NASA's Strategic Analysis Cycle 2021 (SAC21) Human Mars Architecture

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Abstract—**The National Aeronautics and Space Administration's (NASA) Mars Architecture Team (MAT) was challenged to develop a mission architecture capable of transporting humans to the surface of Mars and back as fast—and as soon—as practical. This challenge represented a significant departure from previous approaches that minimized Earth-launched mass and maximized in-space transportation efficiency, often resulting in roundtrip missions of three years or more in duration. In the interest of crew health, MAT's cross-Agency team of subject matter experts was challenged to develop an architecture capable of shortening crew time away from Earth to about two years. MAT was given specific mission constraints, such as number of crew, as well as mandates to minimize surface infrastructure as much as possible and to incorporate nuclear transportation options. The resulting MAT-developed concept, referred to here as the Strategic Analysis Cycle 2021 (SAC21) architecture, leverages Artemis elements and emerging commercial capabilities for cargo and logistics launches, and features a hybrid Nuclear Electric Propulsion (NEP)/Chemical transportation system able to complete the 1.8 billion kilometer round-trip journey to Mars and back in 760 to 850 days transit time for the 2039 Earth departure opportunity. Three Mars Descent Systems (MDS), each capable of landing about 25 metric tons of useful cargo on the surface of Mars, would be pre-deployed in advance of crew departure from Earth; two of these MDS's would deliver a partially fueled Mars Ascent Vehicle (MAV), a fission power system, surface mobility, and additional MAV propellant. To minimize surface infrastructure, only two of the four Mars crew would descend and live in an MDS-landed pressurized rover, exploring the martian surface for 30 martian days, or sols, before returning to Mars orbit aboard their MAV and rejoining the other two crew on the Deep Space Transport for the Earth return voyage. Specifics of many of these architecture elements are detailed in separate technical publications; this paper outlines the end-to-end integrated architecture performance and concept of operations, including synergies with Artemis lunar architecture elements. It is important to note that NASA does not have a formal human Mars program and no decisions have been made; the architecture described here is intended to fill in an often-overlooked corner of the trade space, helping to complete the menu of options available to decision-makers as they chart the course for humans to Mars.**

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1. INTRODUCTION

Mars continues to be an Agency horizon goal [1] for human exploration of our solar system. An initial human Mars mission might search for signs of extant life (i.e., life that still exists today) or assess options for longer term human sustainability. NASA's top priority for the crew once they land and validate habitation/exploration/ascent capabilities would be to perform high priority science objectives, established by the science community, using systems approved and provided by NASA's Science Mission Directorate (SMD). At the architecture level, the objective is to land humans on the surface of Mars and return them safely to Earth. Landing site selection for a first mission will be driven by crew safety, available capabilities, and science priorities.

2. CHALLENGES

As compared to Artemis lunar missions, Mars offers three unique challenges for human exploration. The first challenge is the sheer distance. Graphics that depict minimum distance between Earth and Mars or estimates of one-way trip times can be misleading because they don't adequately communicate that Earth and Mars race around the Sun at different speeds, the distance between them constantly changing. Minimum distance between the two planets varies over an approximately 15 to 16-year synodic cycle, with optimum alignments occurring about every 26 months. In general, the distance traveled *to* Mars will be different than the *return* distance back to Earth, because Earth won't be where we left it. A round trip from Earth to Mars is estimated to put 1.8 to 2 *billion* kilometers on our spaceship's odometer, as compared to less than a million kilometers round-trip from Earth to the Moon. The trajectory we take, the year and month we leave Earth, what type of propulsion system we use, and how long we linger at Mars will all set overall mission duration, but the reality is that round-trip Mars missions are expected to be two to three years long.

This brings us to our second challenge: we have no human performance data for such long periods away from Earth. Fortunately, we are well-positioned to meet this challenge, by using Earth-based analogs [2] and the International Space Station (ISS) to study the effects of closed environments, isolation, and confinement, and of course we use the ISS to study the effects of reduced gravity [3]. Artemis lunar missions will also give us an opportunity to study human re-adaptation to partial gravity and living and working for extended periods in hostile, reduced gravity environments.

The third challenge at the top of our list is landing—and ascending—from Mars. Our robotic Mars exploration missions have thus far been entirely one-way. Mars has less gravity and atmosphere than Earth, but much more than the Moon. To return home, we'll need to climb out of the Mars "gravity well" [Figure 1] and that translates to tons of ascent propellant. There are two ways to acquire our ascent propellant: either haul it from somewhere else and land it on Mars, or haul In Situ Resource Utilization (ISRU) equipment—plus significant power mass—to manufacture ascent propellant at scale on Mars. Either method will require substantial landed mass, which brings us back to the other piece of our third challenge: landing large payloads on Mars, estimated to be at least 20 times larger than our largest robotic landers to date. Our robotic missions, such as *Curiosity* and *Perseverance*, have advanced our landing technologies, and we'll learn more about ascent with the upcoming Mars sample return mission. Artemis will also advance our landing and ascent skills, particularly in the areas of precision landing.

