Performance Evaluation of an Expanded Range XIPS Ion Thruster System for NASA Science Missions

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This paper examines the benefit that a solar electric propulsion (SEP) system based on the 5 kW Xenon Ion Propulsion System (XIPS) could have for NASA's Discovery class deep space missions. The relative cost and performance of the commercial heritage XIPS system is compared to NSTAR ion thruster based systems on three Discovery class reference missions: 1) a Near Earth Asteroid Sample Return, 2) a Comet Rendezvous and 3) a Main Belt Asteroid Rendezvous. It is found that systems utilizing a single operating XIPS thruster provides significant performance advantages over a single operating NSTAR thruster. In fact, XIPS performs as well as systems utilizing *two* operating NSTAR thrusters, and still costs less than the NSTAR system with a *single* operating thruster. This makes XIPS based SEP a competitive and attractive candidate for Discovery class science missions.

I. Introduction

The National Aeronautics and Space Administration's (NASA's) Discovery program gives scientists the opportunity to address questions in solar systems science with lower-cost, highly focused planetary science missions. The Dawn project is the ninth Discovery program project and is designed to increase our understanding of the early solar system by investigating two main belt asteroids, Vesta and Ceres.[i] Dawn utilizes an NSTAR ion thruster based electric propulsion (EP) system for primary propulsion. This system represents the current state of the art for NASA deep space solar electric propulsion (SEP) systems. This paper compares the relative cost and performance of the commercial heritage Xenon Ion Propulsion System (XIPS) system to NSTAR ion thruster based systems and discusses the advantages such a system could provide for this class of mission.

Discovery missions are selected competitively and cover a wide range of scientific goals and destinations. Previous studies examining the benefits of SEP technologies for Discovery class missions have identified a set of reference missions to generic destinations that are generally representative of current and proposed missions that utilize electric propulsion.[ii] In this section, we compare the performance of the BPT-4000 to NSTAR on three reference missions similar to those defined in previous work:[ii]

- Near-Earth Asteroid Sample Return
- Comet Rendezvous
- Main Belt Asteroid Rendezvous

Section II provides an overview description of the XIPS ion propulsion system. Section III describes the XIPS thruster performance model developed for this study. Section IV describes the results of the mission analysis comparing NSTAR and XIPS system performance on the reference missions.

II. Overview of the XIPS Ion Propulsion System

The Xenon Ion Propulsion System (XIPS) has been used to provide on-orbit station keeping on 29 Boeing geosynchronous communications satellites launched since 1997. The XIPS ion propulsion system includes two fully redundant subsystems, each consisting of two thrusters and a power supply, and a xenon gas supply. The first XIPS system, which featured a 13-cm active grid diameter ion thruster, was implemented on the Boeing (then Hughes) 601HP satellite[3] and provided north-south station keeping on a total of 19 of these satellites. The second generation

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XIPS technology, the 25-cm thruster, is used on the Boeing 702 satellites, which were first launched in December 1999. To date, 10 of the Boeing 702 communications satellites with a total of 40 XIPS thrusters have been successfully launched and are still in operation. These thrusters have accumulated approximately 33,000 hours of total in-space operation to date. Including the 13cm XIPS units, there are now a total of 116 XIPS thrusters in orbit with over 150,000 accumulated operating hours.

The XIPS thruster systems and their use in station keeping applications were originally described in a review article by J.Beattie.[iii] An exploded illustration of a 25-cm XIPS thruster is shown in Figure 1. The thruster consists of the standard[iv,v,vi] discharge hollow cathode, 3-ring magnetic cusp confinement, three grid accelerator and neutralizer hollow cathode, and plasma screen enclosing the anode body. A photograph of the 25-cm XIPS thruster is shown in Figure 2. This thruster is of similar conceptual design as the original 13-cm XIPS thruster flown first, but provides nine times the thrust and 50% more specific impulse. The three-grid accelerator used in the 25-cm thruster utilizes shaped molybdenum grids with approximately 11,000 apertures to produce the high perveance (72 μpervs at full power) xenon ion beam.

