

Solar Electric Propulsion (SEP) Benefits for Near Term Space Exploration

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Aerojet Rocketdyne has completed mission analysis trade studies to support near-term cislunar exploration mission concepts by comparing cargo delivery to the Earth-Moon Lagrange points (EML1 or EML2) using a solar electric propulsion (SEP) stage (or “tug”) versus the most efficient all-chemical approach. Aerojet Rocketdyne has also analyzed historical NASA science missions to illustrate how it is possible to reduce mission cost by utilizing SEP technology. The EML2 analysis examined the relationship between total delivered mass to the destination, trip time required, and power level at the SEP thrusters and focused on flight-proven performance regimes for thruster and solar array performance. The EML2 analysis results show how SEP enables the delivery of significantly more total mass versus all-chemical approaches, with the benefits increasing as SEP trip time is allowed to increase. SEP solutions can actually deliver up to twice as much mass to EML2 versus a chemical solution or the same mass on a lower cost launch vehicle. Aerojet Rocketdyne also examined the relationships between transfer time, delivered cargo, and EML2 campaign costs versus chemical solutions, finding that incorporating SEP tugs in the campaign can reduce cost per delivered cargo mass (\$/kg) by over 50% compared to chemical. The results showed that SEP tugs reduce the number of launch vehicles required for the EML2 campaign, which is by far the largest campaign cost driver. The performance trends of the EML2 analysis are also applicable to distant retrograde orbits in the earth-moon space with only a small performance penalty to the performance curves shown herein. Overall, using SEP tugs for space exploration and cargo delivery dramatically increases mission flexibility over all-chemical solutions, and can enable significant mission and campaign cost savings.

Nomenclature

ACS	=	Attitude Control System
AEHF	=	Advanced Extreme High Frequency Satellite
AI&T	=	Assembly, Integration, and Test
BOL	=	Beginning of Life
C3	=	Characteristic Energy
CP	=	Chemical Propulsion
DSN	=	Deep Space Network
EELV	=	Evolved Expendable Launch Vehicle
EML1	=	Earth-Moon Lagrange Point 1
EML2	=	Earth-Moon Lagrange Point 2
GN&C	=	Guidance, Navigation, and Control

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HEO	=	High Earth Orbit
LV	=	Launch Vehicle
I_{sp}	=	Specific Impulse
ISS	=	International Space Station
EP	=	Electric Propulsion
GEO	=	Geostationary Orbit
MEO	=	Medium Earth Orbit
MPLM	=	Multi-Purpose Logistics Module
OTS	=	Off-the-shelf
PMAD	=	Power Management and Distribution System
SADA	=	Solar Array Drive Assembly
S/C	=	Spacecraft
SEP	=	Solar Electric Propulsion
SLS	=	Space Launch System
TRL	=	Technology Readiness Level
USCM8	=	Unmanned Space Vehicle Cost Model, 8 th Edition
WSBT	=	Weak Stability Boundary Trajectory

I. Introduction

SOLAR electric propulsion (SEP) has long been recognized as an efficient way to perform station-keeping and perform primary mission maneuvers for deep space missions. However, since the demonstration of SEP primary propulsion on Deep Space 1, Dawn, and the recent AEHF rescue¹, there has been an intense interest in SEP as a means of primary spacecraft propulsion for other mission types. Earlier this year, NASA announced plans to perform an asteroid redirect mission which will utilize SEP as a major element of the mission architecture.^{2,3} Industry is also committing itself to SEP technologies for full orbit acquisition roles. No piece of news demonstrates this better than Boeing's 2012 announcement of its first all-electric spacecraft, the 702SP, and the fact that Boeing's customers are already exhibiting significant interest in the platform.⁴ Ultimately, end users are realizing that the significantly higher specific impulse (I_{sp}) performance of SEP enables cheaper launch vehicles, larger payloads, and extended mission operations when compared to all-chemical spacecraft. These characteristics often result in significant cost and performance benefits for the end user.

In order to characterize the cost-savings potential of SEP spacecraft, Aerojet Rocketdyne examined a notional campaign in which 20,000 kg of pressurized cargo is required to be delivered to the Earth-Moon Lagrange points (EML1 or EML2), using a solar electric propulsion (SEP) spacecraft (or 'tug'). This analysis is a follow-on to previous studies^{5,6} and focuses on near-term SEP benefits that are achievable with flight-proven components and technologies. Results from the study are contained herein, along with a discussion of the analysis approach used, an example of a detailed SEP "tug" spacecraft design, and some discussion on the practical and historical implementation of SEP technology. The results indicate that utilizing SEP tugs in a cargo delivery campaign can reduce cost per delivered cargo mass (\$/kg) by over 50% compared to chemical. Performance results can be found in Section V, Fig. 7 through Fig. 10 and cost results can be found in Fig. 11 and Fig. 12.

Aerojet Rocketdyne has also analyzed historical NASA science missions to illustrate how it is possible to reduce mission cost by utilizing SEP technology. The results of this analysis indicate that the operations costs of electric propulsion missions can rival the costs of chemically propelled missions and the increased autonomy enabled by EP spacecraft may even lower operations costs for some missions. It was also found that SEP spacecraft enable overall cost savings of up to 2X can be even on small NASA science missions. Analysis results can be found in Section VIII, Fig. 16 thru Fig. 19.

II. Notional EML2 Architecture

The campaign to deliver 20t of pressurized cargo to EML2 is assumed to be part of a larger undertaking to build a habitat at EML2. Figure 1 depicts how a campaign of SEP-tug cargo deliveries might support such an architecture. This architecture assumes that large structural modules and manned transfer vehicles (like Orion) would be lifted to EML2 using SLS with short trip times (days). Additional supplies like food, water and other pressurized cargo could be delivered using a SEP tug with 1 to 2 year transfer times, as shown.

Figure 1 helps frame the campaign requirement for pressurized cargo delivery (20t to EML2) in a larger context. The complexity and multi-flight nature of such an architecture would require extensive operations and logistics coordination. Reducing the number of flights required for pressurized cargo delivery would reduce the costs for that element of the architecture, but it would also reduce the operations and logistics costs of other supporting and dependent missions by providing schedule and mission flexibility. Subsequent sections show how the number of cargo delivery launches can be reduced from as many as ten (using an Atlas V 531 and an all-chemical spacecraft) to as few as three by utilizing SEP spacecraft.

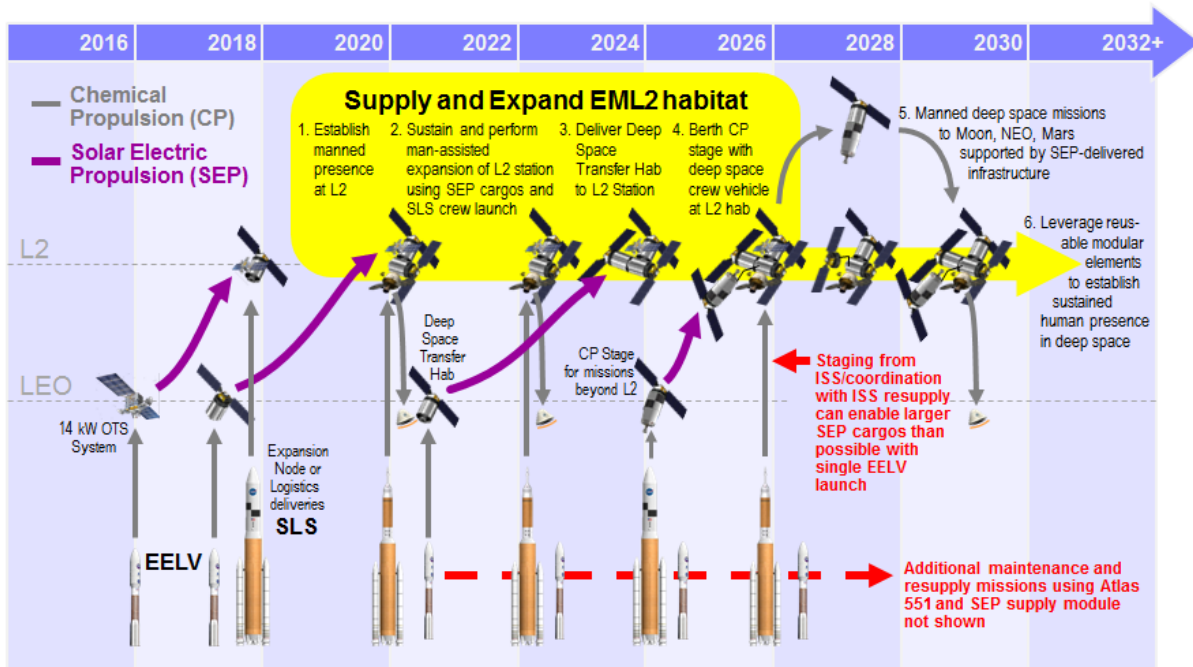


Figure 1. SEP enables a robust and affordable human presence in deep space, as shown in this notional architecture to build a habitat at EML2.

Establishing a constraint on maximum allowable trip time helps refine the trade space of possible solutions, since the high Isp of SEP causes more mass as function of trip time. Since it would take approximately 10 years or more to develop a habitat at EML2 (per Fig. 1), it is reasonable to assume that a 1 to 2 year transfer time for SEP cargo deliveries would not significantly impact the overall schedule. Trip times of less than two years are of special interest because they are short enough to allow for cargo with expiration dates (such as food) and compressed launch windows, but long enough to realize the significant mass and cost savings possible with SEP spacecraft. Subsequent sections show that SEP spacecraft with a trip time less than 1.5 years were targeted as “potential solutions” to deliver 20t of pressurized cargo to EML2. Longer trip times were still analyzed in order to fully characterize the SEP trade space and possible campaign savings therein.

III. Analysis Approach for a Cargo Delivery Campaign to EML2

Working from published launch vehicle (LV) data^{7,8}, one can use the performance capability at a given orbit as the initial wet mass for a spacecraft travelling from earth orbit to EML2. This wet mass can then be translated into a value for total delivered mass at EML2, using the analysis approach shown in Fig. 2. In order to find the total delivered mass, Aerojet Rocketdyne used its Low Thrust Trajectory code⁹ to calculate the amount of propellant required as a function of the initial orbit and wet mass, final destination, and characteristics of the propulsion system.

