Combined 1-MW Solar Electric and Chemical Propulsion for Crewed Mars Missions

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The current Moon to Mars Architecture defines functional capabilities that are essential to achieving NASA's specific exploration goals and objectives[1]. The transportation system goals and objectives or functional capabilities do not prescribe a solution, leaving an open tradespace to be explored. NASA is working to identify power and propulsion technologies that enable feasible transportation options for crewed missions to Mars. During NASA's Strategic Analysis Cycle 2021 (SAC21), nuclear enabled spacecraft concepts were analyzed for moderate duration 850-day Earth-Mars roundtrip mission[2]. During SAC22, the transportation tradespace was expanded to understand the feasibility of using different propulsion systems for crewed Mars missions using a moderate duration reference mission as a comparison point. This paper explores the mission analysis performed for a conceptual MW-class hybrid Solar Electric Propulsion (SEP)-chemical propulsion system (SEP-Chem) spacecraft optimized for an 850-day crewed Mars mission for the 2039 opportunity.

I. Nomenclature

ΔV	=	Change in Velocity
BLT	=	Ballistic Lunar Transit
BOL	=	Beginning-of-Life
CTA	=	Compact Telescoping Array
EDM	=	Earth Departure Mass
EOI	=	Earth Orbit Insertion
EP	=	Electric Propulsion
ESDMD	=	Exploration Systems Development Mission Directorate
isp	=	Specific Impulse
LDHEO	=	Lunar-Distant High Earth Orbit
MOI	=	Mars Orbit Insertion

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NEP	=	Nuclear Electric Propulsion
NRHO	=	Near-Rectilinear Halo Orbit
SAC	=	Strategic Analysis Cycle
SEP	=	Solar Electric Propulsion
TEI	=	Trans-Earth Injection
TMI	=	Trans-Mars Injection
TOF	=	Time of Flight

II. Introduction

The hybrid SEP-Chem spacecraft utilizes chemical engines at Earth and Mars to perform the major departure and capture maneuvers in the planetary gravity wells while the SEP system is used during the interplanetary transit to provide sustained acceleration. The sustained acceleration provided by the efficient low-thrust propulsion system during interplanetary transits reduces the burden on the chemical system, lessening the overall propellant load resulting in a lighter vehicle at Earth departure. NASA has explored using SEP-Chem spacecraft in the past for conjunction-class crewed Mars missions[2][3].

The physiological risk to the crew members continues to be a major challenge that arises with long duration human exploration. To address this challenge, recent focus has shifted to shorter duration missions in order to minimize crew time away from Earth [4]. While opposition-class, short stay Earth-Mars missions have significantly shorter mission durations than conjunction-class missions (500-700 days compared to 800-1100 days), reducing mission duration comes at a cost. Typical ΔV requirements of opposition missions are roughly three times that of conjunction missions for the same opportunity. Optimizing these designs for shorter duration missions has a significant impact on the size of the power and propulsion subsystems of these vehicles. There exists a spectrum of mission durations between opposition and conjunction Time-of-Flight (TOF). Spacecraft with low-thrust propulsion systems benefit from increased transit duration since it allows for the Electric Propulsion (EP) system more time to contribute a larger percentage of the overall propulsion required. As mission duration decreases and less time is available for interplanetary thrusting, power must increase to increase EP thrust in order to avoid exponential growth of the required chemical propellant load.

Past NASA developed conceptual hybrid SEP-Chem spacecraft for manned Mars exploration[3][5] were optimized for longer duration conjunction class missions. Prior to SAC22, SEP-Chem had been limited to longer duration missions due to the perceived infeasibility of developing, integrating, and operating a MW-class SEP-Chem spacecraft. A feasible MW-class SEP-Chem spacecraft provides a non-nuclear alternative for moderate duration crewed missions. The SEP-Chem concept for SAC22 attempts to create a design that is feasible to construct and operate while minimizing Earth Departure Mass (EDM) of the vehicle for the defined 2039 SAC22 850-day reference mission. Due to the underlying similarities between a SEP-Chem and Nuclear Electric Propulsion (NEP)-chemical propulsion system (NEP-Chem) spacecraft, SEP-Chem could provide a developmental steppingstone while working towards a hybrid nuclear spacecraft. The SEP-Chem concept resulting from this study attempted to maximize commonality between the SEP and NEP designs by utilizing a common 200t LOX/LCH4 chemical stage.

III. SEP-Chem Mission Modeling

A dynamically sized SEP-Chem Copernicus trajectory model was developed which incorporated parametric sizing equations. This model was used to perform the preliminary analysis for the Compass design study of a MW-class SEP-Chem spacecraft for the SAC22 transportation trade-space[6].

The SEP-Chem trajectories for this analysis were modeled using Copernicus. Copernicus is a trajectory design and optimization tool in which a series of segments is used to model a 3-Deegree of Freedom trajectory. Copernicus was conceived at the University of Texas at Austin by Dr. Cesar Ocampo and is now primarily developed at NASA[7].

The interplanetary mission was modeled as an end-to-end trajectory including the stay in Mars orbit. Four high-thrust burns and ten low-thrust burns are combined to represent the hybrid operation of the propulsion system. The integrated trajectory utilizes the high thrust propulsion system to impulsively depart and capture from Earth and Mars, separated by series of low-thrust burns and coasts. In the fully optimized mission model, the array power, maximum thruster power, EP specific impulsive, EP burn duration and thrusting direction, coast duration, and impulsive burn magnitudes were all optimization variables.

