# Mars Hybrid Propulsion System Trajectory Analysis Part I: Crew Missions

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**NASAs Human spaceflight Architecture 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 provides the analysis of the interplanetary segments of the three Evolvable Mars Campaign crew missions to Mars using the hybrid transportation architecture. The trajectory analysis provides departure and arrival dates and propellant needs for the three crew missions that are used by the campaign analysis team for campaign build-up and logistics aggregation analysis. Sensitivity analyses were performed to investigate the impact of mass growth, departure window, and propulsion system performance on the hybrid transportation architecture. The results and system analysis from this paper contribute to analyses of the other human spaceflight architecture team tasks and feed into the definition of the Evolvable Mars Campaign.**

## 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 |
| ROSA | Roll-Out Solar Array |
| SEP | Solar Electric Propulsion |
| SLS | Space Launch System |

## 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.

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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 $\Delta$V 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 ($<$ 1100 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 crew missions, while the companion paper focuses on the cargo missions. The paper will show the baseline architecture for the crew missions, summary of the design of the hybrid propulsion stage, result of the interplanetary trajectory analysis, and sensitivities of the trajectory to mass growth, departure date, and performance of the propulsion systems.

## II. EMC Hybrid Crew Transportation Architecture

The initial Hybrid crew mission is depicted in Figure 1. Additional crew missions that reuse the integrated Mars spaceship begin with the vehicle in Lunar Distant Retrograde Orbit (LDRO) after the previous use. The crewed Mars mission begins with initial deployment and checkout of the integrated Hybrid Propulsion Stage (HPS) and the deep space transit habitat stack. The stack is launched on a NASA Space Launch System (SLS) directly to a characteristic energy (C3) of -2 $km^3/s^2$, targets an LGA and performs a six month transit to a stable LDRO. Upon arrival in a LDRO, the HPS/Habitat stack rendezvous with existing cis-lunar infrastructure and additional SLS are launched (or already waiting in LDRO) to transfer fuel and logistics required for the Mars missions. A check-out crew can visit the HPS/Habitat stack to assist in the refueling and outfitting if necessary.

After the HPS/Habitat stack has been fully fueled and stocked with logistics, the stack performs a six month transit from LDRO to lunar distant high Earth orbit (LDHEO) via a solar perturbation loop with a pair of LGAs. The Mars crew is launched on an SLS directly to the LDHEO, where they rendezvous with

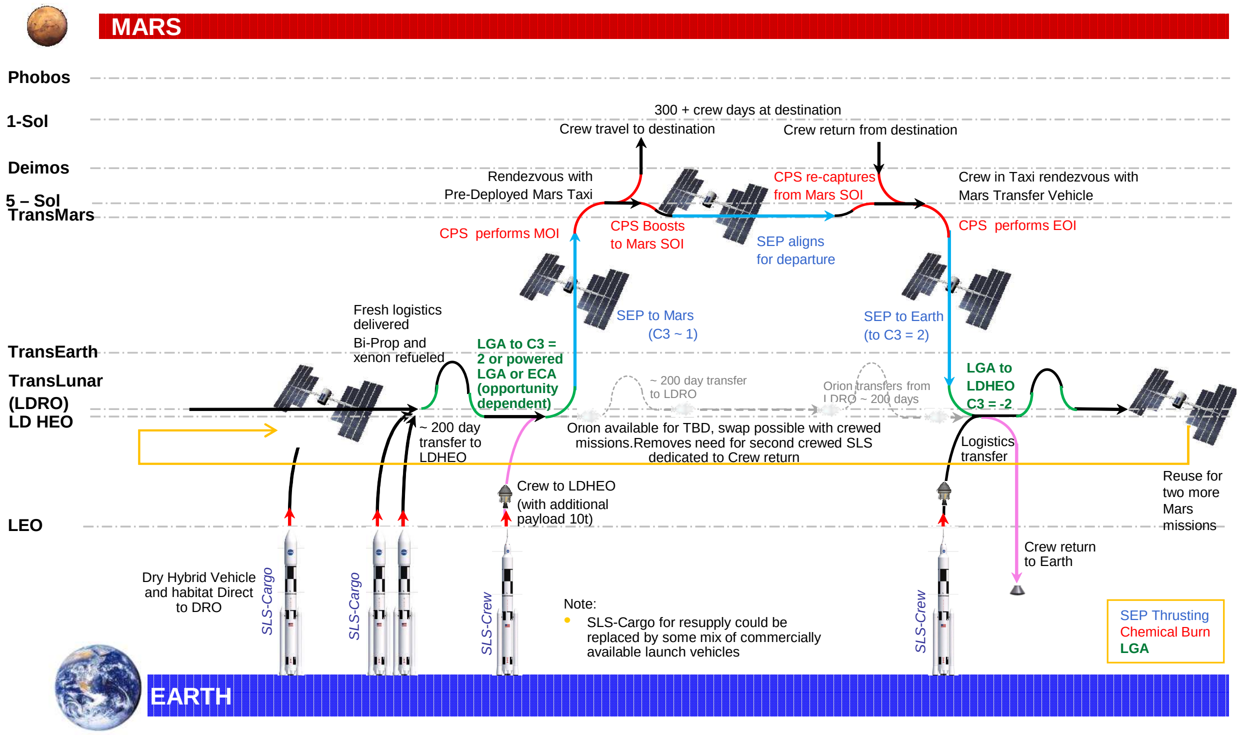


**Figure 1. Mars Hybrid Crew Mission Concept of Operation**

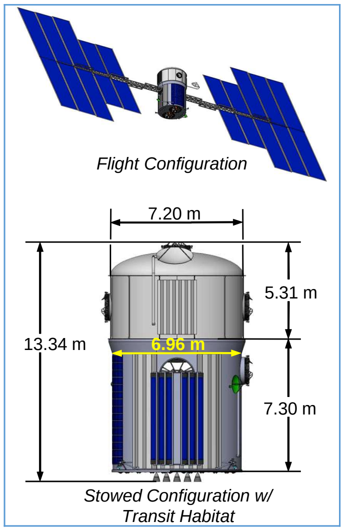
the HPS/habitat stack, transfer final logistics, and depart Earth in the HPS/habitat stack to Mars. From LDHEO, one or two LGA propels the crewed HPS stack to a C3 of 2 $km^3/s^2$. After Earth departure, the EP system uses low thrust mode (with Isp of 3,000 seconds) and thrusts for much of the interplanetary trajectory to increase the vehicle's orbital energy to reach Mars. The crewed HPS stack arrives at Mars 300-400 days after Earth departure with an arrival C3 less than 2 $km^3/s^2$, targeting a Mars close approach at 250 km altitude. The CP component of the HPS performs the Mars orbit insertion maneuver to capture into a highly elliptical Mars orbit with a period of 5-Sol.

