Evaluation of Solar Electric Propulsion Technologies for Discovery Class Missions

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A detailed study examines the potential benefits that advanced electric propulsion (EP) technologies offer to the cost-capped missions in NASA's Discovery program. The study looks at potential cost and performance benefits provided by three EP technologies that are currently in development: NASA's Evolutionary Xenon Thruster (NEXT), an Enhanced NSTAR system, and a Low Power Hall effect thruster. These systems are analyzed on three straw man Discovery class missions and their performance is compared to a state of the art system using the NSTAR ion thruster. An electric propulsion subsystem cost model is used to conduct a cost-benefit analysis for each option. The results show that each proposed technology offers a different degree of performance and/or cost benefit for Discovery class missions. However, lower subsystem costs, particular power processing and digital control interface unit costs, are needed for ion thruster systems to make them more competitive for cost-capped mission. It is also observed that the best mass performance generally comes from EP systems that best utilize available solar array power over the course of the mission. Finally, first flight qualification costs are identified as a significant barrier to the implementation of new EP technologies on cost-capped missions.

I. Introduction

The Dawn spacecraft is the first purely scientific mission to be powered by solar electric propulsion (SEP) and demonstrates the benefit that SEP can bring to the competitively awarded, cost-capped missions in NASA's Discovery program.[1] Dawn's primary propulsion system is based on the NSTAR thruster, a 30 cm diameter ion thruster that was flight demonstrated on Deep Space 1. This paper examines the benefits that several next generation EP technologies could have for Discovery class missions. The new technologies considered in this study are all currently proposed or in development through NASA's In Space Propulsion program. They are:

- NSTAR: 30 cm ion thruster subsystem, previously flown on Deep Space 1, representing the current state of the art in electric propulsion for deep space missions.[2]

- NASA's Evolutionary Xenon Thruster (NEXT): 6 kW ion thruster subsystem currently under development by a joint government-industry-academia team including members of NASA Glenn Research Center (GRC), the Jet Propulsion Laboratory (JPL), Aerojet-Redmond, L3 Communication Electron Technologies Inc. (ETI), the University of Michigan, Colorado State University (CSU), and the Applied Physics Laboratory (APL).[3]

- Enhanced NSTAR: a proposed improvement to the existing NSTAR subsystem using a combination of carbon based ion optics (CBIO) currently under development by a team included members of JPL, L3 ETI, and CSU and a high power processing unit (PPU) developed through the NEXT program.[4]

- Low Power Hall: a proposed Hall thruster subsystem that operates efficiently at low power with enhanced throughput capability currently under development by a team including members of GRC, Aerojet, JPL and the University of Michigan.[5]

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Discovery missions are selected competitively and cover a wide range of scientific goals and destinations. For this study, three straw man missions are selected and evaluated using each SEP technology. Although the destinations are generic, they are similar to current and proposed Discovery class missions that utilize electric propulsion. The primary focus of this study is on the improvements that advanced technologies bring compared to a state of the art NSTAR SEP system. The straw man missions selected for this study are:

- Vesta-Ceres Rendezvous mission (based on Dawn)
- Near-Earth Asteroid Sample Return Mission (targeting Asteroid Nereus)
- Comet Rendezvous Mission (targeting Comet Kopff)

Because cost is a major driver for competed missions, a detailed electric propulsion subsystem cost model is used to conduct a cost-benefit analysis for each option. The model is similar to the electric propulsion subsystem cost model used by JPL's Advanced Projects Team ("Team X") and generates a full cost that includes component costs, labor and integration, subsystem engineering, fabrication, assembly, testing, ground support, and launch operations. Development, qualification and recurring costs are all considered in the study. Where relevant, the cost of the spacecraft's solar array is also considered in the analysis at a specific cost of $1000/W.

The technology/mission matrix in Table 1 shows the different propulsion technologies/mission scenarios considered in this study.

	Near-Earth Asteroid	Comet Rendezvous	Dawn (w/Gravity Assist)
NSTAR, 1 thruster	X		X
NSTAR, 2 thruster	X	X	
NEXT	X	X	X
Enhanced NSTAR w/NEXT Components	X	X	X
Low Power Hall Thruster	X	X	X

Table 1: Study Mission-Technology Matrix

For each scenario, a launch date is chosen and a low thrust trajectory optimizer is used to calculate the flight time, xenon propellant consumed and the total mass delivered to the final destination. The size of the propulsion system is determined from the xenon throughput and a "net mass delivered" is calculated by subtracting the mass of the propulsion system from the total delivered mass. The electric propulsion cost model is used to calculate the total cost of the propulsion system. Where appropriate, the cost of the solar array is also calculated and incorporated into a comparison of the relative costs of each option. The cost and mass results are compared to show the relative cost/benefits for each technology-mission combination and an application matrix is generated showing valid mission options. The application matrix includes results from this study and from other studies conducted on larger missions. Finally, technology readiness level (TRL) and development costs are considered to reach several broad conclusions on the relative benefit of each technology for Discovery missions.

The thruster performance, mass, and cost models used in this study are described in section II. Trajectory and mission analysis assumptions and results are described in section III, and overall conclusions are described in section IV.

II. Methodology and Assumptions

A. Thruster Performance Model

For each propulsion technology, a performance model was created and used to calculate thrust and propellant mass flow rate as a function of input power to the PPU. The model is derived from throttle tables provided by technologists and the source for the throttle table varies depending on the maturity of the technology. For the NSTAR thruster, the throttle table is based on Deep Space 1 flight data and is the same throttle table currently used for mission planning on the Dawn program. For NEXT, two throttle tables, a high thrust option and a high specific impulse option, are derived from laboratory data generated using an engineering model thruster. For Enhanced NSTAR, the throttle table is derived from laboratory data taken using carbon-based optics with a laboratory thruster-cathode model. The Low Power Hall throttle table is derived from theory and not based on laboratory data.

Polynomials are fitted to each table to generate expressions for thrust and mass flow as a function of power. Table 2 shows the resulting polynomial coefficients. The overall system efficiency and specific impulse (I_{sp}) can be derived from these expressions and is shown in Figure 1 and Figure 2. Table 3 shows the allowable operating range for each option.

		Mass Flow Coefficients				
System	**Table Name**	**A**	**B**	**C**	**D**	**E**
NSTAR	Q-Mod	0.36985	-2.5372	6.2539	-5.3568	2.5060
NEXT	Table 9A High Thrust	0.0153	-0.2832	1.660	-2.621	3.131
NEXT	Table 9A High Isp	-0.00602	0.07637	-0.1898	0.1768	1.944
Enhanced NSTAR	Table 1d.1	-0.01647	0.15774	-0.5941	1.5665	0.3594
Low Power Hall	Table 1	0.00000	0.07988	-0.61355	2.4888	0.6131
		Thrust Coefficients				
System	**Table Name**	**A**	**B**	**C**	**D**	**E**
NSTAR	Q-Mod	5.145602	-36.720293	90.486509	-51.694393	26.337459
NEXT	Table 9A High Thrust	0.1102	-2.234	12.93	11.88	16.8
NEXT	Table 9A High Isp	-0.1889	2.926	-14.02	52.32	-0.08954
Enhanced NSTAR	Table 1d.1	0.2340	-1.5554	0.8267	38.4804	-2.2822
Low Power Hall	Table 1	0.0000	0.73434	-5.9528	51.1473	4.0924

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

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

Table 2: Throttle Curve Coefficients

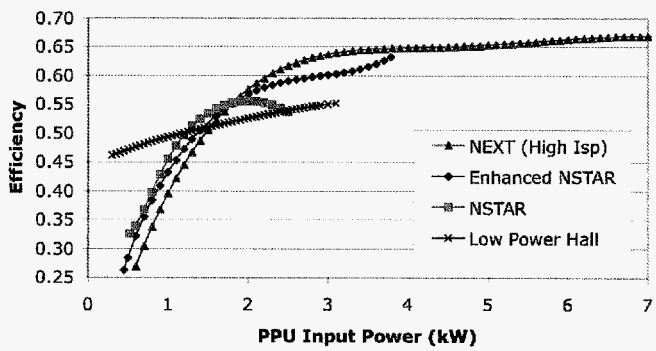

Figure 1: Propulsion Subsystem Efficiency vs. PPU Input Power

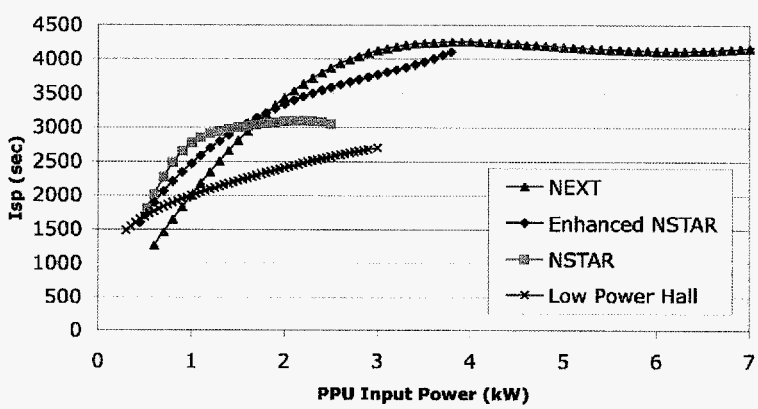

Figure 2: Specific Impulse vs. PPU Input Power

	TRL	Minimum Power	Maximum Power
NSTAR	9	525 W	2.6 kW
NEXT	5	620 W	7.3 kW
Enhanced NSTAR	4	450 W	3.8 kW
Low Power Hall Thruster	3	330 W	3.0 kW

Table 3: Thruster Characteristics Summary

The three ion thruster options have similar efficiency curves at low power but very different operating ranges. The NEXT thruster has the widest power range and at high power operates at the highest efficiency of any of the devices. The high thrust and high I_{sp} throttle curves for NEXT have the same operating range. Both NEXT throttle curves are evaluated for each mission, but only the best performing option is reported in this paper. The Enhanced NSTAR operates at input powers as low as 450 W, but with relatively low efficiency. The Hall thruster operates very efficiently at low power, but does not operate as efficiently as ion thrusters at higher power. This behavior is typical for Hall thrusters and will be shown to significantly benefit power limited missions.

B. Mass Assumptions

Hardware mass is technology dependent and is a function of xenon throughput, the number of thrusters and the number of PPU's required for each mission. A subsystem mass model is used to calculate propulsion dry mass based on mission requirements and unit level masses provided by technologists. Contingency margin is added in a manner consistent with standard JPL design principals that apply mass margins that vary with unit maturity ranging between 2% for "build-to-print" hardware and 30% for new designs. The result is an overall subsystem margin that varies from 10% for NSTAR to 30% for NEXT and Low Power Hall. Xenon tank mass is calculated as a fixed fraction of xenon propellant mass to allow direct comparison of propulsion hardware. Five percent fuel mass margin is added to account for navigation and trajectory errors. Additional fuel is added to account for residuals in the tank and feed system.

The subsystem mass breakdown is shown in Table 4. The inputs selected for this table (shown as shaded regions) are generic, but typical of trends observed in the detailed analysis. The advanced thrusters have greater throughput capability than NSTAR and typically require fewer thrusters to meet mission requirements. The NEXT feed system is unique and is modeled as having somewhat smaller system residuals. The ion systems use redundant Digital Control and Interface Units (DCIUs) to provide command and telemetry interfaces, control the gimbals, and actively regulate xenon flow rates. The Hall system requires no DCIU and incorporates flow control functions into the PPU and gimbal control into the spacecraft command system. This distribution of functions is typical for commercial Hall systems and improves the system's mass and cost. The difference in control architecture is somewhat arbitrary, but partially reflects differences in the operation of Hall and ion thrusters. With ion thrusters, the flow controller regulates separate discharge and neutralizer cathodes and typically closes the loop around temperature and pressure sensors associated with the feed system. This requires the use of redundant pressure sensors and makes the control logic relatively complex. With Hall thrusters, the flow controller regulates only one cathode and closes the loop around the discharge current, making it relatively easy to incorporate the control logic into the PPU. The gimbal control electronics increase the mass and cost of the spacecraft command distribution system, a penalty that is included in this analysis. It may be possible to improve the mass and cost of ion systems by similarly incorporating flow control functions into the PPU.

Thruster	NSTAR Baseline	Enhanced NSTAR	NEXT	Low Power Hall
Inputs				
Number of Engines	3	2	2	2
Number of PPU's	3	2	2	2
Number of DCIU's	2	2	2	0
Xenon Throughput (kg)	200	200	200	300
Xenon Contingency				
Navigation and Trajectory Errors	5%	5%	5%	5%
Residuals	5.0%	5.0%	3.6%	5.0%
Assumptions				
Mass per Thruster	8.2	7.39	12.4	3.6
Mass per PPU	13.9	17.6	26	8.4
Mass per DCIU	5.7	5.7	5.7	0.0
Mass per Gimbal	4.6	4.6	5.0	4.6
Gimbal Drive Electronics	included	included	included	2.0
Feed System				
Fixed Mass	8.1	8.1	2.2	4.0
Additional mass/engine	3.3	3.3	4.1	1.0
Xenon Tank Mass Fraction	4.5%	4.5%	4.5%	4.5%
System Contingency	10%	18%	30%	30%
Calculations				
Thrusters	24.6	14.8	24.8	7.2
PPUs	41.7	35.2	52.0	16.8
DCIUs	11.3	11.3	11.3	0.0
Xenon Feed System	18.1	14.7	10.4	6.0
Xenon Tank(s)	9.9	9.9	9.8	14.9
Gimbals	13.9	9.3	10.0	11.3
Subsystem Dry Mass	**120**	**95**	**118**	**56**
Xenon Residuals	20.0	20.0	17.2	30.0
Hardware Mass Contingency	12.0	17.1	35.5	16.8
Propulsion System Mass (w/Contingency)	**151**	**132**	**171**	**103**
Mass Delta	**Baseline**	**-13%**	**+13%**	**-32%**

Table 4: Electric Propulsion Unit Mass Assumptions

Note: masses shown are current best estimates as of September 2004

C. Costing Methodology

Cost is a major consideration in the design of Discovery class missions and is a major driver in the decision whether or not to use electric propulsion on a given mission. A detailed EP subsystem cost model is used to estimate the relative cost of each option. The model is based on a combination of flight mission actual costs, flight mission estimates, and cost estimates provided by technologists. Four types of cost estimates were generated for this study:

- *Development cost*: cost to develop the subsystem from its current development status (as of August 2004) to technology readiness level (TRL) 6, where the subsystem has been demonstrated in relevant environments.
- *Qualification cost*: cost to develop the subsystem from TRL 6 to a fully flight qualified design
- *Non-Recurring cost*: cost of post-qualification engineering, data, and drawings for the first flight units.
- *Recurring cost*: cost of first/second/third/fourth flight units.

Development and qualification costs were estimated at a subsystem level while non-recurring and recurring costs were estimated at a unit level. The unit costs serve as inputs to a quasi-grass root cost model developed by JPL's Advanced Projects Team ("Team X") that is derived from actual costs incurred and projected on the Deep Space 1 and Dawn missions. The model accounts for component costs, spare parts, labor and integration, subsystem engineering, design and analysis, engineering procurement support, fabrication assembly and test, ground support and launch operations, xenon tanks and gas, and harness manufacturing. The output from the model is combined with the development and qualification cost estimates to provide three outputs:

- Development cost: cost to develop the subsystem from its current development status to TRL 6
- First Flight Cost: sum of subsystem qualification, non-recurring, and recurring costs
- N^{th} Flight Cost: sum of subsystem non-recurring and recurring costs

The unit recurrent and non-recurring cost estimates used in this study are shown in Table 5. The NSTAR values are derived from, but not the same as, Deep Space 1 and Dawn actual costs as of May 2004. They represent the projected cost of these units for the next flight mission build. The NEXT, Enhanced NSTAR, and Hall values are estimates provided by technologists, based on vendor data when available. The inputs selected for this table (shown as shaded regions) are generic, but typical of trends observed in the detailed analysis.

Thruster	NSTAR Baseline	Enhanced NSTAR	NEXT	Low Power Hall
Inputs				
Kg of Xenon	300	300	300	400
Number of Engines	3	2	2	2
Number of PPU's	2	2	2	2
Number of DCIU's	2	2	2	0
Component Cost Assumptions				
Recurring Cost / Thruster	580	580	800	250
Recurring Cost / PPU	1520	1900	1976	800
Recurring Cost /DCIU	1310	1310	1310	0
Recurring Cost / Gimbal	325	325	325	325
Recurring Cost / Xenon tank	450	450	450	450
Fixed Cost / Feed System	1610	1610	1610	1610
Per Thruster Cost / Feed System	200	200	200	200
Non-Recurring / Thruster ($K)	130	250	250	50
Non-Recurring / PPU	200	200	200	200
Non-Recurring / DCIU	0	0	0	0
Non-Recurring / Xenon tank	0	0	0	0
Non-Recurring / Gimbal	510	510	510	1010
Design & Qual new Xenon Tank	0	0	0	0

Table 5: Recurring Cost Assumptions ($FY05 K)

The costs shown in Table 5 comprise a substantial fraction of the total cost of a flight electric propulsion system. Several general observations can be made based on these values. In general, units associated with the Hall system cost considerably less than equivalent units associated with the ion systems. Some of this cost difference may be due to the relative lack of maturity of the Hall estimates, which carry greater uncertainty because the design is conceptual and the hardware is at a relatively low TRL (see Table 3). It should be noted, however, that the Hall units costs reported in Table 5 are consistent with the costs of existing commercial Hall systems.

