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Solar Electric Propulsion for Primitive Body Science Missions

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March 2006

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SOLAR ELECTRIC PROPULSION FOR PRIMITIVE BODY SCIENCE MISSIONS

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ABSTRACT

This paper describes work that assesses the performance of solar electric propulsion (SEP) for three different primitive body science missions: 1) Comet Rendezvous 2) Comet Surface Sample Return (CSSR), and 3) a Trojan asteroid/Centaur object Reconnaissance Flyby. Each of these missions launches from Earth between 2010 and 2016. Beginning-of-life (BOL) solar array power (referenced at 1 A.U.) varies from 10 – 18 kW. Launch vehicle selections range from a Delta II to a Delta IV medium-class. The primary figure of merit (FOM) is net delivered mass (NDM). This analysis considers the effects of imposing various mission constraints on the Comet Rendezvous and CSSR missions. Specifically, the Comet Rendezvous mission analysis examines an arrival date constraint with a launch year variation, whereas the CSSR mission analysis investigates an Earth entry velocity constraint commensurate with past and current missions. Additionally, the CSSR mission analysis establishes NASA's New Frontiers (NF) Design Reference Mission (DRM) in order to evaluate current and future SEP technologies. The results show that transfer times range from 5 – 9 years (depending on the mission). More importantly, the spacecraft's primary propulsion system performs an average 5-degree plane change on the return leg of the CSSR mission to meet the previously mentioned Earth entry velocity constraint. Consequently, these analyses show that SEP technologies that have higher thrust-to-power ratios can: 1) reduce flight time, and 2) change planes more efficiently.

INTRODUCTION

Knowledge acquired from primitive body science missions could help explain many poorly understood astrophysical phenomena (e.g. how primitive bodies serve as the building blocks of planets). Therefore, these kinds of missions are high priority science missions and, in fact, the Decadal Solar System Exploration Survey (DSSES) lists two of them (CSSR and Trojan/Centaur Reconnaissance Flyby) as high-priority medium-class (NF) missions (the Trojan/Centaur Reconnaissance Flyby is listed as a *deferred* high priority medium-class mission). Although not specifically listed in the DSSES, the Comet Rendezvous mission potentially could fly as a small-class (Discovery) mission. Discovery missions offer more opportunities (6 or 7 missions per decade compared to 1 or 2 missions per decade for NF), and mission concepts are not limited to just those listed in the DSSES. The mission cost just needs to be compatible with the fiscal year (FY) 05 ~$250M Discovery cost-cap. In contrast, the FY05 NF cost-cap is ~$750M for the medium-class missions listed in the DSSES.

PAST ANALYSES AND DIFFERENCES

Similar missions have been assessed recently. Oh assessed a Comet Rendezvous mission to Kopff in which the arrival date was *unconstrained*.[1] The analysis in this paper targets a different short-period comet, Wild 2, that has orbital elements similar to Kopff. However, the main difference is that the arrival date is *constrained*: the spacecraft must arrive exactly 60 days prior to the comet's perihelion passage. Such a constraint might be required if some portion of the mission (e.g. global mapping) needs to occur prior to the occurrence of specific event(s) (in this case, before the comet's closest approach to the sun).

There have also been recent CSSR mission analyses that targeted Tempel 1.[2] Upon returning to Earth following a 60-day stay at the comet, those analyses did not consider an Earth entry velocity constraint. The entry velocities were *unconstrained* and typically on the order of 15 km/s. This exceeds the entry velocities of past and current missions by at least 2 km/s as shown in Table I.[3] Consequently, those higher entry velocities may not be physically viable. For this study, a 13 km/s Earth entry velocity at a reference altitude of 125 km (including Earth's angular rotation) served as the upper limit.

Table I. Recent Sample Return Science Missions

Mission	Launch Date	SRC Mass, kg	Reference alt, km	Entry Velocity, km/s	Arrival Date
Genesis	Aug-01	225.0	135	11.0	Sep-04
STARDUST	Feb-99	45.8	135	12.9	Jan-06
Hayabusa	May-03	18.0	?	12.2	Jun-07

Potential ways to mitigate this entry velocity effect include:

(1) compensate for a higher entry velocity via the thermal protection system (TPS) (more and/or better heat-resistant material),
(2) task the spacecraft propulsion system to reduce the entry velocity (slow down some prior to arriving at Earth),
(3) perform an additional revolution around the sun on the return leg, preferably flying by Earth (adjust the geometry of the trajectory to slow down),
(4) some combination of the above.

TPS requirements (material/mass) as a function of entry velocity require careful study and were beyond the scope of this analysis. The TPS is a crucial component contributing to the overall sample return capsule (SRC) masses that are also listed in Table I.[3] Incorporating a gravity assist on the return leg may result in a slower arrival speed, but with increased flight time (likely to be on the order of a year or two). Primarily due to the large number of trajectories to be investigated, only option (2) from above (using the electric propulsion system to slow down) was investigated. Therefore, this analysis did constrain the Earth arrival excess speed without an Earth gravity assist (EGA) on the return leg. Forcing the spacecraft to slow somewhat prior to arriving at Earth might be the worst-case scenario depending on how much additional propellant is required. A comparison with the gravity assist return leg option would be useful to understand the trade-offs between these two options; it is plausible that an in-bound EGA could be required to enable the mission.

Another important difference from past CSSR mission analyses include updating the payload assumptions based on similar missions that are currently flying. These payload assumptions are notional only; they are *not* based on any sort of conceptual design and analysis. Table II lists the CSSR payload mass assumptions for this study and shows that a lander and retrieval system totaling 125 kg remains at the comet—more than double of a recent study.[2]

Table II. NF DRM (CSSR) Payload Assumptions

Element	Mass, kg	left @ comet?	Rationale
Lander	100	Yes	Taken from Rosetta
Retrieval system	25	Yes	estimate
Science instuments	80	No	~1/2 of Rosetta's science package
Sample return capsul	128	No	estimate

The lander's mass was based on a current similar mission: the European Space Agency's (ESA) Rosetta (Comet Surface Sample) mission. Rosetta's lander, *Philae*, includes the sample, drilling, and distribution subsystem (SD2). In an effort to be conservative, this analysis assumes a 125 kg lander and retrieval system. Likewise, the SRC mass used in this analysis is significantly more massive than STARDUST's SRC (a comet sample), but less massive than Genesis's SRC (a solar wind sample).

The emphasis of this analysis is on the relative performance of candidate SEP technologies that could serve as the spacecraft's primary propulsion system. Accordingly, the masses listed in Table II are simply best estimates when the analysis was performed. However, most of the payload assumptions (and entry velocity constraints) are within the range of past and current missions.

In addition to a CSSR mission to Tempel 1, this paper includes a CSSR mission to Wirtanen (the original target of ESA's Rosetta mission). In an effort to better understand SEP efficacy, a comparison is made with a state-of-the-art (SOA) chemical trajectory to Wirtanen.

Regarding the Trojan/Centaur Reconnaissance Flyby mission, the author is not aware of any mission analysis conducted within the last five years that flies past a Trojan asteroid *and* a Centaur object. Therefore, this mission analysis provides potential Trojan asteroid/Centaur object combinations and trajectory options.

STUDY OBJECTIVES

In addition to the top-level objectives of determining the required launch vehicle, BOL array power, number of thrusters, and transfer times for each mission, mission-specific objectives include:

(1) Comet Rendezvous—understand how constraining the arrival date with launch year variations affects the performance of each SEP technology,
(2) CSSR—understand the impact of reducing the Earth entry velocity on the selected SEP technology performance and gain insight into how performance varies with different targets,
(3) Trojan/Centaur Reconnaissance Flyby—identify potential Trojan asteroid/Centaur object combinations and trajectory options.

SEP TECHOLOGIES OVERVIEW

Table III shows the electric thrusters considered in this study, their operating ranges, and their throughput capabilities. The current NASA technology readiness level (TRL), a measure of technology maturity (the higher the number—the more mature the technology), is also listed.[4]

Table III. Operating range, throughput capability, and current NASA TRL

Thruster	Power into PPU, kW		Maximum Throughput, kg	NASA TRL
	Pmin	Pmax		
2.6-kW NSTAR Q-Mod	0.525	2.567	150	9
7-kW NEXT	0.616	7.252	300	5
3-kW Hall	0.232	2.843	282	4

The ion thrusters have more maturity than the Hall system. NASA's Solar Technology Application Readiness thruster (NSTAR), the current SOA electric thruster, is the most mature technology; it's flight qualified and will serve as the primary propulsion system for the DAWN mission launching in 2006.[5] NASA's Evolutionary Xenon Thruster (NEXT), an advanced state-of-the-art (ASOA) ion thruster, is currently undergoing performance testing.[6] It is expected to be ready for flight qualification testing by the end of 2006, so a 2010/2011 mission with NEXT appears realistic. In contrast, the Hall thruster is the least mature and requires more testing and validation to achieve the required lifetimes. A lab test of a model thruster was recently completed.[7] Therefore, missions launching after 2012 seem appropriate for the Hall systems. Of course, funding level variations can cause thruster development to accelerate or decelerate.

