NASA's Evolutionary Xenon Thruster (NEXT)
Ion Propulsion GFE Component Information Summary for Discovery Missions
July 2014

NOMENCLATURE

DCIU	=	DIGITAL CONTROL INTERFACE UNIT	NEXT	=	NASA'S EVOLUTIONARY XENON THRUSTER
EM	=	ENGINEERING MODEL	PFCV	=	PROPORTIONAL FLOW CONTROL VALVE
GRC	=	GLENN RESEARCH CENTER	PM	=	PROTOTYPE MODEL
HPA	=	HIGH PRESSURE ASSEMBLY	PMS	=	PROPELLANT MANAGEMENT SYSTEM
LDT	=	LONG DURATION TEST	PPU	=	POWER PROCESSING UNIT
LPA	=	LOW PRESSURE ASSEMBLY	SEP	=	SOLAR ELECTRIC PROPULSION
IPS	=	ION PROPULSION SYSTEM	SSIT	=	SINGLE STRING INTEGRATION TEST
MSIT	=	MULTI-STRING SYSTEM INTEGRATION TEST			

1. NEXT INTRODUCTION

This document is a guide to Discovery mission proposal teams. The document describes the planning for the NEXT-C Project to provide two NEXT thrusters and two NEXT Power Processing Units (PPU) as Government-Furnished Equipment (GFE) to an awarded mission under the Discovery 2014 Announcement of Opportunity (AO). The document also provides background information on the development and status of the NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system (IPS) technology and its application to planetary and science missions. Information on the other NEXT subsystem components are also be provided for information purposes. Proposers would have the ability to utilize any of these components if desired, but they would not be provided as GFE.

1.1 Background

The NEXT ion propulsion system was developed under the NASA Science Mission Directorate In-Space Propulsion Technology (ISPT) project. The primary objective of the NEXT technology project was to significantly increase performance for primary propulsion to planetary bodies by leveraging NASA's very successful ion propulsion program for low-thrust applications. The government/industry team completed the highest fidelity hardware planned, including a flight prototype model (PM) thruster, an engineering model (EM) power processing unit, EM propellant management assemblies, a breadboard gimbal, and control unit simulators. To transition this technology to flight applications, the Planetary Science Division of the NASA Science Mission Directorate initiated the project to build NEXT thruster and PPU flight hardware and provide as GFE to a mission awarded under this, or future, AOs.

NEXT is an advanced ion propulsion system oriented towards robotic exploration of the solar system using solar-electric power. It is based on an evolutionary design that has strong heritage to the NSTAR (NASA's Solar Electric Propulsion Application Readiness) IPS that is currently flying on the Dawn spacecraft. Potential mission destinations that can benefit from a NEXT Solar Electric Propulsion (SEP) system include inner planets, small bodies, as well as outer planets and their moons when chemical or aerocapture approaches are used for orbit capture at the destination body. This range of robotic exploration missions generally calls for ion propulsion systems with deep throttling capability and system input power ranging from 5 to 25 kW, as referenced to solar array output at one Astronomical Unit (AU).

1.2 NEXT-C Project

The NEXT-C Project is planning a competitive procurement leading to delivery of the GFE hardware to an awarded mission that uses NEXT-based SEP. The project is planning for two phases: a development phase in which a prototype PPU is designed, fabricated and tested to achieve TRL6 and any modifications to the thruster design are verified, and the flight hardware phase. NASA desires for the NEXT thruster and PPU to be readily available to future NASA users as a commercial product. The procurement is being defined such that NASA will consider modifications or alternatives to the existing design, particularly the PPU design, to facilitate broader use in non-NASA applications. Final definition of the specific configurations and deliverables are dependent on the selected contractor and technical approach. The contents of this document provide guidance as understood at the time of publication.

1.3 NEXT Technology-Based System Summary

The NEXT technology development project focused on those elements of an ion propulsion system that are most applicable to a range of mission concepts and have the greatest technology development risks. Figure 1 illustrates the NEXT technology project products in a representative, simplified, system configuration. This figure represents the subset of an overall ion propulsion system that the NEXT technology project team addressed. Appendix J of the "NASA Procedural Requirements (NPR) 7120.8 NASA Research and Technology Program and Project Managements Requirements" provides the definition of technology hardware maturity. Table 1 describes the various major subsystems of a flight ion propulsion system (IPS), and the hardware maturity (per NPR 7120.8) achieved on the NEXT technology project. This document retains the hardware maturity terminology used in prior NEXT publications.

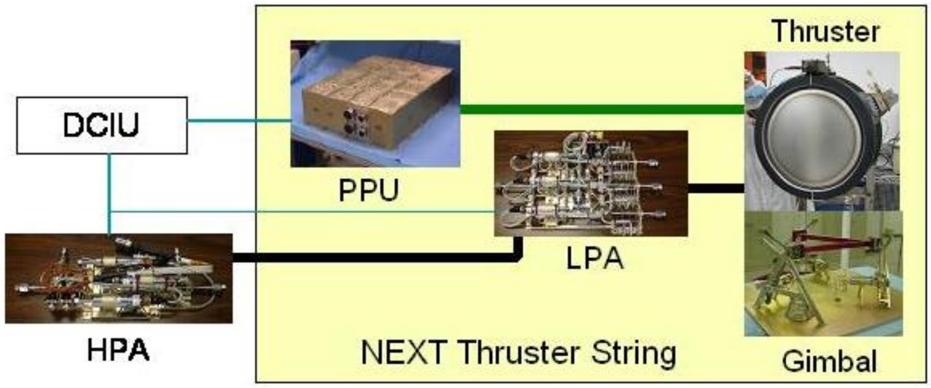

Figure 1. NEXT ion propulsion system elements

Table 1 NEXT-based IPS Subsystems

IPS Subsystem	Function	NEXT Hardware Maturity (per NPR 7120.8)
Ion Thruster	Provide thrust	Engineering Unit
Power Processing Unit	Converts solar array power to thruster input power	Engineering Unit
Propellant Tank	Xenon storage	Not addressed on NEXT
High Pressure Assembly	Control xenon pressure to LPA	Engineering Unit
Low Pressure Assembly	Control xenon flow to thruster	Engineering Unit
Miscellaneous valves, tubing and fitting	Xenon loading, isolation control and purge flow	Not addressed on NEXT
Gimbal	Point thruster to desired vector	Brassboard
Control/Interface Unit	Control/data interface to spacecraft, PPU and xenon feed system	Simulator only, with brassboard xenon flow control cards

2. Component Development and Performance Summary

The following subsections provide a summary description of the NEXT-C flight hardware components, as well as related NEXT technology subsystems. The specification sheets in Appendix A include additional information such as key performance characteristics, mass, dimensions, and subsystem test parameters. The NEXT ion propulsion system can be tailored to a wide range of mission applications.

2.1 Government-Furnished Equipment Components

The NEXT-C Project is being conducted as a NPR 7120.5E project, with GFE product development consistent with the Class B payload guidance in NPR 8705.4. Recommendations received in the NEXT technology project Phase 2 Close-out Review of November 2012 are being incorporated into the project planning.

2.1.1 NEXT Ion Thruster (GFE Component)

2.1.1.1 Ion Thruster Component Summary

The NEXT ion thruster was developed through a two-phase approach during the NEXT technology project. NASA Glenn Research Center (GRC) developed the initial design concept and validated it through fabrication and test of five Engineering Model (EM) thrusters. GRC transferred the thruster concept to Aerojet for implementation in the PM thruster design and hardware. Aerojet delivered a prototype model (PM) thruster (equivalent to Engineering Unit per NPR7120.8), and parts/sub-assemblies for a second thruster to NASA GRC. Key validation activities included performance acceptance testing, environmental analysis and testing, and life analysis and testing. The thruster was judged as TRL 6 in four independent TRL assessments. To preserve the demonstrated performance and lifetime capability, the PM thruster design is the baseline for the GFE flight thruster development. Figure 2 shows the NEXT PM thruster operating during performance acceptance testing.