PPU costs vary widely and are a key differentiator when comparing EP systems. For purposes of this analysis, we are assuming that the recurring cost of the next NSTAR flight PPU will be about half of the cost of the Dawn units, but there is considerable uncertainty in this value. The DCIU costs over $1.3 million per flight unit and also has a significant impact on overall subsystem cost. This is one reason the proposed Hall systems are generally less expensive than the ion options. As discussed in the previous section, the Hall system has no DCIU. The cost to incorporate DCIU functions into other units is incorporated into the Hall PPU and the gimbal non-recurring cost. The recurring cost of the feed system is difficult to estimate because it includes component costs incurred at the subsystem level and assembly/integration costs incurred at the spacecraft level. For this analysis, the cost of a fully integrated NSTAR feed system is used in every case. This assumption is conservative because the NEXT and Hall feed systems incorporate design features that are expected to make them less expensive than the NSTAR feed system. Thruster costs also vary widely, but because the cost of the thrusters is relatively small compared to other units, the nth flight cost is largely driven by PPU and DCIU costs. Based on this observation, we draw the following conclusion.

- The PPU and DCIU unit costs are major cost drivers for electric propulsion systems

Feed system costs may also be a major cost driver, but are not evaluated in this study. The development cost estimated for each subsystem is shown in Table 6. These costs are for single string systems and do not include the cost of multi-thruster testing. The development costs were provided by technologists and contain considerable

schedule and cost uncertainty. They are reported in FY05 dollars and represent cost to complete development as of September 2004. Previously expended funds are not reported. These estimates are of varying fidelity, have not been independently reviewed or compared to historical data, and should be treated as rough order of magnitude values. It is assumed that qualification costs are be paid by the first flight program while development costs are paid by the In-Space Propulsion program. This is consistent with the current financial structure of these programs.

Thruster	SOA NSTAR	Enhanced NSTAR	NEXT	Low Power Hall
Component Cost Assumptions				
Development (to TRL 6) / Thruster	0	3000	7050	7000
Qualification / Thruster	0	1200	2200	2200
Development (to TRL 6) / PPU	0	3800	2280	3500
Qualification / PPU	0	1500	1600	1500
Development (to TRL 6) / DCIU	0	0	1000	0
Qualification / DCIU	0	0	400	0
Development (to TRL 6) / Gimbal	0	0	400	400
Qualification / Gimbal	0	0	800	800
Development (to TRL 6) / PMS	0	0	660	2600
Qualification / PMS	0	0	1000	1000
System Integration Tests (1)		500	500	500
Development cost (to TRL 6)	0	7300	11890	14000
Qualification cost (after TRL 6)	0	2700	6000	5500
Total EP subsystem costs in $k	**0**	**10000**	**17890**	**19500**

Table 6: Technology Development Costs Estimates ($FY05 K), Single String Only

This study focuses on the cost of the electric propulsion system. In most cases, the missions compared have the same flight time and solar array power, so changing the propulsion system has relatively little impact on the overall cost of the mission. When solar array power is varied, a generic cost of $1000/W is used for the power system. This value is representative of rigid solar arrays using existing cell technology. There are also costs associated with the accommodation of multiple thrusters into the spacecraft configuration. These costs are not included in our analysis.

III. System Analysis Results

Discovery missions are selected competitively and cover a wide range of scientific goals and destinations. Three straw man 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. The result's general implications are discussed and some mission specific findings are provided. Additional general findings are given in the final section of this paper.

A. Near Earth Asteroid Mission

The first mission considered is a Near Earth Asteroid sample return mission. The spacecraft launches directly to a positive C_3 Earth escape trajectory and uses SEP to rendezvous with the asteroid Nereus. It remains in the asteroid's vicinity for 90 days before using SEP to return to Earth and conduct a flyby as it releases the sample for direct entry. The basic characteristics of this mission are shown in Table 7.

Near Earth Asteroid Sample Return	
Target Body	Nereus
Launch Vehicle	Delta 2925
Power System	6 kW solar array at 1 AU
Bus Power	300 W
Duration	3.3 years
ΔV	4.5 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 7: Near Earth Asteroid Sample Return Mission Characteristics

A separate optimized trajectory is generated for each scenario using SEPTOP, a well-known low thrust optimization tool. 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. As shown in Table 8, the entry velocity varies from 13.6 to 14.9 km. By comparison, the entry velocity for the Stardust mission will be approximately 12.6 km/s. Higher entry velocities require a heavier and more expensive thermal protection system (TPS). Variations in the mass and cost of the TPS are not accounted for in this analysis. The overall results are summarized in Table 8 and net delivered mass is shown in Figure 3. Net delivered mass is defined as total end-of-mission delivered mass minus the mass of the electric propulsion system. It includes the payload, solar arrays, Earth return vehicle, and main spacecraft bus. Both single and multi-thruster operation are considered. All options carry an extra thruster and power processing unit for redundancy. In some cases, an extra thruster is also required to meet xenon throughput requirements.

	Single NSTAR	Single NSTAR Enhanced	Single Low Power Hall	Single NEXT (High Isp)	Dual NSTAR	Dual Hall
Mission						
Launch Vehicle	Delta 2925	Delta 2925	Delta 2925	Delta 2925	Delta 2925	Delta 2925
Trip Time (yrs.)	3.25	3.20	3.15	3.18	3.16	3.14
C_3(km^2/s^2)	11.8	7.1	4.2	1.8	2.2	1.8
Power (1 AU, BOL)	Baseline 6 kW	Same (3)	Same	Same	Same	Same
Net Payload Mass Delivered (kg)	**542**	**674**	**712**	**772**	**746**	**793**
Launch Mass (kg)	1010	1115	1183	1245	1235	1245
Xenon Propellant Throughput (kg)	194	174	238	167	198	203
Net Trajectory Mass Capability (kg)	677	801	805	938	897	903
Propulsion Subsystem Mass (kg)	135	127	93	166	151	110
Free Space Delta-V (km/s)	6.50	6.34	5.85	5.61	5.27	4.65
Entry Velocity (km/s, approximate)	14.9	14.9	14.3	14.2	14.0	13.6
Configuration						
Simultaneous Operating Thrusters	1 thruster	1 thruster	1 thruster	1 thruster	2 thrusters	2 thrusters
Total Thrusters (Primary + Redundant)	3	2	2	2	3	3
Total PPU's (Primary + Redundant)	2	2	2	2	3	3
nth Mission Cost ($K)	**Baseline**	**-2,283**	**-5,277**	**-1,770**	**+1,529**	**-3,631**
First Mission Cost ($K)	**Baseline**	**+417**	**+223**	**+4,230**	**+1,529**	**+1,869**
Propulsion Subsystem Costs						
Recurring Cost ($K) (4)	Baseline	-2,283	-5,277	-1,770	+1,529	-3,631
Qualification Cost ($K) (5)	Baseline	+2,700	+5,500	+6,000	+0	+5,500
Development						
Maturity (TRL)	9	4	3	5	6	3
Development Schedule (TRL 6, no life test)	None	~1.5 yrs.	~ 4 yrs.	~1.5 yrs.	None	> 4 yrs
Develoment Schedule (w/life test)	None	~ 3 yrs.	> 5.5 yrs.	> 2.5 yrs.	None	> 5.5 yrs.
Development Cost ($M) (2)	None	$9.5M	$19M	$21M	Small	$19M

Table 8: Summary of Results, Near Earth Asteroid Mission

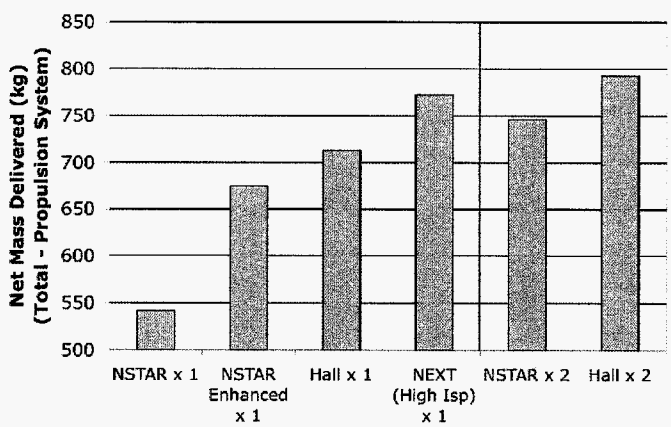

Figure 3: Net Mass delivered, Near Earth Asteroid

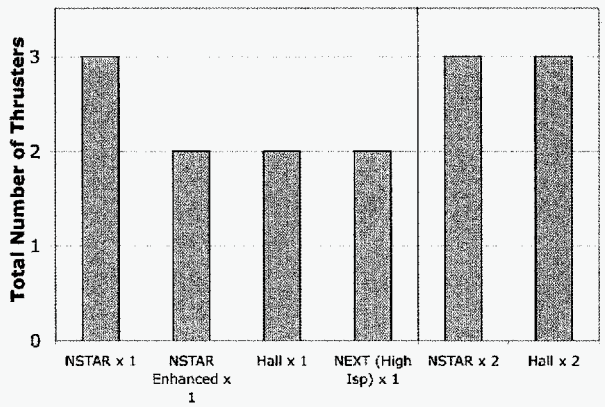

Figure 4: Total Thrusters Required, Near Earth Asteroid

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 the NSTAR thruster. Systems allowing multi-thruster operation are more complex and therefore have higher cost and propulsion system mass than single thruster equivalents. Figure 3 shows that the advanced EP technologies generally offer a considerable mass performance advantage over single NSTAR, but do not necessarily offer an advantage over dual NSTAR. This result is explained below in the discussion of Figures 5-10. Figure 4 shows the total number of thrusters required for each option. All options carry an extra engine for redundancy. The single NSTAR configuration requires the same number of thrusters as the dual NSTAR configuration because the mission's xenon throughput requirements exceed the capability of a single NSTAR thruster. The second thruster provides additional throughput and the third thruster provides redundancy. All of the proposed technologies require fewer thrusters in their single active thruster configuration.

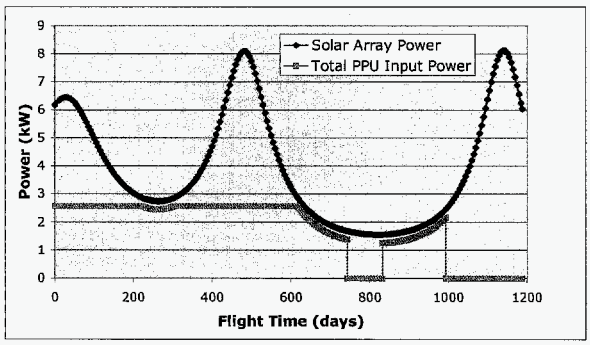

Figure 5: NEAR Power vs. Time
Single NSTAR Thruster
Delivered Mass: 540 kg

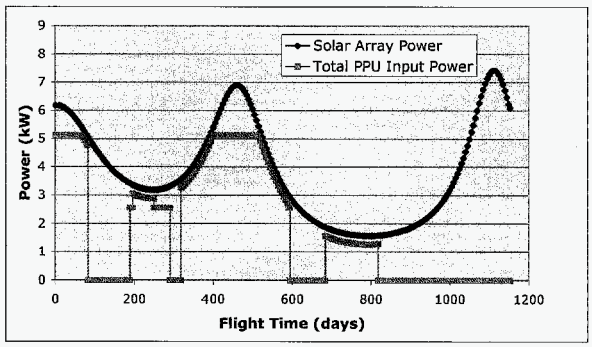

Figure 6: NEAR Power vs. Time
Dual NSTAR thruster
Delivered Mass: 740 kg

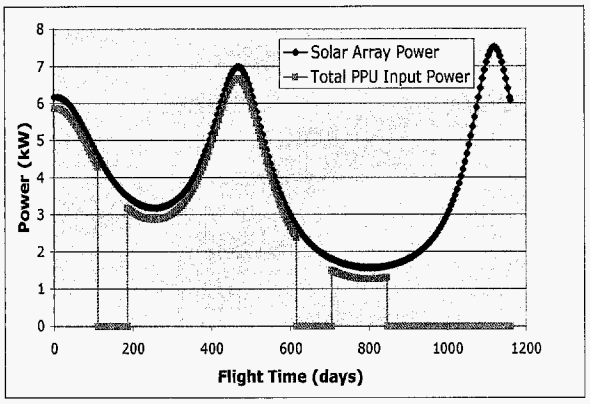

Figure 7: NEAR Power vs. Time
Single NEXT thruster
Delivered Mass: 770 kg

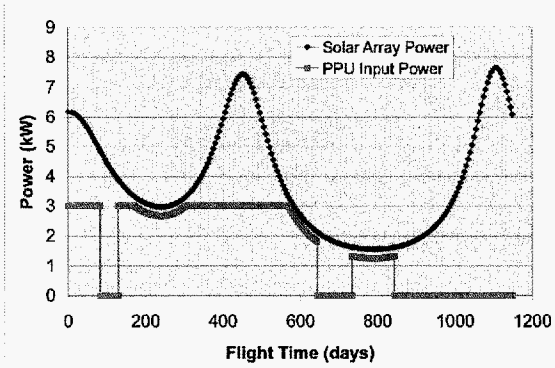

Figure 9: NEAR Power vs. Time
Single Low Power Hall thruster
Delivered Mass: 712 kg

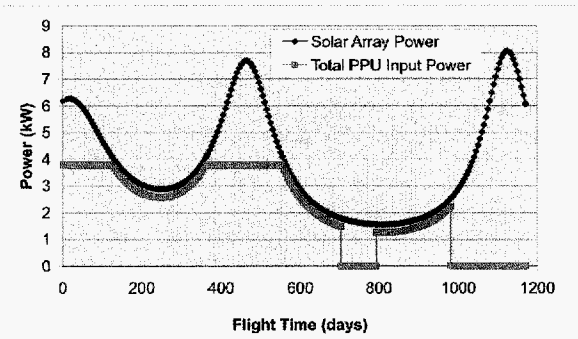

Figure 8: NEAR Power vs. Time
Single Enhanced NSTAR Thruster
Delivered Mass: 674 kg

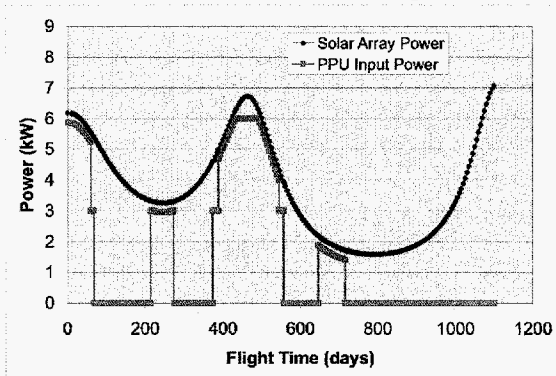

Figure 10: NEAR Power vs. Time
Dual Low Power Hall Thruster
Delivered Mass: 793 kg

Figure 5 shows the power vs. time history for both the array and the PPU for the single NSTAR option. The power generated by the array varies with distance from the sun, starting at 6 kW, dropping as low as 1.4 kW and peaking near 8 kW at the middle and end of the mission. The PPU's input power is limited by NSTAR's power handling capacity and a significant fraction of the array's capability is unused for much of the mission. Figure 7 shows the power vs. time history for the NEXT option. NEXT has a much higher peak input power, better utilizes the array near perihelion, and generates more thrust than NSTAR near perihelion. The higher thrust produces lower gravity losses and more efficient orbital maneuvers. This in turn results in a lower C_3, higher separated mass, and less onboard ΔV than the single NSTAR option. The dual NSTAR option shown in Figure 6 also uses the array more efficiently than single NSTAR and therefore delivers more mass. Enhanced NSTAR uses the array more efficiently than single NSTAR but less efficiently than dual NSTAR and its mass performance lies between these two cases. Based on these results, the following conclusion is reached.

- In general, the best mass performance comes from the EP systems that best utilize available solar array power.

This is a useful generalization that can be used as a guideline by EP system designers seeing to optimize mass performance on SEP missions. However, the system's efficiency as a function of power and the choice of specific impulse will also impact delivered mass capability. The influence of these factors is illustrated in Figure 9 and Figure 10. The single Hall system has roughly the same peak power as Enhanced NSTAR, but delivers somewhat more mass. This occurs because the Hall system operates at lower I_{sp} and generates higher thrust at aphelion and perihelion, lowering the total ΔV required for the mission. The net result is that the Hall system operates closer to this mission's mass optimum I_{sp}. The dual Hall system shown in Figure 10 delivers somewhat more mass than NEXT for the same reasons.