THRUSTER MODELING

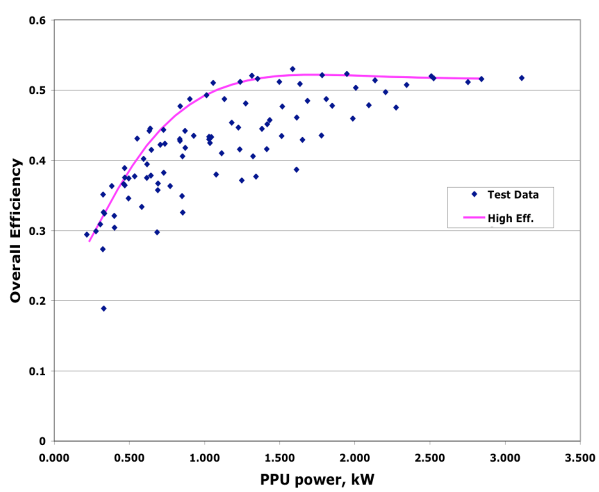
Extensive documentation exists on modeling these thrusters' performance for the use in a low-thrust optimization program.[1,8,9] Polynomial curve fits of thrust and mass flow rate as functions of power into the power-processing unit (PPU) model the thrusters. The form of the polynomial is given in Equation (1), where P is the PPU input power in kilowatts and y represents either thrust or mass flow rate, and a, b, c, d, and e are the coefficients of the polynomial.

$$y = a + bP + cP^2 + dP^3 + eP^4 \tag{1}$$

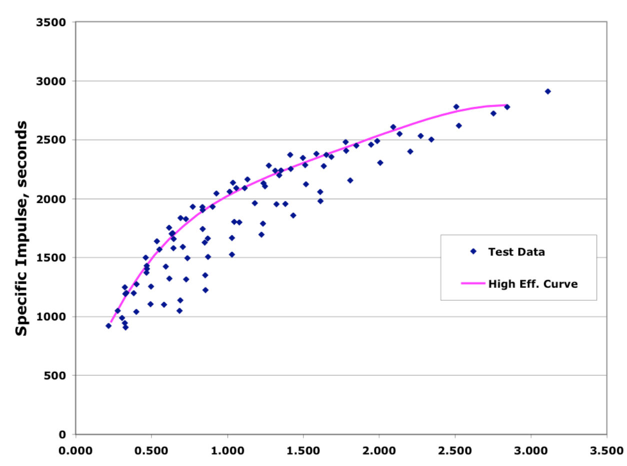
When the models in References 1, 8, and 9 were generated, the Hall thruster had not finished its lab test; therefore, the Hall thruster models in these papers were based on theoretical performance. Because initial testing of the lab model Hall thruster has since been completed, performance models herein are based on the new experimental data. Table IV lists the polynomial coefficients that model each thruster's performance. From theses coefficients, specific impulse and system efficiency as a function of PPU input power were calculated and shown in Figure 1 for the Hall thruster. The Hall thruster curve fits were chosen to emphasize the higher efficiency points. Although a perfectly valid thruster model, this may not be the "best" Hall thruster model for all missions. (As a side note, two curve fits, high efficiency and high specific impulse (I_{sp}), were originally examined, and the high efficiency curve fit outperformed the high I_{sp} for the missions assessed in this paper.) This really underscores the need for increased thruster modeling fidelity in low thrust optimization programs. The ability to incorporate thruster performance data directly into an optimizer would eliminate some of the arbitrariness associated with curve-fitting thruster performance data, and, more importantly, better models the thruster's performance.

Table IV. 4th Order Polynomial Curve Fit Coefficients

Coefficient	3-kW Hall (High Eff)		2.6-kW NSTAR Q-Mod		7-kW NEXT			
					High Isp		High Thrust	
	Mass flow rate, kg/s	Thrust, N	Mass flow rate, kg/s	Thrust, N	Mass flow rate, kg/s	Thrust, N	Mass flow rate, kg/s	Thrust, N
a	1.396E-06	4.723E-03	2.506E-06	2.634E-02	1.944E-06	-8.954E-05	3.131E-06	1.680E-02
b	1.466E-07	3.658E-02	-5.357E-06	-5.169E-02	1.768E-07	5.232E-02	-2.621E-06	1.188E-02
c	1.878E-06	2.041E-02	6.254E-06	9.049E-02	-1.898E-07	-1.402E-02	1.660E-06	1.293E-02
d	-1.109E-06	-1.475E-02	-2.537E-06	-3.672E-02	7.637E-08	2.926E-03	-2.832E-07	-2.234E-03
e	1.898E-07	2.641E-03	3.698E-07	5.146E-03	-6.024E-09	-1.889E-04	1.531E-08	1.102E-04



a) Efficiency vs. PPU power



b) Specific Impulse vs. PPU power

Figure 1. 3-kW Hall Test Data and Curve Fits

To evaluate the performance of the SEP technologies, a mass model developed and used in recent mission analyses was utilized.[1,9] Table V shows this model. A more detailed description of this model can be found in Reference 1. In general, the advanced thrusters (NEXT and Hall) require fewer thrusters relative to NSTAR due to their increased lifetime capability. For this analysis, 80% of each thruster's propellant contingency is assumed to be usable propellant; therefore, this percentage counts against the thruster's maximum throughput limit. If an additional thruster is required in order not to exceed a thruster's maximum throughput capability, the thrusters and PPUs are assumed to be connected in a way (i.e. cross-strapped) so that an additional PPU is not required. All SEP configurations include a dedicated "cold" spare thruster and PPU in addition to any thruster required for lifetime.

The example EP subsystem mass total, shown in Table V, represents a common trend: Hall systems are typically substantially lighter than the ion systems. Subsystem contingency shown is commensurate with each thruster's TRL.

Table V. Electric Propulsion System Masses (as of January 2005)

Thruster	NSTAR	NEXT	Hall
Inputs			
Number of Engines	4	3	3
Number of PPU's	4	2	3
Number of DCIU's	2	2	0
Xenon Throughput (kg)	373	342	416
Xenon Contingency			
Navigation and Trajectory Errors	5%	5%	5%
Residuals and leakage	5.0%	3.6%	5.0%
Assumptions			
Mass per Thruster	8.2	12.4	3.6
Mass per PPU	13.9	34	8.4
Mass per DCIU	5.65	5.65	0
Mass per Gimbal	4.64	5.00	4.64
Gimbal Drive Electronics	included	included	2.0
Feed System			
Fixed Mass	8.1	2.2	4
Additional mass/engine	3.3	4.1	1
Xenon Tank Mass Fraction	4.5%	4.5%	4.5%
System Contingency	10%	30%	30%
Calculations			
Thrusters	32.8	37.2	10.8
PPUs	55.6	68.0	25.2
DCIUs	11.3	11.3	0.0
Xenon Feed System	21.4	14.5	7.0
Xenon Tank(s)	18.5	16.7	20.6
Gimbals	18.6	15.0	15.9
other			
Subsystem Dry Mass	**158**	**163**	**80**
Xenon Residuals	37	29	42
Contingency	16	49	24
Propulsion System Mass (w/Contingency)	**211**	**241**	**145**

These analyses utilized an indirect, sun-centered, two-body optimization program named SEPTOP developed by Carl Sauer at the Jet Propulsion Laboratory (JPL). SEPTOP has the ability to model various mission related parameters pertaining to the power and propulsion system. For all missions assessed, this included:

- $1/R^2$ array model,
- 250 Watts for spacecraft housekeeping activities,
- 2% per year array degradation factor, and a
- 90% propulsion duty cycle.

The first three listed above amount to deductions from the power source (array). The BOL array power for each mission is listed below:

- Comet Rendezvous—10.5 kW
- CSSR (Wirtanen)—10 kW

- CSSR (Tempel 1)—15 kW
- Trojan/Centaur Reconnaissance Flyby—15 kW & 18 kW

Additionally, the Trojan/Centaur Reconnaissance Flyby mission utilized a mass model that was based on a Team X study *for the entire NEXT SEP module*.[10] For this mission only, the solar array specific power was assumed to be 170 W/kg (array mass bookkeeping was not necessary for the other two missions). NSTAR and Hall were not assessed for this mission (the objective was to develop trajectory options).

CHEMICAL ASSUMPTIONS

A chemical and SEP performance comparison for the CSSR mission to Wirtanen hopefully enables the reader to gain insight into SEP effectiveness for these kind of missions. The chemical option uses the same launch vehicle (Atlas 401) as the SEP options. An EGA on the outbound leg is utilized to reduce the launch energy requirement. Without this gravity assist, the chemical option may not be feasible at all. Although the spacecraft launches in 2016, the chemical system is assumed to be a generic bi-propellant system with a specific impulse of 325 seconds. An optimizer maximizes the final mass by finding the optimal event dates and the optimal time between those events while solving Lambert's problem. The velocity change (ΔV) budget is listed in the results section for the unconstrained and constrained entry velocity cases. For the constrained entry velocity case, the velocity difference between the SRC's entry velocity (at 125 km altitude) and the assumed maximum allowable (13 km/s) is simply added to the rest of the mission's ΔV requirements and the trajectory re-optimized.

In order to facilitate a comparison with SEP options, the chemical propulsion system mass had to be estimated. Unfortunately, no chemical spacecraft mass model was available. Therefore, a fixed percentage (7%) of the total propellant mass (which includes 8% for reserves) serves as a rather crude propulsion system (tanks and engines) mass estimate. Despite this, the ΔV budget for the chemical options is, of course, independent of any mass estimates (and independent of any mass left at the comet). Consequently, a mission designer could take the post-launch ΔV (and launch energy requirement) reported in this study and perform a higher fidelity spacecraft/mission point design.

FIGURE-OF-MERIT (FOM)

NDM for each mission is defined as launch mass less propellant mass and less:

- Comet Rendezvous: electric propulsion (EP) system mass,
- CSSR (SEP): EP system mass, mass left at the comet, and SRC mass,
- CSSR (Chemical): propulsion system mass and SRC mass (the mass left at the comet is included in the trajectory optimization and results in less required propellant than if no mass were left at all),
- Trojan/Centaur Reconnaissance Flyby: mass of the *entire SEP module (power, propulsion, structure, etc.)*.

The mass that is left (NDM) for each mission is then comprised of:

- Comet Rendezvous: solar array, spacecraft "bus" (i.e. structure, CH&D, thermal, etc.), and any other necessary mass,
- CSSR (SEP): solar array, 80 kg of spacecraft science instruments, spacecraft bus, and any other necessary mass,
- CCSR (Chemical): power source, spacecraft bus, 80 kg of spacecraft science instruments, and other necessary mass,
- Trojan/Centaur Reconnaissance Flyby: power source (probably a radioisotope power source), spacecraft bus, science payload, and other necessary mass.

Note that the NDM for the Trojan/Centaur Reconnaissance Flyby does *not* include the solar array. The size of the Centaur's orbit (semi-major axis) is between Jupiter and Neptune. To provide power at these distances, a larger array than what may be compatible with the NF mission cost likely would be required. Obviously, the distance between Jupiter and Neptune is great (~ 25 A.U.), and targeting a Centaur object closer to Jupiter could enable a solar-powered only mission. However, for the timeframes investigated, flying by a Trojan asteroid and a Centaur object closer than ~ 10 A.U. appeared infeasible.

TARGET BODY ORBITAL ELEMENTS

Table VI lists the orbital elements of the targeted comets. The orbits for Wirtanen and Tempel 1 are very similar with one major difference: Wirtanen's closest approach is much closer to Earth than Tempel 1. Perihelion for Tempel 1 is near the vicinity of Mars whereas Wirtanen's is near Earth (~ 0.06 A.U. from Earth).