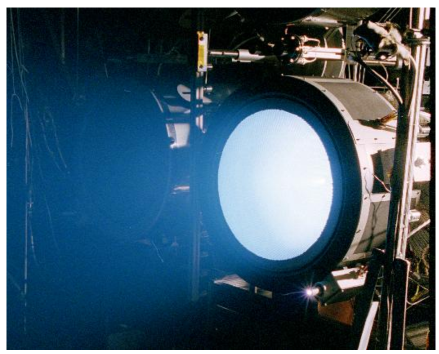

Figure 2. NEXT PM thruster during performance acceptance testing

2.1.1.2 Thruster Performance

Thrust and specific impulse are the primary measures of effective conversion of power and propellant to achieve the required mission velocity change (ΔV). Thruster performance is currently based on NEXT Throttle Table 11 (TT11). Throttle table updates from previously published TT10 include: incorporation of extensive diagnostic test data and measured thrust generated in testing at The Aerospace Corporation, information gleaned from the thruster Long Duration Test, and assessment of operating margins. The key parameters of TT11 are summarized in the thruster specification sheet found in Appendix A. Additional detailed throttle table data is available upon request.

Additional Extended Throttle Level (ETL) throttle points were characterized during testing at The Aerospace Corporation. The ETL points represent capabilities within the current thruster design and PPU output ranges that were not incorporated in testing during the technology project thruster verification test program. These points provide higher thrust-to-power capability, with operations at higher beam currents and propellant flow rates for some beam voltages. While performance verification of these points is extensive, thruster lifetime characterization has not yet been completed; therefore, at this time they should be considered as having potential to provide increased capability (performance margin) for missions benefiting from high thrust-to-power, not as baseline capability. ETL summary parameters are also provided in Appendix A. Further ETL guidance will be provided when it becomes available.

2.1.1.3 Thruster Lifetime Performance

The NEXT thruster has a test-demonstrated mission life capability for throttle levels (TL) 1-40 exceeding 600 kg xenon throughput and 22.5 MN-s total impulse. Given thruster lifetime dependence on throttling strategy, application of the NEXT thruster life model should be applied by GRC personnel against mission-specific throttle profiles to establish life margins for the intended mission applications. The values demonstrated during the execution of the Long Duration Test reflect the operational history of the test and therefore do not necessarily represent hard or firm maxims.

2.1.1.4 GFE Thruster Planning

The project will deliver two flight thrusters to the awarded Discovery mission. The first thruster will undergo a proto-flight test program. The project will provide spare thruster sub-assemblies as needed to mitigate flight hardware issues. Spares tentatively include ion optics assemblies, discharge and neutralizer cathode assemblies, propellant isolator assemblies and front mask and plasma screen components. The thrusters will be configured with integrated harnesses, the length of which will be determined during the project, with flight connectors. The project will provide cable savers, remove-before-flight protective covers, and a remove-before-flight handle or other device to support spacecraft integration. The project will provide the flight thruster specification, acceptance data packages, analytical models, verification reports, interface control documentation, control algorithms to the flow diagram level, and operations documentation to the mission project. Thruster Ground Support Equipment (GSE) and/or Test Support Equipment (TSE) will be provided to the mission project to support spacecraft integration and test. The mission project is responsible for any hardware simulators needed to support propulsion system or spacecraft-level integration and test. The NEXT-C Project can store the thrusters in required conditions until the mission project has need, if requested. The actual flight hardware delivery date is dependent on completion of the NEXT-C procurement process, the content of the awarded contract, and coordination with an awarded mission. For planning purposes, the flight thrusters will be provided to the mission in May 2019.

The NEXT-C Project will also make available high-fidelity NEXT thrusters, on a temporary basis, to support early risk-reduction testing or integration activities, on a non-interference basis with the NEXT-C Project needs. The technology project PM thruster or GRC-fabricated EM thrusters are available, to be jointly selected based on intended use and hardware risk. Development-level GSE and TSE can be provided to support use of these high-fidelity thrusters.

2.1.2 NEXT Power Processing Unit (GFE Component)

2.1.2.1 Power Processing Unit Component Summary

L-3 Communications designed and fabricated the engineering model (EM) power processing unit (PPU) for the NEXT project as shown in Figure 3. This PPU is capable of processing from 0.5 to 7.0 kW of output power for operating the NEXT ion thruster. Its design includes many significant improvements for better performance over the state-of-the-art NSTAR PPU. The most significant difference is the beam supply that is comprised of six modules and is capable of very efficient operation through a wide power and voltage range. The previously validated NSTAR PPU provided the basis for the low voltage power supplies. While EM PPU performance and functionality was successfully tested across a range of relevant operating conditions on both a thruster and resistive load, technical issues prevented completion of environmental testing; therefore, the PPU was judged as TRL 4 in three of the four independent TRL assessments. The GFE flight PPU design is not constrained to the PPU design developed during the technology project, as described in Section 2.1.2.3 below.

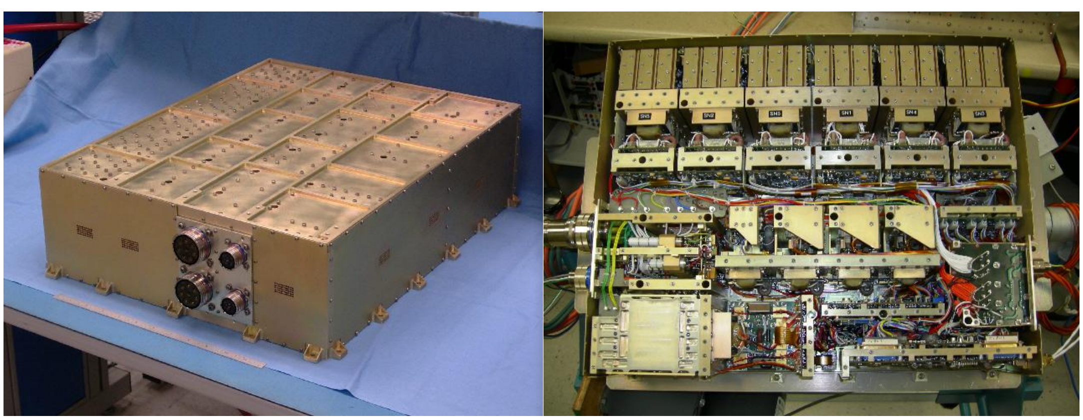

Figure 3. NEXT EM PPU

2.1.2.2 PPU Efficiency Performance

Efficient conversion of array power to thruster power is important in achieving overall IPS performance. A summary of the PPU efficiency over the power throttle range is found in Appendix B. The NEXT PPU accepts unregulated primary power over a range of 82-160V.

2.1.2.3 GFE PPU Planning

The NEXT-C Project will design, fabricate and test a prototype PPU during the development phase. A prototype unit is defined as: 1) a form, fit and function equivalent to a flight unit, with 2) use of non-flight parts acceptable for cost/schedule savings when equivalent flight parts are available, and 3) subjected to functional/performance testing across the full range of allowable conditions and qualification-level environmental testing. Completion of prototype PPU verification at the unit level and in integrated PPU/thruster performance and EMI tests is planned for March of 2017.

The project will deliver two flight PPUs to the awarded Discovery mission. Given that NASA is interested in a commercial product that is not necessarily optimized to NASA applications, the PPU resulting from this project may have different characteristics and capabilities than the technology project design. The project has developed a summary of conceptual properties to support the Discovery AO process, included as Appendix B. Proposing organizations should consider this level of uncertainty in incorporating contingency during mission concept definition.

The project will provide spare parts/sub-assemblies, to be determined during project execution, as needed to mitigate flight hardware issues. The PPUs will be configured with flight connectors on the body of the unit. The mission is responsible for flight harnesses between the PPU and thruster, and between the PPU and spacecraft interfaces. The project will provide the flight PPU specification, acceptance data packages, analytical models, verification reports, interface control documentation, control algorithms to the flow diagram level, and operations documentation to the mission project. PPU Ground Support Equipment (GSE) and/or Test Support Equipment (TSE) will be provided to the mission project to support spacecraft integration and test. The mission project is responsible for any hardware simulators needed to support propulsion system or spacecraft-level integration and test. The NEXT-C Project can store the PPUs in required conditions until the mission project has need, if requested. The actual flight hardware delivery date is dependent on completion of the NEXT-C procurement process, the content of the awarded contract, and coordination with an awarded mission. For planning purposes, the flight PPUs will be provided to the mission in May 2019.