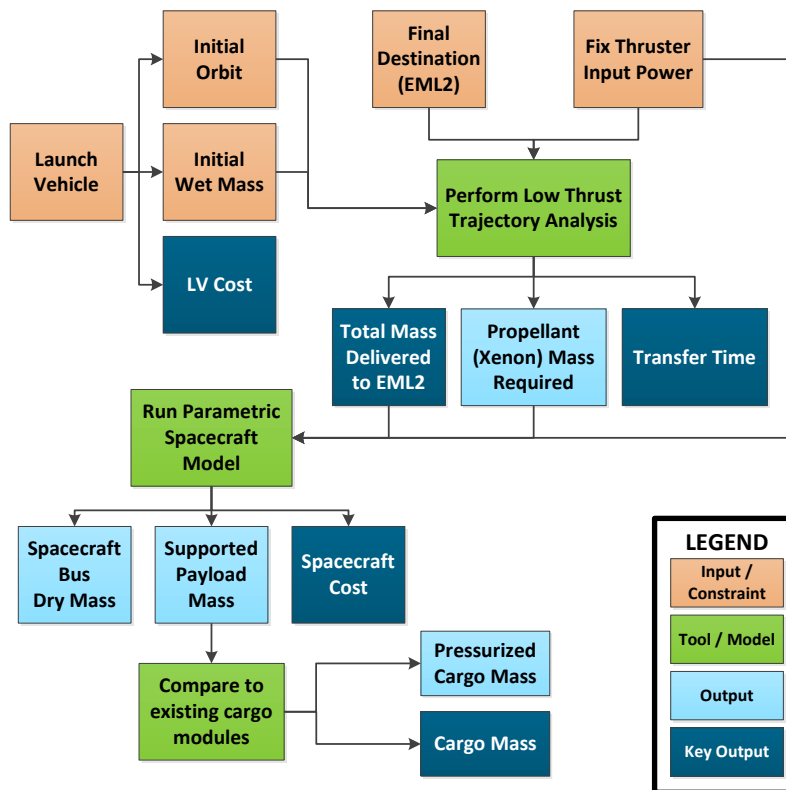


Figure 2. Analysis Approach.

The electric propulsion system of each SEP “tug” spacecraft modeled herein is assumed to make use of multiple Hall thrusters. Hall thrusters were chosen for their higher thrust performance benefits and high TRL level. Other EP thrusters, such as gridded ion, have higher Isp values, but their lower thrust levels are challenging to scale to large payload sizes without incurring prohibitively long transfer times. All of the SEP spacecraft mission analysis results in this study were based on use of the Zero-Erosion™ XR-5 Hall thruster (also known as the BPT-4000), produced by Aerojet Rocketdyne. The Zero-Erosion™ XR-5 is the highest power Hall thruster flown to date (at 4.5 kW) and recently saved the extremely valuable AEHF communication satellite by providing GTO to GEO low thrust orbit raising when the primary chemical propulsion failed.

The approach outlined in Fig. 2 was used to analyze a single SEP “tug” spacecraft. In order to compare different missions and to analyze campaign costs, it was necessary to exercise the analysis approach several times with various launch vehicles, starting orbits, and spacecraft sizes. This made it possible to start cross-plotting several of the key parameters. An annotated example of such a cross-plot is shown in Fig. 3.

Each curve in Fig. 3 has a fixed thruster performance and input power. Thruster input power is a key control variable used to size the spacecraft and to define the trade space, whereas the overall “tug” spacecraft power takes into consideration power needed for the avionics, and losses in the power subsystem. Figure 3 illustrates the performance of SEP spacecraft when launched by an Atlas V 551 launch vehicle. The dashed horizontal lines represent the total mass that various launch vehicles are capable of delivering to EML2 with an all chemical spacecraft and a minimum energy trajectory.

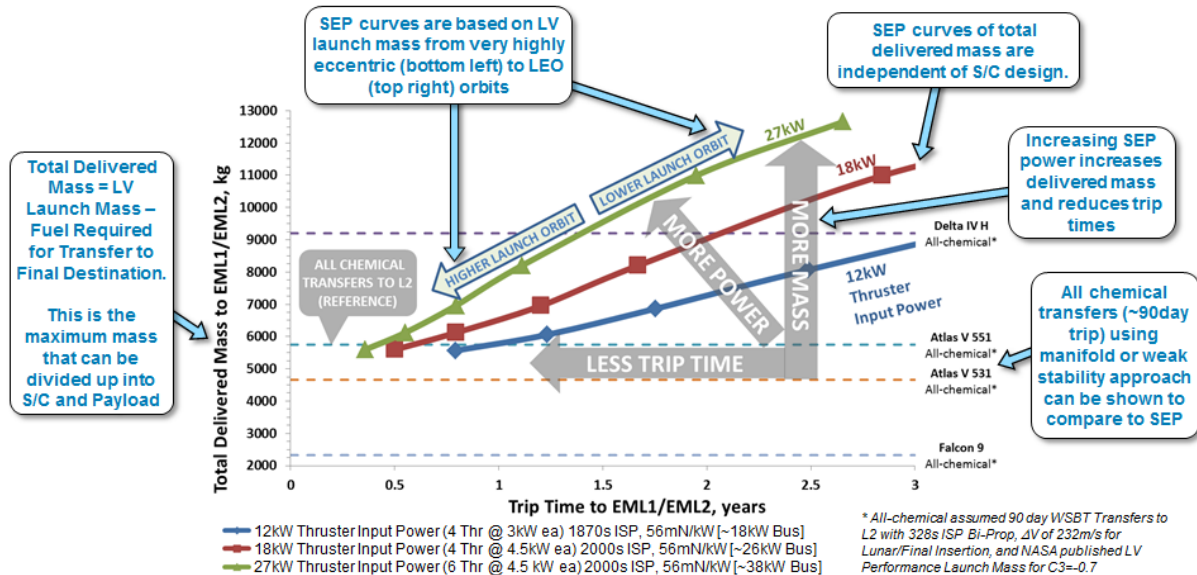


Figure 3. Performance graphs show total delivered mass at EML2 for SEP spacecraft launched from a given launch vehicle.

The EP curves shown in Fig. 3 are generated by varying the starting orbit of a SEP spacecraft and using the launch vehicle capability (in this case, an Atlas V 551) to determine the total starting mass of the wet SEP spacecraft plus payload. Solutions towards the top right of the curves have progressively lower initial orbits (lowest initial orbit modeled for this LV is 400km x 400km x 28.5°) and utilize the electric propulsion system as much as possible. These solutions achieve greater values for total delivered mass due to the high Isp of 2000s, but they also incur longer trip times due to the low thrust associated with electric propulsion. The EP thrusters fire nearly continuously, but even the 27 kW EP case provides only ~1.5N of thrust.

Conversely, solutions towards the bottom left of the curves use increasingly higher eccentric starting orbits (up to 100,000km x 400km x 28.5°). These solutions utilize the launch vehicle more, which decreases trip time at the expense of total delivered mass. The closer a given solution approaches the bottom left (i.e., the more it relies on the launch vehicle), the closer it comes to converging on the all-chemical solution.

The best possible all-chemical solutions for various launch vehicles are shown as dashed lines for comparison. These solutions assume the given LV launches to near escape (C3=-0.7) and puts a small chemical stage plus payload on a weak stability boundary trajectory with a fixed duration of ~90 days. This maximizes delivered mass for the all-chemical approach and only requires a ΔV of ~232m/s from a small chemical stage to maintain the trajectory.

Comparing the SEP curves to the chemical performance values shows that there are a number of scenarios where SEP spacecraft outperform their chemical counterparts. For instance, a SEP spacecraft that takes ~1.4 years to reach EML2 after being launched from an Atlas V 551 can deliver the same amount of mass to EML2 that would otherwise require a Delta-IV H and an all-chemical spacecraft. Depending on the thruster input power and the transfer time, it is actually possible to deliver more mass to EML2 off an Atlas V 551 with a SEP spacecraft than can be delivered from a Delta IV H with an all chemical spacecraft. This performance advantage has significant implications in reducing single mission costs, but the effect is even more noticeable at the campaign level.

In order to size the SEP spacecraft and determine the number of launches necessary to deliver 20t of pressurized cargo to, it is necessary to understand how much cargo needs to be delivered per launch and how much total delivered mass is necessary to achieve this. Required cargo per launch is simply 20t divided by the number of launches. However, the relationship between pressurized cargo and total delivered mass is a function of the spacecraft design, which is itself a function of the thruster input power and other parameters of the particular point design under consideration. These relationships are depicted in Fig. 4.

The relationships presented in Fig. 4 make it possible to run parametric analyses of SEP spacecraft and quickly determine what power level and trip time combinations enable the 20t campaign to be performed with fewer launches. The dashed lines in Fig. 5 show the values for total delivered mass from Fig. 4 overlaid onto the LV +

SEP performance graph from Fig. 3. The regions of Fig. 5 where the dashed lines for number of launches intersect the curves of fixed thruster input power represent good starting points for various bottoms-up point designs as these are the areas where there is a step in the number of launch vehicles required for the campaign, and hence a large jump in overall campaign costs. Figure 5 also highlights those solutions that would make it to EML2 within 1.5 years. As discussed in Section II, trip times of 1.5 years or less are of especial interest because they are able to support a complex station-building architecture and enable time-sensitive pressurized cargo (such as food) to reach its destination in time.

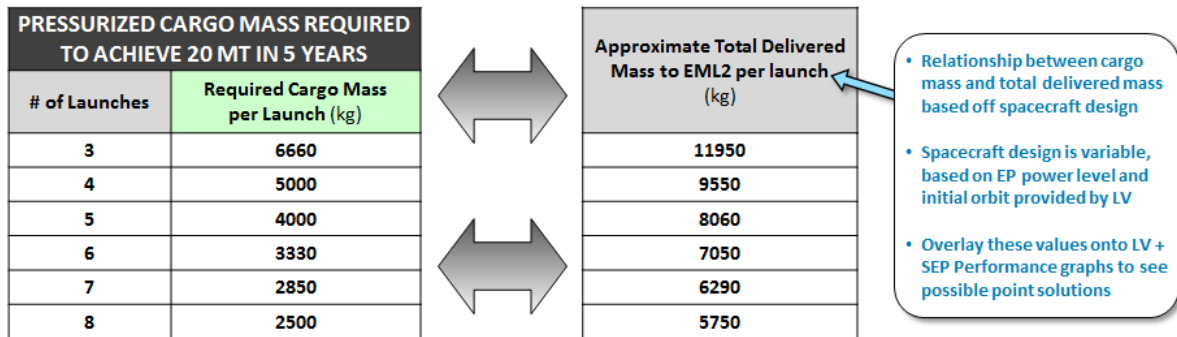


Figure 4. Values for total delivered mass to EML2 per launch can be calculated with a low thrust trajectory code and then mapped to a corresponding value for pressurized cargo mass.

