Mars Hybrid Propulsion System Trajectory Analysis Part II: Cargo Missions

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NASAs Human spaceflight Architecture Team team is developing a reusable hybrid transportation architecture in which both chemical and electric propulsion systems are used to send crew and cargo to Mars destinations such as Phobos, Deimos, the surface of Mars, and other orbits around Mars. By combining chemical and electrical propulsion into a single spaceship and applying each where it is more effective, the hybrid architecture enables a series of Mars trajectories that are more fuel-efficient than an all chemical architecture without significant increases in flight times. This paper shows the feasibility of the hybrid transportation architecture to pre-deploy cargo to Mars and Phobos in support of the Evolvable Mars Campaign crew missions. The analysis shows that the hybrid propulsion stage is able to deliver all of the current manifested payload to Phobos and Mars through the first three crew missions. The conjunction class trajectory also allows the hybrid propulsion stage to return to Earth in a timely fashion so it can be reused for additional cargo deployment. The 1,100 days total trip time allows the hybrid propulsion stage to deliver cargo to Mars every other Earth-Mars transit opportunity. For the first two Mars surface mission in the Evolvable Mars Campaign, the short trip time allows the hybrid propulsion stage to be reused for three round-trip journeys to Mars, which matches the hybrid propulsion stage's designed lifetime for three round-trip crew missions to the Martian sphere of influence.

Nomenclature

ARRM	Asteroid Redirect Robotic Mission
CP	Chemical Propulsion
EMC	Evolvable Mars Campaign
EP	Electric Propulsion
HAT	Human spaceflight Architecture Team
HERMeS	Hall Effect Rocket with Magnetic Shielding
HPS	Hybrid Propulsion Stage
LDHEO	Lunar Distant High Earth Orbit
LDRO	Lunar Distant Retrograde Orbit
LGA	Lunar Gravity Assist
PEV	Pressurized Excursion Vehicle
ROSA	Roll-Out Solar Array
SEP	Solar Electric Propulsion
SLS	Space Launch System

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I. Introduction

THE National Aeronautics and Space Administration is currently developing an Evolvable Mars Campaign (EMC)[1] in support of the policies outlined in the 2010 NASA Authorization Act and U.S. National Space Policy.[2] The EMC outlines an evolving long term strategy for expanding human presence into the solar system and on to the surface of Mars. The journey to Mars involves an incremental buildup of capabilities: from Earth reliant missions to expand the knowledge of operations in space, to missions in cis-lunar space for testing and certification of required technologies, and ultimately to Earth independent missions and long duration stays on the Martian surface.

Many different mission design concepts have been studied and proposed over the past three decades, and many more are currently being investigated. In most of these studies, chemical propulsion has been assumed for the crewed Mars missions because solar electric propulsion, even though much more fuel efficient, produces less thrust and is more suitable for cargo pre-deployment missions when the transit time can be much longer. NASAs Human spaceflight Architecture Team (HAT) is currently developing a new hybrid transportation architecture in which both chemical and electric propulsion are combined in an integrated design.[3] The hybrid transportation architecture was developed with three key strategies that guides the mission design decisions:

- Use celestial energy resources to save propellant where time allows
- Maintain maximum orbital energy for the crew transport spaceship
- Reuse in-space architecture elements as much as possible

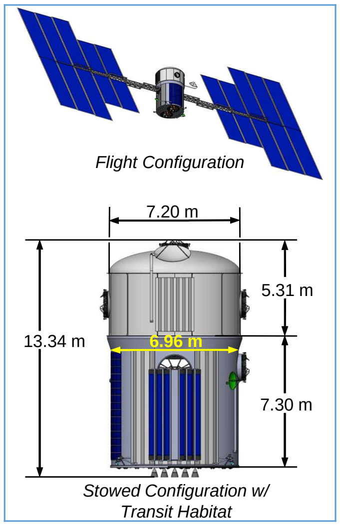
Chemical propulsion is used close to planetary bodies to quickly send the spaceship in and out of the gravity wells, while electric propulsion is used during the long transits to provide continuous change in orbital energy, therefore reducing the ΔV requirements of the chemical maneuvers at escape and capture. By combining chemical and electric propulsion into a single architecture and applying each where it is more effective, the hybrid design enables a series of Mars trajectories that are more fuel efficient than the traditional "conjunction class" trajectories ($<$ 1,100 days total round-trip duration with $>$ 300 days at Mars vicinity) without significant increase in total mission flight times. In addition, because no element is staged off, the hybrid architecture offers a transportation system that can be reused and applied to both crewed and cargo missions.

A common theme for human deep space mission is the aggregation and assembly of propulsion and crew support elements. The ability to launch an entire spaceship that is pre-integrated and able to fly round-trip to Mars has only been possible with very large launch vehicles. One of the hybrid architecture's objectives is to enable launch of an integrated vehicle that only requires rendezvous with fuel and supplies to enable multiple trips from cis-lunar space to Mars. In order to minimize the mass required, orbital energy is maximized and propellant required is minimized across trajectories from cis-lunar space to and from Mars by utilizing a combination of lunar gravity assists (LGA), solar perturbation loops, and high energy elliptical parking orbits.

This paper, along with its companion paper,[4] analyzes the interplanetary segments of the EMC trajectories using the hybrid transportation architecture. This paper focuses on the cargo missions, while the companion paper focuses on the crew missions. This paper will show the baseline architecture for the cargo pre-deployment missions in support of the three crew missions.

