Human Mars Mission In-Space Transportation Sensitivity for Nuclear Electric / Chemical Hybrid Propulsion

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NASA's Human Exploration and Operation Mission Directorate is continuing to study different concepts and options to field human Mars missions as part of NASA's Moon2Mars directive. In this study, an update to the Hybrid propulsion system was established with the introduction of nuclear electric propulsion system to replace the solar electric propulsion system in an effort to understand the potential impact of a shorter mission to Mars. For crewed missions to Mars, the transportation system sizing is highly dependent on the type of mission and the mission duration. An integrated trajectory analysis capability has been developed and updated to enable this investigation. Longer duration missions may utilize higher efficiency low thrust propulsion system more, but would require higher payload mass due to increased crew logistics loading and habitation volume. Conversely, shorter duration missions may have lower payload mass, but will require significant increase to propulsion system performance and/or overall system mass. An integrated trajectory optimization framework that was previously developed was recently updated to address deficiencies and to enable additional capabilities to perform large design space exploration. Using the updated framework, an overall integrated design trade space is defined in this paper to investigate the tradeoff between these scenarios to illuminate the optimality of the transportation system option from a mass perspective. The sensitivity analysis developed in this study will be crucial to understanding the Mars mission design trade space for crewed Mars missions, and will help inform design decisions and investment strategies.

Nomenclature

CPU	Central Processing Unit
ΔV	Velocity Change
EME	Earth-Mars-Earth
LDHEO	Lunar Distant High Earth Orbit
LGA	Lunar Gravity Assist
NDS	NASA Docking System
NEP	Nuclear Electric Propulsion
SAC21	Strategic Analysis Cycle 2021
SEP	Solar Electric Propulsion
SLS	Space Launch System

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I. Introduction

NASA's Mars Architecture Team continues the agency's efforts to study and refine the nation's plan to field a sustainable human Mars campaign as part of NASA's Moon2Mars directive. Building upon the success of the Design Reference Architecture, Evolvable Mars Campaign, and the Mars Study Capability Team, the group is further developing capabilities to improve the fidelity of the Mars campaign and to continue exploring the design trade space to assess the impact of technology investments and architecture decisions for missions to Mars. Many different mission design concepts have been studied and proposed over the past three decades[1–3], all of these proposed concepts assumed minimum energy class missions to Mars with roundtrip mission time upwards of 3 years. This represents a significant leap in the current understanding of the impact on human health for extended exposure to microgravity environment, given the longest continuous crew exposure to microgravity is just over one year. This drives the need for understanding of alternate mission operation modes for human missions to Mars. This paper investigates the in-space transportation sensitivity to mission duration and payload mass for a Nuclear Electric / Chemical Hybrid Propulsion system.

For roundtrip missions to Mars, there are typically two types of trajectories that are available. *Conjunction class trajectory*, alternatively referred to as "Long-Stay Class", are a class of low energy round-trip Mars missions where total mission duration and the time at Mars, from arrival to departure, are allowed to vary. Conjunction-class missions minimize the required change in velocity (ΔV) and therefore energy, and are typically longer than other mission classes with a long stay time at Mars (in orbit or on the surface) to await for optimal Earth return timing. Conjunction class trajectories require the Earth and Mars to be in proper relative alignment, thus opportunities occur roughly 26 months apart, with small variation in energies across mission opportunities. These minimum energy type trajectories have typical mission duration in the 900 - 1200 day range, with Mars orbit stay time in the 300 - 500 day range.

Opposition Class Trajectory, alternatively referred to as "Short-Stay Class", are a class of high energy, fast round-trip Mars missions where the overall mission duration and time at Mars are constrained to be short. Opposition-class missions require large change in velocity (ΔV) and therefore energy, are typically constrained to a short stay time at Mars, and require a flyby of Venus either on the outbound or the return leg to help keep the roundtrip change in velocity to reasonable level. Opposition-class trajectories exist essentially every year, but the energy required to complete the roundtrip mission can vary significantly across different mission opportunities. These high energy class mission have wide range in the mission duration. As the mission duration is reduced, the energy required to achieve the roundtrip mission increases exponentially. Mars stay time is also a significant driver to the overall energy required. Because the total mission duration is constrained to be short, longer Mars stay time reduces the time available for the transit between Earth and Mars, requiring significantly more energy to accelerate and decelerate the spacecraft to cover the same distance in shorter amount of time. For human Mars mission considerations, the Mars stay time directly correlates to time available to perform Mars surface operation for the crew. Typical fast opposition mission are have total mission duration of 700-800 days, with Mars orbit stay time in the range of 30 - 60 days.

For crewed missions to Mars, the transportation system sizing is highly dependent on the type of mission and the mission duration. An integrated trajectory analysis capability has been developed and updated to enable this investigation. Longer duration missions may utilize higher efficiency low thrust propulsion system more, but would require higher payload mass due to increased crew logistics loading and habitation volume. Conversely, shorter duration missions may have lower payload mass, but will require significant increase to propulsion system performance and/or overall system mass. An overall integrated design trade space is defined in this paper to investigate the tradeoff between these scenarios to illuminate the optimality of the transportation system option from a mass perspective. The sensitivity analysis developed in this study will be crucial to understanding the Mars mission design trade space for crewed Mars missions, and will help inform design decisions and investment strategies.