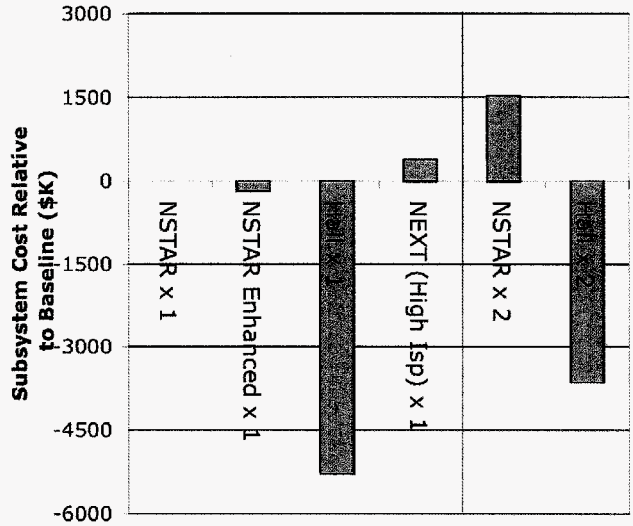

Figure 11: Nth Flight Cost Comparison, Near Earth Asteroid ($FY05)

Figure 11 shows nth flight costs calculated for the Near Earth Asteroid sample return mission. Although all systems offer a significant mass performance advantage over single NSTAR, only the Hall systems simultaneously offers a considerable cost advantage. The cost savings is quite significant for a mission of this size, equivalent to ~25% of the total cost of the subsystem. All of the systems offer considerable cost advantages over dual NSTAR and most require fewer thrusters to achieve similar mass performance. Comparing Figure 3 and Figure 11, we reach the following conclusions concerning the relative cost and benefits of each option.

- All proposed systems offer considerable mass advantage over single NSTAR system.
- Single Low Power Hall offers both significant cost and mass advantages over single NSTAR. It also offers superior mass performance over dual NSTAR at much lower cost.
- Dual Low Power Hall offers the highest mass performance of any option and still costs considerably less than a single NSTAR system.
- Enhanced NSTAR offers a significant mass advantage over single NSTAR and may offer a slight cost advantage.
- NEXT offers superior cost and mass performance to dual NSTAR. It has superior mass performance to single NSTAR, but at somewhat higher cost.

Figure 12 shows first flight costs for this mission. This includes the cost to qualifying the first set of flight hardware after it has been developed to TRL 6.

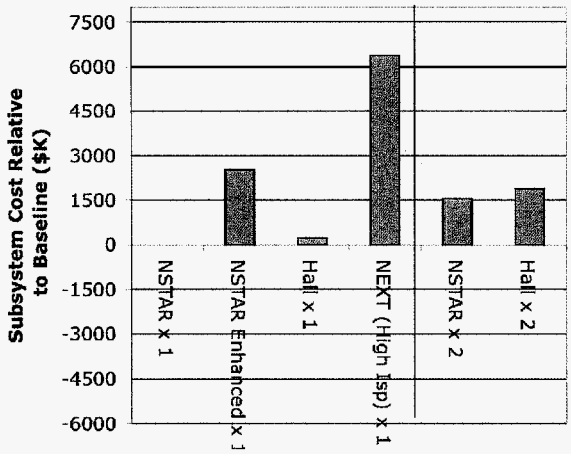

Figure 12: Qualification Cost Estimate, Near Earth Asteroid Mission

The qualification costs considerably increase the cost of the first flight system. Although the newer systems still offer a considerable mass advantage over single NSTAR, from the flight program's point of view, it is often less expensive to use a dual NSTAR system than it is to adopt a newer technology. The only exception to this is the single Low Power Hall system, which still offers comparable performance for less cost than dual NSTAR, even including qualification costs. From these results, it is concluded that

- Qualification costs are a significant barrier to first flight of new SEP technologies on Discovery missions.

Once the first system is flown, future SEP flights will see the full cost benefit from the use of new technology. However, the first program has little incentive to adopt a technology that primarily benefits future missions. This problem could be partially addressed by incorporating additional qualification testing into the technology development programs, incorporating full-length life tests into the development programs, or by procuring flight qualification units as part of the development. It could also be addressed programmatically though cost sharing arrangements that fund qualification efforts outside of the traditional mission cost-cap structure.

B. Vesta-Ceres Rendezvous Mission

The Vesta-Ceres rendezvous mission is a main belt asteroid science mission modeled closely on Dawn. The spacecraft launches directly to an Earth escape trajectory and uses a combination of SEP and a Mars gravity assist to rendezvous with the asteroid Vesta. SEP is used to maneuver in the asteroid's vicinity for 200 days before continuing on to a second rendezvous with the asteroid Ceres. The basic characteristics of this mission are shown in Table 9.

Vesta-Ceres Rendezvous	
Target Bodies	Vesta and Ceres
Launch Vehicle	Delta 2925H
Power System	8.67 kW solar array at 1 AU
Bus Power	540 W
Duration	9 years
ΔV	10.2 to 11.6 km/s
Launch Date	7 July 2006
Ion/Hall Thruster Duty Cycle	90%
Launch and Rendezvous Dates	Fixed
Optimization Method	Mystic
Redundancy	Spare thruster required at Vesta. No spare required for Ceres

Table 9: Vesta-Ceres Rendezvous Mission Characteristics

This mission is based on Dawn and uses the same launch vehicle, solar array, launch date and arrival date. The solar array is modeled using a triple junction InGaP/InGaAs/Ge array model. The power shown in Table 9 is usable power from the array and does not include margins and degradation factors included in the flight power budget. Consistent with Dawn, no thruster redundancy is required after the first rendezvous. A separate optimized trajectory is generated for each scenario using the low thrust optimization tool Mystic.[6] Figure 13 shows the power vs. time profile operating a single NSTAR thruster at a time (the Dawn mission baseline). Three NSTAR thrusters are fired in series to accommodate the 450 kg. of xenon required to complete the mission. One challenging aspect of this mission is the need to maneuver for extended periods far away from the sun. Although significant excess power is available at the beginning of the mission, only 570 watts is available to the PPU at end of mission, which is only 50 W greater than the thruster's minimum operating power. The overall analysis results are summarized in Table 10 with net mass performance shown in Figure 14 and the total number of thrusters required shown in Figure 15.

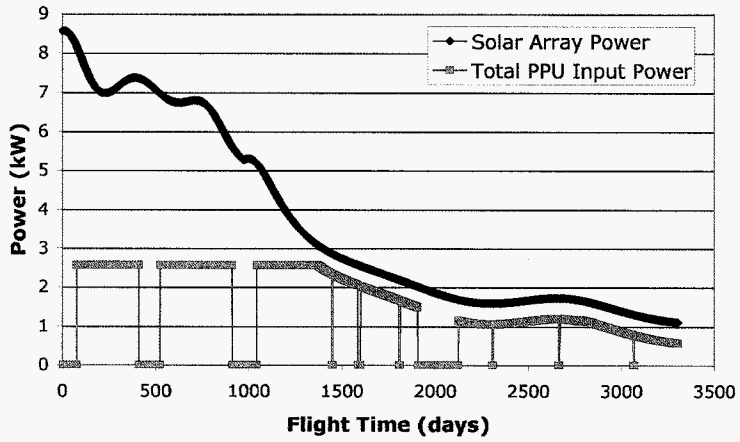

Figure 13: NSTAR Power Profile, Vesta-Ceres Rendezvous

	Single NSTAR	Single NSTAR Enhanced	NEXT (High Thrust)	Low Power Hall	Low Power Hall (small Array)
Mission					
Launch Vehicle	Delta 2925H	Delta 2925H	Delta 2925H	Delta 2925H	Delta 2925H
Trip Time (yrs.)	9.00	9.00	9.00	9.00	9.00
C3(km^2/s^2)	7.3	6.8	0.0	0.0	0.0
Power (1 AU, BOL, kW)	8.67	8.67	8.67	8.67	7.00
Payload Mass Performance (kg)	**702**	**726**	**738**	**800**	**703**
Launch Mass (kg)	1294	1307	1509	1509	1508
Xenon Propellant Throughput (kg)	385	395	527	537	597
Net Trajectory Mass Capability (kg)	882	888	958	942	855
Propulsion Subsystem Mass (kg)	180	162	220	142	152
Free Space Delta-V (km/s)	10.55	NA	10.70	10.59	NA
Configuration					
Simultaneous Operating Thrusters	1 thruster	1 thruster	1 thruster	1 thruster	1 thruster
Total Thrusters (Primary + Redundant)	3	2	2	2	2
Total PPU's (Primary + Redundant)	2	2	2	2	2
nth Mission Cost ($K)	**Baseline**	**-136**	**+653**	**-5,100**	**-6,572**
First Mission Cost ($K)	**Baseline**	**+2,564**	**+6,653**	**+400**	**-1,072**
Propulsion Subsystem Costs					
Recurring Cost ($K)	Baseline	-136	+653	-5,100	-5,100
Qualification Cost ($K)	Baseline	+2,700	+6,000	+5,500	+5,500
System Costs (Power)	Baseline	Baseline	Baseline	Baseline	-1472
Development					
Maturity (TRL)	9	4	5	3	3
Development Schedule (TRL 6, no life test)	None	~1.5 yrs.	~1.5 yrs.	~ 4 yrs.	~ 4 yrs.
Develoment Schedule (w/life test)	None	~ 3 yrs.	> 2.5 yrs.	> 5.5 yrs.	> 5.5 yrs.
Development Cost ($M)	None	$10M	$17.9M	$19.5M	$19.5M

Table 10: Vesta-Ceres Rendezvous Summary Performance Matrix

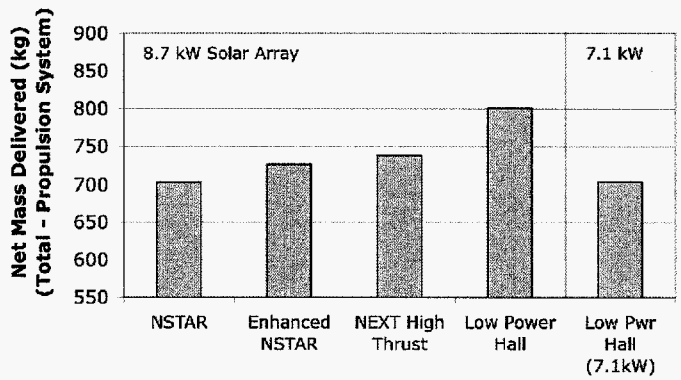

Figure 14: Delivered Mass, Vesta-Ceres Rendezvous Mission

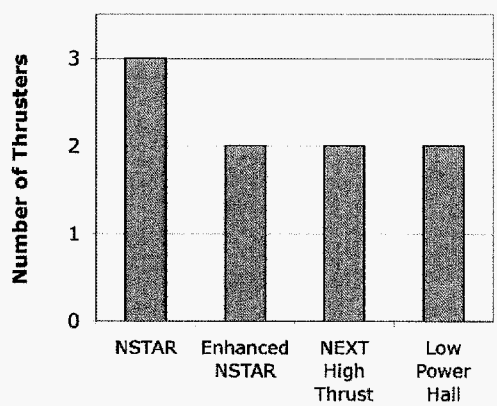

Figure 15: Number of thrusters required, Vesta-Ceres Rendezvous

Figure 15 shows the primary advantages that the proposed EP devices have over NSTAR: significantly greater throughput capability. All of the proposed devices require fewer thrusters to complete the mission compared to the SOA NSTAR system. Since the same conclusion was reached for the Near Earth Asteroid sample return mission, this leads to the following finding.

- Discovery class missions will generally benefit from the increased xenon throughput capability offered by the proposed EP technologies.

Figure 14 shows that Enhanced NSTAR and NEXT deliver relatively small mass advantages over NSTAR, while low power Hall delivers almost 100 kg of extra payload. The Hall system performs well because it operates at relatively high efficiency at low power (see Figure 1), giving it a significant performance advantage for the last third of the mission. Enhanced NSTAR and NEXT better utilize the array at the beginning of the mission, but gain relatively little mass advantage because a Mars gravity assist is used in combination with fixed launch and arrival dates. Most of the extra array power is only available on the initial Earth-Mars leg, so the extra thrust capability is useful for the Mars flyby, but has little benefit for the rest of the mission. The size of the Dawn array is determined by the need to provide enough power to operate the propulsion system at the final destination. Because the Hall thruster operates relatively efficiently at low power, we examined a case where a 7.1 kW array was used to carry out the mission. Using the smaller array, the Hall system is able to deliver the same payload as the baseline case. None of the ion thrusters were able to complete the mission with an array smaller than 8.7 kW. This result clearly shows the benefit that efficient low power operation has for this type of Discovery class mission and leads to the following finding:

- EP systems that operate with high efficiency at low power can greatly benefit Discovery class missions.

This finding is specific to Discovery because these missions are strongly cost and power limited. As a result, the EP system ends up driving the size of the power system, which in turn represents a substantial fraction of the total spacecraft cost.

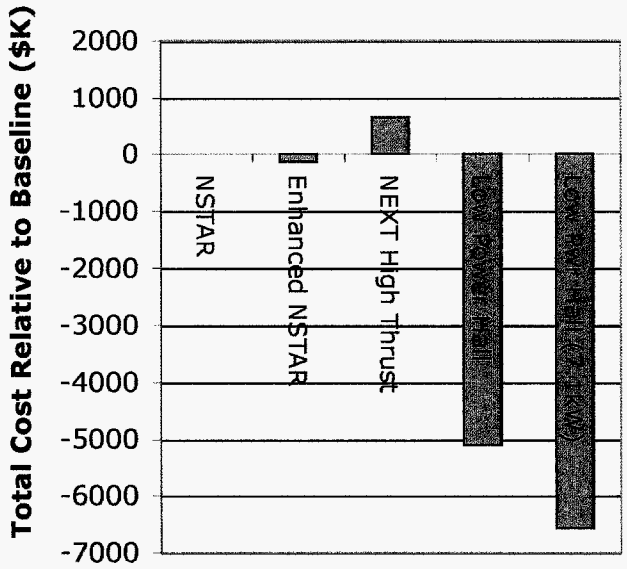

Figure 16: Nth Flight Cost, Vesta-Ceres Rendezvous

Figure 16 shows n^{th} flight cost calculated for the Vesta-Ceres mission. The Hall system offers a considerable cost and performance advantage on this mission at 8.7 kW, saving almost $5 million compared to the SOA case. In addition, because it operates relatively efficiently at low power, the Hall system can instead be used with a smaller array, resulting in over $1 million in additional cost savings. The ion systems, on the other hand, offer a moderate performance advantage, but little to no cost advantage over the SOA. This occurs despite the use of fewer thrusters because low thruster costs are offset by higher costs associated with the PPU. Like many Discovery missions, Dawn is a strongly cost constrained, so these higher costs represent a significant barrier to the adoption of these technologies. Lower subsystem costs, particularly PPU/DCIU costs, are needed for ion thruster options. The costs reported do not account for the system benefits of using fewer thrusters, which include simpler spacecraft configuration and integration testing.

Based on this analysis, we reach the following conclusions for the Vesta-Ceres rendezvous mission.

- For all options, greater throughput allows use of fewer thrusters than NSTAR. This will simplify the spacecraft's configuration and reduce integration testing.
- Hall has a considerable performance and cost advantage over the state of the art. In particular, its high efficiency at low power allows the use of a smaller solar array on this mission, resulting in substantial cost savings at the system level.
- Lower subsystem costs, particularly PPU/DCIU costs, are needed for ion thruster options.

C. Comet Rendezvous Mission

The last mission considered 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 structure of this mission is somewhat similar to concept for the comet Odyssey mission.[7] The basic characteristics of this mission are shown in Table 11.

Comet Rendezvous	
Target Body	Kopff
Launch Vehicle	Delta 2925
Power System	9 kW solar array at 1 AU
Bus Power	250 W
Duration	3.8 years
ΔV	8.1 to 8.9 km/s
Launch Year	2006
Ion/Hall Thruster Duty Cycle	90%
Launch and Rendezvous Dates	Selected by Optimizer
Optimization Method	SEPTOP

Table 11: Comet Rendezvous Mission Characteristics

A separate optimized trajectory is generated for each scenario using SEPTOP. All trajectories assume a nominal array power of 9 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. Although this mission is not as power limited as the Vesta-Ceres rendezvous, it does require extended operation at moderately low power (< 1.5 kW). The baseline SOA mission uses two NSTAR thrusters. Its power profile is shown in Figure 17. The overall results are summarized in Table 12 and net delivered mass and relative cost are shown in Figure 18 and Figure 19.