Plotting these key characteristics allows one to understand large portions of the trade space through a single chart. Subsequent sections show the performance of SEP spacecraft when launched from an Atlas V 531, a Falcon 9 (v1.0), and a Delta-IV H. The Atlas V 531 and Falcon 9 results are of especial interest, since both of these launch vehicles are lower cost than the Atlas V 551 and the Delta-IV H. If a potential operator could launch a SEP spacecraft off an Atlas V 531 or a Falcon 9 and achieve the same performance as they would otherwise get on a much more expensive launch vehicle, the value proposition of SEP spacecraft starts to become clear.

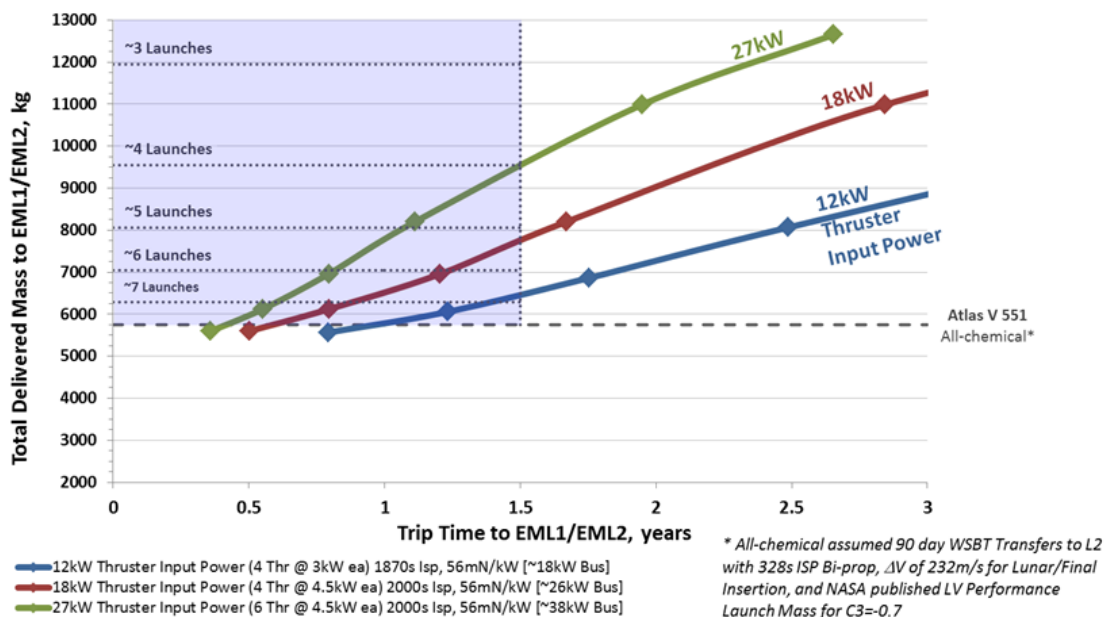


Figure 5. Launch Vehicle + SEP Performance Graph With Number of Launches

IV. SEP “Tug” Spacecraft Model

A parametric spacecraft model was created which outputs detailed mass and cost estimates. By creating a parametric spacecraft model with a small number of inputs, it is possible to model several different spacecraft sizes and power levels, and then compare them to analyze potential areas for mission and campaign cost savings. This is illustrated by the analysis approach in Fig. 2 and the performance graphs shown in Fig. 3 and Fig. 5. Using such a spacecraft model makes it possible to divide the “total delivered mass” values into three major categories: the spacecraft bus dry mass, pressurized cargo module mass (structure holding the cargo), and the cargo mass. The breakdown of these different masses is illustrated in Fig. 6.

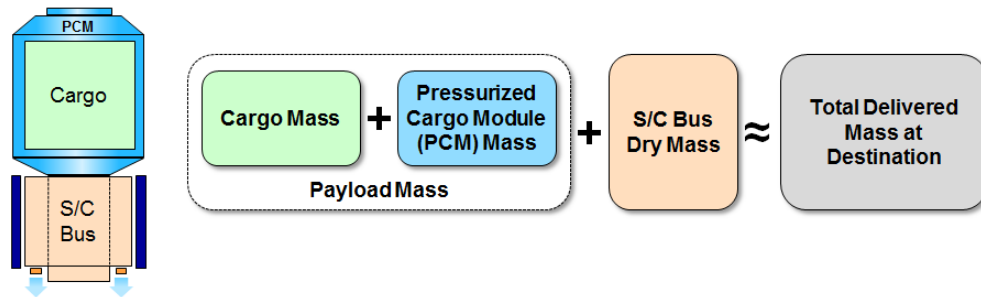


Figure 6. Breakdown of Total Mass Delivered to EML2 per Launch.

The spacecraft model was designed to work for SEP spacecraft and all-chemical spacecraft. Primary inputs to the model for SEP spacecraft are thruster input power, amount of Xenon propellant, and payload mass. The thruster input power and xenon mass help size the solar array and electric propulsion system mass, and the payload mass sizes the spacecraft structure. The model also assumes that each SEP spacecraft will carry 300 kg of hydrazine, to be used for minor attitude control system (ACS) maneuvers during transit to EML2 and during a notional 10 year mission life at EML2. This 10 year “secondary” mission of a given SEP spacecraft could allow it to provide station-keeping and power generation for the notional EML2 habitat. All-chemical spacecraft were modeled to have smaller arrays, no electric propulsion system, much smaller power management and distribution systems, and no propellant for a secondary mission. This study did not analyze SEP tug “reusability” options. SEP tug reusability refers to the concept of returning a SEP spacecraft to earth orbit where it is refueled and loaded with a new payload before performing a “repeat” of its original mission. Such options are major design drivers and are very mission and campaign-specific. More discussion on reusability can be found in Section VII of this document.

Costs were broken into non-recurring and recurring costs for both SEP spacecraft and chemical spacecraft. The starting point for each was to use the parametric cost of a similar complexity HEO (High Earth Orbit) spacecraft. The values for this baseline cost were established using the USCM8 statistical cost model¹⁰, which was created by the Air Force Space and Missile Center and includes costs from 44 satellites, comprised of 23 military, 12 NASA satellites, and 9 commercial satellites. Additional costs were then added to SEP spacecraft for the high power arrays, SEP systems, and spacecraft AI&T and Program costs, each of which were calculated in a more explicit manner.

Operations costs can be very mission specific, and since the majority of this study involved analyzing a large trade space, operations costs were not factored into the campaign costing numbers for this study. Total campaign cost and cost per delivered kilogram of cargo were a function of the spacecraft and launch vehicle costs.

V. Results for a Cargo Delivery Campaign to EML2

A. Performance Results

The campaign analysis results for SEP spacecraft launched from various launch vehicles are shown in Fig. 7 through 10. The stars on each Fig. indicate point solutions that were examined more closely to determine the cost per kilogram of delivered cargo. The cost per kilogram values are not single-launch values, but represent the combined spacecraft and launch vehicle cost to deliver at least 20t of pressurized cargo with the given point solution. These selected point solutions show how the cost per kilogram decreases as a function of power level and transfer time.

The slight step in each of the Falcon 9 v1.0 performance curves in Fig. 10 is due to the fact that not every initial orbit had the same perigee. The available performance data for the Falcon 9 v1.0 was the only data set (of the four launch vehicles analyzed) that did not maintain a fixed perigee value, regardless of the apogee value. Initial SEP orbits provided by the Falcon 9 v1.0 were assumed to be circular until an apogee of 2000 km was reached. For apogee values higher than 2000km, perigee was fixed at 185km, based on available launch vehicle data⁸. This differs slightly from the available Atlas V 551 and Atlas V 531 data, which both start out at a 2000km circular orbit and then fix perigee at 2000 km, regardless of apogee. Performance data for the Delta-IV H started at 5000km x 185km and also maintained a constant perigee value, regardless of the apogee value^{7,8}.

Figure 7 shows the results for SEP spacecraft launched from an Atlas V 551. The minimum energy all-chemical approach off of an Atlas V 551 requires seven launches to deliver 20t of pressurized cargo, at a cost of \$93k per kilogram. Conversely, that same 20t of pressurized cargo could be delivered in only 3 launches at a campaign cost of \$50k per kilogram by a SEP spacecraft with 27 kW of thruster input power and ~2.5 years of transfer time. This represents a cost savings of approximately 46%. If a 2.5 year transfer time is considered to be too long, there are numerous SEP solutions with shorter transfer times that still save significant money compared to an all-chemical approach.

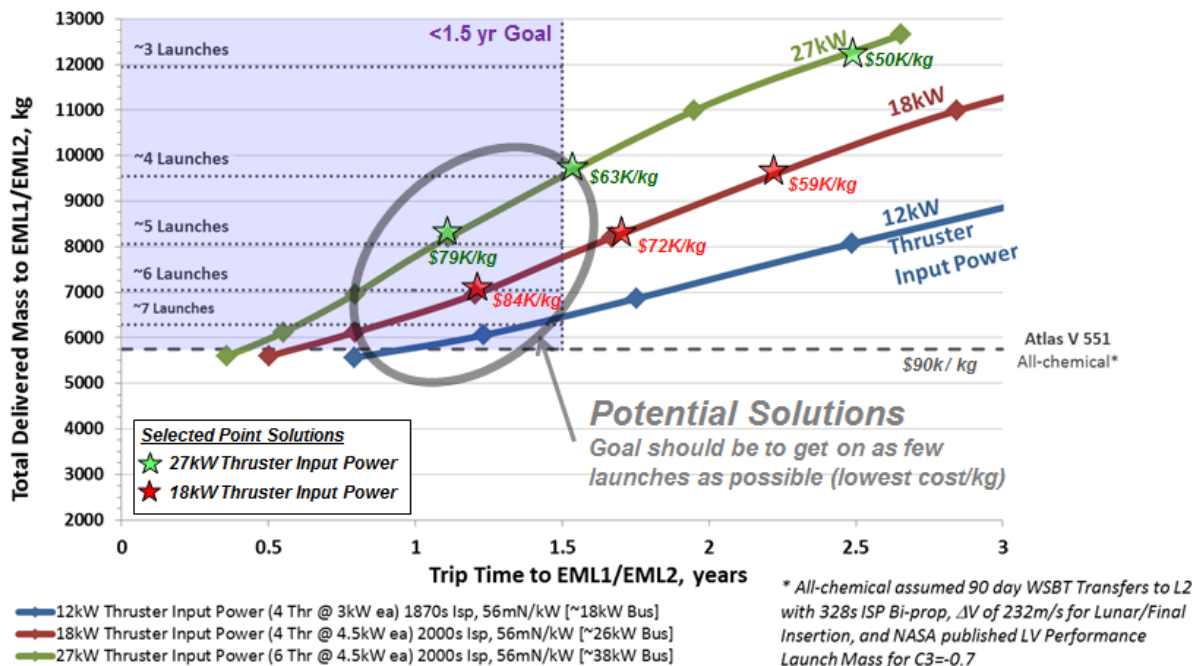


Figure 7. Performance of Atlas V 551 + SEP Spacecraft.

