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THE NASA EVOLUTIONARY XENON THRUSTER (NEXT): THE NEXT STEP FOR U.S. DEEP SPACE PROPULSION

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ABSTRACT

NASA's Evolutionary Xenon Thruster (NEXT) project is developing next generation ion propulsion technologies to enhance the performance and lower the costs of future NASA space science missions. This is being accomplished by producing Engineering Model (EM) and Prototype Model (PM) components, validating these via qualification-level and integrated system testing, and preparing the transition of NEXT technologies to flight system development. The project is currently completing one of the final milestones of the effort, that is operation of an integrated NEXT Ion Propulsion System (IPS) in a simulated space environment. This test will advance the NEXT system to a NASA Technology Readiness Level (TRL) of 6 (i.e., operation of a prototypical system in a representative environment), and will confirm its readiness for flight. Besides its promise for upcoming NASA science missions, NEXT may have excellent potential for future commercial and international spacecraft applications.

INTRODUCTION

NASA's Science Mission Directorate (SMD) funds the NEXT project under its In-Space Propulsion Technology (ISPT) Program. NASA Glenn Research Center (GRC) leads the project team, which includes the Jet Propulsion Laboratory (JPL), Aerojet, L3 Communications, and ATK (formerly Swales). NEXT was initiated through a competitively selected NASA Research Announcement (NRA) awarded in 2002, with the first phase completed in August 2003. Technology validation and mission analysis results from this phase confirmed the merits and benefits of continued NEXT technology development. The second phase of the project began in October 2003, and is now in the midst of completing its final stage of activities.¹

The project has placed special emphasis on configuration and design rigor to facilitate the transition of NEXT system elements to flight.

The project adopted this approach to avoid the development problems encountered with the recently launched Dawn spacecraft, and to ensure repeatability in fabrication. This year of 2008 has seen the completion of several key milestones: (1) functional and qualification-level testing of key system elements; (2) a thruster life test surpassing a throughput representative of the most demanding missions; and (3) integrated system testing with mature hardware products. NEXT will be in a high state of technical readiness to support Announcement of Opportunities (AOs) for new missions in 2008 and beyond. Although NEXT technology was designed to meet a wide range of NASA science applications, including Discovery, New Frontiers and Flagship-class missions,²⁻⁶ it is also well suited for other solar electric propulsion missions of commercial and international interest.

SYSTEM DESCRIPTION

A schematic of the NEXT system is depicted in Fig. 1. It includes a high performance ion thruster; a modular, high-efficiency Power Processor Unit (PPU); a highly flexible advanced xenon Propellant Management System (PMS), consisting of a single High Pressure

Assembly (HPA) and one Low Pressure Assembly (LPA) per thruster; a lightweight engine gimbal; and the key elements of a Digital Control Interface Unit (DCIU) including software algorithms.