The Trojan asteroid/Centaur object combinations shown in Table VII can be thought of as a trade-off between a lower A.U./higher inclination target (4035/2001 BL41) and a higher A.U./lower inclination target (2674/2001 ZX255).

Table VI. Orbital Elements and Radius of Targeted Comets

	Comet RV	CSSR	
Orbital Element	Wild 2	Wirtanen	Tempel 1
sma, AU	3.45	3.09	3.12
ecc	0.54	0.66	0.52
inclination, deg	3.24	11.74	10.53
perihelion, AU	1.59	1.06	1.51
aphelion, AU	5.31	5.13	4.74
Period, years	6.40	5.44	5.52
Radius, km	2.00	0.60	3.10

Table VII. Trojan/Centaur Orbital Elements

	Trojan/Centaur Flyby w/ EGA		Trojan/Centaur Flyby w/ VGA	
	Trojan asteroid	Centaur object	Trojan asteroid	Centaur object
Orbital Element	4035	2001 BL41	2674	2001 XZ255
sma, AU	5.27	9.79	5.17	16.02
ecc	0.06	0.30	0.07	0.03
inclination, deg	12.14	12.46	1.85	2.61
perihelion, AU	4.98	6.90	4.82	15.45
aphelion, AU	5.58	12.65	5.52	16.49
Period, years	12.13	30.58	11.77	63.83

RESULTS AND DISCUSSION

COMET RENDEZVOUS

Figure 2 shows the performance of each SEP technology when launching in 2010 and 2011. BOL array power is 10.5 kW. For the 2010 launch, two operating Hall thrusters deliver the largest mass. NEXT delivers ~ 2.5% and 6.5% less mass than NSTAR and Hall, respectively, but requires the fewest operating thrusters (only one). An additional NEXT is required in order not to exceed its anticipated throughput capability. Launching a year later, in 2011, and still arriving 60 days prior to the comet's perihelion passage, forces the spacecraft to reduce its transfer time by roughly a year. The spacecraft can accomplish this mainly by reducing the coast periods and increasing the thrust periods. Therefore, the ΔV requirement increases. As a result of this reduced flight time requirement, only the Hall thrusters meet this constraint due to their ability to generate more thrust relative to the ion thrusters. The only solutions found for the ion thrusters arrive just 1 – 2 weeks prior to perihelion *assuming the same number of operational thrusters, BOL array power, etc.*

Table VIII provides the detailed performance results. The roughly one year transfer time reduction resulted in an additional 500 m/s ΔV performed by the Hall thrusters and ~ 12% NDM reduction.

Figure 3 shows the path of the spacecraft as it travels to Wild 2 when launched in 2010 while Figure 4 shows that the electric thrusters provide ~ 70% of the energy requirement. Constant energy of the spacecraft in Figure 4 corresponds to coast periods in Figure 3.

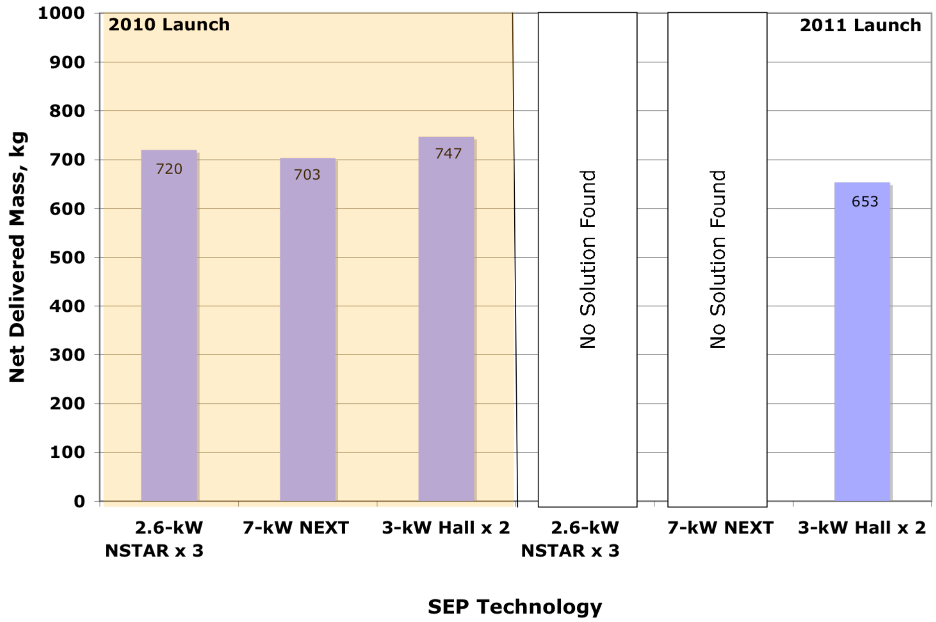


Figure 2. NDM to Wild 2 for Each SEP Technology

Table VIII. SEP Performance Results for Wild 2

Parameter	Unconstrained Arrival Date **2.6-kW NSTAR**	 **7-kW NEXT**	 **3-kW Hall**	Constrained Arrival Date **3-kW Hall**
# operating thrusters	3	1	2	2
# of spare thrusters for lifetime	0	1	0	0
# of spare thrusters redundancy	1	1	1	1
total thrusters	4	3	3	3
total PPUs	4	2	3	3
throttling profile	n/a	High Thrust	High Eff	High Eff
trajectory	Direct	Direct	Direct	Direct
P0, kW	10.5	10.5	10.5	10.5
Propulsion duty cycle	90%	90%	90%	90%
Array degradation	2%/yr	2%/yr	2%/yr	2%/yr
Housekeeping power, W	250	250	250	250
Launch vehicle	Delta 2925H-9.5	Delta 2925H-9.5	Delta 2925H-9.5	Delta 2925H-9.5
C3, km2/s2	4.19	4.86	4.04	6.89
m0, kg	1304	1286	1308	1232
mp, kg	373	342	416	432
Xe contingency	10%	8.6%	10%	10%
Total Xe, kg	410	371	458	475
EP subsystem, kg	158	163	80	80
EP subsystem contingency	10%	30%	30%	30%
Dry EP w/contingency, kg	174	212	103	104
NDM, kg	**720**	**703**	**747**	**653**
Earth Launch	9-Mar-2010	10-Mar-2010	23-Feb-2010	20-May-2011
Wild 2 Arrival	21-May-2016	21-May-2016	21-May-2016	21-May-2016
Wild 2 Perihelion	20-Jul-2016	20-Jul-2016	20-Jul-2016	20-Jul-2016
Days prior to perihelion	**60**	**60**	**60**	**60**
Electric ΔV, km/s	9.85	9.79	9.92	10.48
Transfer time, years	**6.20**	**6.20**	**6.24**	**5.00**

NDM = launch mass - Xe mass - Dry EP system (w/contingency)

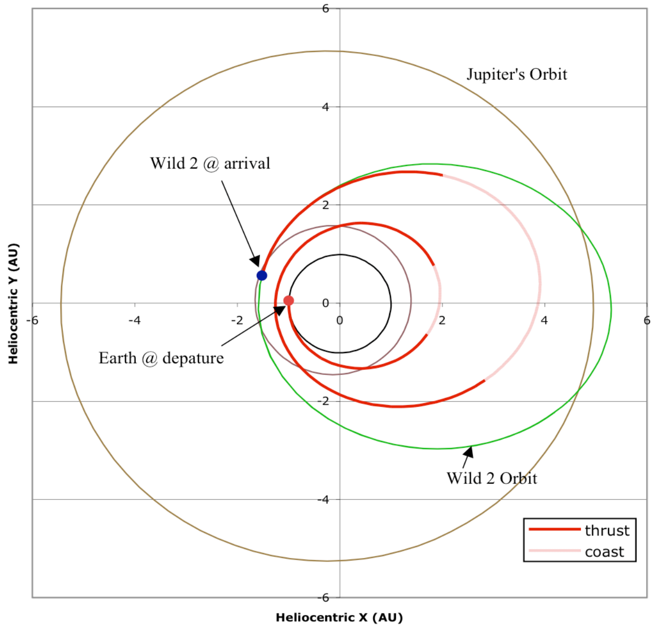


Figure 3. Representative Wild 2 Trajectory

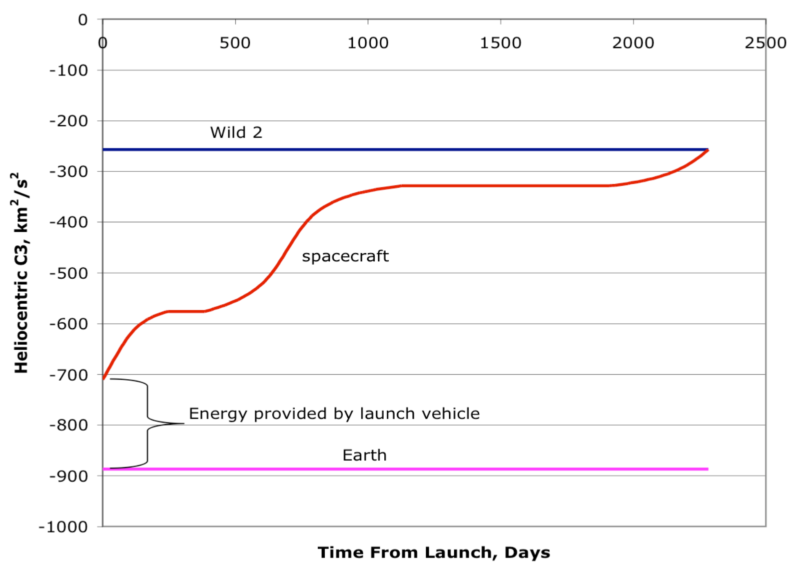


Figure 4. Energy Profile for Wild 2 Trajectory

COMET SURFACE SAMPLE RETURN

SEP technology and chemical performance results for a CSSR mission to Wirtanen are shown in Figure 5. A 10 kW BOL solar array provides power to the EP systems. With no constraint on the Earth entry velocity, the ballistic option requires 7 years with the aid of an EGA whereas the SEP options require 8 years via a direct transfer. Although an additional year is required for the SEP options, they deliver an average of ~20% more mass than the chemical option.