II. Hybrid Electric/Chemical Propulsion System

NASA has been investigating and analyzing hybrid electric / chemical propulsion systems to enable human missions to Mars[4–6]. By combining chemical and solar-electric propulsion (SEP)[7, 8] into a single spacecraft and applying each where it is most effective, the Hybrid architecture enables a series of Mars trajectories that are more fuel efficient than an all chemical propulsion architecture, without significant increases to trip time. Previous efforts focused on minimum energy class missions and utilized solar electric propulsion systems[9, 10] as one half of the hybrid propulsion. To enable Mars missions with shorter mission duration, significant increase to the power of the electric propulsion system is needed to keep the overall system mass down. Power level for the solar electric propulsion system was limited to less than 1 mega-watt due to the integration challenges associated with increasingly large solar arrays. An alternate

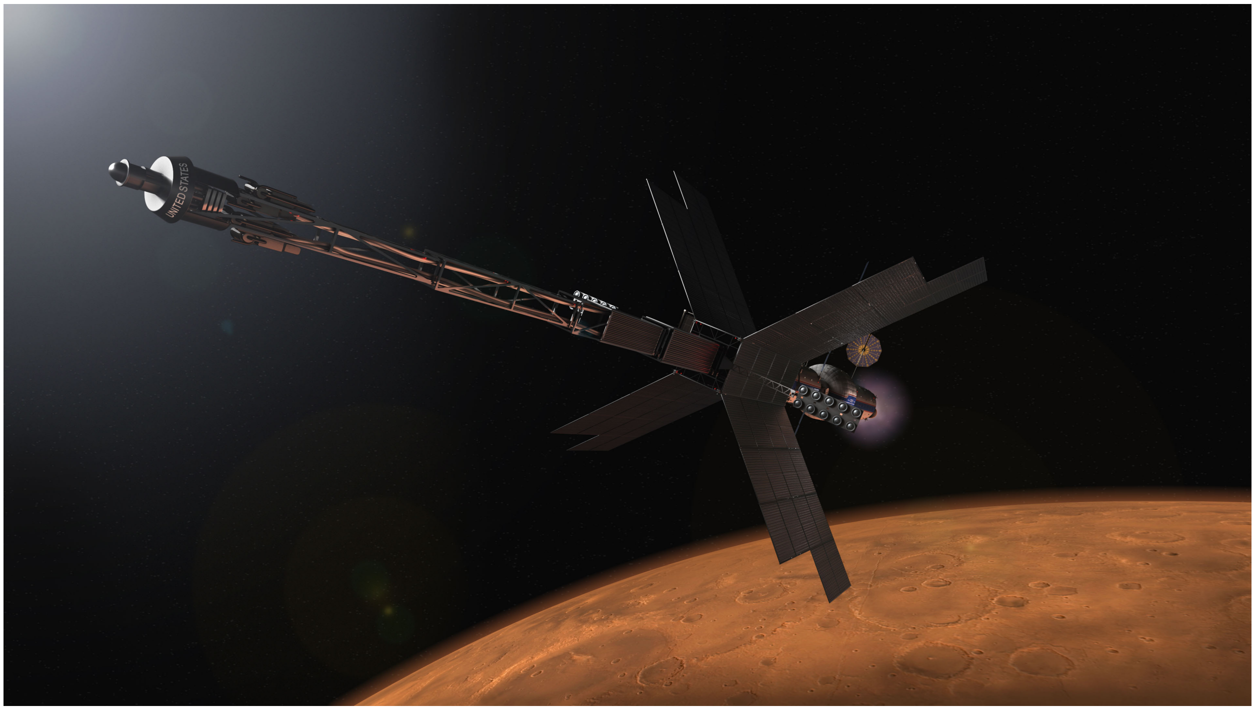

Fig. 1 Concept Rendering of a Nuclear Electric / Chemical Hybrid Propulsion System for Human Mars Exploration Missions

power source for electric thrusters is needed to enable large scale electric propulsion system for shorter Mars missions.

Nuclear Electric Propulsion systems have been studied and proposed in the past for use for planetary exploration missions[11] and cargo delivery for Mars missions[12]. Using a nuclear system to power the electric thrusters compared to solar arrays has the benefit of no power degradation as the spacecraft moves away from the Sun, however it does come at a cost of significantly heavier system mass and more complex system overall. NASA Glenn Research Center's COMPASS concurrent engineering team developed a concept for a Nuclear Electric / Chemical Hybrid Propulsion[13] system for human Mars missions. The vehicle concept builds upon the design experience from previous nuclear electric propulsion system studies, and implemented updated constraints on the vehicle dimensions and mass. The results is a vehicle concept that has a separate Nuclear Electric propulsion element and chemical propulsion element that are integrated together with the deep space habitation[14] system to support the roundtrip mission to Mars.

A reference Nuclear Electric / Chemical Hybrid Propulsion system has been defined for NASA's Human Exploration Operation and Mission Directorate's Strategic Analysis Cycle 21 (SAC21). The reference propulsion system is depicted in an artist rendering in Figure 1 and expands upon the previous work by the COMPASS team and an internal NASA study on Mars Transportation. The reference propulsion system is similar to the previously published concept[13] but with further refinement. There are four total elements that make up the integrated transportation stack, three transportation elements and one habitation element. The habitation element assumption remains similar to previous studies and analysis cycles[4, 6, 15] with only minor updates to the habitation system dry mass. For the SAC21 analysis cycle, the habitation system is assumed to have a dry mass of 26,500 kg. The crew logistics and spares required to support the roundtrip mission to Mars is estimated as a function of the overall mission duration, with roughly 21,000 kg of logistics and spare required to support a nominal 850 days roundtrip mission with a 40 day contingency.

There are three propulsion system elements: the Nuclear Electric Propulsion (NEP) element, the Chemical Propulsion element, and the Xenon Interstage element. The NEP element consists of all of the major element to support the nuclear electric systems, including the nuclear reactor, energy conversion system, heat dissipation radiators, power processing units, electric thrusters, and one of the three xenon tanks that supply the propellant for the integrated vehicle. For SAC21, the NEP system, shown in Figure 2 consists of a 1.8 Megawatt-electric low enriched uranium reactor, with four 500 kilowatt brayton convertors, and 2500m^2 of deployable radiators to dissipate the waste heat. For the electric propulsion system, the element carries eighteen 100 kilowatt-class hall thrusters[7, 8] on two separate booms with