II. EMC Hybrid Propulsion Stage

NASA Glenn Research Center's COMPASS[5] Team performed a detailed design of the EMC Hybrid Propulsion Stage. This effort resulted in a single baseline vehicle for the current EMC hybrid architecture which is utilized in for the initial feasibility study outlined in this paper. The vehicle's design summary and mass break down is shown in Figure 1. The EMC HPS is a single SLS Block 2 10 m shroud launched, 400 kW class, hybrid SEP-Chemical vehicle that is capable of up to three round-trips between LDRO and Mars elliptical 5-Sol orbit. The HPS utilizes two main propulsion systems: a chemical bi-propellant engine that utilizes monomethylhydrazine and nitrogen tetroxide as propellants, and a solar electric propulsion system derived from the NASA Asteroid Redirect Robotic Mission(ARRM)[6,7] block 1A 150 kW class vehicle. The COMPASS team combined the components of two 150 kW ARRM block 1A SEP modules into a single



Design Constraints/Parameters

Designed Lifetime	5500+ days	
Destination	Phobos / Mars	
Stage Diameter	7.20 m	
Stage Length	8.03 m	
Main Propellant Type	Xenon	MMH/N_2O_4
# Engines / Type	24 x 13.3 kW Hall	10 x Aerojet R42
Engine Thrust (100%)		890 N
Engine Isp (100%)	3000 sec @ 800 V	303 sec
# of Restarts	10+	15+
# of Tanks	12 x ARRM Xe Tank	8 x ATK 80434-1
Tank Material	COPV	Al/Ti

RCS Propellant Type	
# Engines / Type	32 x Astrium S22-02
Engine Thrust (100%)	22 N
Engine Isp (100%)	285 sec

Power System	
Arrays	300V MegaROSA + 120V Body Mounted
BOL Generation	435kW Main + 7.5kW Commissioning
Structure	ISS SARJ Gimbals
Cell Type/ Efficiency	Li-ion, 23.8kWH @ 28V

Category	**Mass, kg**
Structure	5,100
Protection	1,080
Electric Propulsion	3,140
Chemical Propulsion	1,300
Power	5,740
Avionics & Control	160
Growth	4,960
DRY MASS SUBTOTAL	21,480
Max Xenon Load	23,100
Max Bi-Prop Load	18,600
TOTAL MAXIMUM WET MASS (w/o Payload)	63,180

Payloads	**Mass, kg**
Deep Space Transit Habitat	40,500
Mars Surface Lander	43,600
Phobos Surface Habitat	32,000
Mars Taxi	13,500
Pressurized Excursion Vehicle	7,500

Figure 1. Hybrid Propulsion Stage Design Summary

vehicle to create the EMC hybrid propulsion stage. An outer structure is wrapped around the two ARRM SEP modules, and propellant tanks and feed lines are added for the chemical propulsion(CP) system.

The main propulsion system consists of 24 13.3 kW Hall Effect Rocket with Magnetic Shielding (HERMeS)[8, 9] thrusters and ten Aerojet R-42 890 N bi-propellant thrusters.[10] The HERMeS thrusters are currently under development at NASA Glenn Research Center for the ARRM SEP module. These Hall thrusters have a nominal specific impulse of 3,000 seconds at 800 V and can operate in a high thrust mode with an Isp of 2,000 seconds. The Aerojet R-42 thrusters have a nominal Isp of 303 seconds and can produce 890 N of thrust with an oxidizer-to-fuel ratio of 1.65. The HPS has twelve ARRM designed composite overwrapped pressure vessels (COPV) xenon tanks that each have a nominal load of 2,000 kg and eight ATK[11] model 80434-1 derived aluminum/titanium bi-propellant tanks that each have a nominal load of 2,325 kg per tank. The bi-propellant tanks are a stretched version of the 80434 which provide increased capacity. In addition to the two primary propulsion systems, the HPS also has thirty-two Astrium S22-02[12] reaction control thrusters located in four pods around the spacecraft with eight thrusters in each pods.

Two 300 V Roll-Out Solar Array (ROSA)[13] wings are attached to International Space Station derived solar alpha rotary joint gimbals[14] to provide the main electrical power to the SEP system. Each of the solar array wings consists of ten winglets: six long 5 m x 23 m winglets similar to the ARRM SEP vehicle, and four short inner 5 m x 14 m winglets to avoid the thrust plume from the SEP thrusters. The arrays are sized to produce 435 kW of power at beginning of life at Earth distance (1 AU). The main array supplies the SEP thrusters with all the power they require to perform the nominal thrusting operation; additionally, the main array supplies 14 kW of power to the transit habitat for the crew. In addition to the main solar array, the vehicle also has a body-mounted commissioning array that provides 8 kW of power at 120 V prior to the ROSA deployment. For eclipse operation, the vehicle carries lithium ion batteries with 25 $kW-hr$ capacity at 28 V.

III. EMC One-Way Cargo to Phobos

The first crew mission to the Martian sphere of influence is a surface mission to Phobos. The crew departs Earth in 2033 and arrives in 2034 as discussed in Part I of this paper.[4] To support the crew at the destination, a cargo pre-deployment flight is required. The cargo pre-deployment for the Phobos mission will need to deliver all of the supplies and hardware that the crew needs to the Martian sphere of influence. Current EMC architecture has defined three required payload to support the Phobos mission: the Phobos habitat, the Mars Taxi, and the Pressurized Excursion Vehicle (PEV).[15]

The Phobos habitat is a pressurized habitation module similar to the crew transit habitat, but built to support the crew up to 500 days at the surface of Phobos. The habitat is connected directly to the HPS

Table 1. EMC Hybrid Architecture Payloads to Phobos

	5-Sol Taxi	PEV	Habitat	
Dry Mass	6,000	5,620	22,500	kg
Cargo/Logistics	1,100	960	10,000	kg
Propellant	6,700	850	0	kg
Total	13,800	7,430	32,500	kg

and draws power from the main HPS arrays. The Mars Taxi vehicle is a liquid oxygen / liquid methane propulsion stage that is based on the design of the Mars ascent vehicle. The purposes of this vehicle are to take the crew from the HPS parking orbit to the surface of Phobos to rendezvous with the Phobos habitat and to return the crew to the parking orbit and the HPS/transit habitat after the conclusion the mission. The PEV is designed to extend the crew's ability to explore Phobos' surface. Similar to a rover on the surface of Mars, the PEV is able to maneuver in the microgravity environment on Phobos to allow the crew to explore away from the habitat. A summary of the current best estimated mass for each of the systems is shown in Table 1.