Figure 5 also illustrates the dramatic effect of constraining the entry velocity at Earth. For the chemical option, this additional ~ 1.4 km/s ΔV means that it is no longer a viable option *when launched on an Atlas 401*: its NDM is insufficient. A larger launch vehicle may enable the chemical option. Flying by Earth on the return leg may also enable this option. In fact, a recent chemical CSSR mission study used the largest launch vehicle available to NASA (Delta IV 4050H-19) and two EGAs (one on the return leg).[11] The result was a 9-yr transfer and a deterministic ΔV of 4.311 km/s. The chemical trajectory used in this analysis compares favorably: a 7-yr transfer with very similar ΔV (4.25 km/s).

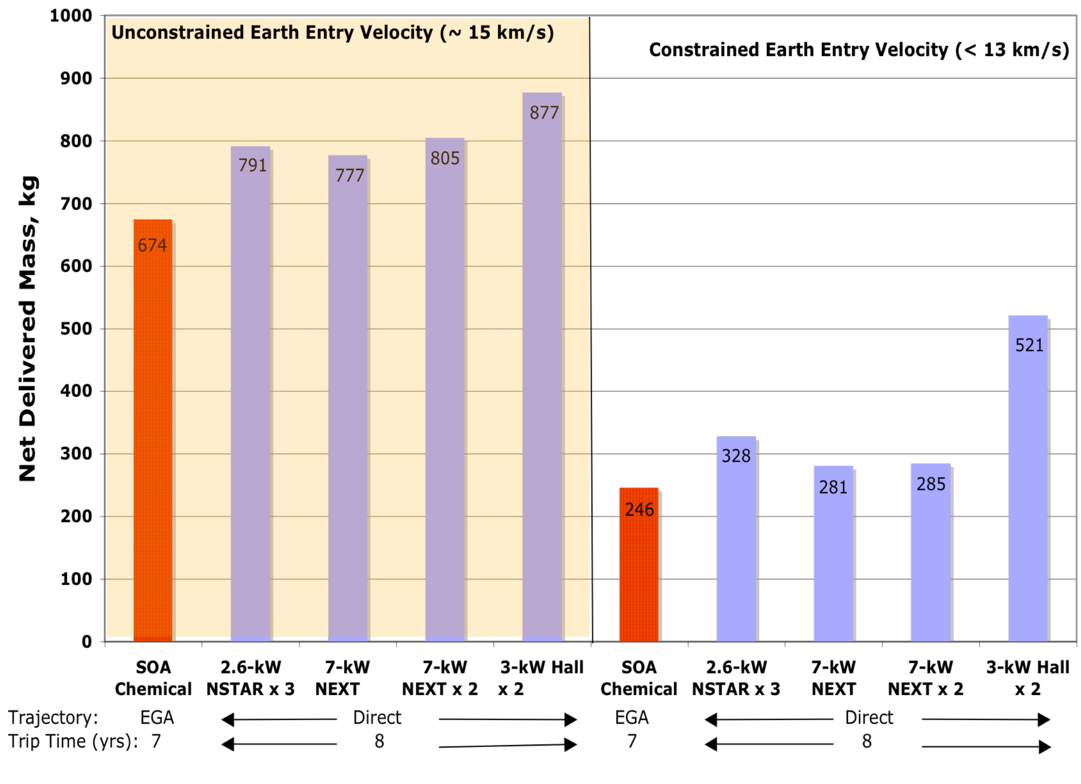


Figure 5. Wirtanen Performance Comparison

For the SEP technologies, the NDM is reduced ~40% - 65%. In fact, after meeting the entry velocity constraint, only the Hall thruster's NDM may be sufficiently large enough to constitute the rest of the spacecraft. This implies that the SEP options require more array power (and possibly more thrusters) *to meet the entry velocity constraint*.

Table IX and Table X details the performance results for the chemical and SEP options, respectively.

Table IX. SOA Chemical Performance Results for CSSR – Wirtanen

Parameter	Unconstrained Entry Velocity	Constrained Entry Velocity
trajectory	EGA	EGA
flyby altitude, km	500	500
Inclination change from flyby, deg	5.0	4.7
"Free" ΔV from flyby, km/s	7.341	7.385
Launch vehicle	Atlas 401	Atlas 401
C3, km2/s2	25.8	25.7
m0, kg	2045	2046
mp, kg	1075	1447
propellant contingency	8%	8%
Total propellant	1161	1563
Propulsion mass (tanks + engines)/mp	7%	7%
chem propulsion mass (tanks + engines)	81.3	109.4
Propulsion + propellant, kg	1242	1673
NDM, kg	**674**	**246**
Earth Launch	20-Jan-2016	21-Jan-16
Comet Arrival Date	18-Feb-2021	2-Jan-21
Comet position at Arrival, AU	4.74	4.85
Out of plane position (Z) at Arrival, AU	-0.218	-0.178
Comet Stay time, days	60	60
Mass left at comet, kg	125 (accounted for in Rocket EQ)	125 (accounted for in Rocket EQ)
Comet Departure Date	19-Apr-21	3-Mar-21
Comet position at Departure, AU	4.58	4.71
Out of plane position (Z) at Departure, AU	-0.267	-0.229
Earth Arrival Date	14-Dec-22	6-Dec-22
Sample Return Capsule mass, kg	128	128
Arrival Vhp, km/s	11.2	9.77
Arrival Declination, deg	46.0	31.2
Entry alt., km	125	125
Entry Velocity, km/s	15.4	14.4
Max Entry Velocity, km/s	13	13
ΔV Deep Space Manuever, km/s	0.744	0.700
ΔV Comet Arrival, km/s	1.399	1.487
ΔV Comet Departure, km/s	0.267	0.699
ΔV that is still needed to meet entry V, km/s	2.389	1.363
ΔV performed to meet entry V, km/s	0	1.363
Post Launch ΔV performed, km/s	**2.411**	**4.249**
Capsule Entry Velocity (after ΔV), km/s	**15.4**	**13.0**
Transfer time, years	**6.90**	**6.87**

NDM = launch mass - propulsion mass (tanks + engines) - propellant mass - sample return capsule mass
NDM includes 80 kg of science instruments

Table X. SEP Technology Performance Comparison Results for CSSR – Wirtanen

	Unconstrained Entry Velocity				Constrained Entry Velocity			
Parameter	2.6-kW NSTAR	7-kW NEXT	7-kW NEXT	3-kW Hall	2.6-kW NSTAR	7-kW NEXT	7-kW NEXT	3-kW Hall
# operating thrusters	3	1	2	2	3	1	2	2
# of spare thrusters for lifetime	0	1	0	0	0	1	0	1
# of spare thrusters for redundancy	1	1	1	1	1	1	1	1
total thrusters	4	3	3	3	4	3	3	4
total PPUs	4	2	3	3	4	2	3	3
throttling profile	n/a	High Thrust	High Thrust	High Eff	n/a	High Thrust	High Thrust	High Eff
trajectory	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct
P0, kW	10	10	10	10	10	10	10	10
Propulsion duty cycle	90%	90%	90%	90%	90%	90%	90%	90%
Array degradation	2%/yr	2%/yr	2%/yr	2%/yr	2%/yr	2%/yr	2%/yr	2%/yr
Housekeeping power, W	250	250	250	250	250	250	250	250
Launch vehicle	Atlas 401	Atlas 401	Atlas 401	Atlas 401	Atlas 401	Atlas 401	Atlas 401	Atlas 401
C3, km2/s2	36.8	36.4	33.4	34.0	48.2	48.3	44.0	36.0
m0, kg	1583.9	1596.5	1715.8	1692.4	1168.0	1165.2	1315.2	1614.8
mp, kg	334.3	327.7	368.8	417.2	375.2	384.0	472.9	646.1
Xe contingency	10%	8.6%	8.6%	10%	10%	8.6%	8.6%	10%
Total Xe, kg	368	356	401	459	413	417	514	711
EP subsystem, kg	156	162	198	80	158	165	203	100
EP subsystem contingency	10%	30%	30%	30%	10%	30%	30%	30%
Dry EP w/contingency, kg	172	211	257	103	174	214	264	130
NDM, kg	**791**	**777**	**805**	**877**	**328**	**281**	**285**	**521**
Earth Launch	9-Dec-15	9-Dec-15	6-Dec-15	30-Nov-15	22-Dec-2015	22-Dec-2015	22-Dec-2015	8-Dec-2015
Comet Arrival Date	8-Mar-19	8-Mar-19	8-Mar-19	2-Apr-2019	7-Dec-2018	4-Dec-2018	7-Dec-2018	22-Jan-19
Comet position at Arrival, AU	1.43	1.43	1.43	1.64	1.08	1.09	1.08	1.13
Out of plane position (Z) at Arrival, AU	0.266	0.266	0.265	0.329	-0.083	-0.098	-0.085	0.112
Comet Stay time, days	60	60	60	60	60	60	60	59
Mass left at comet, kg	125	125	125	125	125	125	125	125
Comet Departure Date	7-May-19	7-May-19	7-May-19	1-Jun-19	5-Feb-19	2-Feb-19	5-Feb-19	22-Mar-19
Comet position at Departure, AU	1.93	1.93	1.93	2.15	1.21	1.19	1.21	1.55
Out of plane position (Z) at Departure, AU	0.392	0.392	0.392	0.427	0.167	0.154	0.166	0.304
Earth Arrival Date	2-Dec-23	5-Dec-23	9-Dec-23	14-Dec-23	25-Dec-23	26-Dec-23	26-Dec-23	27-Dec-23
Sample Return Capsule mass, kg	128	128	128	128	128	128	128	128
Arrival Vhp, km/s	10.92	10.95	11.0	11.2	7.07	7.07	7.07	6.80
Arrival Declination, deg	44.11	45.91	48.2	50.0	34.4	33.5	35.3	24.0
Entry alt., km	125	125	125	125	125	125	125	125
Capsule Entry Velocity, km/s	**15.21**	**15.24**	**15.29**	**15.42**	**12.75**	**12.74**	**12.75**	**12.56**
Max Entry Velocity, km/s	13	13	13	13	13	13	13	13
Req'd ΔV to meet entry V, km/s	2.21	2.24	2.29	2.42	-0.25	-0.26	-0.25	-0.44
Electric ΔV performed, km/s	6.93	6.78	6.79	6.73	11.90	12.25	12.15	11.09
ΔV that is still needed, km/s	2.21	2.24	2.29	2.42	-	-	-	-
Transfer time, years	**7.98**	**7.99**	**8.01**	**8.04**	**8.01**	**8.01**	**8.01**	**8.05**

NDM = launch mass - Xe mass - Dry EP mass (w/contingency) - mass left @ comet - sample return capsule mass
NDM includes 80 kg of science instruments

Figure 6 shows the in-the-ecliptic-plane (hereafter referred to as in-plane or out-of-plane) trajectory for the chemical option. Similar to the Rosetta mission, the spacecraft rendezvous with Wirtanen just past aphelion. Figure 7 and Figure 8 show the out-of-plane trajectory for the unconstrained and constrained entry velocity instances, respectively. Comparing these two figures, one can see that constraining the entry velocity forces the spacecraft to perform a plane change on the return leg. This results in a larger comet departure ΔV, but a lower Earth arrival hyperbolic excess speed (arrival V_∞). To meet this constraint the spacecraft must also arrive sooner at the comet (about a month sooner for this case).

