IEPC 2003-0288

DEVELOPMENT STATUS OF NEXT: NASA'S EVOLUTIONARY XENON THRUSTER

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A NASA Glenn Research Center-led team has been selected to develop the next generation of ion propulsion system technology. The NEXT (NASA's Evolutionary Xenon Thruster) team is composed of NASA GRC, the Jet Propulsion Laboratory, Aerojet Redmond Rocket Center, and Boeing Electron Dynamic Devices, with significant participation by the Applied Physics Laboratory, University of Michigan and Colorado State University.

The need for advanced ion propulsion system capabilities has been demonstrated through in-space propulsion technology assessment analyses conducted by NASA. The NEXT system is targeted for robotic exploration of the outer planets using 25kW-class solar-powered electric propulsion. The team will develop thruster, advanced power processing, xenon propellant management and gimbal technologies that will advance the ion propulsion state-of-art to meet the needs of such missions. The development is being conducted in two phases, with breadboard level development and integration in Phase 1, and engineering model development and integration of a multi-thruster system planned for Phase 2. The NEXT project is intended to advance the technology to NASA Technology Readiness Level (TRL) 5, with significant progress towards TRL 6.

This paper presents a summary of the overall NEXT project status. Mission and system requirements are highlighted. The NEXT ion propulsion system technology approach, overall characteristics and hardware development status are summarized. The NEXT project status, including schedule, product and milestone status is presented. Finally, plans for the second phase of the NEXT project are summarized.

Introduction

Background

The NASA Headquarters Office of Space Science, Solar System Exploration Division, selected Glenn Research Center (GRC) to develop NASA's Evolutionary Xenon Thruster (NEXT) under the Next Generation Ion (NGI) Engine Technology NASA Research Announcement (NRA). The NGI Project, managed by the NASA Marshall Space Flight Center (MSFC), is a technology development project within the In-Space Propulsion Technology Program. The primary objective of NGI is to significantly increase performance for primary propulsion to planetary bodies by leveraging NASA's very successful ion propulsion program for low-thrust applications.

The need for advanced ion propulsion system capabilities has been demonstrated through in-space propulsion technology assessment analyses conducted by NASA. The NEXT system is targeted for robotic exploration of the outer planets using 25kW-class solar-powered electric propulsion. The team will develop thruster, advanced power processing, xenon propellant management and gimbal technologies that will advance the ion propulsion state-of-art to meet the needs of such missions. The NEXT project is intended to advance the technology to NASA Technology Readiness Level (TRL) 5, with significant progress towards TRL 6. TRL 5 requires component and/or breadboard validation in a relevant environment, TRL 6 requires system/subsystem model or prototype demonstration in a relevant environment. The effort will provide sufficient maturity and risk reduction to enable prudent selection of the technologies for a space mission by 2006. The development is being conducted in two phases, with breadboard level development and integration in the one-year Phase 1, and engineering model development and integration of a multi-thruster system planned for the 2.5-year Phase 2. Successful demonstration of NEXT to meet Phase 1 requirements, and availability of funds, would allow for the Phase II option to complete additional system development.

Objectives

The general objectives of NEXT development are to advance ion propulsion component and system technologies, and to demonstrate system performance and lifetime for typical planetary missions. Advances in ion propulsion technology are referenced to the state-of-art NSTAR ion propulsion system that operated successfully on the Deep Space 1 mission[1,2]. Mission performance capabilities are assessed through analysis of two Deep Space Design Reference Missions (DSDRMs), defined within the NRA, that are described further in a following section.

Specific project objectives are focused on the development of the key components of an advanced ion propulsion system, the thruster, Power Processing Unit (PPU) and Propellant Management System (PMS), and integration of those components into a system as summarized below.