Upon arrival at Mars, the pre-deployed Mars taxi or lander rendezvous with the crew HPS stack, then transfers the crew to their exploration destination. After the crew departs for their destination, the uncrewed HPS stack performs a series of maneuvers with both CP and EP systems to reorient itself into the proper orbit for the return trip. After a minimum stay of 300 days in the Martian sphere of influence, the crew completes its exploration mission and returns to the HPS stack using the Mars taxi or the Mars ascent stage. From there, the CP component of the HPS performs a perigee burn to depart Mars with a C3 between 0.5 and 2 $km^3/s^2$. After Mars departure, the EP component uses high $I_{sp}$ mode (3,000 seconds) and thrust to reduce the spacecraft's energy to target an Earth arrival C3 of less than 2 $km^3/s^2$. The stack captures back into LDHEO via one or two LGA sequence similar to Earth departure, but in reverse. An SLS launches an empty Orion to rendezvous with the crewed HPS stack to return the crew to Earth.

The HPS stack transfers from LDHEO to LDRO after the crew departs, using either a slow transfer (≈ 6 months) or fast transfer (≈ 10 days) depending on the departure window and fuel availability of the next mission. The fast transfer would require additional fuel to be carried by the SLS that brought the empty Orion capsule. Once in LDRO, the HPS rendezvous with existing cis-lunar infrastructure to perform refuel and resupply activities in preparation for the next trip to Mars.

## III. 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



**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 2. Hybrid Propulsion Stage Design Summary**

mass break down is shown in Figure 2. 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 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.

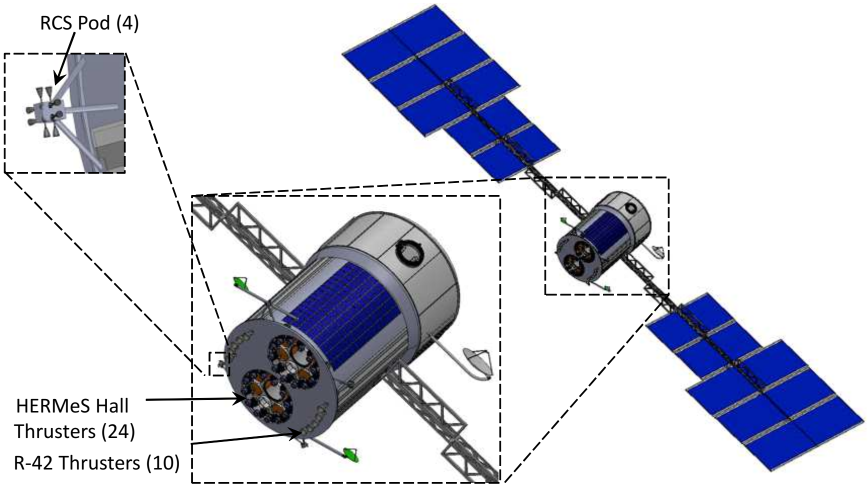


**Figure 3. EMC Hybrid Propulsion Vehicle in the Stowed Configuration**

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.

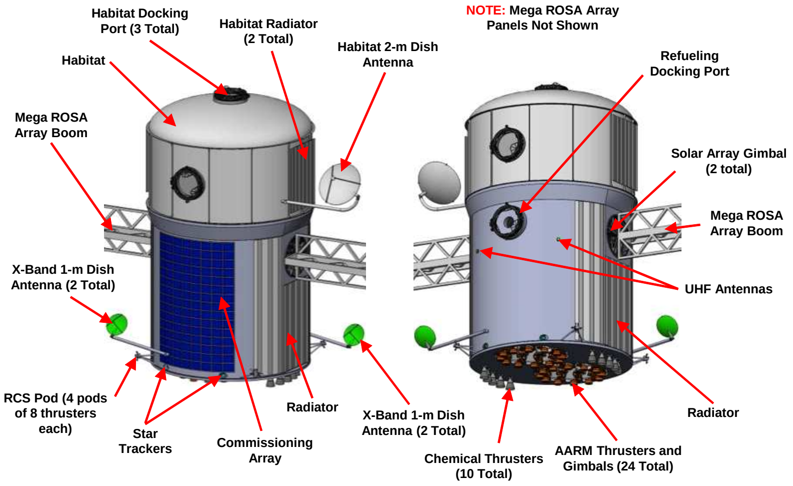


**Figure 4. EMC Hybrid Propulsion Vehicle Components Description**

The bi-propellant tanks are a stretched version of the 80434 which provide increased capacity. The thruster arrangements are shown in Figure 3. 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 $V$. The remaining sub-components and their locations are shown in Figure 4.

## IV. EMC Crew Mission Summary

**Table 1. Logistics and Spares Loading for EMC Hybrid Architecture Crew Missions**

| | 2033 (Phobos) | 2039 (Mars) | 2043 (Mars) | |
|---|---|---|---|---|
| Initial Logistics Load | 17,400 | 17,700 | 17,700 | $kg$ |
| Mars Arrival Waste Dump | -2,630 | -3,470 | -3,230 | $kg$ |
| Mars Departure Waste Dump | -4,890 | -3,620 | -3,620 | $kg$ |
| Earth Arrival Waste Dump | -2,680 | -3,080 | -3,330 | $kg$ |
| Final Logistics Load | 7,200 | 7,530 | 7,520 | $kg$ |

The Evolvable Mars Campaign calls for nominal crew missions to the Martian sphere of influence in 2033, 2039, and 2043. The hybrid transpiration architecture utilizes a single integrated hybrid propulsion stage and transit habitat to perform all three of the crew transits from Earth to Mars and back. The logistics loading for each of the missions is dependent upon the outbound and inbound transit time as well as the stay time within the Martian sphere of influence. In addition, the amount of waste that is available for removal prior to the chemical burns is also dependent upon the interplanetary trip times. The logistic loading for the three initial crew missions are shown in Table 1. Currently, EMC assumes the unused logistics and spares after Earth return is discarded and new logistics and spares are delivered for the next mission.

