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In-Space Propulsion Solar Electric Propulsion Program Overview of 2006

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The primary source of electric propulsion development throughout NASA is implemented by the In-Space Propulsion Technology Project at the NASA MSFC under the management of the Science Mission Directorate. The Solar Electric Propulsion technology area's objective is to develop near and mid-term SEP technology to enhance or enable mission capture while minimizing risk and cost to the end user. Major activities include developing NASA's Evolutionary Xenon Thruster (NEXT), implementing a Standard Architecture, and developing a long life High Voltage Hall Accelerator (HiVHAC). Lower level investments include advanced feed system development, advanced cathode testing and xenon recovery testing. Progress on current investments and future plans are discussed.

Acronyms

ASOA	Advanced State-of-the-Art
DCA	Discharge Cathode Assembly
DCIU	Digital Control Interface Unit
EM	Engineering Model
FCM	Flow Control Module
GRC	Glenn Research Center
HET	Hall Effect Thruster
HiVHAC	High Voltage Hall Accelerator
IPS	Ion Propulsion System
ISPT	In-Space Propulsion Technology
JPL	Jet Propulsion Laboratory
NCA	Neutralizer Cathode Assembly
NEXT	NASA's Evolutionary Xenon Thruster
NRA	NASA Research Announcement
NSTAR	NASA Solar Electric Propulsion Technology Application Readiness
PAT	Performance Acceptance Test
PCM	Pressure Control Module
PM	Prototype Model
PMS	Propellant Management System
PPU	Power Processing Unit
SA	Standard Architecture
SMD	Science Mission Directorate
TRL	Technology Readiness Level
TRV	Technology Requirements and Validation
XFS	Xenon Feed System

I. Introduction

In FY06 the ISPT has made significant investments in ion propulsion system technologies. The primary investment in ISPT electric propulsion technologies has been through the NEXT program developing the next generation ion propulsion system. ISPT has also made investments in higher risk technologies with significant benefits over SOA systems that include a long life high voltage Hall thruster and an advanced xenon feed system. Last, ISP has initiated an evaluation of the potential benefit of using commercially available electric propulsion systems for NASA science mission applications. If these commercial systems were qualified to meet NASA science mission requirements, the use of off-the-shelf type hardware could significantly lower the cost of future EP systems.

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II. NEXT

The NEXT ion propulsion system was selected in 2001 to develop a higher power, longer life thruster based on the heritage of the NSTAR program. The NEXT development activity is led by the Glenn Research Center teamed with the Jet Propulsion Laboratory, Aerojet Redmond Rocket Center, University of Michigan, Colorado State University, and L-3 Communications ETI. The phase I development activities concluded in 2003 with the delivery of three engineering model thrusters, a breadboard power processing unit, a breadboard propellant management system, integrated system performance and thruster wear testing.[1]

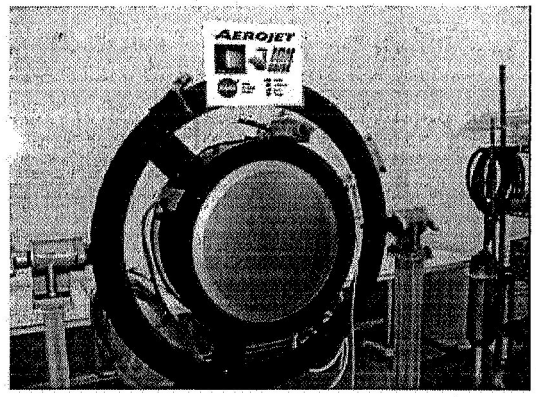

Figure 1: NEXT PM Thruster with Shipping Adaptor.

The current phase of development activities include two prototype model level thrusters manufactured by Aerojet, an EM PPU manufactured by L-3 Comm ETI, an EM PMS and digital control interface unit simulator developed by Aerojet, two breadboard gimbals built by a JPL/Swales team, performance and environmental subsystem testing, integrated system testing, and the start of a thruster qualification life test.

The NEXT program has made significant progress over the past year. Major accomplishments include delivery and performance acceptance testing of the first PM thruster, performance and environmental testing of an EM PMS, multi-thruster array testing, and over 5,500 hours and 110 kilograms of Xenon propellant used in EM3 wear testing.