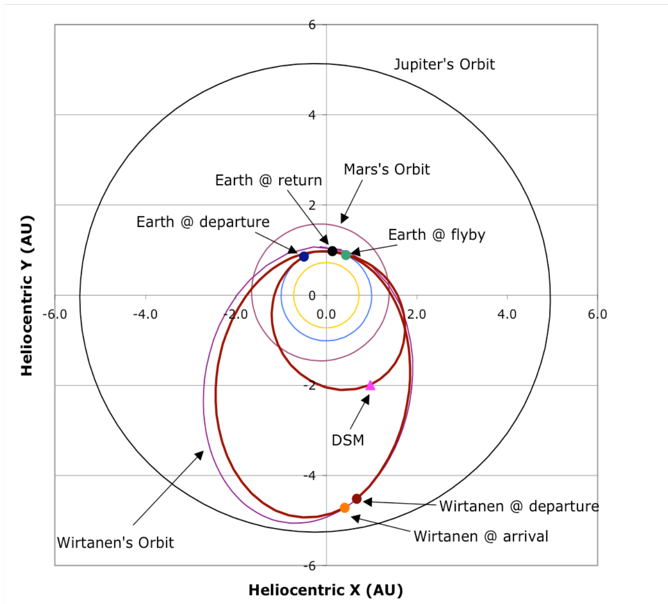


Figure 6. Chemical Trajectory: CCSR Wirtanen

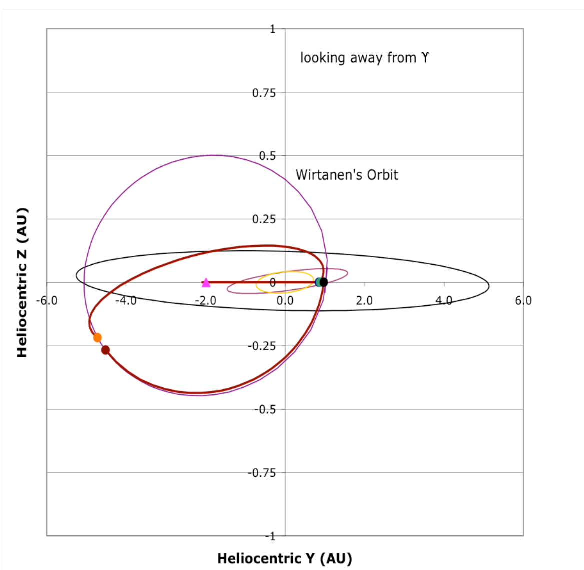


Figure 7. Out-of-Plane Chemical Trajectory (<u>Unconstrained</u> Earth Entry Velocity): CCSR Wirtanen

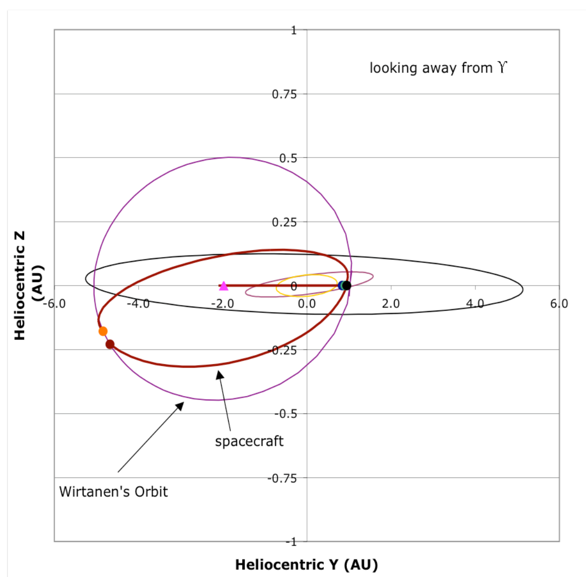


Figure 8. Out-of-Plane Chemical Trajectory (<u>Constrained</u> Earth Entry Velocity): CCSR Wirtanen

Likewise, Figure 9 and Figure 10 show representative in-plane and out-of-plane SEP trajectories when the Earth entry velocity is unconstrained. Unlike the chemical option, the SEP spacecraft does not rendezvous with Wirtanen far away from the sun; it rendezvous with Wirtanen just past perihelion.

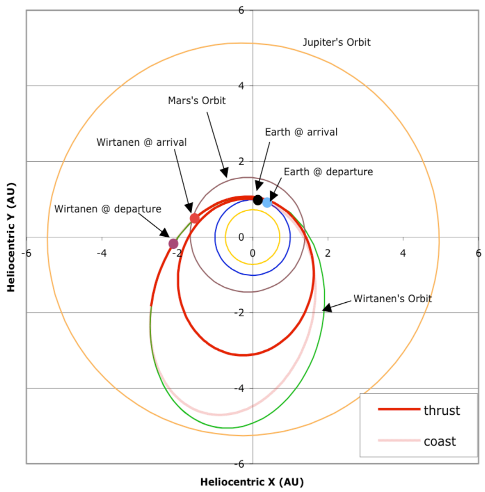


Figure 9. Representative In-Plane SEP Trajectory (Unconstrained Earth Entry Velocity): CCSR Wirtanen

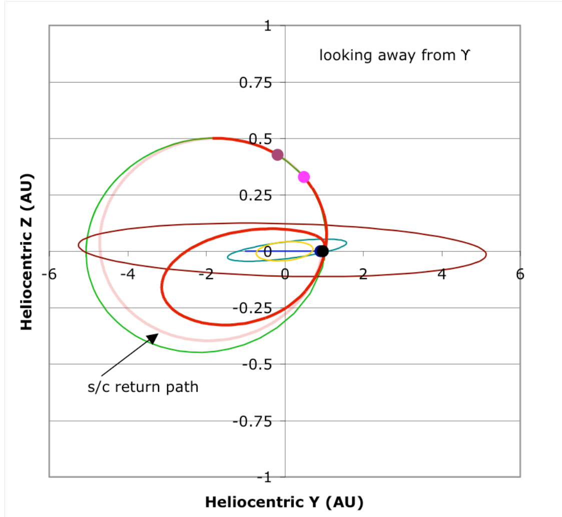


Figure 10. Representative Out-of-Plane Trajectory (Unconstrained Earth Entry Velocity): CCSR Wirtanen

Figure 11 and Figure 12 show the spacecraft's path when constraining the Earth entry velocity using SEP. Again, the return-leg plane change is apparent when comparing Figure 10 and Figure 12. The spacecraft spends much more time thrusting after departing Wirtanen. It also arrives at Wirtanen 2 – 3 months sooner. This means that when meeting the entry velocity constraint, the spacecraft arrives at the comet when it is even closer to the sun.

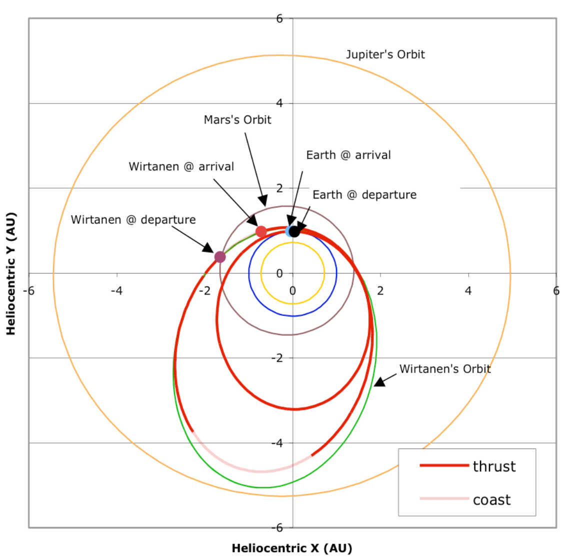


Figure 11. Representative In-Plane SEP Trajectory (Constrained Earth Entry Velocity): CCSR Wirtanen

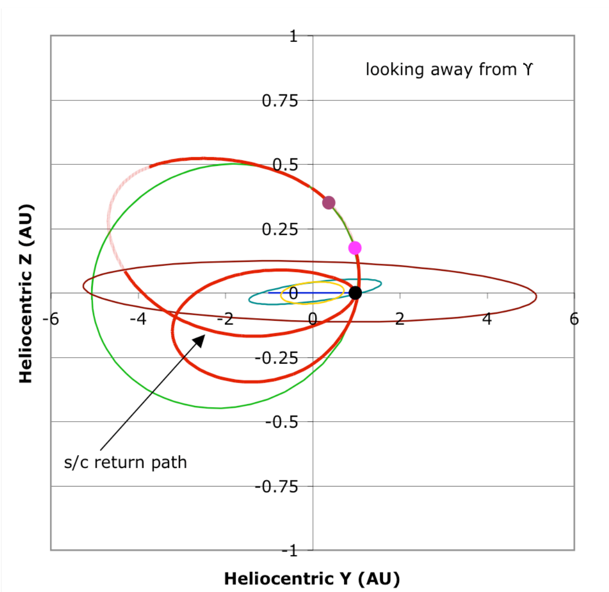
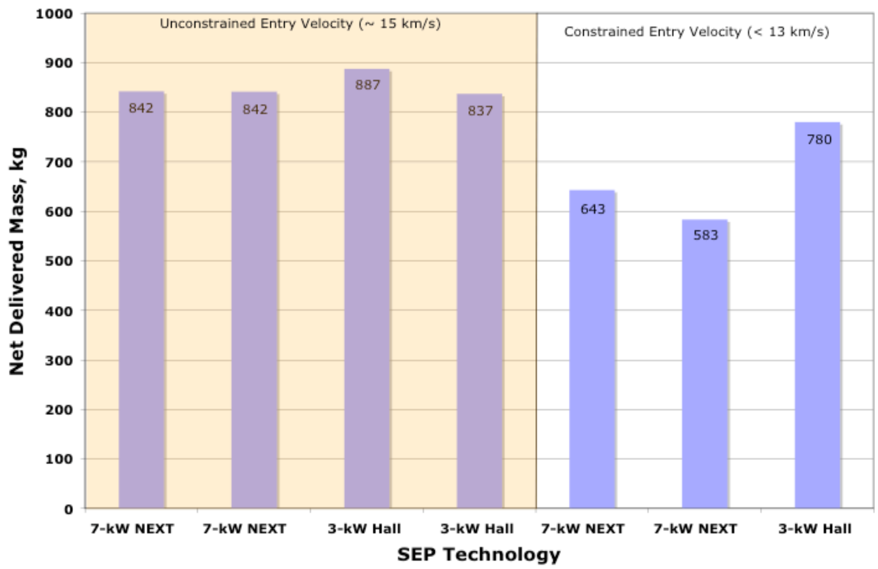