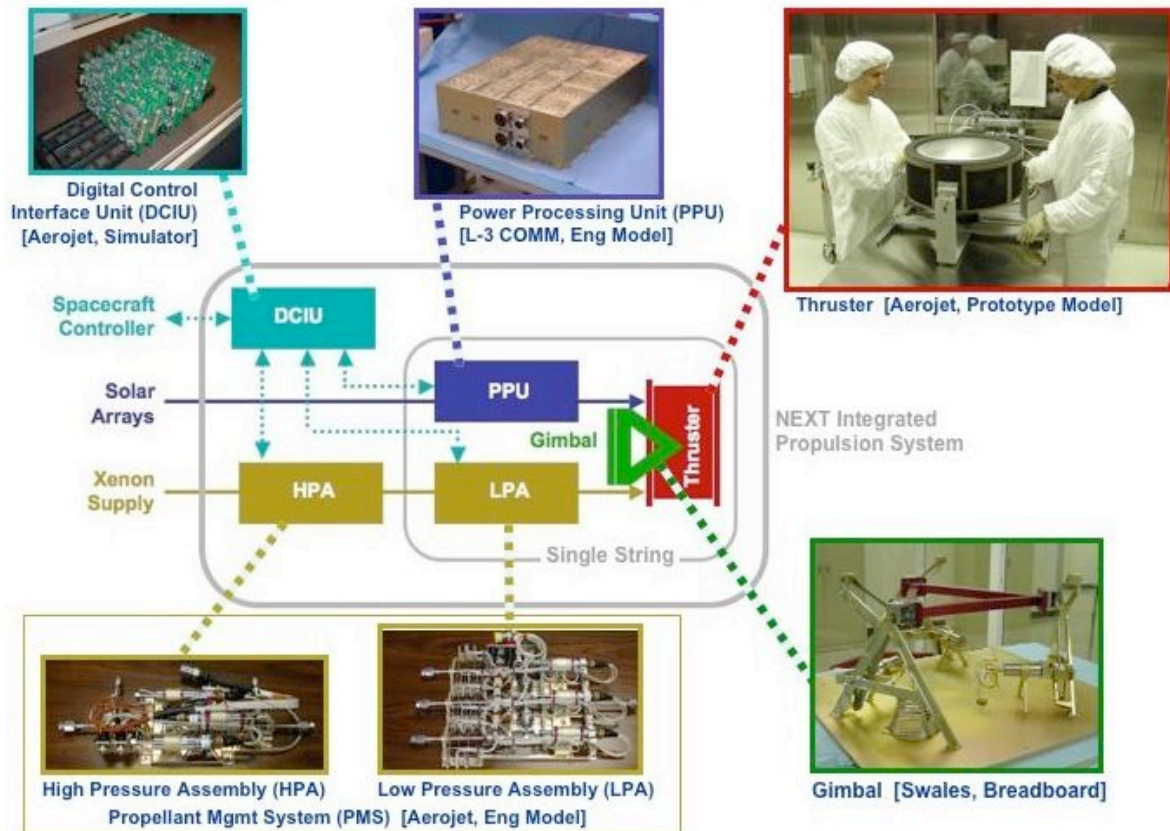


Figure 1: NEXT Propulsion System Elements.

The IPS consists of a series of independent thruster-strings. Each string is composed of a thruster and gimbal assembly, a PPU, and a PMS LPA. A DCIU and PMS HPA complete the system. Thruster-strings are added depending on the mission performance requirements, and an additional spare string can be added for failure tolerance. This approach offers flexibility in using the system on different spacecraft, and enables NASA to apply its investment in NEXT development to multiple future science missions.

The NEXT system represents a significant advancement over current state-of-the-art (SOA) EP systems, which for the U.S. is represented by the NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) thruster. The NEXT thruster is shown undergoing thermal vacuum testing at JPL in Fig. 2.

The thruster employs a 2-grid ion optic with a beam diameter of 36 cm, and can operate over an input power range of 0.54 to 6.9 kW. The beam current is 3.52 A at the full power level of 6.9 kW. NEXT has a maximum specific

impulse (Isp) of 4,190 sec, a maximum thrust of over 236 mN, and a peak efficiency in excess of 70%. The project requirement for xenon throughput is 300 kg (1.23×10^7 N-sec total impulse), with a 450 kg qualification throughput goal. Analysis has predicted the onset of the first failure mode at a total throughput of >730 kg, well beyond the design requirement.⁷