## A. 2033 Crew to Phobos

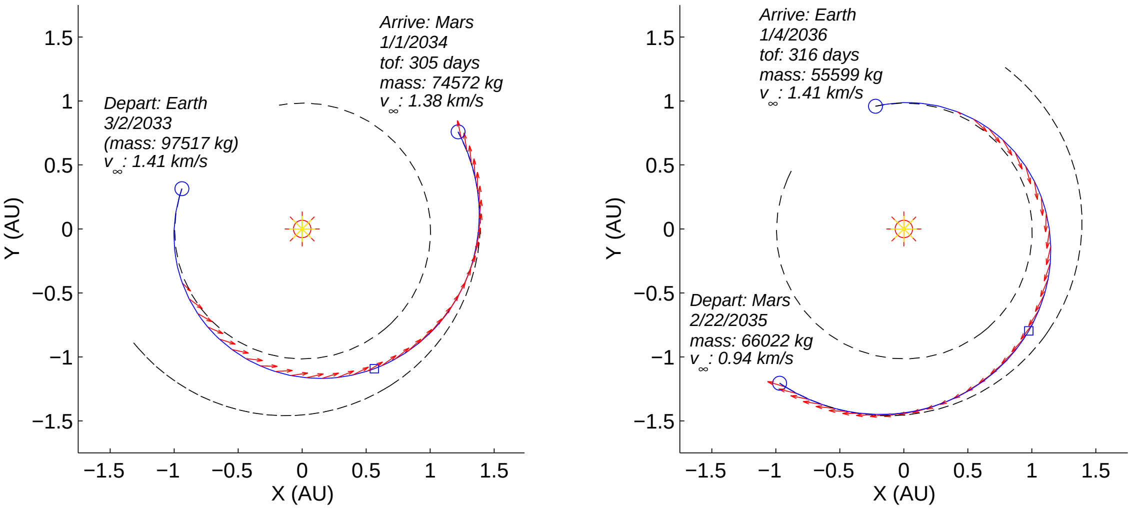


**Figure 5. 2033 EMC Crew Mission**

The 2033 crew mission to Phobos utilizes a brand new hybrid propulsion stage that is fully powered (435kW @ 1AU) at Earth departure. The interplanetary trajectory is shown in Figure 5, with the EP system thrusting vector shown as vectors along the trajectory. The optimal trajectory departs the Earth sphere of influence on March 2, 2033 via lunar gravity assist (with Earth departure C3 of 2 $km^3/s^2$) and arrives at Mars on January 1, 2034 for an outbound transit time of 305 days. Prior to the Mars orbit insertion maneuver, 2,630 kg of waste is jettisoned. The crew then rendezvous with assets already in position around Mars orbit[4] and conducts a surface mission to Phobos. Total duration for the Phobos surface operation is 417 days. After the conclusion of the surface mission, the crew returns to the transit habitat and jettisons 4,890 kg of waste prior to the Mars departure maneuver. The optimal trajectory departs Mars on February 22, 2035, arrives at Earth on January 4, 2036 with an arrival C3 of 2 $km^3/s^2$, and reinserts into a lunar distant high Earth orbit via lunar gravity assist. Prior to the lunar gravity assist maneuver, the crew performs the final 2,680 kg of waste dump. Total heliocentric mission duration for the 2033 crew opportunity is 1,038 days.

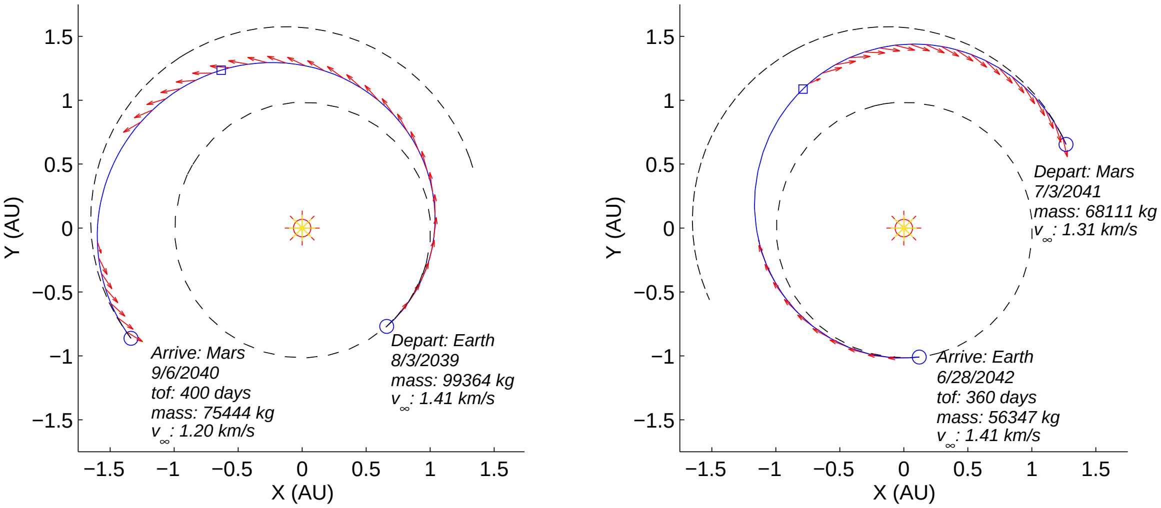


**Figure 6. 2039 EMC Crew Mission**

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### B. 2039 Crew to Mars

The 2039 crew mission to Mars departs Earth 1,307 days after the 2033 crew returns to the Earth sphere of influence. With an approximate solar array degradation of 1% per year, the HPS will depart Earth with only 409 kW of power supplied by the arrays. The 2039 trajectory is shown in Figure 6. The crew departs Earth on August 3, 2039 via LGA with Earth departure C3 of 2 $km^3/s^2$ and arrives at Mars on September 6, 2040 for an outbound trip time of 400 days. The waste dump prior to Mars orbit insertion is 3,470 kg. A pre-positioned Mars lander[4] rendezvous with the crew HPS stack and takes the crew from the 5-Sol parking orbit to the Martian surface for the surface mission. After a 300 day mission (from entering Mars 5-Sol to departing Mars), the crew returns to the HPS stack, removes 3,620 kg of waste, and departs Mars on July 3, 2041. The inbound trip time is 360 days, with an Earth arrival date of June 28, 2042 after a final waste dump of 3,080 kg. The crew then rendezvous with an empty Orion vehicle in LDHEO and returns to Earth while the HPS is positioned for the third and final Mars mission for its lifetime. The total heliocentric duration for this second Mars mission is 1,060 days.

