrated for PM1, EM3, and EM1 in figure 10. The PM1 coupling voltage is approximately one volt larger in magnitude than the EM thrusters for all beam currents investigated.

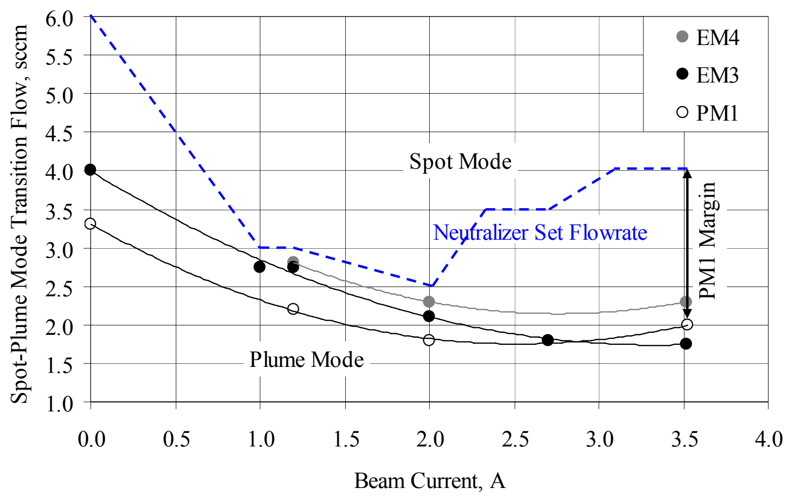


Figure 9.—Neutralizer spot-plume mode transition flow as a function of beam current for PM1, EM3, and EM4.

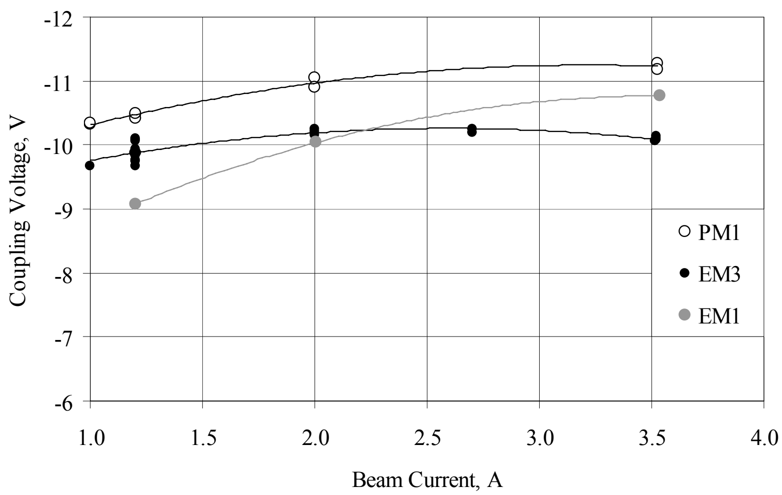


Figure 10.—Coupling voltage as a function of beam current for PM1, EM3, and EM1.

## PM Margins

The PM1 ion optics and neutralizer performance margins that were measured during the PM1 PAT are summarized in table 7. Improvements over EM optics are demonstrated for every ion optics parameter owing to the improved manufacturing technique of the PM ion optics that results in greater uniformity and smaller active area. Significant gains to neutralizer flow margin between operating flow rate and spot-to-plume transition at low beam currents have been made by enlarging the cathode-to-keeper gap with a modest increase in the magnitude of the coupling voltage.

Thermal data are acquired to assist in validation of the PM thruster thermal model and can be found in reference 27. The NEXT PM design is shown to exhibit substantial thermal margin even at the most harsh thermal conditions with magnet rings operating 30° to 100° cooler compared to EM hardware, validating the PM design improvements made by altering materials and emissivities. The PM1 thruster mass, 12.7 kg, and thruster envelope have been shown to comply with the EPT technical requirements defined (refs. 7, 17, and 22).

