

Reusable In-Space Transportation Architecture Options for Human Mars Expeditions

Patrick R. Chai^a, Raymond G. Merrill^b, Min Qu^c

^aAerospace Engineer, NASA Langley Research Center, Hampton, VA, United States, patrick.r.chai@nasa.gov

^bAerospace Engineer, NASA Langley Research Center, Hampton, VA, United States, raymond.g.merrill@nasa.gov

^cStaff Scientist, Analytical Mechanics Associates, Inc., Hampton, VA, United States, min.qu-1@nasa.gov

NASA has been investigating the use of Solar Electric Propulsion, Chemical Propulsion, and Nuclear Thermal Propulsion systems to deliver crew and cargo to Mars orbit in support of expeditions to the Martian surface. In order to evaluate the effect of the selection of in-space transportation options on a series of human Mars missions across multiple opportunities, campaign level analysis must be performed and the transportation options must be evaluated using the same set of ground rules and assumptions to provide equal comparison. In this study, a comparison of three in-space transportation options was shown from a campaign level perspective. Campaign level metrics such as total launch mass, launch vehicle launch rate, and total launch vehicle required are presented to show how the different transportation systems perform to field a series of Mars missions across multiple mission opportunities. Each transportation option was utilized to perform three crew roundtrip missions to Mars, with supporting cargo missions starting in 2029, the first crewed mission to Mars in 2035. The transportation options each have strengths and weaknesses from a campaign and strategic investment point of view, as evident by the comparison between the total launch mass and the total number of launch vehicles required. While the analysis shown in this study provides an initial comparison between the transportation options, significant challenges still exists for each options in terms of the detailed mission operations and the feasibility of all of the assumptions.

Keywords: Mars, Solar-Electric, Nuclear Thermal, In-Space Propulsion, Campaign

Acronyms/Abbreviations

Apotwist Manuever	APO
Commercial Launch Vehicle	CLV
Earth Orbit Insertion	EOI
Earth to Mars	E-M
Hybrid Propulsion System	HPS
Liquid Methane	LCH4
Liquid Oxygen	LOx
Lunar Distance High Earth Orbit	LDHEO
Lunar Gravity Assist	LGA
Trans-Lunar Injection	TLI
Trans-Mars Injection	TMI
Mars Orbit Insertion	MOI
Mars to Earth	M-E
Methane Cryogenic Propulsion System	MCPS
Near Rectilinear Halo Orbit	NRHO
Nuclear Thermal Propulsion	NTP
Space Launch System	SLS
Solar Electric Propulsion	SEP

1. Introduction

NASA's Mars Integration Group (formerly the Mars Study Capability Team) continue the agency's efforts to study and refine the nation's plan to field a sustainable human Mars campaign. Building upon the success of the Evolvable Mars Campaign[1], the team is further developing capabilities to improve the fidelity of the Mars cam-

paign and to continue exploring the design trade space to assess the impact of technology investments and architecture decisions for missions to Mars. NASA has been investigating the use of Solar Electric Propulsion[2] (SEP), Chemical Propulsion, and Nuclear Thermal Propulsion[3] (NTP) systems to deliver crew and cargo to Mars orbit in support of expeditions to the Martian surface. Chemical propulsion systems have been utilized for all human exploration missions to date. SEP systems have been utilized for long duration science missions to outer planets[4] and have been proposed as an option to deliver cargo in support of human expeditions. NTP systems have been proposed to field long duration human missions since the Apollo program[5]. Advancements in technologies have prompted NASA to evaluate each of the transportation options for updated Mars expedition architectures[6]. Additionally, NASA has been investigating the Hybrid transportation architecture,[7] which combines a chemical propulsion system with a solar electric propulsion system into a single integrated design.

This paper presents the in-space transportation system architecture options in support of human Mars expeditions. Campaign level metrics such as total launch mass, launch vehicle launch rate, and total launch vehicle required are presented to show how the different transportation systems perform to field a series of Mars missions across multiple mission opportunities.

2. Mars Campaign Definition & Ground Rules

A number of studies in the past have evaluated different in-space transportation options[8, 9]. In order to evaluate the effect of the selection of in-space transportation options on a series of human Mars missions across multiple opportunities, campaign level analysis must be performed. The transportation options must be evaluated using the same set of ground rules and assumptions in order to provide equal comparison. This study's ground rules for the campaign represents an amalgamation of multiple previous studies[1, 10, 11] for human Mars missions with updates based on newly available data and changes to the mission design philosophy. The study ground rules do not represent official NASA ground rules for human Mars campaigns, rather a basis of comparison between multiple in-space transportation options.

The role of the in-space transportation system is to deliver crew and cargo to Mars orbit in support of Mars surface activities. From an integrated campaign perspective, the ground rules for an in-space transportation study must clearly define the payload mass and the desired delivery cadence. The launch vehicles under consideration for this particular study are NASA's Space Launch System[12] (SLS) and a generic commercial launch vehicle (CLV) that is capable of delivering 15t of payload to Trans-Lunar Injection (TLI) conditions. A summary of the campaign level ground rules for this in-space transportation study are:

- Crew missions to Jezero Crater (18.8° latitude) in 2035, 2039, and 2043
- Perform a crew Shakedown test mission of habitation and propulsion elements at least five years prior to first mission
- Each crew mission requires three landers to support surface activities, two must be pre-deployed one opportunity prior to the crew mission
- In-space habitation element must be return to cis-lunar space for reuse; two CLVs supply logistics for each Mars missions
- Payload mass:
 - 53 t lander
 - 22.3 t habitat
 - 21-22 t logistics based on mission duration
- 45 t SLS capability to TLI condition
- 15 t CLV capability to TLI condition

3. Propulsion System Options

3.1. Hybrid Solar Electric/Chemical Propulsion

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, impulsive, high thrust propulsion has been assumed for the crewed Mars missions. Solar electric propulsion, even though much more fuel efficient than

Table 1: Hybrid SEP/Chemical Vehicle Mass Summary

System	Mass, kg
1.0 Structure	5,810
2.0 Thermal	2,040
3.0 Electrical Power	6,300
4.0 Avionics & Control	140
5.0 Propulsion	
5.1 Chemical	3,010
5.2 Electric	4,120
6.0 Growth	6,430
Dry Mass Subtotal	27,850
7.0 Propellant	
7.1 Max Xenon Load	34,000
7.2 Max LO _x /CH ₄ Load	24,000
Maximum Wet Mass	85,850

chemical propulsion, produces less thrust and is more suitable for cargo pre-deployment missions when the transit time can be much longer. In order to field crew missions with short trip times, it would require very high power level[13]. The Hybrid SEP/Chemical propulsion option combines both systems in an integrated spacecraft[7, 14, 15] without significant power requirements. 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 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 element 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 impulsive chemical "conjunction class" trajectories (< 1100 days total round-trip duration with roughly 300 days at Mars vicinity) without significant increase in total mission flight times and high electric propulsion power. In addition, because no element is staged off, the hybrid architecture offers a transportation system that can be fully reused and applied to both crewed and cargo missions.

Table 1 shows a summary of the Hybrid Propulsion System (HPS) vehicle mass. The vehicle carries two wings of roll out solar arrays[16] capable of producing 675 kilowatt of power at beginning of life at 1 astronomical unit. The vehicle uses eight 50 kilowatt class SEP thrusters[17, 18] and six 4.5 kilo-Newton class chemical thrusters to produce thrust for the in-space impulsive maneuvers. Twelve composite over-wrapped pressure vessels at 2000 psi can carry up to 34,000 kilograms of Xenon, and two liquid propellant tanks can carry up to 24,000 kilograms of liquid oxygen (LO_x) and liquid methane (LCH₄). The system is launched partially fueled directly to TLI conditions for rendezvous and docking with the payload and is designed for a fifteen year lifetime or roughly three round-trip missions to Mars.