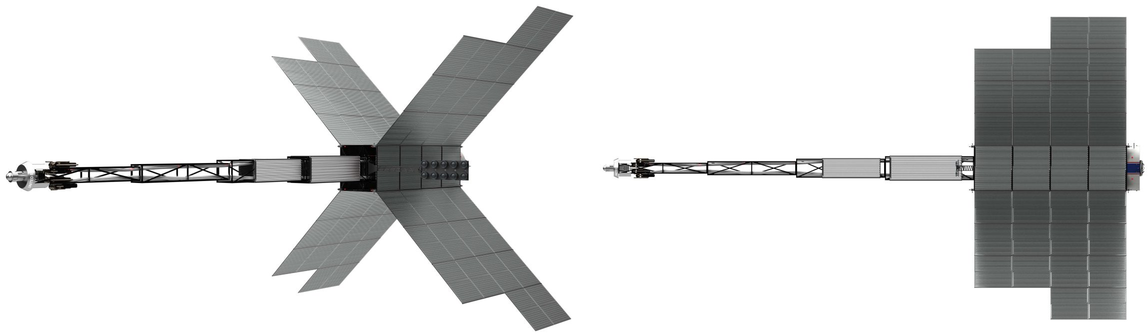

Fig. 2 Concept Rendering of the SAC21 Nuclear Electric Propulsion Element

Fig. 3 Concept Rendering of the SAC21 Xenon Interstage Element

nine thrusters (eight active and one spare) per boom. As seen in Figure 2, the deployable booms provides separation between the reactor, thrusters, and the electronics. The central truss system provides the backbone for the deployable radiator and boom as well as houseing the electronics and the xenon tanks within. Finally, deployable solar arrays are utilized for commissioning of the spacecraft and autonomous rendezvous and docking. The element is designed to be launched without xenon propellant on an Space Launch System (SLS) with on-orbit refueling of xenon to reach operational capacity.

The Xenon Interstage, shown in Figure 3, element's primary function is to serve as the free flying tanker to hold two of the three xenon tanks for the integrated vehicle, with the third tank embedded inside the NEP element. The Xenon Interstage element is designed to be launched on a commercial launch vehicle with large diameter payload fairing. It houses two 4.5 meter diameter composite over-wrapped pressure vessel storage tanks that can store roughly 42t of xenon each, at ambient 300 kelvin temperature. The element has solar arrays and batteries for commissioning and for autonomous rendezvous and docking operation. It has storable reaction control systems to perform the maneuvers necessary after launch vehicle injections, and houses two NASA Docking System[16] (NDS) to connect the NEP element on one side and the habitation system on the other. The element is designed to be launched partially fueled with xenon in its tanks, with additional propellant resupplied in orbit to reach operational capacity.

The Chemical Propulsion element, shown in Figure 4, is a liquid oxygen/liquid methane chemical propulsion system similar to existing launch vehicle upper stages. It has internal common bulkhead propellant tanks that can carry up to 200t of propellant, with appropriate insulation and cryocoolers to keep the two propellants at cryogenic temperatures. It has solar arrays and batteries for commissioning and for autonomous rendezvous and docking operations. It utilizes storable reaction control systems to perform post launch injection maneuvers. For the main propulsion system, the element utilizes three RL-10 class chemical engines that have been converted to use oxygen and methane as its

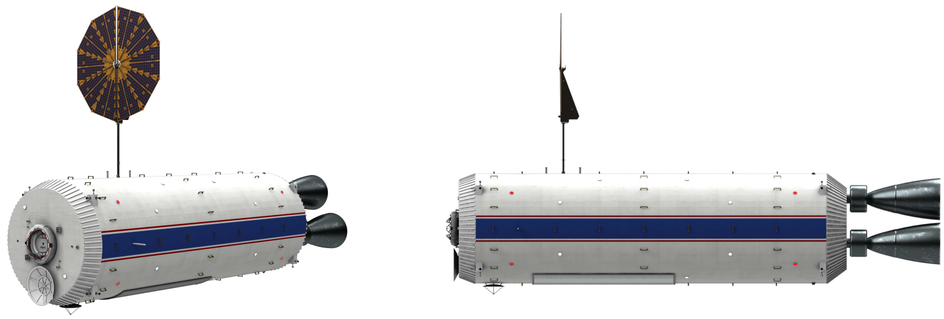

Fig. 4 Concept Rendering of the SAC21 Chemical Propulsion Element

propellant. It houses two NDS, one active NDS for connection to the habitation system (or other cargo if the system is utilized for cargo delivery) and one passive NDS for on-orbit refueling. The element is designed to be launched mostly empty on a SLS with propellant resupply in orbit.

For the integrated mission analysis in this study, a parametric model of the three propulsion system element was created using a detailed bottoms-up, model as anchor points. The detailed model of the propulsion system was created with assistance from the GRC COMPASS team using the LaRC EXAMINE[17] modeling framework. The parametric model that was created for this study allows for sizing of each of the system based primarily on the propellant demand from the trajectory optimization, which will be discuses in detail in the following section. Due to the nature of the low thrust trajectory optimization, the mass sizing of the element and trajectory optimization has circular dependency relationship and must be solved concurrently.

For the current SAC21 study reference, the integrated mission concept of operations is shown in Figure 5. The individual elements are launched on separate launch vehicles to high Earth orbit, then boosted to cis-lunar space for aggregation into the integrated Mars transit vehicle. Propellant resupply operation also occurs in cis-lunar space, as the elements are launched mostly empty. The habitation module is also outfitted in cis-lunar space with the necessary logistics and spares for the crewed mission to Mars in cis-lunar space. Once the integrated vehicle has been fully provisioned, the vehicle performs a low energy transit into a lunar distant high Earth orbit (LDHEO) that's roughly 400 x 400,000 km in altitude. The mission crew then launches on an Orion vehicle to meet the transport in LDHEO, where final checkout of the integrated vehicle is performed by the crew prior to the Earth departure maneuver. Similar to previous mission concepts[4], the vehicle has the options to perform a low energy lunar gravity assist (LGA) Earth departure maneuver if the trajectory offers an opportunity to do so. Performing this maneuver increases the mission duration by 30 days due to phasing and targeting requirement of the LGA maneuver. After Earth departure, the nuclear electric propulsion system is utilized during the transit to continuously thrust to increase the vehicle's energy to target a Mars rendezvous. A chemical burn is performed to capture into Mars 5-sol parking orbit, where the pre-deployed lander system will rendezvous with the transport to carry the crew to the surface of Mars. For SAC21 study reference, a nominal surface mission of 30 days is assumed. The Mars transport spends a minimum of 50 days in Mars orbit to account for the 30 days of Mars surface mission and the necessary time required for rendezvous between the lander, ascent stage, and the transport, and the time required for the crew to transit to and from the surface. After the crew returns to the transport from the surface, the vehicle performs chemical maneuver to depart Mars, uses the NEP system during the transit home, and finally arrives at Earth using either a direct chemical maneuvers or a combination of chemical and LGA maneuver. A second Orion is launched to rendezvous with the transport in the LDHEO to return the crew to Earth surface, while the transport returns to cis-lunar space for potential reuse.