The high-thrust maneuvers are used at Earth departure to escape from a Lunar-Distant High Earth Orbit (LDHEO), at Mars arrival and departure to assist capture into and escape from a 5-sol Mars parking orbit, and then at Earth to re-capture into the LDHEO. The Mars parking orbit is designed to reach a 35° latitude landing site. The outbound transit consists of three low-thrust EP burn segments (EP 1-3) separated by coasting segments. EP burns were modeled with a 90% duty cycle to account for any planned outages. One EP burn segment (EP 4) follows the high-thrust Mars Orbit Insertion (MOI) burn to assist in aligning the capture orbit. Similarly, one EP burn segment (EP 5) precede the Trans-Earth Injection (TEI) maneuver. The EP burns during capture and departure offer the optimizer efficient plane-change maneuver opportunities to lessen any large out-of-plane ΔV components that would have been required during MOI and TEI. Fig. 1 shows the hybrid capture and departure from the Mars 5-sol parking orbit and the extent to which the EP system is used to change the plane of the SEP-Chem vehicle after MOI and before TEI.

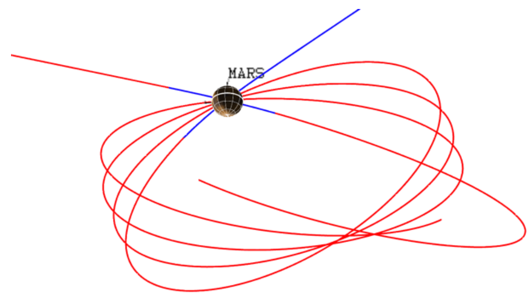

Fig. 1 Hybrid Capture and Departure from 5-sol Mars Orbit

During the stay in Mars orbit, an additional EP reorientation burn opportunity (EP 6) is utilized to offset any precession of the parking orbit and align the spacecraft for departure. The inbound transit consists of four EP burn segments (EP 7-10) separated by coasting segments. At Earth arrival a high-thrust Earth Orbit Insertion (EOI) burn is completed to re-capture into the LDHEO which is where the crew will disembark to another spacecraft to return to the surface. The duration of each burn and coast is determined by the optimizer in order to minimize EDM in LDHEO. Transitions between high-thrust and EP burns are modeled as coast segments with a minimum duration of 1 hour to allow for any reorientation of the spacecraft.

For the initial analysis to determine optimal array power, EP power, and EP specific impulsive, the inert mass of the SEP Module was dynamic, adjusting during optimization based on array power, EP power, mission duration, and xenon propellant load. Parametric equations were created to estimate the mass of the vehicle. These parametric equations were based on the conceptual design for a 700 kW conjunction-class SEP-Chem spacecraft and a 1.9 MW NEP-Chem[9] spacecraft. The model also included an option to dynamically size the chemical stage to the fluctuating chemical propellant load. The scaling factors are provided in Table 1. The dynamically sized SEP-Chem trajectory model was used to perform the preliminary analysis for the Compass design study of a MW-class SEP-Chem spacecraft for the SAC22 transportation trade-space. Significant margins were assumed due in the dynamic model due to the uncertainty in a megawatt-class SEP-Chem design: 100% growth was added to structure mass while 50% growth was added to all EP module subsystems.

Table 1 Scaling Factors used in Dynamic SEP-Chem Trajectory Model

EP Module Subsystem Scaling	*Scale Factor*
Power (kg/kW)	8.19
thermal (kg/kW)	3.85
Chem Hardware (kg/kg fraction of wet stack)	0.0210
Chem Tankage (kg/kg prop)	0.0631
EP Hardware (kg/kW)	7.0
EP tankage (kg/kg prop)	0.04
Mechanical (fraction of dry)	0.200

IV. SEP-Chem Spacecraft

The SAC22 reference design optimized for an 850-day moderate duration reference mission is a SEP-Chem spacecraft with two 500 kW Compact Telescoping Arrays (CTA) providing 1-MW Beginning-of-Life (BOL) power combined with an EP subsystem consisting of eight operational plus two spare 400 V DDU 50 kW Hall thrusters.