Table 2: Methane Cryogenic Propulsion Vehicle Mass Summary[19]

System	Mass, kg
1.0 Structure	2,580
2.0 Thermal	635
3.0 Electrical Power	565
4.0 Avionics & Control	750
5.0 Propulsion	2,320
6.0 Growth	1,430
Dry Mass Subtotal	8,280
7.0 Propellant	
7.1 Inert Fluids	2,240
7.2 Usable Propellant	33,350
Launch Mass	43,870

3.2. Methane Cryogenic Propulsion

The general concept of utilizing chemical propulsion systems for Mars missions dates to before the Apollo Program. Typically, in-space chemical propulsion systems studies try to maximize the performance of the engine, leading to the selection of hydrogen based systems that create significant challenges to both launch vehicle volumetric constraints and the thermal system management of the cryogenic fluid. The utilization of liquid methane as the fuel for in-space propulsion sacrifices performance to mitigate the impact of these challenges. The reduction in specific impulse will depend on engine design, and recent development in the advancement of in-space engines has shown promise. The Methane Cryogenic Propulsion System (MCPS)[19] utilized for this study is based on the design developed during NASA's Evolvable Mars Campaign[1] study. Table 2 shows the summary of the MCPS mass summary. The stage is sized and loaded to be launched on an SLS directly to TLI conditions for aggregation and rendezvous with the payload. Detail information on the MCPS system can be found in previous publications[19].

3.3. Nuclear Thermal Propulsion

A NTR system provides thrust by heating propellant that is passed through a nuclear fission reactor. The propellant exits the reactor at high temperature and expands through a nozzle to generate thrust. The NTP system considered in this study is based on the recent work by Aerojet Rocketdyne[20, 21] designed for potential Lunar and Mars application. The vehicle consists of a core stage that houses the main reactor and the nozzles to produce thrust, and inline tanks that dock to the core stage to provide additional propellant capacity. Both the core and the inline stages are launched on an SLS directly to cis-lunar space, where they aggregate and rendezvous with the payload. From an operations stand point, the core stage is the heart of the propulsion system and can be reused for multiple trips to destinations, while the inline stages can be disposable. Table 3 provides a high level summary of the NTP system mass

Table 3: Nuclear Thermal Propulsion Vehicle Mass Summary[20, 21]

Core Stage	
System	Mass, kg
1.0 Dry Mass	26,180
2.0 Growth	1,250
3.0 Propellant	
3.1 Usable Propellant	13,440
3.2 RCS Propellant	3,000
Launch Mass	43,870
Inline Stage	
System	Mass, kg
1.0 Dry Mass	10,700
2.0 Growth	2,380
3.0 Propellant	
3.1 Usable Propellant	26,750
3.2 RCS Propellant	4,040
Launch Mass	43,870

summary for both the core and the inline stages. Detail information on the NTP system can be found in the Aerojet Rocketdyne publications[20, 21].

4. Mars Trajectory Parameters

In order to compare the different propulsion systems equally from a campaign perspective, it is imperative that the trajectory enables each system to perform its optimal mission. For the high thrust impulsive systems, the Earth departure Trans-Mars Injection (TMI) and arrival Earth Orbit Insertion (EOI) maneuvers are performed at near perigee of the orbit to maximize the Oberth effect. For the hybrid high/low thrust system, Earth departure and arrival maneuvers require a series of small maneuvers and Lunar Gravity Assists[22] (LGA) to achieve Earth escape. Details of this departure and arrival sequence can be found in a previous publication on the Hybrid Transportation System[23].

The Mars arrival and departure sequence is the same for all transportation systems but of different magnitudes. In order to target a specific landing site latitude across multiple mission opportunities[24], a three-burn bi-elliptic maneuver is performed for the Mars Orbit Insertion[25] (MOI). The first burn puts the vehicle in an intermediate orbit that has a period of 10-sol with an perigee of 250 km altitude. The second maneuver, performed at apogee of the intermediate orbit, changes the inclination of the orbit to match the desired landing site latitude. Finally, a third burn back at perigee of the intermediate orbit lower the apogee to the final 5-sol parking orbit. For Mars departure, a similar sequence is performed, with the inclination change targeting the desired final Trans-Earth Injection (TEI) burn velocity direction. Because the high apogee of the parking orbit (chosen to minimize the ΔV requirement) does not precess very fast, depending on the mission opportunity, an additional maneuver may be required at Mars to reorient the

Table 4: Trajectory Summary for High Thrust Missions Departing 400x400,000 km High Earth Orbit to Mars 5-Sol Parking Orbit Targeting 18.8° Latitude Landing Site

Year	Earth	Mars	Mars	Earth	Transit [days]			Maneuvers [km/s]					Total ΔV [km/s]
	Departure	Arrival	Departure	Arrival	E-M	Orbit	M-E	TMI	MOI	APO	TEI	EOI	
2033	04/17/33	11/14/33	04/29/35	11/24/35	211	531	210	0.501	1.288	0.024	1.081	0.503	3.397
2035	06/27/35	01/22/36	06/26/37	03/29/38	209	522	275	0.553	0.829	0.001	1.521	0.606	3.510
2037	08/17/37	08/10/38	07/14/39	05/02/40	358	337	293	0.832	1.001	0.005	1.028	0.461	3.327
2039	09/18/39	09/01/40	07/22/41	05/30/42	349	324	312	0.665	0.678	0.002	1.003	0.463	2.812
2041	10/19/41	09/10/42	07/26/43	07/03/44	326	319	343	0.532	0.706	0.007	0.929	0.592	2.766
2043	11/13/43	09/23/44	08/08/45	08/04/46	314	319	361	0.498	0.891	0.009	0.917	0.763	3.078

Table 5: Trajectory Summary for Hybrid SEP/Chemical Missions Departing 400x400,000 km High Earth Orbit to Mars 5-Sol Parking Orbit Targeting 18.8° Latitude Landing Site

Crew Missions													
Year	Earth	Mars	Mars	Earth	Transit [days]			Chemical Maneuvers [km/s]					EP ΔV [km/s] E-M M-E
	Departure	Arrival	Departure	Arrival	E-M	Orbit	M-E	TMI	MOI	APO	TEI	EOI	
2035	05/22/35	05/07/36	04/15/37	04/19/38	351	323	369	0.000	0.116	0.000	0.119	0.000	3.957 3.976
2039	08/05/39	09/01/40	06/28/41	07/03/42	393	280	370	0.024	0.299	0.056	0.209	0.000	3.239 3.716
2043	10/18/43	10/19/44	08/15/45	09/15/46	367	280	396	0.000	0.334	0.094	0.187	0.000	3.243 4.039

Cargo Missions													
Year	Earth	Mars	Mars	Earth	Transit [days]			Chemical Maneuvers [km/s]					EP ΔV [km/s] E-M M-E
	Departure	Arrival	Departure	Arrival	E-M	Orbit	M-E	TMI	MOI	APO	TEI	EOI	
2033	02/15/33	12/20/33	01/22/35	02/10/36	308	378	384	0.000	0.377	0.039	0.082	0.000	3.472 4.582
2035	04/26/35	03/20/36	04/02/37	04/20/38	329	358	383	0.093	0.200	0.000	0.097	0.000	3.709 4.203
2037	06/01/37	11/06/38	06/01/39	05/26/40	523	187	360	0.000	0.130	0.003	0.116	0.000	4.213 4.225
2039	08/05/39	08/20/40	06/21/41	07/02/42	381	285	376	0.042	0.308	0.052	0.117	0.000	3.164 3.910
2041	09/09/41	12/11/42	06/14/43	09/06/44	458	165	450	0.000	0.140	0.007	0.127	0.000	3.941 4.033
2043	10/18/43	09/30/44	06/28/45	10/14/46	348	251	473	0.000	0.435	0.075	0.109	0.000	2.721 4.121

parking orbit to align in preparation for the Mars departure sequence[25]. This maneuver is called the apotwist (APO) maneuver, and additional details for the Mars sphere of influence maneuvers can be found in previously published work[23, 25, 26].