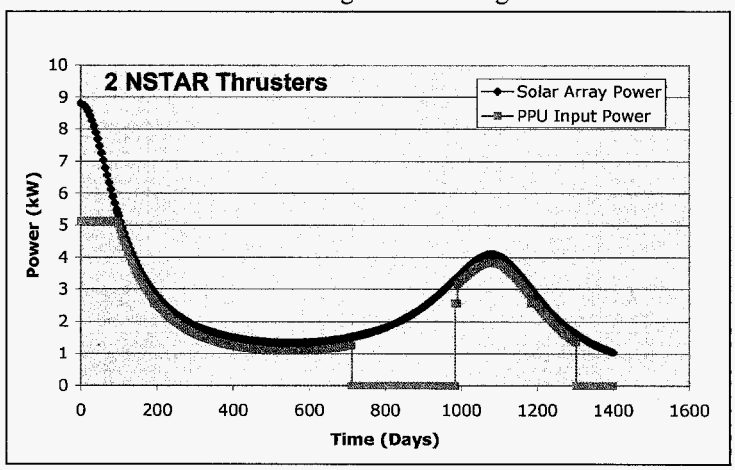

Figure 17: Power Profile, Comet Rendezvous Mission

	Dual NSTAR	NEXT (High Thrust)	Dual Enhanced NSTAR	Dual Hall	NEXT (High Isp)	Triple NSTAR
Mission						
Launch Vehicle	Delta 2925	Delta 2925	Delta 2925	Delta 2925	Delta 2925	Delta 2925
Trip Time (yrs.)	3.83	3.84	3.81	3.86	3.80	3.83
C3(km^2/s^2)	15.8	13.7	15.3	11.0	15.8	12.9
Power (1 AU, BOL)	Baseline 9 kW	Same (3)	Same	Same	Same	Same
Payload Mass Performance (kg)	**592**	**610**	**611**	**633**	**609**	**592**
Launch Mass (kg)	987	1030	997	1090	987	1047
Xenon Propellant Throughput (kg)	238	246	213	327	204	261
Net Trajectory Mass Capability (kg)	749	784	785	763	783	786
Propulsion Subsystem Mass (kg)	157	174	174	130	174	194
Free Space Delta-V (km/s)	8.15	8.41	8.17	8.88	8.10	8.50
Configuration						
Simultaneous Operating Thrusters	2 thrusters	1 thruster	2 thrusters	2 thrusters	1 thruster	3 thrusters
Total Thrusters (Primary + Redundant)	3	2	3	3	2	4
Total PPU's (Primary + Redundant)	3	2	3	3	2	4
nth Mission Cost ($K)	**Baseline**	**-1,128**	**+1,321**	**-5,020**	**-1,128**	**+2,693**
First Mission Cost ($K)	**Baseline**	**+4,872**	**+4,021**	**+480**	**+4,872**	**+2,693**
Propulsion Subsystem Costs						
Recurring Cost ($K)	Baseline	-1,128	+1,321	-5,020	-1,128	+2,693
Qualification Cost ($K)	Baseline	+6,000	+2,700	+5,500	+6,000	+0
Development						
Maturity (TRL)	6	5	4	3	5	6
Development Schedule (TRL 6, no life test)	None	~1.5 yrs.	~1.5 yrs.	> 4 yrs	~1.5 yrs.	None
Develoment Schedule (w/life test)	None	> 2.5 yrs.	~ 3 yrs.	> 5.5 yrs.	> 2.5 yrs.	None
Development Cost ($M)	Small	$17.9M	$10M	$19.5M	$17.9M	Small

Table 12: Comet Rendezvous Summary Performance Matrix

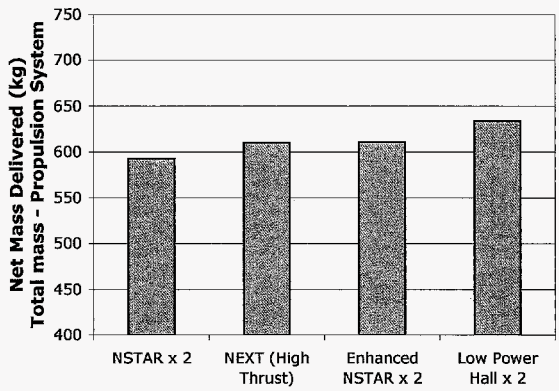

Figure 18: Delivered Mass, Comet Rendezvous

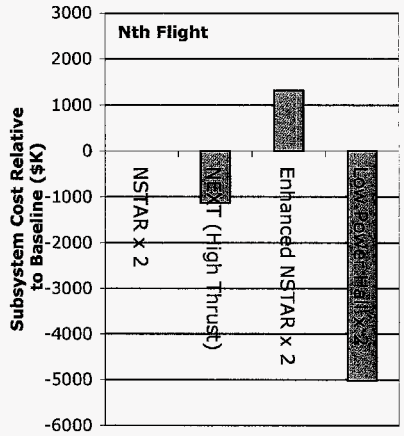

Figure 19: N^{th} Flight Cost Comparison, Comet Rendezvous ($FY05)

All proposed SEP systems offer a relatively small mass advantage over the SOA. The Hall system also offers considerably lower n^{th} flight cost, while NEXT offers a moderate cost savings and requires only one thruster rather than the two thrusters used in the other options. The Enhanced NSTAR offers only a slight mass advantage and

costs more than the SOA system, so it is not considered applicable for this mission. As with the previous two missions, qualification costs exceed the nth flight cost savings shown above, resulting in unattractively high first flight costs on this mission. This represents a significant barrier to the implementation of these technologies on Discovery missions.

D. General Observations

In the previous section, two general observations were made about the overall performance of EP systems for SEP missions.

- In general, the best mass performance comes from EP systems that best utilize available solar array power.
- EP systems that operate with high efficiency at low power can greatly benefit Discovery class missions

These qualitative findings were made in the context of specific missions (the Near Earth Asteroid and Vesta-Ceres rendezvous). To better understand the relationship between system performance and array power, a series of optimized trajectories were run at different powers on a separate model main belt asteroid mission. The model mission is also a Vesta-Ceres rendezvous, but to simplify the analysis, the Mars gravity assist is *removed* and the optimizer is allowed to select the launch and arrival dates. The resulting mission is notional and is intended to clarify governing relationships. The trajectories were optimized using SEPTOP, were constrained to an 8.5 year flight time and use a Delta 2925H launch vehicle. Figure 20 shows total delivered mass as a function of array power for a series of different EP options. The "final mass" in this case includes the mass of the EP system. Also shown in black is a notional ion performance curve that is created empirically from the performance data.

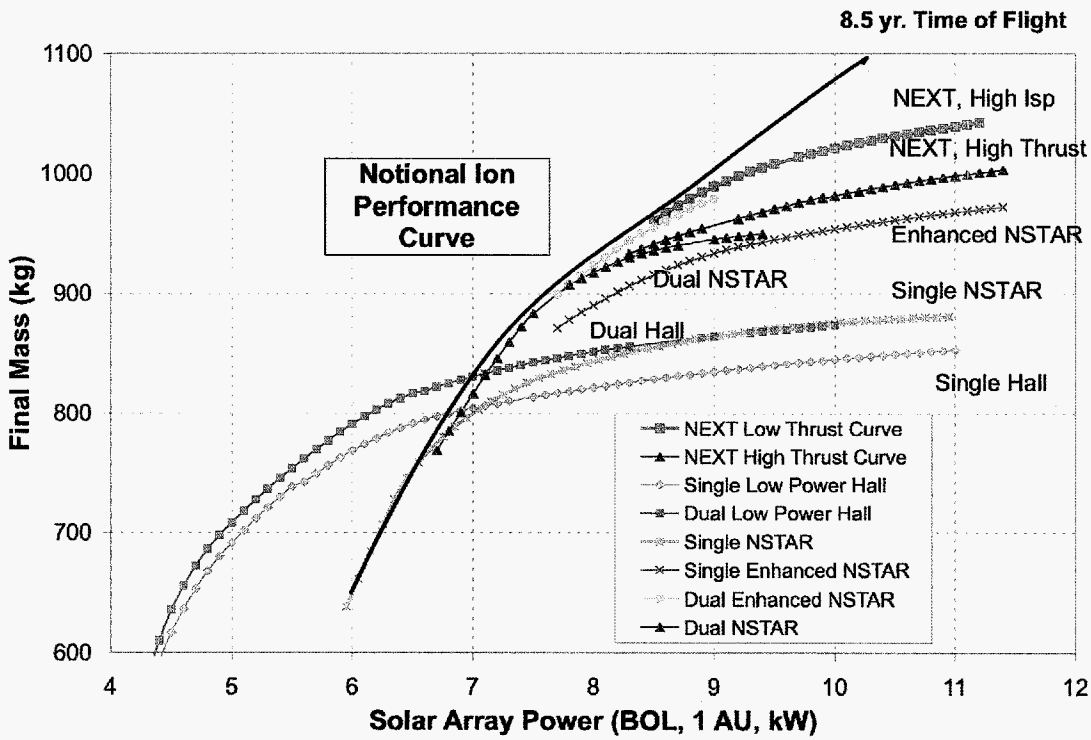

Figure 20: Final Mass vs. Solar Array Power, Notional Main Belt Asteroid Mission

In general, for low power operation, delivered mass increases rapidly with array power then transitions to a flatter region at high power. The location of the transition varies directly with the maximum allowable PPU input power. As array power increases, the delivered mass increases until it reaches a point where the PPU input is saturated and the EP system is no longer able to take advantage of extra power from the array. The ion systems have similar low and mid power efficiency curves, so their performance overlaps until the PPU input is saturated. Beyond this point, the performance curves flatten and the delivered mass is primarily a function of maximum PPU input power. The

black line in Figure 20 corresponds to an empirically derived "ion performance curve" corresponding to the mass delivered by an ion thruster system that has no maximum power limit. The ion thruster systems follow this curve until the PPU input is saturated and then transition to a plateau region. These results show how EP systems that best utilize available solar array power deliver the most mass at higher array powers. The choice of specific impulse also influences delivered mass, but this influence is secondary compared to the thruster's min/max power range.

The mass vs. power performance curves for the Low Power Hall system shows the influence that efficient low power operation has on delivered mass. The ion systems deliver more mass above 7 kW, but their performance falls off rapidly with reduced array power while the Hall system continues to offer reasonable performance below 5 kW. The higher performance is due to the Hall system's relatively high efficiency when operating far away from the sun. At higher powers, Hall systems operate less efficiently than ion, so their performance is not as good. With heavier spacecraft, it is necessary to use a larger solar array and an EP system with a higher maximum power to meet mission requirements. However, the Hall system offers better performance with smaller spacecraft and small solar arrays, which is highly desirable for cost-capped missions. This result shows how EP systems that operate with high efficiency at low power benefit small missions by enabling the use of smaller solar arrays, significantly lowering the cost of these missions.

Table 13 provides a matrix showing the applicability of each proposed technology to the Discovery missions analyzed in this study as well as to larger missions considered in other studies.[8,9] Applicability is defined as a combination of performance and n^{th} flight cost, and the mission is marked "applicable" if the technology either provides a performance benefit or a cost benefit compared to the SOA. As discussed previously, adding qualification costs to the nth flight cost significantly reduces the range of application for each technology. The low power hall system is marked as "possibly cost enabling" because the magnitude of the cost savings may be large enough to enable use of electric propulsion on some missions that would otherwise be cost-limited to chemical propulsion.

	"Discovery" (< 10 kW)			"New Frontiers" (< 18 kW)			Larger Missions (> 20 kW)	
	Vesta-Ceres RV	Near-Earth Asteroid	Comet RV	Titan Lander (Notional)	Comet Surface Sample Return	Jupiter Polar Orbiter	Titan Explorer	Neptune Orbiter
BOL Array Power	9 kW	6 kW	9 kW	6 kW	15 kW	15 kW	~ 30 kW	~ 30 kW
NSTAR, 1 thruster	X	X						
NSTAR, multi-thruster		X	X	?				
Low Power Hall Thruster	XX	XX	XX	?				
Enhanced NSTAR	X	X		?	(X)			
NEXT Low Power Update	X	X	X	X	X		X	X

XX = Possibly Cost Enabling
X = Applicable
(X) = Possibly Applicable
Red = Not Applicable
? = Not evaluated
Gray = Not Designed for this Application

Table 13: [General Application Matrix]

IV. Conclusions

A detailed study has been conducted to examine the potential benefits that advanced electric propulsion (EP) technologies offer to the competitively awarded, cost-capped missions in NASA's Discovery program. The study looked at the cost and performance benefits provided by three EP technologies currently proposed or in development through NASA's In-Space propulsion (ISP) program on three straw man Discovery class missions and compares their performance to a state of the art system using the NSTAR ion thruster. The different propulsion technologies/mission scenarios considered are shown in Table 1. Because cost is a major driver for competed missions, a detailed electric propulsion subsystem cost model was used to conduct a cost-benefit analysis for each option. Development, qualification and recurring costs were all considered in the study.

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. The electric propulsion cost model was used to calculate the total cost of the propulsion system and where appropriate the cost of the solar array was also calculated and incorporated into a comparison of the relative costs each option. Based on the results, the following general conclusions have been reached about each of the proposed EP technologies.

- Low Power Hall offers very significant performance and cost benefits to Discovery class missions. However, this technology is relatively immature (TRL 3), and further investment is required to determine if the technology can achieve its performance and cost goals.

- The NEXT thruster offers moderate performance and noticeable cost benefits to Discovery class missions vs. dual NSTAR systems. It also offers strong performance benefits vs. single NSTAR systems.

- An Enhanced NSTAR thruster using carbon-carbon based ion optics and components from the NEXT subsystem development offers moderate performance and cost benefits to Discovery class missions with relatively moderate total subsystem development costs.

It has also been found that for many missions, the increased throughput capability for the proposed EP technologies reduces the number of thrusters required to conduct the mission, leading to the following finding.

- Discovery class missions will generally benefit from increased xenon throughput capability offered by the proposed EP technologies.

In addition, two important conclusions have been reached about the cost of EP subsystems and the improvements needed to increase their application to cost capped missions.

- Lower subsystem costs, particular Power Processing Unit (PPU) and Digital Control and Interface Unit (DCIU) costs, are needed for ion thruster systems.

The proposed Low Power Hall system carries a significantly lower n^{th} flight cost than the ion thruster systems, primarily because of lower PPU and DCIU costs associated with the subsystem. The NSTAR DCIU costs over $1.3 million per a flight unit, and both primary and redundant units are required for a flight system, while the Hall system requires no DCIU. Future ISP development efforts should consider incorporating DCIU functions into other units to lower the cost of ion thruster systems.

- First flight qualifications costs are a significant barrier to implementation of new SEP technologies on Discovery missions.

With the current structure of ISP's development programs, significant qualification costs are borne by the first flight mission using a new EP technology. The qualification cost generally exceeds the hardware and subsystem cost benefit brought by the new technology, leaving the first program no financial incentive to adopt a technology that will benefit future missions. This problem can be addressed programmatically by lowering qualification costs, perhaps by incorporating qualification testing into the subsystem technology development program or procuring flight qualification units as part of the development program. It can also be addressed by allowing/creating cost sharing arrangements that fund the flight qualification effort outside the mission cost-cap limit.

Finally, two observations have been made regarding the general performance of EP systems on solar electric propulsion (SEP) missions.

- In general, the best mass performance comes from the EP systems that best utilize available solar array power.

When excess array power is available, thrusters with the widest PPU input power range generally perform the best because they can convert more of the available electrical power into kinetic energy over the course of the mission. The choice of specific impulse also influences delivered mass, but this influence is secondary compared to the thruster's minimum-maximum power range.

- EP systems that operate with high efficiency at low power can greatly benefit Discovery class missions.

Low power performance is useful for Discovery missions because these missions are cost limited, so the solar array is generally made as small as possible to lower program costs. This results in missions with extended periods of low power operation. The proposed Low Power Hall system operates at much higher efficiency and at lower power than the ion systems. As a result, it offers significant performance and cost benefits to some Discovery missions. In particular, the device's relatively high thrust at low power enables it to accomplish a Dawn-like Vesta-Ceres rendezvous using a solar array that is 20% smaller than the ion systems.

It should be noted that this study uses straw man missions derived from current mission concepts that use the state-of-the-art NSTAR ion thruster. Discovery missions cover a wide range of scientific goals, so these missions do not encompass the full range of possible destinations and challenges. Principal investigators are continually asking for more challenging missions within the Discovery program, and advanced electric propulsion technologies may enable a class of missions more challenging than those considered in this study.

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References

[1] "Dawn Fact Sheet," http://www.orbital.com/NewsInfo/Publications/Dawn_fact.pdf, FS006-02, Orbital Sciences Corporation, Dulles, VA.

[2] Brophy, J. et al. "Status of the Dawn Ion Propulsion System," AIAA-2004-3433, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, FL, July 2003.

[3] Patterson, M.J., et al., "NEXT: NASA'S Evolutionary Xenon Thruster Development Status," AIAA Paper No. 2003-4862 (July 2003).

[4] Snyder, J.S. and Brophy, J.R. "Performance Characterization and Vibration Testing of 30-cm Carbon-Carbon Ion Optics," AIAA 2004-3959, 40th Joint Propulsion Conference, Fort Lauderdale, FL, July 2004.

[5] Witzberger, K. and Manzella, D. "Performance of Solar Electric Powered Deep Space Missions Using Hall Thruster Propulsion," AIAA 2005-4268, 41st Joint Propulsion Conference, Tucson, AZ, July 10-13, 2005.

[6] Whiffen, Gregory J. and Jon A. Sims, "Application of a Novel Optimal Control Algorithm to Low-Thrust Trajectory Optimization," AAS paper 01-209, AAS/AIAA Space Flight Mechanics Conference, San Antonio, TX, USA, 27-30 January 2003.

[7] Nilsen, E. and Weissman, P. "Odyssey – A Comet Nucleus Orbiter," Aerospace Conference, 2001, IEEE Proceeedings. Vol. 1, March 10-17 2001, pp. 1/397-1/402.

[8] Witzberger, K., Benson, S., Manella, D., Oh, D., Brophy, J. and Cupples, M. "NASA's 2004 In-Space Propulsion Re-Focus Studies for New Frontiers Class Missions," AIAA-2005-4271, 41st Joint Propulsion Conference, Tucson, AZ, July 10-13, 2005.

[9] Oleson, S., Gefert, L., Benson, S., Patterson, M., Noca, M. and Sims, J. "Mission Advantages of NEXT: NASA's Evolutionary Xenon Thruster," AIAA-2002-3969, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference," Indianapolis, IA, July 7-10, 2002.