Figure 8 shows the results for SEP spacecraft launched from an Atlas V 531. For comparison, the minimum energy all-chemical approach off of an Atlas V 531 requires 10 launches at a cost of \$114k per kilogram of delivered cargo.

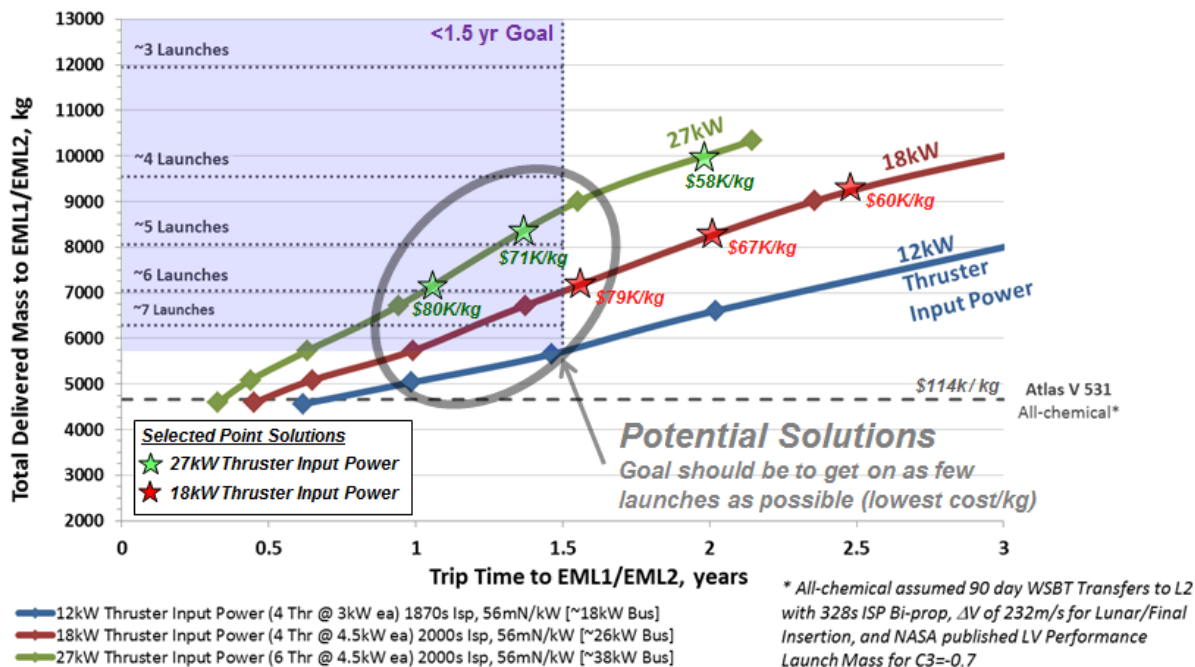


Figure 8. Performance of Atlas V 531 + SEP Spacecraft.

Figure 9 shows the results for SEP spacecraft launched from a Delta IV H. Note that because the Delta IV H can lift such large payloads, the values for “total delivered mass” are significantly larger than solutions off of smaller launch vehicles. Since the thruster input power levels (12, 18, and 27 kW of Thruster input power) haven’t changed, the increase in delivered mass causes the overall power/mass ratio of the SEP spacecraft to be lowered. Launching a SEP tug from a Delta IV H at these power levels is not recommended because the cost savings are minimal and it is difficult to increase the delivered mass to the point where the number of launches can be reduced. Given the expensive nature of the Delta IV H compared to other launch vehicles, the biggest benefit of SEP is that it allows cargo delivery that once was only possible on the Delta IV H using chemical to be launched off of a smaller, lower cost vehicle like an Atlas V, thus reducing campaign costs.

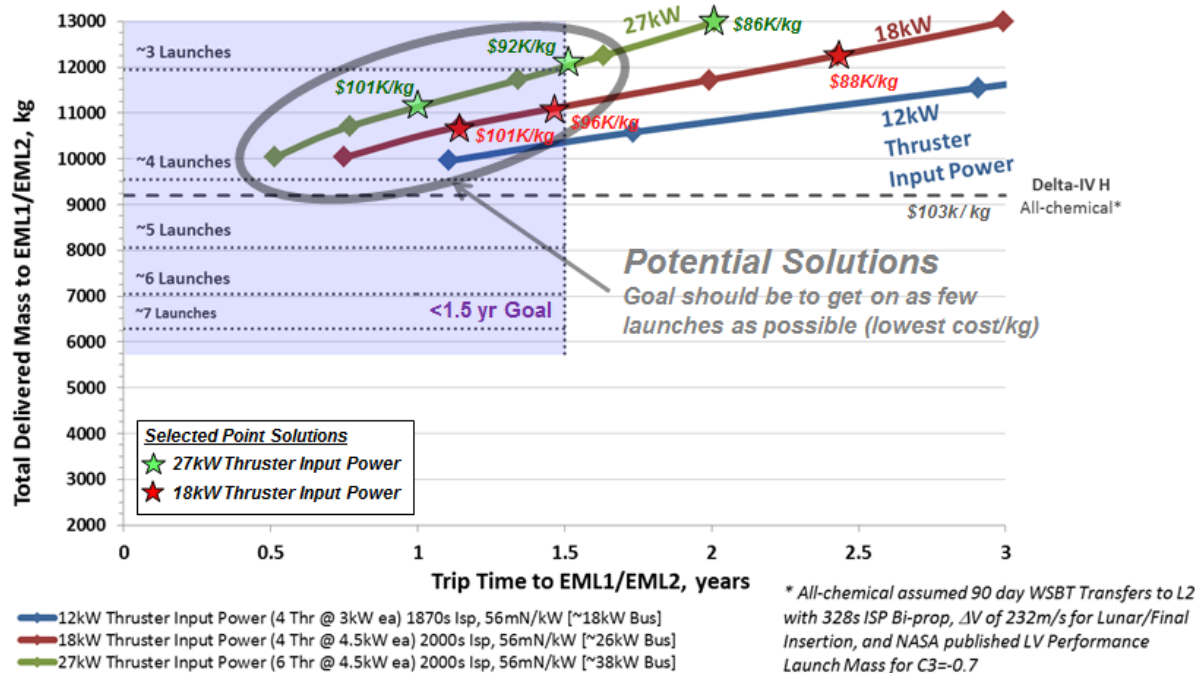


Figure 9. Performance of Delta IV Heavy + SEP Spacecraft.

Figure 10 shows the results for SEP spacecraft launched from a Falcon 9 v1.0^{††,11}. The Falcon 9 v1.0 has the smallest lift capability of the four launch vehicles analyzed herein, but it also has the lowest cost per launch. Since the Falcon 9 v1.0 cannot deliver the desired mass to EML2 using chemical alone, this is a prime example of how SEP spacecraft enable mission flexibility. In terms of campaign costs, launching six SEP spacecraft from a Falcon 9 v1.0 is comparable to launching 3 SEP spacecraft from an Atlas V 551 or 4 SEP spacecraft from an Atlas V 531 (see Fig. 11 and Fig. 12).

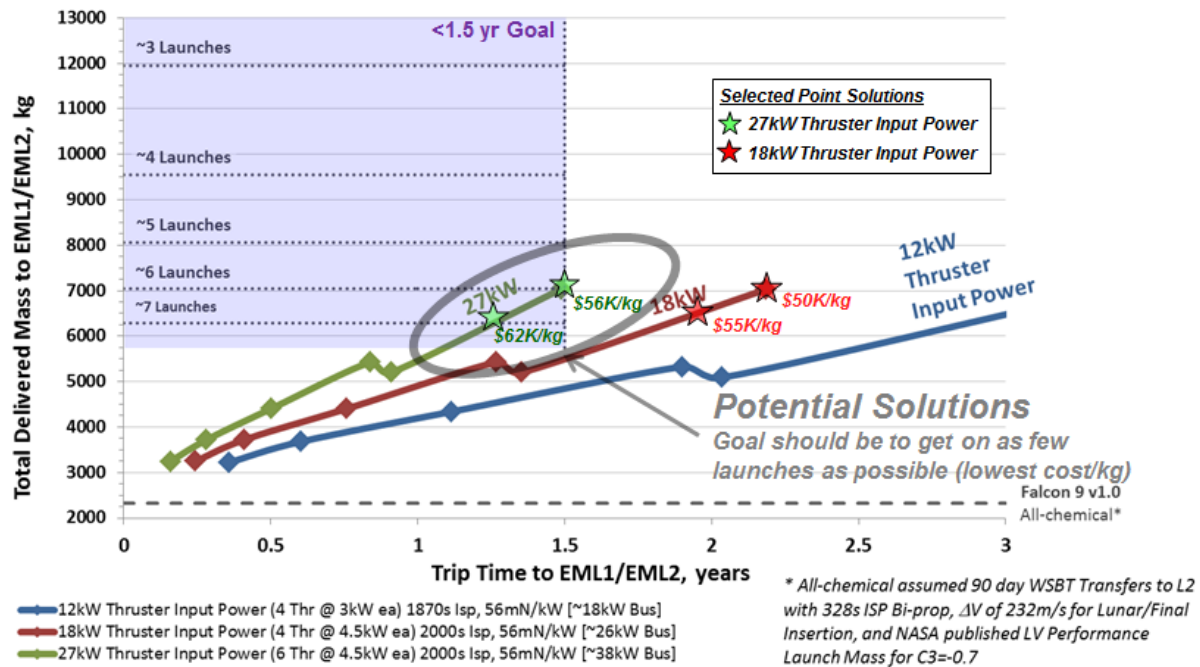


Figure 10. Performance of Falcon 9 v1.0 + SEP Spacecraft.