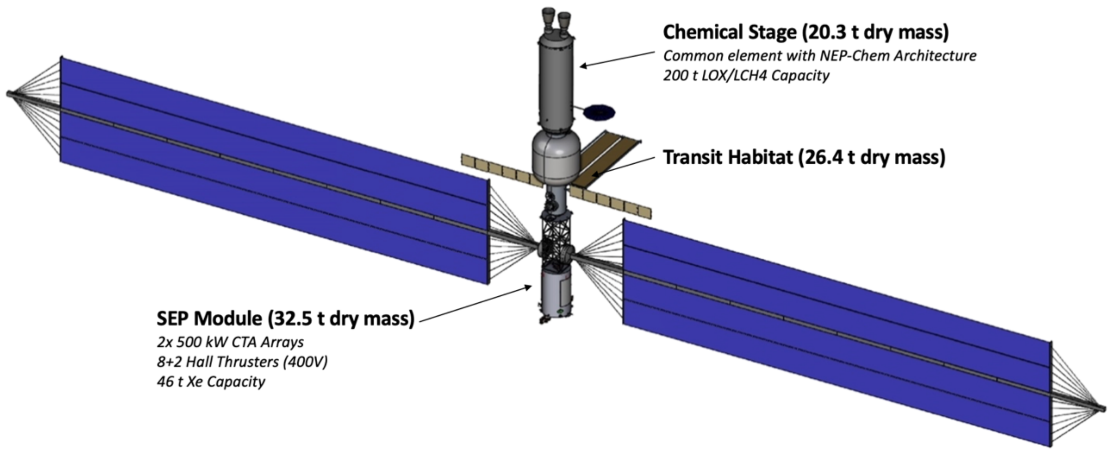

Fig. 2 SAC22 1-MW SEP-Chem Conceptual Design

A. SEP Module

The 400kW EP system includes 8 active 50 kW Xenon Hall thruster plus 2 spare thrusters. These thrusters are anticipated to be an evolution of the AEPS thrusters[4] that will be demonstrated on Gateway. Theses thrusters are assumed to operate at a 90% duty cycle with a specific impulse (isp) of 2380 s and be 59.4% efficient.

Trades on the solar array structural design for a MW-class spacecraft compared the merits of having multiple sets of array wings along a central truss versus a single massive wing on each side of the EP module. The final design opted to use two 500 kW CTAs which are being developed under NASA's game changing development program by NASA LaRC and Angstron Designs (add reference) due to the simplicity of the two-array design and the CTA's high packing efficiency. The CTAs have 36% efficient IMM solar cells with 95 cells per string and 1,000 strings per wing. The arrays have a specific power of 108 W/kg with each wing having a deployed area of 1637 m^2 and 75% packing efficiency. To further simplify the design and reduce the mass of the EP subsystem, the arrays are regulated to provide 350 V near Earth and 400 V near Mars. This enables the use of 99% efficient direct drive units (DDUs) rather than PPUs for the EP thrusters. 30 kW of bus power is provided for non-propulsive purposes to the spacecraft while the EP thrusters draw a maximum of 400 kW.

A degradation rate of 1.5% per year was assumed for the CTAs. The duration of a mission phase combined with mission elapsed time up to that point and an initial 2-year on-orbit assembly period were used to calculate the power level provided by the arrays at the end of each phase. Since the trajectory model does not include a time-based array power level, these calculated final power levels were used as the available power during the associated mission phase. The structure of the SEP module is designed with withstand applied mechanical and thermal loads from launch and operation, 5.5 g and 0.1 g respectively, and have a first modal frequency of 0.05 Hz or greater. The CTA array gimbals are based on the International Space Station Solar Array Rotary Joint design.

The SEP Module has a dry mass of 32.5 t and the capacity to carry 50 t of Xenon propellant.

B. Chemical Stage

The chemical propulsion systems performs the departure and capture burns around Earth and Mars. The chemical stage on the SEP-Chem spacecraft is comprised of two 110 kN Class LOX/LCH_4 engines and carries approximately 200 t of propellant and has a dry mass of 20.3 t. Nominally the isp of the chemical stage is 370 s but for this study isp was decremented to 351.5 s to model the unused propellant margin being dropped following each burn.

C. Transit Habitat and Logistics

The Transit Habitat element was not designed as part of this study. The assumed Transit Habitat has a dry mass of 26.4 t. The logistics mass was sized as a fixed mass of 7,220 kg plus an additional 15.44 kg/day. This study added 40 days to the crew time to account for contingency logistics and spares. Trash dumping occurs throughout the mission at a rate of 11.6 kg/day. For the purposes of trajectory modeling, the sum of this mass for each mission phase is dumped at the conclusion of that phase: following outbound transit, stay in Mars parking orbit, and inbound transit.

V. Analysis Trades

The mission analysis done to support optimization of the SEP-Chem design for a moderate duration mission included trades on chemical stage sizing and aggregation location as well as identifying optimal power and propulsion operational setpoint sensitivity to TOF, and analyzing performance across a range of opportunities.

A. Chemical Stage Sizing

Maintaining commonality with previous crewed NEP-Chem design was a priority for this study. Having common subsystems between these two designs could allow a crewed SEP-Chem spacecraft to be a developmental steppingstone while working towards a hybrid nuclear spacecraft. The key difference between SEP and NEP is the power generation method but many of the subsystems have common elements due to the underlying design similarities. Common subsystems or spacecraft elements could be developed and tested on a SEP spacecraft which could provide crewed opportunities during the nuclear-development timeline. Development of a SEP and NEP based propulsion system may be structured to allow single program to develop evolutionary advancement in performance capabilities. 50 kW Hall thrusters could be used for both SEP and NEP vehicles while large SEP-Chem deployable arrays mimic the mechanics required for the NEP-Chem deployable radiators. Initial analysis was performed to determine the impact of using the 200 t LOX/LCH_4 stage of the NEP-Chem design. The dynamic Copernicus mission model includes the option to resized LOX/LCH_4 stage based on the propellant needs of the optimized mission. Fig. 3 shows a comparison of EDM versus interplanetary TOF for either using the common 200 t LOX/LCH4 or right sizing the stage and the EDM if the stage is dropped following TEI or returned to a Near-Rectilinear Halo Orbit (NRHO) for refurbishment and refueling along with the rest of the spacecraft.