Evaluation of Solar Electric Propulsion Technologies for Discovery Class Missions

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A detailed study examines the potential benefits that advanced electric propulsion (EP) technologies offer to the cost-capped missions in NASA's Discovery program. The study looks at potential cost and performance benefits provided by three EP technologies that are currently in development: NASA's Evolutionary Xenon Thruster (NEXT), an Enhanced NSTAR system, and a Low Power Hall effect thruster. These systems are analyzed on three straw man Discovery class missions and their performance is compared to a state of the art system using the NSTAR ion thruster. An electric propulsion subsystem cost model is used to conduct a cost-benefit analysis for each option. The results show that each proposed technology offers a different degree of performance and/or cost benefit for Discovery class missions. However, lower subsystem costs, particular power processing and digital control interface unit costs, are needed for ion thruster systems to make them more competitive for cost-capped mission. It is also observed that the best mass performance generally comes from EP systems that best utilize available solar array power over the course of the mission. Finally, first flight qualification costs are identified as a significant barrier to the implementation of new EP technologies on cost-capped missions.

I. Introduction

The Dawn spacecraft is the first purely scientific mission to be powered by solar electric propulsion (SEP) and demonstrates the benefit that SEP can bring to the competitively awarded, cost-capped missions in NASA's Discovery program.[1] Dawn's primary propulsion system is based on the NSTAR thruster, a 30 cm diameter ion thruster that was flight demonstrated on Deep Space 1. This paper examines the benefits that several next generation EP technologies could have for Discovery class missions. The new technologies considered in this study are all currently proposed or in development through NASA's In Space Propulsion program. They are:

- NSTAR: 30 cm ion thruster subsystem, previously flown on Deep Space 1, representing the current state of the art in electric propulsion for deep space missions.[2]

- NASA's Evolutionary Xenon Thruster (NEXT): 6 kW ion thruster subsystem currently under development by a joint government-industry-academia team including members of NASA Glenn Research Center (GRC), the Jet Propulsion Laboratory (JPL), Aerojet-Redmond, L3 Communication Electron Technologies Inc. (ETI), the University of Michigan, Colorado State University (CSU), and the Applied Physics Laboratory (APL).[3]

- Enhanced NSTAR: a proposed improvement to the existing NSTAR subsystem using a combination of carbon based ion optics (CBIO) currently under development by a team included members of JPL, L3 ETI, and CSU and a high power processing unit (PPU) developed through the NEXT program.[4]

- Low Power Hall: a proposed Hall thruster subsystem that operates efficiently at low power with enhanced throughput capability currently under development by a team including members of GRC, Aerojet, JPL and the University of Michigan.[5]

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Discovery missions are selected competitively and cover a wide range of scientific goals and destinations. For this study, three straw man missions are selected and evaluated using each SEP technology. Although the destinations are generic, they are similar to current and proposed Discovery class missions that utilize electric propulsion. The primary focus of this study is on the improvements that advanced technologies bring compared to a state of the art NSTAR SEP system. The straw man missions selected for this study are:

- Vesta-Ceres Rendezvous mission (based on Dawn)
- Near-Earth Asteroid Sample Return Mission (targeting Asteroid Nereus)
- Comet Rendezvous Mission (targeting Comet Kopff)

Because cost is a major driver for competed missions, a detailed electric propulsion subsystem cost model is used to conduct a cost-benefit analysis for each option. The model is similar to the electric propulsion subsystem cost model used by JPL's Advanced Projects Team ("Team X") and generates a full cost that includes component costs, labor and integration, subsystem engineering, fabrication, assembly, testing, ground support, and launch operations. Development, qualification and recurring costs are all considered in the study. Where relevant, the cost of the spacecraft's solar array is also considered in the analysis at a specific cost of $1000/W.

The technology/mission matrix in Table 1 shows the different propulsion technologies/mission scenarios considered in this study.

	Near-Earth Asteroid	Comet Rendezvous	Dawn (w/Gravity Assist)
NSTAR, 1 thruster	X		X
NSTAR, 2 thruster	X	X	
NEXT	X	X	X
Enhanced NSTAR w/NEXT Components	X	X	X
Low Power Hall Thruster	X	X	X

Table 1: Study Mission-Technology Matrix

For each scenario, a launch date is chosen and a low thrust trajectory optimizer is used to calculate the flight time, xenon propellant consumed and the total mass delivered to the final destination. The size of the propulsion system is determined from the xenon throughput and a "net mass delivered" is calculated by subtracting the mass of the propulsion system from the total delivered mass. The electric propulsion cost model is used to calculate the total cost of the propulsion system. Where appropriate, the cost of the solar array is also calculated and incorporated into a comparison of the relative costs of each option. The cost and mass results are compared to show the relative cost/benefits for each technology-mission combination and an application matrix is generated showing valid mission options. The application matrix includes results from this study and from other studies conducted on larger missions. Finally, technology readiness level (TRL) and development costs are considered to reach several broad conclusions on the relative benefit of each technology for Discovery missions.

The thruster performance, mass, and cost models used in this study are described in section II. Trajectory and mission analysis assumptions and results are described in section III, and overall conclusions are described in section IV.

II. Methodology and Assumptions

A. Thruster Performance Model

For each propulsion technology, a performance model was created and used to calculate thrust and propellant mass flow rate as a function of input power to the PPU. The model is derived from throttle tables provided by technologists and the source for the throttle table varies depending on the maturity of the technology. For the NSTAR thruster, the throttle table is based on Deep Space 1 flight data and is the same throttle table currently used for mission planning on the Dawn program. For NEXT, two throttle tables, a high thrust option and a high specific impulse option, are derived from laboratory data generated using an engineering model thruster. For Enhanced NSTAR, the throttle table is derived from laboratory data taken using carbon-based optics with a laboratory thruster-cathode model. The Low Power Hall throttle table is derived from theory and not based on laboratory data.

Polynomials are fitted to each table to generate expressions for thrust and mass flow as a function of power. Table 2 shows the resulting polynomial coefficients. The overall system efficiency and specific impulse (I_{sp}) can be derived from these expressions and is shown in Figure 1 and Figure 2. Table 3 shows the allowable operating range for each option.

System	Table Name	Mass Flow Coefficients A	B	C	D	E
NSTAR	Q-Mod	0.36985	-2.5372	6.2539	-5.3568	2.5060
NEXT	Table 9A High Thrust	0.0153	-0.2832	1.660	-2.621	3.131
NEXT	Table 9A High Isp	-0.00602	0.07637	-0.1898	0.1768	1.944
Enhanced NSTAR	Table 1d.1	-0.01647	0.15774	-0.5941	1.5665	0.3594
Low Power Hall	Table 1	0.00000	0.07988	-0.61355	2.4888	0.6131
System	**Table Name**	**Thrust Coefficients A**	**B**	**C**	**D**	**E**
NSTAR	Q-Mod	5.145602	-36.720293	90.486509	-51.694393	26.337459
NEXT	Table 9A High Thrust	0.1102	-2.234	12.93	11.88	16.8
NEXT	Table 9A High Isp	-0.1889	2.926	-14.02	52.32	-0.08954
Enhanced NSTAR	Table 1d.1	0.2340	-1.5554	0.8267	38.4804	-2.2822
Low Power Hall	Table 1	0.0000	0.73434	-5.9528	51.1473	4.0924

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

$$T\ [\text{mN}] = A(P\ [\text{kW}])^4 + BP^3 + CP^2 + DP + E$$

Table 2: Throttle Curve Coefficients

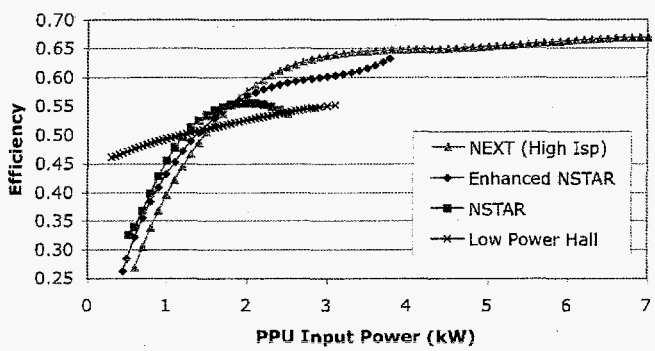

Figure 1: Propulsion Subsystem Efficiency vs. PPU Input Power

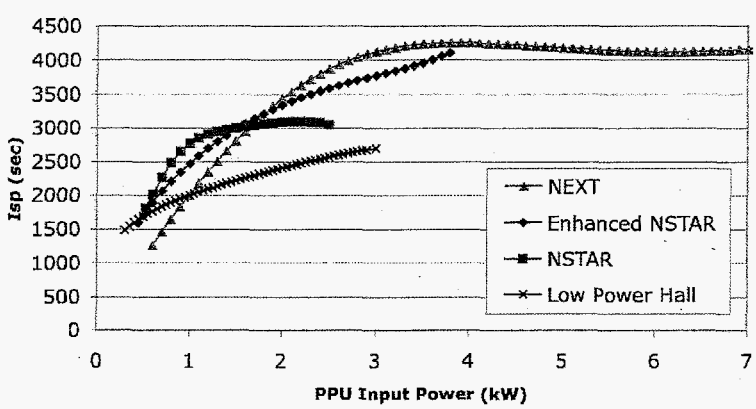

Figure 2: Specific Impulse vs. PPU Input Power

	TRL	Minimum Power	Maximum Power
NSTAR	9	525 W	2.6 kW
NEXT	5	620 W	7.3 kW
Enhanced NSTAR	4	450 W	3.8 kW
Low Power Hall Thruster	3	330 W	3.0 kW

Table 3: Thruster Characteristics Summary

The three ion thruster options have similar efficiency curves at low power but very different operating ranges. The NEXT thruster has the widest power range and at high power operates at the highest efficiency of any of the devices. The high thrust and high I_{sp} throttle curves for NEXT have the same operating range. Both NEXT throttle curves are evaluated for each mission, but only the best performing option is reported in this paper. The Enhanced NSTAR operates at input powers as low as 450 W, but with relatively low efficiency. The Hall thruster operates very efficiently at low power, but does not operate as efficiently as ion thrusters at higher power. This behavior is typical for Hall thrusters and will be shown to significantly benefit power limited missions.

B. Mass Assumptions

Hardware mass is technology dependent and is a function of xenon throughput, the number of thrusters and the number of PPU's required for each mission. A subsystem mass model is used to calculate propulsion dry mass based on mission requirements and unit level masses provided by technologists. Contingency margin is added in a manner consistent with standard JPL design principals that apply mass margins that vary with unit maturity ranging between 2% for "build-to-print" hardware and 30% for new designs. The result is an overall subsystem margin that varies from 10% for NSTAR to 30% for NEXT and Low Power Hall. Xenon tank mass is calculated as a fixed fraction of xenon propellant mass to allow direct comparison of propulsion hardware. Five percent fuel mass margin is added to account for navigation and trajectory errors. Additional fuel is added to account for residuals in the tank and feed system.

The subsystem mass breakdown is shown in Table 4. The inputs selected for this table (shown as shaded regions) are generic, but typical of trends observed in the detailed analysis. The advanced thrusters have greater throughput capability than NSTAR and typically require fewer thrusters to meet mission requirements. The NEXT feed system is unique and is modeled as having somewhat smaller system residuals. The ion systems use redundant Digital Control and Interface Units (DCIUs) to provide command and telemetry interfaces, control the gimbals, and actively regulate xenon flow rates. The Hall system requires no DCIU and incorporates flow control functions into the PPU and gimbal control into the spacecraft command system. This distribution of functions is typical for commercial Hall systems and improves the system's mass and cost. The difference in control architecture is somewhat arbitrary, but partially reflects differences in the operation of Hall and ion thrusters. With ion thrusters, the flow controller regulates separate discharge and neutralizer cathodes and typically closes the loop around temperature and pressure sensors associated with the feed system. This requires the use of redundant pressure sensors and makes the control logic relatively complex. With Hall thrusters, the flow controller regulates only one cathode and closes the loop around the discharge current, making it relatively easy to incorporate the control logic into the PPU. The gimbal control electronics increase the mass and cost of the spacecraft command distribution system, a penalty that is included in this analysis. It may be possible to improve the mass and cost of ion systems by similarly incorporating flow control functions into the PPU.

Thruster	NSTAR Baseline	Enhanced NSTAR	NEXT	Low Power Hall
Inputs				
Number of Engines	3	2	2	2
Number of PPU's	3	2	2	2
Number of DCIU's	2	2	2	0
Xenon Throughput (kg)	200	200	200	300
Xenon Contingency				
Navigation and Trajectory Errors	5%	5%	5%	5%
Residuals	5.0%	5.0%	3.6%	5.0%
Assumptions				
Mass per Thruster	8.2	7.39	12.4	3.6
Mass per PPU	13.9	17.6	26	8.4
Mass per DCIU	5.7	5.7	5.7	0.0
Mass per Gimbal	4.6	4.6	5.0	4.6
Gimbal Drive Electronics	included	included	included	2.0
Feed System				
Fixed Mass	8.1	8.1	2.2	4.0
Additional mass/engine	3.3	3.3	4.1	1.0
Xenon Tank Mass Fraction	4.5%	4.5%	4.5%	4.5%
System Contingency	10%	18%	30%	30%
Calculations				
Thrusters	24.6	14.8	24.8	7.2
PPUs	41.7	35.2	52.0	16.8
DCIUs	11.3	11.3	11.3	0.0
Xenon Feed System	18.1	14.7	10.4	6.0
Xenon Tank(s)	9.9	9.9	9.8	14.9
Gimbals	13.9	9.3	10.0	11.3
Subsystem Dry Mass	**120**	**95**	**118**	**56**
Xenon Residuals	20.0	20.0	17.2	30.0
Hardware Mass Contingency	12.0	17.1	35.5	16.8
Propulsion System Mass (w/Contingency)	**151**	**132**	**171**	**103**
Mass Delta	**Baseline**	**-13%**	**+13%**	**-32%**

Table 4: Electric Propulsion Unit Mass Assumptions

Note: masses shown are current best estimates as of September 2004

C. Costing Methodology

Cost is a major consideration in the design of Discovery class missions and is a major driver in the decision whether or not to use electric propulsion on a given mission. A detailed EP subsystem cost model is used to estimate the relative cost of each option. The model is based on a combination of flight mission actual costs, flight mission estimates, and cost estimates provided by technologists. Four types of cost estimates were generated for this study:

- *Development cost*: cost to develop the subsystem from its current development status (as of August 2004) to technology readiness level (TRL) 6, where the subsystem has been demonstrated in relevant environments.
- *Qualification cost*: cost to develop the subsystem from TRL 6 to a fully flight qualified design
- *Non-Recurring cost*: cost of post-qualification engineering, data, and drawings for the first flight units.
- *Recurring cost*: cost of first/second/third/fourth flight units.

Development and qualification costs were estimated at a subsystem level while non-recurring and recurring costs were estimated at a unit level. The unit costs serve as inputs to a quasi-grass root cost model developed by JPL's Advanced Projects Team ("Team X") that is derived from actual costs incurred and projected on the Deep Space 1 and Dawn missions. The model accounts for component costs, spare parts, labor and integration, subsystem engineering, design and analysis, engineering procurement support, fabrication assembly and test, ground support and launch operations, xenon tanks and gas, and harness manufacturing. The output from the model is combined with the development and qualification cost estimates to provide three outputs:

- Development cost: cost to develop the subsystem from its current development status to TRL 6
- First Flight Cost: sum of subsystem qualification, non-recurring, and recurring costs
- N^{th} Flight Cost: sum of subsystem non-recurring and recurring costs

The unit recurrent and non-recurring cost estimates used in this study are shown in Table 5. The NSTAR values are derived from, but not the same as, Deep Space 1 and Dawn actual costs as of May 2004. They represent the projected cost of these units for the next flight mission build. The NEXT, Enhanced NSTAR, and Hall values are estimates provided by technologists, based on vendor data when available. The inputs selected for this table (shown as shaded regions) are generic, but typical of trends observed in the detailed analysis.

Thruster	NSTAR Baseline	Enhanced NSTAR	NEXT	Low Power Hall
Inputs				
Kg of Xenon	300	300	300	400
Number of Engines	3	2	2	2
Number of PPU's	2	2	2	2
Number of DCIU's	2	2	2	0
Component Cost Assumptions				
Recurring Cost / Thruster	580	580	800	250
Recurring Cost / PPU	1520	1900	1976	800
Recurring Cost /DCIU	1310	1310	1310	0
Recurring Cost / Gimbal	325	325	325	325
Recurring Cost / Xenon tank	450	450	450	450
Fixed Cost / Feed System	1610	1610	1610	1610
Per Thruster Cost / Feed System	200	200	200	200
Non-Recurring / Thruster ($K)	130	250	250	50
Non-Recurring / PPU	200	200	200	200
Non-Recurring / DCIU	0	0	0	0
Non-Recurring / Xenon tank	0	0	0	0
Non-Recurring / Gimbal	510	510	510	1010
Design & Qual new Xenon Tank	0	0	0	0

Table 5: Recurring Cost Assumptions ($FY05 K)

The costs shown in Table 5 comprise a substantial fraction of the total cost of a flight electric propulsion system. Several general observations can be made based on these values. In general, units associated with the Hall system cost considerably less than equivalent units associated with the ion systems. Some of this cost difference may be due to the relative lack of maturity of the Hall estimates, which carry greater uncertainty because the design is conceptual and the hardware is at a relatively low TRL (see Table 3). It should be noted, however, that the Hall units costs reported in Table 5 are consistent with the costs of existing commercial Hall systems.

