

MARS TRANSPORTATION

BACKGROUND

As discussed in the Systems Analysis of Architecture Drivers white paper, the systems engineering process identifies several example trades and design drivers to selecting an architecture. These trades reflect the tightly coupled dependency on the order and weighting applied answering the fundamental questions of Who, What, Where, When, Why, and How to meet the Moon to Mars objectives. One of the most visible and significant portions of the Mars architecture is the Earth to Mars transportation system. While numerous previous studies, analyses, and trades have been conducted with respect to this system, most were highly constrained with initial conditions or assumptions made in the absence of objective clarity that did not permit accurate or meaningful "apples to apples" comparisons, making selections between concepts difficult. It is NASA's intention to utilize the Moon to Mars Goals & Objectives as a foundation to establish the key architectural needs, use cases, and functions, conduct assessments to the performance of multiple solutions, and ultimately establish a roadmap of system, mission, and technology demonstrations to enable informed architectural decisions. This effort and planning will be communicated through the Architecture Definition Document and future revisions. The purpose of this paper is to orient the greater community to the breadth, variations, and associated risks of the range of Earth-to-Mars transportation systems under study.

INTRODUCTION

Spacecraft traveling either to the Moon or Mars do not travel in a straight line; rather, they must travel along arced paths shaped by the relevant gravity wells. A single round-trip journey between Earth and Mars will put about 1.8 to 2 billion kilometers on a Mars transportation system's odometer, which is different than the straight-line distance between the two planets. To put this distance in context, the recent Artemis I mission between Earth and the Moon put about 2.2 million kilometers on Orion's odometer.

The distance and velocity that the Moon orbits Earth varies by a relatively small amount. However, both Mars and Earth orbit the Sun at different velocities, so the distance between the two planets is constantly changing, hence the energy required to travel between Earth and Mars is also constantly changing. This variation leads to some mission opportunities requiring 20 to 60% more transportation energy to complete the interplanetary transits between Earth and Mars for the same mission duration than in other calendar years. Figure 1 shows the cyclical variation in energy during interplanetary round-trip transits between Earth and Mars. In this particular analysis, Lunar Distance High Earth Orbit (LDHEO) is used as the starting point for Earth departure staging for Mars missions, and a 5-sol orbit is used for Mars arrival staging and departure.

Transportation energy is a function of many variables, including the distance and relative velocity of the planets as well as the mission duration and orbital stay time. This is shown in the comparison between two example mission types in Figure 1. The conjunction class Mars



Figure 1. Variation of roundtrip interplanetary energy needs between LDHEO earth and 5-sol Mars orbits

mission on the left is a minimum energy style mission, where the outbound and inbound portions of the interplanetary trajectory are optimized for the best planetary alignment between Earth and Mars, resulting in a roundtrip mission duration of ~1,000 days, with more than 300 days loiter time in Mars vicinity while awaiting the next optimal planetary alignment for the return journey. The opposition class Mars mission shown on the right shortens the total mission duration to ~760 days or less but requires more energy to achieve and shortens the Mars vicinity loiter time to about 30- 50 days. It is important to note that Mars missions are not restricted to a binary choice between these two options as the mission duration can be varied across a continuous space.

The interplanetary energy required for the Mars mission may be a major component of achieving the roundtrip mission, but the energy required to get in and out of the planet's gravity well cannot be overlooked. Figure 2 shows an Earth-Moon-Mars energy map for missions to the surface of the Moon or Mars. Both missions have unique challenges, and systems designed for one may not be directly applicable to the other as they have different energy and mission needs. Missions to Mars generally have a higher energy need, require much longer system service life, and have more stringent departure window constraints.