TABLE 7.—NEXT PM1 MARGINS FROM PERFORMANCE ACCEPTANCE TEST RESULTS IN VF-6

| $P_{IN}$, kW | $J_B$, A | $V_B$, V | $V_A$, V | Neutralizer flow, sccm | Backstreaming margin, V | Perveance margin, V | Neutralizer transition margin, sccm |
|---|---|---|---|---|---|---|---|
| 6.86 | 3.53 | 1800 | –210 | 4.01 | 40 | 1150 | 2.0 |
| 4.70 | 3.53 | 1180 | –200 | 4.01 | 80 | 500 | Not measured |
| 3.99 | 2.00 | 1800 | –210 | 2.50 | 85 | 1330 | 0.7 |
| 2.75 | 2.00 | 1180 | –200 | 2.50 | 100 | 720 | Not measured |
| 2.46 | 1.20 | 1800 | –210 | 3.00 | 125 | 1440 | 0.8 |
| 1.71 | 1.20 | 1180 | –200 | 3.00 | 120 | Not measured | Not measured |
| 1.13 | 1.20 | 679 | –115 | 3.00 | 65 | 250 | Not measured |
| 0.545 | 1.00 | 275 | –500 | 3.00 | Not measured | 250 | Not measured |

# Conclusion

The NEXT project is developing the next generation ion propulsion system. Significant advances have been made from the state-of-the-art NSTAR ion thruster in the baseline NEXT thruster design: higher-power operation, reduced discharge losses, increased beam flatness, increased thermal margin, employment of a compact propellant isolator, and incorporation of advanced ion optics design for greater throughput capability. The Aerojet-manufactured NEXT PM thruster has been designed to meet the challenging NEXT project technical requirements while improving manufacturability, reducing mass, and complying with thermal environment and launch load requirements. The first PM thruster, PM1, has been performance acceptance tested and the results presented against NEXT potential mission requirements and the EM thrusters' performance. The PM thruster complies with all of the mission-derived technical requirements at the throttle conditions investigated. Specific impulse varies from 1400 s at low-power (0.545 kW) to 4190 s at full-power (6.86 kW). Peak thrust efficiency and calculated thrust values of 0.71 and 237 mN, respectively occur at the full-power operating condition. PM1 performance is consistent with EM thrusters validating Aerojet's PM thruster design philosophy. The PM1 optics demonstrate improved electron backstreaming and impingement-limited total voltage margins due to improved ion optics manufacturing that reduced aperture variability compared to the EM ion optics. The PM1 neutralizer flow margin at low beam currents is greater than the EM design.