Thruster
- Engineering Model in Phase 1, Prototype Model in Phase 2
- Demonstration of life capability through tests and analyses, including a 2000 hour wear test in Phase 1, and a long duration life test in Phase 2

PPU
- Breadboard Model in Phase 1, Engineering Model in Phase 2

PMS
- Single-string Breadboard Model in Phase 1, Three-string Engineering Model in Phase 2

System Integration
- Single-string system demonstration in Phase 1
- Single- and three-string system demonstrations in Phase 2
- Evaluation of system life capability
- Breadboard Model thruster gimbal in Phase 2
- Control algorithm demonstration in a digital control interface unit simulator

Performance characterizations of component technologies will occur at the component level and at system levels and in a relevant environment. The NEXT thruster, PPU, and PMS will complete performance and relevant environmental tests at the Engineering Model (EM) level with flight representative packages. The NEXT test activities will provide high confidence in the ability of individual components to perform as an integrated propulsion system.

Project Structure

The NEXT team is composed of NASA GRC, the Jet Propulsion Laboratory, Aerojet Redmond Rocket Center, and Boeing Electron Dynamic Devices, with significant participation by the Applied Physics Laboratory, University of Michigan and Colorado State University. Team member roles are summarized in Table 1.

NASA Glenn Research Center	Technology Lead and Project Office System Definition Engineering Model Thruster Gimbal Design
Boeing Electron Dynamic Devices	Power Processing Unit
Aerojet Redmond Rocket Center	Prototype Model Thruster Propellant Management System Digital Control Interface Unit Simulator
Jet Propulsion Laboratory	System and Mission Requirements System Integration Testing Service Life Validation Breadboard Gimbal Fabrication and Test
Colorado State University, University of Michigan	Thruster Modeling and Assessment
Applied Physics Laboratory	Propellant Management System Support

Table 1 - NEXT Project Organizational Responsibilities

The NASA GRC is the organization responsible for overall implementation of the project. The GRC project team includes the Principal Investigator and a Project Manager who work together to share the responsibility for successful project execution. The multi-organizational project is managed in an Integrated Product Development approach, with appropriate organizations participating in product-oriented Integrated Product

Teams (IPT). The IPTs engage all team member organizations in requirement definition, system engineering and analysis, development planning, integration and testing. Separate IPTs have been established for the thruster, the PPU, the PMS, and for system integration. Each product team is led by the project Co-Investigator from the organization responsible for that subsystem.

System Definition

Requirements

The key NEXT requirements, defined initially by the NRA, address component-level technology advances over the NSTAR state-of-art (SOA) and system performance in the DSDRMs. Critical component-level technology advancement requirements include:

Thruster

- Increase in maximum specific impulse of at least 30 percent over SOA (NEXT must achieve >4050 seconds)
- Specific mass comparable to or less than the SOA (<3.6 kg/kW)
- Efficiencies that exceed the SOA across all power levels (>63% at peak)

PPU

- Increase in the power level and specific power over SOA (>0.17 kW/kg)
- Increase in efficiency over that of the SOA (>94% at peak power)

PMS

- Significant mass and volume reductions over the SOA (<9.2 kg for a single string system)

The DSDRMs also directly define component and system level capabilities required to meet the DSDRM objectives and requirements. Two specific outer planet reference missions were defined and analyzed, a Titan Observer and a Neptune Orbiter. From the ion propulsion system perspective, the two missions are very similar. The DSDRMs begin with launch to an earth-escape trajectory using a Delta IV-class expendable launch vehicle. Solar electric propulsion is used in the inner solar system, with a Venus gravity assist, to accelerate to rapid transfers to the destination planet. After completion of electric propulsion operations, the module containing the solar power system, which is sized for approximately 25 kW at 1 astronomical unit (A.U), and the electric propulsion system is jettisoned to reduce system dry mass and volume. Electric propulsion system jettison occurs within 3 A.U. for these missions. The separated spacecraft, powered by radioisotope power sources, coasts to the planet and captures into planetary orbit through aerocapture techniques. The critical DSDRM performance requirements are the delivery of the separated spacecraft mass, 1400 kg to Saturn and 850 kg to Neptune, to a transfer trajectory that minimizes total trip time. The DSDRM requirements and constraints effectively determine key system flow-down requirements, including system and unit power input and throttling, operating duration, propellant throughput, and operating location with the associated thermal and radiation environments. The DSDRMs also, in most cases, drive the component performance requirements beyond the technology objectives defined above.