III. Integrated Mission Design Analysis Framework

Solving the complete end-to-end trajectory for human Mars missions with the hybrid transportation system is more complex than the trajectories for traditional chemical transportation system. Typically, the trajectory optimization of a traditional all chemical transportation system is independent of the vehicle sizing optimization of the transportation vehicle. For the hybrid system, because the thrust delivered by the electric propulsion system is so low, the trajectory optimization is highly coupled with the vehicle sizing and optimization. This requires the trajectory optimization to be solved simultaneously with the vehicle sizing and closure. Previous publication[18] details the integrated

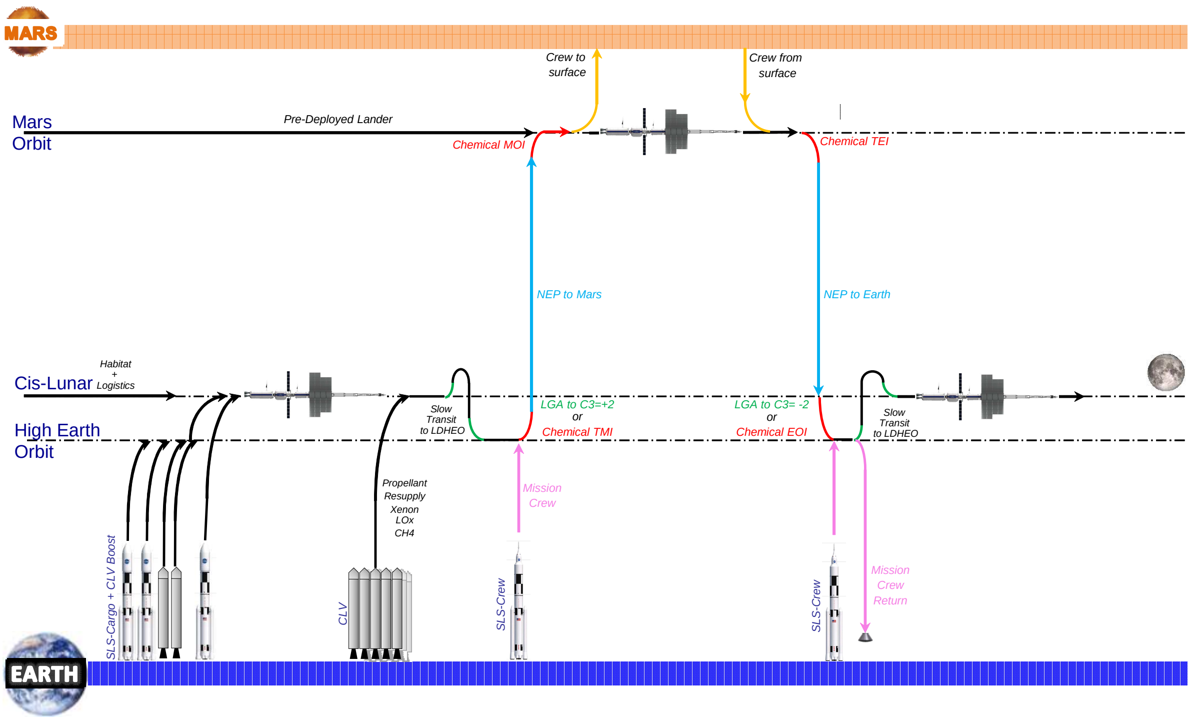

Fig. 5 Mission Concept of Operation for a Crewed Mission to Mars using Nuclear Electric / Chemical Hybrid Propulsion System

analysis method developed to solve this complex problem. Using the Copernicus Trajectory Design and Optimization System[19] and a series of internally developed plug-ins, the end-to-end trajectory can be modeled and coupled with system sizing to allow Copernicus to perform optimization of the trajectory. Since the publication, Copernicus has moved to a python based distribution, which allowed for opportunities to develop additional scripts to streamline the analysis process.

The previous integrated mission analysis framework relied on internally developed scripts and MATLAB's parallel computing toolbox to perform the analysis[18]. This significantly improved upon the previous manual method of analyzing and converging cases, reducing computational time required by an order of magnitude or more. Despite its success, significant deficiencies still exist for the previously developed framework. The analysis requires significant file system manipulation operation, with copying, renaming, and manipulating thousands of files when running a large batched case. MATLAB's internal file manipulation function to perform these tasks is a significant bottleneck for the framework. In addition, from a computing resource perspective, the overhead for the MATLAB software itself consumes resources that could otherwise be utilized for the main computation. Finally, there are significant limitations in the MATLAB's parallel computing toolbox in the way the framework was implemented. The group batching of the cases meant that blocks of cases would be assigned to various cores, and with high variability in the convergence time for the cases, this meant significant core time was wasted waiting on group batch of cases to be completed on other cores.