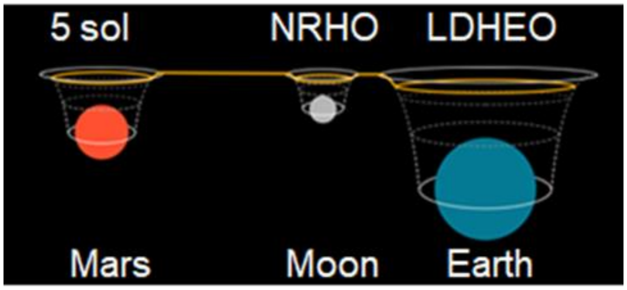
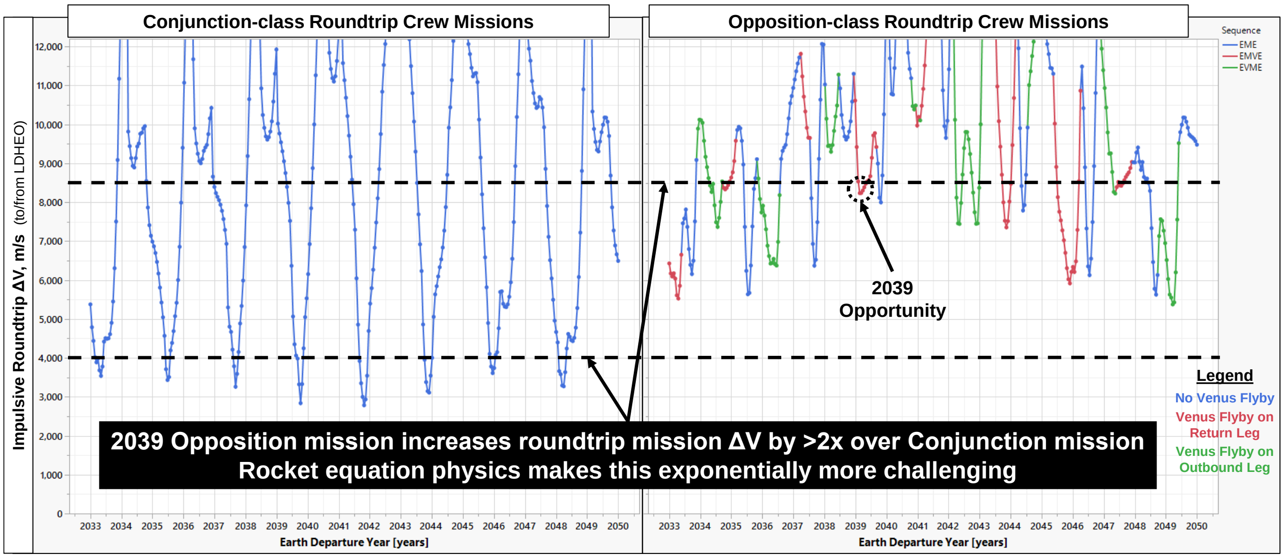


Figure 1. Gravity Wells: Relative energy states for 5-sol Mars orbit, Near Rectilinear Halo Orbit (NRHO), and Lunar Distant High Earth Orbit (LDHEO)

3. HUMAN MARS MISSION TRADE SPACE

The three challenges outlined above, plus mission goals and objectives, generally define the trade space for human Mars missions. NASA's last published human Mars reference architecture focused on what is known as a conjunction class or long-stay mission, characterized by relatively fast transit to Mars when the planets' relative positions allow a minimum energy transit, followed by a very long loiter period at Mars waiting for an optimum trajectory that enables a fast return transit. Design Reference Architecture 5.0 [4] opted to spend a 500+ day loiter period on the surface of Mars, which offered substantial exploration time, but at the expense of substantial surface infrastructure. Surface systems included a large habitat, 40 kiloWatts of electric power (kWe), ISRU, and multiple surface mobility systems. The overall mission duration kept crew away from Earth for more than three Earth years and required at least 80 metric tons (t) of useful landed mass at Mars.

More recently, NASA was challenged to explore a different corner of the trade space, focusing instead on minimizing crew time away from Earth and emphasizing a lighter surface exploration footprint. Using what is known as an opposition class or short-stay mission mode, crew would minimize loiter time at Mars before their return departure window closes. At least one leg of the journey (either in- or out-bound) requires significantly more energy than a comparable conjunction class mission. As shown in Figure 2, the impulsive roundtrip change in velocity (meters per second) required for transit to Mars from a Lunar Distant High Earth Orbit (LDHEO) and return, for an opposition class mission in the 2039 example, is more than twice that of the conjunction class mission. In practical terms, this can equate to hundreds of tons more propellant mass, though in some cases the gravity assist offered by a Venus flyby can aid in reducing propellant mass. Why would we attempt such a difficult mission? The advantage of these opposition class missions is that they can shave many months from the duration that crew are away from Earth, relative to conjunction class missions.