4.1. High Thrust Systems

For the high thrust impulsive systems, the trajectory optimization and the vehicle sizing can be assumed to be independent of each other for this level of analysis. The trajectory optimization purely minimizes the total roundtrip ΔV while meeting the desired mission constraints. A typical minimum energy conjunction style Mars mission utilizes the optimal Earth-Mars planetary positions to minimize the total ΔV with overall roundtrip time in the 1,000 to 1,100 days range. These mission opportunities occur approximately every 26 months. Trajectory summary for the high thrust missions targeting the reference landing site latitude of 18.8 degrees (Jezero Crater) is shown in Table 4.

4.2. Hybrid Low/High Thrust Systems

Solving the complete end-to-end trajectory for human Mars missions with the HPS is more complex than the traditional chemical high thrust impulsive system. For the hybrid system, because the thrust delivered by the SEP system is very low, the trajectory optimization is coupled with the vehicle sizing and optimization due to gravity loss

and other factors. This requires the trajectory optimization to be solved simultaneously with the vehicle sizing and closure[23].

The Hybrid SEP/Chemical propulsion option departs for Mars from a 400x400,000 km high Earth orbit where it rendezvous with the crew and allows the crew to perform final check out. The departure orbit is selected and maintained to avoid lunar encounter until after crew rendezvous and the spacecraft being ready for departure, at which point a small maneuver initiates the departure sequence by targeting an encounter with the Moon for LGA maneuvers[22]. Multiple LGA maneuvers may be required to achieve Earth escape velocity of 1.4 km/s with proper direction to match the velocity requirement for the heliocentric transit.

If the the SEP system is underpowered for the heliocentric transit and a V_∞ higher than 1.4 km/s is required, a small impulsive maneuver can be added during the LGA's perilune passage to boost the V_∞ by a small amount. After achieving the appropriate Earth escape V_∞ , the Hybrid spacecraft utilizes the SEP system to thrust for the majority of the heliocentric transit to target a low V_∞ arrival at the destination. Once the Hybrid spacecraft arrives at the Mars parking orbit, it must reorient itself into the parking orbit such that it can meet the Mars departure velocity direction and magnitude. The return sequence is identical to the departure sequence but in reverse.

There is no simple solution to the mission design problem, as the combination of the low-thrust optimization and

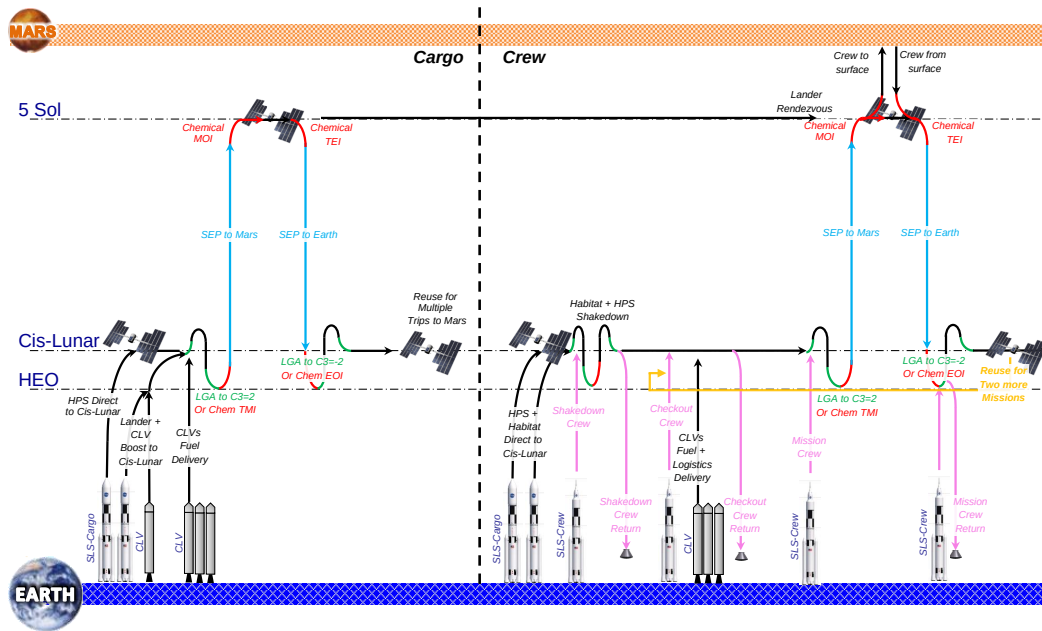


Figure 1: Mars Hybrid SEP/Chemical Propulsion System Mission Concept of Operation

the traditional orbital mechanics closed-form solution of the Lambert problem makes the optimization more challenging. To solve the trajectory optimization problem, the complete Mars roundtrip trajectory mission must be modeled in an integrated fashion and solved iteratively to ensure performance closure. Details of the solution method and the development of the optimization framework can be found in previous publication[27]. Table 5 shows the trajectory summary for the Hybrid SEP/Chemical transportation system to field the missions required for this study. Note that because the payload is different for the crew and cargo cases, separate trajectories must be generated for each payload scenario and mission opportunity.

5. Transportation Mission Concept of Operations

A set of common assumptions was applied to the three transportation options in the present study. First, the landers are in the 53t class, delivering 20t of payload to the surface of Mars from a 5-sol parking orbit. Because 53t is greater than the SLS TLI capability[12], a commercial boost stage is required to deliver the lander to cis-lunar space. This boost stage will launch from the generic CLV and rendezvous with the lander in a high Earth orbit that the SLS delivered the lander to, and provide the necessary propulsive maneuver to deliver the lander to the cis-lunar aggregation orbit. Second, the initial crew shakedown mission is to occur in 2030 as set by the ground rules. The shakedown mission is meant to test the integrated habitation and propulsion elements in a simulated mission around cis-lunar space. The assumption for this mission will be the propellant utilized can be resupplied by a single CLV tanker after the conclusion of the shakedown mission. Finally, all three transportation options will utilize the SLS and Orion combination to deliver crew for all missions.

Table 6: Hybrid SEP/Chemical Propulsion Option Mission Breakdown

Mission 1	Vehicle	Payload	Chemical Propellant	SEP Propellant	Logistics & Spares	
2030 Shakedown	HPS 1	22,300	5,000	10,000	10,000	kg
2033 Lander x1	HPS 1	53,000	18,300	23,100		kg
2033 Lander x1	HPS 2	53,000	18,300	23,100		kg
2035 Lander x1	HPS 3	53,000	15,600	22,700		kg
2035 Crew	HPS 4	22,300	12,800	30,100	22,200	kg

Mission 2	Vehicle	Payload	Chemical Propellant	SEP Propellant	Logistics & Spares	
2037 Lander x1	HPS 1	53,000	10,600	24,800		kg
2037 Lander x1	HPS 2	53,000	10,600	24,800		kg
2039 Lander x1	HPS 3	53,000	17,900	20,200		kg
2039 Crew	HPS 4	22,300	22,900	27,100	22,200	kg

Mission 3	Vehicle	Payload	Chemical Propellant	SEP Propellant	Logistics & Spares	
2041 Lander x1	HPS 1	53,000	11,000	23,200		kg
2041 Lander x1	HPS 2	53,000	11,000	23,200		kg
2043 Lander x1	HPS 3	53,000	20,700	18,900		kg
2043 Crew	HPS 4	53,000	24,000	28,700	22,200	kg