The NEXT-C Project will also make available high-fidelity NEXT PPUs, on a temporary basis, to support early risk-reduction testing or integration activities. The technology project EM PPU is being configured into a testbed to support the NEXT-C PPU development. This testbed and the Prototype PPU will be available for mission use, on a non-interference basis with the NEXT-C Project needs. Development-level GSE and TSE can be provided to support use of these high-fidelity PPUs.

2.1.2.4 Technology Project PPU Technical Issues

The NEXT technology project encountered a number of PPU technical issues during unit and system testing. Early issues involved a design error that was easily corrected and a second source part that did not have equivalent capability. The more demanding issue was multiple occurrences of multi-layer ceramic (MLC) capacitor failures. This issue was ultimately traced to the piezoelectric characteristic of the custom capacitor being excited in the PPU application. Reference 32 summarizes these issues and Reference 33 provides detailed information on the MLC capacitor failure resolution. Each issue was resolved with paths to flight production identified. The specific mitigations and lessons learned will be incorporated into the NEXT-C PPU development.

2.2 Other NEXT Technology Project Components

This section provides summaries of other products of the NEXT technology project for information only. These components are *not part of the GFE provisions*.

2.2.1 Propellant Management Subsystem (PMS)

Aerojet designed and fabricated the NEXT EM high pressure and low pressure assemblies (HPA, LPA) and the primary flow control components of an overall xenon feed system. Both assemblies are shown in Figure 4. The HPA, composed of parallel redundant proportional flow control valves (PFCV) and pressure transducers, steps the xenon pressure from tank pressure to a nominal regulated LPA inlet pressure of 35 psia, or provides unregulated pressure below 35 psia for end-of-mission operations. The LPA consists of three flow-control kernels to supply throttled xenon flow to the thruster main plenum, discharge cathode and neutralizer cathode. Initial validation of the propellant management system (PMS) technology was accomplished during breadboard system integration testing in the first NEXT project phase in 2003. EM assemblies were fabricated and tested in the project phase 2. Key PMS validation activities include performance acceptance and environmental testing, and testing in integrated single-string and multi-string thruster strings, all of which were successfully completed. The PMS assemblies were judged as TRL 6 in three of four independent TRL assessments.

Figure 4. NEXT EM High Pressure Assembly (top) and Low Pressure Assembly (bottom) from the Propellant Management System

2.2.2 Gimbal Component Summary

ATK, under contract to the Jet Propulsion Laboratory (JPL), designed and fabricated the NEXT gimbal. ATK delivered one complete gimbal assembly with sufficient parts for a second assembly. The gimbal provides maximum angular authority of ±19° and ±17° about the primary gimbal axes and a rough cone about the thruster centerline within those boundaries. The NEXT gimbal has a significantly smaller spacecraft interface footprint as compared to the Dawn/NSTAR gimbal. The gimbal is a flight-like design using JPL-approved materials with certifications, and stepper motors have a space-rated option. The design of the gimbal was as a flight-packaged unit without substantive thermal analysis. Therefore, only functional testing and structural dynamic analyses and testing were performed on the gimbal. The gimbal successfully completed functionality tests with the PM thruster. The gimbal passed two qualification-level vibration tests and low-level shock tests with minor issues. The gimbal was judged as being across a range of TRL 4-6 in the four independent TRL assessments.

2.2.3 Digital Control Interface Unit (DCIU) Summary

The NEXT project developed a simulator for the system Digital Control Interface Unit (DCIU), providing the capability to operate the key technology products in an integrated system. The primary functions of the DCIU are to interface to the spacecraft flight processor for high level commands and telemetry, and to control the PPU and PMS assemblies, effectively throttling the ion thruster(s). The simulator is personal computer-based test equipment with brassboard-level PMS pressure loop control cards, and is capable of operating a three-thruster-string system. Implementation of DCIU functionality is user dependent. The NEXT-C Project will provide PPU/Feed System/Thruster control algorithms to the flow diagram level.

3. System Integration

3.1 NEXT Technology Project System Integration Tests

Three test activities categorized as system-level tests were conducted during the NEXT technology project: multi-thruster array tests, a single-string system integration test (SSIT) and a multi-string system integration test (MSIT).

The objective of the multi-thruster array test was to assess thruster and plasma interactions with sensitivities to thruster spacing, gimbaled thrusters and neutralizer operating modes. The configuration included four GRC EM thrusters; three operating and one instrumented non-operating as well as an extensive suite of diagnostics to collect data for multi-thruster system modeling and analyses. The multi-thruster array test included single, dual, and triple thruster operations. Results indicate that expected thruster performance was achieved and thruster operations were understood without significant sensitivity to system configuration.

The scope of the Single-String System Integration Test (SSIT) was to verify that the integrated system of NEXT components meets the project requirements in a relevant environment. The primary objectives were to demonstrate:

- operation of the thruster over the throttle table with PPU and PMS,
- operation of system at off-nominal conditions,
- recycle and fault protection operation;
- and to verify a wide range of system-level requirements, including functional, performance, environmental and interface requirements.

The test configuration included the PM thruster, EM PPU, the EM PMS as well as the DCIU simulator. The test started in May 2008 and continued through August when a PPU part failure interrupted the test sequence. Testing that did not require the PPU was then completed, resulting in completion of 70-80 percent of the test objectives.

A Multi-string System Integration Test (MSIT) was conducted following the SSIT, demonstrating successful operations of three thrusters (PM1R and two EM thrusters) with the PMS HPA and three LPAs controlled by the DCIU simulator.

3.2 NEXT-C System Integration Tests

The NEXT-C Project is planning to conduct the following system integration tests.

- Prototype PPU/PM thruster integrated performance and functional testing. This test will be performed after Prototype PPU verification testing at the unit level;
- Prototype PPU/PM thruster integrated EMI/EMC testing will follow above integration test;
- Flight PPU/Flight thruster integrated performance and functional testing will complete the acceptance test sequence.

4. Discovery Mission Support

The following represents current planning and may be revised upon award of the project contract.

4.1 Pre-Delivery Support

The NEXT-C Project will support mission teams using NEXT GFE during Phase A studies. All interactions will be coordinated through the NEXT-C Project Office. The project team will support technical interactions with the mission team to provide GFE hardware requirements and capabilities information, and to coordinate interface definition and integration/operations planning. The project team will support programmatic interactions with the mission team to coordinate hardware development and delivery schedules, risk analysis, and resource planning for in-scope support after mission selection. The project will provide thruster and PPU review material for, and will participate in, a Mission Concept Review at the end of Phase A.

The NEXT-C Project will support a selected mission team using NEXT GFE from initiation of Phase B through GFE hardware delivery. All interactions will be coordinated through the NEXT-C Project Office. The project team will support technical interactions with the mission team to provide GFE hardware requirements and capabilities information, to coordinate interface definition, and to provide GFE product inputs into integration/operations planning. The project team will support programmatic interactions with the mission team to coordinate hardware development and delivery schedules and risk analysis. The project will provide thruster and PPU review material for, and will participate in, mission project reviews within project scope. NEXT-C Project development hardware is available, on a non-interference basis, for mission use as described in paragraphs above.

4.2 Post-Delivery Support

The NEXT-C Project will provide technical support related to understanding the delivered hardware and accompanying documentation. All interactions will be coordinated through the NEXT-C Project Office. The mission project is responsible for any support from NEXT-C team members (government or industry) to spacecraft integration and test activities and mission operations.

5. Other Documentation

The following information is available upon request to the contact identified below.