^{††} The bulk of this analysis was performed early in 2012, and performance curves in Fig. 10 are based on the Falcon 9 v1.0 performance data available at that time. Since then, SpaceX has introduced the Falcon 9 v1.1, which has comparable performance to an Atlas V 531.

B. Cost Results

This analysis confirmed that the cost and number of launch vehicles required are by far the biggest driver in campaign costs. Cost per kilogram of delivered cargo to EML2 is shown in Fig. 11, which compares SEP spacecraft (shown at 27 kW thruster input power for varying trip times) to all-chemical spacecraft. Cost values in this figure have been normalized relative to the all-chemical approach with the highest cost per kilogram. The results illustrate that SEP's substantially higher specific impulse, coupled with increasing trip times, enables a 57% savings in cost per kilogram, made possible by using fewer and smaller launch vehicles.

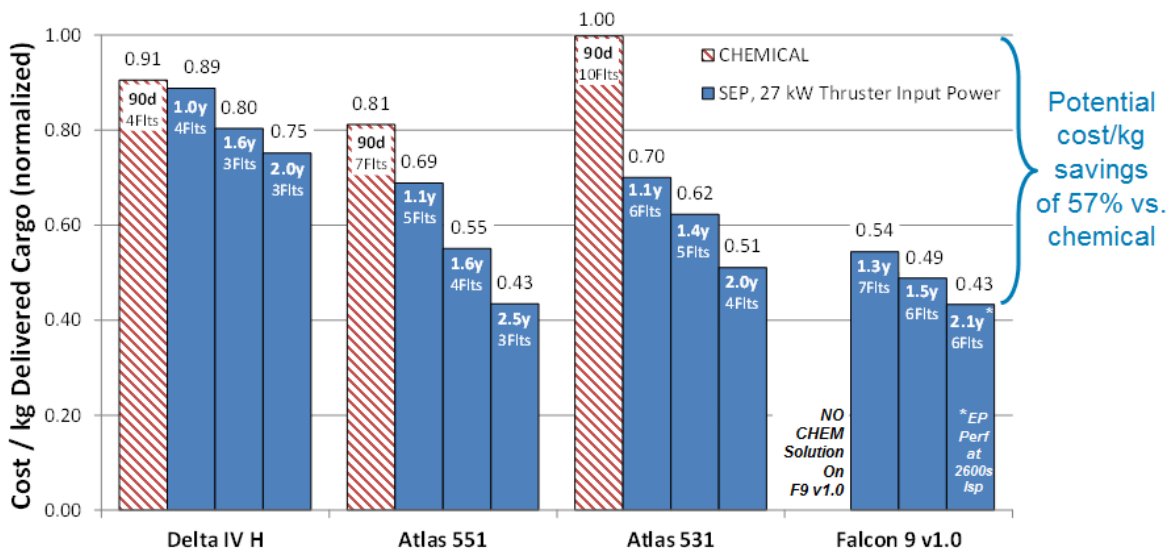


Figure 11. SEP reduces campaign cost per kilogram by decreasing the number of launches required and enabling smaller launch vehicles. Cost savings benefits continue to grow as trip time increases.

Another way of looking at the results is to plot the total cost of all the launch vehicles and spacecraft in the campaign. For this particular campaign, using SEP can enable aggregate savings of almost 60% compared to an all-chemical approach, as shown in Fig. 12.

As mentioned previously, launching a SEP tug from a Delta IV H at these power levels is not recommended because the cost savings are minimal, as shown in Fig. 12. For short trip times on large launch vehicles such as the Delta-IV H, it is actually possible that using a SEP tug for cargo delivery cargo may cost more than an all-chemical approach. The reason for this is that the launch vehicle is doing most of the work and it is difficult for the SEP tug to increase the delivered mass to the point where the number of launches can be reduced. However, when the trip time requirement is relaxed, SEP still enables approximately 20% total campaign savings from a Delta IV H.

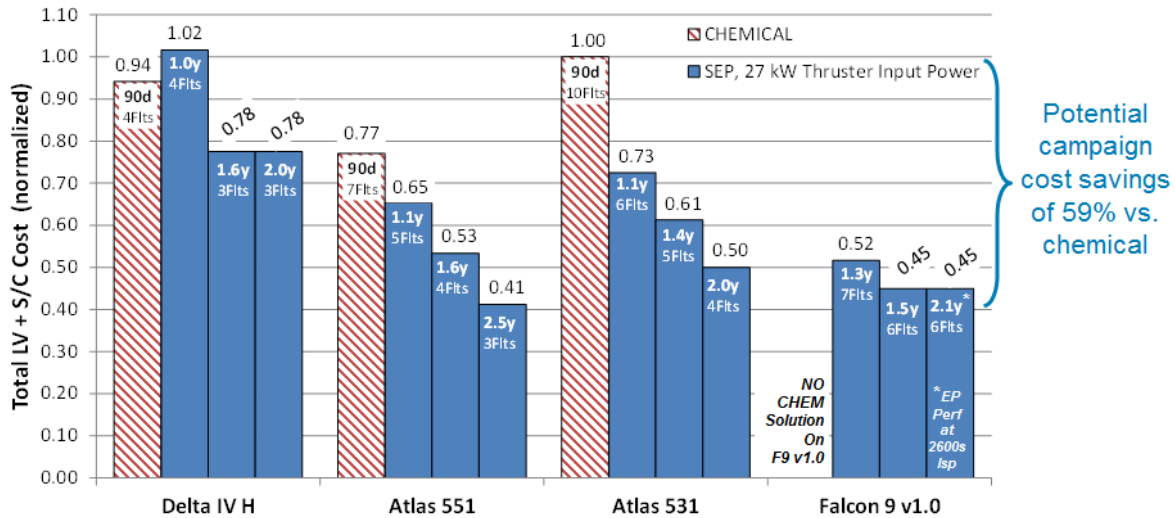


Figure 12. SEP reduces total campaign cost by decreasing the number of launches required and enabling smaller launch vehicles. Cost savings benefits continue to grow as trip time increases.

Overall, using electric propulsion for space exploration and cargo delivery enables a large amount of flexibility over all chemical solutions, and can enable significant campaign savings. Almost all of the SEP spacecraft solutions represented in Fig. 11 and Fig. 12 support the notional EML2 architecture and 2 year cargo delivery timeframe depicted in Fig. 1. With trip times of two years or less, SEP spacecraft can provide significant savings over all-chemical approaches, and cost savings grow dramatically as trip time increases. Subsequent sections will also show that high power SEP spacecraft can be developed with an “integration not innovation” approach. This approach lowers cost and risk by integrating flight-proven systems into a configuration that has not flown before, but is grounded in current, high-TRL technologies.

VI. Heavy Payload Point Design for Near-Term Cargo Delivery to EML2

The mission analysis results presented thus far have helped define the possible solution space for near-term SEP spacecraft, but since this analysis has been parametric in nature, one might ask how these results compare to SEP spacecraft that have been through the subsystem design process? To answer this question, Aerojet Rocketdyne performed detailed sizing for a “Heavy Payload Point Design”. It was decided that the vehicle’s mission would be to demonstrate cargo delivery capability, maximize the benefits of electric propulsion, and to prove out a high power SEP spacecraft with significant payload capabilities.

In order to fully demonstrate the capability of a high power SEP spacecraft, it was decided that the spacecraft needed to have at least 27 kW of thruster input power and be capable of supporting payloads greater than 6 MT. Based on these two requirements and the data in Figures 7, 8, and 10, potential solutions were down-selected for the Atlas V 551, Atlas V 531, and the Falcon 9 v1.0. The Delta-IV H was not considered because the cost savings associated with launching SEP spacecraft off a Delta-IV H are minimal at best. These three reduced data sets were then compared to one another, along with the respective structural and envelope constraints of the three launch vehicles. Since the Atlas V 551 solutions were found to drive spacecraft dry bus mass, payload mass, and structural load requirements, a MEO starting orbit off an Atlas V 551 was chosen as the baseline set of spacecraft requirements.

The baseline requirements were then compared to known values for subcomponents and the traditional spacecraft design activities further refined the spacecraft properties. Ultimately, a mass budget, power budget, cost analysis, and detailed design of every major subsystem was completed. The resulting spacecraft was baselined to launch from an Atlas V 551, but was designed so as to not preclude the ability to ride on an Atlas V 531 or a Falcon 9 v1.0. Riding on an Atlas V 531 or Falcon 9 v1.0 would require smaller payload masses and xenon loads, but the design would be largely the same. See Fig. 13 for a summary of the spacecraft design. Figure 14 shows alternative views of the design, along with snapshots of some of the flight-proven components.

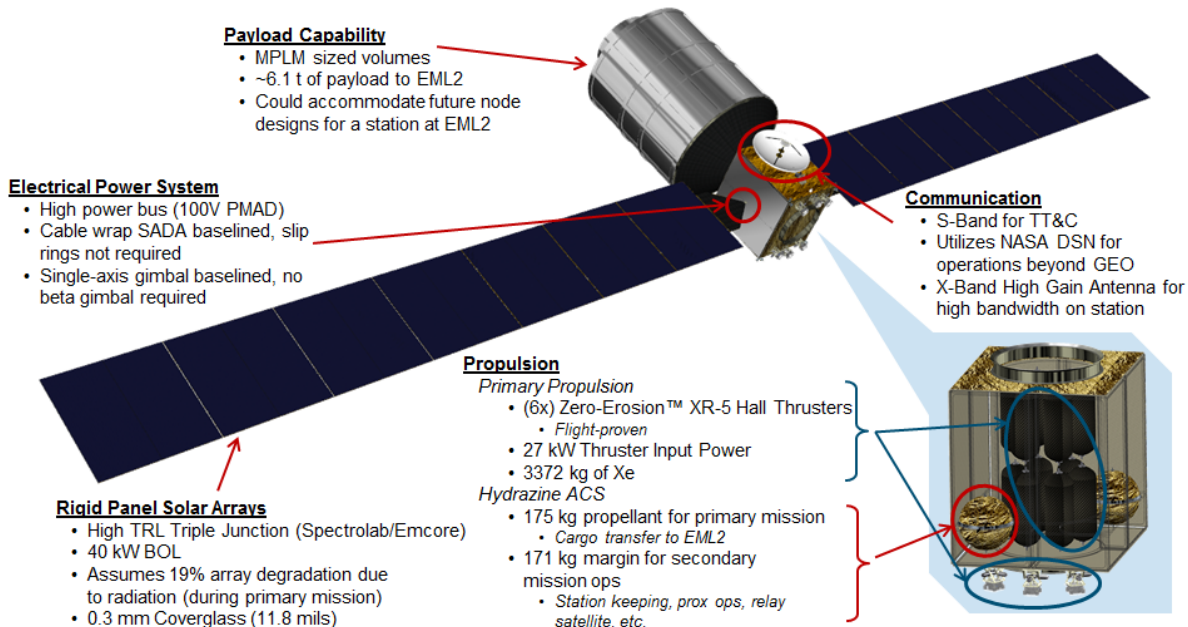


Figure 13. Utilizing current technologies and flight-proven components, Aerojet Rocketdyne created a SEP Heavy Payload Point Design (with 27 kW thruster input power and 40 kW BOL spacecraft power) capable of delivering large Payloads to EML2 in approximately 1.5 years.