Conjunction-class Roundtrip Crew Missions

Opposition-class Roundtrip Crew Missions

2039 Opportunity

2039 Opposition mission increases roundtrip mission ΔV by >2x over Conjunction mission
Rocket equation physics makes this exponentially more challenging

Conjunction-class data presented only includes <1000 d roundtrip times

Opposition-class data presented only includes <760 d roundtrip times

Figure 2. Roundtrip Mars Mission Energy Requirements, Full Synodic Cycle 2033 - 2050

Several factors prompted NASA's interest in evaluating such a challenging approach, including recent analysis indicating that shorter roundtrip mission durations could reduce crew health risk [5], the emergence of robust commercial capabilities [6] that lower the cost of Earth-launch access to space, and a desire to leverage Artemis-derived lunar surface systems as much as possible for Mars, rather than place much longer-duration surface technologies into the first human mission's critical path. To achieve the higher energy transits required for an opposition class mission, NASA evaluated two different nuclear propulsion options: Nuclear Thermal Propulsion (NTP), which uses heat generated from a fission reaction to propel hydrogen; and Nuclear Electric Propulsion (NEP) which generates electricity from the fission reaction to drive electric thrusters. Both technologies would also align with renewed national interest in space nuclear power and propulsion [7].

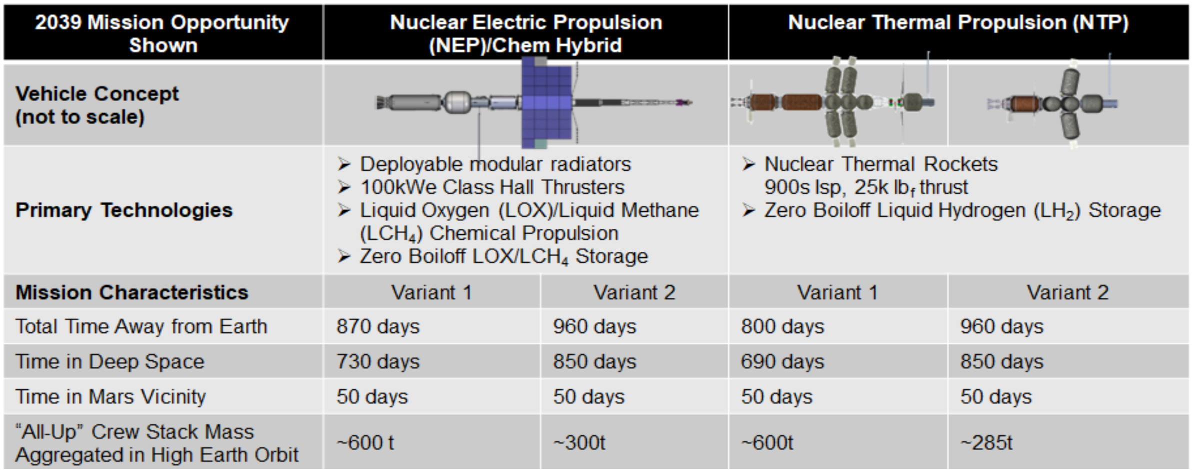
For analysis purposes, NASA developed two nuclear-enabled, opposition class Mars transportation concepts, one featuring an NTP system, the other a hybrid transport [8, 9] that paired a high-efficiency NEP module with a chemical stage for high thrust maneuvers. Both profiles assumed a 2039 Earth departure to assess one of the more challenging opposition class opportunities, and both assumed a 50-day loiter period in Mars orbit to enable a 30-sol surface exploration period. Both transportation systems also assumed the payload was a 47.5 t, 4-crew Mars transit habitat.

Figure 3 shows a high-level comparison of the two nuclear-enabled crew transportation systems in an "all up" configuration, meaning they would depart Earth carrying all the propellant needed to get to Mars and back again. Two variants for each architecture were explored: in each case, Variant 1 held time in deep space to two years or less, but Variant 2 relaxed mission duration to optimize mass. As noted above, holding crew time in deep space to less than about two years in the opposition class mode requires significant energy. For the 2039 opportunity, both nuclear-enabled transportation systems Variant 1 are estimated at about 600 t stack mass in High Earth Orbit (HEO). To put this into perspective, ISS is about 400 t, but in *Low* Earth Orbit (LEO). As expected, relaxing mission duration to about 850 days (~2.3 years, Variant 2) in deep space can cut stack masses by half, which translates to fewer Earth-launched vehicle fueling flights.