PPU costs vary widely and are a key differentiator when comparing EP systems. For purposes of this analysis, we are assuming that the recurring cost of the next NSTAR flight PPU will be about half of the cost of the Dawn units, but there is considerable uncertainty in this value. The DCIU costs over $1.3 million per flight unit and also has a significant impact on overall subsystem cost. This is one reason the proposed Hall systems are generally less expensive than the ion options. As discussed in the previous section, the Hall system has no DCIU. The cost to incorporate DCIU functions into other units is incorporated into the Hall PPU and the gimbal non-recurring cost. The recurring cost of the feed system is difficult to estimate because it includes component costs incurred at the subsystem level and assembly/integration costs incurred at the spacecraft level. For this analysis, the cost of a fully integrated NSTAR feed system is used in every case. This assumption is conservative because the NEXT and Hall feed systems incorporate design features that are expected to make them less expensive than the NSTAR feed system. Thruster costs also vary widely, but because the cost of the thrusters is relatively small compared to other units, the nth flight cost is largely driven by PPU and DCIU costs. Based on this observation, we draw the following conclusion.

- The PPU and DCIU unit costs are major cost drivers for electric propulsion systems

Feed system costs may also be a major cost driver, but are not evaluated in this study. The development cost estimated for each subsystem is shown in Table 6. These costs are for single string systems and do not include the cost of multi-thruster testing. The development costs were provided by technologists and contain considerable

schedule and cost uncertainty. They are reported in FY05 dollars and represent cost to complete development as of September 2004. Previously expended funds are not reported. These estimates are of varying fidelity, have not been independently reviewed or compared to historical data, and should be treated as rough order of magnitude values. It is assumed that qualification costs are be paid by the first flight program while development costs are paid by the In-Space Propulsion program. This is consistent with the current financial structure of these programs.

Thruster	SOA NSTAR	Enhanced NSTAR	NEXT	Low Power Hall
Component Cost Assumptions				
Development (to TRL 6) / Thruster	0	3000	7050	7000
Qualification / Thruster	0	1200	2200	2200
Development (to TRL 6) / PPU	0	3800	2280	3500
Qualification / PPU	0	1500	1600	1500
Development (to TRL 6) / DCIU	0	0	1000	0
Qualification / DCIU	0	0	400	0
Development (to TRL 6) / Gimbal	0	0	400	400
Qualification / Gimbal	0	0	800	800
Development (to TRL 6) / PMS	0	0	660	2600
Qualification / PMS	0	0	1000	1000
System Integration Tests (1)		500	500	500
Development cost (to TRL 6)	0	7300	11890	14000
Qualification cost (after TRL 6)	0	2700	6000	5500
Total EP subsystem costs in $k	**0**	**10000**	**17890**	**19500**

Table 6: Technology Development Costs Estimates ($FY05 K), Single String Only

This study focuses on the cost of the electric propulsion system. In most cases, the missions compared have the same flight time and solar array power, so changing the propulsion system has relatively little impact on the overall cost of the mission. When solar array power is varied, a generic cost of $1000/W is used for the power system. This value is representative of rigid solar arrays using existing cell technology. There are also costs associated with the accommodation of multiple thrusters into the spacecraft configuration. These costs are not included in our analysis.

III. System Analysis Results

Discovery missions are selected competitively and cover a wide range of scientific goals and destinations. Three straw man 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. The result's general implications are discussed and some mission specific findings are provided. Additional general findings are given in the final section of this paper.

A. Near Earth Asteroid Mission

The first mission considered is a Near Earth Asteroid sample return mission. The spacecraft launches directly to a positive C_3 Earth escape trajectory and uses SEP to rendezvous with the asteroid Nereus. It remains in the asteroid's vicinity for 90 days before using SEP to return to Earth and conduct a flyby as it releases the sample for direct entry. The basic characteristics of this mission are shown in Table 7.

Near Earth Asteroid Sample Return	
Target Body	Nereus
Launch Vehicle	Delta 2925
Power System	6 kW solar array at 1 AU
Bus Power	300 W
Duration	3.3 years
ΔV	4.5 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 7: Near Earth Asteroid Sample Return Mission Characteristics

A separate optimized trajectory is generated for each scenario using SEPTOP, a well-known low thrust optimization tool. 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. As shown in Table 8, the entry velocity varies from 13.6 to 14.9 km. By comparison, the entry velocity for the Stardust mission will be approximately 12.6 km/s. Higher entry velocities require a heavier and more expensive thermal protection system (TPS). Variations in the mass and cost of the TPS are not accounted for in this analysis. The overall results are summarized in Table 8 and net delivered mass is shown in Figure 3. Net delivered mass is defined as total end-of-mission delivered mass minus the mass of the electric propulsion system. It includes the payload, solar arrays, Earth return vehicle, and main spacecraft bus. Both single and multi-thruster operation are considered. All options carry an extra thruster and power processing unit for redundancy. In some cases, an extra thruster is also required to meet xenon throughput requirements.

	Single NSTAR	Single NSTAR Enhanced	Single Low Power Hall	Single NEXT (High Isp)	Dual NSTAR	Dual Hall
Mission						
Launch Vehicle	Delta 2925	Delta 2925	Delta 2925	Delta 2925	Delta 2925	Delta 2925
Trip Time (yrs.)	3.25	3.20	3.15	3.18	3.16	3.14
C_3(km^2/s^2)	11.8	7.1	4.2	1.8	2.2	1.8
Power (1 AU, BOL)	Baseline 6 kW	Same (3)	Same	Same	Same	Same
Net Payload Mass Delivered (kg)	**542**	**674**	**712**	**772**	**746**	**793**
Launch Mass (kg)	1010	1115	1183	1245	1235	1245
Xenon Propellant Throughput (kg)	194	174	238	167	198	203
Net Trajectory Mass Capability (kg)	677	801	805	938	897	903
Propulsion Subsystem Mass (kg)	135	127	93	166	151	110
Free Space Delta-V (km/s)	6.50	6.34	5.85	5.61	5.27	4.65
Entry Velocity (km/s, approximate)	14.9	14.9	14.3	14.2	14.0	13.6
Configuration						
Simultaneous Operating Thrusters	1 thruster	1 thruster	1 thruster	1 thruster	2 thrusters	2 thrusters
Total Thrusters (Primary + Redundant)	3	2	2	2	3	3
Total PPU's (Primary + Redundant)	2	2	2	2	3	3
nth Mission Cost ($K)	**Baseline**	**-2,283**	**-5,277**	**-1,770**	**+1,529**	**-3,631**
First Mission Cost ($K)	**Baseline**	**+417**	**+223**	**+4,230**	**+1,529**	**+1,869**
Propulsion Subsystem Costs						
Recurring Cost ($K) (4)	Baseline	-2,283	-5,277	-1,770	+1,529	-3,631
Qualification Cost ($K) (5)	Baseline	+2,700	+5,500	+6,000	+0	+5,500
Development						
Maturity (TRL)	9	4	3	5	6	3
Development Schedule (TRL 6, no life test)	None	~1.5 yrs.	~ 4 yrs.	~1.5 yrs.	None	> 4 yrs
Develoment Schedule (w/life test)	None	~ 3 yrs.	> 5.5 yrs.	> 2.5 yrs.	None	> 5.5 yrs.
Development Cost ($M) (2)	None	$9.5M	$19M	$21M	Small	$19M

Table 8: Summary of Results, Near Earth Asteroid Mission

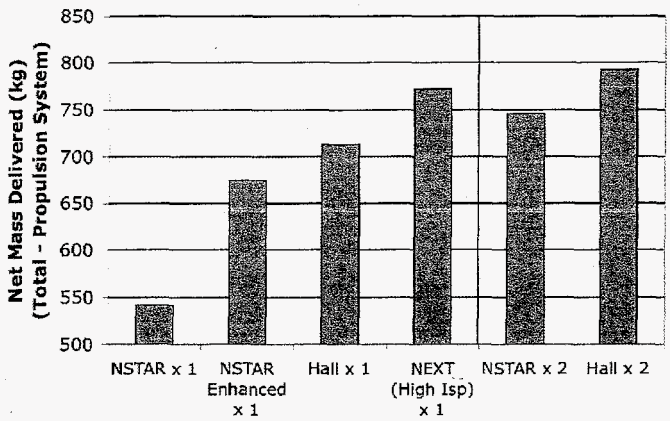

Figure 3: Net Mass delivered, Near Earth Asteroid

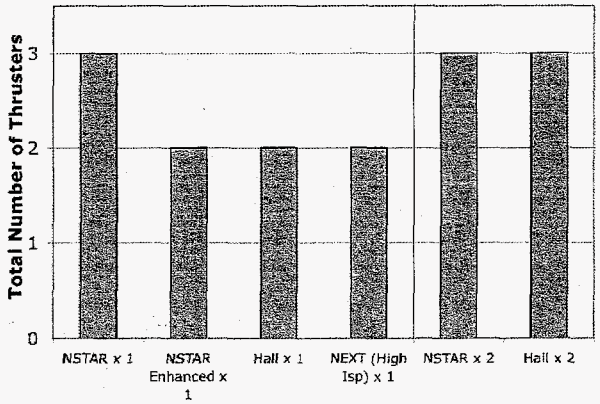

Figure 4: Total Thrusters Required, Near Earth Asteroid

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 the NSTAR thruster. Systems allowing multi-thruster operation are more complex and therefore have higher cost and propulsion system mass than single thruster equivalents. Figure 3 shows that the advanced EP technologies generally offer a considerable mass performance advantage over single NSTAR, but do not necessarily offer an advantage over dual NSTAR. This result is explained below in the discussion of Figures 5-10. Figure 4 shows the total number of thrusters required for each option. All options carry an extra engine for redundancy. The single NSTAR configuration requires the same number of thrusters as the dual NSTAR configuration because the mission's xenon throughput requirements exceed the capability of a single NSTAR thruster. The second thruster provides additional throughput and the third thruster provides redundancy. All of the proposed technologies require fewer thrusters in their single active thruster configuration.

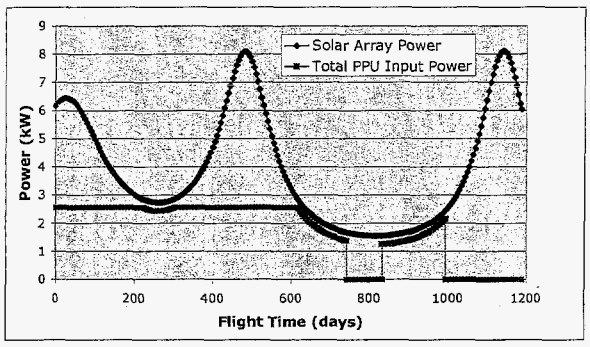

Figure 5: NEAR Power vs. Time
Single NSTAR Thruster
Delivered Mass: 540 kg

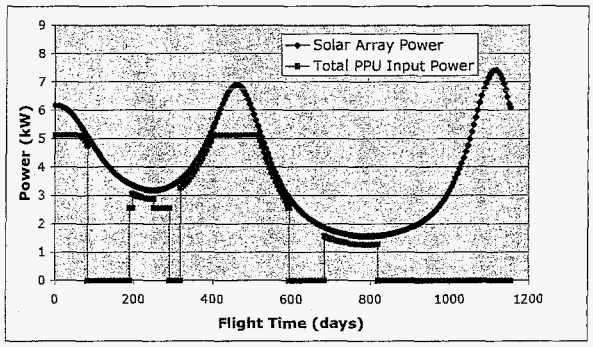

Figure 6: NEAR Power vs. Time
Dual NSTAR thruster
Delivered Mass: 740 kg

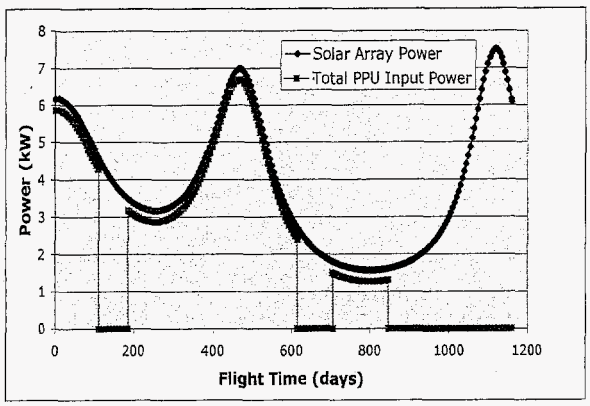

Figure 7: NEAR Power vs. Time
Single NEXT thruster
Delivered Mass: 770 kg

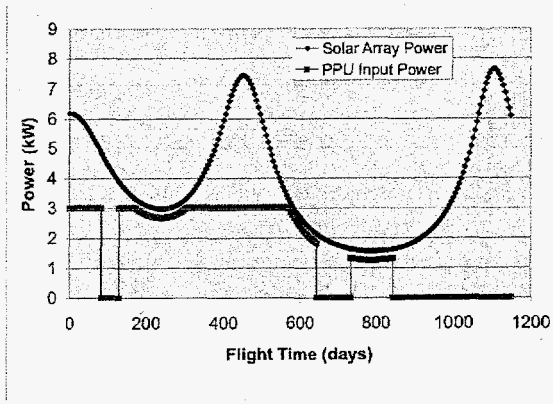

Figure 9: NEAR Power vs. Time
Single Low Power Hall thruster
Delivered Mass: 712 kg

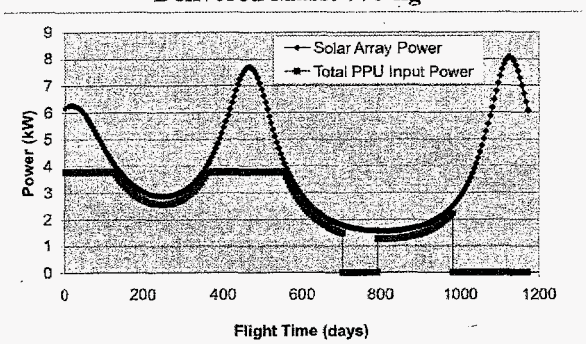

Figure 8: NEAR Power vs. Time
Single Enhanced NSTAR Thruster
Delivered Mass: 674 kg

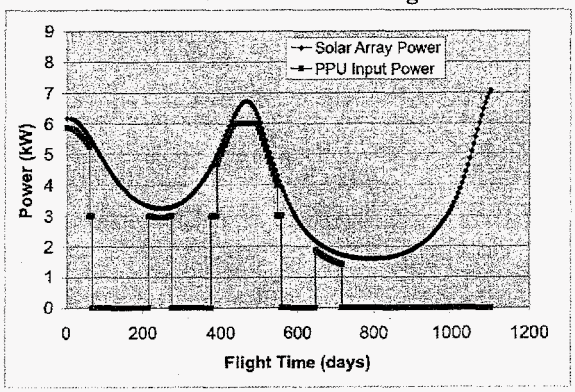

Figure 10: NEAR Power vs. Time
Dual Low Power Hall Thruster
Delivered Mass: 793 kg

Figure 5 shows the power vs. time history for both the array and the PPU for the single NSTAR option. The power generated by the array varies with distance from the sun, starting at 6 kW, dropping as low as 1.4 kW and peaking near 8 kW at the middle and end of the mission. The PPU's input power is limited by NSTAR's power handling capacity and a significant fraction of the array's capability is unused for much of the mission. Figure 7 shows the power vs. time history for the NEXT option. NEXT has a much higher peak input power, better utilizes the array near perihelion, and generates more thrust than NSTAR near perihelion. The higher thrust produces lower gravity losses and more efficient orbital maneuvers. This in turn results in a lower C_3, higher separated mass, and less onboard ΔV than the single NSTAR option. The dual NSTAR option shown in Figure 6 also uses the array more efficiently than single NSTAR and therefore delivers more mass. Enhanced NSTAR uses the array more efficiently than single NSTAR but less efficiently than dual NSTAR and its mass performance lies between these two cases. Based on these results, the following conclusion is reached.

- In general, the best mass performance comes from the EP systems that best utilize available solar array power.

This is a useful generalization that can be used as a guideline by EP system designers seeing to optimize mass performance on SEP missions. However, the system's efficiency as a function of power and the choice of specific impulse will also impact delivered mass capability. The influence of these factors is illustrated in Figure 9 and Figure 10. The single Hall system has roughly the same peak power as Enhanced NSTAR, but delivers somewhat more mass. This occurs because the Hall system operates at lower I_{sp} and generates higher thrust at aphelion and perihelion, lowering the total ΔV required for the mission. The net result is that the Hall system operates closer to this mission's mass optimum I_{sp}. The dual Hall system shown in Figure 10 delivers somewhat more mass than NEXT for the same reasons.