### C. 2043 Crew to Mars

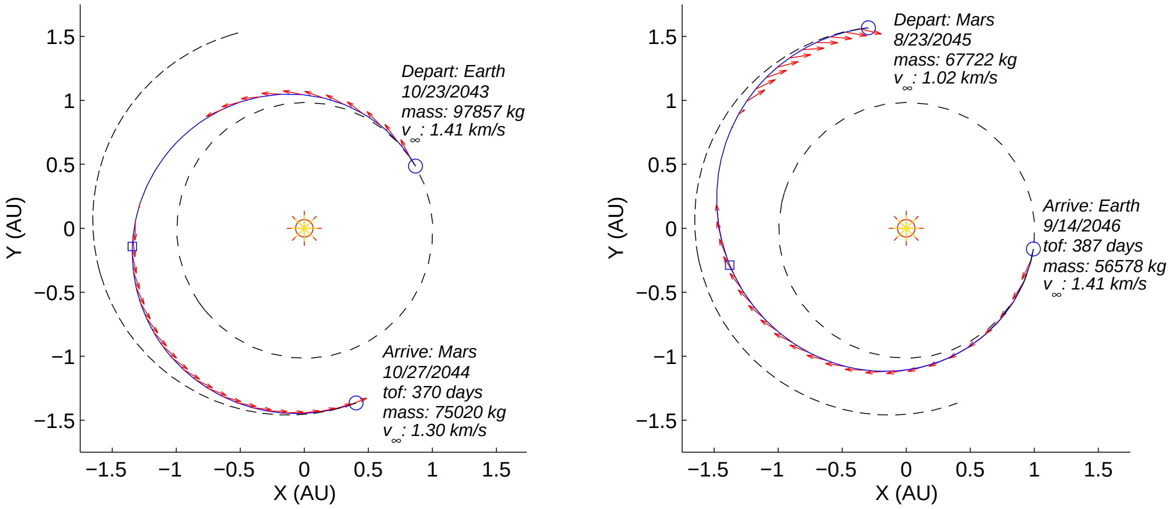

**Figure 7. 2043 EMC Crew Mission**

The 2043 crew mission departs Earth only 481 days after the return of the previous Mars expedition. The short turnaround imposes tighter constraints on the refueling and resupply operation. On this third Earth-Mars round-trip flight, the HPS array degrades another 5% from the previous trip, leaving only 392kW of power to the EP system. The 2043 trajectory is shown in Figure 7. The crew stack departs Earth on October 23, 2043 via LGA and arrives at Mars 370 days later on October 27, 2044. The Mars orbit insertion waste dump is 3,230 kg for the 2043 opportunity. The Mars sphere of influence stay time is 300 days, which results in the same waste dump as the 2039 opportunity. The Mars departure date for this mission is August 23, 2045, and the crew returns to Earth 387 days later on September 14, 2046. Total trip time for this mission is 1,057 days. The crew returns from LDHEO to Earth after rendezvousing with an Orion capsule. The HPS and transit habitat are nearing their respective end of design life, after over 5,000 days in space, and will be retired from EMC Mars missions. Addition use of the HPS and transit habitat will depend on retrofit of the components to extend its lifetime.

### D. Crew Trajectory Summary

The nominal EMC crew trajectories using the hybrid SEP/Chem are summarized in Table 2. The mission phasing for the three crew missions is described in the previous sections and summarized in Part A of the table. Part B of Table 2 shows the vehicle characteristic for each of the three opportunities and Part C shows the trajectory characteristics at planetary encounters. For the 2033 opportunity to Phobos, the total crew stack departs Earth with a initial mass of just under 98 metric ton (mT), carrying round-trip propellant of 21,850 kg of xenon and 14,150 kg of chemical bi-propellant, which translates to a propellant loading of 94.6% in the xenon tanks and 76.1% in the chemical tanks. For the 2039 and 2043 Mars opportunity, the propellant loadings are 97.8% / 80.5% and 95.6% / 75.2% for xenon and chemical, respectively. Looking at the vehicle characteristics across the three opportunities, it is clear that the chemical tanks for the HPS are oversized for the crew missions while the xenon tanks are near capacity for all three opportunities.

**Table 2. Evolvable Mars Campaign Hybrid SEP/Chem Transpiration Architecture Crew Mission Summary**

*A. Crew Mission Phasing Characteristics*

| | Earth Departure | Mars Arrival | Mars Departure | Earth Arrival | Days to Next Departure | Outbound | Stay | Inbound | Total Trip Time |
|---|---|---|---|---|---|---|---|---|---|
| 2033 Phobos | 03/02/33 | 01/01/34 | 02/22/35 | 01/04/36 | 1,307 days | 305 days | 417 days | 316 days | 1,038 days |
| 2039 Mars | 08/03/39 | 09/06/40 | 07/03/41 | 06/28/42 | 481 days | 400 days | 300 days | 360 days | 1,060 days |
| 2043 Mars | 10/23/43 | 10/24/44 | 08/23/45 | 09/14/46 | – | 370 days | 300 days | 387 days | 1,057 days |

*B. Hybrid Propulsion Vehicle Characteristics*

| | Array Power | Earth Dep. Mass ($kg$) | Hybrid Dry ($kg$) | Habitat Dry ($kg$) | Logistics Mass ($kg$) | Xenon Load ($kg$) | Bi-Prop Load ($kg$) | % Xenon Tank Fill | % Bi-Prop Tank Fill |
|---|---|---|---|---|---|---|---|---|---|
| 2033 Phobos | 435 $kW$ | 97,750 | 21,480 | 22,850 | 17,400 | 21,800 | 14,200 | 94.6% | 76.1% |
| 2039 Mars | 409 $kW$ | 99,590 | 21,480 | 22,850 | 17,700 | 22,600 | 15,000 | 97.8% | 80.5% |
| 2043 Mars | 392 $kW$ | 98,130 | 21,480 | 22,850 | 17,700 | 22,100 | 14,000 | 95.6% | 75.2% |

*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 Phobos | 1.4142 | 1.3780 | 0.9371 | 1.4142 | -1.007° | -5.099° | -8.873° | 7.507° |
| 2039 Mars | 1.4142 | 1.2012 | 1.3131 | 1.4142 | -2.434° | -4.724° | -1.920° | -5.061° |
| 2043 Mars | 1.4142 | 1.2960 | 1.0152 | 1.4142 | 10.984° | -18.247° | 13.247° | 9.951° |

The xenon propellant required is directly related to the outbound and inbound trip times. When the planetary alignment requires the trajectory to have longer interplanetary trip times, the HPS has more time to perform EP thrusting, and because the EP system's efficiency is always higher than the chemical system, the optimal trajectory will always try to maximize the use of EP system to change the vehicle's energy. The chemical bi-propellant requirement is not a function of the trip times but a function of the Mars arrival and departure $V_\infty$ . Because the EP system is always more efficient (from a propellant usage standpoint), the trajectory optimization will attempt to minimize the arrival and departure $V_\infty$ at Mars to limit the use of the chemical system. In an ideal setting, the EP system would have infinite amount of time and propellant to increase or decrease the vehicle's energy so that the arrival/departure condition are perfectly aligned with the target. However, the conjunction class trajectory limits the time available for EP thrusting, thus, the system compensates for this with chemical propulsion. The arrival conditions at Mars for the three opportunities are very similar, with $V_\infty$ between 1.2 $km/s$ and 1.4 $km/s$. The Mars departure $V_\infty$ for the three opportunities vary between 0.9 $km/s$ and 1.31 $km/s$. The 2039 opportunity has the highest combined arrival and departure $V_\infty$ and thus have the highest chemical propellant required. Conversely, the 2043 opportunity has the lowest combined $V_\infty$ and lowest chemical propellant load. The chemical propellant requirement is also a function of the vehicle's mass.