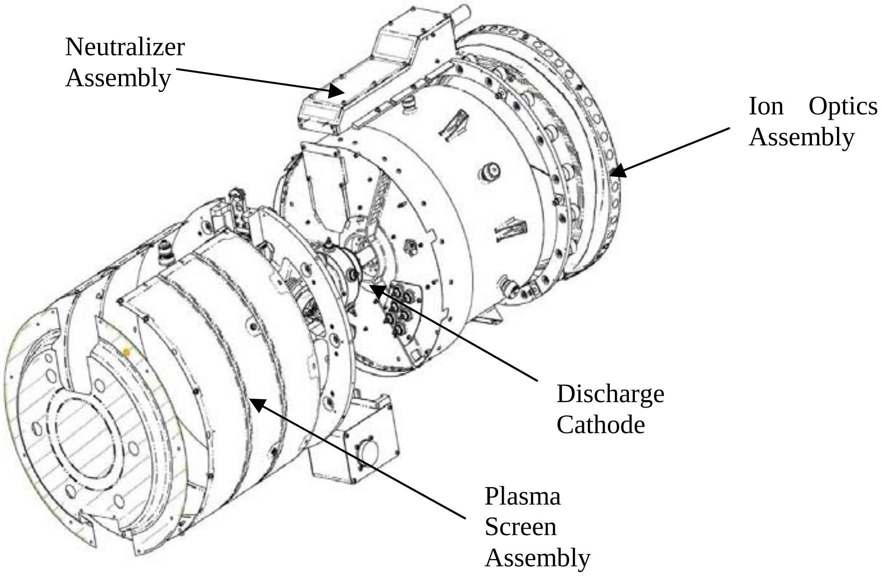

Figure 1: XIPS thruster schematic illustration

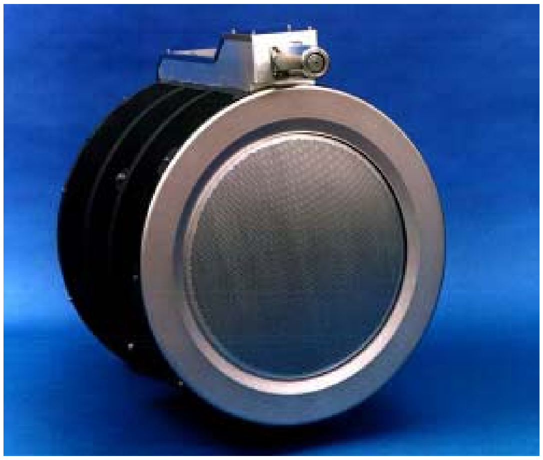

Figure 2: Photograph of the 25-cm XIPS thruster.

Initial operation of the 25 cm thrusters on the 702 satellites was first described[vii] in 2002. Shortly after launch, the 25-cm thrusters are used in a "high power" mode for orbit insertion, where they boost the perigee of satellite's initial elliptical orbit into a 24-hour circular geosynchronous orbit. The high-power mode utilizes about 4.5 kW of bus power to produce a 1.2 kV, 3 A ion beam. The ion engine in this mode produces 165 mN thrust at a specific impulse (Isp) of about 3500 seconds. The high power mode is used exclusively for the orbit insertion phase, which greatly reduces the amount of chemical propellant carried by the spacecraft for this task. Nearly continuous operation in the high-power mode is required for times of 500 to 1000 hours, depending on the launch vehicle and satellite weight.

Once this task is completed and the satellite is on station, each of the four thrusters is fired once daily in a "low power", 2.3 kW mode to provide all of the propulsion requirements for orbit control; including north-south and east-west station keeping, attitude control, and momentum dumping. On the average, each thruster fires about forty-five minutes each day. However, depending on the station keeping function being performed, the burn duration of a given firing can be less than ten minutes long. The thrusters are also used for any optional station change and orbit raising strategies, and will ultimately be used for de-orbit at the end of the satellite's lifetime. In the low-power mode, the beam acceleration voltage is kept the same, and the discharge current and gas flow are reduce to generate a 1.2 kV, 1.5 A beam. In this mode, the thruster produces nominally 79 mN of thrust. Since the beam voltage remains unchanged from the high power mode and the thruster mass utilization efficiency is nearly the same, the specific impulse degrades only slightly compared to the high power mode to about 3400 seconds. Typical parameters of the 25 cm thruster are summarized in Table 1, and the parameters of the XIPS power-processing unit (called the "XPC") are summarized in Table 2.