System Configuration

A general system configuration that will meet the DSDRM requirements, illustrated in Figure 1, has been defined.

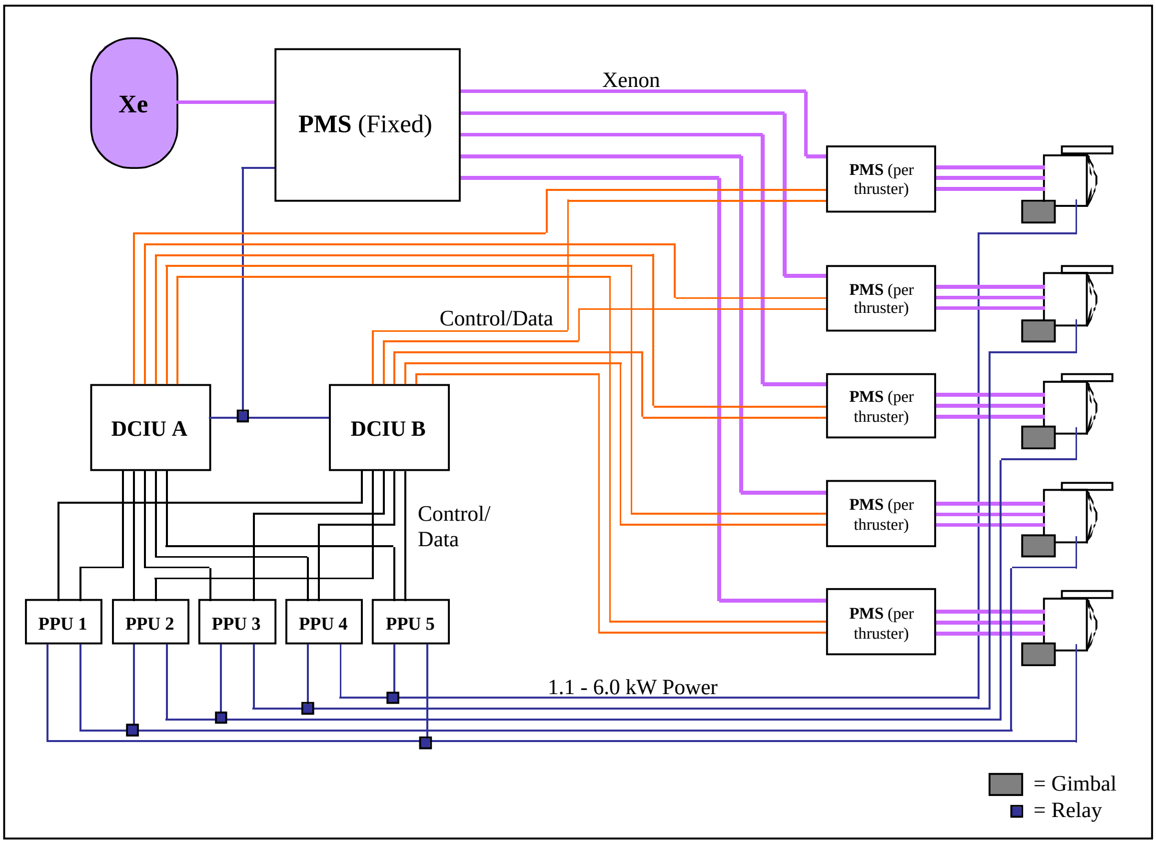

Figure 1 - NEXT DSDRM System Configuration

The NEXT DSDRM system is a five 6 kW thruster configuration. Total system power and per unit thruster power capability were inputs into determination of the minimum number of thrusters. Prior analyses performed for missions similar to the DSDRMs indicated that a power baseline of approximately 25 kW at one astronomical unit was near-optimal for mass delivery and trip time trades; thus 25 kW became a DSDRM constraint. Maximum per-unit thruster capability, for the baseline thruster geometry, is limited by thruster life effects. The NEXT and NGI Projects jointly agreed that a 6 kW thruster was an appropriate balance between mission performance and technology development risk; thus 4 thrusters are operated when maximum power is available (considering PPU losses). A requirement to provide single fault tolerance at the system level results in a fifth thruster.

Each thruster has a dedicated primary PPU, PMS flow control component, and gimbal. The PPUs have switching capability such that each PPU can power one of two thrusters, thus any 4 thrusters can be operated after a single PPU failure. The PMS is divided into two elements: the fixed PMS controls xenon flow from the tank and provides distribution to each thruster; the per-thruster PMS provides the flow control functions for each thruster. PMS cross-feed capability and fixed PMS component redundancy (not shown in Figure 1) can be implemented per mission specific criteria to allow similar single failure tolerance.

The system is controlled by one of two redundant Digital Control Interface Units (DCIU). Requirements to operate over a broad input power range, as the solar electric system moves about the inner solar system, necessitate a significant thruster throttling capability and flexibility in operating at different specific impulse/thrust set-points within that range. NEXT system throttling, in the DSDRM configuration provides a power input range of 1.2 to 25 kW to the PPUs. The DCIU controls the PPU and PMS, in a manner similar to NSTAR, to implement the desired thruster performance condition.

Analysis