The bulk of current human spaceflight experience is limited to six months or less in space, with just a few data points around the one-year mark, and almost all within the Earth's magnetosphere. While International Space Station (ISS) research is helping to answer some questions about human health and performance during long duration spaceflight, we don't yet understand all of the mechanisms involved, or the extent that multifactorial contributors to human system risks may limit which countermeasures would be effective or potentially introduce other stressors. Researchers believe that the combined effects of many stressors such as microgravity, radiation exposure, isolation, confinement, and closed environment are at issue, so many different countermeasures may be needed. Crew cabin mass/volume limitations and lack of on-demand resupply for medical countermeasures supplies further complicates planning. Some proposed countermeasures, such as active radiation protection or artificial gravity, would drive transportation mass and complexity. NASA's Human Research Program has identified a plateau for some—but not all—adverse health and performance effects. In other words, by some metrics, human health and performance may continue to degrade or adapt the longer crew remain away from Earth, but we don't yet know the extent of these changes, whether adverse effects are reversible, or what individual variation we'll see across a larger cohort of astronauts. Health and performance issues have implications for a Mars crew's ability to perform their surface mission and poses uncertainty for their long-term health after returning to Earth.

To mitigate crew health and performance risks, NASA has recently revisited "opposition" class missions that can shave a year or more off total mission duration by shortening Mars vicinity stay time, and not waiting for optimal planetary alignment before returning to Earth.



FIGURE 2. Earth-Moon-Mars ΔV (energy) map

Though this type of mission can significantly reduce crew time away from Earth, the penalty is significantly higher transportation energy (and propellant mass). Heritage chemical propulsion systems were historically considered impractical for opposition-class missions, but the emergence of reusable launch systems and in-space propellant depot concepts potentially changes the calculus. Alternatively, highly efficient nuclear propulsion systems can mitigate the potential for exponential propellant mass growth of all-chemical transportation but will require significant technology investments. In addition to crew health and performance risks, vehicle reliability and operational risks must also be considered when comparing different transportation and mission options.

NASA ANALYSIS APPROACH

Crew departure opportunity – As noted in Figure 1, transportation energy varies significantly over mission opportunities. Instead of designing a transport for the lowest energy opportunity (which only enables missions about every 15-20 years), or for the highest energy opportunity (resulting in an oversized vehicle for most missions), recent NASA analysis has focused on moderate energy opportunities, such as 2039, as an analysis reference. This is not to say that 2039 is the recommended mission date, only that 2039 is a representative energy opportunity for the purpose of evaluating transportation system performance.

Transportation architecture – NASA is evaluating four transportation propulsion systems (Figure 3): Nuclear Electric Propulsion/Chemical hybrid (NEP/Chem), Nuclear Thermal Propulsion (NTP), Solar Electric Propulsion/Chemical hybrid (SEP/Chem), and All-Chemical propulsion (All-Chem). For initial apples-to-apples performance analysis comparisons, a separable transit habitat, sized to accommodate 4 crew for up to 1200 days is assumed for all four transportation systems, but an integrated transit habitat case is part of the AllChem trade space, and the impacts of varying number of crew will be assessed. Launch cadence and costs for the Space Launch System (SLS) and emerging super-heavy Commercial Launch Vehicles (CLVs) are also being assessed for each transportation option.

Entry, Descent, Landing and Ascent (EDLA) architecture – in all analysis cases, NASA assumes surface mission cargo—most importantly a Mars Ascent Vehicle—will be pre-deployed prior to crew arrival to ensure crew are able to return. All four transportation systems are also being assessed for cargo transport use. Two different lander types (Figure 3) are also being analyzed: a "flat bed" lander with a lower payload capacity, but readily accessible cargo deck, and a vertical lander with higher payload capacity, sometimes referred to in previous analyses as a "mid L/D" lander. Again, for the sake of apples-to-apples comparison analyses, roughly the same cargo suite is assumed for both approaches, the difference being the number of landers required and some differences in cargo operations, particularly Mars Ascent Vehicle propellant loading.

Surface Mission – for the sake of apples-to-apples comparisons, initial analysis held the surface mission constant across all options for various in-space mission profiles, focusing on the minimum practical corner of the trade space: two crew to the surface for 30 days, with limited surface infrastructure. Release of the September 2022 Moon-to-Mars Strategy and Objectives provides guidance to expand surface mission analysis to include longer surface stay durations and expanded surface infrastructure, such as in-situ resource utilization. Architectural impacts of varying the number of surface crew is also being assessed.