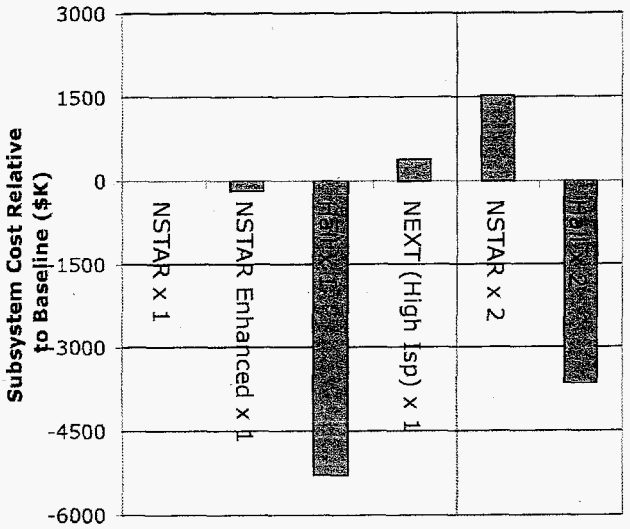

Figure 11: Nth Flight Cost Comparison, Near Earth Asteroid ($FY05)

Figure 11 shows nth flight costs calculated for the Near Earth Asteroid sample return mission. Although all systems offer a significant mass performance advantage over single NSTAR, only the Hall systems simultaneously offers a considerable cost advantage. The cost savings is quite significant for a mission of this size, equivalent to ~25% of the total cost of the subsystem. All of the systems offer considerable cost advantages over dual NSTAR and most require fewer thrusters to achieve similar mass performance. Comparing Figure 3 and Figure 11, we reach the following conclusions concerning the relative cost and benefits of each option.

- All proposed systems offer considerable mass advantage over single NSTAR system.
- Single Low Power Hall offers both significant cost and mass advantages over single NSTAR. It also offers superior mass performance over dual NSTAR at much lower cost.
- Dual Low Power Hall offers the highest mass performance of any option and still costs considerably less than a single NSTAR system.
- Enhanced NSTAR offers a significant mass advantage over single NSTAR and may offer a slight cost advantage.
- NEXT offers superior cost and mass performance to dual NSTAR. It has superior mass performance to single NSTAR, but at somewhat higher cost.

Figure 12 shows first flight costs for this mission. This includes the cost to qualifying the first set of flight hardware after it has been developed to TRL 6.

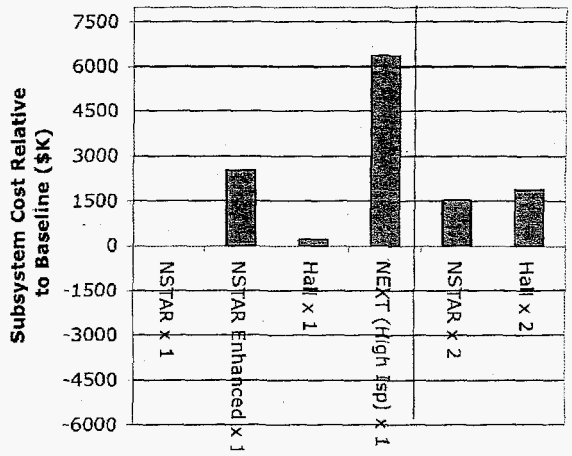

Figure 12: Qualification Cost Estimate, Near Earth Asteroid Mission

The qualification costs considerably increase the cost of the first flight system. Although the newer systems still offer a considerable mass advantage over single NSTAR, from the flight program's point of view, it is often less expensive to use a dual NSTAR system than it is to adopt a newer technology. The only exception to this is the single Low Power Hall system, which still offers comparable performance for less cost than dual NSTAR, even including qualification costs. From these results, it is concluded that

- Qualification costs are a significant barrier to first flight of new SEP technologies on Discovery missions.

Once the first system is flown, future SEP flights will see the full cost benefit from the use of new technology. However, the first program has little incentive to adopt a technology that primarily benefits future missions. This problem could be partially addressed by incorporating additional qualification testing into the technology development programs, incorporating full-length life tests into the development programs, or by procuring flight qualification units as part of the development. It could also be addressed programmatically though cost sharing arrangements that fund qualification efforts outside of the traditional mission cost-cap structure.

B. Vesta-Ceres Rendezvous Mission

The Vesta-Ceres rendezvous mission is a main belt asteroid science mission modeled closely on Dawn. The spacecraft launches directly to an Earth escape trajectory and uses a combination of SEP and a Mars gravity assist to rendezvous with the asteroid Vesta. SEP is used to maneuver in the asteroid's vicinity for 200 days before continuing on to a second rendezvous with the asteroid Ceres. The basic characteristics of this mission are shown in Table 9.

Vesta-Ceres Rendezvous	
Target Bodies	Vesta and Ceres
Launch Vehicle	Delta 2925H
Power System	8.67 kW solar array at 1 AU
Bus Power	540 W
Duration	9 years
ΔV	10.2 to 11.6 km/s
Launch Date	7 July 2006
Ion/Hall Thruster Duty Cycle	90%
Launch and Rendezvous Dates	Fixed
Optimization Method	Mystic
Redundancy	Spare thruster required at Vesta. No spare required for Ceres

Table 9: Vesta-Ceres Rendezvous Mission Characteristics

This mission is based on Dawn and uses the same launch vehicle, solar array, launch date and arrival date. The solar array is modeled using a triple junction InGaP/InGaAs/Ge array model. The power shown in Table 9 is usable power from the array and does not include margins and degradation factors included in the flight power budget. Consistent with Dawn, no thruster redundancy is required after the first rendezvous. A separate optimized trajectory is generated for each scenario using the low thrust optimization tool Mystic.[6] Figure 13 shows the power vs. time profile operating a single NSTAR thruster at a time (the Dawn mission baseline). Three NSTAR thrusters are fired in series to accommodate the 450 kg. of xenon required to complete the mission. One challenging aspect of this mission is the need to maneuver for extended periods far away from the sun. Although significant excess power is available at the beginning of the mission, only 570 watts is available to the PPU at end of mission, which is only 50 W greater than the thruster's minimum operating power. The overall analysis results are summarized in Table 10 with net mass performance shown in Figure 14 and the total number of thrusters required shown in Figure 15.

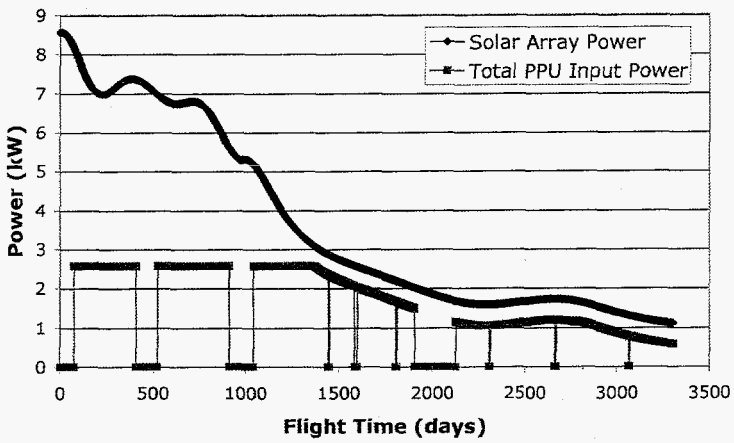

Figure 13: NSTAR Power Profile, Vesta-Ceres Rendezvous

	Single NSTAR	Single NSTAR Enhanced	NEXT (High Thrust)	Low Power Hall	Low Power Hall (small Array)
Mission					
Launch Vehicle	Delta 2925H	Delta 2925H	Delta 2925H	Delta 2925H	Delta 2925H
Trip Time (yrs.)	9.00	9.00	9.00	9.00	9.00
C3(km^2/s^2)	7.3	6.8	0.0	0.0	0.0
Power (1 AU, BOL, kW)	8.67	8.67	8.67	8.67	7.00
Payload Mass Performance (kg)	**702**	**726**	**738**	**800**	**703**
Launch Mass (kg)	1294	1307	1509	1509	1508
Xenon Propellant Throughput (kg)	385	395	527	537	597
Net Trajectory Mass Capability (kg)	882	888	958	942	855
Propulsion Subsystem Mass (kg)	180	162	220	142	152
Free Space Delta-V (km/s)	10.55	NA	10.70	10.59	NA
Configuration					
Simultaneous Operating Thrusters	1 thruster	1 thruster	1 thruster	1 thruster	1 thruster
Total Thrusters (Primary + Redundant)	3	2	2	2	2
Total PPU's (Primary + Redundant)	2	2	2	2	2
nth Mission Cost ($K)	**Baseline**	**-136**	**+653**	**-5,100**	**-6,572**
First Mission Cost ($K)	**Baseline**	**+2,564**	**+6,653**	**+400**	**-1,072**
Propulsion Subsystem Costs					
Recurring Cost ($K)	Baseline	-136	+653	-5,100	-5,100
Qualification Cost ($K)	Baseline	+2,700	+6,000	+5,500	+5,500
System Costs (Power)	Baseline	Baseline	Baseline	Baseline	-1472
Development					
Maturity (TRL)	9	4	5	3	3
Development Schedule (TRL 6, no life test)	None	~1.5 yrs.	~1.5 yrs.	~ 4 yrs.	~ 4 yrs.
Develoment Schedule (w/life test)	None	~ 3 yrs.	> 2.5 yrs.	> 5.5 yrs.	> 5.5 yrs.
Development Cost ($M)	None	$10M	$17.9M	$19.5M	$19.5M

Table 10: Vesta-Ceres Rendezvous Summary Performance Matrix

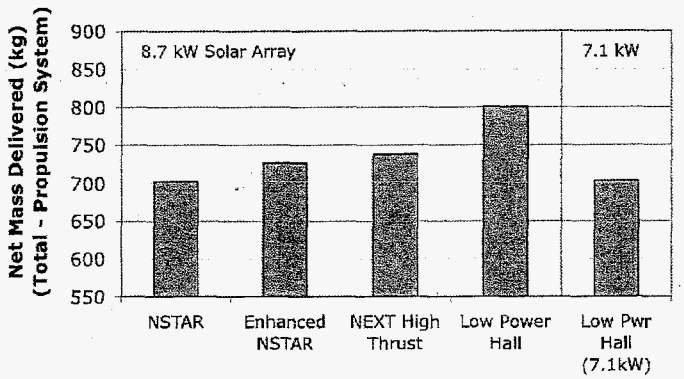

Figure 14: Delivered Mass, Vesta-Ceres Rendezvous Mission

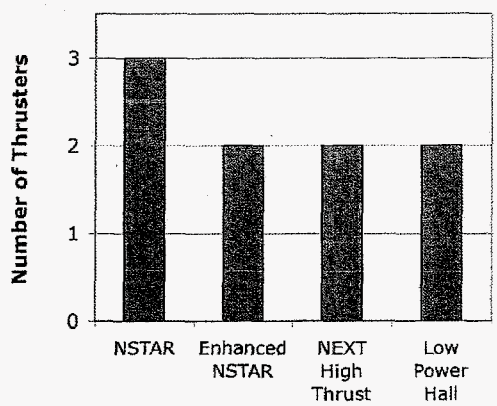

Figure 15: Number of thrusters required, Vesta-Ceres Rendezvous

Figure 15 shows the primary advantages that the proposed EP devices have over NSTAR: significantly greater throughput capability. All of the proposed devices require fewer thrusters to complete the mission compared to the SOA NSTAR system. Since the same conclusion was reached for the Near Earth Asteroid sample return mission, this leads to the following finding.

- Discovery class missions will generally benefit from the increased xenon throughput capability offered by the proposed EP technologies.

Figure 14 shows that Enhanced NSTAR and NEXT deliver relatively small mass advantages over NSTAR, while low power Hall delivers almost 100 kg of extra payload. The Hall system performs well because it operates at relatively high efficiency at low power (see Figure 1), giving it a significant performance advantage for the last third of the mission. Enhanced NSTAR and NEXT better utilize the array at the beginning of the mission, but gain relatively little mass advantage because a Mars gravity assist is used in combination with fixed launch and arrival dates. Most of the extra array power is only available on the initial Earth-Mars leg, so the extra thrust capability is useful for the Mars flyby, but has little benefit for the rest of the mission. The size of the Dawn array is determined by the need to provide enough power to operate the propulsion system at the final destination. Because the Hall thruster operates relatively efficiently at low power, we examined a case where a 7.1 kW array was used to carry out the mission. Using the smaller array, the Hall system is able to deliver the same payload as the baseline case. None of the ion thrusters were able to complete the mission with an array smaller than 8.7 kW. This result clearly shows the benefit that efficient low power operation has for this type of Discovery class mission and leads to the following finding:

- EP systems that operate with high efficiency at low power can greatly benefit Discovery class missions.

This finding is specific to Discovery because these missions are strongly cost and power limited. As a result, the EP system ends up driving the size of the power system, which in turn represents a substantial fraction of the total spacecraft cost.

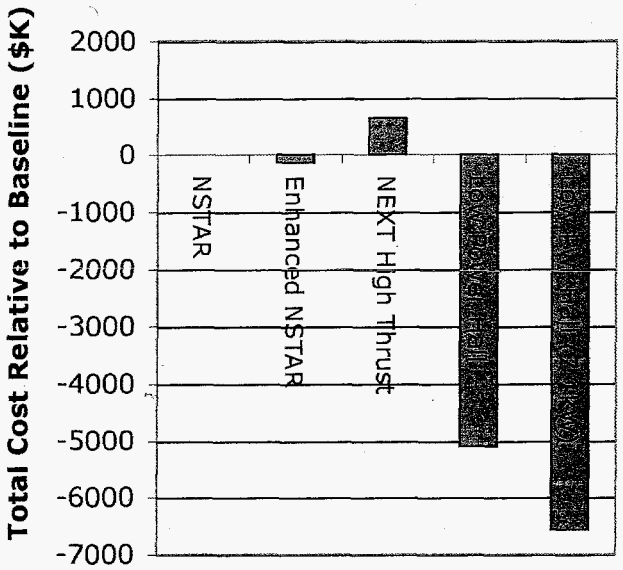

Figure 16: Nth Flight Cost, Vesta-Ceres Rendezvous

Figure 16 shows n^{th} flight cost calculated for the Vesta-Ceres mission. The Hall system offers a considerable cost and performance advantage on this mission at 8.7 kW, saving almost $5 million compared to the SOA case. In addition, because it operates relatively efficiently at low power, the Hall system can instead be used with a smaller array, resulting in over $1 million in additional cost savings. The ion systems, on the other hand, offer a moderate performance advantage, but little to no cost advantage over the SOA. This occurs despite the use of fewer thrusters because low thruster costs are offset by higher costs associated with the PPU. Like many Discovery missions, Dawn is a strongly cost constrained, so these higher costs represent a significant barrier to the adoption of these technologies. Lower subsystem costs, particularly PPU/DCIU costs, are needed for ion thruster options. The costs reported do not account for the system benefits of using fewer thrusters, which include simpler spacecraft configuration and integration testing.

Based on this analysis, we reach the following conclusions for the Vesta-Ceres rendezvous mission.

- For all options, greater throughput allows use of fewer thrusters than NSTAR. This will simplify the spacecraft's configuration and reduce integration testing.
- Hall has a considerable performance and cost advantage over the state of the art. In particular, its high efficiency at low power allows the use of a smaller solar array on this mission, resulting in substantial cost savings at the system level.
- Lower subsystem costs, particularly PPU/DCIU costs, are needed for ion thruster options.

C. Comet Rendezvous Mission

The last mission considered 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 structure of this mission is somewhat similar to concept for the comet Odyssey mission.[7] The basic characteristics of this mission are shown in Table 11.

Comet Rendezvous	
Target Body	Kopff
Launch Vehicle	Delta 2925
Power System	9 kW solar array at 1 AU
Bus Power	250 W
Duration	3.8 years
ΔV	8.1 to 8.9 km/s
Launch Year	2006
Ion/Hall Thruster Duty Cycle	90%
Launch and Rendezvous Dates	Selected by Optimizer
Optimization Method	SEPTOP

Table 11: Comet Rendezvous Mission Characteristics

A separate optimized trajectory is generated for each scenario using SEPTOP. All trajectories assume a nominal array power of 9 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. Although this mission is not as power limited as the Vesta-Ceres rendezvous, it does require extended operation at moderately low power (< 1.5 kW). The baseline SOA mission uses two NSTAR thrusters. Its power profile is shown in Figure 17. The overall results are summarized in Table 12 and net delivered mass and relative cost are shown in Figure 18 and Figure 19.