System and mission analyses have been performed to determine the performance capabilities of the defined system configuration, and to support quantification of design goals. Optimum total trip times were determined to be approximately 10.3 years for the Neptune Orbiter and 5.5 years for the Titan Orbiter. The NEXT system is throttled both by power per thruster and number of thrusters operating. System performance characteristics associated with these optima include: total propellant throughput of 700 – 900 kg, total system operation time of 782 – 971 days and average thruster on time of 12,000 – 15,000 hrs assuming equal distribution of on time over 4 of the 5 thrusters. The system performance was shown to be relatively insensitive to a number of system design variables with trip time impacts on the order of less than ± 2 months. Sensitivity studies included: high specific impulse or high thruster throttling strategies, minimum number of operating thrusters of 1 or 2, maximum array power level, specific impulse at full power, depth of throttle range, and thruster life effects. System margin analysis indicated that the NEXT system configuration provides robust capability and mission flexibility for the DSDRMs.

Technology Assessment and Selection

Thruster

The thruster is based on a technical approach previously developed at NASA GRC[3]. The approach retains many features from the NSTAR thruster technical approach while making significant changes to increase power and to improve performance characteristics. Figure 2 illustrates the features of the NEXT thruster, with an image of the engineering model thruster developed in Phase 1 of the NEXT Project.

NEXT Thruster Characteristics

- 1.1 – 6 kW input power
- Ring-cusp electron bombardment discharge chamber
- 40 cm beam diameter
- 2-grid ion optics
- Beam current at 6 kW: 3.1 A
- Maximum specific impulse > 4050 sec
- Maximum thrust > 200 mN
- Peak efficiency > 68%
- Xenon throughput > 270 kg, 405 kg qualification level
- Mass target < 12 kg

Figure 2 - NEXT Thruster Technology Approach

Power Processing Unit

The Power Processing Unit combines a technical approach previously developed by Boeing Electron Dynamic Devices and NASA GRC[4] with NSTAR-heritage approaches. A new modular supply approach provides high efficiency for the beam supply. Other supplies, including discharge, accelerator, neutralizer and heater supplies, are based on NSTAR designs, providing low development costs and risks. PPU characteristics include:

- 1.2 – 6.25 kW Input Power
- Peak efficiency > 95%
- Primary input power voltage range 80 – 160 V
- Mass target < 24 kg