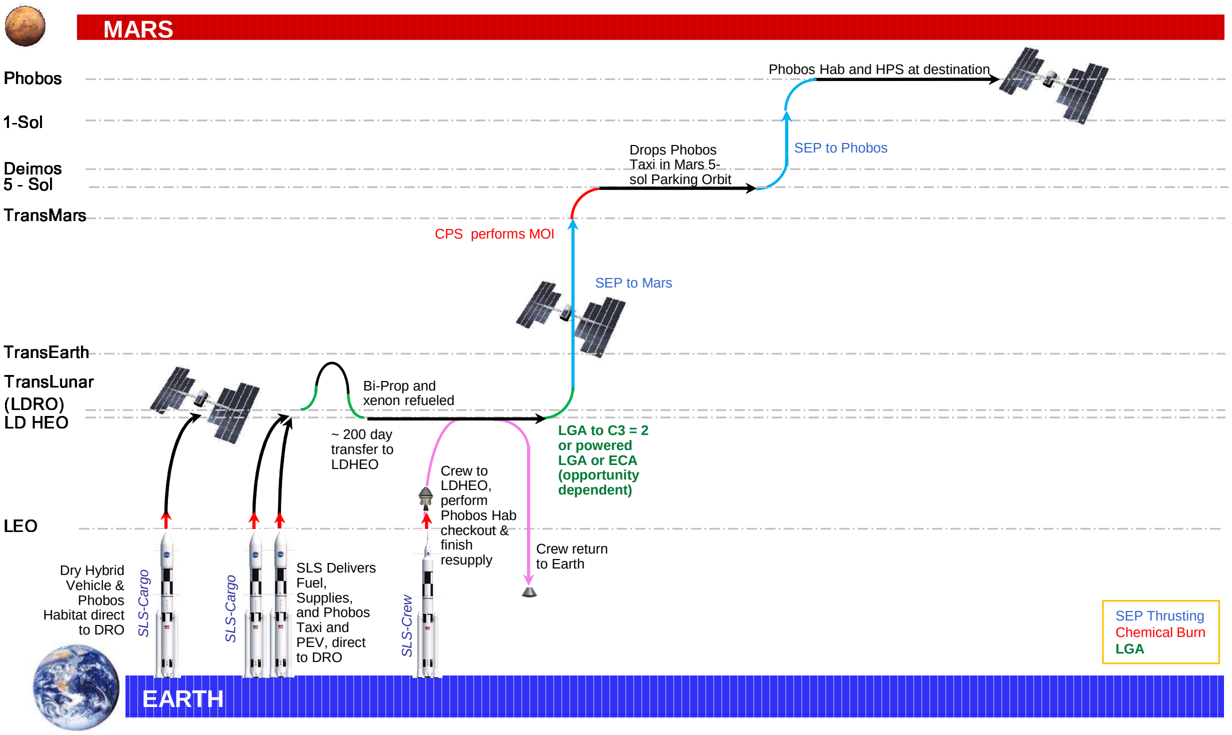


Figure 2. Mars Hybrid One-Way Cargo Mission to Phobos Concept of Operation

The Phobos cargo pre-deployment concept of operation is shown in Figure 2. This pre-deployment marks the only time in which the HPS is not reused for multiple missions. The HPS is attached to the Phobos habitat and needs to remain on the surface of Phobos through the 2033 crew mission, which drastically limits its potential for reuse. The HPS is launched pre-integrated with the Phobos habitat directly to LDRO. Two additional flights of the SLS deliver the propellant, the Mars Taxi, the PEV, and crew logistics to the HPS stack. After the HPS is fully supplied, it performs a ballistic lunar transfer[16] to insert into an lunar distant high Earth orbit (LDHEO), where it rendezvous with a check out crew. The check out crew ensures the Phobos habitat is fully operational and stocked with supplies for the Phobos mission. The HPS stack then departs Earth via a lunar gravity assist, targeting a departure C3 of 2 km^3/s^2. During the interplanetary phase, the EP system is continuously thrusting to increase the spacecraft's orbital energy. Arriving at Mars, the CP system performs a maneuver to insert the HPS stack into a 5-Sol parking orbit. The Mars Taxi decouples from the HPS stack and remains in the 5-Sol parking orbit to await the arrival of the Phobos mission crew. After the departure of the Mars taxi, the HPS stack first performs eccentricity change spiral to circularize the orbit before a spiraling down to rendezvous with Phobos.[16] First order analysis provides the trajectory ΔV budgets of 2 km/s for the maneuver. High fidelity analysis will be required to refine the spiral propulsive requirement.

Table 2. Evolvable Mars Campaign Hybrid SEP/Chem Transportation Architecture Phobos Cargo Pre-Deployment Summary

A. Mission Phasing Characteristics

	Earth Departure	Mars Arrival	Trip Time	Begin Spiral	Phobos Arrival	Spiral Time
2031 Phobos	12/01/30	12/25/31	389 days	01/04/32	08/16/32	225 days

B. Hybrid Propulsion Vehicle Characteristics

	Earth Dep. Mass (kg)	Hybrid Dry (kg)	Mars Payload (kg)	Phobos Payload (kg)	Transit Xenon (kg)	Spiral Xenon (kg)	Bi-Prop Load(kg)
2031 Phobos	107,500	21,480	13,800	40,000	16,500	4,900	11,000

C. Interplanetary Trajectory Characteristics

	Earth Dep. $V_\infty(km/s)$	Mars Arr. $V_\infty(km/s)$	Earth Dep. Declination	Mars Arr. Declination
2031 Phobos	1.4142	1.0631	22.41 °	8.686 °

For the Phobos cargo pre-deployment, the total HPS payload mass delivered to Mars 5-Sol parking orbit is just shy of 54 metric ton (mT = 1,000 kg), and the total payload to Phobos is 40 mT. As a point of comparison, the HPS delivers 41 mT of payload to Mars 5-Sol parking orbit for each of the crew missions.[4] The primary difference between the crew mission and the Phobos cargo is that there is no return trip to Earth, thus reducing the propellant required by a significant amount. Table 2 shows the mission characteristics for the 2031 cargo pre-deployment to Phobos using the EMC hybrid architecture. The optimized trajectory departs Earth on December 1, 2030, travels 389 days to Mars, and captures into the Mars 5-Sol parking orbit on December 25, 2031. After a 10 day loiter period, during which the Mars Taxi vehicle detaches from the HPS and Phobos cargo, the HPS begins thrusting to raise the orbit's periapsis to circularize the orbit before the spiraling down to Phobos.[16] With the current EMC payload mass, the periapsis raise maneuver takes roughly 90 days, and the spiral down to Phobos takes 125 days for a total of 225 days transit from Mars 5-Sol to Phobos. Once in Phobos' orbit, the chemical system has a ΔV budget of 150 m/s to perform proximity and rendezvous operations to land the payload on Phobos.