While the 25-cm thrusters were developed first in a prototype form at Hughes Research Laboratories (HRL) in the 1980's, the 13-cm thruster developed at HRL in the early 1990's was the first put into production and launched in 1997. Several improvements were designed into the 25 cm thruster going into production that makes it simpler and low-cost to manufacture. The power-processing unit (XPC), shown in Figure 3, was also completely redesigned to be manufactureable and reliable compared to the first generation 13-cm PPU, and includes several circuit improvements such as feedback control to stabilize the output thrust and higher grid clear capability.

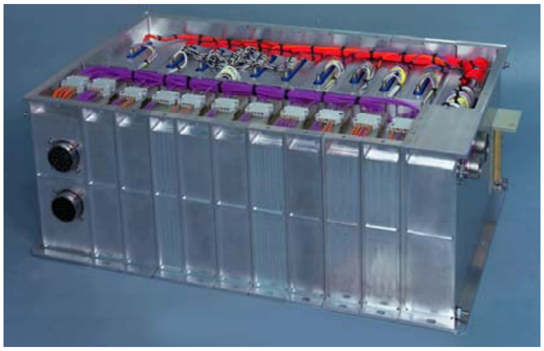

Figure 3: Photograph of the 25-cm XIPS power supply (XPC).

	Low Power Station Keeping	High Power Orbit Raising
Active grid diameter (cm)	25	25
PPU Input Power (kW)	2.3	4.5
Average ISP (seconds)	3400	3500
Thrust (mN)	79	165
Total Efficiency (%)	63	65
Mass Utilization Efficiency (%)	82	84
Typical Electrical Efficiency (%)	87	87
Beam Voltage	1215	1215
Beam Current	1.49	3.01

Table 1: Typical parameters of the 25 cm XIPS thruster.

Parameter	Performance Low Power	Performance High Power
Total Input Power (kW)	2.3	4.5
Bus Input Voltage (V)	100	100
Efficiency (%)	91	93
Size (cm)	20.6 x 54.1 x 35.3	
Mass (kg)	21.3	

Table 2: Typical parameters of the 25-cm XIPS power processing unit.

For NASA applications, the 25-cm thruster and XPC cannot operate at the two points normally set for station keeping applications, but must throttle over a large range as the solar array power changes. Figure 4 shows the measured XPC power supply and thruster efficiencies as a function of the input power to the thruster from 300 W to 4.5 kW. We see that the XIPS power supply efficiency remains over 90% from 1 to 4.5 kW of output power, and falls to lower levels at low power. The thruster efficiency likewise remains above 60% above 1 kW, and falls at lower power levels. In addition, the XIPS system demonstrated operation down to 300 W into the thruster, which is about 200 W lower than the NSTAR thruster.

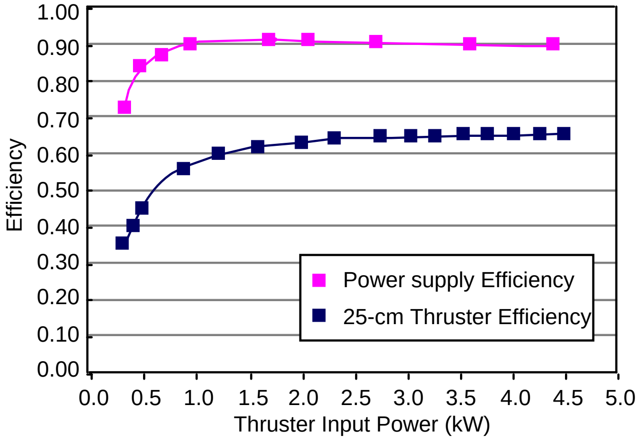

Figure 4. 25-cm thruster and PPU efficiency as a function of thruster input power.

To compare with the NSTAR thruster system used on the DAWN mission, the measured thruster and power supply efficiency (the product) is plotted in **Figure 5** versus the input power to the PPU/XPC for the two systems. We see that over the entire throttle range of NSTAR, the total system efficiency of XIPS is higher. In addition, XIPS maintains its high efficiency to twice the power capability of the NSTAR system.