5.1. Hybrid SEP/Chemical Propulsion

The Hybrid SEP/Chemical propulsion mission concept of operation is shown in Figure 1. For both crew and cargo missions, the Hybrid element performs the full roundtrip missions without staging or needing to be resupplied at Mars. The propulsion elements and payloads are launched separately on the SLS directly to TLI condition, and they meet in cis-lunar space for aggregation. The HPS is launched with enough propellant for the rendezvous and docking maneuver in cis-lunar space and to perform the propulsion system shakedown mission. The HPS vehicles are refueled by commercial launch vehicles in cis-lunar space prior to each Mars mission. After the vehicle has been fully fueled and stocked with logistics, the vehi-

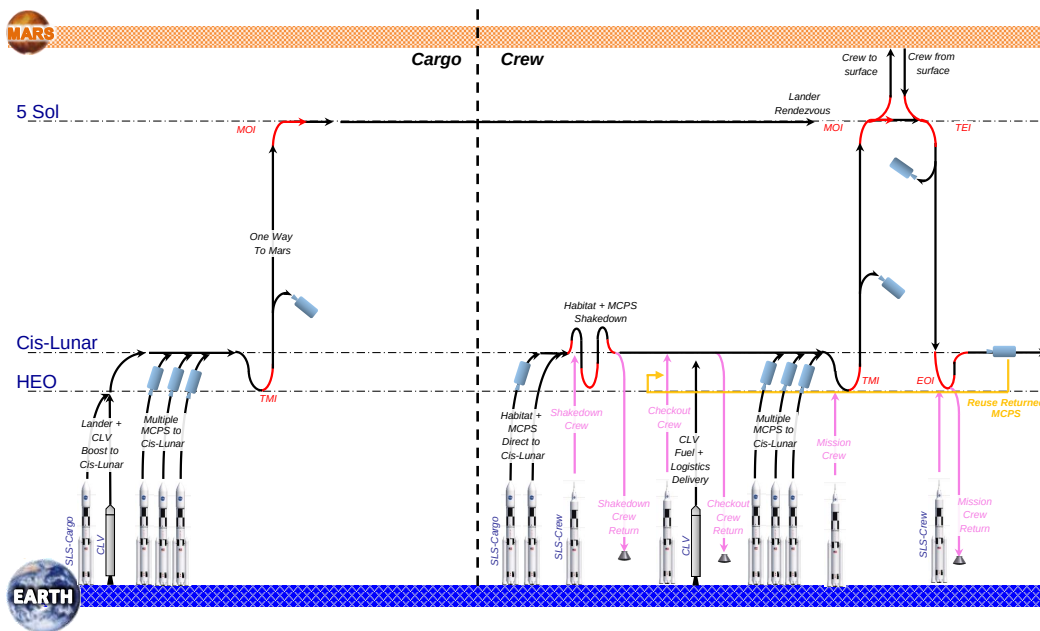


Figure 2: Mars Methane Cryogenic Propulsion System Mission Concept of Operation

Table 7: Methane Cryogenic Propulsion Option Mission Breakdown

Mission 1	Vehicle	Payload	Propellant	Logistics & Spares	
2030 Shakedown	MCPS x1	22,300	10,000	10,000	kg
2033 Lander x2	MCPS x3	106,000	97,500		kg
2035 Lander x1	MCPS x2	53,000	48,500		kg
2035 Crew	MCPS x4	22,300	125,000	21,300	kg

Mission 2	Vehicle	Payload	Propellant	Logistics & Spares	
2037 Lander x2	MCPS x3	106,000	98,500		kg
2039 Lander x1	MCPS x1	53,000	32,700		kg
2039 Crew	MCPS x3	22,300	91,100	21,000	kg

Mission 3	Vehicle	Payload	Propellant	Logistics & Spares	
2041 Lander x2	MCPS x2	106,000	61,400		kg
2043 Lander x1	MCPS x1	53,000	48,800		kg
2043 Crew	MCPS x3	22,300	94,900	21,100	kg

cle performs a six month weak stability boundary transit from cis-lunar space to lunar distant high Earth orbit (LDHEO) via a solar perturbation loop to minimize the propellant used when the vehicle is heaviest. The Mars crew is launched on an SLS/Orion directly to the LDHEO, where they rendezvous with the HPS and habitat, transfer final logistics, and departs for Mars.

Upon arrival at Mars, both crew and cargo Hybrid vehicles perform maneuvers to align the parking orbit properly for direct sub-perigee landings to Jezero crater. The crew Hybrid will rendezvous with the third lander stage and the crew transfers to the lander to descend to the surface. The HPS vehicle loiters in Mars orbit while the crew is on the surface, performing orbit maintenance and propulsive maneuvers to realign the parking orbit for ascend stage ren-

dezvous and for Mars departure. The cargo HPS vehicles return to Earth without a payload.

An SLS launches an empty Orion to LDHEO to rendezvous with the crewed Hybrid vehicle and return the crew to Earth. After crew return, the Hybrid vehicle transits from LDHEO to cis-lunar space 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 or an additional CLV refueling launch. Once in cis-lunar space, the HPS rendezvous with existing cis-lunar infrastructure to perform refuel and resupply activities in preparation for the next mission to Mars.

Each Hybrid vehicle can be reused for up to three roundtrip missions to Mars. Table 6 shows the mission cadences and the propellant mass requirement to achieve the three missions as defined by the ground rules. A total of four Hybrid vehicles are required to field the three roundtrip missions. The first Hybrid vehicle will perform the initial shakedown mission with the habitat with the propellant it was launched with, then it is refueled for three additional cargo trips to Mars. The second and third Hybrid vehicles will also each perform three roundtrip lander delivery missions with a slightly different cadence. The fourth and final Hybrid vehicle will serve as the primary crew mission vehicle. It will be launched in time for the checkout and resupply mission in 2033 in preparation for the first crew mission in 2035 and will carry the crew to Mars and back three times.

5.2. Methane Cryogenic Propulsion

The Methane Cryogenic Propulsion System's mission concept of operation is shown in Figure 2. For both crew