Figure 3. Mars transportation system options trade space

Total Mission Duration – To understand how the transportation architecture changes as a function of mission duration, each of the four transportation concepts is evaluated under three different reference missions, ranging from 870 to 1250 total days away from Earth (actual transit duration, plus rendezvous, staging, and crew launch opportunity time), resulting in 27 different mission concepts; design concepts and campaign analysis has been completed for about a third of these to date. Additional analysis cases that expand the surface mission will be added in a future analysis cycle.

PRELIMINARY ANALYSIS RESULTS

As mission duration decreases, the total energy required to perform a roundtrip Mars mission increases exponentially, significantly increasing Earth-launched mass. For both high thrust propulsion systems (NTP

and All-Chem), the total mass required is at the mercy of the exponential nature of the rocket equation. For the hybrid systems (SEP and NEP), for any given power level, there is a limitation to how much energy the low thrust system can produce. Thus, to enable higher energy missions, either the chemical part of the hybrid system must be more heavily utilized, or the power level must be increased. Mass curves for the low thrust systems are therefore also exponential in nature as mission duration is shortened.

Assuming active Cryogenic Fluid Management (CFM), a one-MegaWatt (MW)-class SEP/Chem, 2 x 12.5 kilo-pound force (klbf) thruster NTP, or 1.8 MW NEP/Chem all weigh in at about 300 metric tons (t) Earth departure mass from high Earth orbit for the moderate 850-day transit duration (roughly in the middle between opposition and conjunction class). For reference, the fully assembled International Space Station (ISS) is about 400t in low Earth orbit. Initial analysis of an All-Chem concept without active CFM (similar to designs being considered for lunar transportation) is nearly five times the mass of the other concepts. For the longer duration, conjunction class end of the trade space, a similar pattern is evident: for a 1000-day round-trip mission, the All-Chem concept would shed the equivalent mass of an assembled ISS as compared to the moderate duration variant—but it would still be about five times the mass of similar duration SEP or NEP hybrid concepts, and nearly twice the mass of nuclear concepts flying the much shorter duration opposition class mission.

Addition of active CFM shows promise in bringing the All-Chem stack mass more in line with the other three options. NASA analysis found that active CFM could reduce the number of Earth- launched propellant tankers needed by 30% for an All-Chem transportation system flying the 850- day mission; active CFM could reduce the number of propellant tankers needed by 50% for an All-Chem concept flying a 1000-day conjunction class mission. In addition to significant stack mass savings, reducing the number of propellant launches can also reduce launch costs and shorten the in-space transport fueling timeline prior to Earth departure, which in turn relaxes launch cadence pressure and operational risk. Note that All-Chem concept analysis is not yet complete, but trends indicate that opposition-class All-Chem vehicle mass will be much higher than for other concepts. Additional analysis is required to pinpoint a mission duration length where All-Chem mass would be competitive with nuclear transportation mass at various power levels.

DISCUSSION

Historically, launched mass has served as a cost analog when comparing options, but if reusable launch systems promise to drive down Earth launch costs, transportation mass may not be a useful metric. If it was as simple as using our lunar all-chemical transportation system and just paying the cost to launch extra propellant mass, it could significantly decrease Mars transportation costs as compared to developing new technologies. But current lunar approaches cannot be used as-is for Mars. Even when the planets are as close as they ever get, the round-trip distance between Earth and Mars is about 950 times that to the Moon and back. What's more, Mars gravity is twice Lunar gravity, requiring even more energy for Mars ascent and descent. As compared to their lunar counterparts, Mars transportation systems not only have to carry much more propellant, but they also need to maintain that propellant for much longer periods of time. Even a fraction of a percent boil-off loss per day will result in significant cryogenic propellant loss over a two to three-year round-trip Mars mission, so Mars transportation systems must either employ active CFM or carry significant additional propellant to offset losses. In considering Mars extensibility for All-Chem lunar transportation systems in development, it is important to note that active CFM is not required for the shorter duration Artemis lunar missions so Mars extensibility may require additional technology infusion and vehicle redesign.