4. SHORT STAY MISSION ARCHITECTURE

For the purpose of analyzing short stay mission concepts with a light exploration footprint, NASA developed a mission concept around the relaxed duration NEP/Chemical hybrid transportation system (Variant 2 in Figure 3), paired with a long duration Mars transit habitat sized for four crew.

Two of the four crew would descend to the surface, living and working out of a pressurized rover for the 30-sol exploration period before ascending back to the 5-sol orbit in a pre-deployed Mars Ascent Vehicle (MAV) and rejoining their crewmates. For this architecture, NASA assumed a 25-t



2039 Mission Opportunity Shown	Nuclear Electric Propulsion (NEP)/Chem Hybrid		Nuclear Thermal Propulsion (NTP)	
Vehicle Concept (not to scale)				
Primary Technologies	➢ Deployable modular radiators ➢ 100kWe Class Hall Thrusters ➢ Liquid Oxygen (LOX)/Liquid Methane (LCH_4) Chemical Propulsion ➢ Zero Boiloff LOX/LCH_4 Storage		➢ Nuclear Thermal Rockets 900s Isp, 25k lb_f thrust ➢ Zero Boiloff Liquid Hydrogen (LH_2) Storage	
Mission Characteristics	Variant 1	Variant 2	Variant 1	Variant 2
Total Time Away from Earth	870 days	960 days	800 days	960 days
Time in Deep Space	730 days	850 days	690 days	850 days
Time in Mars Vicinity	50 days	50 days	50 days	50 days
"All-Up" Crew Stack Mass Aggregated in High Earth Orbit	~600 t	~300t	~600t	~285t

Figure 3. Comparison of Mars nuclear-enabled, opposition class transportation options

Useful payload envelope per lander, comfortably within the bounds of key entry, descent, and landing technologies. This payload envelope means that each major Mars cargo item must either be less than 25 t, or be divisible into smaller pieces, delivered on separate landers and reassembled on the surface of Mars. For an initial exploration mission limited to just 30 sols on the surface, two crew could comfortably live in a Pressurized Rover (PR), eliminating the need for a large, long-duration habitat (and substantial surface power for long-duration close-loop life support). For this analysis, NASA assumed the PR features suit ports [10] and suit port-compatible Extravehicular Activity (EVA) suits to facilitate rapid crew ingress/egress with minimal loss of cabin atmosphere, and to aid in dust mitigation. Other crew support systems, such as 10 kWe Fission Surface Power (FSP) [10] or crew logistics also fit within the 25-t envelope. Without ISRU in the short stay scheme, landing a fully fueled MAV, capable of lifting two crew and return cargo to 5-sol orbit, is challenging to package within the 25 t envelope; however, some ascent propellant could be delivered on a separate lander and robotically transferred to the MAV. Note that many of these surface systems, particularly the FSP and PR could be derived from lunar equivalents built for and tested on the Moon to gain experience before an eventual Mars mission.

To best balance these competing constraints and challenges, the resulting multi-phase scheme, depicted in Figure 4, would consist of three 25 t landers. The first lander, shown left in the image, would deliver the MAV propellant, FSP, and a robotic surface mobility system. The second lander, shown center, would deliver a partially fueled MAV, which would be robotically topped-off with propellant before the crew arrives on the third lander, shown on the right. Crew would live in and work from a pressurized rover, also delivered on the third lander, as they explore the martian surface, returning to orbit aboard the MAV for rendezvous with the Mars transportation system.

5. SHORT STAY MISSION OPERATIONS

In this concept, a human Mars campaign might begin up to 10 years before "boots on Mars," with launch of a Transit Habitat (TH). After assembly and outfitting at Gateway, the fully assembled TH might spend several years in cis-lunar space, undergoing crewed test and evaluation and serving as a Mars mission analog to validate the long habitation durations needed for the Mars mission. Three landers, each with ~25-ton payload capacity, called Mars Descent Systems (MDS) would be launched, aggregated with their Mars transportation stage(s), and fueled in cis-lunar space before departing for Mars orbit. Landers 1 and 2 launch and depart Earth up to six years prior to crew arrival at Mars while the third lander launches and begins its transit to Mars about three years prior to crew arrival. The three landers and their cargo would be delivered via Liquid Oxygen (LOX)/Liquid Methane (LCH4) chemical stages on an energy-efficient, conjunction-class trajectory to Mars vicinity. The third lander, carrying a pressurized rover, a docking adapter, and crew consumables, would loiter in a 5-sol Mars parking orbit awaiting crew arrival. Spreading these deliveries out over several mission opportunities deconflicts Earth launch availability with other active campaigns, such as the Artemis lunar flights, and helps level year-to-year costs, but all three landers *could* be deployed during the same mission opportunity if budget, launch availability, and risk posture allows.