Figure 12. Representative Out-of-Plane Trajectory (Constrained Earth Entry Velocity): CCSR Wirtanen

The results for a CSSR mission to Tempel 1 are presented in the same fashion as the results for Wirtanen. Figure 13 shows the selected SEP technology performance comparison. This mission utilized a 15 kW BOL array. A larger SEP system (an additional 5 kW in BOL array power and more thrusters), relative to Wirtanen, results in a ~ 6% average NDM increase *for the unconstrained Earth entry velocity instance*. However, the largest NDM for Wirtanen (877 kg) and Tempel 1 (887 kg) differs by only 10 kg (~ 1%).



# operating thrusters:	2	2	3	2	2	2	3
# thrusters for lifetime:	1	0	0	1	1	1	0
# total thrusters:	4	3	4	4	4	4	4
Throttle profile:	high thrust	high Isp	high eff	high eff	high thrust	high Isp	high eff
Transfer time (yrs):	8	8	7	7	8	8	7

Figure 13. Tempel 1 Performance Comparison

In contrast to the flight time for Wirtanen, not all the SEP technologies require the same transfer time for Tempel 1. The spacecraft with ion thrusters still requires 8 years, but the spacecraft with Hall thrusters requires only 7 years. The trade-off for this reduced flight time is an additional operating thruster (3 vs. 2). However, when constraining the entry velocity, both SEP technologies require a total of four thrusters.

Figure 13 also shows that imposing an entry velocity constraint significantly reduces the NDM by ~12% - 30%. This mass reduction is less severe than the CSSR mission to Wirtanen. I attribute this to two factors: 1) the difference in array power (15 kW—Tempel 1 vs. 10 kW—Wirtanen), and 2) the difference in perihelion (1.51 A.U.—Tempel 1 vs. 1.06 A.U.—Wirtanen). It is unclear which one affects performance more.

Table XI lists the detailed Tempel 1 performance results. Two particular results are worth noting. Firstly, the spacecraft arrives at Tempel 1 about two months sooner when meeting the entry velocity constraint for the 8-yr trajectories. This spacecraft Tempel 1 arrival date variation is much less for the 7-year trajectory (on the order of a week). Secondly, the differences in Earth arrival declination between the unconstrained and constrained entry velocity instances (for the same SEP technology) indicate that the spacecraft performs a plane change on the return leg. This return leg plane change is similar to the Wirtanen mission albeit from a different direction (above Earth instead of below Earth).

Figure 14 shows the in-plane trajectory for the 7-year transfer. Figure 15 illustrates the magnitude of the plane change that the spacecraft's primary propulsion performs when returning to Earth from Wirtanen or Tempel so as not to exceed the 13 km/s entry velocity constraint.

Table XI. SEP Technology Performance Comparison Results for CSSR – Tempel 1

Parameter	Unconstrained Entry Velocity				Constrained Entry Velocity		
	7-kW NEXT	7-kW NEXT	3-kW Hall	3-kW Hall	7-kW NEXT	7-kW NEXT	3-kW Hall
# operating thrusters	2	2	3	2	2	2	3
# of spare thrusters for lifetime	1	0	0	1	1	1	0
# of spare thrusters for redundancy	1	1	1	1	1	1	1
total thrusters	**4**	**3**	4	4	4	4	4
total PPUs	3	3	4	3	3	3	4
throttling profile	High Thrust	High Isp	High Eff	High Eff	High Thrust	High isp	High Eff
trajectory	Direct	Direct	Direct	Direct	Direct	Direct	Direct
P0, kW	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Propulsion duty cycle	90%	90%	90%	90%	90%	90%	90%
Array degradation	2%/yr	2%/yr	2%/yr	2%/yr	2%/yr	2%/yr	2%/yr
Housekeeping power, W	250	250	250	250	250	250	250
Launch vehicle	Atlas 401	Atlas 401	Atlas 401	Atlas 401	Atlas 401	Atlas 401	Atlas 401
C3, km2/s2	24.5	26.8	26.2	29.6	28.8	31.3	26.3
m0, kg	2013.1	1915.8	2026.0	1877.6	1910.1	1805.7	2019.2
mp, kg	570.7	510.8	675.0	600.1	654.3	615.5	761.4
Xe contingency	8.6%	8.6%	10.0%	10.0%	8.6%	8.6%	10.0%
Total Xe, kg	620	555	743	660	711	668	838
EP subsystem, kg	229	205	110	98	233	232	114
EP subsystem contingency	30%	30%	30%	30%	30%	30%	30%
Dry EP w/contingency, kg	298	266	143	127	304	301	149
NDM, kg	**842**	**842**	**887**	**837**	**643**	**583**	**780**
Earth Launch	18-May-13	16-May-13	19-May-13	21-May-13	24-May-13	27-May-13	20-May-13
Comet Arrival Date	5-Oct-16	22-Oct-16	27-Aug-16	3-Sep-16	28-Jul-16	31-Jul-16	18-Aug-16
Comet position at Arrival, AU	1.74	1.82	1.58	1.61	1.51	1.52	1.56
Out of plane position (Z) at Arrival, AU	-0.249	-0.288	-0.147	-0.169	-0.059	-0.066	-0.121
Comet Stay time, days	60	60	60	60	60	60	60
Mass left at comet, kg	125	125	125	125	125	125	125
Comet Departure Date	4-Dec-16	21-Dec-16	26-Oct-16	2-Nov-16	26-Sep-16	29-Sep-16	17-Oct-16
Comet position at Departure, AU	2.06	2.16	1.84	1.88	1.70	1.71	1.80
Out of plane position (Z) at Departure, AU	-0.367	-0.391	-0.297	-0.312	-0.229	-0.235	-0.277
Earth Arrival Date	3-Jun-21	1-Jun-21	27-May-20	27-May-20	14-Jun-21	14-Jun-21	24-May-20
Sample Return Capsule mass, kg	128	128	128	128	128	128	128
Arrival Vhp, km/s	9.81	9.81	10.55	10.60	6.80	6.80	7.00
Arrival Declination, deg	-42.20	-41.79	-57.39	-57.62	-34.05	-32.80	-33.76
Entry alt., km	125	125	125	125	125	125	125
Capsule Entry Velocity, km/s	**14.44**	**14.44**	**15.04**	**15.07**	**12.60**	**12.59**	**12.70**
Max Entry Velocity, km/s	13	13	13	13	13	13	13
Req'd ΔV to meet entry V, km/s	1.44	1.44	2.04	2.07	-0.40	-0.41	-0.30
Electric ΔV performed, km/s	10.41	10.03	9.71	9.35	12.64	12.40	11.71
ΔV that is still needed, km/s	1.44	1.44	2.04	2.07	-	-	-
Transfer time, years	**8.04**	**8.04**	**7.02**	**7.02**	**8.06**	**8.05**	**7.01**

NDM = launch mass - Xe mass - Dry EP mass (w/contingency) - mass left @ comet - sample return capsule mass
NDM includes 80 kg of science instruments