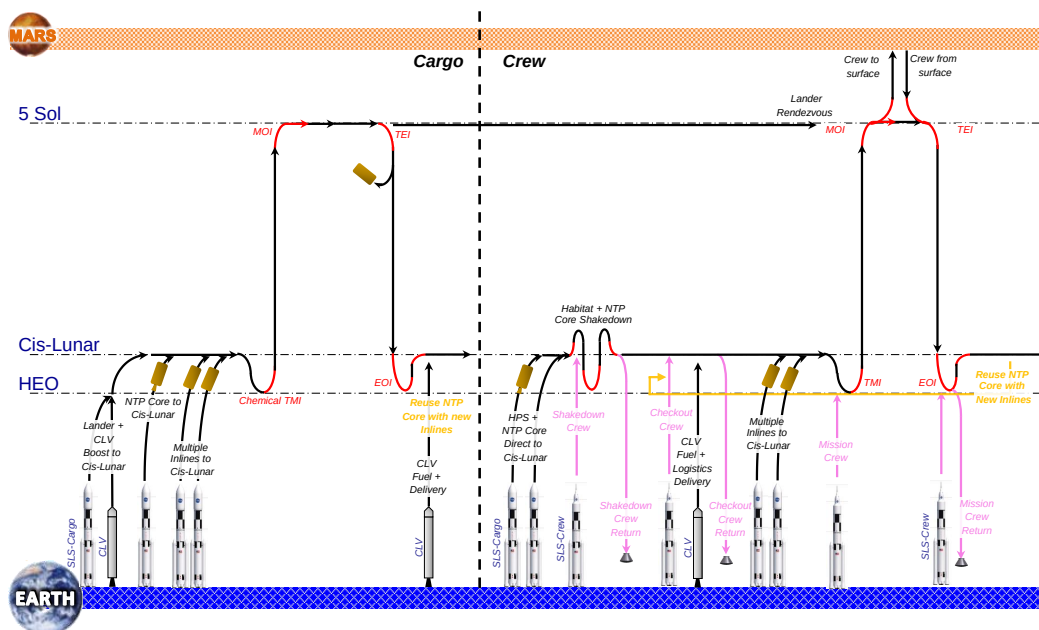


Figure 3: Mars Nuclear Thermal Propulsion System Mission Concept of Operation

and cargo missions, the MCPS are launched directly to TLI conditions, where they rendezvous with each other and the payload. For the cargo missions, once aggregation is complete, the propulsion stage stack and the payload depart Earth on a ballistic trajectory for Mars. For the crew missions, the propulsion stages and the habitat will perform a small maneuver to transit from the cis-lunar aggregation orbit to LDHEO to rendezvous with the crew before performing the TMI burn to depart Earth. Depending on how much propellant is used for the TMI maneuver, some of the propulsion stages may be disposed of after the maneuver.

For the cargo missions, the propulsion stage performs the MOI burn with the payload into a 5-sol parking orbit, then it performs the reorientation maneuvers required to align the parking orbit properly for lander sub-perigee landing. Once the lander is detached the cargo propulsion stages are disposed of and will not return to Earth for reuse. One important note on the cargo mission for the MCPS option is that the feasibility of docking and delivering multiple landers in a single vehicle stack was outside the scope of this study. It is likely that additional structure and docking mechanisms are required to enable this mission mode, especially with the high thrust chemical maneuvers. If the landers cannot be delivered simultaneously, additional MCPS stages will be required to deliver each lander separately.

For crew missions, the propulsion stages perform the same maneuvers as the cargo missions, but the stages will remain in Mars orbit with the habitat to return the crew back to Earth. Additional stages may be disposed of once they are depleted. After the crew returns from the surface, the propulsion stage performs TEI maneuver with the habitat to depart Mars for Earth on a ballistic trajectory, inserting into LDHEO back at Earth. An SLS launches an empty Orion

to LDHEO to rendezvous with the crewed vehicle and return the crew to Earth. The remaining propulsion stage then returns itself and the habitat to cis-lunar aggregation orbit with its remaining propellant where it is refueled with commercial tankers and rendezvous with new propulsion stages for the following mission.

Table 7 shows the mission cadences and propellant mass requirements to achieve the three missions as defined by the ground rules for the MCPS option. The first MCPS is utilized for the habitat and propulsion system shakedown mission in 2030 after being launched directly to cis-lunar space. In the 2033 Mars mission opportunity, two landers are delivered with three MCPS stage on a one way mission, and a single lander is delivered in 2035 with two MCPS in support of the 2035 crew mission. For the Crew mission, the same MCPS used for the shakedown mission is refueled with a commercial tanker in cis-lunar space. It then is joined by three additional MCPS before departing for Mars in the 2035 mission opportunity. For the second Mars mission, a total of seven MCPS are required in addition to the single MCPS that is returned from the 2035 crew mission, and six additional MCPS are required for the 2043 mission to deliver both cargo and crew. Each of the MCPS has its own engines and propellant feed systems, so the design permits disposal of empty stages to maximize the performance of the overall propulsion system.

5.3. Nuclear Thermal Propulsion

The Nuclear Thermal Propulsion System's mission concept of operation is shown in Figure 3. The propulsion concept is unique in that it has separate core and inline stages that perform different functions. The high performance of the system results in a mission con-op that requires only two core stages to field all of the missions, one

Table 8: Nuclear Thermal Propulsion Option Mission Breakdown

Mission 1	Vehicle	Payload	Propellant	Logistics & Spares	
2030 Shakedown	Core 1	22,300	10,000	10,000	kg
2033 Lander x3	Core 1 + Inline x2	159,000	64,100		kg
2035 Crew	Core 2 + Inline x1	22,300	59,500	21,300	kg
Mission 2	Vehicle	Payload	Propellant	Logistics & Spares	
2037 Lander x3	Core 1 + Inline x2	159,000	64,600		kg
2039 Crew	Core 2 + Inline x1	22,300	37,000	21,300	kg
Mission 3	Vehicle	Payload	Propellant	Logistics & Spares	
2041 Lander x3	Core 1 + Inline x2	159,000	50,300		kg
2043 Crew	Core 2 + Inline x1	22,300	39,500	21,300	kg

for cargo and one for the crew. For both crew and cargo missions, the NTP core and inline stages are launched directly to TLI conditions and maneuver to cis-lunar space for aggregation. The first NTP core stage is launched in time for the crewed habitation and propulsion system shakedown mission. That NTP core stage is then refueled in cis-lunar space, rendezvous with additional inline stages and all three landers, and departs for Mars. Because of the way the NTP vehicle is assembled, empty inline stages cannot be disposed of while the payload is attached. While there is potential for this to be achieved, it will require additional structure and is outside the scope of this study. After the landers have been delivered to Mars orbit, the empty inline stages can be jettisoned, and the NTP core stage returns to Earth (with or without some of the inline stages) for reuse.

One important note on the NTP mission concept is that the feasibility of docking and delivering all three lander payloads in one vehicle stack was outside the scope of this study. It is likely that additional structure is required to enable three landers to be simultaneously docked to a single vehicle much like for the MCPS mission (where two landers are delivered in a single vehicle stack). If the option of delivering multiple landers is not possible, then each lander would require its own NTP core stage, which represents a significant financial investment to the campaign. Though it would eliminate the need for inline stages for the cargo missions for most opportunities, additional trades and analysis are required to fully understand the impact of this option.

The Crew missions follow a scenario similar to the cargo missions. After core and inline stages have been aggregated in cis-lunar space, the vehicle returns to LHDEO to rendezvous with the crew, which launches on an Orion. Since the habitat is always attached to the vehicle stack, no staging of empty inline stages will occur outside of cis-lunar space as it would require un-docking the habitat. The crew NTP vehicle performs the roundtrip mission to Mars in a manner similar to the MCPS option and returns to cis-lunar space where it is refueled by commercial tankers for subsequent missions.

Table 8 shows mission cadences and propellant mass requirement to achieve the three missions as defined by the