Pre-Deployed Cargo

Upon reaching Mars orbit, two of the three MDS—one carrying the MAV and the other carrying MAV propellant, a 10 kWe FSP unit, and a robotic mobility system—descend using a Hypersonic Inflatable Aerodynamic Decelerator (HIAD) [12] and a LOX/LCH4 supersonic retro-propulsion system to land within one kilometer (km) of each other and the planned crew landing site. After autonomously activating the FSP, MAV propellant is robotically transferred from the first lander to fill the partially empty MAV tanks on the second lander. To meet the minimum surface infrastructure constraint, ISRU was ground-ruled out of this architecture, which required splitting the MAV propellant load across two landers to keep each landed payload within a 25 t landed payload capacity, thus mitigating the entry, descent, and landing risk of larger landers.

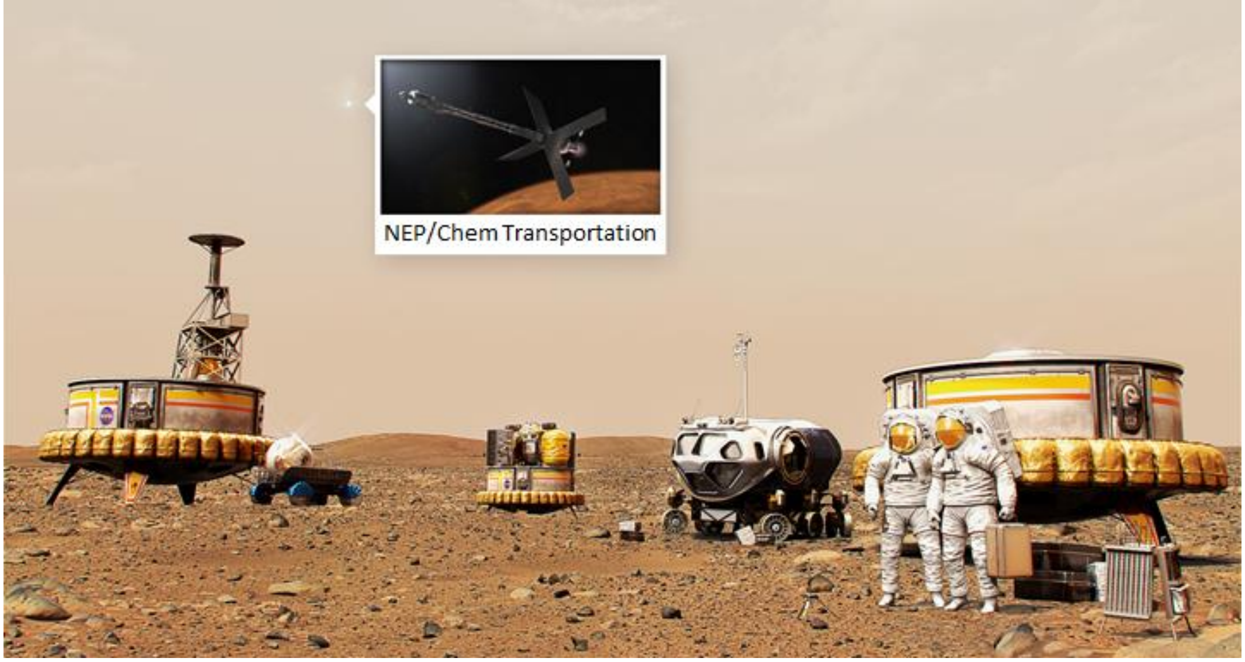


Figure 4. Artist's concept of first human Mars short stay mission architecture

Many of the human Mars mission concepts previously studied planned cargo delivery years in advance of crew to allow sufficient time for surface infrastructure deployment and subsequent MAV fueling via ISRU (which is a lengthy process). Without ISRU MAV fueling, critical cargo could theoretically be delivered shortly before crew, with just enough lead time for robotic MAV surface propellant transfer. However, three reasons to consider delivering cargo well in advance of crew are 1) to gain 25 t payload entry, descent, and landing experience in a timeframe that enables crew lander modifications based on cargo lander lessons learned; 2) to take advantage of lower-energy conjunction class opportunities for more efficient cargo delivery; and 3) as noted above, to deconflict heavy lift launch availability and level costs while operating lunar and Mars missions concurrently.