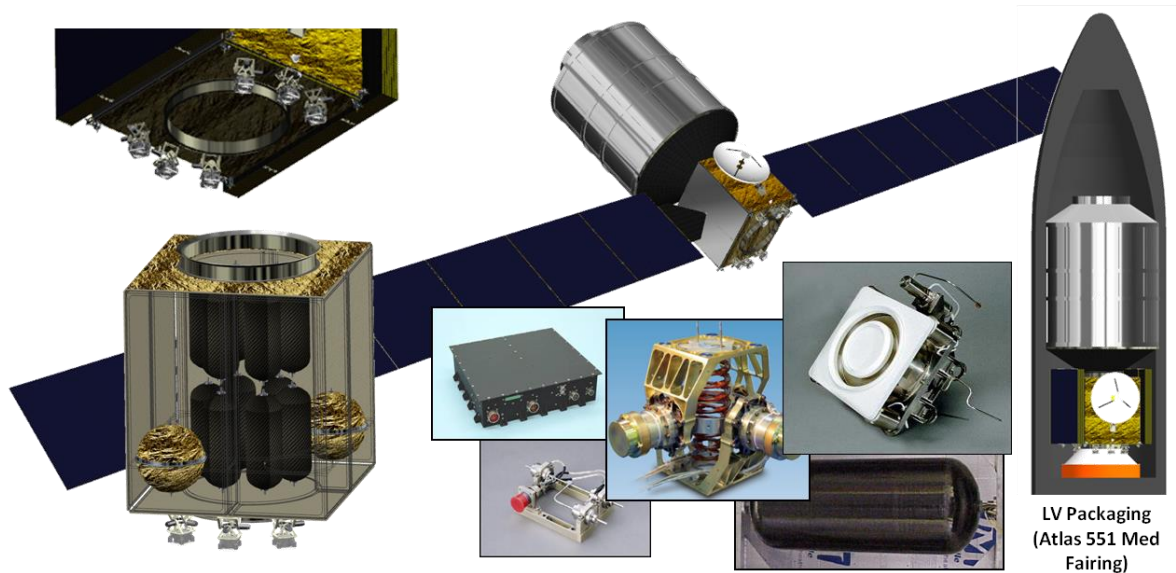


Figure 14. The SEP Heavy Payload Point Design (27kW Thruster input power, 40kW BOL Spacecraft Power) was based on current technologies and flight-proven components.

This heavy payload design shows that it is possible to perform meaningful missions with high power SEP spacecraft (27 kW of Thruster input power, in this case) using current technology. All of the subsystems and components are flight-proven, but the spacecraft depicted in Fig. 13 integrates them in a manner that has never flown before. Although the Zero-Erosion™ XR-5 thruster (also known as the BPT-4000) has already flown on AEHF^{1,12}, operating these thrusters in a multi-clustered arrangement at a total thruster input power of 27kW has never been done before. The solar arrays proposed are rigid panel, but would be the highest power configuration ever flown at 40kW beginning of life (BOL) power. The payload is also large, and was designed to accommodate MPLM sized volumes. Demonstrating all these aspects working together would significantly push forward the state of the art for SEP vehicles, while still being grounded in current technology.

The pricing estimate for the detailed heavy payload point design only had a ~6% difference from the top-down parametric estimate used to evaluate the trade space. This helps to verify the legitimacy of the parametric cost modeling used to create Fig. 11 and Fig. 12, therefore reinforcing the cost savings conclusions evident in those figures.

VII. Practical Considerations for SEP Spacecraft

A. Mission-Specific Considerations

The benefits of a SEP spacecraft from a mission and cost analysis point of view are enticing, but what about the practical implementation of such a stage? One might pose the question of whether it would be more efficient to just incorporate the SEP propulsion system onto the spacecraft payload, and for already high powered communication satellites this may indeed be the best approach. However, for some outer planet missions where the solar arrays are of little benefit and the array and SEP system mass requires additional chemical propellant for maneuvers such as orbit insertion, a separable SEP spacecraft is more mass efficient.

High energy interplanetary transfers, such as Mars or asteroid intercepts, already require a very long coast period (often years) after the initial boost from chemical upper stages. SEP spacecraft are very well suited in this situation, since they would be firing nearly continuously during what would typically be the coast period, and the low thrust trajectories can provide equivalent trip times to chemical. Depending on the mission, the significantly higher efficiency of SEP stages can also allow for elimination of time consuming gravity assists.

SEP spacecraft are also very well suited for cargo delivery, where the payload is essentially a “dumb” mass, such as a MPLM module holding cargo (see Fig. 13). In these cases, the high powered SEP spacecraft can even be used to provide power to the cargo for “housekeeping” services (such as powering the heaters, avionics, etc), possibly eliminating the need for a second set of solar arrays on the payload. The heavy payload point design presented herein shows it is possible to design, build, power, and control such a SEP spacecraft with today’s flight-proven components and a bus design similar to high power communication satellites (see Fig. 13).

B. SEP Design Considerations

When designing a SEP stage, the first fundamental trade that must be performed is to determine what type of electric propulsion thruster to use. There are several types of electric propulsion thrusters, including arcjets, Hall thrusters, gridded ion engines, resistojets and pulsed plasma thrusters, among others.

Arcjets are widely used for station-keeping needs, whereas the Hall effect thruster is often the best choice for Earth-centric transfers, since it provides a good balance between trip time and mass savings. For very long duration interplanetary missions with extremely high delta-v requirements, gridded ion thrusters are often the best choice. Gridded ion thrusters can have much higher specific impulse than Hall thrusters, but their thrust-to-power levels are generally lower, as can be seen in Fig. 15. However, even in interplanetary missions, the higher thrust-to-power level of the Hall thrusters can still save significant mass over chemical stages and provide quicker transfer times than ion thrusters. The final decision on which thruster class works best usually needs to be determined through detailed trajectory analysis of the specific mission.

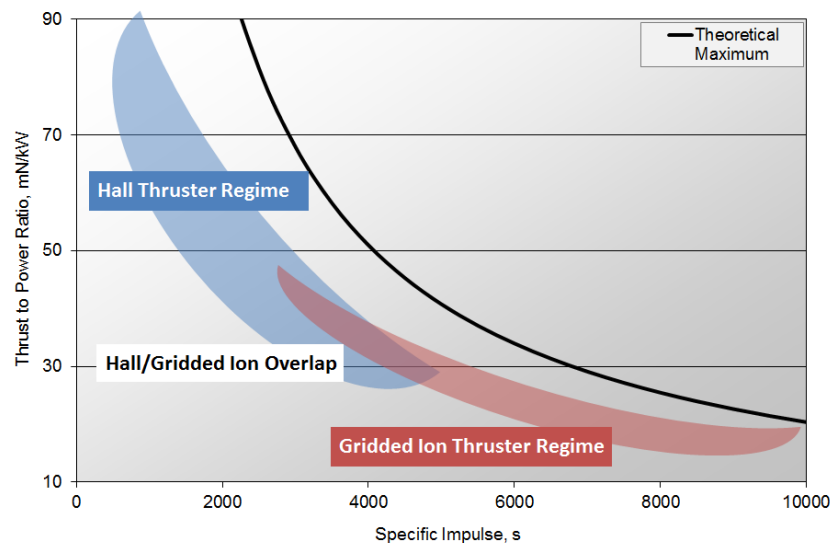


Figure 15. Thrust-to-Power Ratio versus Specific Impulse for Electric Propulsion Thrusters

Guidance, navigation and control (GN&C) aspects of SEP spacecraft also have important differences compared to traditional chemical spacecraft. Similar to large chemical stages that use thrust vector control gimbals to move the nozzle and direct thrust, SEP thrusters must also be gimballed, since they cannot be rapidly pulsed on/off like chemical reaction control thrusters to provide attitude control authority. Using multiple, individually gimballed SEP thrusters can provide the additional benefit of being able to fully control roll, pitch, and yaw of the stage during the long SEP maneuvers, which greatly reduces the need for any type of additional chemical attitude control system. Despite this characteristic of multi-thruster designs, a small chemical ACS system is still considered prudent for periods of eclipse, proximity operations, or occasional momentum dumping.

During the detailed design of the SEP spacecraft shown in Fig. 13, Aerojet Rocketdyne found that only a small chemical reaction control propulsion system was needed. This was mainly to provide attitude control and momentum wheel dumping during the initial on-orbit checkout period in LEO, prior to firing the SEP stage, after which point the individually gimballed SEP thrusters (along with the reaction wheels) provided all the control authority required. It is possible that starting from an already hyperbolic initial trajectory, like that discussed earlier, the chemical reaction control propulsion system may be removed altogether, further simplifying the stage design. In fact, this approach has already been taken with the design of Boeing's commercial, all-electric 702SP GEO bus from which the chemical propulsion system has been completely removed.

C. Reusability of SEP Spacecraft

SEP tug reusability refers to the concept of returning a SEP spacecraft to earth orbit where it is refueled and loaded with a new payload before performing a repeat of its original mission. The goal is to use a single spacecraft to perform multiple missions and thereby reduce the spacecraft-specific costs for a campaign or series of individual missions. In practice, this capability must be designed into the SEP spacecraft and mission logistics ahead of time.