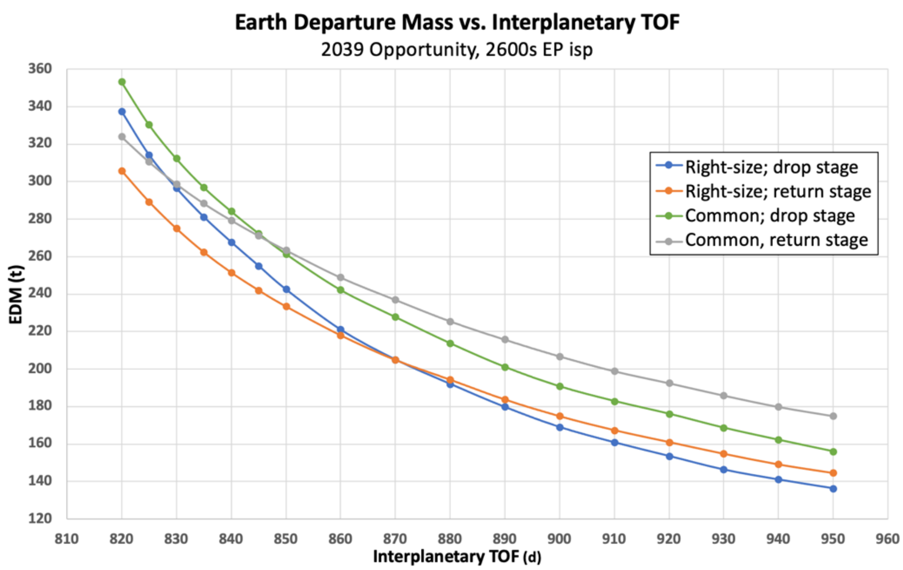

Fig. 3 Trading Stage Size and Ballistic vs. Chemical EOI for 2039 Opportunity

If the chemical stage is jettisoned following TEI, the remainder of the mission will be all-EP, eliminating the possibility of a chemical EOI burn. Fig. 3 shows that lower TOFs favor a chemical EOI while returning the chemical stage at longer TOFs hinders performance. This is likely since at shorter TOFs there is less time for the EP system to impart energy, requiring a larger contribution from the chemical system. Without a chemical system for EOI, additional array power is required to increase the EP thrust to impart the energy necessary to re-capture in LDHEO at Earth, increasing the inert mass of the spacecraft. Jettisoning the inert mass of the spent chemical stage following TEI is favorable at longer interplanetary TOFs where the magnitude of an impulsive EOI burn would be lessened naturally as more of the propulsion can be performed by interplanetary EP thrusting.

Although optimizing the size of the LOX/LCH4 stage decreases EDM at 850 days, the common stage was selected for the final design to enhance NEP-Chem commonality. Additionally, since the EDM when dropping the stage versus returning the stage is approximately equal, the decision was made to return the stage for to allow for possible refurbish and refueling for future missions. At 850 days, the optimal power for all options was ~1-MW.

B. Aggregation Location

LEO to NRHO spiral-out duration was estimated to deliver 240 t to NRHO. The required spiral-out propellant and mass flow rate for different EP specific impulses were used to estimate the thrusting time required to deliver the required 6,100 m/s, a representative spiral-out ΔV. Total transit time was determined by adding a 90% duty cycle and an additional 20% time margin to account for shadowing. The estimated spiral-out times to deliver the fully fuel SEP-Chem vehicle to NRHO is shown in Fig. 4.

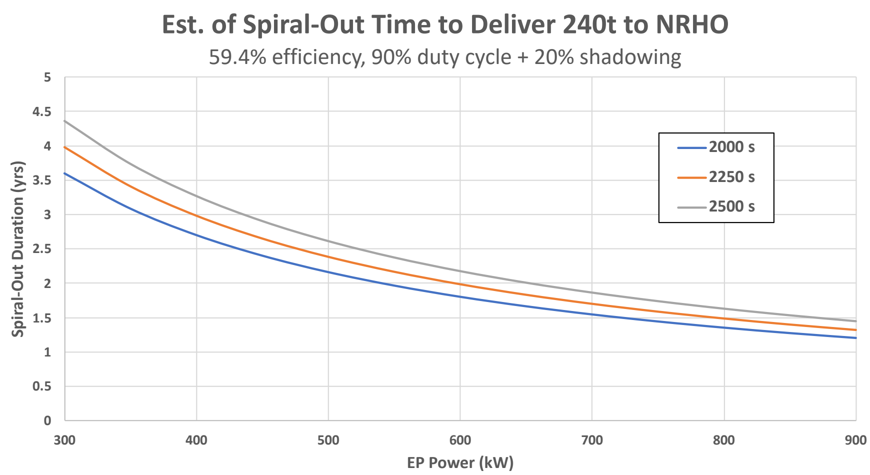

Fig. 4 Estimate of SEP-Chem Spiral-Out Duration from LEO to NRHO

A comparison of benefits and detriments of a LEO versus NRHO aggregation location are provided in Table 2. Although aggregation in LEO would reduce the number of CLVs required to fuel the vehicle, array degradation and the excessive time that would be required to spiral-out ultimately lead to the decision to aggregation in the NRHO. Degradation of 5-10% is estimated to occur during spiral-out due to the radiation experienced while passing through the Van Allen belts. This impact to power before the interplanetary mission begins would result in propellant increases as the power available to the EP system near Mars is further reduced. Additionally, the EP power identifies as near-optimal for the interplanetary phase of the mission, ~400 kW, corresponds to unreasonably long spiral-out durations.