Table 9: Transportation Options Campaign Launch Manifest

<i>Hybrid SEP/Chemical Propulsion Option</i>					
SLS Cargo		SLS Crew		Commercial LV	
1	Habitat	1	Shakedown	1-2	M1 Logistics x2
2	HPS1	2	M1 Checkout	3-5	M1 Boost Stage x3
3	HPS2	3	M1 Mission	6-17	M1 Tankers x12
4	HPS3	4	M1 Return	18-19	M2 Logistics x2
5	HPS4	5	M2 Checkout	20-22	M2 Boost Stage x3
6-8	M1 Lander x3	6	M2 Mission	23-38	M2 Tankers x16
9-11	M2 Lander x3	7	M2 Return	39-40	M3 Logistics x2
12-14	M3 Lander x3	8	M3 Checkout	41-43	M3 Boost Stage x3
		9	M3 Mission	44-60	M3 Tankers x17
		10	M3 Return		
<i>Methane Cryogenic Propulsion Option</i>					
SLS Cargo		SLS Crew		Commercial LV	
1	Habitat	1	Shakedown	1-2	M1 Logistics x2
2-4	M1 Lander x3	2	M1 Checkout	3-5	M1 Boost Stage x3
5-8	M1 Crew CPS x4	3	M1 Mission	6	M1 Tanker x1
9-13	M1 Cargo CPS x5	4	M1 Return	7-8	M2 Logistics x2
14-16	M2 Lander x3	5	M2 Checkout	9-11	M2 Boost Stage x3
17-18	M2 Crew CPS x2	6	M2 Mission	12-15	M2 Tankers x4
19-22	M2 Cargo CPS x4	7	M2 Return	16-17	M3 Logistics x2
23-25	M3 Lander x3	8	M3 Checkout	18-20	M3 Boost Stage x3
26-27	M3 Crew CPS x2	9	M3 Mission	21-24	M3 Tanker x4
28-31	M3 Cargo CPS x4	10	M3 Return		
<i>Nuclear Thermal Propulsion Option</i>					
SLS Cargo		SLS Crew		Commercial LV	
1	Habitat	1	Shakedown	1-2	M1 Logistics x2
2-4	M1 Lander x3	2	M1 Checkout	3-5	M1 Boost Stage x3
5	Crew Core	3	M1 Mission	6	M1 Tanker x1
6-7	Crew Inline x2	4	M1 Return	7-8	M2 Logistics x2
8	Cargo Core	5	M2 Checkout	9-11	M2 Boost Stage x3
9-10	M1 Cargo Inline x2	6	M2 Mission	12-18	M2 Tankers x7
11-13	M2 Lander x3	7	M2 Return	19-20	M3 Logistics x2
14-15	M2 Cargo Inline x2	8	M3 Checkout	21-23	M3 Boost Stage x3
16-18	M3 Lander x3	9	M3 Mission	24-30	M3 Tanker x7
19-20	M3 Cargo Inline x2	10	M3 Return		

ground rules for the Nuclear Thermal Propulsion option. The first NTP core stage is utilized for the crew shakedown mission along with all three cargo missions. Each cargo mission will require two new inline stages as empty ones are disposed of, while the crew missions retain both the core and the single inline stage for all three missions.

6. Campaign Comparison and Discussions

To field the three crewed missions, each of the three transportation options requires different elements to be launched and aggregated in cis-lunar space. As discussed in the previous sections, the mode of operation for each of the transportation options can vary, however they ultimately achieve the same objective. There are many ways to evaluate and compare the differences between each of the transportation options. In this study, the launch vehicle manifest, launch cadence, and total launch mass required is used to compare and contrast the options. Table 9 shows a summary of the launch manifest for each of the three transportation options for all three missions using the three types of launch vehicles available.

Each column in Table 9 shows the number of launch vehicles required and the payload delivered for each transportation option. One item to note is that the SLS Crew launch is constant across the three transportation options due to the mission requirements and ground rules. However there is significant variation in the other two launch

	'29	'30	'31	'32	'33	'34	'35	'36	'37	'38	'39	'40	'41	'42	'43	'44+
	Delivery of Deep Space Habitation Module and 1 st Hybrid Propulsion Element to Cis-Lunar Space	Shakedown Mission with Habitation and Propulsion Elements Delivery of 1 st Lander & Boost Stage for 1 st Mission	Delivery of 2 nd Hybrid Element Delivery of 2 nd Lander & Boost Stage for 1 st Mission	Delivery of 3 rd Hybrid Element	Two Cargo Hybrids Depart for Mars with Landers Early-February Delivery of 3 rd Lander & Boost Stage for 1 st Mission	Delivery of 4 th Hybrid Element Crewed Mission to Checkout & Supply Habitat for 1 st Mars Mission	1 st Mission Crew & Lander Depart for Mars Mid-May Delivery of 1 st Lander & Boost Stage for 2 nd Mission	Delivery of 2 nd Mars Lander & Boost Stage for 2 nd Mission Two Cargo Hybrid Elements Return from Mars Late-February	Two Cargo Hybrids Depart for Mars with Landers Early-June Delivery of 3 rd Lander & Boost Stage for 2 nd Mission	1 st Mission Crew Return Mid-April Crewed Mission to Checkout & Supply Habitat for 2 nd Mars Mission	2 nd Mission Crew & Lander Departs for Mars Early-August Delivery of 1 st Lander & Boost Stage for 3 rd Mission	Delivery of 2 nd Lander & Boost Stage for 3 rd Mission Two Cargo Hybrid Elements Return from Mars Late-May	Two Cargo Hybrids Depart for Mars with Landers Early-September Delivery of 3 rd Lander & Boost Stage for 3 rd Mission	2 nd Mission Crew Return Early-July Crewed Mission to Checkout & Supply Habitat for 3 rd Mars Mission	3 rd Mission Crew & Lander Departs for Mars Mid-October	3 rd Mission Crew Return Mid-September 2046
SLS Crew		Shakedown				Checkout	Mission			Return Checkout	Mission			Return Checkout	Mission	Return
SLS Cargo	Hybrid Habitat	Lander	Hybrid Lander	Hybrid	Lander	Hybrid	Lander	Lander	Lander		Lander	Lander	Lander			
Commercial		Boost Stage Tanker	Boost Stage Tanker Tanker Tanker	Tanker Tanker Tanker Tanker	Boost Stage Tanker Tanker	Tanker Tanker Logistics Tanker	Boost Stage Tanker Tanker Tanker Tanker	Boost Stage Tanker Tanker Tanker Tanker	Boost Stage Tanker Tanker Tanker Tanker	Tanker Tanker Tanker Tanker	Logistics Logistics Boost Stage Tanker	Boost Stage Tanker Tanker Tanker Tanker	Boost Stage Tanker Tanker Tanker Tanker	Logistics Logistics Tanker Tanker Tanker Tanker	Tanker Tanker Tanker Tanker Tanker	

Figure 4: Mars Hybrid SEP/Chemical Propulsion System Campaign Integrated Launch Cadence and Manifest

	'29	'30	'31	'32	'33	'34	'35	'36	'37	'38	'39	'40	'41	'42	'43	'44+
	Delivery of Deep Space Habitation Module and 1 st Methane Cryogenic Propulsion Element to Cis-Lunar Space	Shakedown Mission with Habitation and Propulsion Elements Delivery of 1 st Lander & Boost Stage for 1 st Mission	Delivery of 2 nd Lander & Boost Stage for 1 st Mission	Commercial Delivery of Propellant to Refuel Shakedown MCPs for Cargo Mission	Two Landers with Multiple MCPs Depart for Mars Mid-April Delivery of 3 rd Lander & Boost Stage for 1 st Mission	Crewed Mission to Checkout & Supply Habitat for 1 st Mars Mission	1 st Mission Crew & Lander Depart for Mars Late-June Delivery of 1 st Lander & Boost Stage for 2 nd Mission	Delivery of 2 nd Mars Lander & Boost Stage for 2 nd Mission	Two Landers with Multiple MCPs Depart for Mars Mid-August Delivery of 3 rd Lander & Boost Stage for 2 nd Mission	1 st Mission Crew Return Late-March Crewed Mission to Checkout & Supply Habitat for 2 nd Mars Mission	2 nd Mission Crew & Lander Departs for Mars Mid-September Delivery of 1 st Lander & Boost Stage for 3 rd Mission	Delivery of 2 nd Lander & Boost Stage for 3 rd Mission	Two Landers with Multiple MCPs Depart for Mars Mid-October Delivery of 3 rd Lander & Boost Stage for 3 rd Mission	2 nd Mission Crew Return Late-May Crewed Mission to Checkout & Supply Habitat for 3 rd Mars Mission	3 rd Mission Crew & Lander Departs for Mars Mid-November	3 rd Mission Crew Return Early-August 2046
SLS Crew		Shakedown				Checkout	Mission			Return Checkout	Mission			Return Checkout	Mission	Return
SLS Cargo	Habitat MCPs	Lander	MCPs Lander	MCPs MCPs	Lander MCPs MCPs	MCPs MCPs	Lander MCPs	Lander MCPs	Lander MCPs MCPs	MCPs	Lander MCPs MCPs	Lander MCPs MCPs	Lander MCPs	MCPs MCPs	MCPs	
Commercial		Boost Stage	Boost Stage	Tanker	Boost Stage	Logistics Logistics	Boost Stage	Boost Stage	Boost Stage Tanker	Tanker Tanker Tanker	Logistics Logistics Boost Stage	Boost Stage	Boost Stage	Logistics Logistics Tanker	Tanker Tanker	