Crew Deep Space Transportation

About four years before boots on Mars, the hybrid NEP/Chemical crew transportation stage launches to cis-lunar space where the hybrid system is fueled in space via a series of commercially launched tankers. The hybrid NEP-Chem system then mates with the TH to begin a series of "sea trials" to validate integrated vehicle performance. This hybrid Mars transportation system concept was sized with a 1.8-MegaWatt (MW), 1200 Kelvin (K) reactor NEP stage featuring 100 kW electric thrusters using Xenon propellant, paired with a LOX/LCH4 chemical stage for high-energy maneuvers. When this integrated vehicle, referred to here as the Deep Space Transport (DST) is cleared for Mars service, it would transit to High Earth Orbit for rendezvous with four Mars crew members who would launch from Earth on Orion. After crew transfer to the DST, the Orion crew capsule returns to Earth. Crew transit to Mars for this particular opportunity and vehicle design would take just under 10 months. Note that duration would vary for other departure opportunities and vehicle performance assumptions. During the outbound transit, nominal crew operations would include routine vehicle system health monitoring, maintenance, and repair, and vehicle course monitoring and corrections. Housekeeping activities will include TH cleaning and periodic trash disposal. Live interface education and public outreach activities will become increasingly difficult as the crew transit farther from Earth and roundtrip communications time lags, but recorded question and answer sessions or lessons will be possible. In deep space, crew would have opportunities for solar system astronomical observations, to conduct research on the effects of the deep space environment on humans and vehicle systems, and to conduct other planned microgravity science research. To maintain fitness for landing, crew would exercise daily, undergo health and performance monitoring and testing, and utilize on-board training systems to maintain proficiency for critical entry, descent, and landing operations. The landing crew would use on-board training systems to virtually practice surface mission transits and science operations in collaboration with scientists and mission controllers on Earth.

Mars Arrival

Upon arrival at Mars, the DST would enter a 5-sol Mars parking orbit for a 50-Earth day loiter, allowing a 30-Mars sol surface stay period plus up to 10 days on either end to account for vehicle staging and phasing. Note that in-space transportation timekeeping would use Earth days to ensure correct propellant loads for the Earth-Mars transit, but surface operation timekeeping would use Mars sols to synchronize with the martian day/night cycle. After rendezvous with the third MDS, two of the four crew members would transfer from the TH to a lunar-derived Pressurized Rover (PR) via a pressurized mating adapter for their descent to the martian surface. The pressurized mating adapter is envisioned as a limited functionality solid structure, capable of carrying the docking loads between the DST and the PR, and allowing shirt-sleeve or unpressurized Launch/Entry Suit crew transfer between the TH and PR. Prior to initiation of the surface mission, the crew will have verified that all propellant has been robotically transferred to the MAV.

The two remaining crew would tend the DST, serving as a communications relay back to Earth during the 30-sol surface mission and providing low-latency communications technical support to the surface crew during critical operations. The orbital crew could handle remote tasks, such as telerobotic operation or monitoring of surface assets, or data analysis to support next-day planning and coordination with subject matter experts on Earth. During surface EVA operations, orbital crew serve much the same function as mission control’s EVA console position does for ISS, providing oversight and immediate support faster than Earth-based ground personnel could, due to the communications lag back to Earth. The orbital crew may also use their vantage point for Mars surface or Phobos/Deimos observations.

Mars Surface Exploration

To best balance accessibility to pre-deployed cargo—but avoid landing plume-induced damage of pre-deployed cargo—crew would land about one km from the other two landers. The pre-deployed mobility system would robotically connect the crewed lander to the pre-deployed surface power grid. After allowing at least three sols for crew adaptation to Mars gravity, the pressurized rover and science equipment would be off-loaded from the MDS and surface exploration begins.

Due to limited rescue options and contingency equipment, crewed exploration around the landing zone for this first mission is perhaps a 20 km radius, though the crew may deploy robotic assets to explore farther. Crew will collect samples, take environmental readings, and conduct a host of experiments. This mission concept allocates about two metric tons of science equipment.

To begin integrated stakeholder conversations about what could be accomplished during a short stay mission, a notional daily surface schedule of surface activities is outlined here. It must be emphasized that no decisions have been made and activities are likely to change as systems are refined, science objectives are better defined, and integrated operations analyses are completed.

Sols 1-3 would be nominally reserved for crew re-adaptation to a gravity environment with no scheduled EVA activity, but there is one potential contingency situation that must be protected for: if robotic assets are unable to connect the crew lander to the surface power grid, crew may have to conduct a contingency EVA to hook up the power before the lander’s on-board power supply is depleted. It remains forward work to assess this and other potential contingency operations.

During the gravity re-adaptation period, crew would exercise, reconfigure their PR cabin as needed, inspect and prepare their EVA equipment, and telerobotically inspect surface equipment. Following medical clearance, the first EVA might occur on Sol 4, when the crew would conduct a short EVA with the primary objective of testing suit functionality and crew ability to function in the suit. This first EVA might include descending from the MDS deck to the surface to demonstrate the crew’s ability to transition between the deck and the surface by EVA alone and to conduct the first human exploration activities on the surface of Mars. The crew would return to the PR for a mid-day meal. A second EVA could be conducted in the afternoon to continue preparation for off-loading the PR and other deck cargo such as science instruments and other utilization equipment. On Sol 5, crew might perform another short EVA with the primary objective of off-loading the PR, an activity that is assumed to be carried out while the crew is outside of the PR. A second EVA following a mid-day meal would complete off-loading other cargo from the lander deck and any final PR preparations before extended traverses begin. The actual off-loading concept of operations is not yet defined, pending better definition of MDS and cargo off-loading systems.