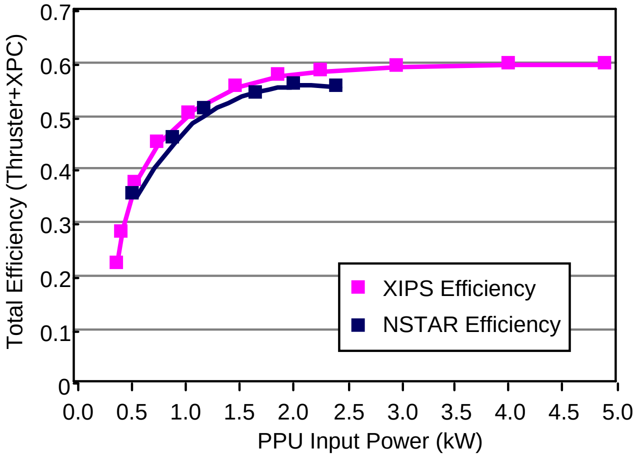

Figure 5. Total efficiency of thruster and PPU as a function of the power supply input power

III. Thruster Performance Modeling

A XIPS system performance model was created from the experimental data shown in Figure 4 and Figure 5 by fitting polynomials to the throttle table to generate expressions for thrust and propellant flow rate as a function of input power to the power processing unit (PPU). Table 3 shows the resulting polynomial coefficients for XIPS as well as coefficients for the NSTAR thruster. The NSTAR curve fit is derived from NSTAR throttle table Q-mod (or modification to Table Q) which is based on Deep Space 1 (DS1) flight data and is the throttle table used for mission planning in the initial design phases of the Dawn program.[viii] The overall system efficiency can be derived from these expressions and is shown in Figure 6. Table 4 shows the available operating range and throughput capability for each device.

		Mass Flow Coefficients				
System	**Table Name**	**A**	**B**	**C**	**D**	**E**
NSTAR	Q-Mod	0.36985	-2.5372	6.2539	-5.3568	2.5060
XIPS	Table 7d	0.0091	-0.1219	0.5402	0.0426	0.8211

		Thrust Coefficients				
System	**Table Name**	**A**	**B**	**C**	**D**	**E**
NSTAR	Q-Mod	5.145602	-36.720293	90.486509	-51.694393	26.337459
XIPS	Table 7d	0.0367	-0.4966	1.4111	35.3591	-0.3984

$$T\ [\mathrm{mN}] = A(P\ [\mathrm{kW}])^4 + BP^3 + CP^2 + DP + E$$
$$\dot{m}\ [\mathrm{mg/s}] = A(P\ [\mathrm{kW}])^4 + BP^3 + CP^2 + DP + E$$

Table 3: Throttle Curve Coefficients

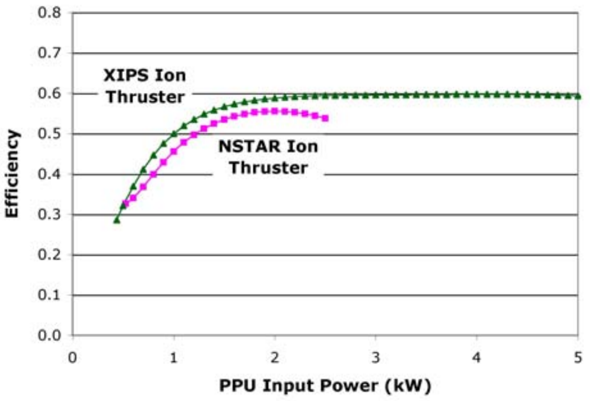

Figure 6: Propulsion System Efficiency vs. PPU Input Power

	TRL	Minimum Power	Maximum Power	Throughput Capability Assumption
NSTAR	9	525 W	2.6 kW	150 kg
XIPS	5	436 W	5.03 kW	200 kg

* NSTAR has demonstrated this flight throughput requirement with 50% margin in a life test. The XIPS has not yet demonstrated the throughput capability assumed.

Table 4: Thruster Characteristics Summary

IV. Mission Analysis

Discovery missions are selected competitively and cover a wide range of scientific goals and destinations. Three reference missions are used for performance evaluations in this study. The destinations are generic, but are similar to current and proposed Discovery class missions that utilize electric propulsion. This section discusses each of the three concepts and provides analysis results for each mission.

A. Near Earth Asteroid Sample Return

The first reference mission examined was a Near Earth Asteroid sample return mission. The spacecraft launches on a Delta II 2925 directly to an Earth escape trajectory and uses SEP to rendezvous with the asteroid Nereus. The spacecraft remains in the asteroid's vicinity for 90 days before using SEP to return to Earth and conducts a flyby as it releases the sample for direct entry. The basic characteristics of this mission are shown in Table 5.