# Appendix

TABLE A1.—NEXT THROTTLE TABLE WITH PM1 PAT OPERATING CONDITIONS SHADED AND FULL-POWER IN BOLD

| $P_{IN}$, kW[a] | $J_B$, A | $V_B$, V | $V_A$, V | $m_M$, sccm | $m_C$, sccm | $m_N$, sccm | $J_{NK}$, A |
|---|---|---|---|---|---|---|---|
| **6.83** | **3.52** | **1800** | **–210** | **49.6** | **4.87** | **4.01** | **3.00** |
| 6.03 | 3.52 | 1570 | –210 | 49.6 | 4.87 | 4.01 | 3.00 |
| 5.43 | 3.52 | 1400 | –210 | 49.6 | 4.87 | 4.01 | 3.00 |
| 4.68 | 3.52 | 1180 | –200 | 49.6 | 4.87 | 4.01 | 3.00 |
| 6.03 | 3.10 | 1800 | –210 | 43.5 | 4.54 | 4.01 | 3.00 |
| 5.32 | 3.10 | 1570 | –210 | 43.5 | 4.54 | 4.01 | 3.00 |
| 4.80 | 3.10 | 1400 | –210 | 43.5 | 4.54 | 4.01 | 3.00 |
| 4.14 | 3.10 | 1180 | –200 | 43.5 | 4.54 | 4.01 | 3.00 |
| 5.27 | 2.70 | 1800 | –210 | 37.6 | 4.26 | 3.50 | 3.00 |
| 4.65 | 2.70 | 1570 | –210 | 37.6 | 4.26 | 3.50 | 3.00 |
| 4.19 | 2.70 | 1400 | –210 | 37.6 | 4.26 | 3.50 | 3.00 |
| 3.61 | 2.70 | 1180 | –200 | 37.6 | 4.26 | 3.50 | 3.00 |
| 3.20 | 2.70 | 1020 | –175 | 37.6 | 4.26 | 3.50 | 3.00 |
| 4.60 | 2.35 | 1800 | –210 | 32.4 | 4.05 | 3.50 | 3.00 |
| 4.06 | 2.35 | 1570 | –210 | 32.4 | 4.05 | 3.50 | 3.00 |
| 3.66 | 2.35 | 1400 | –210 | 32.4 | 4.05 | 3.50 | 3.00 |
| 3.16 | 2.35 | 1180 | –200 | 32.4 | 4.05 | 3.50 | 3.00 |
| 2.80 | 2.35 | 1020 | –175 | 32.4 | 4.05 | 3.50 | 3.00 |
| 4.00 | 2.00 | 1800 | –210 | 25.8 | 3.87 | 2.50 | 3.00 |
| 3.54 | 2.00 | 1570 | –210 | 25.8 | 3.87 | 2.50 | 3.00 |
| 3.20 | 2.00 | 1400 | –210 | 25.8 | 3.87 | 2.50 | 3.00 |
| 2.77 | 2.00 | 1180 | –200 | 25.8 | 3.87 | 2.50 | 3.00 |
| 2.46 | 2.00 | 1020 | –175 | 25.8 | 3.87 | 2.50 | 3.00 |
| 3.24 | 1.60 | 1800 | –210 | 20.0 | 3.70 | 2.75 | 3.00 |
| 2.87 | 1.60 | 1570 | –210 | 20.0 | 3.70 | 2.75 | 3.00 |
| 2.60 | 1.60 | 1400 | –210 | 20.0 | 3.70 | 2.75 | 3.00 |
| 2.26 | 1.60 | 1180 | –200 | 20.0 | 3.70 | 2.75 | 3.00 |
| 2.01 | 1.60 | 1020 | –175 | 20.0 | 3.70 | 2.75 | 3.00 |
| 2.43 | 1.20 | 1800 | –210 | 14.2 | 3.57 | 3.00 | 3.00 |
| 2.15 | 1.20 | 1570 | –210 | 14.2 | 3.57 | 3.00 | 3.00 |
| 1.95 | 1.20 | 1400 | –210 | 14.2 | 3.57 | 3.00 | 3.00 |
| 1.70 | 1.20 | 1180 | -200 | 14.2 | 3.57 | 3.00 | 3.00 |
| 1.51 | 1.20 | 1020 | –175 | 14.2 | 3.57 | 3.00 | 3.00 |
| 1.41 | 1.20 | 936 | –150 | 14.2 | 3.57 | 3.00 | 3.00 |
| 1.31 | 1.20 | 850 | –125 | 14.2 | 3.57 | 3.00 | 3.00 |
| 1.11 | 1.20 | 679 | –115 | 14.2 | 3.57 | 3.00 | 3.00 |
| 1.08 | 1.20 | 650 | –144 | 14.2 | 3.57 | 3.00 | 3.00 |
| 0.777 | 1.20 | 400 | –394 | 14.2 | 3.57 | 3.00 | 3.00 |
| 0.656 | 1.20 | 300 | –525 | 14.2 | 3.57 | 3.00 | 3.00 |
| 0.529 | 1.00 | 275 | –500 | 12.3 | 3.52 | 3.00 | 3.00 |

[a]Nominal values

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| **14. ABSTRACT**<br>The performance testing results of the first prototype model NEXT ion engine, PM1, are presented. The NEXT program has developed the next generation ion propulsion system to enhance and enable Discovery, New Frontiers, and Flagship-type NASA missions. The PM1 thruster exhibits operational behavior consistent with its predecessors, the engineering model thrusters, with substantial mass savings, enhanced thermal margins, and design improvements for environmental testing compliance. The dry mass of PM1 is 12.7 kg. Modifications made in the thruster design have resulted in improved performance and operating margins, as anticipated. PM1 beginning-of-life performance satisfies all of the electric propulsion thruster mission-derived technical requirements. It demonstrates a wide range of throttle-ability by processing input power levels from 0.5 to 6.9 kW. At 6.9 kW, the PM1 thruster demonstrates specific impulse of 4190 s, 237 mN of thrust, and a thrust efficiency of 0.71. The flat beam profile, flatness parameters vary from 0.66 at low-power to 0.88 at full-power, and advanced ion optics reduce localized accelerator grid erosion and increases margins for electron backstreaming, impingement-limited voltage, and screen grid ion transparency. The thruster throughput capability is predicted to exceed 750 kg of xenon, an equivalent of 36,500 hr of continuous operation at the full-power operating condition. | | | | | |
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