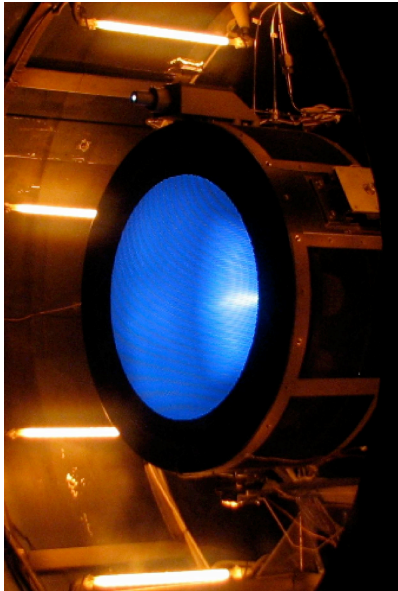


Figure 2: PM Thruster undergoing Thermal Vacuum Testing at JPL

The improved performance characteristics and benefits of NEXT relative to NSTAR are summarized in Table 1. NEXT performance exceeds single or multiple NSTAR thrusters over most of the input power range. Higher efficiency and Isp, and lower specific mass reduce the wet propulsion system mass and parts count. The NEXT thruster xenon propellant throughput capability is more than twice that of NSTAR, thereby reducing the number of required thrusters. The NEXT power processor and propellant feed system technologies also provide mass and performance benefits over the NSTAR system.

The PPU incorporates a modular beam power supply and packaging that is better performing and more producible than the NSTAR PPU.⁸ It has a flexible, scalable architecture that can be adapted to a number of missions, with a wide

throttling range of 250 W to 7,200 W, a >0.2 kW/kg specific power, and a simple thermal interface. The PPU utilizes a modular construction designed for manufacturability and low cost. It has separate electrical outputs capable of operating two thrusters, one at a time. The PPU can also accommodate independent neutralizer keeper operation so that the PPU can operate the beam of one thruster with the neutralizer from another thruster.

The EM Propellant Management System (PMS) delivers low-pressure gas to the thruster from a supercritical xenon supply source. It provides independent xenon flow control to the thruster main discharge, and discharge and neutralizer cathodes. Xenon flow is controlled via a thermal throttle flow control device (FCD) and a proportional flow control valve (PFCV). The FCD is a porous metal plug that provides a desired flow rate for a given inlet pressure and operating temperature. Fine control of flow rate is achieved by precise variation of the FCD inlet pressure, while the operating temperature of the porous metal plug is controlled at a constant set-point.

The inlet pressure and operating temperature of the FCD are actively controlled by the DCIU. The inlet pressure is controlled using the PFCV with pressure transducer signal feedback, while the operating temperature is controlled using a resistive element heater and temperature sensor feedback signal. This NEXT PMS design concept provides significant mass and volume reductions in the system as compared to the bang-bang regulation scheme implemented for the Deep Space 1 and Dawn missions.

The Digital Control Interface Unit (DCIU) is the primary interface between the spacecraft and the ion propulsion system. It performs all the command and control functions for the PMS and PPU.

Table 1. Performance Characteristics of NEXT vs. NSTAR SOA.

Characteristic	NSTAR (SOA)	NEXT	Benefit
Max Thruster Power (kW)	2.3	6.9	Enables high power missions (outer planet) with fewer thruster strings.
Max Thrust (mN)	91	236	
Throttling Range (Max/Min Thrust)	4.9	13.8	Allows use over broader range of distances from Sun.
Max Specific Impulse (Isp) (sec)	3120	4190	Reduces propellant mass, thus enabling more payload and/or lighter spacecraft.
Total Impulse (10 ⁶ N-sec)	4.6	>18	Enables low power, high ΔV Discovery-class missions with a single thruster.
Propellant Throughput (kg)	150	450	
Max Thruster Efficiency (%)	>61	>70	Reduces power and thermal management requirements.
Max PPU Efficiency (%)	92	95	Reduces mass and thermal management requirements.
PPU Specific Mass (kg/kw)	6.0	4.8	Reduces spacecraft dry and non-payload mass.
PMS Single-String Mass (kg)	11.4	5.0	
PMS Unusable Prop Residual (%)	2.40	1.00	