Figure 5: Mars Methane Cryogenic Propulsion System Campaign Integrated Launch Cadence and Manifest

	'29	'30	'31	'32	'33	'34	'35	'36	'37	'38	'39	'40	'41	'42	'43	'44+
	Delivery of Deep Space Habitation Module and 1 st Nuclear Thermal Propulsion Core Element to Cis-Lunar Space	Shakedown Mission with Habitation and Propulsion Elements Delivery of 1 st Lander & Boost Stage for 1 st Mission	Delivery of 2 nd Lander & Boost Stage for 1 st Mission Delivery of 1 st Nuclear Thermal Propulsion Inline Element to Cis-Lunar	Commercial Delivery of Propellant to Refuel Shakedown NTP Core for Cargo Mission Delivery of 3 rd Lander & Boost Stage for 1 st Mission	Three Landers with NTP Core and Multiple Inlines Depart for Mars Mid-April Delivery of 2 nd NTP Core Element	Crewed Mission to Checkout & Supply Habitat for 1 st Mars Mission	1 st Mission Crew Depart for Mars Late-June Delivery of 1 st Lander & Boost Stage for 2 nd Mission Cargo NTP Core Returns Late-November	Delivery of 2 nd Mars Lander & Boost Stage for 2 nd Mission	Delivery of 3 rd Lander & Boost Stage for 2 nd Mission Three Landers with NTP Core and Multiple Inlines Depart for Mars Mid-August	1 st Mission Crew Return Late-March Crewed Mission to Checkout & Supply Habitat for 2 nd Mars Mission	2 nd Mission Crew Departs for Mars Mid-September Delivery of 1 st Lander & Boost Stage for 3 rd Mission	Delivery of 2 nd Lander & Boost Stage for 3 rd Mission Cargo NTP Core Returns Early-May	Delivery of 3 rd Lander & Boost Stage for 3 rd Mission Three Landers with NTP Core and Multiple Inlines Depart for Mars Mid-October	2 nd Mission Crew Return Late-May Crewed Mission to Checkout & Supply Habitat for 3 rd Mars Mission	3 rd Mission Crew & Lander Departs for Mars Mid-November	3 rd Mission Crew Return Early-August 2046
SLS Crew		Shakedown				Checkout	Mission			Return Checkout	Mission			Return Checkout	Mission	Return
SLS Cargo	Habitat NTP Core	Lander	Lander NTP Inline	Lander NTP Inline	NTP Core NTP Inline	NTP Inline	Lander	Lander NTP Inline	Lander NTP Inline		Lander	Lander NTP Inline	Lander NTP Inline			
Commercial		Boost Stage	Boost Stage	Boost Stage Tanker		Logistics Logistics	Boost Stage Tanker	Boost Stage Tanker Tanker	Boost Stage Tanker Tanker	Logistics Logistics Tanker Tanker	Boost Stage	Boost Stage Tanker	Boost Stage Tanker	Logistics Logistics	Tanker Tanker Tanker	

Figure 6: Mars Nuclear Thermal Propulsion System Campaign Integrated Launch Cadence and Manifest

vehicles. For the Hybrid SEP/Chemical option, fourteen SLS Cargo launches are required to deliver all of the payloads: one for the habitat, four for the HPS and nine for the Mars landers. In addition, the Hybrid SEP/Chemical option requires sixty CLVs to deliver all of the logistics and fuel in support of the missions: nine lander boost stages, six crew logistics resupply, and forty-five commercial tankers to refuel the propulsion stages. A total of eighty-four launch vehicles are required to support the campaign of three Mars missions. For the Methane Cryogenic Propulsion option, thirty-one SLS cargo launches are required: one for the habitat, none for the landers, and twenty-one for the MCPS. In addition, twenty-four CLVs are required for the MCPS option: nine lander boost stages, six crew logistics resupply, and nine commercial tankers to refuel the propulsion stages. For the Nuclear Thermal Propulsion option, twenty SLS cargo launches are required: one for the habitat, nine for the landers, and ten for the NTP core and inline stages. Additionally, thirty CLVs are required for the NTP option: nine lander boost stages, six crew logistics resupply, and fifteen commercial tankers to refuel the core and inline stages.

Comparing the three transportation options, the Hybrid option utilizes the fewest number of SLS cargo and the most CLVs; the MCPS option utilizes the most SLS cargo and the fewest number of CLVs; and the NTP option fall in the middle between the other two options. The difference can be more clearly understood if the common launches (like the landers) are removed. In this comparison, the Hybrid option requires four SLS cargo and forty-five CLVs; the MCPS option requires twenty-one SLS cargo and nine CLVs; and the NTP option requires ten SLS cargo and fifteen CLVs. It is difficult to ascertain the merit of three transportation options by examining the total number of launches required, however, some observations can be made. The large number of SLS required for the MCPS option could potentially pose as an added risk to the overall mission, as it relies heavily on a single launch vehicle family. Any failure of the launch vehicle can have dramatic impact on the ability to complete the missions. On the other hand, requiring a large number CLVs also presents a risk challenge even if the campaign can utilize a family of launch vehicles, as large number of CLVs can increase the probability of failure.

Figures 4, 5, and 6 show the integrated campaign launch cadence and manifest for the three transportation options. These figures can be a valuable tool for evaluating different campaign options as they can identify pinch points in the mission requirements. For each of the figures, the mission description for each of the mission years from 2029 to 2044 and beyond is shown on the top row, while the launch requirements and payloads are shown in the next three rows. For each launch, the number shows which mission the payload is directly supporting. A few elements are utilized for all three missions (e.g. the habitat), and they are designated by the infinity symbol. From the figures, a few observations can be made. All of the option requires the habitat and the initial propulsion elements to be launched in 2029

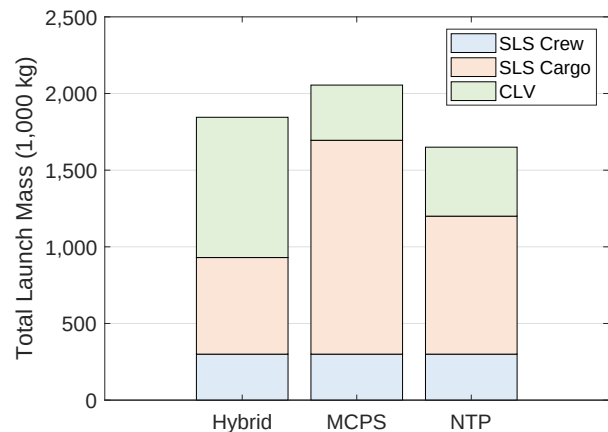


Figure 7: Total Launch Mass For Each Transportation Option Broken Down by Launch Vehicle Type

to support a 2030 crewed shakedown mission as required by the ground rules. The SLS crew launches are all common across the three options as previously discussed.