Propellant Management System

The propellant management system represents a significant departure from the NSTAR technical approach. The PMS Integrated Product Team conducted a technology trade study at the beginning of the Phase 1 project, resulting in selection of the approach illustrated in Figure 3. The PMS is built around a flow control kernel consisting of a Moog Proportional Flow Control Valve (PFCV) and three new Aerojet-designed thermal throttles, one for each of the three xenon feeds to a thruster. The thermal throttle consists of heaters and temperature sensors integrated onto a Mott sintered-plug flow control device. The flow control kernel has both a pressure control loop and temperature control loop to precisely provide the xenon flow rates within ± 3% of the appropriate thruster throttle setting. Upstream of each flow control kernel is the fixed PMS, which provides first stage pressure regulation. Selection of fixed PMS components will occur in Phase

2 of the project; both fixed regulator and PFCV approaches are being considered. This overall approach is expected to significantly reduce the PMS mass and volume over the NSTAR SOA approach, while improving significantly aspects of the system performance.

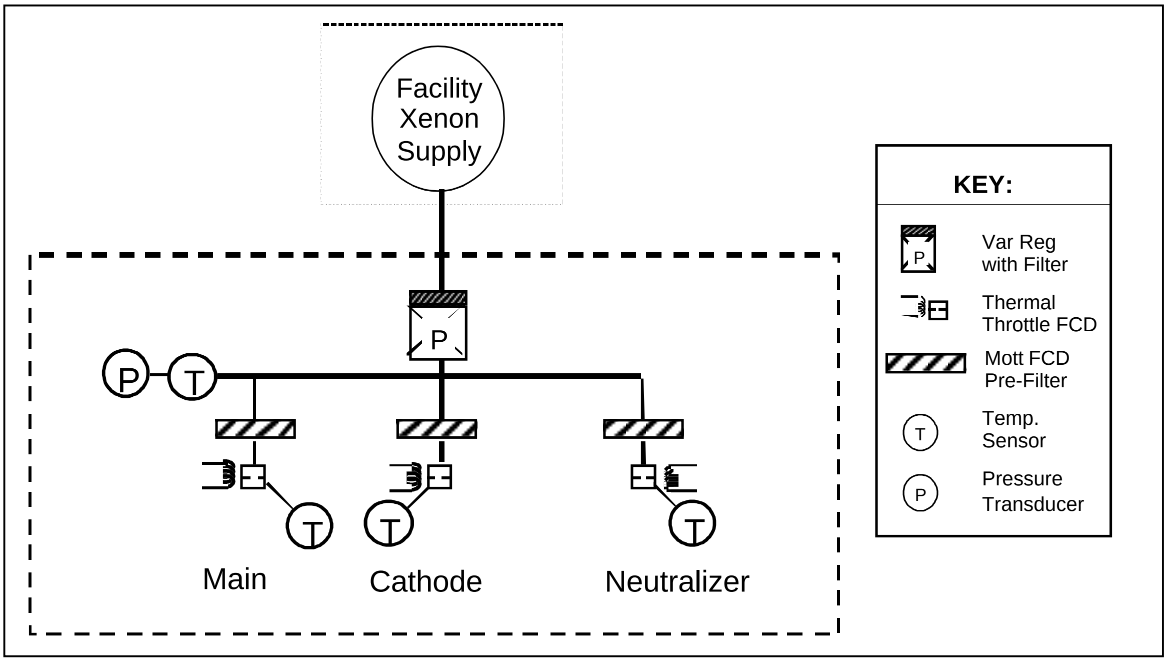

Figure 3 - NEXT Phase 1 Propellant Management System Concept

System Integration Elements

Two other components of an integrated ion propulsion system are considered in the NEXT Project, the thruster gimbal and the DCIU. In Phase 2, the NEXT Project will develop a breadboard gimbal based on a technical approach previously developed at NASA GRC. For the 40 cm beam diameter NEXT thruster, the gimbal mass target is 3.2 kg. The NEXT Project is developing a DCIU simulator that will perform many of the PPU and PMS control functions of a flight unit. The intent of the DCIU simulator is to provide a system that allows demonstration of the other NEXT components, and to validate the algorithms that will ultimately be used to operate NEXT. The DCIU simulator is to be expanded from a PMS controller in Phase 1 to provide the interface to the PPU in Phase 2. Xenon storage technology is not addressed by the NEXT Project.