The nominal trajectory results show that the COMPASS[5] designed Hybrid vehicle is more than capable of performing the round-trip crew missions to Mars for the given habitat system mass and logistic load. Even after the solar array degrades by more than 10% from beginning of life, the propellant required to perform the round-trip transit to Mars does not exceed the maximum capacity of the vehicle. However, with the xenon tank at near capacity for all three opportunities, the sensitivity of the feasibility of the current designed vehicle to mass growth needs to be investigated.

# V. Sensitivity Analyses

## A. Payload Mass Growth

The primary payload for the EMC Hybrid crew mission is the deep space transit habitat. The habitat contains the environmental control and life support systems for the crew, and there is large mass uncertainty associated with these long duration systems. The HPS was sized to deliver the currently sized habitat[15] for the most difficult opportunity across the Earth-Mars synodic period. As a result, the propulsion system is oversized for the nominal missions (shown in Table 2), as the three planned crew mission did not fall on the most difficult opportunity. As the habitat design matures, there is potential for the dry mass to change, and the impact of the mass change on the propulsion performance must be understood. Table 3 and Figure 8 show the result of the sensitivity analysis of the propulsion system performance on the habitat dry mass, assuming fixed logistic and spare loading.

**Table 3. EMC Hybrid Propellant Usage as Function of Payload Mass**

| | 2033 (Phobos) | | 2039 (Mars) | | 2043 (Mars) | | |
|---|---|---|---|---|---|---|---|
| | Xenon | Chemical | Xenon | Chemical | Xenon | Chemical | |
| 20.0 mT Habitat | 21,600 | 11,500 | 21,200 | 13,700 | 21,700 | 12,400 | *kg* |
| 22.8 mT Habitat | 21,800 | 14,200 | 22,600 | 15,000 | 22,100 | 14,000 | *kg* |
| 25.0 mT Habitat | 22,000 | 16,400 | 23,100 | 18,500 | 23,100 | 14,900 | *kg* |
| 27.5 mT Habitat | Did Not Close† | | Did Not Close† | | 23,100 | 17,700 | *kg* |

† *Propellant Required Exceeds Vehicle Propellant Storage Capacity*

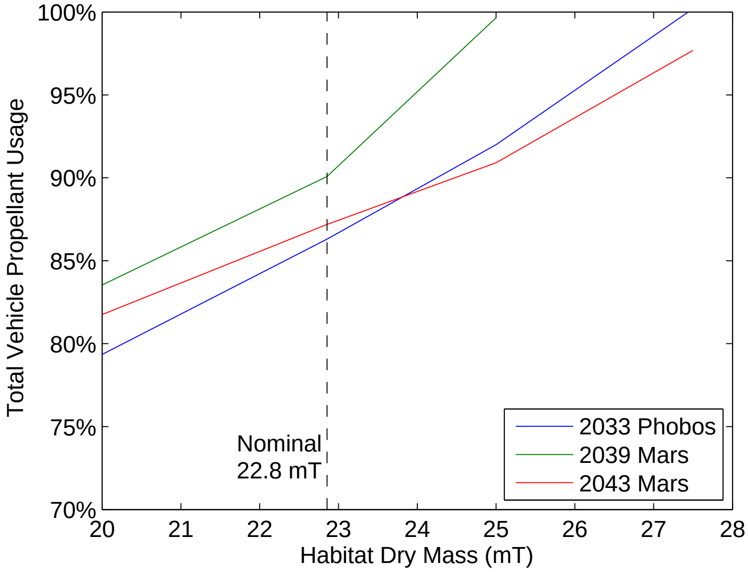

**Figure 8. EMC Hybrid Crew Mission Performance Sensitivity to Habitat Mass Growth**

A 10% growth in the habitat dry mass to 25 mT pushes the total propellant required for each of the opportunity to above 90%. An additional 10% growth in the habitat dry mass to 27.5 mT results in non-closure for the 2033 and 2039 opportunities and pushes the the propellant required to above 95% for the 2043 opportunity. Non-closure of the propulsion system is the result of the propellant required to perform the round-trip trajectory exceeding the propellant capacity of the designed system. Figure 8 shows the 2039 opportunity as the dominating case, as it requires the most propellant and is most sensitive to changes in habitat mass compared to the other crew opportunities. A 10% growth in the habitat mass to 25 mT requires the propulsion system to be essentially at maximum capacity for the 2039 opportunity and does not leave much margin of error. In comparison, the 2033 and 2043 opportunities have more flexibility and can handle more habitat mass growth. However, the current EMC strategy is to utilize the same habitat design for all of the in-space transpiration needs; thus the 2039 opportunity is the limiting case. If the current HPS design remains unchanged, the flexibility of the 2033 and 2043 opportunities is irrelevant.

One final observation on the performance sensitivity to habitat mass is that the trend is clearly non-linear. Examining the nominal mission with a 22.8mT habitat, the xenon required is near the capacity of the current vehicle with over 95% fill for each of the opportunity. As the habitat mass grows, the interplanetary trajectory remains relatively unchanged as there is not much time or xenon available for EP thrusting. Thus, the system makes up the difference in the energy required by using more chemical propellant at planetary departures and arrivals. Given the low specific impulse of the storable bi-propellant system, the propellant required scales exponentially with respect to dry mass growth, as dictated by the rocket equation. There is potential to reduce the effect of dry mass growth with higher performing chemical systems as well of more power to the EP system, the sensitivity to propulsion system performance will be presented in a later section.