Table 2 Comparison of LEO vs. NRHO Aggregation

LEO Aggregation	NRHO Aggregation
Reduces CLVs for fueling	Additional CLVs for fueling
Assembly with commercial crew assistance	Assembly with crewed Gateway assistance
High EP power required for reasonable spiral out duration	Select EP power to optimize interplanetary performance
Arrays incur 5-10% radiation damage	No additional radiation damage to arrays

C. Identifying Optimal Operation Setpoints and Sensitivity to TOF

Following this initial trade, analysis of the optimal operational power and propulsion setpoints for the 2039 opportunity was done to identify design targets for BOL array power, EP power, and EP specific impulse (Fig. 5).

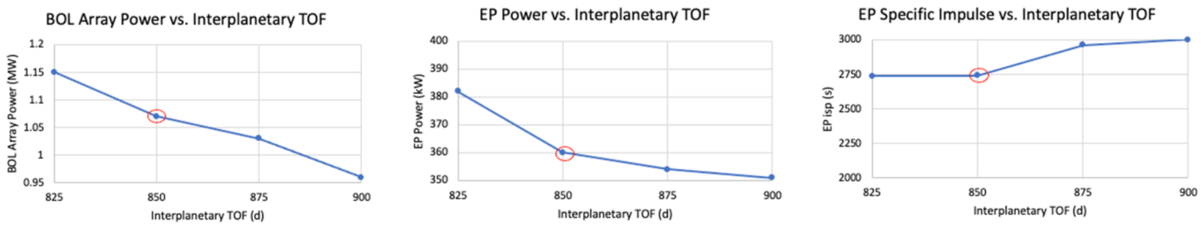

Fig. 5 Optimized Power and Propulsion: Array Power, EP Power, and EP Specific Impulse vs. Interplanetary TOF (2039 Opportunity)

A BOL array power of 1-MW was selected as it was near-optimal for 2039 and further analysis showed good performance at 1-MW for other opportunities. EDM and optimal EP power was assessed for all opportunities between 2039 and 2050 assuming 1-MW array power to help make informed power and propulsion decisions for the final 1-MW design. Ultimately, a 400 kW EP subsystem was selected for the final design. In order to maximize the number of opportunities this SEP-Chem design can perform, the EP subsystem power was sized to capture some of the "borderline" cases from Fig. 7. Although a 400 kW EP subsystem is oversized for 2039 it is near optimal the 2041 borderline opportunity and makes both mission opportunities feasible by keeping the propellant load within the 200 t constraint of the common LOX/LCH4 stage.

Additional trades looking at how EDM, optimal EP power, and optimal EP isp vary for constant array powers between 700 kW and 1 MW over a range of TOFs were completed (Fig. 6). These plots show that as TOF is reduced, increasing the thrust of the EP propulsion system by raising array power and lowering EP isp become more essential to minimize EDM. The Max EP power at lower TOFs is also reduced, reducing the inert mass of the vehicle. Array power and thrust are less essential at longer TOFs when the EP system has sufficient time to impart ΔV. At longer TOFs, EP isp is increased which results in more efficient EP propulsion.

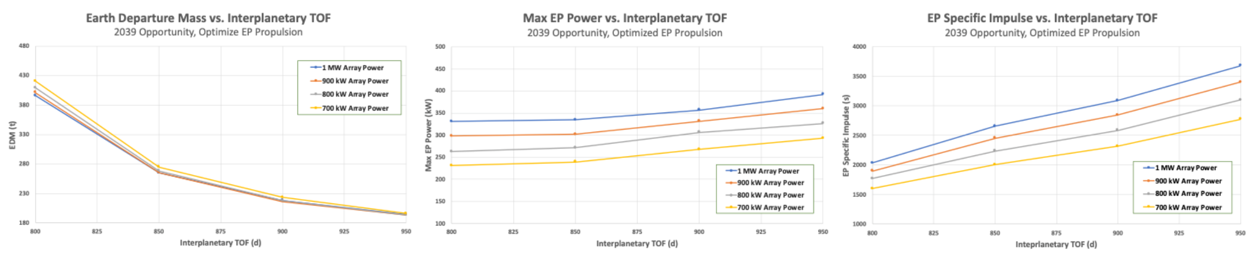

Fig. 6 Optimized EP Propulsion vs. Interplanetary TOF for Constant Array Power

D. 1-MW SEP-Chem Performance Across Opportunities

Fig. 7 shows that a 1-MW spacecraft with a fully optimized EP subsystem can perform most opportunities between 2039 and 2050, within the 200t chemical propellant limit of the common LOX/LCH4 stage except for 2043. Analysis looking at methods to make 2043 a feasible SEP-Chem opportunity included extending TOF and adding an additional LOX/LCH4 booster stage for the trans-Mars injection (TMI) burn. Alternatively, if the SEP-Chem spacecraft is a technological stepping stone to a hybrid nuclear spacecraft, more difficult opportunities such as 2043 could be excluded from the SEP-Chem tradespace and reserved for future nuclear-enabled missions.