A. PM1 Thruster Manufacturing and Acceptance Testing

Aerojet successfully manufactured and delivered the first PM thruster to GRC in January, 2006. The PM1 optics assembly has a mass of 3.26 kg. The initial alignment was within 11μm in the radial direction and 7.3μm in the axial direction; well within the 25μm and 13μm requirements, respectively. The optics assembly demonstrated the ability to reassemble and re-measure the optics within 1.3μm of the original alignment in less than seven hours. The discharge cathode and neutralizer cathode assemblies successfully passed 10^{-8} sccs He leak tests and were installed on the PM thruster. The final masses were 550g and 470g for the DCA and NCA respectively. The final thruster assembly has a mass of 12.7 kg or 13.5 kg with the harnesses.

The PM1 Performance Acceptance Test (PAT) was completed in February of 2006. The objectives of the PAT are to assess the prototype model performance, validate the PM thruster design, and validate successful technology transfer with commercial manufacturing processes. The PAT test also provides both steady-state and transient thermal data on a PM thruster for thermal margin validation and model development.

The PM1 thruster successfully ignited during the first attempt. The TRV requirements of the NEXT thruster are to perform greater than 67% efficiency and 4,050s of specific impulse at full power. The PAT test was conducted on the multi-thruster array in VF6. The results of the PAT test are shown in table 1. The PM thruster met or exceeded the EM performance at all operating conditions tested. The numbers in red are the thruster results and the numbers in blue are the requirements established by the EM thruster performance. The PAT also demonstrated a lower recycle rate, increased plume mode operation margin for the neutralizer at low beam currents, and significantly reduced steady-state temperatures compared to the EM thruster design. The initial PAT did expose one necessary rework item, the DCA conducted too much heat leading to delayed emitter ignition times. The DCA redesign was minor and has undergone successful demonstration with a second PAT on PM1, and will be further validated with the PM2 thruster.

Table 1: Comparison of TRV requirements and PM1 PAT test results.

Vb, V	Jb, A	Pin, kW	TRV Eff. Req.	Thrust Eff.	TRV Thrust Req., mN	Thrust, mN	TRV Isp Req., sec	Isp, sec
1800	3.524	6.860	0.708	0.710	236	237	4188	4190
1180	3.525	4.700	0.677	0.680	192	192	3393	3395
1800	2.003	3.990		0.711		134		4315
1179	2.002	2.750		0.676		108		3495
1800	1.202	2.435	0.645	0.647	80	80	3999	4000
1179	1.203	1.715	0.606	0.606	65	65	3240	3245
679	1.202	1.135		0.524		49		2455

B. Multi-thruster Array Testing

The NEXT program successfully completed a 3+1, three operating thrusters and one spare, multi-thruster array test in December, 2005.[2,3,4,5,6,7] The multi-thruster test represents the most comprehensive test of multiple ion thrusters firing simultaneously by NASA in two decades using SOA thrusters and diagnostics. The objective of the test was to determine the impact of startup, throttling, and shutdown of adjacent operating thrusters. The test array is shown in figure 2. During the test EM1, EM4, and EM5 were all operated successfully with EM2 serving as a thruster spare that was not operated, but contained multiple diagnostics.

The multi-thruster tests successfully demonstrated 1+1, 2+1, and 3+1 thruster configurations. The setup also allowed for testing with two operating thrusters at a separation distance of both 0.64m and 0.91m center-to-center. EM1 thruster was also placed on a gimbal mount capable of rotating up to 12°. Multi-thruster testing also evaluated the effect of neutralizer placement and distance from the operating thrusters, in addition to operating multiple thrusters on a single neutralizer.

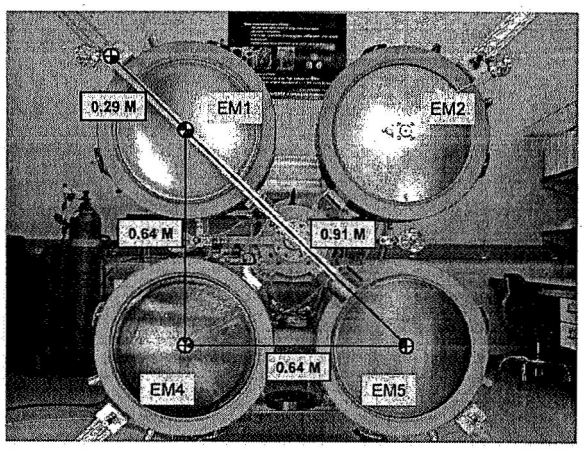

Figure 2: NEXT Multi-thruster test array.