DEVELOPMENT STATUS

Five engineering model (EM) NEXT ion thrusters have been manufactured at GRC and tested. During Phase 1, EM thruster testing included detailed performance evaluations, a 2,000-hour wear test at full power, integrated testing with a breadboard PPU and PMS, and structural tests to characterize dynamic behavior for further thruster development. During Phase 2, EM thruster performance was also evaluated in a multi-thruster array.⁹ In addition, a long-duration life test with an EM thruster has accumulated approximately 17,000 hours of operation at full power with 345 kg of propellant throughput demonstrated to date.¹⁰

During Phase 2, the first prototype model (PM) thruster was manufactured by Aerojet and delivered to GRC in January 2006. Acceptance testing of the thruster was completed at GRC and the performance was consistent with that demonstrated with multiple EM thrusters. The PM thruster successfully completed a series of validation tests at JPL including: thruster/gimbal functional validation, a thermal development assessment, and qualification-level vibration and thermal vacuum environmental evaluations.

Manufacturing of components for a second PM thruster has been completed at Aerojet. These components are available for assembly into a

qualification unit for the first mission to use the NEXT system. Thruster work instructions and drawings have been formally released under the contractor configuration management process.

An engineering model (EM) PPU was manufactured at L3 Comm ETI in 2007, and has been delivered to GRC for integrated system tests. This culminated from fabrication and successful integration test of a breadboard PPU during Phase 1. Upon completion of the integrated system tests, the PPU will be subjected to qualification-level vibration and thermal vacuum testing.

Aerojet has completed manufacturing of the EM PMS elements, including two HPAs (one flight-like) and three LPAs (one-flight like). All assemblies have completed functional testing, and both flight-like HPA and LPA assemblies have successfully completed qualification-level vibration testing and thermal vacuum testing. The assemblies have been delivered to GRC and are being prepared for integrated system tests.

Under the scope of the NEXT program only DCIU simulators have been developed. The DCIU simulator consists of a computer, test support equipment, EM PMS pressure loop control cards, and the associated algorithms to control the PMS and PPU. The DCIU simulators are capable of operating a 3-thruster

string system, and are being used to validate control algorithms, support PPU input/output testing and single-string and multi-string integration tests, and operate a PMS kernel during thruster life testing. Fully integrating the DCIU functionality into the PPU is under consideration as an approach that may be implemented in a follow-on PPU build cycle. Elimination of the separate DCIU should reduce system cost and complexity.

JPL has completed the development of a breadboard gimbal for the NEXT thruster. Designed and fabricated by ATK, the gimbal is of a flight-like design using JPL-approved materials with certifications. The mass of the gimbal is less than 6 kg (less than the Dawn gimbal used for the smaller NSTAR thruster), and has a two-axis range of motion. The gimbal has successfully completed integration and functional testing with the PM thruster, and has passed two qualification level vibration tests and low-level shock tests, with minor issues. Few if any modifications are anticipated for transitioning to flight.

SYSTEM INTEGRATION

Single string integration testing was conducted in Phase 1. This test included an EM thruster with a breadboard PPU and PMS. Early in Phase 2, a multi-thruster array test (MTAT), shown in Fig. 3, was performed at GRC. The focus was on characterizing performance and behavior as affected by the simultaneous operation of multiple ion thrusters.⁹ The subject of this effort was a four EM NEXT thruster array in a 3+1 flight-representative configuration, where one thruster served as a spare. This test was performed with detailed plasma environments and plume measurements.

The array was operated over a broad range of conditions including the simultaneous firing of three thrusters at 20.6 kW total input power, yielding a total thrust of about 710 mN, at an Isp of 4,190 sec and an efficiency of approximately 71%. Major findings from the MTAT include: the performance observed for a thruster during operation in an array configuration is equivalent to that measured during singular thruster

operation with no apparent deleterious interactions; and, operation of one neutralizer to neutralize two or more thruster beams appears to be a viable fault-recovery mode, and viable system architecture with significant system performance advantages. Overall, the results indicated single thruster operations are independent of array configuration. This finding may have significant implications with regard to architectural flexibility for multi-thruster systems.