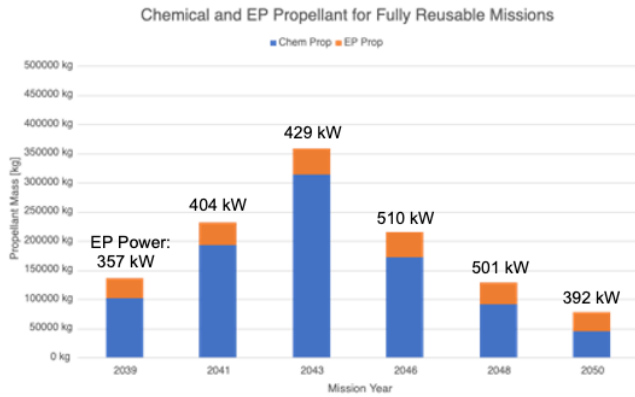

Fig. 7 Combined Propellant Load (Optimal EP Power, 1-MW/2600s)

Making 2043 feasible for the 1-MW SEP-Chem vehicle will require a combination of added interplanetary TOF and additional LOX/LCH_4 since the current configuration does not produce the EP thrust required to complete the reference mission within the 200 t capacity of the chemical stage. Table 3 shows a comparison of the mission options considered for how to accommodate the additional chemical propellant required for the 2043 opportunity. If no additional chemical storage was added, extending the interplanetary TOF from 850 days to 917 days reduces the chemical propellant load to within the 200 t capacity of the LOX/LCH_4 stage. Adding either a 80 t booster or an additional 200 t LOX/LCH_4 stage could reduce the interplanetary TOF closer to the 850 day target but the added inert mass of those elements also increased the propellant load.

Table 3 Comparison of Mission Options for 2043

	LOX/LCH_4	*Xe*	*Interplanetary TOF*
2039 Reference	134 t	46 t	850 d
2043 @850 d	314 t	45 t	850 d
2043 Nominal	200 t	47 t	917 d
2043 + 80 t Booster	280 t	49 t	894 d
2043 + 200 t Stage	400 t	50 t	871 d

VI. Reference Missions

The SAC22 moderate duration reference mission used to compare transportation architectures is an 850-day Earth-Mars roundtrip mission with a 50 sol stay in Mars orbit. A crew of 4 will be sent during the 2039 opportunity for the roundtrip mission with 2 crew descending and ascending from a single Mars surface landing site at 35º latitude.

This design assumed NRHO would be used for assembly of the SEP-Chem spacecraft. The chemical stage launches aboard an SLS and follows a Ballistic Lunar Transit (BLT) trajectory to insert into the NRHO. A series of Super-Heavy launchers deliver the LOX/LCH_4 required for the mission to the chemical stage. A second SLS launches the SEP Module which also follows a BLT to insert into the NRHO and rendezvous with the fueled chemical stage. Additional Super Heavy launches deliver xenon to the SEP-Module. Once fully fueled, the SEP-Chem vehicle departs the NRHO using a BLT to insert into LDHEO following which the crew will arrive in Orion and transfer into the SEP-Chem vehicle. The crewed SEP-Chem vehicle will loiter in the LDHEO awaiting the opening of the launch window at which point the chemical propulsion system will perform TMI to begin the interplanetary phase of the mission. The reference trajectory for the hybrid SEP-Chem vehicle is shown in Fig. 8.

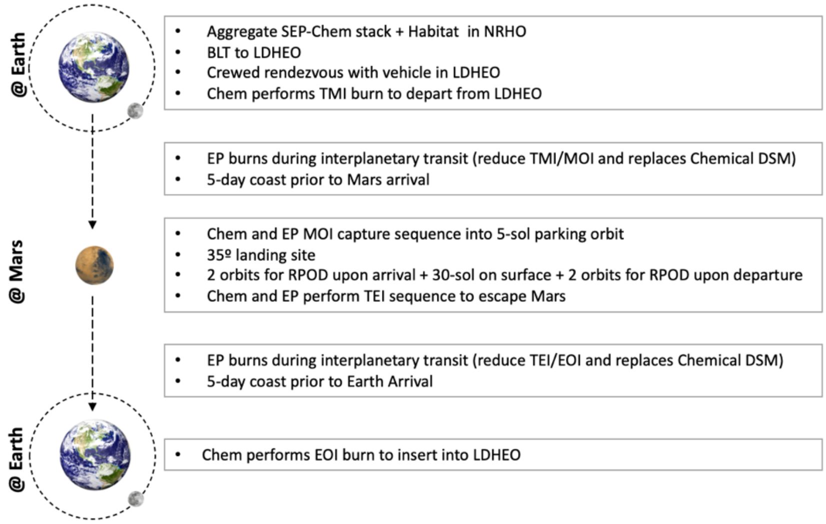

Fig. 8 SEP-Chem Earth-Mars Crewed Mission Overview and Assumptions

Reference trajectories for 2039 and 2041 were generated for the SEP-Chem vehicle described in Section IV. Table 4 shows a comparison of the propellant required to complete each reference mission. Details of the 2039 and 2041 reference trajectories are provided in the following subsections.