- NEXT System ICD – This document was generated during the NEXT technology project and characterizes the interfaces within the ion propulsion system and includes limited information on PPU and thruster interfaces to the spacecraft. This document does not necessarily represent the NEXT-C design and is intended for concept planning purposes only.
- Draft PPU Specification – This document is an initial draft of a PPU specification, created as an input to the NEXT-C procurement process, and is intended for planning purposes only.
- Draft Thruster Specification – This document is an initial draft of a thruster specification, created as an input to the NEXT-C procurement process, and is intended for planning purposes only.

This information is ITAR-sensitive; release will be controlled through the following process:

1. Initiator notifies contact identified below of request;
2. NASA will provide an export control request form to initiator;
3. Initiator completes form and submits request;
4. Documentation is provided through appropriate controlled-release mechanism.

6. Contact Information

Please direct all inquiries and requests related to the NEXT-C Project to provide GFE PPUs and thrusters to the following individual:

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[33] Soeder J., Scheidegger, R., Pinero, L., Birchenough, A., Dunning, J., NASA's Evolutionary Xenon Thruster (NEXT) Power Processing Unit (PPU) Capacitor Failure Root Cause Analysis”, AIAA 2012-4221, 10th International Energy Conversion Engineering Conference, 30 July–01 August, 2012, Atlanta, GA.

[34] Soulas, G., et al., “The Impact of Back-Sputtered Carbon on the Accelerator Grid Wear Rates of the NEXT and NSTAR Ion Thrusters”, IEPC-2013-157, 33rd International Electric Propulsion Conference, Washington, DC, October 6-10, 2013.

[35] Shastry, R., et al., Status of NASA’s Evolutionary Xenon Thruster (NEXT) Long-Duration Test as of 50,000 h and 900 kg Throughput”, IEPC-2013-121, 33rd International Electric Propulsion Conference, Washington, DC, October 6-10, 2013.

APPENDIX A

Specification sheets on the components of the Ion Propulsion system follow.

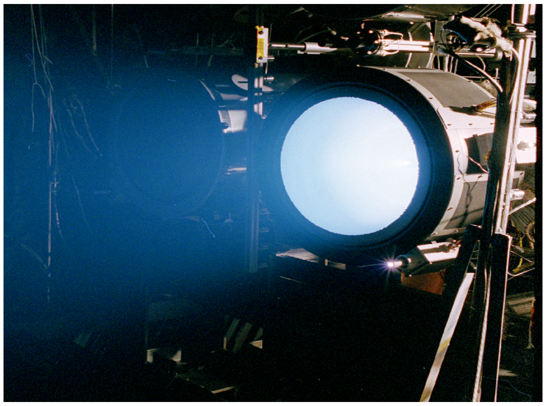
Thruster Data Sheet and Supporting Information

Power Processing Unit Data Sheet

Propellant Management System Assemblies Data Sheet

Gimbal Data Sheet

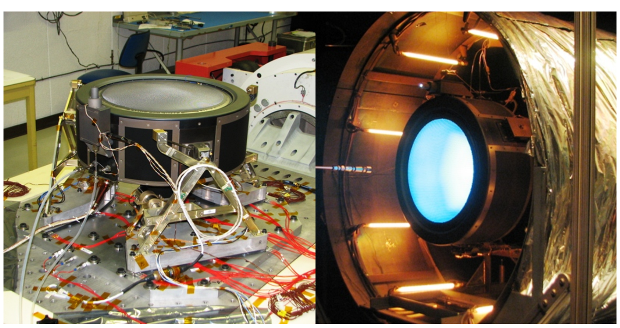
NEXT — Thruster Data Sheet

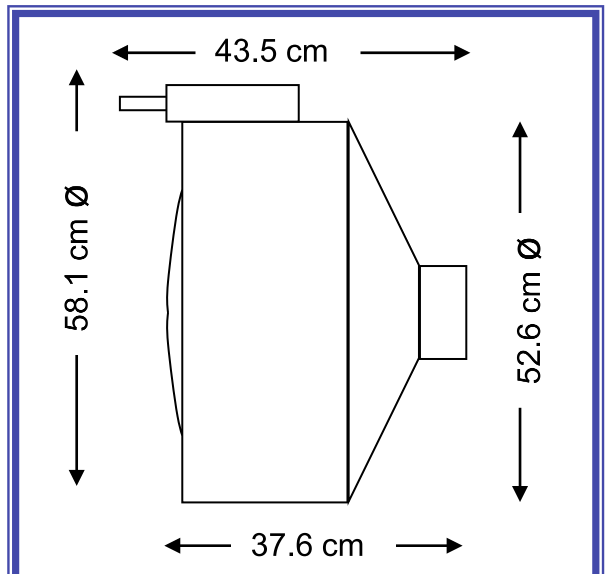


PM1— Flight Prototype Thruster

Performance Characteristics	
Thruster Power Range, kW	0.5-6.9
Max. Specific Impulse, sec	4220
Thrust, mN	25-235
Max. Thruster Efficiency	70%
Beam Diameter, cm	36
Max. Beam Current, A	3.52
Max. Beam Voltage, V	1800
Mass (with harness), kg	13.5

Tested to Qualification-Level Environments	
Vibration	10 G_{rms} 2 min/axis
Thermal/Vacuum	-120 to +215ºC 3 full cycles 3 hot and 3 cold thruster starts 24 h dwell at +215ºC





Thruster Envelope

NEXT Throttle Table 11

NEXT Throttle Table 11 (Beginning of Life)

Throttle Level	Xenon Flow	Beam Current	Beam Voltage	Thrust	Isp	Thruster Efficiency	Thruster Input Power
	mg/s	A	V	mN	seconds	Efficiency	W
TL40	5.76	3.52	1,800	235	4,155	0.70	6,853
TL39	5.76	3.52	1,567	219	3,886	0.69	6,046
TL38	5.76	3.52	1,396	208	3,683	0.69	5,454
TL37	5.76	3.52	1,179	192	3,408	0.68	4,703
TL36	5.12	3.10	1,800	206	4,096	0.68	6,052
TL35	5.12	3.10	1,567	193	3,838	0.68	5,341
TL34	5.12	3.10	1,396	183	3,638	0.68	4,819
TL33	5.12	3.10	1,179	169	3,360	0.67	4,158
TL32	4.46	2.70	1,800	178	4,082	0.68	5,285
TL31	4.46	2.70	1,567	167	3,823	0.67	4,666
TL30	4.46	2.70	1,396	159	3,626	0.67	4,212
TL29	4.46	2.70	1,179	146	3,348	0.66	3,636
TL28	4.46	2.70	1,021	137	3,137	0.66	3,217
TL27	3.92	2.35	1,800	155	4,032	0.66	4,614
TL26	3.92	2.35	1,567	145	3,773	0.66	4,075
TL25	3.92	2.35	1,396	137	3,571	0.65	3,680
TL24	3.92	2.35	1,179	127	3,299	0.65	3,178
TL23	3.92	2.35	1,021	119	3,090	0.64	2,814
TL22	3.16	2.00	1,800	131	4,220	0.68	4,002
TL21	3.16	2.00	1,567	123	3,951	0.67	3,541
TL20	3.16	2.00	1,396	116	3,736	0.66	3,204
TL19	3.16	2.00	1,179	107	3,450	0.65	2,778
TL18	3.16	2.00	1,021	100	3,235	0.64	2,470
TL17	2.60	1.60	1,800	104	4,087	0.64	3,244
TL16	2.60	1.60	1,567	98	3,824	0.64	2,876
TL15	2.60	1.60	1,396	92	3,613	0.63	2,606
TL14	2.60	1.60	1,179	85	3,332	0.61	2,265
TL13	2.60	1.60	1,021	80	3,117	0.60	2,019
TL12	2.05	1.20	1,800	78	3,882	0.61	2,437
TL11	2.05	1.20	1,567	73	3,633	0.60	2,160
TL10	2.05	1.20	1,396	69	3,432	0.59	1,958
TL09	2.05	1.20	1,179	63	3,163	0.58	1,702
TL08	2.05	1.20	1,021	59	2,953	0.57	1,517
TL07	2.05	1.20	936	57	2,839	0.56	1,419
TL06	2.05	1.20	850	54	2,716	0.55	1,319
TL05	2.05	1.20	679	49	2,449	0.53	1,120
TL04	2.05	1.20	650	48	2,389	0.52	1,085
TL03	2.05	1.20	400	37	1,850	0.43	788
TL02	2.05	1.20	300	31	1,564	0.36	668
TL01	1.85	1.00	275	25	1,395	0.32	545