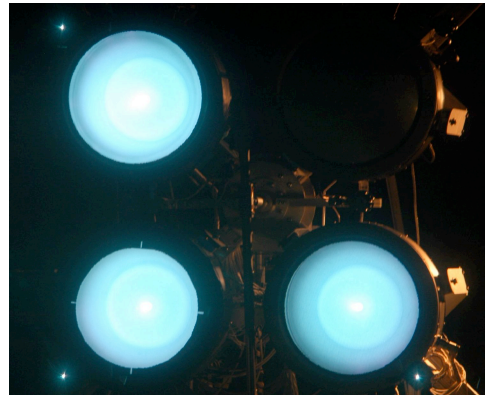


Figure 3: Multi-Thruster Array Test

Phase 2 integrated system tests were initiated in July 2008. These tests are currently evaluating a single thruster string consisting of the PM thruster, EM PPU, EM PMS and DCIU simulator. An exhaustive series of tests are planned to verify that the integrated NEXT components meet project requirements and that the interfaces between the system components are consistent. If project schedule and resources permit, a complete integrated test of three thruster strings in a 3+1 configuration will be conducted later in 2008.

Primary objectives of the single-string test include: demonstrating operation of a thruster over the full NEXT throttle table with the EM PPU and EM PMS; demonstrating operation of the system at off-nominal conditions; and demonstrating recycle and fault protection operation. Over 100 system level requirements will be validated. If performed, primary objectives of the multi-thruster string test include: validating DCIU and PMS functionality supporting multi-thruster operation; and

documenting any potential subsystem interactions. It has been proposed to retain the integrated assembly that would remain after the Phase 2 multi-thruster test to serve as a flight-system test-bed and risk reduction tool for the first mission that uses NEXT.

LIFE VALIDATION

Validation of the NEXT thruster life requirement is being addressed via a combination of test and analyses. An EM thruster successfully completed a 2,000-hour wear test. A second EM thruster (with PM ion optics manufactured by Aerojet) is presently undergoing long duration life testing at full power, having processed over 345 kg of xenon and accumulated approximately 17,000 hours of operation to date. The thruster has demonstrated a total impulse of over 13.6×10^6 N-sec, the highest total impulse mark ever demonstrated by an ion thruster. The EM thruster performance and wear rates of critical thruster components are consistent with model predictions.

A mission representative throttle profile is now being implemented in the life test, in which throttle points addressing various wear factors will be evaluated. The life test was operated at full power to about 267 kg xenon throughput at which point the thruster was power throttled to simulate a typical mission profile. The lifetime capability of the PM thruster will be established by considering several factors: (1) results from the on-going EM thruster life testing; (2) similarity analysis to the EM thruster; (3) thruster service life modeling; and (4) a wear test of a PM thruster. A service life assessment of the NEXT thruster was conducted for a number of throttle conditions. The assessment involved the application of several models to evaluate all the known failure modes. For the conditions investigated, the assessment conservatively predicted that the earliest failure would occur in the accelerator grid, with a structural failure occurring sometime after 730 kg of xenon throughput. At full power, this would represent over 35,000 hrs of operation. Other failure modes were predicted to occur at conditions in excess of 800 kg thruster xenon

throughput, well beyond the mission-derived lifetime requirement of 300 kg.

PERFORMANCE

NEXT provides significant performance benefits as compared to NSTAR SOA. The higher propellant throughput capability of the thruster and its greater total impulse allow it to accomplish low power, high ΔV missions, similar to Dawn, with a fewer number of thrusters. The higher power and thrust capability of NEXT allow the accomplishment of outerplanetary and other power-driven missions with fewer thruster strings. The higher Isp capability of the NEXT thruster reduces the spacecraft propellant mass, thus accommodating more payload mass.