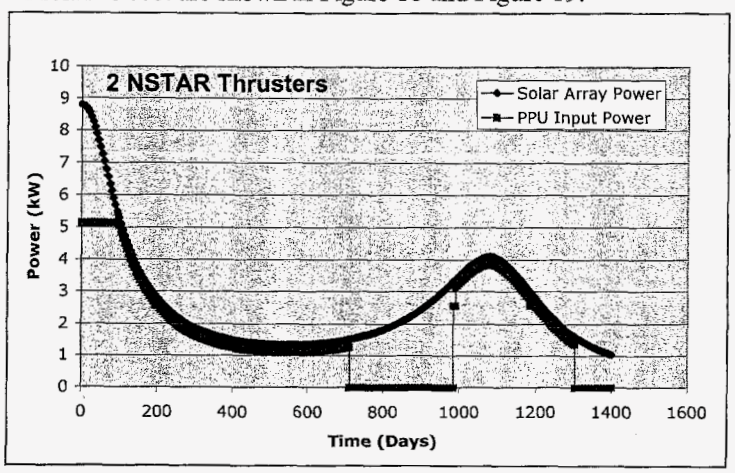

Figure 17: Power Profile, Comet Rendezvous Mission

	Dual NSTAR	NEXT (High Thrust)	Dual Enhanced NSTAR	Dual Hall	NEXT (High Isp)	Triple NSTAR
Mission						
Launch Vehicle	Delta 2925	Delta 2925	Delta 2925	Delta 2925	Delta 2925	Delta 2925
Trip Time (yrs.)	3.83	3.84	3.81	3.86	3.80	3.83
C3(km^2/s^2)	15.8	13.7	15.3	11.0	15.8	12.9
Power (1 AU, BOL)	Baseline 9 kW	Same (3)	Same	Same	Same	Same
Payload Mass Performance (kg)	**592**	**610**	**611**	**633**	**609**	**592**
Launch Mass (kg)	987	1030	997	1090	987	1047
Xenon Propellant Throughput (kg)	238	246	213	327	204	261
Net Trajectory Mass Capability (kg)	749	784	785	763	783	786
Propulsion Subsystem Mass (kg)	157	174	174	130	174	194
Free Space Delta-V (km/s)	8.15	8.41	8.17	8.88	8.10	8.50
Configuration						
Simultaneous Operating Thrusters	2 thrusters	1 thruster	2 thrusters	2 thrusters	1 thruster	3 thrusters
Total Thrusters (Primary + Redundant)	3	2	3	3	2	4
Total PPU's (Primary + Redundant)	3	2	3	3	2	4
nth Mission Cost ($K)	**Baseline**	**-1,128**	**+1,321**	**-5,020**	**-1,128**	**+2,693**
First Mission Cost ($K)	**Baseline**	**+4,872**	**+4,021**	**+480**	**+4,872**	**+2,693**
Propulsion Subsystem Costs						
Recurring Cost ($K)	Baseline	-1,128	+1,321	-5,020	-1,128	+2,693
Qualification Cost ($K)	Baseline	+6,000	+2,700	+5,500	+6,000	+0
Development						
Maturity (TRL)	6	5	4	3	5	6
Development Schedule (TRL 6, no life test)	None	~1.5 yrs.	~1.5 yrs.	> 4 yrs	~1.5 yrs.	None
Develoment Schedule (w/life test)	None	> 2.5 yrs.	~ 3 yrs.	> 5.5 yrs.	> 2.5 yrs.	None
Development Cost ($M)	Small	$17.9M	$10M	$19.5M	$17.9M	Small

Table 12: Comet Rendezvous Summary Performance Matrix

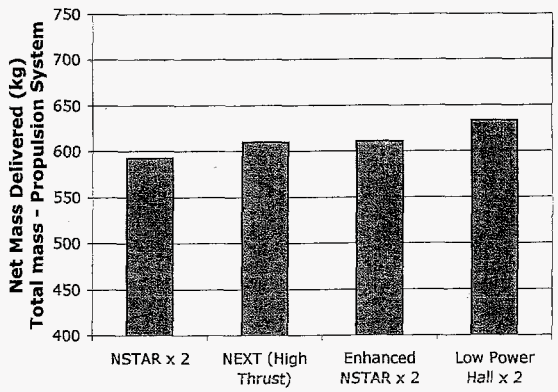

Figure 18: Delivered Mass, Comet Rendezvous

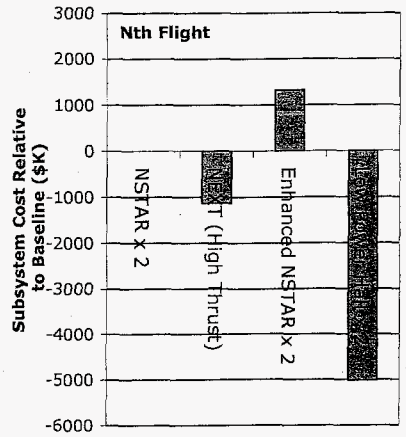

Figure 19: N^{th} Flight Cost Comparison, Comet Rendezvous ($FY05)

All proposed SEP systems offer a relatively small mass advantage over the SOA. The Hall system also offers considerably lower n^{th} flight cost, while NEXT offers a moderate cost savings and requires only one thruster rather than the two thrusters used in the other options. The Enhanced NSTAR offers only a slight mass advantage and

costs more than the SOA system, so it is not considered applicable for this mission. As with the previous two missions, qualification costs exceed the nth flight cost savings shown above, resulting in unattractively high first flight costs on this mission. This represents a significant barrier to the implementation of these technologies on Discovery missions.

D. General Observations

In the previous section, two general observations were made about the overall performance of EP systems for SEP missions.

- In general, the best mass performance comes from EP systems that best utilize available solar array power.
- EP systems that operate with high efficiency at low power can greatly benefit Discovery class missions

These qualitative findings were made in the context of specific missions (the Near Earth Asteroid and Vesta-Ceres rendezvous). To better understand the relationship between system performance and array power, a series of optimized trajectories were run at different powers on a separate model main belt asteroid mission. The model mission is also a Vesta-Ceres rendezvous, but to simplify the analysis, the Mars gravity assist is *removed* and the optimizer is allowed to select the launch and arrival dates. The resulting mission is notional and is intended to clarify governing relationships. The trajectories were optimized using SEPTOP, were constrained to an 8.5 year flight time and use a Delta 2925H launch vehicle. Figure 20 shows total delivered mass as a function of array power for a series of different EP options. The "final mass" in this case includes the mass of the EP system. Also shown in black is a notional ion performance curve that is created empirically from the performance data.

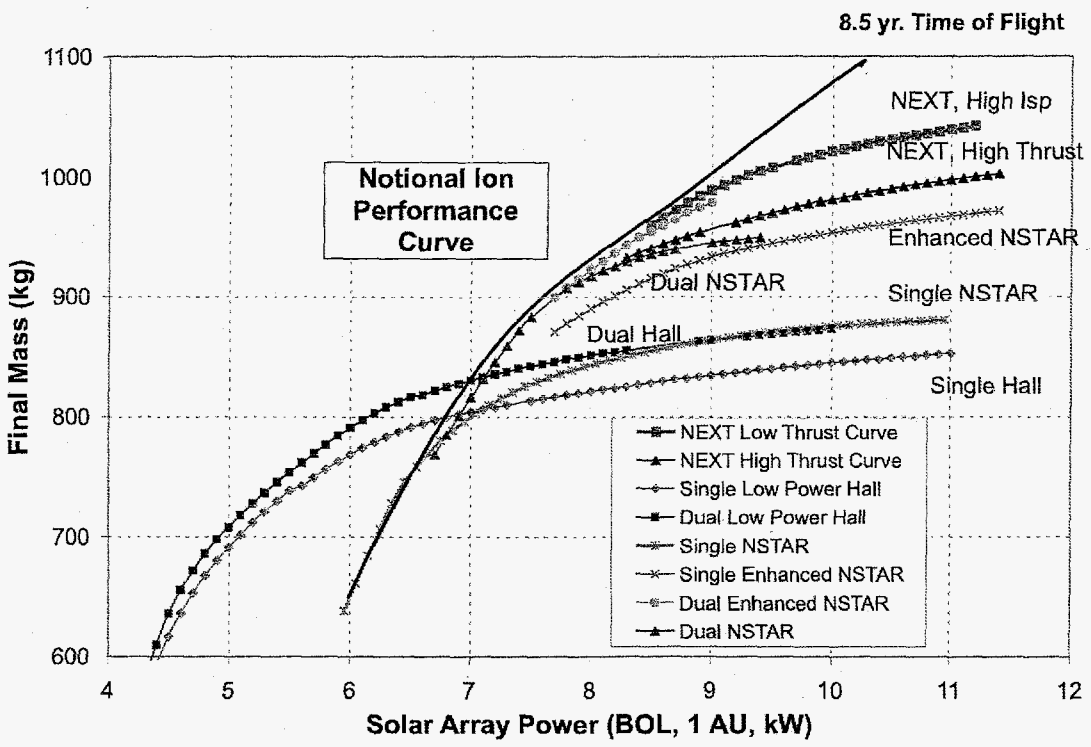

Figure 20: Final Mass vs. Solar Array Power, Notional Main Belt Asteroid Mission

In general, for low power operation, delivered mass increases rapidly with array power then transitions to a flatter region at high power. The location of the transition varies directly with the maximum allowable PPU input power. As array power increases, the delivered mass increases until it reaches a point where the PPU input is saturated and the EP system is no longer able to take advantage of extra power from the array. The ion systems have similar low and mid power efficiency curves, so their performance overlaps until the PPU input is saturated. Beyond this point, the performance curves flatten and the delivered mass is primarily a function of maximum PPU input power. The

black line in Figure 20 corresponds to an empirically derived "ion performance curve" corresponding to the mass delivered by an ion thruster system that has no maximum power limit. The ion thruster systems follow this curve until the PPU input is saturated and then transition to a plateau region. These results show how EP systems that best utilize available solar array power deliver the most mass at higher array powers. The choice of specific impulse also influences delivered mass, but this influence is secondary compared to the thruster's min/max power range.

The mass vs. power performance curves for the Low Power Hall system shows the influence that efficient low power operation has on delivered mass. The ion systems deliver more mass above 7 kW, but their performance falls off rapidly with reduced array power while the Hall system continues to offer reasonable performance below 5 kW. The higher performance is due to the Hall system's relatively high efficiency when operating far away from the sun. At higher powers, Hall systems operate less efficiently than ion, so their performance is not as good. With heavier spacecraft, it is necessary to use a larger solar array and an EP system with a higher maximum power to meet mission requirements. However, the Hall system offers better performance with smaller spacecraft and small solar arrays, which is highly desirable for cost-capped missions. This result shows how EP systems that operate with high efficiency at low power benefit small missions by enabling the use of smaller solar arrays, significantly lowering the cost of these missions.

Table 13 provides a matrix showing the applicability of each proposed technology to the Discovery missions analyzed in this study as well as to larger missions considered in other studies.[8,9] Applicability is defined as a combination of performance and n^{th} flight cost, and the mission is marked "applicable" if the technology either provides a performance benefit or a cost benefit compared to the SOA. As discussed previously, adding qualification costs to the nth flight cost significantly reduces the range of application for each technology. The low power hall system is marked as "possibly cost enabling" because the magnitude of the cost savings may be large enough to enable use of electric propulsion on some missions that would otherwise be cost-limited to chemical propulsion.

	"Discovery" (< 10 kW)			"New Frontiers" (< 18 kW)			Larger Missions (> 20 kW)	
	Vesta-Ceres RV	Near-Earth Asteroid	Comet RV	Titan Lander (Notional)	Comet Surface Sample Return	Jupiter Polar Orbiter	Titan Explorer	Neptune Orbiter
BOL Array Power	9 kW	6 kW	9 kW	6 kW	15 kW	15 kW	~ 30 kW	~ 30 kW
NSTAR, 1 thruster	X	X						
NSTAR, multi-thruster		X	X	?				
Low Power Hall Thruster	XX	XX	XX	?				
Enhanced NSTAR	X	X		?	(X)			
NEXT Low Power Update	X	X	X	X	X		X	X

XX = Possibly Cost Enabling
X = Applicable
(X) = Possibly Applicable
Red = Not Applicable
? = Not evaluated
Gray = Not Designed for this Application

Table 13: [General Application Matrix]

IV. Conclusions

A detailed study has been conducted to examine the potential benefits that advanced electric propulsion (EP) technologies offer to the competitively awarded, cost-capped missions in NASA's Discovery program. The study looked at the cost and performance benefits provided by three EP technologies currently proposed or in development through NASA's In-Space propulsion (ISP) program on three straw man Discovery class missions and compares their performance to a state of the art system using the NSTAR ion thruster. The different propulsion technologies/mission scenarios considered are shown in Table 1. Because cost is a major driver for competed missions, a detailed electric propulsion subsystem cost model was used to conduct a cost-benefit analysis for each option. Development, qualification and recurring costs were all considered in the study.

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. The electric propulsion cost model was used to calculate the total cost of the propulsion system and where appropriate the cost of the solar array was also calculated and incorporated into a comparison of the relative costs each option. Based on the results, the following general conclusions have been reached about each of the proposed EP technologies.

- Low Power Hall offers very significant performance and cost benefits to Discovery class missions. However, this technology is relatively immature (TRL 3), and further investment is required to determine if the technology can achieve its performance and cost goals.

- The NEXT thruster offers moderate performance and noticeable cost benefits to Discovery class missions vs. dual NSTAR systems. It also offers strong performance benefits vs. single NSTAR systems.

- An Enhanced NSTAR thruster using carbon-carbon based ion optics and components from the NEXT subsystem development offers moderate performance and cost benefits to Discovery class missions with relatively moderate total subsystem development costs.

It has also been found that for many missions, the increased throughput capability for the proposed EP technologies reduces the number of thrusters required to conduct the mission, leading to the following finding.

- Discovery class missions will generally benefit from increased xenon throughput capability offered by the proposed EP technologies.

In addition, two important conclusions have been reached about the cost of EP subsystems and the improvements needed to increase their application to cost capped missions.

- Lower subsystem costs, particular Power Processing Unit (PPU) and Digital Control and Interface Unit (DCIU) costs, are needed for ion thruster systems.

The proposed Low Power Hall system carries a significantly lower n^{th} flight cost than the ion thruster systems, primarily because of lower PPU and DCIU costs associated with the subsystem. The NSTAR DCIU costs over $1.3 million per a flight unit, and both primary and redundant units are required for a flight system, while the Hall system requires no DCIU. Future ISP development efforts should consider incorporating DCIU functions into other units to lower the cost of ion thruster systems.

- First flight qualifications costs are a significant barrier to implementation of new SEP technologies on Discovery missions.

With the current structure of ISP's development programs, significant qualification costs are borne by the first flight mission using a new EP technology. The qualification cost generally exceeds the hardware and subsystem cost benefit brought by the new technology, leaving the first program no financial incentive to adopt a technology that will benefit future missions. This problem can be addressed programmatically by lowering qualification costs, perhaps by incorporating qualification testing into the subsystem technology development program or procuring flight qualification units as part of the development program. It can also be addressed by allowing/creating cost sharing arrangements that fund the flight qualification effort outside the mission cost-cap limit.

Finally, two observations have been made regarding the general performance of EP systems on solar electric propulsion (SEP) missions.

- In general, the best mass performance comes from the EP systems that best utilize available solar array power.

When excess array power is available, thrusters with the widest PPU input power range generally perform the best because they can convert more of the available electrical power into kinetic energy over the course of the mission. The choice of specific impulse also influences delivered mass, but this influence is secondary compared to the thruster's minimum-maximum power range.

- EP systems that operate with high efficiency at low power can greatly benefit Discovery class missions.

Low power performance is useful for Discovery missions because these missions are cost limited, so the solar array is generally made as small as possible to lower program costs. This results in missions with extended periods of low power operation. The proposed Low Power Hall system operates at much higher efficiency and at lower power than the ion systems. As a result, it offers significant performance and cost benefits to some Discovery missions. In particular, the device's relatively high thrust at low power enables it to accomplish a Dawn-like Vesta-Ceres rendezvous using a solar array that is 20% smaller than the ion systems.

It should be noted that this study uses straw man missions derived from current mission concepts that use the state-of-the-art NSTAR ion thruster. Discovery missions cover a wide range of scientific goals, so these missions do not encompass the full range of possible destinations and challenges. Principal investigators are continually asking for more challenging missions within the Discovery program, and advanced electric propulsion technologies may enable a class of missions more challenging than those considered in this study.

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References

[1] "Dawn Fact Sheet," http://www.orbital.com/NewsInfo/Publications/Dawn_fact.pdf, FS006-02, Orbital Sciences Corporation, Dulles, VA.

[2] Brophy, J. et al. "Status of the Dawn Ion Propulsion System," AIAA-2004-3433, 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Fort Lauderdale, FL, July 2003.

[3] Patterson, M.J., et al., "NEXT: NASA'S Evolutionary Xenon Thruster Development Status," AIAA Paper No. 2003-4862 (July 2003).

[4] Snyder, J.S. and Brophy, J.R. "Performance Characterization and Vibration Testing of 30-cm Carbon-Carbon Ion Optics," AIAA 2004-3959, 40th Joint Propulsion Conference, Fort Lauderdale, FL, July 2004.

[5] Witzberger, K. and Manzella, D. "Performance of Solar Electric Powered Deep Space Missions Using Hall Thruster Propulsion," AIAA 2005-4268, 41st Joint Propulsion Conference, Tucson, AZ, July 10-13, 2005.

[6] Whiffen, Gregory J. and Jon A. Sims, "Application of a Novel Optimal Control Algorithm to Low-Thrust Trajectory Optimization," AAS paper 01-209, AAS/AIAA Space Flight Mechanics Conference, San Antonio, TX, USA, 27-30 January 2003.

[7] Nilsen, E. and Weissman, P. "Odyssey – A Comet Nucleus Orbiter," Aerospace Conference, 2001, IEEE Proceeedings. Vol. 1, March 10-17 2001, pp. 1/397-1/402.

[8] Witzberger, K., Benson, S., Manella, D., Oh, D., Brophy, J. and Cupples, M. "NASA's 2004 In-Space Propulsion Re-Focus Studies for New Frontiers Class Missions," AIAA-2005-4271, 41st Joint Propulsion Conference, Tucson, AZ, July 10-13, 2005.

[9] Oleson, S., Gefert, L., Benson, S., Patterson, M., Noca, M. and Sims, J. "Mission Advantages of NEXT: NASA's Evolutionary Xenon Thruster," AIAA-2002-3969, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference," Indianapolis, IA, July 7-10, 2002.