The performance observed for a thruster in an array configuration appears to be consistent with that measured during single thruster operation. The minor observed effect of multi-thruster operation, such as an increase in accelerator current, appears to correlate to a facility effect due to an increase in background pressure. There were no demonstrable thruster-to-thruster interactions observed during steady-state, throttling, or recycle events. The preliminary results were very positive, indicating that thruster life established through single thruster long duration testing may accurately reflect expected life during multi-thruster operation and that a single neutralizer has no negative impacts for multiple thruster operation. Using a single neutralizer improves multi-thruster performance, particularly at low power operation.

Another objective of the test was multi-thruster plume characterization. The test utilized several diagnostics to create ion current density, plasma potential and electron temperature maps, record ion energies and plasma flux at the array, and characterize neutralizer plasma during steady-state, throttling, start-up, shutdown and thruster gimbaling operation. Overall, there were no plume-to-plume interactions observed. Preliminary results indicate little change in plume profile due to multi-thruster operation, neutralizer configuration or thruster gimbaling, and that superposition may be sufficient to predict multi-thruster plume profiles.

C. EM3 Wear Testing

The EM3 wear test began on June 5, 2005. As of May 1, 2006, the EM3 wear tests had accumulated more than 5,000 hrs of operation and processed more than 100 kg of xenon. Figure 3 shows the propellant throughput rate over time. The NEXT thruster has already processed more propellant than both the DS1 flight demonstration and the NSTAR 8,200 hour life-demonstration test.

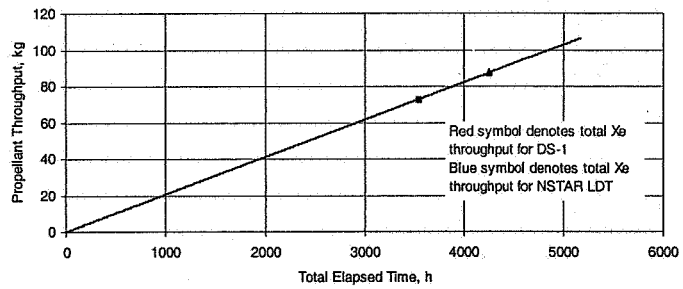

Figure 3: NEXT LDT Propellant throughput over time.

The test article thruster, EM3, is GRC-built with Aerojet-built prototype model ion optics. The materials, processes, and dimensions of the thruster hardware exposed to the plasma erosion processes are made to be identical to the PM thruster. The wear test objective is to identify and characterize thruster wear mechanisms and operation and compare results to predictive models. Initially, the EM3 wear test had been planned to continue until demonstrating that the thruster's qualification propellant throughput is greater than 450kg. Under the baseline plan, the NEXT thruster will have demonstrated its qualification level throughput in 2009. The EM3 thruster may undergo destructive analysis and be replaced with a prototype model thruster for the full a full qualification level life test.

A NEXT service life assessment has determined the full-power life of the NEXT thruster to be greater than 730 kg.[8] The EM3 wear test results are consistent with the predicted wear rates. The thruster has shown no change in thruster performance and no noticeable change in grid gap. The predicted life limitations and failure mechanisms are of the NEXT IPS are shown in Table 2. The propellant throughput and total impulse capability of the NEXT thruster are significant improvements over the SOA NSTAR engine.

Table 2: Summary of NEXT Thruster Life Assessment.

Component	Failure Mechanism	Xenon Throughput, kg			
		3.52 A I_b 1800 V V_b	1.20 A I_b 1800 V V_b	1.20 A I_b 1179 V V_b	1.20 A I_b 679 V V_b
DCA	Insert Barium Depletion	1450	5200	4100	3700
	Excessive Wear of Orifice Plate	No excessive wear prior to excessive keeper wear			
	Excessive Wear of Keeper	1800	TBD	TBD	TBD
NCA	Insert Barium Depletion	1600	2400	2400	2400
	Excessive Wear of Orifice Plate	No excessive wear			
	Excessive Wear of Keeper	> 800	TBD	TBD	TBD
	Neutralizer orifice clogging	Controlled through requirements			
Accelerator Electrode	Pit and Groove Wear / Structural Failure	> 730	> 800	TBD	TBD
	Aperture Enlargement / Electron Backstreaming	> 730	> 800	TBD	TBD
Screen Electrode	Excessive Wear	No excessive wear anticipated			
Optics Assembly	An Unclear able Short	Controlled through requirements			
Discharge Chamber	Flake Retention of Sputtered Material	1850	TBD	TBD	TBD
	Magnet Temperatures Excessive	100 °C margin (dependent on mission)			
High Voltage Propellant Isolators	Deposition of Sputter Material Degrading Voltage Standoff	Monitoring of manufacturing process, Design verification test ongoing			

D. PPU, PMS, and Gimbal Status

The phase II NEXT activities include the delivery of an EM PPU, EM PMS, and breadboard gimbal. The subsystem hardware will undergo environmental testing to qualification levels and integrated system testing.