Phase 1 Development Plans and Status

Phase 1 of the NEXT Project began in August 2002. The first phase emphasizes fabrication and test of hardware, such that the technology approach is validated prior to advancing to the next level of hardware maturity in Phase 2. Project level requirements were established through development of a Project Requirements Document. Concept Design Reviews were conducted in October 2002, during which the team evaluated and agreed upon the thruster, PPU, PMS and DCIU simulator technical concept prior to detailed design and fabrication. Requirements development continued with documentation of the system and component-level flow-down requirements, culminating in a Project Requirements Review in December 2002. A Breadboard System Preliminary Design Review was conducted in January 2003 to assess the integrated ion propulsion system design, updates to the component designs, and project planning to execute the remainder of Phase 1. Significant testing is planned in Phase 1 to validate that the NEXT hardware products meet the project and flow-down requirements, and meet the Phase 1 objectives. Planned Phase 1 testing is shown in Table 2.

Phase 1 Test Description	Location	Dates
EM1 Performance Tests	GRC, VF6	Jan – Mar/03
EM1 2000-Hour Wear Test	GRC, VF6	Apr – Jul/03
EM2 Sine Sweep Vibration Test	GRC	Mar/03
EM2 Performance Tests	GRC, VF11	Apr/03
Breadboard PPU Functional Tests	BEDD	Apr – May/03
Breadboard PMS Component Tests	Aerojet	Jan – Mar/03
DCIU Simulator Functional Tests	Aerojet	Apr/03
Breadboard PMS Functional Tests	Aerojet	Apr – May/03
NEXT Breadboard System Integration Test	GRC, VF5	Jun – Jul/03

Table 2 – NEXT Phase 1 Test Plan

Two of the planned three engineering model thrusters, EM1 and EM2, have been fully assembled. Initial performance testing of EM1 was completed in January 2003. In these series of tests the thruster configuration was verified, demonstrating all functional and performance requirements over the intended power throttling range. Initial performance results are consistent with previously reported performance characteristics of prior 40-cm thruster generations[5]. The EM1 thruster is scheduled to begin a 2000-hour wear test in April of 2003, with completion anticipated prior to the end of Phase 1. The wear test will be conducted in GRC Vacuum Facility 6, a 7.6 meter diameter by 21 meter long facility with a pumping speed in excess of 200,000 liters/second on Xenon. Diagnostics will be a key aspect of evaluating thruster wear mechanisms in situ. Planned diagnostics include an E x B probe, Langmuir probe, multiple-probe Faraday rake, laser profilometer, beam centroid probe and cameras. EM2 is scheduled for sine vibration testing to assess structural design characteristics and potential issues that can be addressed in the Phase 2 design.

The breadboard PPU is scheduled for module-level fabrication and testing completion through March, with unit integration and testing to occur prior to delivery to NASA GRC. Risk mitigation and design iteration testing has been performed on two modular beam supplies produced by BEDD under a prior NASA contract[4].

Risk mitigation testing of a laboratory model thermal throttle for the breadboard PMS has been successfully completed, providing confidence in thermal throttle fabrication approach and performance characteristics. The thermal throttle is scheduled for piece part fabrication and component assembly through March 2003, at which time all other components of the PMS will be ready for integration. Breadboard PMS final assembly, functional testing and calibration begins in April 2003. In parallel to the PMS development, Aerojet is developing the Phase 1 DCIU simulator, which controls only the PMS, and xenon feed support equipment. The three related subsystems will be validated together in the PMS development testing. All pre-integration development testing of the PPU and PMS occurs at the BEDD and Aerojet facilities respectively.