With each one-way trip from earth orbit to a distant retrograde orbit or a destination such as EML2, the spacecraft must pass through the Van-Allen radiation belts. Each pass through the belts reduces the solar array output by approximately 12% (possibly more, depending on the cover-glass thickness and solar array type). Increasing the solar array size is an obvious work-around to this issue, but since a single re-use of a SEP spacecraft would require an additional two trips through the Van-Allen belts, the requisite increase in solar array size can become a major design driver. Another design path is to live with the reduced solar array performance on subsequent missions. This would increase the trip times for subsequent missions, but would still allow those missions to be performed. Additionally, the design life of the thrusters and electronics would need to be qualified for significantly longer durations than a one-way mission.

The reusability concept necessitates the ability to refuel the SEP tug on each return to earth. The cost of the infrastructure to launch and/or store Xenon fuel on orbit is often not a cost-effective solution for smaller SEP tugs. The technology to perform in-space refueling is currently in development and would need to be fully matured for a reusable SEP spacecraft. The possibility of reusing a SEP tug spacecraft is feasible with the above considerations in mind and could be cost-effective for future higher-power SEP tug missions.

VIII. SEP Spacecraft are Cost-Effective

The electrically propelled Deep Space I and Dawn missions have demonstrated that the operations and spacecraft costs associated with SEP missions are as cost-effective as comparably sized chemical missions. To better understand the comparisons, costs for the Deep Space 1 and Dawn missions were analyzed, along with those of several chemically propelled NASA science missions.

Figure 16 shows the mission costs for recent NASA science missions. It can be seen that the Dawn and Deep Space 1 missions, which use electric propulsion, were significantly less than the Lunar Reconnaissance Orbiter (LRO) or the Mars Reconnaissance Orbiter (MRO), which used chemical propulsion. Dawn is the most comparable to LRO and MRO and is significantly lower cost despite its implementation of three ion thruster systems and 10kW of solar power. Deep Space 1 is less expensive than all of the other missions except for Lunar Prospector, which stands alone as an extremely cost effective mission compared to others in its class. NASA has clearly demonstrated that highly capable electrically propelled spacecraft can be flown on NASA science missions at costs comparable to (and potentially lower than) chemically propelled missions.^{13, 14, 15, 16, 17, 18, 19, 20, 21, 22}

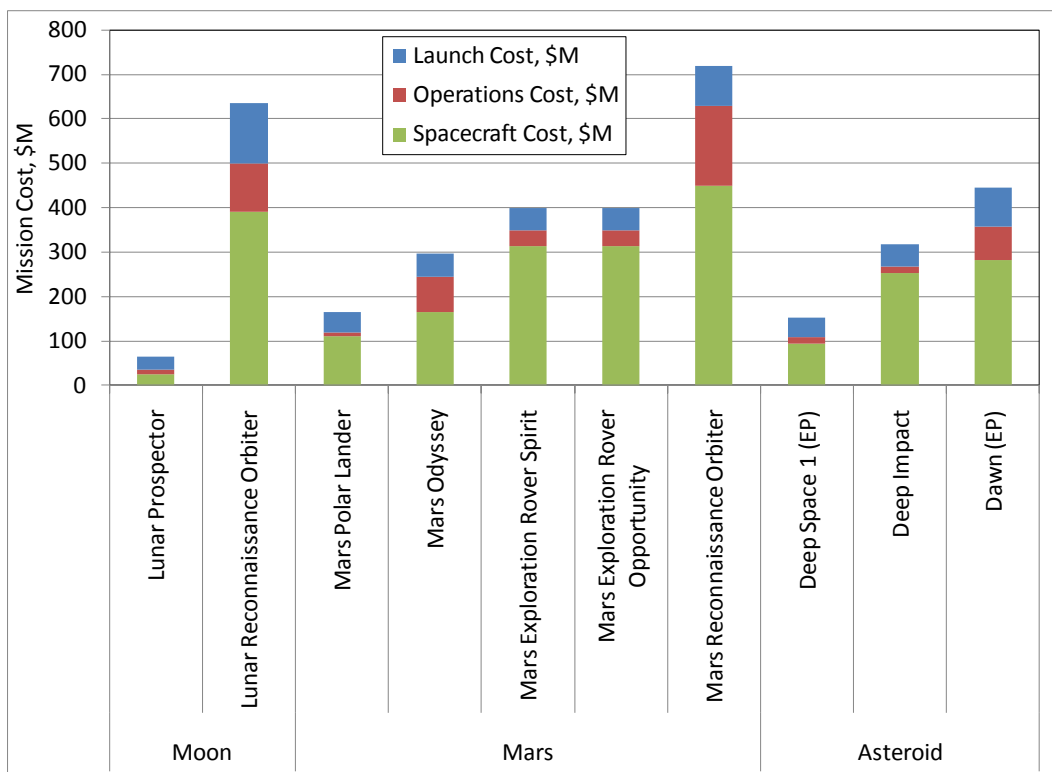


Figure 16. Cost Breakout for NASA Science Missions

Figure 17 shows the mission level cost distribution on NASA science missions.^{13, 14, 15, 16, 17, 18, 19, 20, 21, 22} On average, the NASA missions that are shown spent about 60% on the spacecraft, 20% on the launch, and 20% on operations. The electrically propelled Dawn and Deep Space 1 missions are clearly average in their distributions indicating that there was little to no shift in mission cost distribution due to the use of electric propulsion or high power solar array systems. The Deep Space 1 mission showed a slight shift from operations into launch. This is likely due to the fact that the mission was the first flight of the Delta II 7326. This shift would not be expected on repeat missions using the same launch vehicle.

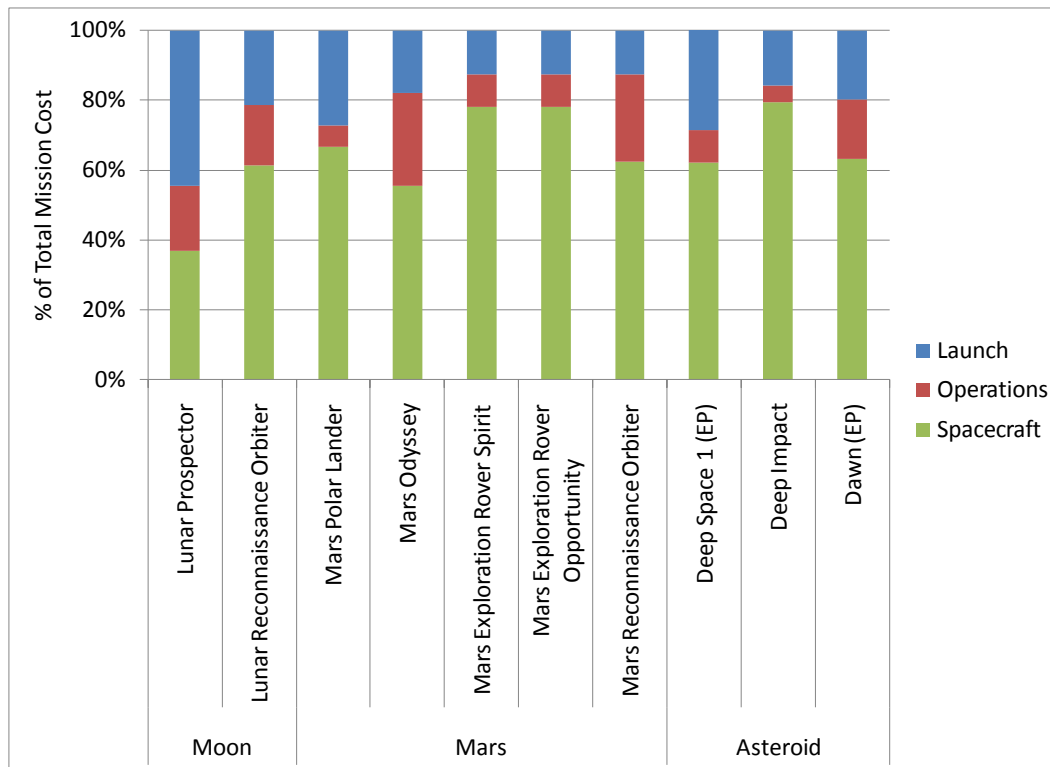


Figure 17. Mission Element Cost Percentage for NASA Science Missions

Figure 18 shows the spacecraft specific cost of NASA science missions, in \$M/kg.^{13, 14, 15, 16, 17, 18, 19, 20, 21, 22} Although, there is a fairly wide distribution about the average cost of \$0.3M/kg, it can be seen that Deep Space 1 and Dawn are clearly in line with the average specific cost of comparable chemical spacecraft. This indicates that the solar power system and electric propulsion system are not driving a change in spacecraft specific costs even though the power systems are larger.

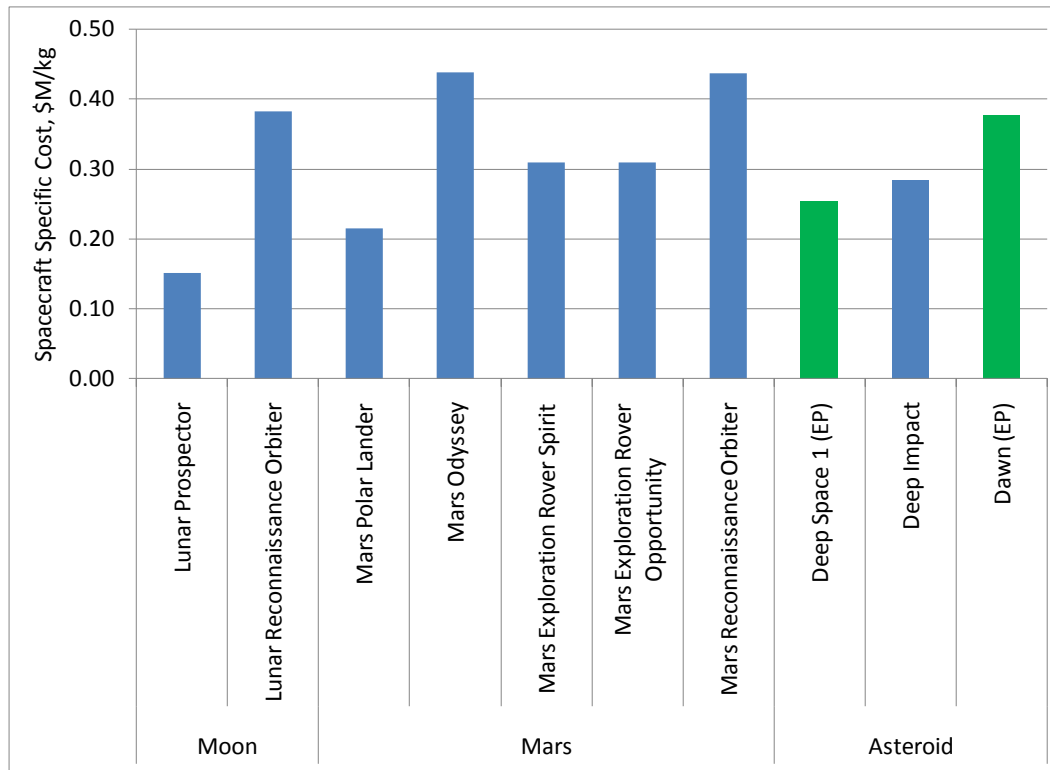


Figure 18. Specific Cost of NASA Science Spacecraft

Figure 19 shows the yearly cost of mission operations.^{13, 14, 15, 16, 17, 18, 19, 20, 21, 22} This cost was calculated by dividing the total operations cost by the mission's expected duration. There is again a wide distribution in costs with LRO, MRO, and Deep Impact deviating significantly from the average. However, Dawn and Deep Space 1 operations are very comparable to the other missions, with Deep Space 1 providing the lowest yearly operations cost for all missions. NASA has demonstrated that the yearly operations cost of electrically propelled missions is comparable to (and potentially less than) chemically propelled missions.