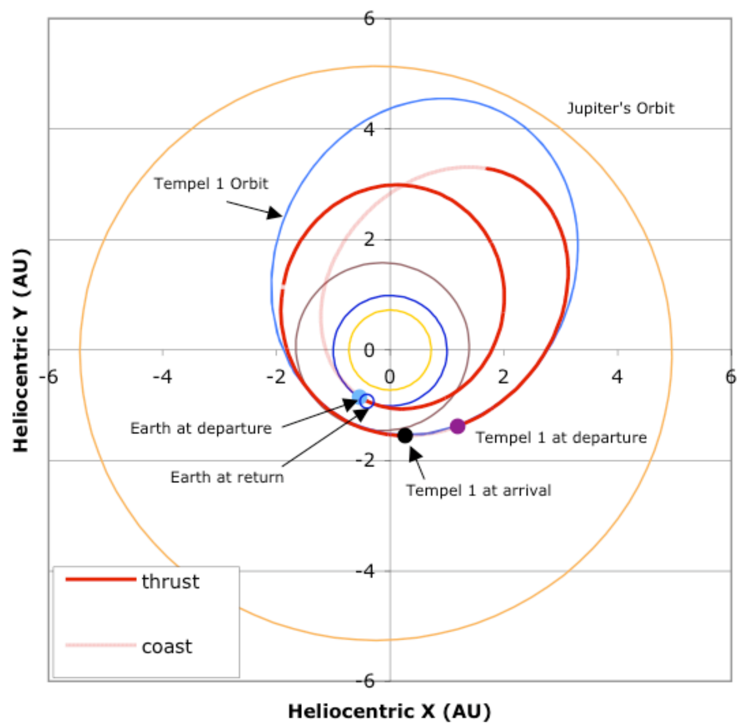


Figure 14. In-Plane 7-Year Tempel 1 Trajectory

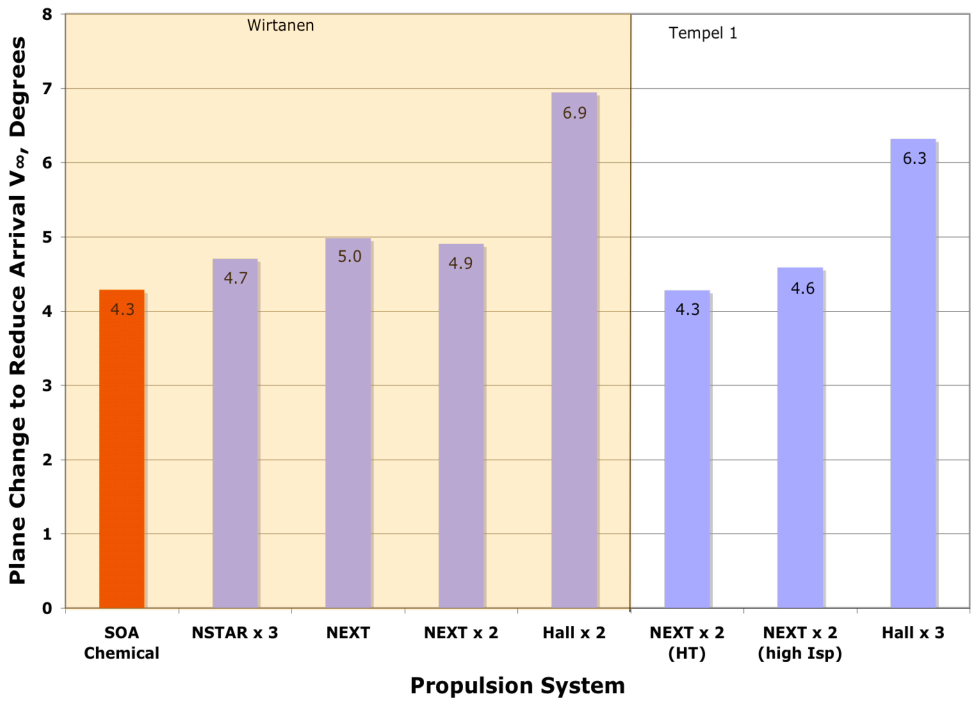


Figure 15. Return Leg Plane Change from Wirtanen and Tempel 1

TROJAN ASTEROID/CENTAUR OBJECT RECONNAISSANCE FLYBY

Performance results for NEXT are shown in Figure 16 for two different Trojan asteroid/Centaur object combinations. Table XII lists the detailed performance results. Although flight times can vary for these missions, the flight times shown are nearly optimal for each Trojan asteroid/Centaur object combination. The spacecraft's NDM to the higher A.U./lower inclination target (2764/2001 XZ255) roughly doubles that of the lower A.U./higher inclination target (4035/2001 BL41). The trade-offs for this larger NDM include an additional two years of flight, thermal issues associated with a Venus flyby, and a higher Trojan asteroid flyby speed. This flyby speed at the Trojan asteroid and Centaur object will be influenced by transfer time and trajectory variations. Table XIII compares flyby speeds for this notional Trojan/Centaur mission to past and current missions. The flyby speeds for the Trojan asteroid are greater than the Centaur objects. Flyby speeds of both targets are approximately within the range of flyby speeds of past and current missions. Pandares's (2674) relatively larger radius may enable a relatively higher flyby speed.

Figure 17 and Figure 18 show the in-plane and out-of-plane spacecraft trajectory when targeting 4035/2001 BL41. Figure 20 shows the in-plane trajectory for the 2764/2001 XZ255 mission. These figures show the spacecraft thrusting all the way out to ~ 4 A.U. The gravity assist increases orbital kinetic energy (velocity) of the spacecraft to reduce some of the propulsive burden. The EGA also provides about a 7-degree plane change for the higher inclined targets. The out-of-plane trajectory (Figure 18) gives insight into one of the more challenging aspects of trajectory design: flying by three points in space whose orbits all have different orientations.

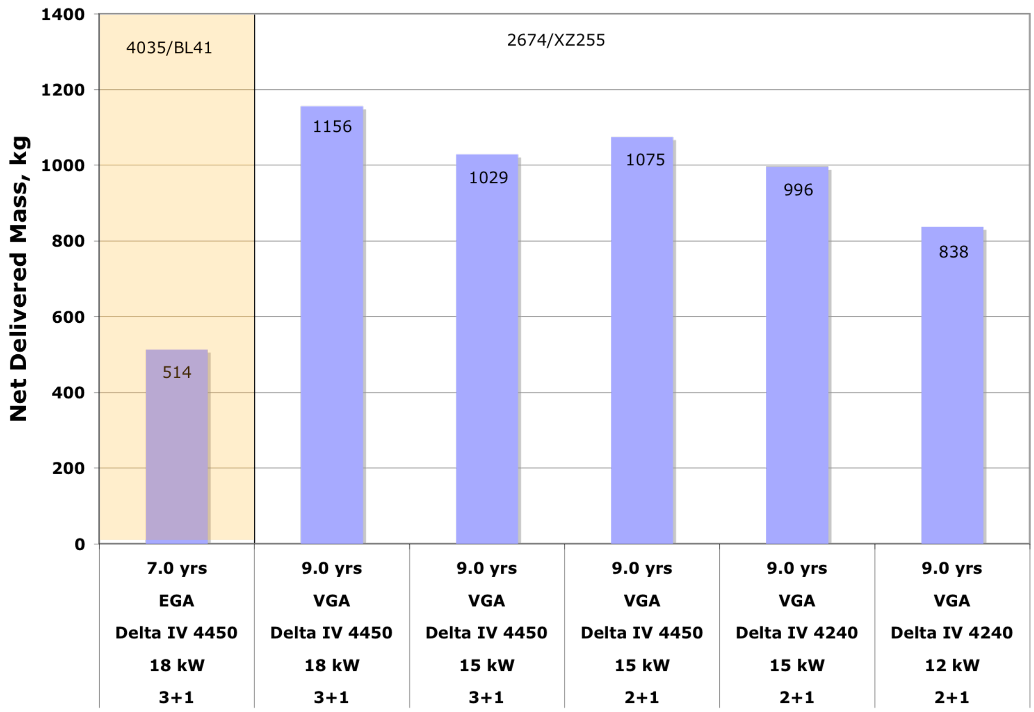


Figure 16. NEXT Performance for Trojan/Centaur Reconnaissance Flyby

Table XII. NEXT Detailed Performance Results for Trojan/Centaur Reconnaissance Flyby

		Trojan/Centaur				
Parameter	**4035/BL41**	**2674/XZ255**	**2674/XZ255**	**2674/XZ255**	**2674/XZ255**	**2674/XZ255**
# operating thrusters	3	3	3	2	2	2
# of spare thrusters for lifetime	0	0	0	0	0	0
# of spare thrusters for redundancy	1	1	1	1	1	1
total thrusters	4	4	4	3	3	3
total PPUs	4	4	4	3	3	3
throttling profile	High Thrust	High Thrust	High Thrust	High Thrust	High Thrust	High Thrust
trajectory	EGA	VGA	VGA	VGA	VGA	VGA
P0, kW	18	18	15	15	15	12
Propulsion duty cycle	90%	90%	90%	90%	90%	90%
Array degradation	2%/yr	2%/yr	2%/yr	2%/yr	2%/yr	2%/yr
Housekeeping power, W	250	250	250	250	250	250
Launch vehicle	Delta IV 4450	Delta IV 4450	Delta IV 4450	Delta IV 4450	Delta IV 4240	Delta IV 4240
C3, km2/s2	30.3	20.8	24.1	26.2	23.8	27.4
m0, kg	2185.1	2836.7	2599.4	2457.8	2353.7	2140.4
mp, kg	636.4	598.8	542.1	487.9	472.8	462.9
Xe contingency	8.6%	8.6%	8.6%	8.6%	8.6%	8.6%
Total Xe, kg	691	650	589	530	514	503
SEP dry mass	754	792	755	656	649	615
SEP contingency	30%	30%	30%	30%	30%	30%
Dry SEP w/contingency, kg	980	1030	982	853	844	800
NDM, kg	**514**	**1156**	**1029**	**1075**	**996**	**838**
Earth Launch	20-Feb-14	17-Oct-15	23-Oct-15	28-Oct-2015	24-Oct-2015	30-Oct-2015
Gravity Assist Date	21-Jan-16	10-Apr-18	9-Apr-18	12-Apr-2018	11-Apr-2018	11-Apr-2018
"Free" ΔV from GA, km/s	7.237	5.830	5.848	5.691	5.727	5.733
Inclination change from GA, deg	6.69	1.30	1.36	1.59	1.51	1.63
Trojan Flyby Date	9-Aug-17	11-Apr-19	11-Apr-19	11-Apr-19	11-Apr-19	11-Apr-19
Trojan Flyby Vhp, km/s	12.33	17.76	17.74	17.74	17.75	17.72
Centaur Flyby Date	19-Feb-21	17-Oct-24	22-Oct-24	27-Oct-24	23-Oct-24	29-Oct-24
Centaur Flyby Vhp, km/s	7.85	8.80	8.76	8.74	8.77	8.73
Centaur Flyby DAP, deg	-15.763	3.32	3.32	3.32	3.32	3.32
Minimum Radius, AU	0.982	0.679	0.681	0.670	0.672	0.675
Maximum Radius, AU	10.574	16.450	16.450	16.449	16.450	16.449
Maximum Thrusting Radius, AU	4.418	4.035	4.024	4.024	4.024	3.604
Electric ΔV, km/s	10.48	8.19	7.74	7.26	7.62	7.18
Transfer time, years	**7.00**	**9.00**	**9.00**	**9.00**	**9.00**	**9.00**

NDM = launch mass - Xe mass - dry SEP stage mass (w/contingency)
NDM consists of power (RPS) mass, structure, science package, etc.