The one-way pre-deployment mission requires 21.4 mT of xenon and 11 mT of chemical propellant. The xenon load is near the capacity of the HPS vehicle, while the chemical tanks are offloaded by a significant amount. Without a return trip to perform and no reuse of the stage, the Phobos cargo HPS is significantly oversized in almost all subsystems. However, the Phobos HPS represents the first time the HPS is sent on an interplanetary journey, and will arrive at its destination six or more months prior to the next HPS departure from Earth. Thus valuable lesson can be learned from the subsystems' performance and reliability with this first mission. This is critical in reducing the overall risk to the architecture and the campaign.

IV. EMC Round-Trip Cargo to Mars

To support crew missions to the Martian surface, a plethora of surface elements needs to be delivered prior to sending a crew mission to the Martian sphere of influence. These systems includes surface habitat, power generation units, in-situ resource production plants, as well as the Mars ascent vehicle.[17] In order to deliver all of these systems to the surface, the EMC has been developing Mars landers of varying sizes to optimize the delivery of the surface elements. The current baseline Mars lander has a total wet mass of 43.6 mT and can deliver roughly 18 mT to the Martian surface. From the in-space transportation perspective, the HPS must be able to deliver the fully loaded lander to Mars 5-Sol and return to Earth for reuse.

The Mars cargo pre-deployment concept of operation is shown in Figure 3. A new HPS is launched fully fueled for Mars transit on an SLS directly to LDRO. This is different from the crew mission and the Phobos cargo pre-deployment mission, as the SLS can not deliver the combined lander and HPS to LDRO directly. The fully fueled HPS rendezvous with the fully fueled lander in LDRO, which is delivered by a second SLS. The combined HPS/lander stack then departs Earth via LGA and travels to Mars in the same

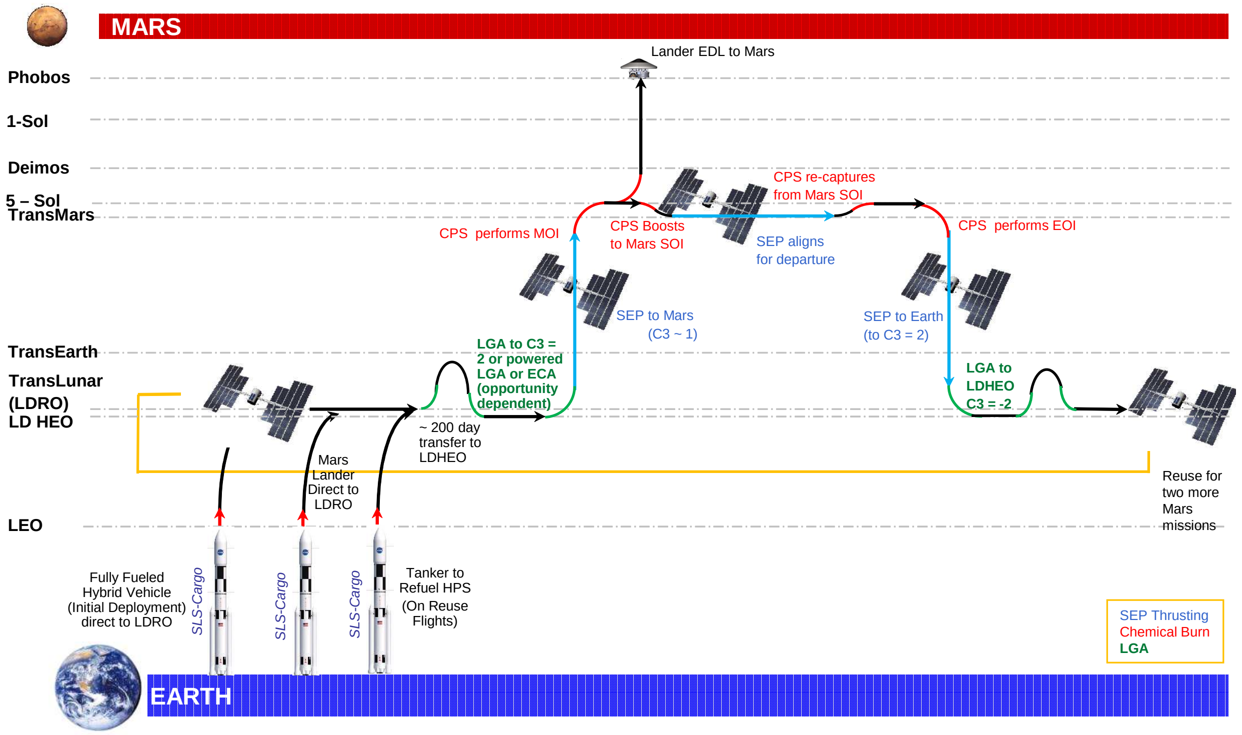


Figure 3. Mars Hybrid Round-trip Cargo Mission to Mars Concept of Operation

type of trajectory as the crew and Phobos cargo missions. After inserting into the Mars 5-Sol parking orbit, the lander detaches from the HPS and enters the atmosphere to the Mars landing site. The payload-less HPS then performs the necessary maneuver to realign its orbit for departure.[16] This maneuver can take anywhere between 120 days and 300 days. So, despite not having any payload, the HPS must remain in Mars sphere of influence for a minimum stay time before it can return to Earth for reuse. The payload-less HPS returns to Earth in the same type of trajectory as the crew return[4] and inserts into LDRO for reuse.

On subsequent uses of the HPS, the fully loaded lander is launched on an SLS and rendezvous with the HPS, and an additional SLS is utilized to supply the HPS with the fuel required to perform the next round-trip mission to Mars. Thus, each delivery of the Mars lander to Martian surface requires two SLS launches. The HPS lifetime of 15 years allows it to be used on three round-trip missions to deliver landers. In order to deliver all of the necessary systems to the surface by the first 2039 crew Mars mission, the Mars cargo pre-deployment must begin by 2033, during the same opportunity as the Phobos crew mission. A limitation on the number of available SLS launches per-year drives the delivery schedule of the Mars landers. In addition, for reuse on subsequent trips to Mars, the HPS must have returned to Earth sphere of influence to rendezvous with a new lander and be refueled. These factors drove the hybrid architecture to baseline a total of four HPS vehicles for cargo deliveries, with two HPS delivering a lander to Mars during every other opportunity.