With the Copernicus software moving to a Python distribution, it was natural to redevelop the analysis framework to utilize the new distribution on an open source platform. Several portion of the analysis framework were easy to translate to Python as it mainly dealt with file managements and manipulation. Here the python framework showed significant improvement to the previous method. To generate a batch of cases for Copernicus to optimize, the framework begins with a series of template files, which are modified based on the desired input variables for the specific run. This newly updated set of files is then renamed and organized appropriately for easy identification and processing by Copernicus and by post-processing scripts. The change to python from the MATLAB script to handle file manipulation resulted in several orders of magnitude increase in productivity on the front end of framework. To generate all of the files required for a sample 4,200 case trade space exploration, the MATLAB framework took nearly four hours to complete, while the Python script completed the task in just under three minutes. This reduction is likely due to the inefficiency in the

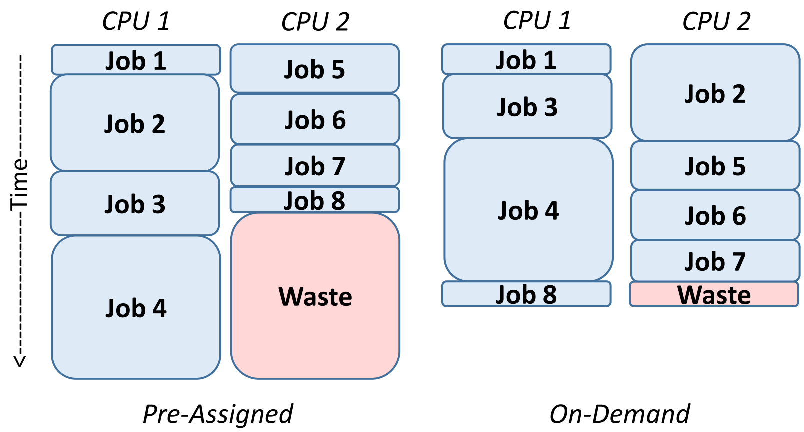

Fig. 6 Example Performance Comparison Between Pre-Assigned vs On-Demand Case/Worker Assignment Framework

MATLAB scripts itself, but nonetheless, the push for the new framework yielded significant improvement in the front end of the overall integrated analysis loop.

The second major piece of the analysis framework that required updating is in the batch processing of the Copernicus optimization. Copernicus has some built in functions for performing batched runs, however, these are limited to specific set of conditions and trades. To evaluate the wide mission trade space for human Mars mission using the hybrid propulsion system, an alternate solution was required. The previous framework utilized the MATLAB parallel processing toolbox to run cases in batches[18], primarily using the "parfor" function to batch out the runs to different CPU workers. The biggest challenge with this method is that the function pre-assigns each CPU worker a set number of cases to process, and the CPU workers will work until their assigned batch is complete. Once they are complete, those works then become idle. This framework work well for tasks with relatively similar completion time, but for low-thrust trajectory optimization, each case run time can vary drastically. This resulted in significant inefficiencies as the idle workers cannot pick up the cases from other workers.

For implementation in python and to improve on the inefficiencies within the previous framework, the team utilized the open sources GNU Parallel[20] to handle all of the batch processing in the updated analysis framework. GNU Parallel in this framework helps facilitates both the generation of the Copernicus input decks and execution of the Copernicus optimization routine. For the input decks generation, the already updated framework can be further improved by having multiple input deck specification files that allows for batching of the input deck generation. The framework utilizes an open standard file and data exchange format called JavaScript Object Notation (JSON)[21]. The new Copernicus framework also already uses JSON as its primary file and data exchange format, and JSON works well with python scripts. The updated trajectory analysis architecture uses JSON input files to define the input variables of interest and provide specifications on the desired the range and discretization of the variables. The scripts then takes the inputs and generate the Copernicus input decks using the defined templates, and GNU parallel allow the scripts to handle multiple input JSON files using parallel processes.

Finally, the new framework utilizes GNU parallel to batch out the cases to different central processing unit (CPU) workers for Copernicus to iterate and optimize. Instead of pre-allocating the cases to each workers, GNU parallel utilizes an on-demand structure to facilitate the worker assignment., reducing waste time significantly. Figure 6 shows an example of this effect, depicting the savings in the waste time and the how the updated framework can provide significant time savings overall. Additionally, the computing and memory overhead of the python based scripts is significantly lower than than the previous MATLAB-based scripts, which further improves the performance of the overall process.

IV. Reference Mars Mission Sensitivity Study

Using the developed framework, a series of mission performance sensitives were performed to understand the performance of the current SAC21 reference propulsion system. For these mission design sensitivities, the payload for the transportation system changes based on the mission duration, mostly in the form of the logistics and spares that are

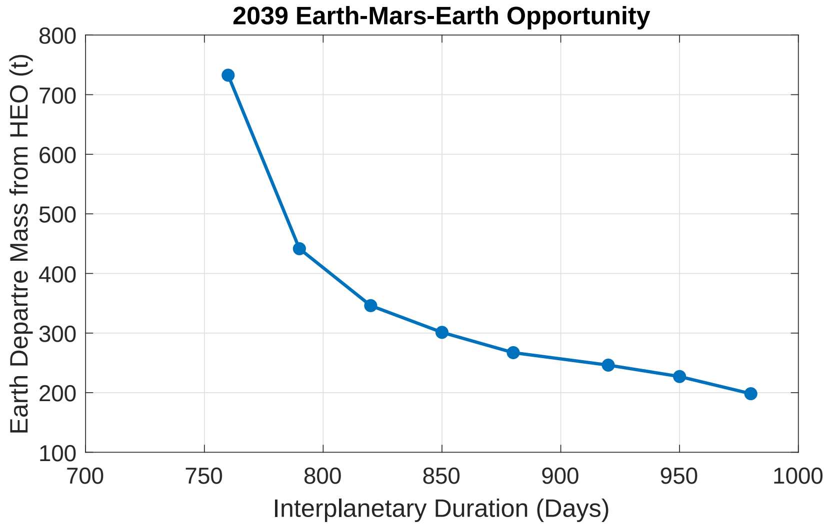

Fig. 7 NEP/Chemical Hybrid Transportation Stack Mass as Function of the Deep Space Mission Duration for the 2039 Earth-Mars-Earth Mission Opportunity

required to support the crew for the planned mission duration. The trajectory optimization framework then utilizes the parametric model developed for the transportation elements to estimate the mass of the individual elements based on propellant demands and the mass of the payload, and a system closure process ensures the propellant demand from the trajectory meets the propellant capacity associated with the sized element. This closure process is completed for a set number of iterations with occasional randomization of the input variables to ensure the solution set does not converge on local minimum solutions. The set number of iterations also ensures the optimization routine has sufficient time to search and converge to a good solution, due to the nature of the optimization routine[22] utilized by Copernicus to solve the under-constrained non-linear problem. The result of the optimization framework is a converged trajectory that is coupled with appropriate vehicle and mission closure models that represent feasible mission concept to field the mission as specified by the input. For this sensitivity study, the primary figure of merit is the integrated stack mass at Earth departure that must be assembled in high Earth orbit to support the roundtrip crew mission.