Near Earth Asteroid Sample Return	
Target Body	Nereus
Launch Vehicle	Delta 2925
Power System	Triple junction GaAs solar array, 6 kW at 1 AU
Bus Power	300 W
Duration	3.3 years
Onboard ΔV	4.2 to 6.5 km/s
Launch Year	2007/08
Ion/Hall Thruster Duty Cycle	90%
Launch and Rendezvous Dates	Selected by Optimizer
Optimization Method	SEPTOP

Table 5: Near Earth Asteroid Sample Return Mission Characteristics

The SEPTOP low thrust optimization tool was used to generate optimized trajectories for three different operating scenarios: single XIPS, single NSTAR, and dual NSTAR. The terms "single" and "dual" refer to the maximum number of thrusters operating *simultaneously* at any point in the mission. The *total* number of thrusters mounted on the spacecraft is higher when spares and throughput limitations are considered (see Figure 8). The single and dual NSTAR options both represent state of the art systems. Single NSTAR operation has been flight demonstrated on DS1 and is the baseline for Dawn. Simultaneous operation of multiple thrusters has been flight demonstrated on commercial missions, but has not been demonstrated with NSTAR. All trajectories assume a nominal array power of 6 kW at 1 AU distance from the Sun and include no power margin or allowance for array degradation. The array sizing is typical for a cost capped EP mission. Power available from the array varies with distance from the sun and is modeled using a high efficiency gallium arsenide array model. The entry velocity at Earth return is not constrained and is optimized for maximum total delivered mass.

The total burnout mass for the XIPS and NSTAR options are shown in Figure 7. Burnout mass is defined as the total mass of the spacecraft when it reaches its final destination (in this case, returns to Earth) including the payload, propulsion system, and residual propellant.

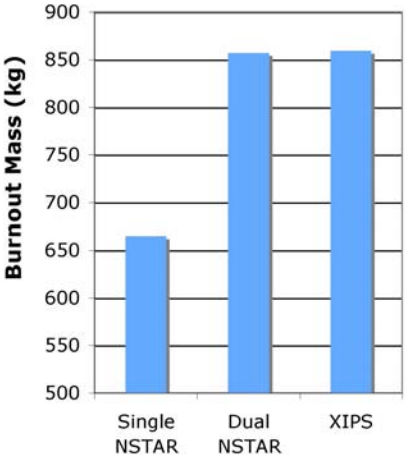

Figure 7: Burnout Mass, Near Earth Asteroid

The XIPS system offers considerably better performance than a single NSTAR system, delivering approximately 200 kg of additional mass to the final destination with the same launch vehicle. XIPS also offers slightly better performance than the dual NSTAR system for this trajectory, but with fewer thrusters and at much lower cost. Figure 8 shows the xenon throughput and total number of thrusters required for each option. The number of thrusters is calculated by dividing the total xenon throughput by the thruster's throughput capability and adding an extra engine for redundancy. Because it operates at higher efficiency and slightly higher specific impulse, the XIPS system utilizes less xenon than the NSTAR options. This, in combination with the higher throughput capability of the XIPS, means that fewer total thrusters are required to meet the mission's throughput requirements, resulting in a less complex and less expensive XIPS system compared to NSTAR equivalents.