NEXT Expanded Throttle Levels:

The Throttle levels below represent additional performance capability of the NEXT thruster, and are provided for reference information only. See paragraph 2.1.1.2 for further information

NEXT Extended Throttle Table 11 (Beginning of Life)							
Throttle Level	Xenon Flow	Beam Current	Beam Voltage	Thrust	Isp	Thruster Efficiency	Thruster Input Power
	mg/s	**A**	**V**	**mN**	**seconds**	**Efficiency**	**W**
ETL3.52A	5.71	3.52	1,021	177	3,169	0.66	4,155
ETL3.52B	5.66	3.52	936	170	3,060	0.66	3,861
ETL3.52C	5.66	3.52	850	162	2,926	0.65	3,563
ETL3.52D	5.66	3.52	700	146	2,638	0.62	3,038
ETL3.1A	5.07	3.10	1,021	156	3,147	0.66	3,676
ETL3.1B	5.02	3.10	936	150	3,042	0.65	3,416
ETL3.1C	5.02	3.10	850	143	2,898	0.64	3,154
ETL3.1D	5.02	3.10	700	129	2,624	0.62	2,694
ETL3.1E	5.02	3.10	679	127	2,581	0.61	2,629
ETL2.7A	4.41	2.70	936	130	3,018	0.65	2,991
ETL2.7B	4.41	2.70	850	124	2,875	0.63	2,763
ETL2.7C	4.41	2.70	700	113	2,606	0.61	2,364
ETL2.7D	4.41	2.70	679	111	2,565	0.60	2,306
ETL2.7E	4.41	2.70	650	108	2,506	0.60	2,228
ETL2.35A	3.88	2.35	936	114	2,993	0.64	2,617
ETL2.35B	3.88	2.35	850	108	2,851	0.63	2,418
ETL2.35C	3.88	2.35	700	98	2,585	0.60	2,071
ETL2.35D	3.88	2.35	679	97	2,544	0.60	2,023
ETL2.35E	3.88	2.35	650	95	2,487	0.59	1,955
ETL2.0A	3.21	2.00	936	96	3,053	0.63	2,304
ETL2.0B	3.21	2.00	850	92	2,909	0.61	2,136
ETL2.0C	3.21	2.00	700	83	2,639	0.58	1,844
ETL2.0D	3.21	2.00	679	82	2,598	0.58	1,803
ETL2.0E	3.21	2.00	650	80	2,541	0.57	1,747
ETL1.6A	2.63	1.60	936	77	2,982	0.60	1,886
ETL1.6B	2.63	1.60	850	73	2,839	0.58	1,752
ETL1.6C	2.63	1.60	700	66	2,574	0.55	1,518
ETL1.6D	2.63	1.60	679	65	2,534	0.55	1,485
ETL1.6E	2.63	1.60	650	64	2,479	0.54	1,440
ETL1.6F	2.63	1.60	400	50	1,921	0.45	1,043

NEXT Thruster/PPU Curve Fits

The following table provides curve fit coefficients for use in mission analysis. P_0 is power into the PPU in kilowatts. The three data sets represent the:

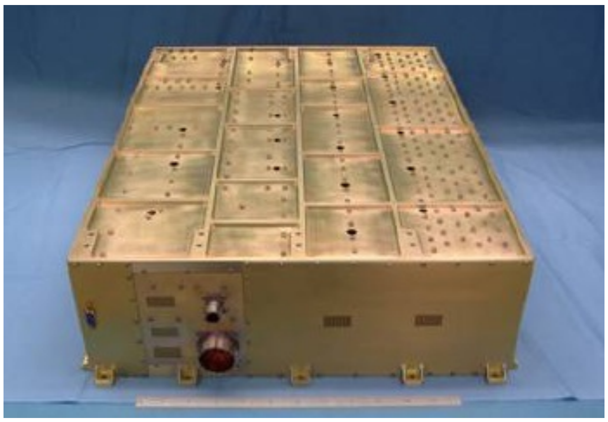
- High Specific Impulse boundary of the throttle table
- High Thrust boundary of the baseline throttle table (TL 1-40)
- High Thrust boundary of the throttle table including Expanded Throttle levels

			1	P_0^1	P_0^2	P_0^3	P_0^4
Baseline Throttle Table 11 (Throttle Levels 1-40)	High Thrust	Thrust Fit (N)	1.19388817E-02	1.60989424E-02	1.14181412E-02	-2.04053417E-03	1.01855017E-04
		Mdot Fit (kg/s)	2.75956482E-06	-1.71102132E-06	1.21670237E-06	-2.07253445E-07	1.10213671E-08
	High I_{sp}	Thrust Fit (N)	3.68945763E-03	4.05432510E-02	-7.91621814E-03	1.72548416E-03	-1.11563126E-04
		Mdot Fit (kg/s)	2.22052155E-06	-1.80919262E-07	2.77715756E-08	2.98873982E-08	-2.91399146E-09

Expanded Throttle Levels (ETLs)	High Thrust	Thrust Fit (N)	-8.04281458E-04	3.71873936E-02	5.17797704E-03	-1.42659172E-03	8.51206723E-05
		Mdot Fit (kg/s)	1.40535083E-06	5.34442545E-07	5.35910391E-07	-1.38009326E-07	9.01951897E-09

NEXT — Power Processing Unit Data Sheet

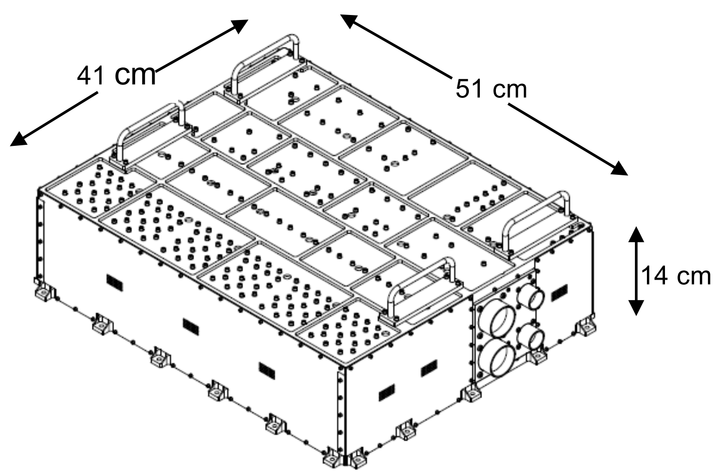
Information is provided for both the existing EM PPU (demonstrated) and the conceptual properties, as described in paragraph 2.1.2.3



Performance Characteristics		
	Existing	**Planning**
Input Power Range, W	**630-7260**	**640-7360**
Peak Efficiency (HV Bus)	**95%**	**> 93.5%**
Primary Power Input Voltage, V	**82-160**	**80-160**
Housekeeping Input Bus, V	**28**	**28**
Housekeeping Power, W	**16-28**	**< 40**
Mass, kg	**33.9**	**< 36**
Power Output to Single Thruster		√

Environmental Requirements	
Vibration	**14.1 G_{rms}**
Thermal	
Operating temperature*	**-20 to +50ºC**
Survival temperature*	**-40 to +70ºC**