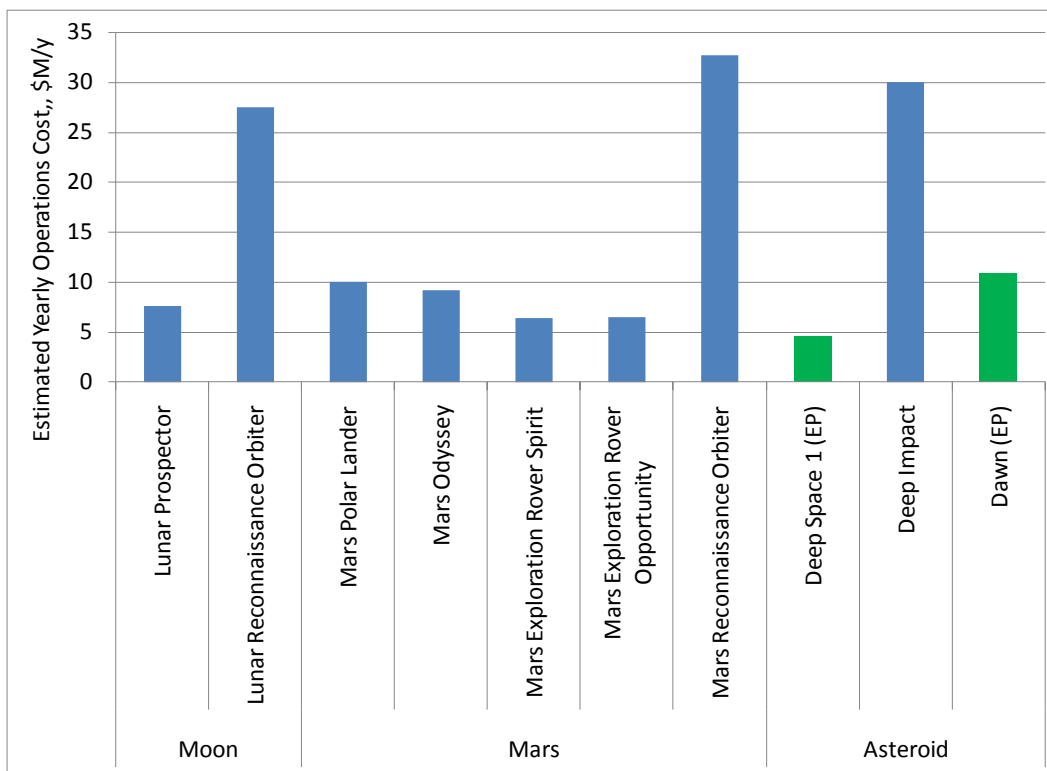


Figure 19. Estimated Yearly Operations Cost for NASA Science Missions

NASA has demonstrated that the operations costs of electric propulsion missions can rival the costs of chemically propelled missions. The increased autonomy enabled by EP spacecraft may even enable lower the cost of mission operations for some missions. NASA has also demonstrated high performance, highly throttleable electric propulsion systems that are capable of meeting a wide range of mission requirements. Trade studies performed herein have shown that cost savings up to 2X can be realized even on small NASA science missions.

IX. Conclusions

Aerojet Rocketdyne has completed mission analysis trade studies to support near term cislunar exploration mission concepts by comparing cargo delivery to the Earth-Moon Lagrange points (EML1 or EML2) using a solar electric propulsion (SEP) spacecraft (or “tug”) versus the most efficient all chemical approach. Aerojet Rocketdyne has also analyzed historical NASA science missions to illustrate how it is possible to reduce mission cost by utilizing SEP technology. This research found the following conclusions:

- SEP reduces cost/kg of cargo delivery to EML2 by up to 57% versus all-chemical solutions
- SEP can reduce the total cost of a campaign to deliver 20t of pressurized cargo to EML2 by almost 60% versus all-chemical solutions
- Launch vehicle cost and number of launches are the biggest drivers of cost/kg
- SEP allows cost savings by reducing number of launches required and enabling the use of lower cost launch vehicles
- SEP with only 1 year trip times can provide significant savings over chemical, and cost savings grow dramatically as trip time increases
- Useful SEP “tug” spacecraft can be developed with an “Integration not Innovation” approach using current technology and act as a stepping stone for developing higher power systems
- NASA has demonstrated that the operations costs of electric propulsion missions can rival the costs of chemically propelled missions and shown that overall cost savings up to 2X can be realized even on small NASA science missions.

SEP spacecraft can provide greater mission flexibility and significant overall cost savings by enabling the use of lower cost launch vehicles, providing higher payload delivery, and enabling missions that are not possible otherwise. Practical and useful SEP spacecraft can also be designed using current flight proven electric propulsion thrusters and existing spacecraft technology, without the need for costly and lengthy development.

Aerojet Rocketdyne has decades of experience working with electric propulsion, with hundreds of engines delivered, and is responsible for the majority of all electric propulsion systems that have flown to date. As a combined company, Aerojet Rocketdyne also possesses the integration experience of the ISS power system and unparalleled experience in space power systems and power management. Aerojet Rocketdyne remains at the forefront of these continually developing fields, and has flight proven electric propulsion technology that is paving the way for a new era in space exploration.

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References

- ¹ Ray, Justin, "The fight to save AEHF 1 produces remarkable rescue," *Spaceflight Now*, January 3, 2012, URL: <http://www.spaceflightnow.com/atlas/av019/120103rescue.html>, [cited August 13, 2013].
- ² National Aeronautics and Space Administration, "Asteroid Redirect Mission Fact Sheet," URL: http://www.nasa.gov/sites/default/files/files/AsteroidRedirectMission_FS_508_2.pdf, [cited August 13, 2013].
- ³ National Aeronautics and Space Administration, "NASA's FY2014 Asteroid Strategy," URL: http://www.nasa.gov/pdf/740684main_LightfootBudgetPresent0410.pdf, [cited August 13, 2013].
- ⁴ Clark, Stephen, "Electric propulsion could launch new trend," *Spaceflight Now*, March 19, 2012, URL: <http://spaceflightnow.com/news/n1203/19boeing702sp/>, [cited August 13, 2013].
- ⁵ Carpenter, Christian B., "Electrically Propelled Cargo Spacecraft for Sustained Lunar Supply Operations," AIAA 2006-4435, 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Sacramento, CA, 9 - 12 July 2006.
- ⁶ Carpenter, Christian B., Myers, R., and Kimbrel, S., "A Space Logistics System Based on Efficient In-space Transportation," AIAA SPACE 2012 Conference & Exposition, Pasadena, CA, 11 - 13 September 2012.
- ⁷ National Aeronautics and Space Administration, "NASA Launch Service Program's Launch Vehicle Performance Web Site," URL: <http://elvperf.ksc.nasa.gov>, [cited March 19, 2012].
- ⁸ Space Exploration Technologies, "Falcon 9 Payload User's Guide," SCM 2008-010 Rev. 1, 2009.
- ⁹ Kleuver, C.A., and Monheiser, J.M., "Computing Low-Thrust Orbit-Raising and Lunar Transfer," 2006 AAS/AIAA Space Flight Mechanics Meeting, Paper No. AAS 06-180, Tampa FL, January, 2006
- ¹⁰ Wertz, J. R., Everett, D. F., and Puschell, J. J., *Space Mission Engineering: The New SMAD*, Microcosm Press, Hawthorne, CA, 2011, pp. 289-323.
- ¹¹ Wang, B., "SpaceX Future Missions, Falcon 9 with Upgraded Engines and SpaceX Heavy," *NextBigFuture*, May 29, 2012, URL: <http://nextbigfuture.com/2012/05/spacex-future-missions-falcon-9-with.html>, [cited August 13, 2013].
- ¹² Mathers, A., de Grys, K., Paisley, J., "Performance Variation in BPT-4000 Hall Thrusters," IEPC-2009-144, 31st International Electric Propulsion Conference, Ann Arbor, MI, September 20 - 24, 2009.
- ¹³ National Aeronautics and Space Administration, "Lunar Prospector End of Mission & Overview," Press Kit, July 1999.
- ¹⁴ National Aeronautics and Space Administration, "Lunar Reconnaissance Orbiter (LRO): Leading NASA's Way Back to the Moon," Press Kit, June 2009.
- ¹⁵ Moon Daily, "NASA Chooses LM For LRO Launch Services," URL: http://www.moondaily.com/reports/NASA_Chooses_LM_For_LRO_Launch_Services_999.html, [cited 08 December 2009].
- ¹⁶ National Aeronautics and Space Administration, "Mars Polar Lander/Deep Space 2," Press Kit, December 1999.
- ¹⁷ National Aeronautics and Space Administration, "2001 Mars Odyssey Launch," Press Kit, April 2001.
- ¹⁸ National Aeronautics and Space Administration, "Mars Exploration Rover Launches," Press Kit, June 2003.
- ¹⁹ National Aeronautics and Space Administration, "Mars Reconnaissance Orbiter Launch," Press Kit, August 2005.
- ²⁰ National Aeronautics and Space Administration, "Deep Space 1 Launch," Press Kit, October 1998.
- ²¹ National Aeronautics and Space Administration, "Deep Impact Launch," Press Kit, January 2005.
- ²² National Aeronautics and Space Administration, "Dawn Launch Mission to Vesta and Ceres," Press Kit, September 2007.