The NEXT project began with Flagship-class Deep Space Design Reference Missions (a Titan Explorer, and Neptune Orbiter, both assuming aerocapture at the destinations) as the 'design driver' mission applications. A refocus study was conducted in 2004 to investigate NEXT IPS applications for both Discovery and New Frontiers-class missions. The Discovery-class mission results confirmed NEXT's ability to outperform NSTAR, yielding a higher net payload mass with fewer thrusters. Studies showed that NEXT was enhancing and sometimes enabling for several New Frontiers and Flagship-class missions. These findings are summarized in Table 2, which indicates the benefits provided by NEXT across all categories of planetary science missions.

TRANSITION TO FLIGHT

A number of activities are being conducted to transition NEXT technology to flight in the near-term with minimal technical difficulties and costs. These activities include: (1) reviewing Dawn IPS 'lessons-learned' and implementing strategies to mitigate the likelihood of experiencing similar difficulties; (2) conducting independent reviews of NEXT status with potential users and incorporating their feedback into the development plan; and (3) identifying additional technology development and validation activities that may facilitate

transitioning from TRL 6 technology products to flight, thus reducing the barriers to first-user implementation (e.g., non-recurring costs).

Table 2: NEXT Mission Benefits

Mission	NEXT Mission Benefits
Discovery-class - NEO Rendezvous - Vesta-Ceres (Dawn) - Comet Rendezvous - Deimos Sample/Return	Higher net payload mass with fewer thrusters than NSTAR system.
New Frontiers-class - Comet Sample/Return	Higher net payload mass than NSTAR. Simpler EP system: 2+1 NEXT vs. 4+1 NSTAR thrusters.
New Frontiers-class - Titan Direct Lander	>700 kg entry package with 1+1 NEXT system, potentially within New Frontiers cost cap.
Flagship-class - Titan - Enceladus	>2400 kg to Saturn Orbit Insertion with 1+1 NEXT system, EGA and Atlas 5 EELV – doubles delivered mass of chemical/JGA approach. >4000 kg to Saturn Orbit Insertion with 3+1 NEXT system, EGA and Delta IV Heavy.

The NEXT project has placed particular emphasis on avoiding the difficulties experienced by the Dawn mission in transitioning NSTAR technology to an operational system. An independent review (IR) of the NEXT project was held to assess NEXT technical status and the project’s ability to meet its objectives. The IR board, which included members from the potential user community, identified project risks and recommended project modifications. With implementation of its 11 findings, the IR board concluded that the NEXT project was on a course that would effectively support future users. The NEXT team concurred with the findings and has since implemented them into the project.

Based on Dawn lessons-learned, the IR findings, and EP architecture studies conducted under ISPT, the NEXT project has identified additional activities to promote the transition of the NEXT elements to flight and reduce risk for the first user. These include: (1) manufacturing a second

PM thruster under configuration control, which could be provided as a qualification unit to the first user; (2) fabricating an updated, 2nd-generation NEXT PPU with integral DCIU and taking it through qualification-level testing; and (3) maintaining use of the NASA Multi-Thruster Array with integrated EM and PM thrusters, EM PPU, EM PMS and gimbal. The latter measure will provide a test bed that can be used to support flight system integration activities and address issues both before and during flight.

CONCLUSION

The NEXT project has brought next-generation ion propulsion technology to a mature state, with current tasks leading to complete technology validation in the latter part of 2008. At that point, NEXT systems will be ready for flight development and eventual use in actual missions. Functional and qualification-level tests of key system elements will be completed; the thruster life test will have accumulated a throughput total well in excess of the 300 kg requirement; and integrated system tests with mature components will be finished. In addition, the project has identified several straightforward tasks that would facilitate transition to flight and reduce the risk to first users. Although the most promising applications appear to be upcoming NASA Discovery, New Frontier and Flagship-class missions, NEXT may have excellent potential for many commercial and international spacecraft applications.

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