The EM2 thruster, Breadboard PPU and PMS are brought together at NASA GRC in June and July for integrated system testing. Testing will occur in the GRC Vacuum Facility 5, a 4.6 meter diameter by 18.3 meter long facility with pumping speed in excess of 1,000,000 liters/second on Xenon. The integrated test will demonstrate system functionality, stable integrated operations, and system level performance characteristics.

The Phase 1 integrated system test, 2000-hr thruster wear test, and associated thruster life analyses will be key inputs to the decision to proceed to Phase 2.

Phase 2 Development Plans

Phase 2 of the project will advance the technology maturity of the thruster, PPU and PMS designs demonstrated in Phase 1. Development of a prototype model thruster and engineering model PPU and PMS, with component, subsystem and system level testing, will accomplish most of the criteria associated with Technology Readiness Level 6, the level prior to flight demonstration or implementation.

Thruster

The engineering model thruster design will be matured to the prototype model level by Aerojet. The objectives include design and analysis of qualification-level hardware, including full thermal and structural analyses, design for producability to minimize thruster recurring costs, and reduced mass. Two Prototype Model (PM) thrusters will be assembled to support thruster-level performance and environment testing and integrated system testing.

Power Processing Unit

The BEDD Engineering Model PPU design will incorporate flight-like packaging and the associated thermal, vibration, and electromagnetic interference environmental testing. The EM PPU will include an input/output module to allow interface to the DCIU simulator that will control the ion propulsion system. The Phase 1 breadboard PPU will be modified to provide the same capability, providing two fully functional units for integrated system testing.

Propellant Management System

The EM PMS will be designed based on a spacecraft packaging concept representative of the DSDRM-class missions. Two versions of the EM PMS will be fabricated, a single-string system to support detailed development testing, and a three-string system to support integrated system testing. The single-string system will undergo functional/performance, proof/leak, thermal-vacuum, vibration, and burst tests associated with spacecraft propulsion system development.

System Integration

A breadboard gimbal will be fabricated in Phase 2 to demonstrate the gimbal technical approach and it's compatibility within the ion propulsion system. The thruster/gimbal assembly will undergo random vibration testing to validate the lightweight gimbal design. The DCIU Simulator will be expanded in Phase 2 to include control of the PPUs. The completion of Phase 2 is highlighted by integrated system testing in both a single-string mode and a three-string mode. Single string testing will focus on demonstrating system functional and performance requirements. The three-string testing will investigate environments and performance to determine if interactions are taking place between operating units, or if operating units affect non-operating units. The three-string test will be conducted using both PM thrusters, an EM thruster, the three-string EM PMS, the EM and breadboard PPUs and a laboratory power supply, and the DCIU simulator.

Life Validation

Life validation of the NEXT system will be accomplished through a combination of test and analysis. Thruster life will be assessed through a long-duration life test of an EM thruster, in which a significant fraction of the required 270 kg of Xenon will be expended, component-level tests and detailed thruster modeling and analysis. PPU and PMS component and subsystem life will be assessed primarily through analyses. Full duration system life testing, while desirable, would exceed the schedule and budget allocated to this phase of development.

The Phase 2 NEXT system design and test activities will accomplish many of the qualification-level testing that will be required by future mission users. Through flight-like design and packaging and thorough environmental and performance testing, the NEXT project will facilitate the transition to flight hardware for future mission users.

Concluding Remarks

The NEXT Project is progressing through an aggressive first year, and is on plan to complete the objectives of Phase 1. System and mission analyses show that the planned system meets the defined mission requirements. Initial testing indicates that thruster performance meets the characteristics necessary to meet DSDRM performance parameters. The project team expects that the remainder of Phase 1 will provide information and experiences that will support the Phase 2 goal of providing the next generation ion propulsion system.

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