## B. Departure Window

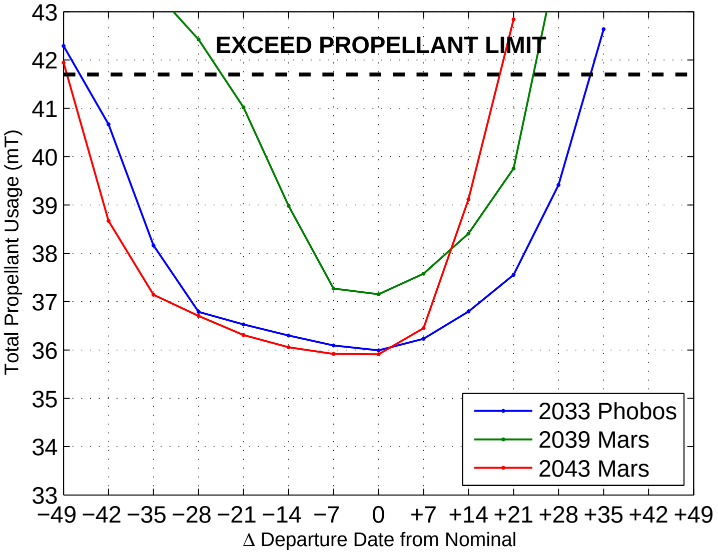

**Figure 9. EMC Hybrid Crew Mission Performance Sensitivity to Departure Date**

The EMC hybrid crew missions require very specific maneuvers for Earth departure. After the vehicle has been fully outfitted for a mission, the vehicle enters a LDHEO inclined at 30 °to rendezvous with the crew. The crew launches directly to LDHEO on an Orion capsule on the SLS to rendezvous with the HPS. In order to target an optimal Earth departure date, the crew must target a launch date early enough in order to mitigate the risk of launch and/or rendezvous delays. However, with limited lifetime on the Orion capsule, the crew cannot launch too early before the rendezvous with the HPS. Thus there remains some risk of not being able to depart Earth on the nominal departure date. In addition, by utilizing the lunar gravity assist to depart the Earth-Moon system to Mars, the departure opportunity is relatively limited as it requires the moon to be in the proper location in the lunar cycle to achieve the desired hyperbolic asymptote. To help mitigate this, an understanding of propulsion performance sensitivity to varying departure dates from nominal is desired.

Table 4 shows the summary of the propellant required as a function of delta departure date from the optimal departure date of the heliocentric trajectory, and Figure 9 plots the total propellant load as function of the delta departure dates. The results of the sensitivity analysis shows each opportunity has drastically different sensitivity to the departure date. For the 2033 opportunity, the window for departure extends from -42 days to +28 days from the optimal departure date. This 70-day window yields two to three distinct departure opportunities for the 2033 mission because the moon can be at the optimal departure location in the lunar cycle 2 to 3 times during the 70-day window, depending on how early the first opportunity arises in the window. If the first opportunity arises within the first 16 days of the window, then the second opportunity arises 27 days later, and the third opportunity arises 54 days later. If the first opportunity

**Table 4. EMC Hybrid Propellant Usage as Function of $\Delta$ Departure Date from Nominal**

| | 2033 Phobos | | 2039 Mars | | 2043 Mars | | |
|---|---|---|---|---|---|---|---|
| | Xenon | Chemical | Xenon | Chemical | Xenon | Chemical | |
| -49 Days | Did Not Close[†] | | Did Not Close[†] | | Did Not Close[†] | | kg |
| -42 Days | 23,000 | 17,600 | Did Not Close[†] | | 23,100 | 15,600 | kg |
| -35 Days | 23,100 | 15,100 | Did Not Close[†] | | 23,000 | 14,100 | kg |
| **-28 Days** | **22,900** | **13,800** | **Did Not Close[†]** | | **23,000** | **13,700** | kg |
| -21 Days | 22,600 | 13,900 | 23,000 | 18,100 | 22,500 | 13,800 | kg |
| -14 Days | 22,300 | 14,000 | 23,100 | 15,900 | 22,200 | 13,800 | kg |
| -7 Days | 22,000 | 14,100 | 22,900 | 14,400 | 22,200 | 13,700 | kg |
| **Nominal** | **21,800** | **14,200** | **22,600** | **15,000** | **22,100** | **14,000** | kg |
| + 7 Days | 22,000 | 14,200 | 21,900 | 15,600 | 22,300 | 14,200 | kg |
| +14 Days | 22,100 | 14,700 | 21,200 | 17,200 | 23,100 | 16,100 | kg |
| +21 Days | 22,500 | 15,000 | 21,200 | 18,600 | Did Not Close[†] | | kg |
| **+28 Days** | **22,800** | **16,600** | **Did Not Close[†]** | | **Did Not Close[†]** | | kg |
| +35 Days | Did Not Close[†] | | Did Not Close[†] | | Did Not Close[†] | | kg |
| +42 Days | Did Not Close[†] | | Did Not Close[†] | | Did Not Close[†] | | kg |
| +49 Days | Did Not Close[†] | | Did Not Close[†] | | Did Not Close[†] | | kg |

[†] *Propellant Required Exceeds Vehicle Propellant Storage Capacity*

arises after day 16, only one more opportunity can fit into the remaining time of the window. The 2039 opportunity is a limiting case, as the departure window only extends from -21 days to 21 days, which means the moon can be at the optimal departure location 1 to 2 times during the 42-day window. The 2043 mission has two to three departure opportunities, as its departure window extends from -42 days to +14 days (58 days).

Having potentially only one departure opportunity for the 2039 mission presents an added risk to the architecture. Further refinement of the departure maneuver is needed to determine if the second opportunity is possible that can allow for non-optimal departures or powered lunar flyby departures. However, these maneuvers will likely increase the propellant required for the interplanetary phase and can result in non-closure for the currently designed system. For the 2033 and 2043 missions, the departure window is slightly more forgiving. Having potentially three departure opportunities for the 2033 mission is important for the EMC architecture as this is the first crewed mission to the Martian sphere of influence. It provides the architecture additional flexibility to ensure all of the systems are functioning correctly before the crew departs the Earth sphere of influence. The 2043 mission, despite having an additional departure opportunity, presents a challenge to the architecture. As shown in Table 2, there are only 481 days between the return of the HPS from the 2039 Mars mission to the scheduled departure of the 2043 Mars mission. During this time, the crew must depart the HPS to return to Earth, the HPS must be resupplied with logistics and fuel, waste from the previous mission must be removed, and the HPS and habitat must be inspected to ensure it is ready for the next mission. Compared to the previous refit of the HPS and habitat, the time available for this refit is significantly less. Examining the performance sensitivity to departure date for 2043, it is clear that any delay in departure from the nominal date will result in vehicle non-closure. In order to take advantage of the additional departure opportunity, the crew must target a departure one month prior to the optimal departure date, which will put further stress on the HPS/habitat refit schedule. There is a need to develop further studies to investigate the feasibility of the refit and resupply tasks in such short period of time.