The Hybrid SEP/Chemical option keeps the SLS launch rates relatively low, with twenty-four required across fifteen plus years, averaging less than two required per year. This option requires a large number of CLVs, with a maximum launch rate of five per year, and requiring that maximum launch rate to be sustained for nearly a decade. This could represent a significant government-industry commitment to a sustained launched cadence for a decade or more in support of a human Mars program, especially considering the mass required in orbit is not constrained to a single launch provider or launch vehicle. The ability for the HPS to be fully reusable across the campaign is demonstrated by the reduction in the SLS cargo launches late in the campaign, as the only launches required are the landers.

In contrast, the MCPS option requires a large number of SLS cargo launches across the entire campaign, requiring two to three cargo launches a year for a significant number of years in addition to the SLS crew launches. This represents a tremendous challenge for the campaign as the launch rate requirement likely exceeds the capability of the SLS program's launch cadence. There isn't much to remedy this either, as the MCPS is too large to fit in a traditional CLV, and reducing the size of the MCPS would likely increase the total number of CLVs to significantly greater than the Hybrid SEP/Chemical option. Additionally, the uncertainty on the feasibility of the simultaneous lander delivery creates additional risk to this option, as even more MCPS launches would likely be required to field the missions.

For the NTP option, the system strikes a relative balance between the Hybrid and the MCPS option. It would require a sustained SLS launch cadence of two per year for the duration of the campaign, and would require a maximum CLV launch rate of four per year with an average of three. The primary differentiator of this option is that be-

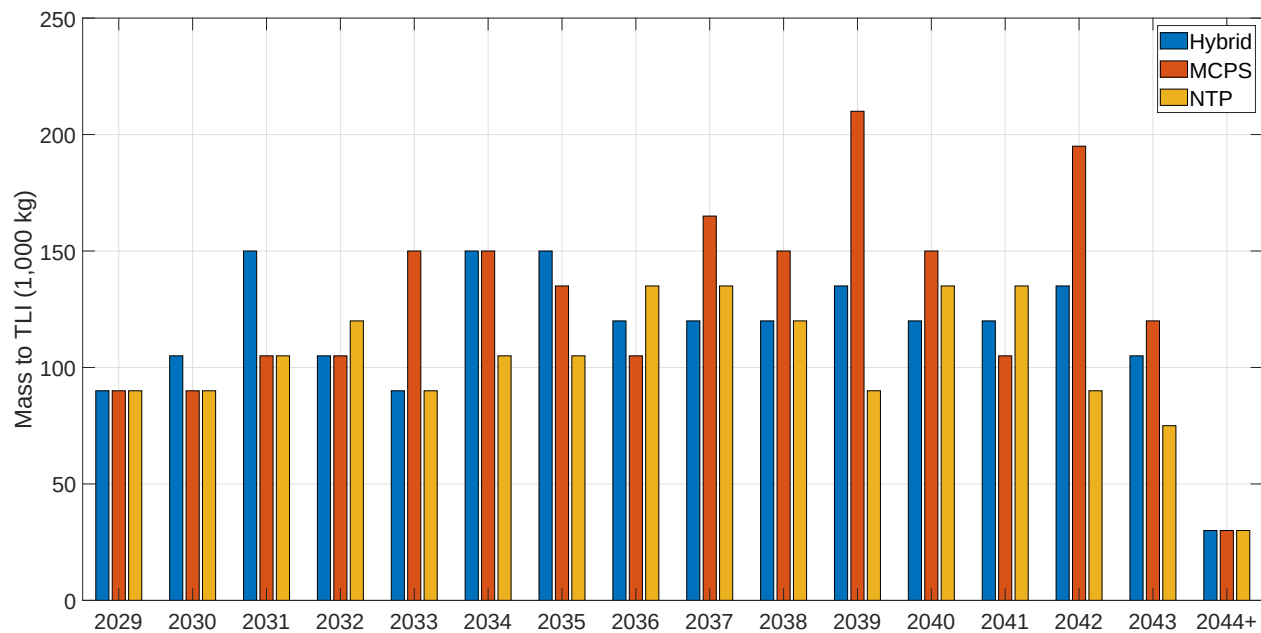


Figure 8: Launch Mass Per Year For Each Transportation Option

cause the landers are delivered all in the same opportunity, all three need to be delivered to cis-lunar space in consecutive years. For certain mission opportunities, this can create a bottleneck in the launch cadence if the Earth departure date is early in the calendar year, as it would require the landers to be launched a year in advance and result in significant loiter time in cis-lunar space. Additionally, as previously discussed, the feasibility of docking and delivering all three landers in one single vehicle stack remains to be determined, and additional NTP core and inline stages would drive the SLS launch rate to greater than two per year.

Figure 7 shows the total launched mass required for each transportation option to field the three crew mission campaigns broken down by the different launch vehicles used. In total, the campaign requires between 1,600 t to 2,100 t of mass to be delivered to orbit. The MCPS option requires the most mass, the NTP option requires the least mass, and the Hybrid falls between the two options. This is in contrast to the total number of launch vehicles, as previously discussed. This shows how the total number of launch vehicle doesn't tell the full story, and launch mass must be considered.

An additional perspective is shown in Figure 8, which shows the total launch mass per year for each of the transportation options. This shows how much mass is required for each option on any particular year, which complements Figures 4, 5, and 6, and provides additional insight into the overall campaign. Overall, the total mass required by the three transportation options per year isn't significantly different, with the exception of the MCPS option which has several peak years in terms of launch mass required. This correlates well with the large number of SLS

cargo launches required for those years. For the Hybrid option, the peak in the launch vehicles required doesn't correlate with peaks in mass required, as most of the increased launches are small commercial launch vehicles delivering propellant.

7. Summary

In this study, a comparison of three in-space transportation options was shown from a campaign level perspective. Each transportation option was utilized to perform three crew roundtrip missions to Mars with supporting cargo missions starting in 2029. Trajectory analysis shows the variation in performance requirements between the high thrust chemical transportation option and the hybrid SEP/Chemical option. The analysis also shows variation in the performance requirements across different mission opportunities, thus selection of which mission opportunity to field crew missions would impact the overall campaign launch manifest and cadence. For this study, the reference campaign calls for fielding crew missions in 2035, 2039, and 2043. This results in the need for the first propulsion elements and the habitation element to be delivered to cis-lunar space in 2029 in preparation for a shakedown flight test in 2030. The Mars landers must depart Earth in the 2033 mission opportunity to provide time for pre-deployment of surface elements, which necessitates additional propulsion elements to be delivered in the early 2030s time frame.

The three transportation options each show strengths and weaknesses from a campaign and strategic investment point of view. The early delivery requirement of these elements could present a challenge to the more advanced technology transportation options (i.e. NTP and Hybrid

SEP/Chemical) compared to the traditional chemical option (i.e. MCPS). However, the comparatively low performance of the MCPS option requires significantly more launch vehicles and launched mass to perform the mission. The Hybrid SEP/Chemical option requires the fewest number of SLSs and the most number of CLVs, the MCPS option requires the most number of SLSs and fewest number of CLVs, and the NTP option falls between the two options for both launch vehicles. The surge in SLS launch rate for the MCPS option and the CLV launch rate for the Hybrid SEP/Chemical option could pose challenges for the campaign. Finally, significant challenges still exist for the MCPS and the NTP options in terms of detailed mission operations and feasibility of assumptions for simultaneous delivery of multiple payloads. Additional propulsion stages and launch vehicles may be required for the NTP and MCPS options if the multi-payload mission mode proves to be too challenging.

Overall, this study provides an initial investigation of the three transportation options identified. Additional work is required to fully understand the utility for each of the options in fielding a Mars campaign. This includes understanding how each transportation options is able to handle changes to mission dates, payload mass, and other program level ground rules. Finally, full cost, schedule, and risk analysis would provide detailed insight into the overall system and programmatic level metrics that is critical to decision makers in selecting transportation options for Mars missions.

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