Allowable temperatures at the baseplate interface to the spacecraft

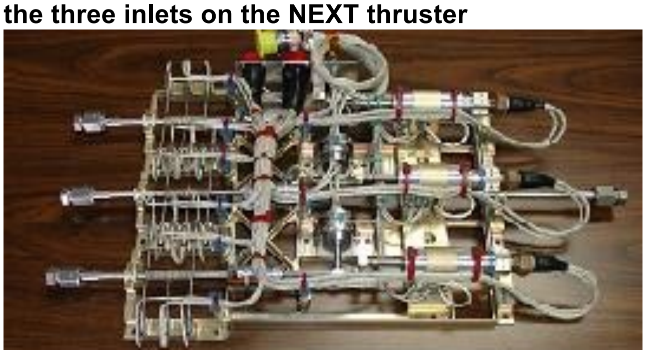


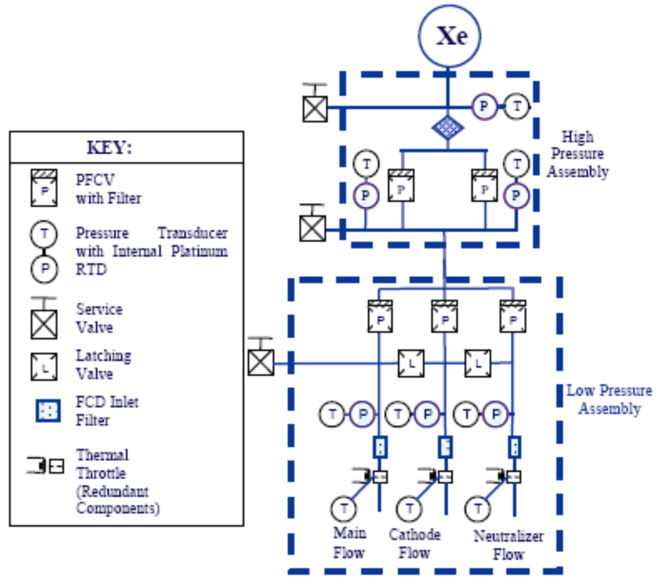
Existing PPU Envelope (excluding mounting feet)

NEXT — Propellant Management System Assemblies Data Sheet

High Pressure Assembly (HPA): Pressure stepdown from tank pressure to nominal operating pressure

Low Pressure Assembly: Xenon flow control to the three inlets on the NEXT thruster





Schematic

Tested to Qualification-Level Environments	
Vibration	**14.1 G_{rms}** **2 min/axis**
Thermal/Vacuum	**-12 to +70ºC** **3 full cycles** **24 h of operations at -12 ºC and +70ºC**

Performance Characteristics	
HPA Mass, kg	**1.9**
LPA Mass, kg	**3.1**
HPA Dimensions, cm	**33x18x7**
LPA Dimensions, cm	**44x28x7**
HPA Power Consumption, W	**1.6**
LPA Power Consumption, W	**8.1**
Flow Rate Accuracy	**<3%**
HPA Inlet Pressure, psia	**<2700**
Tank unusable residual xenon	**<1%**

LPA Operating Modes

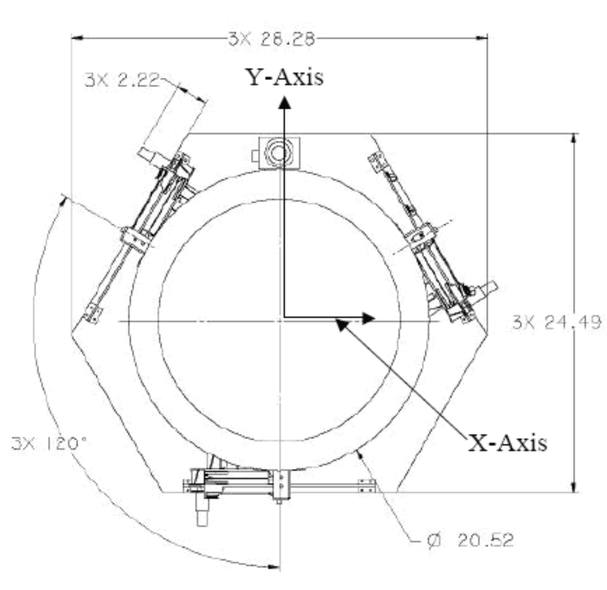
Nominal:
- **Pressure Control Loop**
  - **Fixed thermal throttle temperature**
  - **Variable PFCV orifice to control pressure and calibrated flow rate**

Fault Mode
- **Thermal Control Loop**
  - **Fixed PFCV orifice and internal pressure**
  - **Variable thermal throttle temperature to control flow rate**
  - **Allows control of multiple thruster flows with one or two PFCVs by opening cross-over latch valves.**
  - **LPA power consumption is higher in fault mode than in normal mode**

NEXT —Gimbal Data Sheet

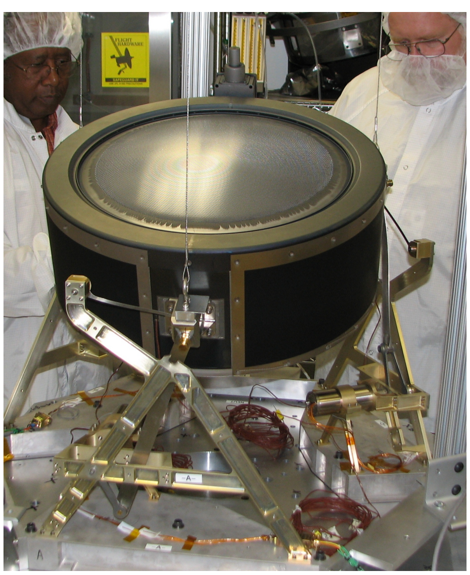
Performance Characteristics	
Mass, kg	6
X-Axis Range of Motion, Degrees	±19
Y-Axis Range of Motion, Degrees	±17
Slew rate, degrees/sec	>0.6

- Three strut attachment to spacecraft
- Thruster retention in launch position
- Thruster deployed to raised operation position after launch.



Gimbal mounting envelope

Tested to Qualification-Level Environments	
Vibration (in thruster/gimbal assembly)	10 G_{rms} 2 min/axis



Post-vibration functional testing

APPENDIX B

Power Processing Unit (PPU) Definition of Conceptual Properties

Research and Engineering Directorate/ Power Division
National Aeronautics and Space Administration
Glenn Research Center, Cleveland Ohio 44135

NASA's Evolutionary Xenon Thruster (NEXT)

Power Processing Unit (PPU)
Definition of Conceptual Properties

TABLE OF CONTENTS

TABLE

FIGURE

1.0 Introduction

The NEXT PPU processes the power for operating the spacecraft electric thruster. The unit consists of six power supplies. Four power supplies (beam, accelerator, discharge, and neutralizer keeper) are needed for steady state operation, while two heater supplies (neutralizer and discharge cathode heaters) are only used during thruster startup. The largest and perhaps the most critical of these power supplies is the beam, as it processes more than 90% of the thruster power. In combination with the accelerator supply, it is used to produce thrust by accelerating the ions generated by the discharge supply. The NEXT PPU design implemented in the technology development project is based on elements of the previously flight validated NASA's Solar Electric Propulsion Technology Application Readiness (NSTAR) PPU. The most significant difference is the beam supply which is capable of very efficient operation across a wide voltage range. This PPU is capable of processing from 0.5 to 7.0 kW of output power for the NEXT ion thruster.

NASA GRC is in process of procuring the NEXT PPU flight hardware to be delivered as government-furnished equipment (GFE) to a selected Discovery mission. The PPU implementation is not being constrained to the technology project design; thus, properties may differ from those established for the existing design. The conceptual properties herein are intended for assessment by mission personnel in evaluating uses of such a power processor in mission concept studies.

1.1 *Purpose*

This document defines the set of conceptual properties of the Power Processing Unit (PPU) of the NEXT Ion Propulsion System (IPS).

1.2 *Scope*

This document presents the conceptual properties for the PPU. These are anticipated properties, and many of which are based on hardware designed during the technology development phase of the project.

2.0 PPU Functionality and Conceptual Properties

This section presents the conceptual properties, as well as basic functionality of the PPU.