### C. Propulsion System Performance

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

**Table 5. Δ Array Power Supplied to Electric Propulsion System at Earth Departure (1AU)**

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

impacts the overall mission performance. For the EP system, the solar arrays do not provide enough power to the system to utilize the all of the EP thrusters during the entire trajectory. At Mars distance, the solar irradiance is only 40% compared to Earth distance, thus the array output is significantly lower as the spacecraft travels from Earth to Mars. The trajectory simulation accounts for this difference by turning off pairs of EP thrusters to match the power output by the solar arrays. The performance of the EP system can be improved if the arrays can produce more power. For this sensitivity analysis, the underlying assumption is that the improvement to array efficiency can be achieved without adding more dry mass to the HPS. A summary of the array power delivered by the solar arrays with changes to the array's efficiency is shown in Table 5.

For the chemical propulsion system, the performance of the engine is based on the specific impulse. Aerojet is currently developing the R42DM[16] which is an improved version of the R42 and can improve the Isp from 303 seconds to 327 seconds. Additionally, there are hydrazine engines that are under development a with specific impulse as high as 333 seconds.[17] These specific impulse were utilized to understand the impact of improved engine performance on the overall mission performance. In addition to improved array efficiencies and improved specific impulse for the hydrazine engines, analyses were also conduced to see the effect of reduced performance for both EP and CP systems.

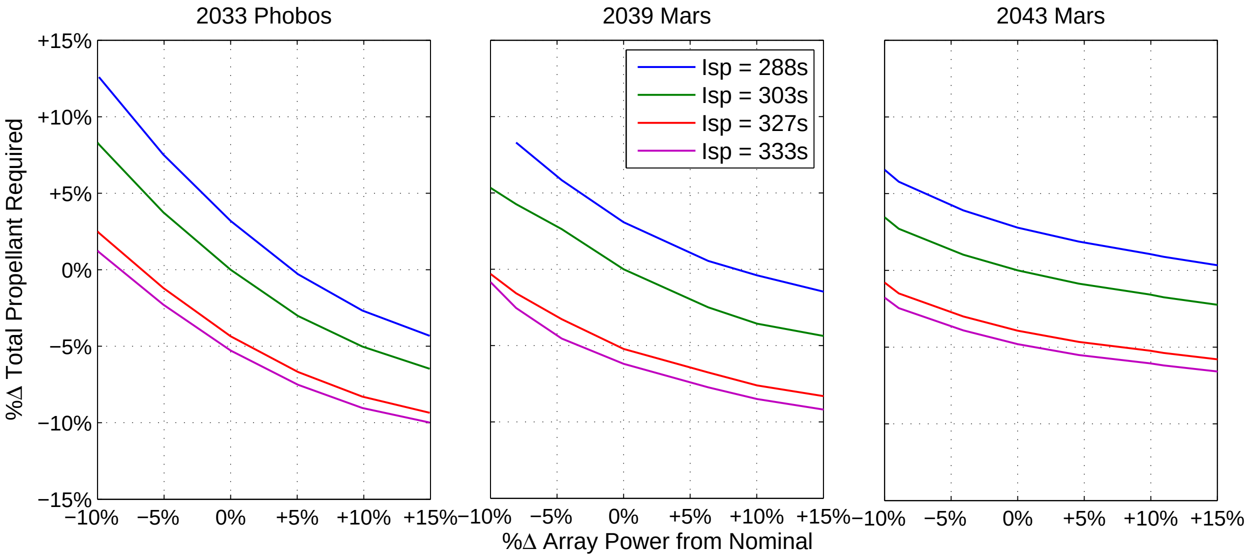

**Figure 10. EMC Hybrid Crew Mission Total Propellant Required Sensitivity to Changes to Propulsion System Performance Parameter**

Figure 10 shows the percent change in total propellant mass required as a function of the percent change in array power at the various CP specific impulse levels. Looking across the three missions, the 2033 mission opportunity is the most sensitive to changes to the propulsion performance parameters, while the 2043 mission is the least sensitive from a total propellant required perspective. For all three missions, regardless of the performance of the chemical systems, the total propellant required can be reduced by increasing the array power, assuming no change to the overall system dry mass. Similarly, as the chemical engine performance increases, the propellant required decreases as well. As previous discussions showed, the 2039 mission is the most sensitive to habitat mass growth and departure date slippage. Figure 10 shows that with a 10% increase in the array power and specific impulse can reduce the propellant required by 5% or more, which can improve the sensitivity to the other parameters.

Figures 11 and 12 show the breakdown of the total propellant required by the EP and CP systems, respectively. Examining the breakdown of propellant required as function of propulsion system performance reveal slightly non-intuitive results. Figure 11 shows a positive correlation between array power and xenon required for all missions. This is especially profound in the 2033 opportunity. The increase in xenon propellant required is actually a favorable result, as it means the HPS has enough power to keep the more EP thrusters active during the interplanetary phase, which would require more propellant to operate. As discussed previously, the EP system is a much more efficient system in terms of propellant usage compared to the CP system. Thus, given the choice, the trajectory optimizer, while trying to minimize the departure mass, will always try to use as much EP thrusting as possible. From an energy stand point, the less EP thrusting that is available to the spacecraft, the more CP thrusting is required to make up the difference.

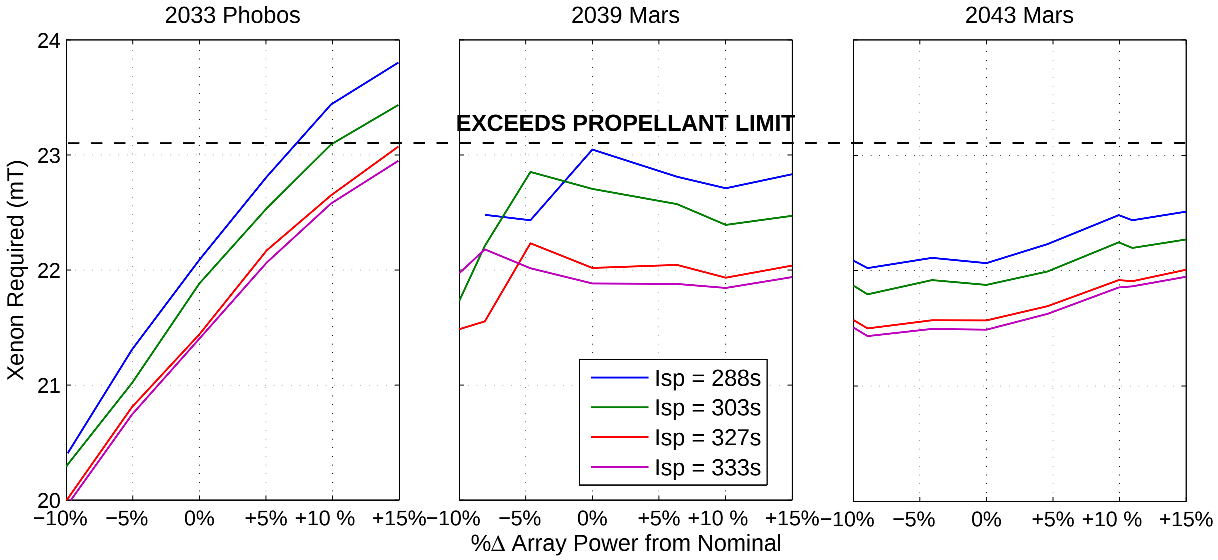

**Figure 11. EMC Hybrid Crew Mission Xenon Requirement as Function of Changes to Propulsion Systems Performance Parameter**