A. Sensitivity to Mission Duration

Figure 7 shows the transportation system mass as a function of the interplanetary mission duration for the 2039 mission opportunity. The range of interplanetary duration varied from 760 days to 980 days for this mission opportunity. For the purpose of this study, the interplanetary duration is defined as the time between Earth departure maneuver and the Earth arrival maneuver. It must be noted that the total crew time off of Earth's surface could be significantly more than the interplanetary duration due to crew launch window requirements, rendezvous and docking with the transport, and any additional maneuvers required in Earth vicinity. The optimization framework was not able to converge mission duration shorter than 760 days for the 2039 mission opportunity. For the converged cases, the figure shows a clear exponential trend of the mass sensitivity to the mission duration for the SAC21 reference NEP/Chemical propulsion system. For a 760 day roundtrip mission to Mars, the integrated stack mass for the SAC21 reference NEP/Chemical Hybrid Propulsion system is on the order of more than 700t at Earth departure. As a point of comparison, the fully assembled operational mass of the International Space Station is on the order of 400t in low Earth orbit, which is significantly lower energy than the high Earth orbit that the Mars transit vehicle's final assembled destination. This high mass represents a significant challenge to the current mission concept of operations and to the overall launch campaign to field and operate such a mission. Recall that for the current concept of operation, the vehicle is launched and assembled in cis-lunar space to take advantage of the more benign environment. This translates to a significant number of launch vehicle that are required to be launched to cis-lunar space to fully provision the Mars transport vehicle.

For the shorter mission duration, there's simply not enough time for the highly efficient electric propulsion system to provide enough thrust and energy for the roundtrip transit, so the burden falls upon the less efficient, but higher

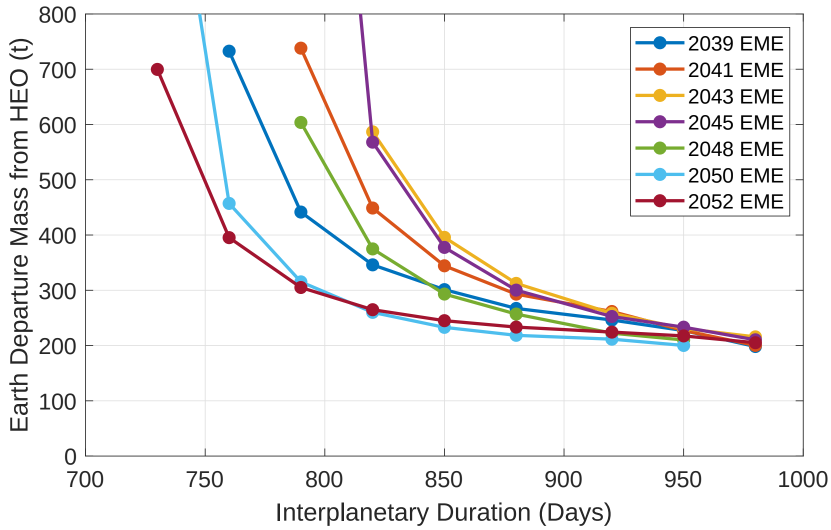

Fig. 8 NEP/Chemical Hybrid Transportation Stack Mass as Function of the Deep Space Mission Duration for the Earth-Mars-Earth Mission Opportunity between 2039 and 2052

thrust chemical propulsion system to make up the difference, resulting in an exponential increase in the overall system mass. For the 2039 mission opportunity, a small increase in the overall mission duration can significantly reduce the required transportation stack mass. Increasing the mission duration by 90 days (from 760 to 850) reduces the total stack mass required in high Earth orbit by more than fifty percent. In the 850 day mission duration regime, as the high efficient electric propulsion system delivers more energy to the system with the increased time, the sensitivity is no longer exponential in nature resulting in much lower mass as compared to the shorter mission duration. Additional increase in mission duration does continue to decrease the mission mass required, but the return is not as pronounced as the initial drop. This shows that mission duration is a significant driver to the integrated mass sensitivity.

To understand how the mass sensitivity to mission duration varies across mission opportunities, the same analysis is performed for six additional Mars mission opportunities after 2039, and the results are shown in Figure 8. Similar trends can be observed across all of the different mission opportunities, with the mass sensitivity going exponential as the mission duration is decreased. However, each mission opportunity has its own location for the "knee" of the exponential curve. For the 2039 mission opportunity, the knee of the curve is rough around 820-850 days, where the curve begins to flatten and the mass sensitivity becomes more linear. This is similar to the 2048 mission opportunity. The 2041, 2043, and 2045 mission opportunities all appears to be more "difficult" than the 2039/2048 mission opportunities, with the knee of the mass sensitivity curve in the 880-920 days range. Alternatively, the 2050 and 2052 mission opportunities are "easier" than the other opportunities, with the knee of the sensitivity curve in the 790-820 day range. These two opportunities are also the only opportunities that have converged solutions for the 730 days mission duration. The mass variation across mission opportunities for a given mission duration is also a good indication of the difficulty of the particular mission opportunity.

For mission duration greater than 900 days, all of the mission opportunities asymptotes to roughly 200-250t of mass required in high Earth orbit. In this regime, there is sufficient time to perform most of the maneuvers for the roundtrip mission using the much more efficient electric propulsion system and the energy required across different mission opportunity gets absorbed by the electric propulsion system which reduces the sensitivity of the overall system mass. In this design space regime, more mass optimal solution exist if the electric propulsion power and thruster power can be reduce to remove excess mass that is not needed from a performance perspective, though this trade is outside the scope of the current study. The sensitivity across the mission opportunities also presents an interesting design consideration. If an integrated vehicle is designed for a particular mission opportunity, it could perform mission for other mission opportunities but with different mission duration. For example, a vehicle designed to fly a 850 day mission in the 2039 opportunity can also fly a 790 day mission in 2052 or a 880 day mission in 2041. This type of flexibility can be useful to design a robust transportation system as long as the mission duration can be a flexible mission parameter.