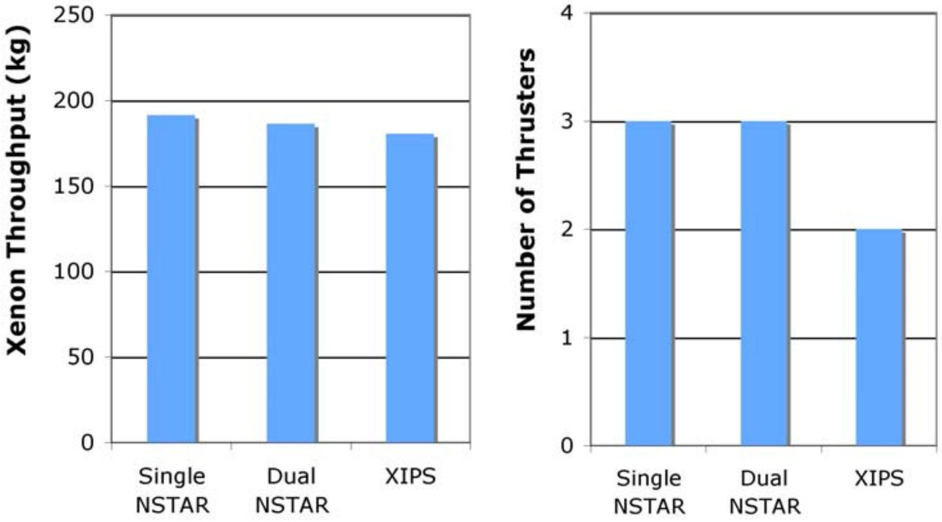

Figure 8: Xenon Propellant Throughput and Total Thrusters, Near Earth Asteroid

The relative cost benefits of a XIPS system vs. the NSTAR system is shown in Figure 9. Both systems have two PPU's, sufficient to operate one thruster at a time, with a second PPU for redundancy. The NSTAR system has three thrusters and the XIPS system has two, consistent with the number of thrusters shown in Figure 8. The NSTAR cost estimate is based on actuals from the DAWN project. The XIPS cost estimate is based on DAWN costs for the feed system, tank and gimbal, and estimates of the thruster and PPU costs from the vendor. The cost reduction if three XIPS engines is specified is reduced by about the line width in Figure 9.

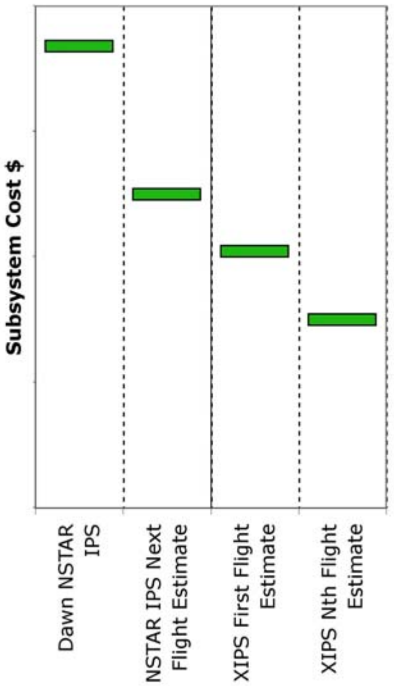

Figure 9: Cost Comparison of Single NSTAR vs. Single XIPS Electric Propulsion Subsystem
(Note: this chart does not include the cost of the solar array)

Figure 9 clearly shows that even for the first deep space use of the XIPS, the cost of the system is substantially less than the cost of an equivalent NSTAR system. For subsequent flights, the cost of a single XIPS system is expected to be slightly more than half that of a single-operating NSTAR system with equivalent xenon throughput capability. This is a substantial benefit, as XIPS not only costs less, but also performs better than single NSTAR. The cost benefit is even larger when XIPS is compared to a dual NSTAR system offering roughly equivalent mission performance.

Overall, the XIPS system offers better mass performance at lower cost than NSTAR for the reference Near Earth Asteroid sample return mission. Based on these results, the following general conclusion can be reached.

- On the Near Earth Asteroid sample return mission, XIPS offers mass performance competitive with a dual NSTAR and is expected to cost less than a single NSTAR system.

B. Comet Rendezvous

The second reference mission considered in this study is a rendezvous mission with an active short period comet. The spacecraft launches directly to an Earth escape trajectory and uses SEP to rendezvous and orbit the comet Kopff. The basic characteristics of this mission are shown in Table 6.

Comet Rendezvous	
Target Body	Kopff
Launch Vehicle	Delta 2925-9.5
Power System	Triple junction GaAs solar array, 6 kW solar array at 1 AU
Bus Power	250 W
Duration	3.8 years
ΔV	7.1 to 7.7 km/s
Launch Year	2006
Ion Thruster Duty Cycle	90%
Launch and Rendezvous Dates	Selected by Optimizer
Optimization Tool	SEPTOP

Table 6: Comet Rendezvous Mission Characteristics

A separate optimized trajectory is generated for each scenario using SEPTOP. All trajectories assume a nominal array power of 6 kW at 1 AU and include no power margin or allowance for array degradation. The array model used is a triple junction GaAs array model. The overall results are summarized in Figure 10, which shows total delivered mass for both the XIPS and NSTAR options.