The PPU to operate the NEXT thruster is being developed by L3, Torrance, CA (formerly Boeing Electron Dynamics Division). The Phase II engineering model topologies are based on the breadboard developed during Phase I with some modifications to the screen supply to improve efficiency especially at low power. The EM PPU is also designed for vibration and thermal vacuum environmental qualification testing.

The screen supply for the EM PPU is modular in design, being made up of six modules which can be individually turned off as the power requirement decreases. This approach significantly increased the efficiency at low power such that it is near 90% at minimum power and near 95% at maximum power. The last of the six modules is currently being completed. Full screen supply integration and test is scheduled for May '06.

Some minor changes are being implemented in the discharge supply, and all other supplies and subassemblies are nearly complete. The chassis design is nearly complete and integration of the entire PPU is scheduled to begin in June.

The NEXT propellant management system is being developed by Aerojet. It is designed to independently control the propellant flow rates to the main discharge chamber, discharge cathode, and neutralizer cathode. It has already passed baseline flow calibration testing, random vibration, and post-vibe functional testing. Thermal vacuum, multi-string testing and integration with a NEXT thruster is scheduled for FY07.

The breadboard gimbal development has been led by JPL and Swales Aerospace. The integrated gimbal and thruster performance and vibration testing is planned for the summer of 2006. In preparation for the NEXT thruster delivery, a gimbal shock and vibration test was completed in March, 2006, with a mass simulator. The objectives of the mass simulator testing were to validate the breadboard gimbal to NEXT protoflight random vibration specifications, acquire gimbal-thruster interface data for additional thruster analysis, and validate procedures for the NEXT thruster vibration testing.

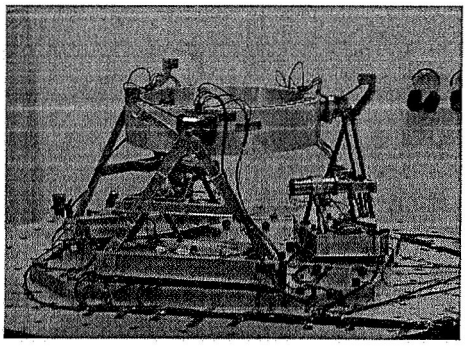

Figure 4: NEXT Gimbal Assembly.

III. HiVHAC

Figure 5: NASA 77M HiVHAC Thruster.

The HiVHAC thruster development project was selected in 2003 to develop a 6-8 kW Hall thruster with moderate Isp for Flagship class missions. The project is led by NASA's GRC teamed with Aerojet, JPL and the University of Michigan. After the focus of ISPT project turned from large missions to smaller Discovery and New Frontiers missions, the HiVHAC project was re-vectored to develop a smaller thruster with a lower maximum power level specifically to increase low power performance and reduce cost for Discovery class electric propulsion missions[10]. In March 2005 a prototype HiVHAC thruster was experimentally evaluated[11]. The demonstrated performance confirmed the capability of this technology to provide mission enabling performance for certain science mission applications through a unique combination of a large throttle range and a large specific impulse range. The range of operational power for this thruster was from 0.2 – 2.8 kW. Beginning in October of 2005 the focus of project became thruster technology developments needed to make possible thruster operational lifetimes needed for the targeted cost constrained robotic science missions Initially mission analysis was undertaken to quantify operational lifetime capability needs. These analyses concluded that lifetime had a much weaker influence of mission performance than did thruster throughput capability. As a result the maximum thruster power level was increased from 2.8 to 3.5 kW. This change allowed equivalent propellant throughput with an operational lifetime reduction of more than 40%. Despite this reduction in required operational lifetime, the needs of many

targeted robotic science missions exceed the throughput capability achievable without advanced development. Two different approaches to increasing HiVHAC propellant throughput have been identified and are under development. These two different approaches offer parallel development paths referred to as the state-of-the-art (SOA) approach and an advanced state-of-the-art (ASOA) approach. Each of these efforts is discussed below.