Table 3 summarizes the EMC hybrid architecture Mars cargo pre-deployment mission characteristics. The tables shows two HPS vehicles: HPS1 delivering Mars landers in 2033, 2037 and 2041 and HPS2 delivers Mars landers in 2035, 2039, and 2043. HPS1 denotes HPS that make their first journey to Mars in 2033 while HPS2 denotes HPS that make their maiden voyage in 2035. During each opportunity, two HPS deliver landers to Mars sphere of influence. The EMC campaign team will optimize the actual cadence of launches and Mars transit based on the availability of launch vehicles, lander hardware, and other mission decision factors.

The mission phasing characteristics for the cargo missions show similar conjunction class mission times as the crew trajectories.[4] Both the Earth-Mars outbound trip times and Mars-Earth inbound trip times are between 300 and 400 days. This combined with a 300 or more days minimum stay time at Mars puts the total round-trip trip time of roughly 1,100 days. Similar to the crew trajectory, there is a 500 days refit window for the HPS before the departure date for the next Mars mission. The vehicle characteristics for the

Table 3. Evolvable Mars Campaign Hybrid Transportation Architecture Mars Cargo Pre-Deployment Summary

A. Cargo Mission Phasing Characteristics

	Earth Departure	Mars Arrival	Mars Departure	Earth Arrival	Days to Next Departure	Outbound	Stay	Inbound
2033 (HPS1)	02/27/2033	01/10/2034	03/16/2035	01/02/2036	548 days	317 days	430 days	292 days
2037 (HPS1)	07/03/2037	08/17/2038	06/13/2039	05/09/2040	495 days	410 days	300 days	331 days
2041 (HPS1)	09/16/2041	10/16/2042	08/12/2043	07/24/2044	–	395 days	300 days	347 days
2035 (HPS2)	05/24/2035	03/20/2036	04/09/2037	04/09/2038	490 days	300 days	386 days	364 days
2039 (HPS2)	08/11/2039	09/14/2040	07/11/2041	06/16/2042	490 days	400 days	300 days	340 days
2043 (HPS2)	10/19/2043	11/17/2044	09/13/2045	08/31/2046	–	395 days	300 days	352 days

B. Hybrid Propulsion Vehicle Characteristics

	Array Power	Earth Dep. Mass (kg)	Hybrid Dry (kg)	Lander Wet (kg)	Xenon Load (kg)	Bi-Prop Load (kg)	% Xenon Tank Fill	% Bi-Prop Tank Fill
2033 (HPS1)	435 kW	89,390	21,482	43,600	17,300	7,300	74.9%	39.2%
2037 (HPS1)	409 kW	88,470	21,482	43,600	18,200	5,500	78.8%	29.6%
2041 (HPS1)	392 kW	89,230	21,482	43,600	17,100	7,400	74.0%	39.8%
2035 (HPS2)	435 kW	88,290	21,482	43,600	18,100	5,400	78.4%	29.0%
2039 (HPS2)	409 kW	88,720	21,482	43,600	17,200	6,800	74.5%	36.6%
2043 (HPS2)	392 kW	88,940	21,482	43,600	17,600	6,600	76.2%	35.5%

C. Interplanetary Trajectory Characteristics

	Earth Dep. $V_\infty(km/s)$	Mars Arr. $V_\infty(km/s)$	Mars Dep. $V_\infty(km/s)$	Earth Arr. $V_\infty(km/s)$	Earth Dep. Declination	Mars Arr. Declination	Mars Dep. Declination	Earth Arr. Declination
2033 (HPS1)	1.4142	1.1094	0.4784	1.4142	-2.658°	-4.676°	-7.367°	4.283°
2037 (HPS1)	1.4142	0.7335	0.5634	1.4142	-9.223°	8.758°	-2.785°	-15.105°
2041 (HPS1)	1.4142	1.0186	0.9241	1.4142	4.973°	-13.555°	7.016°	10.051°
2035 (HPS2)	1.4142	0.7332	0.4712	1.4142	-12.709°	17.902°	-13.168°	-10.690°
2039 (HPS2)	1.4142	0.9492	0.7826	1.4142	-2.692°	-5.013°	-4.604°	-0.525°
2043 (HPS2)	1.4142	0.9111	0.7622	1.4142	11.791°	-15.642°	15.518°	16.138°

cargo missions show significant reduction in the Earth departure mass as compared to the crew missions and the Phobos mission. Despite having similar payload mass (40 mT for the transit habitat[4] vs 43.6 mT for the lander), the Earth departure mass for the cargo mission is 10 mT or more less than the crew missions. After the HPS delivers the cargo, it returns to Earth payload-less, which reduces the propulsion requirements by a significant amount, as seen by the propellant requirements for the cargo missions. The xenon tanks are no more than 80% full and the chemical propellant tanks are no more than 40% full for any of the cargo opportunities.

The removal of the return trip payload provides significant savings to the overall propulsion system mass, as the HPS has to carry the return trip propellant during the outbound trajectory. The HPS was sized to be able to deliver the crew round-trip from Earth to Mars; thus, it is oversized for the cargo missions. Thus, there is potential for the HPS to be optimized to deliver the landers, however this would require redesign of the vehicle which could increase the complexity and cost of the architecture. Additionally, with the cargo mission requiring far less performance from the propulsion systems, there is potential to utilize the older and more degraded vehicles for the cargo missions while saving the newer, higher preforming HPS for the crew missions. A separate HPS designed for the cargo mission will not allow the availability and flexibility of swapping out HPS vehicles for different missions.

V. Phobos Cargo Sensitivity Analysis

The Phobos payload delivery is slightly more complicated than the Mars cargo as it places two payload into two different orbits. The HPS has to deliver both Phobos payload and Mars taxi from Earth to Mars 5-Sol parking orbit, but only the Phobos cargo spirals down from the parking orbit to Phobos. The nominal Phobos mission delivers 13.8 mT of payload to Mars 5-Sol and 40 mT to Phobos and utilizes 78% of the propellant capacity of the HPS (as shown in Table 1). The payload to both destinations can have dramatic variation depending on the design decisions form the campaign analysis, thus it is desired to understand the impact of these changes to the transportation architecture. Payload mass to Mars 5-Sol and Phobos were varied across a range to understand the impact of the change to the overall propellant load requirement of the HPS.