During Sol 7, the crew might begin their first excursion away from the landing site, driving to Exploration Site 1 and conducting brief EVA reconnaissance before preparing the PR for an overnight stay. On Sol 8, the crew would conduct a morning EVA, return to the PR for a mid-day meal, then conduct an afternoon EVA. On Sol 9, the crew might remain inside the PR to conduct Intravehicular Activity (IVA) activities, before venturing back outside on Sol 10. For the surface system concepts assumed, crew would need to drive the PR back to the landing site on Sol 11 and connect the PR to the surface power grid to recharge batteries. The remainder of the day could be used for housekeeping and routine maintenance on the PR and EVA systems.

On Sol 12, crew might conduct their first logistics restocking and trash removal operation, retrieving a Small Pressurized Logistics Container (SPLC) from the lander deck for repositioning onto a PR suit port. Fresh logistics would be transferred from the SPLC into the PR, then the empty SPLC would be filled with trash. The now trash filled SPLC would then be placed at a location on the surface next to the lander as its permanent disposal location. Note that trash containment and disposal will be guided by planetary protection considerations as they become available.

To comply with crew health and performance best practices, Sol 13 would be an off-duty day for the crew. Beginning on Sol 14, the crew might traverse to a second exploration site. The pattern of activity and duration of EVAs would notionally be the same as that used for the first exploration site (Sols 7-11), with the crew returning to the landing site on Sol 18 to recharge batteries, restock logistics, and remove trash. During this second restocking event, the crew could take on 14 sols of logistics, sufficient for both the next exploration site traverse and the supplies needed in the MAV for the return to orbit. Sol 20 would be another crew off-duty day before beginning traverse to a third exploration site on Sol 21. The pattern of activity and EVA durations would be like that used for the first and second exploration sites (Sols 7-11 and 14-18). The crew would make their final return to the landing site on Sol 25. On Sol 26, the crew might conduct both morning and afternoon EVAs for final science and utilization tasks in the local landing site vicinity. Sol 27 would be a scheduled off-duty day for the crew.

Crew Ascent

On Sol 28, the crew would drive to the MAV lander then deploy and dock with a pressurized tunnel for pressurized access between the PR and MAV. A short EVA period would be available for external preparation of the MAV for departure plus any other final tasks required before departure. The remainder of Sol 28 plus all of Sol 29 would be used for IVA activities necessary for MAV departure, such as transferring returned samples and logistics for the return flight, activation and checkout of MAV systems, safing selected PR systems (such as life support) to prepare for uncrewed operations, configure robotic science equipment, etc. Prior to departure, return cargo and equipment that have been exposed to the martian surface environment will be prepared in accordance with applicable planetary protection requirements and guidelines. The crew would ingress the MAV wearing their clean launch/entry suits to mitigate dust transfer back to Earth. Extravehicular activity planetary suits would be left behind to further mitigate dust transfer in accordance with planetary protection best practices. On ascent day (nominally Sol 31), the PR and tunnel would be undocked from the MAV, and the uncrewed PR would relocate a safe distance away from the MAV, nominally about 1 km, where it will remain until after crew ascent.

Post-Crew Ascent Operations

After launching in the MAV, the crew spends about 2.5 sols flying to the orbiting Deep Space Transport. After rendezvous with the TH in Mars orbit, surface crew and cargo transfer back to the TH and dispose of the MAV. The approximately 17-month return transit makes this an 850-day roundtrip mission, though additional time built into the schedule to stage and transfer crew at the front and back end of the 2039 mission makes the maximum crew time off Earth as much as 960 days. When the Deep Space Transport arrives back in a High Earth Orbit, an Orion would retrieve all four crew for return to Earth. The Mars transit vehicle could then return to Gateway for refurbishment and resupply in preparation for either continued lunar support or subsequent Mars missions. Meanwhile, back on Mars, robotic science would continue, aided by the surface assets left behind, which would include a fission power system that is impervious to the kinds of disruptions that martian dust storms might cause to solar-powered science platforms, high data rate communications, and a robotically controllable PR.

6. CONCLUSIONS AND PLANNED WORK

The architecture outlined in this paper was intended to fill in an often-overlooked corner of the architecture trade space. As expected, transporting crew to Mars and back again on an accelerated timeline requires more energy than traditional approaches, which in turn translates to significant transportation system mass. Although the total crew time away from Earth for this concept is less than traditional long-stay missions, crew time spent in transit (not on the martian surface) is longer. This reduces some crew risks—shorter overall duration means less time for equipment to break down or for crew to develop health issues—but potentially increases other risks, such as crew exposure to the deep space radiation and microgravity environment. Similarly, the short duration, light exploration footprint reduces the number of hardware developments required—and the required certification life of those developments, particularly surface systems—but puts new technologies such as nuclear-enabled propulsion into the critical path.