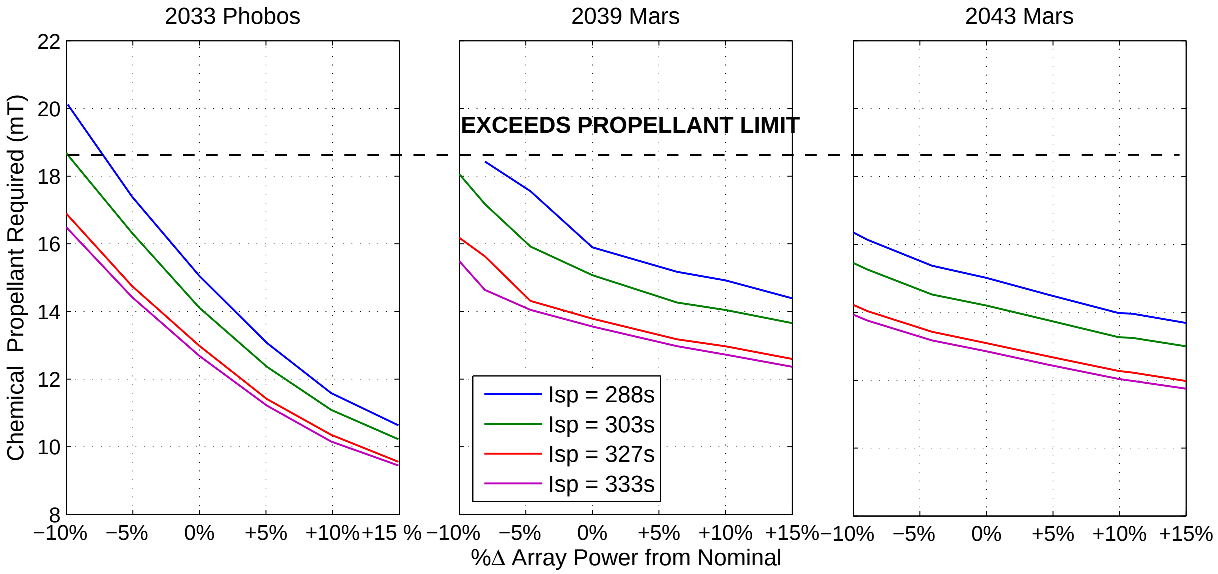

**Figure 12. EMC Hybrid Crew Mission Chemical Propellant Requirement as Function of Changes to Propulsion Systems Performance Parameter**

This relationship is demonstrated in Figure 12, which shows the chemical propellant required as a function of changes to the propulsion system performance parameters. The figure shows a clear negative correlation between the chemical propellant required and the propulsion system parameters. As the array power avaliable to the HPS increases, the chemical propellant required is reduced dramatically, especially in the 2033 mission. A 10% increase in the array power and specific impulse can reduce the total chemical propellant required by over 20% in the 2033 mission. The reduction is not nearly as profound in the 2039 and 2043 missions, but significant reduction can still be achieved with improvement to the propulsion system performance. These improvements will have positive impact on the sensitivities of the 2039 and 2043 mission to both habitat mass growth and changes to departure dates.

The high sensitivity of the propellant required to propulsion system performance for the 2033 mission reveals that the mission is power limited. Despite having full power at the start of the trajectory, the planetary alignment in 2033 does not allow for much time for EP thrusting; thus any increase in the array power can have dramatic impact on the overall mission performance from a mass standpoint. As the EP system increases its operation, the Mars arrival and departure conditions become less strenuous to the CP system, thus dramatically reducing the propellant demand for these maneuvers. The 2039 and 2043 missions, in comparison, have relatively benign planetary alignments from the EP system's perspective. Thus, increasing the array power to the system provides significantly less benefits as compared to the 2033 mission, as the trajectory is already near optimal given the same level of EP thruster power. These two mission benefit more from improvement to the chemical propulsion's performance than from increased array powers. Overall, the results show slight improvement in the propulsion system performance can have significant impact on mission performance, which can in turn reduce the risk of the sensitivities to mass growth and schedule challenges.

## VI. 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. A 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 over multiple trips. The baseline trajectories for the 2033, 2039, and 2043 crew missions to Mars sphere of influence are presented in this paper. The trajectory analysis provided departure and arrival dates and propellant needs for the three crew missions the HAT campaign team is using for campaign build-up and logistics aggregation analysis.

Sensitivity analyses were performed to investigate the impact of mass growth, departure window, and propulsion system performance on the hybrid transportation architecture. The crew HPS missions are quite sensitive to the transit habitat mass growth. A modest 20% increase in the habitat dry mass results in non-closure for the transportation system. The sensitivity analyses identified the 2039 opportunity as the most difficult opportunity from the transportation perspective. This is also observed in the departure window analysis, which showed that the 2039 opportunity has a departure window of only 42 days, compared to the 2033 and 2043 opportunities, which have departure windows of 70 and 63 days, respectively. For the LGA departure, the moon is only in the proper orientation every 28 days, thus, the 2039 opportunity provides very little margin in regards to its departure date with the COMPASS designed HPS. Final sensitivity analysis examined the performance of the HPS for the crew missions with respect to propulsion system performance. The results show the balancing between EP and CP systems in the trajectory can vary drastically from opportunity to opportunity, which can result in non-intuitive results. The results show that the 2033 opportunity is the most sensitive to changes in the propulsion system performance, while the 2043 opportunity is the least sensitive.

This paper has shown the feasibility of the hybrid transportation architecture to support crew missions to Phobos and Mars in the 2030s and presents an example design of the transportation stage. The hybrid architecture enables conjunction class trajectories for both the crew and the cargo deployment without significant increase to the propellant requirement as compared to all chemical architecture. The conjunction class trajectory allows the HPS to return to Earth with the crew in a timely fashion so that the system can be reused for multiple crew trips to Mars with a minimum stay time in Mars sphere of influence of 300 days. The logistics resupply of the HPS and transit habitat will need to be refined to understand the impact of strict departure and arrival dates for the crew missions. Additional refinement in the trajectory and 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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