Table 4 Comparison of 2039 and 2041 Reference Missions

	2039 850 d	***2041 850 d***
Array Power (MW)	1.0	1.0
Power to EP (kW)	400	400
Isp (s)	2380	2380
Mars Orbit Stay Time (d)	51.5	51.5
Earth Departure Mass (t)	289	398
Inert Mass at Earth Return (t)	97	97
Usable Interplanetary Xenon (t)	50	53
Total Interplanetary LOX/LCH$_4$ (t)	134	242

A. 2039 Reference Mission

NRHO is used for assembly of the SEP-Chem spacecraft. The chemical stage launches aboard an SLS and follows a BLT trajectory to insert into the NRHO. A series of five Super-Heavy launches deliver the LOX/LCH$_4$ required for the 2039 mission to the chemical stage. A second SLS launches the SEP Module which also follows a BLT to insert into the NRHO and rendezvous with the fueled chemical stage. Two additional Super Heavy launches deliver xenon to the SEP Module. Once fully fueled, the SEP-Chem vehicle departs the NRHO using a BLT to insert into LDHEO following which the crew will arrive in Orion and transfer into the SEP-Chem spacecraft. The crewed SEP-Chem vehicle will loiter in the LDHEO awaiting the opening of the launch window at which point the chemical propulsion system will perform TMI to begin the interplanetary phase of the mission.

The SEP-Chem vehicle departs Earth on October 7, 2039. During the 269 day transit the highly efficient low-thrust propulsion system provides sustained acceleration to reduce the magnitude of the chemical departure and capture maneuvers. The vehicle inserts into the 5-sol Mars parking orbit on June 21, 2040. The SEP-Chem vehicle spends 2 orbits performing RPOD activities with the lander prior to descent. After successfully rendezvousing with the lander the crew descends to the surface for 30 sols to complete surface operations. Another two orbits following ascent are used to complete RPOD operations between the ascent vehicle and the SEP-Chem vehicle. The crewed

SEP-Chem vehicle departs Mars orbit on August 11, 2040 and transits for 530 days before re-inserting into LDHEO. An overview of the 2039 interplanetary trajectory and the ΔV history is shown in Fig. 9.

Mission ΔVs	
TMI	736.9 m/s
EP-1	443.8 m/s
EP-2	348.6 m/s
EP-3	693.1 m/s
MOI	571.9 m/s
EP-4	137.9 m/s
Mars Stay	
Re-orientation	34.2 m/s
EP-6	29.3 m/s
TEI	569.4 m/s
EP-7	0.0 m/s
EP-8	1324.6 m/s
EP-9	2782.3 m/s
EP-10	492.9 m/s
EOI	579.2 m/s

Total EP ΔV: 6284.6 m/s
Total Chem ΔV: 2457.4 m/s

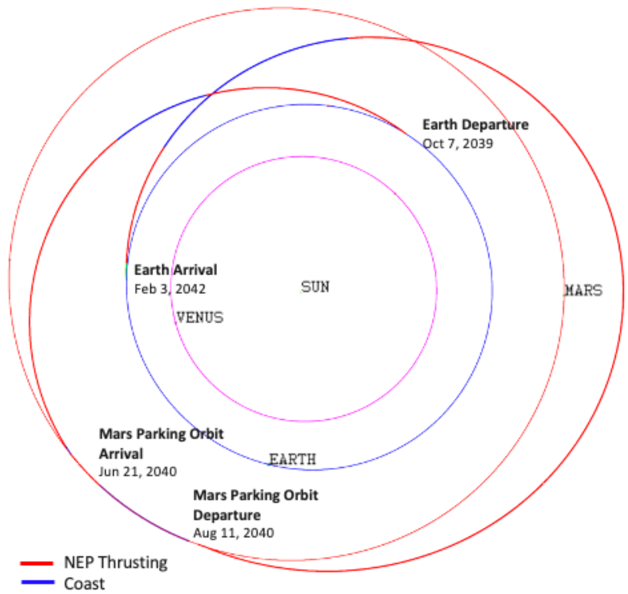

Fig. 9 2039 1-MW/400 kW/2380s Reference Mission

B. 2041 Reference Mission

While 2039 was used as the reference opportunity for the 1-MW SEP-Chem design, a second reference mission was developed for the 2041 opportunity. This mission utilizes the same 850-day mission assumptions and vehicle design as the 2039 reference. Fig. 10, shown below, details the reference mission trajectory and ΔV history for the 2041 opportunity.

Mission ΔVs	
TMI	907.1 m/s
EP-1	5.4 m/s
EP-2	425.3 m/s
EP-3	804.3 m/s
MOI	1337.2 m/s
EP-4	74 m/s
Mars Stay	
Re-orientation	42.7 m/s
EP-5	33.7 m/s
TEI	628.5 m/s
EP-6	0 m/s
EP-7	1510 m/s
EP-8	2724 m/s
EP-9	210.7 m/s
EOI	786.7 m/s

Total EP ΔV: 5787.4 m/s
Total Chem ΔV: 3659.5 m/s

Fig. 10 2041 1-MW/400 kW/2380s Reference Mission

In contrast with the 2039 reference, the 2041 reference uses less EP propellant and more chemical propellant. The total ΔV in 2041 is slightly higher than in 2039, with 9446.9 m/s of ΔV required as opposed to 2039's 8742 m/s. The spacecraft departs Earth on November 17, 2041 with an Earth departure mass of 398 t. Arrival at Mars occurs on June 11, 2042, yielding an outbound time-of-flight of 236.5 days. After staying at Mars for 51.5 days, the spacecraft departs on August 31, 2042. Finally, the spacecraft arrives back at Earth on March 16, 2044 after an inbound time-of-flight of 563 days.