NASA assessed the short stay human Mars architecture concept using a structured process to identify top risks and development challenges. Key mission risks identified include: transit propulsion system failures; transit habitat mass growth and integration with the transit propulsion element; loss of primary habitable environment on the Mars surface; MAV refueling on the martian surface; advanced EVA architecture uncertainty; entry, descent and landing criticality; and long-duration spaceflight crew health concerns. Programmatic risks include nuclear transportation system technology development; entry, descent, and landing, and cryogenic propellant zero boil-off technology maturation; and multiple, parallel design, development, and test activities. Several additional aspects of the Mars mission were identified for study during the next analysis cycle, including assessment of logistics and fueling launch rates; lander delivery timing; reuse implications of first mission elements for subsequent missions; and planetary protection considerations.

A key take-away is that shorter round-trip Mars missions are certainly possible from a performance standpoint, though challenging, with flow-down implications to capabilities and cadences needed to launch, assemble, and fuel the vehicle in space. That, in turn, has implications to overall mission complexity, risk, and cost: given the very short departure and return windows for opposition class missions, there may be little margin for a single launch delay that might domino across an integrated campaign schedule. In the next analysis cycle, the short stay, hybrid NEP/chemical transportation architecture will be used as a measuring stick against which alternative mission architectures may be compared. Continuing research into NTP propulsion technologies [13] will aid NASA in refining NTP-based transportation architectures. Solar Electric Propulsion (SEP), used on Gateway, paired with a chemical stage similar to the NEP/Chemical hybrid configuration, is an attractive non-nuclear transportation option. SEP/Chemical systems optimized for propellant mass efficiency are better suited to the longer duration conjunction class missions, but NASA will evaluate potential component commonality and extensibility from SEP/Chemical to NEP/Chemical architectures, and options for accelerated SEP/Chemical mission durations. Finally, the emergence of reusable, commercial chemical transportation systems offers possibilities to enhance the human Mars architecture. A series of trade studies and analyses will evaluate various emerging launch capabilities, and potential extensibility of integrated lunar capabilities to Mars operations, helping to complete the menu of options available to decision-makers as they chart the course for humans to Mars.

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Michael Chappell *earned his undergraduate and graduate degrees in Electrical Engineering from Mercer University. He began his career at the Advanced Missile Signature Center at Arnold Air Force Base as a member of the measurements team. Continuing as a civilian with the United States Air Force, Michael moved to Robins AFB where he worked in several engineering roles including avionics sustainment, industrial controls and electrical infrastructure design, and electronic countermeasures. After many years serving the Air Force, Michael moved to a position as a guidance, navigation, and control (GN&C) integration engineer for NASA's Space Launch System (SLS) at Marshall Space Flight Center (MSFC), eventually becoming the integration lead. Currently, Michael is the deputy lead of the Mars Architecture Team (MAT) developing crewed Mars mission concepts and project manager for the supporting activities at MSFC.*

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Douglas J. Trent, PhD. *is Space Systems Team Lead in the Advanced Concepts Office at NASA's Marshall Space Flight Center. His focus areas include architecture design and analysis, technology assessment, advanced design methods, and human landing systems concepts. Current work assignments include support of the Human Landing System Architecture and Systems Analysis group, as well as the entry, descent, landing, and ascent lead for the Mars Architecture Team. Additional duties include developing a model-based, multi-objective design optimization framework for the synthesis of space systems architectures. Dr. Trent joined NASA in June 2012. Dr. Trent obtained a B.S in Mechanical Engineering from California State University, Sacramento, as well as an M.S. and Ph.D. in Aerospace Engineering from the Georgia Institute of Technology.*

Pat Troutman *graduated in 1984 from Virginia Tech with a BS in Aerospace & Oceanographic Engineering along with a minor in Computer Science. In the past 35 years he has worked for NASA designing and assessing the International Space Station, leading systems analysis related to future space scenarios including managing the NASA Revolutionary Aerospace Systems Concepts (RASC) program, helping to define the Vision for Space Exploration, leading the integration for the Constellation Program lunar surface architecture, and leading human space exploration mission design for the NASA Human Spaceflight Architecture Team and the Evolvable Mars Campaign. Mr. Troutman currently leads an Agency-wide team to integrate exploration mission systems analyses to support NASA Agency level strategic decision process with respect to the Artemis initiative. In support of the NASA Human Exploration & Operations Mission Directorate Systems Engineering & Integration, he leads the campaign integration function with respect to the human Mars & lunar architecture activity, by performing integrated assessments across objectives, requirements, performance, cost, risk and technology needs.*