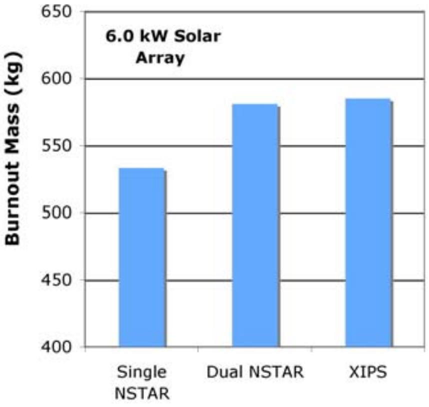

Figure 10: Burnout Mass for Comet Rendezvous, 6 kW Array

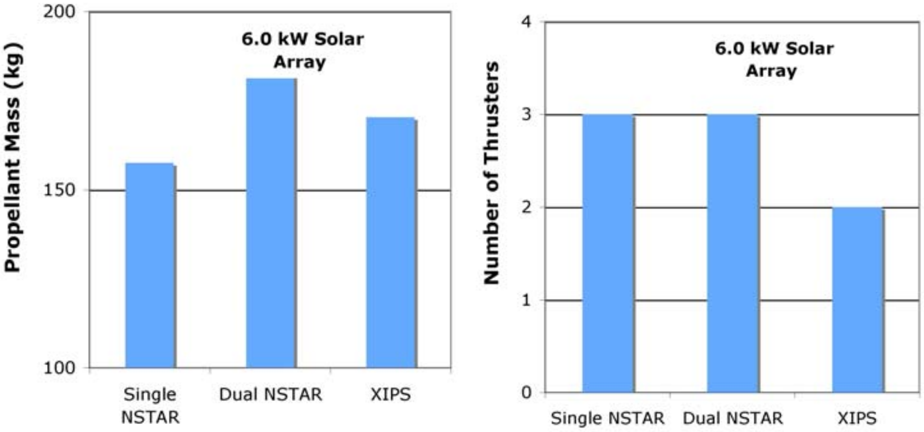

Figure 11: Xenon Propellant Throughput and Total Thrusters, Comet Rendezvous

Again, the XIPS system offers noticeably better performance than a single NSTAR system and slightly better performance than the dual NSTAR system for this trajectory. Figure 11 shows the xenon throughput and total number of thrusters required for each option. In this case, the XIPS system utilizes more xenon than the single NSTAR system, but less than the dual NSTAR system. Again, because of the higher throughput capability of the XIPS thruster, fewer XIPS thrusters are required to meet the mission's throughput requirements. These results, combined with the cost comparison provided in Figure 9, lead again to the following general conclusion.

- On the Comet Rendezvous mission, XIPS offers mass performance competitive with a dual NSTAR at a lower cost than the cost of the single NSTAR system.

C. Main Belt Asteroid Rendezvous

The Main Belt Asteroid rendezvous mission is a simplified version of the Dawn mission. Where Dawn will rendezvous with two targets, Vesta and Ceres, after a eight year transit, the reference asteroid mission rendezvous with a single target, Vesta, after a 3.5 year transit. The spacecraft launches on a Delta 2925-9.5 directly to an Earth escape trajectory and uses SEP to rendezvous with the target asteroid. The basic characteristics of this mission are shown in Table 7.

Main Belt Asteroid Rendezvous	
Target Body	Vesta
Launch Vehicle	Delta 2925-9.5
Power System	Triple junction GaAs solar array, 8 kW at 1 AU
Bus Power	400 W
Duration	3.5 years
ΔV	9.3 to 10.3 km/s
Launch Year	2011-2012
Ion Thruster Duty Cycle	95%
Launch and Rendezvous Dates	Selected by Optimizer
Optimization Tool	SEPTOP

Table 7: Main Belt Asteroid Rendezvous Mission Characteristics

As before, the solar array model is a GaAs array model, but with a beginning of life power of 8 kW at 1 AU. No margin or degradation is included in the solar array or power budget. The overall results are summarized in Figure 12 and Figure 13.