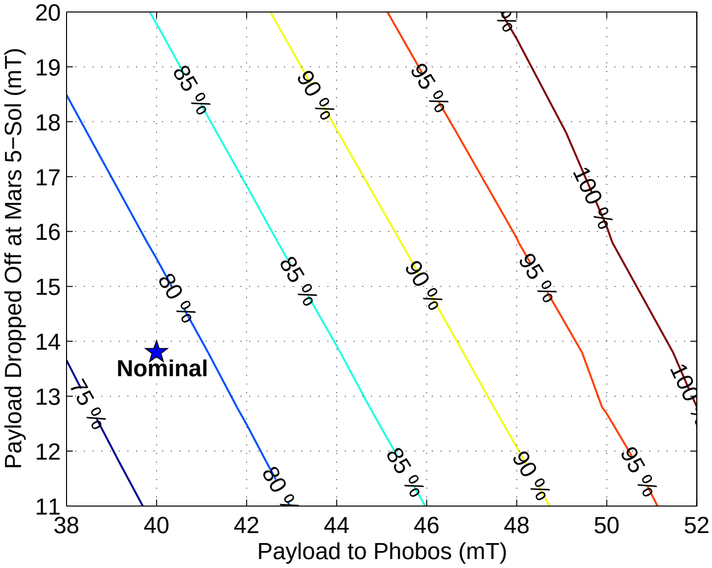


Figure 4. Hybrid Propulsion System Total Propellant Usage as Function of Phobos and Mars 5-Sol Payloads

Figure 4 shows the constant level contour plots of the HPS total propellant usage as function of the payload mass delivered to Mars 5-Sol and Phobos. The nominal case of 40 mT to Phobos and 13.8 mT to Mars 5-Sol is shown as a single point on the plot. The contour plot shows that the propellant loading increases near linearly as the payload mass to both destination increases. For the nominal 13.8 mT Mars taxi to 5-Sol, the HPS has enough propulsion capability to deliver close to 51 mT to the surface of Phobos given the current vehicle and the trajectory assumptions. Similarly, extrapolating the data based on the results of the sensitivity analysis, with the nominal 40 mT payload to Phobos, the HPS has enough capacity to deliver 30 mT of payload to Mars 5-Sol before spiraling to Phobos. This analysis shows that the HPS vehicle provides significant margin to the cargo pre-deployment for the Phobos mission. As a result, minor mass growth to payload systems does not pose significant closure risks to the transportation architecture at this point. However, increase in propellant demand will have impact on the campaign analysis from logistics and resupply stand points.

VI. Mars Cargo Sensitivity Analysis

For the cargo missions to Mars, the only payload delivered by the HPS is the Mars lander. For the EMC crew missions to Mars, multiple landers are required per mission to deliver all the necessary systems to the Martian surface. These landers incorporate significant advanced technologies that allow for precision entry, descent, and landing in the thin Martian atmosphere. These advanced technologies present potential for mass growth as the lander design matures. Thus it is critical for the transportation architecture to understand the impact of lander mass growth.

Table 4 shows the impact of changing payload mass on the transportation architecture across each of the Mars cargo delivery opportunities. Because the HPS utilizes both high thrust chemical propulsion and low thrust electric propulsion, the propellant required can vary drastically across the Earth-Mars synodic period based on the planetary alignment as shown in Table 3. The energy required to transit from Earth to Mars and back is the same within each opportunity, but as the payload mass changes, the optimized balance between using the EP versus the CP system changes. As the payload mass increases, the trajectory tries to increase the thrusting period for the EP system first to achieve the required energy change, as it is more efficient than the CP system. However, as the payload mass grows, the HPS may not have enough time to allow the EP system to make up for the energy, thus requiring an increase in chemical propellant. This balancing act can be observed in the results shown in the Table.

For the 2033 and 2037 delivery opportunities, as the payload mass increases, the HPS requires significantly

Table 4. Evolvable Mars Campaign Hybrid Transportation Mars Cargo Sensitivity to Payload Mass

Payload		Xenon (*kg*)	Chem (*kg*)	Total (*kg*)	% Xenon Load	% Chem Load		Xenon (*kg*)	Chem (*kg*)	Total (*kg*)	% Xenon Load	% Chem Load
40.0 mT	2033	17,000	6,200	23,200	73.6%	33.3%	2035	17,300	5,200	22,500	74.9%	28.0%
43.6 mT		17,400	7,300	24,700	75.3%	39.2%		18,100	5,400	23,500	78.4%	29.0%
56.0 mT		17,900	13,100	31,000	77.5%	70.4%		18,600	11,800	30,400	80.5%	63.4%
65.0 mT		18,300	18,000	36,300	79.2%	96.8%		18,100	19,400	37,500	**Did Not Close**†	
75.0 mT		18,600	24,300	42,900	**Did Not Close**†			17,300	25,200	42,500	**Did Not Close**†	
40.0 mT	2037	17,400	5,200	22,600	75.3%	28.0%	2039	16,600	6,200	22,800	71.9%	33.3%
43.6 mT		18,200	5,500	23,700	78.8%	29.6%		17,200	6,700	23,900	74.5%	36.0%
56.0 mT		18,900	13,200	32,100	81.8%	71.0%		20,500	8,200	28,700	88.7%	44.1%
65.0 mT		19,900	18,200	38,100	86.1%	97.8%		21,700	16,200	37,900	93.9%	87.1%
75.0 mT		21,600	23,300	44,900	**Did Not Close**†			22,300	20,900	43,200	**Did Not Close**†	
40.0 mT	2041	16,800	6,700	23,500	72.7%	36.0%	2043	16,900	6,200	23,100	73.2%	33.3%
43.6 mT		17,300	7,100	24,400	74.9%	38.2%		17,600	6,500	24,100	76.2%	34.9%
56.0 mT		19,500	8,600	28,100	84.4%	46.2%		20,200	7,500	27,700	87.4%	40.3%
65.0 mT		21,700	9,400	31,100	93.9%	50.5%		21,500	8,900	30,400	93.1%	47.8%
75.0 mT		22,400	14,100	36,500	97.0%	75.8%		23,000	10,500	33,500	99.6%	56.5%

† *Propellant Required Exceeds Vehicle Propellant Storage Capacity*

more chemical propellant, while the EP propellant load is relatively insensitive to the payload mass. The planetary alignments in 2033 and 2037 make it difficult to increase the interplanetary transit time, which limits the amount of time available for EP thrusting. Thus, as the payload mass increases, a significant increase to chemical propellant is required to provide the energy required to reach Mars. This is drastically different as compared to the 2043 opportunity, where the xenon load is much more sensitive to payload mass as compared to the chemical propellant. The 2043 opportunity has a relatively long transit time, and thus it allows the EP system to have more time for thrusting when the payload mass increases. The remaining opportunities see a relatively balanced increase in both EP and CP propellant need as the payload mass increases.