Table XIII. Primitive Body Flyby Speeds of Past and Current Missions

Mission	Body	Radius, km	Flyby Velocity, km/s	Encounter Date
Galileo	Gaspra	6.1	8.0	Oct-91
Galileo	Ida	16.0	12.6	Aug-93
NEAR	Mathilde	26.4	9.9	Jun-97
DS1	Braille	n/a	15.6	Jul-99
DS1	Borrelly	2.4	16.5	Sep-01
STARDUST	Annefrank	2.4	7.0	Nov-02
Rosetta	Steins	?	9.0	Sep-08
Rosetta	Lutetia	47.9	15.0	Jul-10
Trojan/Centaur	**4035**	**34.3**	**12.3**	**Aug-17**
Trojan/Centaur	**Pandarus**	**49.0**	**17.7**	**Apr-19**
Trojan/Centaur	**2001 BL41**	**?**	**7.9**	**Feb-21**
Trojan/Centaur	**2001 XZ255**	**?**	**8.8**	**Oct-24**

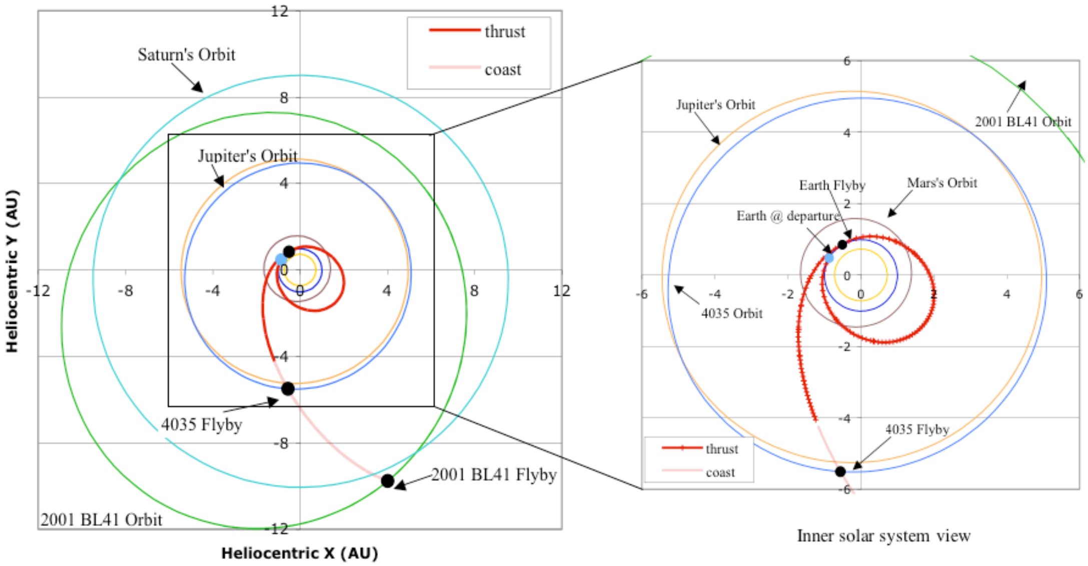


Figure 17. Trojan/Centaur Reconnaissance Flyby Trajectory (EGA)

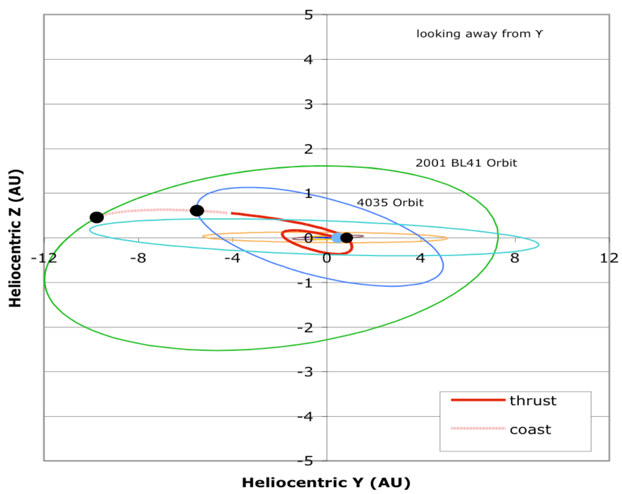


Figure 18. Trojan/Centaur Trajectory With EGA Out-of-Plane View

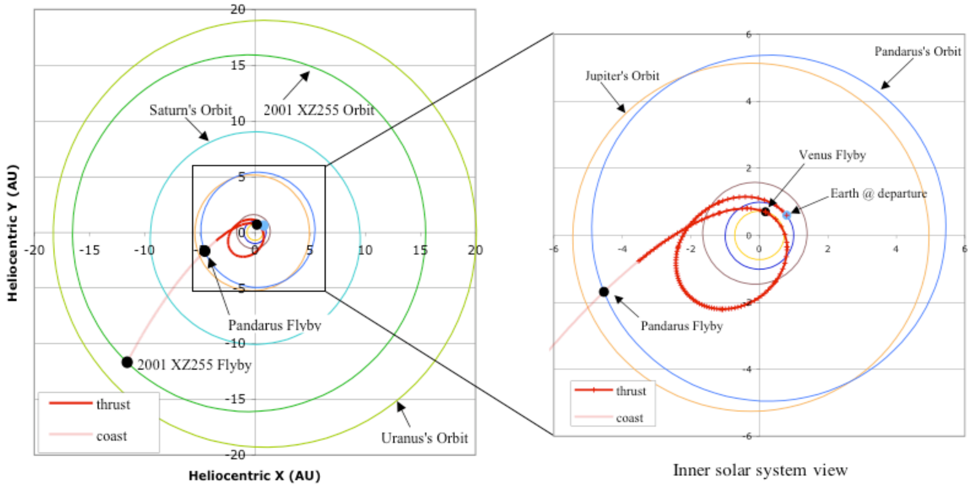


Figure 20. Trojan/Centaur Reconnaissance Flyby Trajectory (VGA)

SUMMARY AND CONCLUSIONS

The performance of SEP was assessed for three different primitive body science missions—two NF class missions (CSSR and Trojan/Centaur Reconnaissance Flyby) and one Discovery class mission (Comet Rendezvous). Two of the three missions considered mission constraints such as arrival date and Earth entry velocity. The other mission (Trojan/Centaur Reconnaissance Flyby) provided potential Trojan asteroid/Centaur object combinations and trajectory options. Additionally, the CSSR mission analysis provided payload assumptions (and rationale) in large part to serve as NASA's NF DRM. This DRM enables the evaluation of current and future SEP technologies for this mission class.

As a result of this work, several general findings are noted:

- NEXT generally requires the fewest operating thrusters, but is also the heaviest EP system;
- The advanced Hall EP system is generally the lightest, but is also the least mature. Consequently, for certain missions (*not all*) this enables a larger NDM. These missions include the 2010 Comet Rendezvous and the *unconstrained* Earth entry velocity CSSR instances.
- All missions require thrusting as far as ~ 3 – 4 A.U.
- Launch vehicle requirements range from a Delta II (heavy) to a Delta IV medium-class.
- BOL solar array power requirements range from 10 – 18 kW.
- Transfer times range from 5 – 9 years.
- The number of simultaneously operating thrusters range from 1 – 3.

Findings noted for each specific mission include:

- Comet Rendezvous (arrival date constraint with launch year variation): All three SEP technologies deliver an average of ~ 725 kg. However, no solution was found for NSTAR and NEXT when launching a year later—only the advanced Hall system could meet the arrival date constraint when launched a year later.

- CSSR (Earth entry velocity constraint): the spacecraft performs an average 5-degree plane change when returning from Wirtanen or Tempel 1. Consequently, NDM is reduced 12% - 65% (relative to the unconstrained option). This mass reduction is more severe: 1) when returning from Wirtanen rather than Tempel 1, and 2) for the ion thrusters (NEXT and NSTAR). Additionally, the SEP spacecraft tends to arrive at the comet close to perihelion and even closer when meeting the entry velocity constraint. In contrast, the chemical option arrives at the comet near aphelion. Finally, not all SEP technologies require the same flight time—the advanced Hall system requires one less year for a CSSR mission to Tempel 1.

- Trojan/Centaur Reconnaissance Flyby: the spacecraft delivers more NDM to the higher A.U./lower inclination target than the lower A.U./higher inclination target.

As a result of these findings, I conclude the following:

- SEP technologies with higher thrust-to-power ratios can reduce flight time. This flight time reduction could enable the mission (e.g. the 2011 Comet Rendezvous) or reduce operational costs (e.g. a 7-year vs. 8-year CSSR mission).

- Higher thrust-to-power ratios provide more efficient plane changes—advanced Hall systems NDM is reduced less than that of NEXT and NSTAR for the CSSR constrained Earth entry velocity instances.

- Regarding the CSSR mission to Wirtanen, if arriving at the comet near *aphelion* is preferred, a chemical option (possibly utilizing the largest launch vehicle) with at least one gravity assist *appears* to be enabling (requires further study).

- The Trojan/Centaur Object Reconnaissance Flyby mission (for the Trojan asteroid/Centaur object combinations assessed in this study) will likely require a radioisotope power source if the mission launches in 2014/2015. It is unknown what launch year or Centaur object would enable just a solar-powered mission.

FUTURE WORK

The CSSR mission offers obvious opportunities for future work. Because a return leg plane change increases propellant loading, an examination of other ways to reduce the entry velocity at Earth (assuming that Earth entry velocities that are commensurate with past and current missions are desirable or necessary) would be beneficial. Specifically desirable would be an assessment of the trade-offs of TPS improvements or an EGA on the return leg vs. tasking the spacecraft's primary propulsion system to slow down prior to arriving at Earth. Moreover, if rendezvousing with the comet far way from the sun is desirable, trajectory adjustments for SEP need to be assessed.

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13. ABSTRACT *(Maximum 200 words)*

This paper describes work that assesses the performance of solar electric propulsion (SEP) for three different primitive body science missions: 1) Comet Rendezvous 2) Comet Surface Sample Return (CSSR), and 3) a Trojan asteroid/Centaur object Reconnaissance Flyby. Each of these missions launches from Earth between 2010 and 2016. Beginning-of-life (BOL) solar array power (referenced at 1 A.U.) varies from 10 to 18 kW. Launch vehicle selections range from a Delta II to a Delta IV medium-class. The primary figure of merit (FOM) is net delivered mass (NDM). This analysis considers the effects of imposing various mission constraints on the Comet Rendezvous and CSSR missions. Specifically, the Comet Rendezvous mission analysis examines an arrival date constraint with a launch year variation, whereas the CSSR mission analysis investigates an Earth entry velocity constraint commensurate with past and current missions. Additionally, the CSSR mission analysis establishes NASA's New Frontiers (NF) Design Reference Mission (DRM) in order to evaluate current and future SEP technologies. The results show that transfer times range from 5 to 9 years (depending on the mission). More importantly, the spacecraft's primary propulsion system performs an average 5-degree plane change on the return leg of the CSSR mission to meet the previously mentioned Earth entry velocity constraint. Consequently, these analyses show that SEP technologies that have higher thrust-to-power ratios can: 1) reduce flight time, and 2) change planes more efficiently.

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