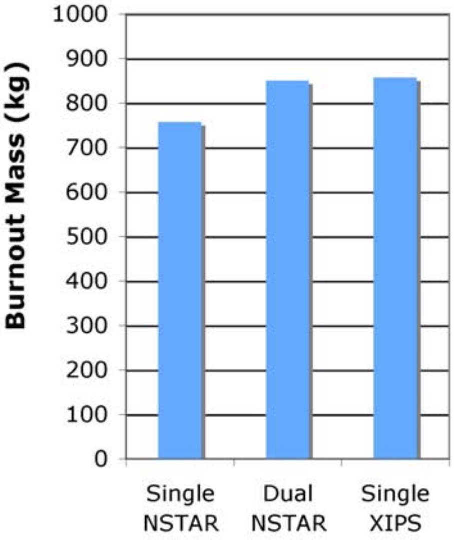

Figure 12: Burnout Mass for Main Belt Asteroid Rendezvous

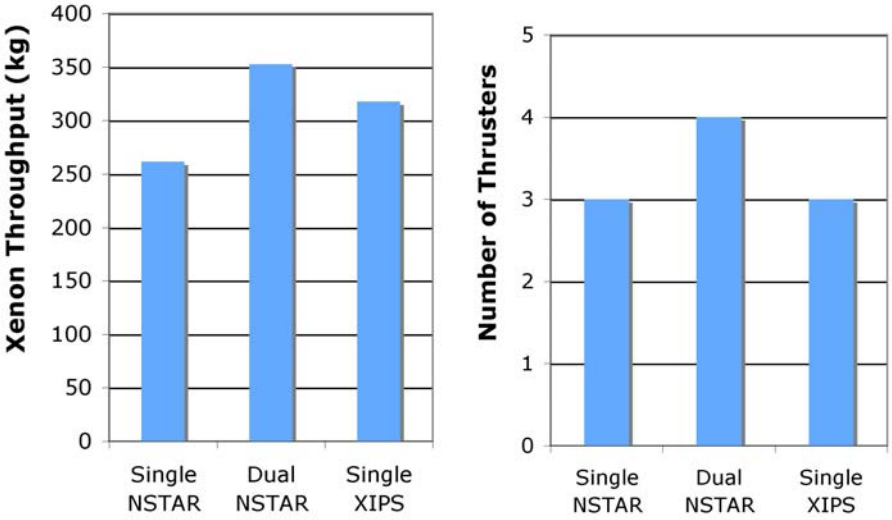

Figure 13: Xenon Propellant Throughput and Total Thrusters, Main Belt Asteroid Rendezvous

Again, the XIPS system offers noticably better performance than a single NSTAR system, though it shows slightly worse performance than dual NSTAR for this mission. Although dual NSTAR has a higher burnout mass than XIPS, because of the very high xenon thoughput requirements for that configuration, both an extra thruster and an extra PPU are required in this configuration. The extra mass associated with these units is likely to offset the difference in burnout mass, again resulting in roughly equivalent performance for XIPS and the dual NSTAR system. These results, combined with the cost comparison provided in Figure 9, lead again to the following general conclusion.

- On the Main Belt Asteroid Rendezvous mission, XIPS offers mass performance competitive with a dual NSTAR at a lower cost than the cost of the single NSTAR system.

V. Conclusions

A study has been conducted to examine the potential benefits that a solar electric propulsion (SEP) system based on the 5 kW Xenon Ion Propulsion System (XIPS) offers to the competitively awarded, cost-capped missions in NASA's Discovery program. The study looked at the cost and performance benefits provided by XIPS when compared to a state of the art system using the NSTAR ion thruster. Three different Discovery class reference missions were considered in this study: 1) a Near Earth Asteroid Sample Return, 2) a Comet Rendezvous and 3) a Main Belt Asteroid Rendezvous.

For each scenario, a launch date was selected and a low thrust trajectory optimizer was used to calculate the flight time and total mass delivered to the final destination. An estimate was generated for the cost of a XIPS system and an NSTAR system delivering equivalent xenon throughput performance. The analysis results for all three missions consistently show the following:

- In all three cases, EP systems utilizing a single operating XIPS thruster deliver significantly more mass than systems utilizing a single operating NSTAR thruster.
- The higher xenon throughput capability of the XIPS thruster generally results in systems that require fewer thrusters than NSTAR equivalent systems.
- XIPS generally XIPS performs as well as systems utilizing *two* operating NSTAR thrusters, but costs less than NSTAR systems with a *single* operating thruster.

Based on these results, we conclude that a XIPS based solar electric propulsion (SEP) system is a cost and performance competitive system that appears to be an attractive candidate for Discovery class science missions.

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