Table 5. Evolvable Mars Campaign Hybrid Transportation Maximum Mars Cargo Capability

	Isp	Array Power	Payload
2033	303 sec	435 *kW*	66,200 *kg*
2035		435 *kW*	62,400 *kg*
2037		409 *kW*	65,800 *kg*
2039		409 *kW*	70,400 *kg*
2041		392 *kW*	77,000 *kg*
2043		392 *kW*	76,600 *kg*

From a transportation closure perspective, the 2035 opportunity is the most difficult, as an increase in payload mass to 65 mT results in non-closure of the transportation system. The 2041 and 2043 opportunities allow payload delivery of 75 mT or more even with the degraded solar arrays. Table 5 shows the maximum payload that can be delivered by the HPS to Mars 5-Sol for each of the opportunities. With the current HPS propulsion system design, there is significant margin in the HPS performance to mitigate the effect of lander mass growth. Even the most difficult 2035 opportunities has more than 40% vehicle performance margin. It is interesting to note that the later opportunities have significantly higher maximum payload, despite the reduction in solar array performance. The planetary alignment in these years allows the balance between the EP and CP system to reach optimality, which results in significantly higher payload capability as compared to the other opportunities.

As discussed in Part I of this paper,[4] the propulsion system chosen for the EMC HPS represents current state-of-the-art technology. There is potential for improvements to the performance of the propulsion systems in the coming decades before the EMC mission begins; thus it is desired to understand how the potential change in propulsion performance impacts the overall mission performance. Table 6 shows the percent increase in array power delivered to the HPS vehicle. For the chemical systems, specific impulses of 288, 303, and 333 seconds were considered for evaluation.

Table 6. Change in Solar Array Power Supplied to Electric Propulsion System at Earth Departure (1AU) for Sensitivity Analysis

	-10%	-5%	Nominal	+5%	+10%	+15%	
2033 / 2035	392	413	435	457	478	500	kW
2037 / 2039	365	389	409	430	450	470	kW
2041 / 2043	353	372	392	412	431	451	kW

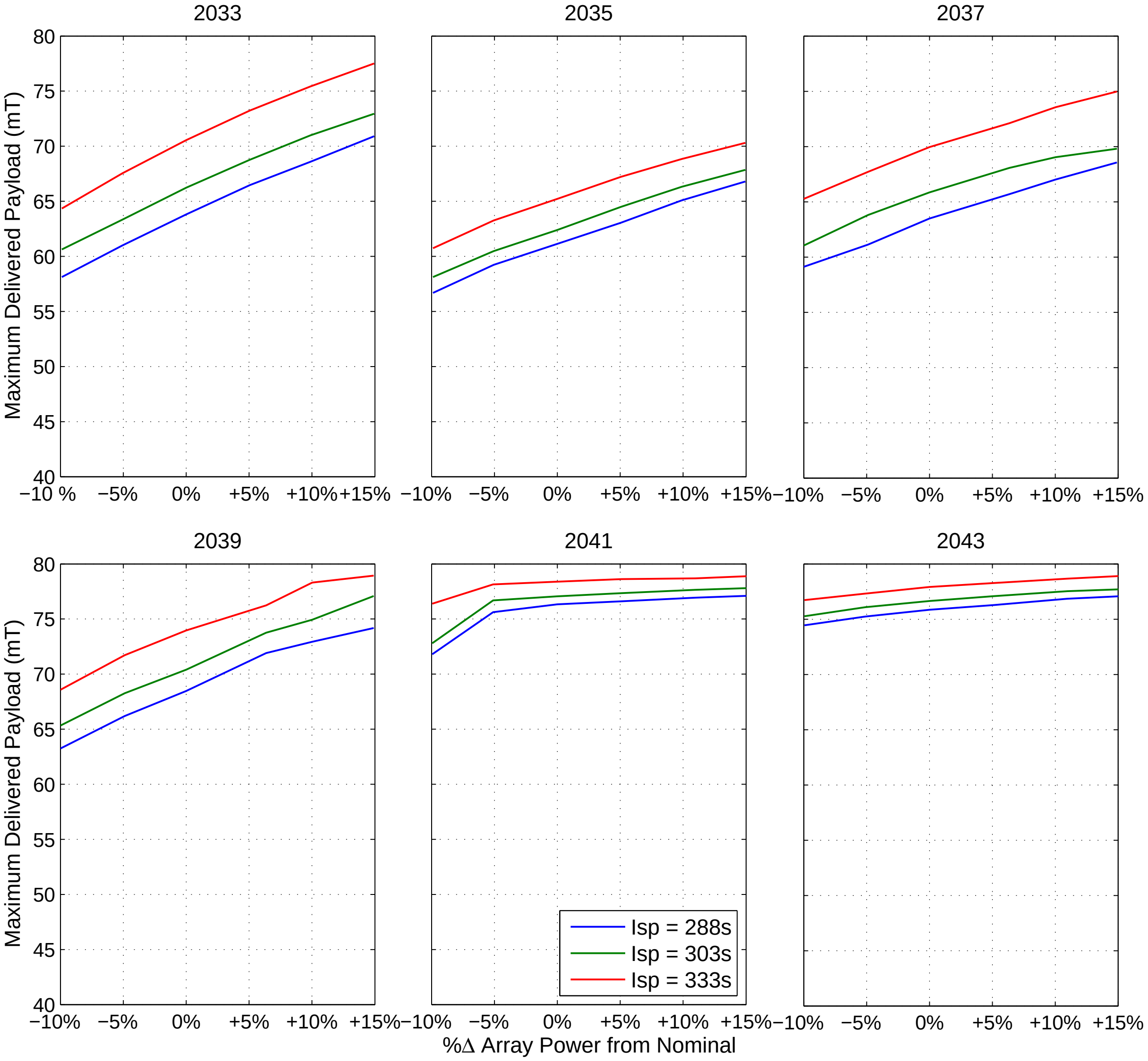


Figure 5. Evolvable Mars Campaign Hybrid Transportation Maximum Cargo Capability to Mars as Function of Propulsion System Parameters