A. SOA HiVHAC Thruster

The SOA HiVHAC thruster development is a low risk approach to extending thruster lifetime by incorporating a number of design features previously proven to enhance thruster lifetime. The primary challenge of this approach is to ensure that discharge channel erosion is minimized sufficiently to ensure full power (3.5 kW) operation for a minimum of 7500 hours. This operational lifetime corresponds to a nominal propellant throughput of 150 kg. This throughput capability must be achieved at a discharge voltage of 700 Volts. The high voltage operation allows the thruster to operate at specific impulses much higher than conventional Hall thrusters. The high voltage also allows the thruster to operate at a much higher power density than conventional Hall thrusters. A comparison of the HiVHAC thruster to a conventional HET is shown in Table 3. A SOA prototype thruster designed to provide a 150 kg throughput has been fabricated and will be evaluated to confirm this capability.

Table 3: Comparison of BPT-4000 and HiVHAC thrusters.

	BPT-4000	HiVHAC
Thruster Max. Power	4.5 kW	3.6 kW
Throttle Ratio	4:1*	12:1
Operating Voltage	300V - 400V	200V - 800V
Specific Impulse	900s - 1500s	900s - 2900s
Thrust	161mN - 282mN	20 mN - 150mN
Thruster Alpha	2.7 kg/kW	1.5 kg/kW
Lifetime	~9,000 hrs**	~9,000 hrs (>30,000 hrs ASOA)

B. ASOA HiVHAC Thruster

The ASOA HiVHAC thruster development approach is a less traditional approach to extending thruster lifetime with the potential of enabling lifetimes in excess of 15,000 hours and throughputs in excess of 300 kg. An ASOA laboratory-model thruster designed to provide a 150 kg throughput has been fabricated and will be evaluated to confirm this capability. Further details about either the prototype SOA thruster or the ASOA laboratory-model thruster cannot be provided to due to export regulations.

C. Wear Characterization and Modeling

In order to predict the lifetime and throughput capability of both SOA and ASOA thrusters an effort to accurately numerically simulate discharge channel erosion was undertaken. This activity, lead by the University of Michigan, was based on previous Hall thruster discharge channel wear simulations[12]. Developments needed to allow these analytic tools to be used in support of the HiVHAC program are a result of the increase in discharge voltage, and power density of the HiVHAC thruster relative to conventional HETs. In order to allow early benchmarking of this improved simulation capability, the 2.8kW prototype thruster demonstrated in 2005 was utilized in a number of abbreviated accelerated wear tests. Initial bench-marking of the improved wear simulation against experimental data have provided the HiVHAC project with confidence that both the SOA and ASOA thruster development approaches will be successful in achieving their lifetime and throughput goals. Additional erosion data will be generated and continued modeling effort will both be used to mitigate the thruster lifetime challenges as the HiVHAC project proceeds. In addition, progress has been made in the modeling of other degradation mechanisms with Hall thrusters operated in a variety of modes. This is of vital importance not only to projecting the operational lifetime of advanced technology thrusters developed within NASA but also in adapting commercial thrusters designed for earth orbital operation to use in Deep Space where they must be throttled over a much broader range.

IV. Advanced Xenon Feed System

An advanced xenon feed system development was selected under the 2002 ROSS NRA award and initially funded in 2004 for Lightweight, Reliable Xenon Feed System components based on All-Metal ChEMS™ Manufacturing Technology. The task is led by VACCO Industries, Inc. of South El Monte, California, seeks to improve the reliability of ion propulsion feed systems while decreasing mass and volume over SOA XFS technologies as shown in Table 3. Following a user requirements definition study early in the base phase, the conceptual feed system architecture was changed from a digital fuel control array to an architecture that utilizes piezoelectrically actuated proportional micro valves to meet flow accuracies and reliability requirements while maintaining reduced mass and volume. VACCO has utilized IR&D funds to develop the proportional micro valves. These valves along with latch valves and micro pressure and temperature sensors will be integrated into a diffusion-bonded Flow Control Module. Two FCMs are scheduled to be delivered in July 2006 and subsequently tested to TRL 5. During the option phase in 2007, VACCO will focus on development of a XFS controller, fabrication and testing of a Pressure Control Module, and end-to-end testing of these components with an ion thruster.

Table 4: Comparison NEXT and ChEMS™ XFS.