In short, a vehicle designed to fly to, land on, and ascend from the Moon simply can't perform the same operation to Mars without refueling or modification to the design. As noted above, without active CFM, a large number of propellant tankers is required to fuel a single round-trip Mars crew mission. Even if these propellant launches are inexpensive, the complexity of fielding a significant number of individual launches, rendezvous, docking, and propellant transfer operations within a very specific deadline increases mission risk: the longer it takes to complete the entire in-space fueling operation, the more propellant will boil off before Earth departure. If a weather delay or launch pad issue causes the Mars transport to miss its narrow Earth departure window, it may have to loiter in Earth vicinity for several years until the next departure opportunity, and by then the propellant (and any other life-limited cargo) will have to be replaced, further adding to the mission cost.

So why haul round-trip propellant, why not just carry enough to get to Mars and refuel there? Historically, NASA has been hesitant to send humans anywhere without on-board capability to return to Earth, although NASA's Design Reference Architecture 5.0 (DRA5, 2009) did rely on surface refueling for a pre-deployed ascent vehicle to orbit. In that architecture the transport itself carried round-trip propellant, but the crew would not commit to the surface mission until after the pre-deployed ascent vehicle was confirmed fueled, thus mitigating the risk crew would be stranded on Mars in the event of an ISRU problem. The DRA5 architecture required about 40 kiloWatts (kW) of surface power, operating for more than a year prior to crew arrival, to robotically manufacture and liquefy enough oxygen propellant to boost a single-purpose ascent vehicle to Mars orbit. More recent concepts have gone beyond DRA5, proposing to fuel a combination ascent vehicle/ Earth return all-chemical transport on the Mars surface. Propellant loads will obviously depend on mission mode, ascent vehicle design, and Mars return cargo mass, but these concepts would require a leap from tens of kW to hundreds of kW surface power for propellant production. Expanding from atmospheric to regolith ISRU could reduce fueling time and enable other fueling strategies, but additional power would be required for the vehicles and equipment needed to collect, transport, and process Martian regolith or water ice.

For context, a one MW power capability would require 25 each of the 40-kiloWatt (kW) fission surface power units that NASA is currently developing, or perhaps tens of acres of solar arrays sized for seasonal solar variations and dust storm disruptions. It remains forward work to complete assessment of various surface mission cases and assess the number of landers required to deliver the power systems and equipment needed to robotically deploy and maintain the power infrastructure, plus robotic ice mining systems that could supply water ice to the ISRU plant. Atmospheric extraction could eliminate the need for robotic ice mining equipment, but the lower process efficiency will either require much more propellant production time, or much higher power, with flow-down impacts to operations and preparation timeline before the first crew return vehicle arrives on Mars.

FORWARD WORK

As this paper highlighted, design trades to address the architectural Who, What, Where, When, Why, and How come at a trade of cost, risk, and benefit. NASA will continue to analyze and publish the key findings of architectural trades and their effectiveness during annual updates to the Architecture Definition Document. This approach to refine and define a path to objective success informed by system, mission, and technology demonstrations will be reflected and communicated through the architectural process initiated by the Moon to Mars Goals & Objectives. NASA will continue developing transportation conceptual designs for the remaining cases, plus expanded surface mission concepts with heavier Mars surface infrastructure, to assess campaign impacts, technology development needs, and affordability.

KEY TAKE-AWAYS

- Mars missions require significantly more energy (propellant mass), require much longer system service life, and have more stringent departure window constraints than the lunar missions that NASA is developing under the Artemis program, even for the most optimal planetary alignment and trajectories.
- Shorter total roundtrip duration missions potentially mitigate crew health and performance concerns but increase the energy (propellant mass & technology development) required for Mars missions.
- Four In-Space Transportation Systems are currently under consideration: Nuclear Thermal Propulsion, Nuclear Electric/Chemical Hybrid, Solar Electric/Chemical Hybrid, and All Chemical Propulsion.
- Active CFM reduces required propellant loads for all Mars propulsion systems.
- Both Moon and Mars missions have their unique challenges, and systems designed for one may not be directly applicable to the other.

This white paper was developed as part of NASA's 2022 strategic analysis cycle to address topics of frequent discussion. For the latest white papers or other architectural documents related to human missions to the Moon and Mars, please visit: www.nasa.gov/MoonToMarsArchitecture.