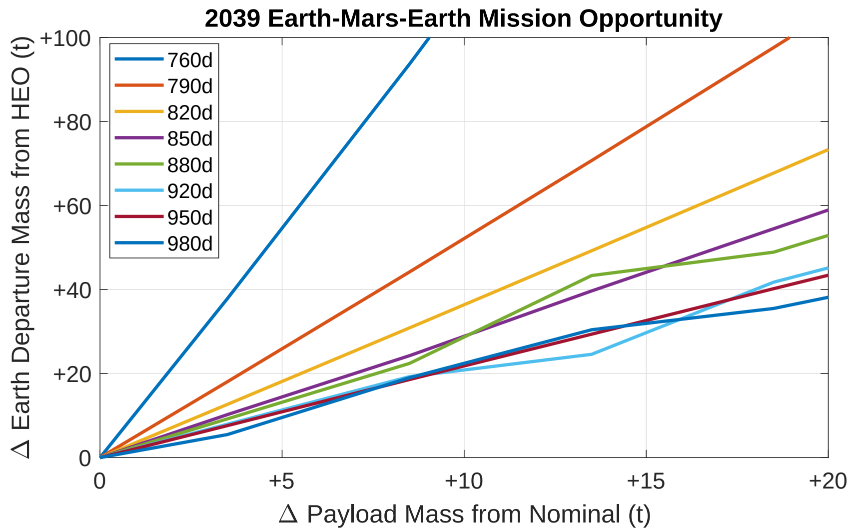

Fig. 9 NEP/Chemical Hybrid Transportation Stack Mass Sensitivity to Payload Mass for the 2039 Earth-Mars-Earth Mission Opportunity for a Range of Deep Space Mission Duration

B. Mission Sensitivity to Payload Mass

Figure 9 shows the integrated stack mass sensitivity to payload mass for the same mission duration range as discussed in the previous section. The figure shows the change in the integrated stack mass as function of the change in the payload mass. In this sensitivity, the change in the payload mass can be be not only changes to the habitation mass, but any of the transport element as well. One can imagine a scenario in which the parametric model developed for the analysis framework under-predicting the element mass due to errors in the model or uncertainty in the system estimation. This sensitivity analysis shows the potential impact of that effect to the integrated system mass. As Figure 9 show, the mass sensitivity is significant especially for the shorter mission duration cases. This is not a surprise based on the discussion in the previous section, but it is still jarring to see a "gear ratio" of more than 10 for the shorter 760 day mission (5t increase in payload mass yields a >50t increase in overall stack mass). For the longer mission duration, the mass increase is not as extreme is still significant. Interesting to note that the mass sensitivity here is mostly linear, though this is likely due to the relatively small range of the change in the payload mass.

Figure 10 shows the stack mass sensitivity to payload mass across the mission opportunities of interest for a fixed 850 day mission duration. This figure reiterates and more clearly shows which mission opportunity is more difficult compared to another. As previously discussed and confirmed by this figure, the 2041, 2043, and 2045 mission opportunities appears to be the most difficult opportunities with highest mass and highest mass sensitivity to payload mass growth. The two mission opportunities in the 2050s remain the easiest opportunities, with relatively low sensitivity to the changes to payload mass.

V. Summary

In this study, an update to the Hybrid propulsion system was established with the introduction of nuclear electric propulsion system to replace the solar electric propulsion system in an effort to enable shorter mission to Mars. In addition, an updated integrated trajectory and mission analysis framework was developed to facilitate the analysis of the updated vehicle and mission trade space. Using the developed framework, a series of mission performance sensitives were performed to understand the performance of the updated propulsion system for various mission design parameters. The results show significant sensitivity to the overall transportation system mass to both mission duration and mission opportunities. In particular, the mass sensitivity is exponential in nature for mission duration less than 800 days for most mission opportunities. The wide range of the sensitivity curve showcase the significant challenge associated with the design of the integrated roundtrip mission to Mars. Designing a mission to a single mission opportunity as a reference can simplify the design process, but can lead to a non-robust design that is not capable to supporting alternate mission opportunities. Additionally, these sensitivity curves are only valid for the reference SAC21 NEP/Chemical Hybrid propulsion system. If an element with different power to mass ratio is assumed, then the performance of the

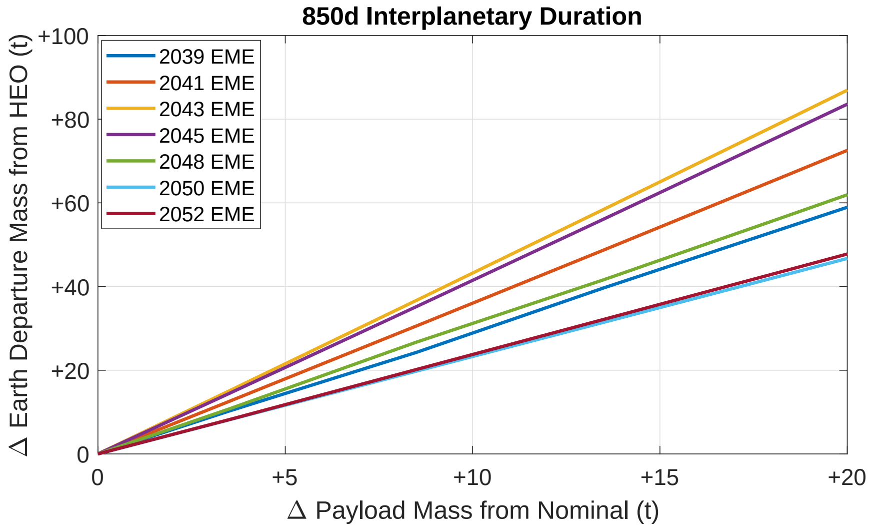

Fig. 10 NEP/Chemical Hybrid Transportation Stack Mass Sensitivity to Payload Mass for the 2039 Earth-Mars-Earth Mission Opportunity for a Range of Deep Space Mission Duration

vehicle and its mass sensitivity to duration will be drastically different, making it very difficult to draw generalized conclusion or rule of thumb estimates for these types of missions. The integrated nature of the low-thrust trajectory coupled with the higher energy requirement of these shorter duration mission makes this an extremely challenging problem to solve.