	NEXT System	*ChEMSR System*
Propellant Utilization (mass savings)	30 psia left in Tanks at end-of-life	20 psia left in Tanks at end-of-life
Size	(1) HPA, (3) LPA = 520 sq in	(1) PCM, (3) FCM = 40 sq in
Mass	14.5 kg	3 kg

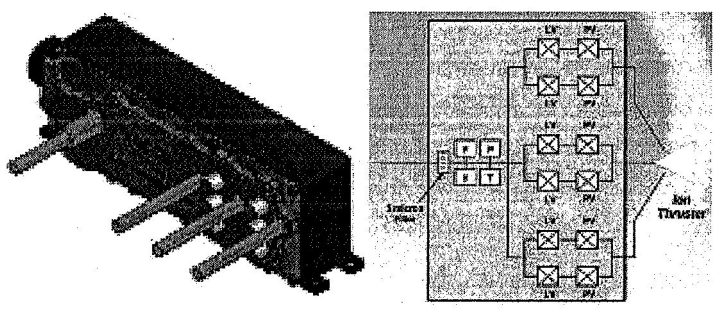

Figure 7: VACCO Flow Control Module and Internal Layout.

V. Commercial Thruster Systems

Aerojet has developed and recently completed qualification of the BPT-4000 HET system[13]. There was an opportunity to leverage a significant DOD investment for NASA by extending the life test of the Aerojet thruster. The BPT-4000 life test accumulated more than 5,000 hrs of erosion data that may benefit future Hall erosion models. Because an earth orbiting satellite does not need to operate over large power ranges, the Aerojet qualification test occurred at only four operating conditions. To supplement the erosion modeling data, the life test has been extended to include lower power and lower voltage operation. The magnetic field and performance mapping at 1 kW – 2 kW has already been completed, and the life test extension is expected to accumulate an additional 1,000 hrs of data. The erosion data shall be used to further validate HET erosion models that will likely benefit the ongoing HiVHAC development.

VI. Future Planned Activities

The Solar Electric Propulsion technology area currently has the NEXT and HiVHAC thruster development activities within its portfolio, in addition to potential application of commercially available ion propulsion systems. There is also a possibility for a standard architecture development, discussed below, that could include an integrated PPU and DCIU to reduce the cost of the NSTAR IPST. Because the flight rate of electric propulsion missions is relatively low, a major effort within ISP is to down-select future investments into the systems that yield the most benefit to SMD mission users.

A. NEXT

The NEXT program is expected to complete all NRA Phase II activities in FY06. These activities include the delivery and environmental testing of the EM PPU, environmental testing of the PM thruster, vibration testing of the integration thruster and gimbal, and integrated IPS testing followed by the final performance evaluation review. The NEXT life test is projected to continue until full demonstration of the qualification level throughput. The life test is expected to continue through 2009.

B. HiVHAC

The near term plans for the HiVHAC program include the completion of fabrication both the SOA and ASOA thrusters for performance testing. The ASOA thruster is scheduled to begin a long duration wear test starting in October, 2006. Further investment into the HiVHAC program is largely dependent on the outcome of the performance and wear tests.

C. Advanced Xenon Feed System

The advanced xenon feed system near term activities include integrated testing of the VACCO flow control module with a thruster. Planned activities include the development of a pressure control module (PCM) for single string PCM-FCM-thruster integrated testing to occur near the end of FY07.

D. Commercial Thruster Systems

Commercial ion propulsion systems may have potential application to science missions. ISPT is currently planning to investigate the use the Aerojet BPT-4000 and the Boeing 25cm XIPS for SMD applicability. If the commercially available systems can meet science mission objects, there is potential to significantly lower the cost of flight hardware. Topics under consideration include throttleability functionality of the system, spacecraft interfaces and interaction, and necessary testing required to validate and qualify the hardware for science mission requirements.

E. Standard Architecture

ISP has continued to investigate strategies to help lower the cost of ion propulsion systems for Discovery and New Frontiers class missions. The recent experience with cost growth and complexity of the DAWN IPS has emphasized the critical importance of Standard Architecture to address the needs of SMD cost-capped missions. One SA strategy is to simplify the subsystem architecture into a single string configuration which minimizes cross-strapping within the IPS subsystem. This single-string architecture will likely reduce spacecraft integration costs while hardware and flight software will be developed in a flight like configuration. A key element of this approach is the development of a common power processing unit that is integrated with the Digital Control and Interface Unit. It is likely that the SA PPU/DCIU would be a modular design that is reconfigurable for use with other Ion subsystems.

VII. Acknowledgments

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