2.1 *PPU Description*

The NEXT PPU processes the power for operating the spacecraft electric thruster. The unit consists of six power supplies. Four power supplies (beam, accelerator, discharge, and neutralizer keeper) are needed for steady state operation, while two heater supplies (neutralizer and discharge cathode heaters) are only used during thruster startup. The largest and perhaps the most critical of these power supplies is the beam, as it processes more than 90% of the thruster power. In combination with the accelerator supply, it is used to produce thrust by accelerating the ions generated by the discharge supply. The PPU was designed to operate from two separate inputs. The high power bus (HPB) provides power for all PPU outputs. The low power bus (LPB) is used exclusively for the housekeeping supply. A block diagram of the PPU and its electrical interface to the thruster is shown in Figure 2-1. **Error! Reference source not found.** summarizes the output power requirements for the PPU. The PPU provides an interface to only one thruster, and does not allow for cross strapping thrusters. The PPU is also required to exchange digital telemetry and power supply output control functions with a control interface unit within the ion propulsion system or at the spacecraft system level. The unit contains under-voltage and over-voltage lockout that disables the outputs to the thruster in the case of anomalous input voltages on either power bus. Also provided are neutralizer and discharge current interlocks, which inhibit operation of the high voltage (beam and accelerator) power supplies if cathode currents are not present. Finally, the unit implements recycle controls that sequence the high voltage supplies in case an over-current condition is detected in the beam supply.

Table 2-1 PPU Output Power Overview

	Beam	Accelerator	Discharge	Neutralizer Keeper	Discharge Cathode Heater	Neutralizer Heater
Output Voltage, V	275 to 1800	115 to 525	15 to 35	8 to 32	3 to 24	3 to 12
Output Current, A	1.00 to 3.53	0 to 40 mA 0.4 A surge for 100ms	4 to 24	1 to 3	3.5 to 8.5	3.5 to 8.5
Regulation Mode	Voltage	Voltage	Current	Current	Current	Current

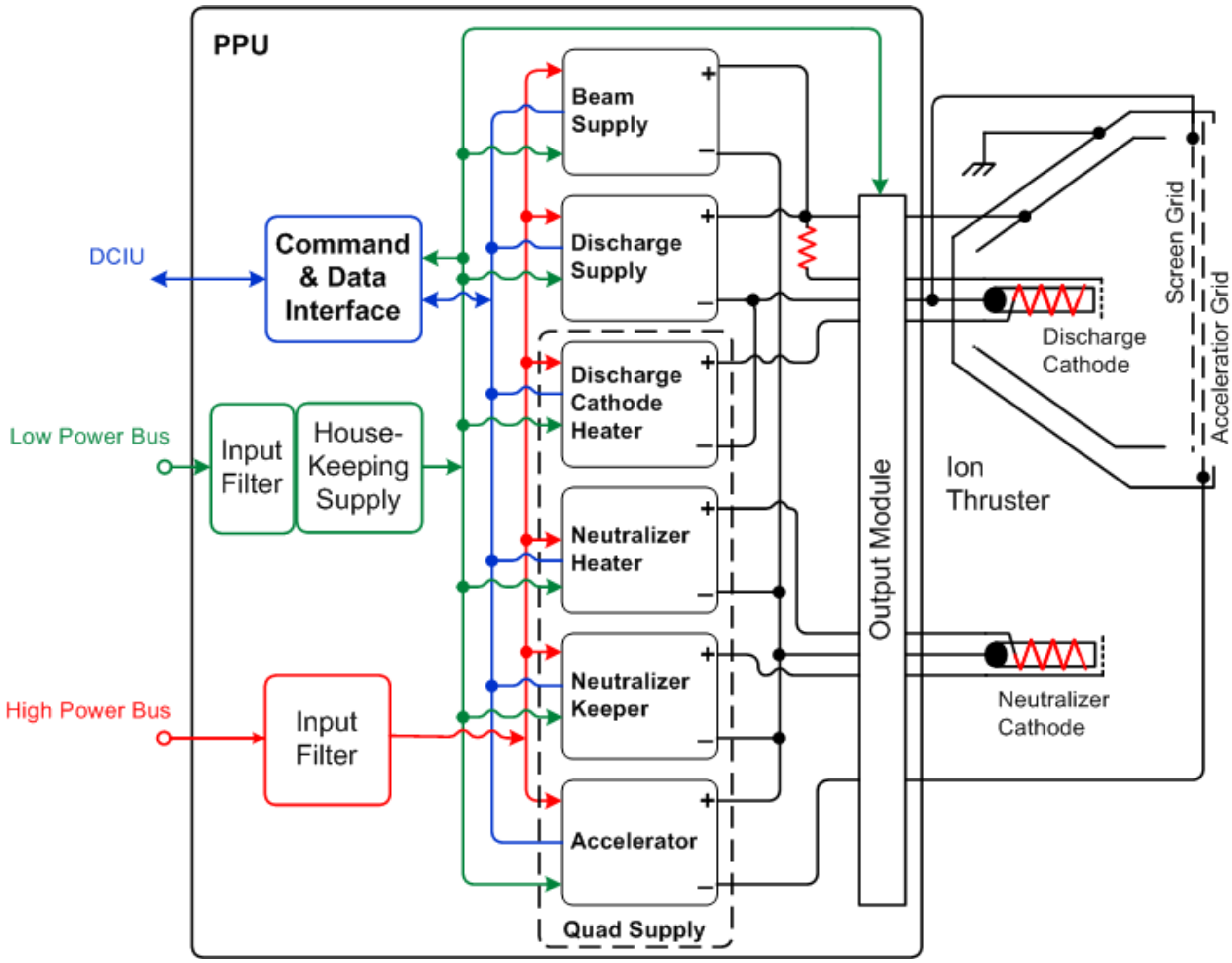


Figure 2-1 PPU Functional Diagram

2.2 *PPU Conceptual Properties*

The conceptual properties herein are intended for assessment by mission personnel in evaluating uses of such a power processor in mission concept studies. These are anticipated properties, and many of which are based on hardware designed during the technology development phase of the project.

2.2.1 PPU Electrical Properties

2.2.1.1 High Power Bus

2.2.1.1.1 *High Power Bus Input Voltage Range*

The PPU accepts high voltage power from an unregulated bus in the range of 80 to 160 Vdc. *Rationale: The existing PPU hardware accepts electrical power from an 82 to 160 Vdc unregulated high-voltage power bus for thruster operation, including the Neutralizer Keeper, Neutralizer Cathode Heater, Discharge, Discharge Cathode Heater, Accelerator, and Beam Supply. A 2 Vdc margin has been provided to the minima of this property.*

2.2.1.1.2 *High Power Bus PPU Efficiency*

The PPU has better than or equal to high voltage bus efficiencies as follows, while operating with a nominal 100 V input, high beam voltage, high ISP, and baseplate temperature of 25° C:

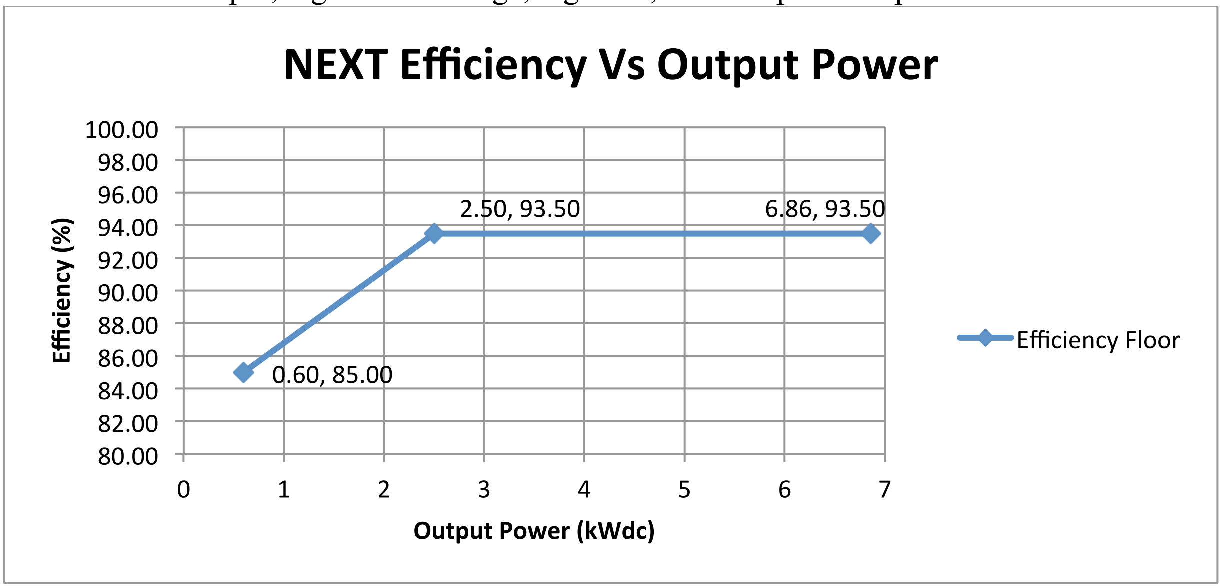


Figure 2-2 NEXT PPU Efficiency

Rationale: The existing PPU hardware has an efficiency of 94.8% at rated power (as reported in the NEXT Power Processing Unit Data Sheet). A margin of 25% increase in power losses to the beam, discharge, and quad power supplies was applied. The resultant efficiency is 93.5%. The delta of 1.3% reduction to efficiency was applied across the entire efficiency curve to provide a floor for high beam voltage, high ISP operation.

2.2.1.1.3 *High Power Bus Maximum Average Power*

The PPU requires no more than 7360 Watts of maximum average power during rated power (<= 6882 W) operation, over the steady state high voltage input voltage range.

Rationale: PPUs must be designed to meet the Electric Propulsion power budget. Per the High Power Bus PPU Efficiency Section, the full power efficiency floor of 93.5% was applied to the rated power output to obtain maximum average input power.

2.2.1.2 **Low Power Bus (Housekeeping Power)**

2.2.1.2.1 *Low Power Bus Input Voltage Range*

The PPU accepts low voltage power from an unregulated bus in the range of 22 to 34 Vdc.
Rationale: The existing PPU hardware accepts 22 to 34 Vdc power, and converts it to regulated power for internal PPU loads (housekeeping power). No additional margin has been provided with this property.

2.2.1.2.2 *Low Power Bus Maximum Power*

The PPU does not exceed 40 W of power consumption on the low power bus.
Rationale: The existing PPU hardware low power bus power consumption was reported as not exceeding 30 W. A margin of 10 W was applied to this number.

2.2.1.3 Fault Protection Requirements

2.2.1.3.1 *Steady State Voltages*

The PPU endures steady-state voltages between 0 V dc and the minimum operating voltages on the low- and high-voltage power busses without incurring damage or permanent degradation.

2.2.1.4 Data Subsystems

The PPU has a command and telemetry interface to an external source within the ion propulsion subsystem (typically called a Data & Control Interface Unit, DCIU) or to the spacecraft Command and Data Handling (C&DH) subsystem.
Rationale: The existing PPU hardware utilized an RS-485 communication interface.

2.2.2 PPU Physical Properties

2.2.2.1 Envelope

The envelope of the PPU does not exceed the dimensions shown in Table 2-2.
Rationale: The PPU must fit within the defined envelope for integration with the vehicle. Actual values of existing PPU hardware were approximately 41 x 51 x 14 cm. A margin based upon NEXT and other existing state of the art PPU hardware was applied to the envelope property.

Table 2-2 PPU Envelope

Width in (cm)	Length in (cm)	Depth in (cm)
20.0 (50.7)	20.7 (52.6)	6.8 (17.3)

2.2.2.2 Weight

The weight of each PPU does not exceed that given in Table 2-3 .

Rationale: The PPU must weigh within the defined value for integration with the vehicle. Actual value of existing PPU hardware was ~34 kg. A margin based upon NEXT and other existing state of the art PPU hardware was applied to the weight property.

2.2.2.3 Volume

The volume of each PPU does not exceed that given in Table 2-3.
Rationale: The PPU volume must be within the defined value for integration with the vehicle. Actual value of existing PPU hardware was ~29,300 cm^3. A margin based upon NEXT and other existing state of the art PPU hardware was applied to the volume property.

2.2.2.4 Baseplate Mounting Area

The PPU baseplate mounting area does not exceed the surface area provided in Table 2-3.
Rationale: The PPU baseplate mounting area must be within the defined value for integration with the vehicle. Actual value of existing PPU hardware was ~2,090 cm^2. A margin based upon NEXT and other existing state of the art PPU hardware was applied to the area property.

Table 2-3 PPU Physical Properties

Weight lb (kg)	Volume in^3 (cm^3)	Surface Area in^2 (cm^2)
78.9 (35.8)	2,813 (46,093)	413 (2,664)

2.2.2.5 Baseplate Heat Dissipation

The PPU is designed such that over 90% of the heat is transferred through the baseplate.

Rationale: The PPU is designed such that the majority of the hot components are strongly coupled to the baseplate. A single baseplate is intended as the primary path for heat transfer.

2.2.2.6 Structural

2.2.2.6.1 *Random Vibration*

The PPU meets performance requirements after exposure to the random vibration environments specified in **Error! Reference source not found.** below, applied at the PPU spacecraft mounting interfaces.

Table 2-4 Random Vibration Environments

Frequency	ASD Level (g^2/Hz)	
(Hz)	Qualification	Acceptance
20	0.0167	0.0083
20-50	+6 dB/oct	+6 dB/oct
50-800	0.1038	0.0519
800-2000	-6 dB/oct	-6 dB/oct
2000	0.0167	0.0083

2.2.3 Reliability and Availability

2.2.3.1 Mean Time to Failure (MTTF)

The PPU has a mean time to failure of at least 50,000 hours for the specified environment.
Rationale: MTTF is required for a long duration mission.

2.2.3.2 Service Life (Post-Launch)

The PPU meets performance requirements for a cumulative operational period of 10 years in space over the full range of input power levels, after being subjected to pre-launch operation and ground storage (shelf life).
Rationale: Service Life is required for a long duration mission.

2.2.3.3 Shelf Life

The PPU meets performance requirements after 5 years of non-operational storage.
Rationale: Shelf life is consistent with Discovery launch date constraint and anticipated delivery of flight PPU hardware.

2.2.4 Environmental Conditions

2.2.4.1 Temperature

The PPU meets performance requirements during operating temperature range and after exposure to the non-operating temperature range as identified in **Error! Reference source not found.** applied at the PPU baseplate.

Table 2-5 Worst Case Environments

Cold Operating	-20 oC (TBR)
Hot Operating	+50 oC (TBR)
Cold Non-Operating	-40 oC (TBR)
Hot Non-Operating	+70 oC (TBR)

Rationale: The cold and hot operating and non-operating temperatures are representative of the existing PPU hardware.

Appendix A

Acronyms and Abbreviations

AWG	American Wire Gage
BIT	Built in Test
BITE	Built in Test Equipment
CEI	Component End Item
NEXT	NASA Evolutionary Xenon Thruster
dB	decibel
EDU	Engineering Development Unit
EEE	Electrical, Electronic, and Electromechanical
ESD	Electro Static Discharge
EMC	Electro Magnetic Compatibility
F	Fahrenheit
PPU	Power Processing Unit
FDIR	Fault Detection, Isolation, and Recovery
FU	Flight Unit
g	gravity
GSE	Ground Support Equipment
Hz	Hertz
IPS	Ion Propulsion System
ITAR	International Traffic in Arms Regulations
NEDD	Natural Environments Design Document
OFI	Operational Flight Instrumentation
PWB	Printed Wiring Board
RMS	Root Mean Square
SBU	Sensitive But Unclassified
SMT	Surface Mounted Technology
SRU	Shop Replaceable Unit
TBD	To Be Determined
TBR	To Be Reviewed
NASA	National Aeronautics and Space Agency
VDC	Volts Direct Current