Because the preliminary trades done for this study were analyzed for the 2039 reference mission, additional trades were performed for the 2041 reference mission. These trades are in line with those performed for 2039, comparing results for jettisoning the chemical stage following TEI or retaining the chemical stage to perform EOI and refurbishment and refueling after mission completion. For 2041, jettisoning the chemical stage before returning to Earth results in a significantly higher EDM than returning with the stage and performing an impulsive EOI. For a case with 1 MW array power, optimized max EP power, and an EP isp of 2600 s, EDM for the jettisoned option is 667 t compared to the 331 t EDM if the stage is retained for EOI. Additionally, maximum EP power increases in the jettisoned chemical stage scenario to ~675 kW to off-set the loss of an impulsive EOI with added EP output.

VII. Summary

The described spacecraft concept combines two propulsion technologies, LOX/LCH_4 chemical engines, and SEP. Chemical engines are used for major maneuvers within Earth and Mars' gravity wells, such as departure and capture, while SEP is used during interplanetary transit for sustained acceleration. This hybrid approach optimizes the use of both propulsion systems.

The shift towards shorter-duration crewed Mars missions to minimize the time spent away from Earth comes with higher mission ΔV requirements, impacting the design of the power and propulsion subsystems. Although other hybrid propulsion systems have been considered for non-conjunction crewed mission to Mars, the anticipated solar array power requirements necessary to achieve an 850-day roundtrip mission were considered a nonstarter. Spacecraft with low-thrust propulsion systems benefit from longer transit durations, allowing the EP system to contribute more to overall propulsion. As mission duration decreases, power requirements must increase to maintain EP thrust to minimize chemical propellant load.

Characteristics of the SEP-Chem power and propulsion subsystems, including array power, maximum thruster power, and EP-specific impulsive were optimization variables in the mission model. Parametric equations, which were derived from conceptual designs for conjunction-class SEP-Chem and opposition-class NEP-Chem spacecraft, used the value of these parameters as well as others to estimate the mass of the SEP Module. By including these subsystem parameters and parametric sizing in the mission model, preliminary analysis was able to identify optimal operational power and propulsion setpoints. Designing around these optimal setpoints ensure excess mass, either inert or propellant, wasn't unnecessarily added through over or under sizing the power and propulsion subsystems.

The SEP-Chem analysis and design completed during SAC22 aimed to create a feasible design while minimizing EDM for the 2039 reference mission. The SEP-Chem reference mission for 2039 provided in Section VI was compared against other transportation systems during NASA's Exploration Systems Development Mission Directorate's (ESDMD) first Architecture Concept Review (ARC22) [10]. This comparison showed that SEP-Chem, NEP-Chem, and NTP vehicles all have an EDM of approximately 300 t for the moderate 850-day transit duration. This comparison shows that a 1 MW SEP-Chem vehicle provides a feasible non-nuclear alternative for moderate duration crewed Mars missions or serve as an evolutionary path from the current high powered SEP spacecrafts being developed and a future nuclear enabled hybrid vehicle.

References

[1] *Moon to Mars Objectives*, NASA September, 2022.

[2] Mercer, C. R., Oleson, S. R., Drake, B., "A Combined Solar Electric and Storable Chemical Propulsion Vehicle for Piloted Mars Missions," NASA TM-2014-218093.

[3] Merrill, R. G., Chai, P. R., Qu, M., "An Integrated Hybrid Transportation Architecture for Human Mars Expeditions," AIAA Space, 2015.

[4] Rucker, M. A., "NASA's Strategic Analysis Cycle 2021 (SAC21) Human Mars Architecture," NASA ESDMD Mars Architecture Team 2022 IEEE Aerospace Conference, Bik Sky, March 7, 2022.

[5] Connolly, J. F., "The Moon as a Stepping Stone to Human Mars Missions,", IAC-18,A3,1,3,x43905.

[6] Oleson, S., Burke, L., Turnbull, E., Klefman, B., Kamhawi, H., Faller, B., Johnson, W., Lantz, N., Dosa, B., Schmid, C., Zoloty, Z., Smith, D., Packard, T., Colozza, A., Gyekenyesi, J., Fittje, J., "A 1 MW Solar Electric and Chemical Propulsion Vehicle for Piloted Mars Opposition Class Missions," ASCEND, 2023.

[7] Ocampo, C., Senent, J., "The Design and Development of Copernicus: A Comprehensive Trajectory Design and Optimization System," IAC-06-C1.4.04, 2006.

[8] Burke, L. M., McCarty, S. L., Oleson, S. R., “Combined Nuclear Electric and Chemical Propulsion for Crewed Mars Opposition Missions,” NETS, 2022.
[9] Oleson, S. R., “Compass Final Report: Nuclear Electric Propulsion (NEP)-Chemical Vehicle 1.2,” NASA TM-20210017131
[10] *Mars Transportation,* NASA ESDMD Architecture Concept Review White Paper, 2022.