Figure 5 shows the maximum cargo capability of the HPS for each of the opportunities and their changing propulsion performance parameters. Some very interesting trends can be observed from this sensitivity analysis. First, the 2033, 2035, 2037, and 2039 opportunities all see significant payload mass sensitivity to the propulsion performance parameters. In contrast, the 2041 and 2043 opportunities, while having the highest maximum payload, do not have appreciable sensitivity to changes in the propulsion parameters. With 303 seconds of specific impulse on the chemical engines, a 10% increase in the array power can increase the payload delivery capability by as much as 6-8 mT. Similarly, with the nominal array power, increasing the specific impulse to 333 seconds can increase the maximum payload by 5 mT in certain opportunities. 2035 remains the most difficult opportunity, as a 15% increase in array power in addition to increasing the specific impulse to 333 seconds only results in a maximum payload of 70 mT, which several opportunities were able to achieve with the nominal propulsion system performance. On important item to note is that within the range of propulsion system performance considered here, none of the opportunities saw a decrease in payload to levels that would threaten the current 43.6 mT lander design.

For the 2041 and 2043 opportunities, the trajectory of the nominal propulsion system is near optimized for the transit, thus a further increase in the performance of the propulsion system performance yields a relatively insignificant increase in maximum payload. The results from the 2041 and 2043 opportunities are encouraging. If solar array degradation becomes worse than the assumed 1% per year rate, the sensitivity analysis shows that the HPS has enough performance margin to mitigate the additional degradation. However, a combination of significant payload mass growth and additional array degradation may cause transportation closure issues for the 2037 and 2039 opportunities.

It is important to note that while it is good to understand the maximum capacity of the cargo deployment capacity of the hybrid architecture, the reality of actually delivering the full capacity is very challenging. Currently, the SLS Block 2B is capable of delivering 47 mT of payload to the LDRO staging orbit. Thus in order for the HPS to deliver anything above 47 mT to Mars, it would require multiple SLS launches to aggregate the payload in LDRO. Additionally, the current propellant resupply assumption is a single SLS flight to deliver the nominal propellant load for the Mars lander cargo missions. Thus, to fully fuel the HPS for a full load payload to Mars would require multiple SLS launches for fuel delivery. With the current anticipated launch rate of the SLS, this would require multiple years of aggregation in LDRO to achieve. The analysis shown here in the paper will assist the HAT campaign analysis team in formulating the optimal strategy to launch, aggregate, and deliver all of the necessary elements to support EMC.

VII. Summary and Future Work

A hybrid transportation architecture is being developed by NASA's Human spacecraft Architecture Team for the Evolvable Mars Campaign for both crew and cargo delivery to the Martian sphere of influence. One version of the hybrid propulsion stage for the EMC hybrid transportation architecture was designed by the NASA Glenn Research Center COMPASS team based on proposed hardware from the NASA Asteroid Robotic Redirect Mission and used for this feasibility study. The HPS is capable of delivering both crew and cargo to Mars and is designed to be reused for multiple trips. The trajectory summary for the cargo pre-deployment to both Phobos and Mars are presented in this paper. The analysis show that the HPS is oversized for delivering cargo to the Martian sphere of influence, as it was designed to deliver crew round-trip from Earth to Mars. With excess performance available, the HPS is able to deliver the current manifested payload to Phobos and Mars through the first three crew missions bu making multiple trips to Mars.

For the Phobos cargo pre-deployment, the HPS delivers payload to both Mars 5-Sol and the surface of Phobos. The sensitivity analysis performed showed the propellant required to deliver these elements can vary dramatically as the two payload masses change. However, the HPS does have excess performance to be able to handle significant payload mass growth. The more challenging issue with Phobos payload mass growth is the launch and aggregation of these element in cis-lunar space as compared to the interplanetary transportation. For the Mars cargo pre-deployment, the sensitivity of the HPS performance to payload mass growth varies depending on the launch opportunity. The 2035 opportunity, despite having a fully powered HPS, is the most difficult opportunity as the payload mass grows. Conversely, the 2041 and 2043 opportunities, despite having degraded solar arrays, presents the easiest opportunity for cargo delivery. This shows that the cargo pre-deployment is influenced by planetary alignment more significantly than by the performance of the propulsion systems with the current set of assumptions.

This paper has shown the feasibility of the hybrid transportation architecture to pre-deploy cargo to

Mars and Phobos in support of the EMC crew missions. The hybrid architecture enables conjunction class trajectories for both crew and cargo deployment without significant increase to the propellant requirements as compared to all chemical architectures. The conjunction class trajectory also allows the HPS to return to Earth in a timely fashion so it can be reused for additional cargo deployment. The 1100 day total trip time allows the HPS to deliver cargo to Mars every other Earth-Mars transit opportunity. For the first two Mars surface mission in the EMC, this allows the HPS to be reused for three round-trip journeys to Mars, which matches the HPS designed lifetime for three round-trip crew missions to the Martian sphere of influence. Additional cargo deployment strategies are available, which can improve the transportation architecture. These include drop-off style trajectories where the HPS does not enter the Mars gravity well; instead the HPS drops off the payload during a Mars flyby, which requires the payload to capture itself into Mars via a combination of aero-brake, aero-capture, and chemical insertion. This strategy has the potential to significantly reduce the amount of propellant required to deliver the payload, which can improve the campaign aggregation complexity of the EMC. Refinement in the trajectory and the hybrid vehicle design will continue as the HAT task leads work to integrate the EMC. Design of the hybrid propulsion stage will continue to mature to ensure the architecture feasibility to the evolving requirements definition and concept selection activity within EMC.

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