References

[1] Mars Architecture Steering Group, and Drake, B. G., "Human Exploration of Mars Design Reference Architecture 5.0," Special Publication 2009-566, National Aeronautics and Space Administration, July 2009.

[2] Stanley, D. O., Cook, S., Connolly, J., Hamaker, J., Ivins, M., Peterson, W., Geffre, J., Cirillo, B., McClesky, C., Hanley, J., et al., "NASA's Exploration System Architecture Study," Technical Memorandum 2005-214062, National Aeronautics and Space Administration, November 2005.

[3] Olson, J., "Human Exploration Framework Team Phase I Closeout," National Aeronautics and Space Administration, September 2, 2010.

[4] Chai, P. R., Merrill, R. G., and Qu, M., "Mars Hybrid Propulsion System Trajectory Analysis, Part I: Crew Missions," *AIAA SPACE 2015 Conference and Exposition*, American Institute of Aeronautics and Astronautics, 2015. https://doi.org/10.2514/6.2015-4443, AIAA 2015-4443.

[5] Merrill, R. G., Strange, N., Qu, M., and Hatten, N., "Mars conjunction crewed missions with a reusable hybrid architecture," *2015 IEEE Aerospace Conference*, IEEE, 2015. https://doi.org/10.1109/aero.2015.7118956.

[6] Chai, P. R., Joyce, R. T., Kessler, P. D., and Merrill, R. G., "Sensitivity Analysis of Hybrid Propulsion Transportation System for Human Mars Expeditions," *AIAA SPACE 2017 Conference and Exposition, Orlando, FL*, 2017.

[7] Hofer, R., and Gallimore, A., "High-Specific Impulse Hall Thrusters, Part 1: Influence of Current Density and Magnetic Field," *Journal of Propulsion and Power*, Vol. 22, No. 4, 2006, pp. 721–731. https://doi.org/10.2514/1.15952.

[8] Hofer, R., and Gallimore, A., "High-Specific Impulse Hall Thrusters, Part 2: Efficiency Analysis," *Journal of Propulsion and Power*, Vol. 22, No. 4, 2006, pp. 732–740. https://doi.org/10.2514/1.15954.

[9] Bérend, N., Moreno, E. C., Ruault, J.-M., and Epenoy, R., "Feasibility Assessment of Rapid Earth–Mars Transfers Using High-Power Electric Propulsion," *Journal of Spacecraft and Rockets*, Vol. 51, No. 3, 2014, pp. 946–957. https://doi.org/10.2514/1.a32560.

[10] Oh, D. Y., Snyder, J. S., Goebel, D. M., Hofer, R. R., and Randolph, T. M., "Solar Electric Propulsion for Discovery-Class Missions," *Journal of Spacecraft and Rockets*, Vol. 51, No. 6, 2014, pp. 1822–1835. https://doi.org/10.2514/1.a32889.

[11] Oleson, S., "Electric Propulsion Technology Development for the Jupiter Icy Moon Orbiter Project," *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, American Institute of Aeronautics and Astronautics, 2004. https://doi.org/10.2514/6.2004-3449.

[12] LaPointe, M., Oleson, S., Pencil, E., Mercer, C., Stefano, S. D., Gilland, J., and Mason, L., "MW-Class Electric Propulsion System Designs for Mars Cargo Transport," *AIAA SPACE 2011 Conference and Exposition, Long Beach, California*, 2011. https://doi.org/10.2514/6.2011-7253.

[13] Oleson, S. R., Burke, L., Dudzinski, L., Fittje, J., Mason, L. S., Packard, T., Schmitz, P., Gyekenyesi, J., and Faller, B., "A Combined Nuclear Electric and Chemical Propulsion Vehicle Concept for Piloted Mars Opposition Class Missions," *ASCEND 2020*, American Institute of Aeronautics and Astronautics, 2020. https://doi.org/10.2514/6.2020-4055.

[14] Polsgrove, T., Simon, M. A., Waggoner, J., Smitherman, D. V., Howard, R. L., and Percy, T. K., "Transit Habitat Design for Mars Exploration," *2018 AIAA SPACE and Astronautics Forum and Exposition*, American Institute of Aeronautics and Astronautics, 2018. https://doi.org/10.2514/6.2018-5143, AIAA 2018-5143.

[15] Craig, D. A., Herrmann, N. B., and Troutman, P. A., "The Evolvable Mars Campaign - study status," *2015 IEEE Aerospace Conference*, IEEE, 2015. https://doi.org/10.1109/aero.2015.7118925, 2015-8.0101.

[16] McFatter, J., Keiser, K., and Rupp, T. W., "NASA Docking System Block 1: NASA's New Direct Electric Docking System Supporting ISS and Future Human Space Exploration," *Aerospace Mechanisms Symposium*, 2018.

[17] Komar, D., Hoffman, J., Olds, A., and Seal, M., "Framework for the Parametric System Modeling of Space Exploration Architectures," *AIAA SPACE 2008 Conference & Exposition*, American Institute of Aeronautics and Astronautics, 2008. https://doi.org/10.2514/6.2008-7845.

[18] Chai, P., Merrill, R. G., Qu, M., and Shen, H., "Integrated Optimization of Mars Hybrid Solar-Electric/Chemical Propulsion Trajectories," *2018 AIAA SPACE and Astronautics Forum and Exposition*, American Institute of Aeronautics and Astronautics, 2018. https://doi.org/10.2514/6.2018-5346, AIAA 2018-5346.

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

[20] Tange, O., *GNU Parallel 2018*, Zenodo, 2018. https://doi.org/10.5281/ZENODO.1146014.

[21] "Information Technology. The JSON Data Interchange Syntax," , 2017. https://doi.org/10.3403/30344876.

[22] Gill, P. E., Murray, W., and Saunders, M. A., "SNOPT: An SQP Algorithm for Large-Scale Constrained Optimization," *SIAM Review*, Vol. 47, No. 1, 2005, pp. 99–131. https://doi.org/10.1137/s0036144504446096.