A Minimal Architecture for Human Journeys to Mars

Hoppy Price, John Baker, and Firouz Naderi

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

ABSTRACT

Proposed architectures for human journeys to Mars need to take note of the two competing constraints of an executable program: the annual NASA human spaceflight budget will likely remain constrained (possibly growing with inflation), and going to Mars and landing on Mars need to happen within the interest horizon of the various stakeholders, including the public. In this article we describe a stepwise approach for human journeys to Mars using a minimal architecture. We refer to this architecture as minimal because it would minimize large new development efforts and rely largely on elements currently being developed or planned by NASA, such as SLS, Orion, a deep space habitat, and a 100-kWe-class SEP tug. In the architecture proposed here, human missions to Mars would begin with a crewed landing on Phobos in 2033, followed by a short-stay landing on Mars in 2039, and continue with a one-year stay in 2043. Each mission campaign would build on previous campaigns, leaving a legacy and new capabilities for those that follow. A first look independent cost assessment by the Aerospace Corporation suggests that this example could plausibly fit within an inflation-adjusted budget. Furthermore, although not considered here, international contributions could offset some of the cost.

BACKGROUND

In response to a Congressional charter to assess America's human spaceflight (HSF) program, the National Research Council (NRC) recently published its study findings in a report titled "Pathways to Exploration",[1] in which multiple pathways were assessed to land humans on Mars. The results were sobering: Using Design Reference Architecture 5 (DRA-5) as the technical baseline,[2] the cost for options that meet an early schedule (landing on Mars by 2033) peak well above the current annual HSF budget adjusted for inflation (*Fig. 1*). With the annual budget constrained, the schedule pushes out to near mid-century (*Fig. 2*).

Barring some compelling geopolitical phenomenon, there is not likely to be another "Kennedy moment," and the NASA budget is unlikely to see a dramatic increase. This was the motivation for this study of a "minimal architecture" based on a high technology readiness level and the concept of staggered mission campaigns, in order to stay close to the current HSF annual budget adjusted for inflation.

A STEPWISE APPROACH

Getting a human crew to Mars orbit and then safely back to Earth poses significant technical challenges for the first mission. If one adds the challenges of landing a crew on the surface of Mars, conducting surface operations, and then lifting them off the surface all on that first mission, then it becomes an unaffordable first step to the red planet. To spread out the technical risk and also the annual cost, we have examined a stepwise approach as described below:

- a round trip to Mars orbit with a crew of four and a landing on Phobos;
- a one-month surface-stay mission with a crew of two on Mars; and
- a four-crew, one-year surface-stay mission.

These campaigns would be supported by the following earlier missions/activities:

- International Space Station research, technology development, and risk reduction;
- flight testing of a 50 kWe version of the solar electric propulsion (SEP) vehicle in interplanetary space with crewed docking operations in cislunar space—this would be executed as part of the asteroid redirect mission (ARM) or, absent that, as a technology demonstration mission;
- a robotic test of the Mars lander entry and supersonic retro-propulsion (SRP) technology at Mars;
- a dress rehearsal and test flight of the first Mars landing system performed as a crewed landing on Earth's moon; and
- crewed testing of a deep space habitat (DSH) in cislunar space.

Figure 3 shows the proposed schedule for each of these steps starting with the International Space Station (ISS), which would continue to provide invaluable research and risk

DOI: 10.1089/space.2015.0018

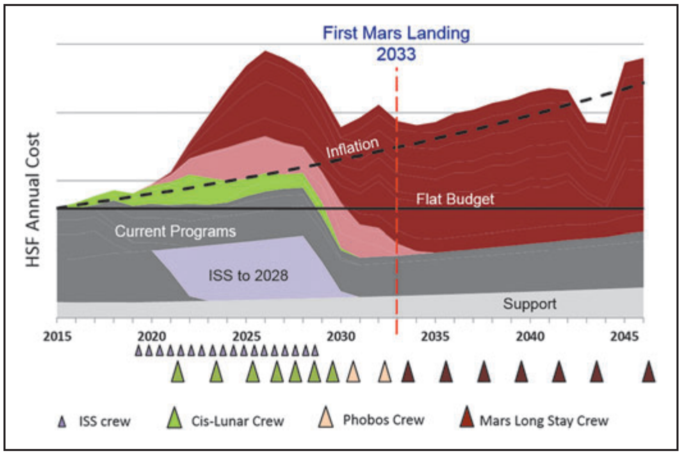


Fig. 1. National Research Council (NRC) cost profile, schedule-constrained case.

reduction for human missions to Mars through 2028. Initial test flights of the SLS and Orion systems would start in 2018 and continue through 2025, leading to the next phase, which would be the checkout of a deep space habitat prototype to test the system and validate the technologies (e.g., regenerative life support, radiation shielding) to support crewed missions to Mars. Two simulated Mars missions would be conducted in cislunar space, relatively close to Earth to provide abort opportunities, to validate the systems required for the 900-day missions. A robotic mission to Mars would be conducted to test the entry and SRP technology needed to reduce the risk for a human landing on Mars. Finally, a system test of the Mars lander would be performed at Earth's moon to validate the system design of the Mars lander. This approach provides a reasonable cadence of flight opportunities for astronauts on both the ISS and in cislunar space through 2029 prior to sending astronauts to Phobos in 2033.

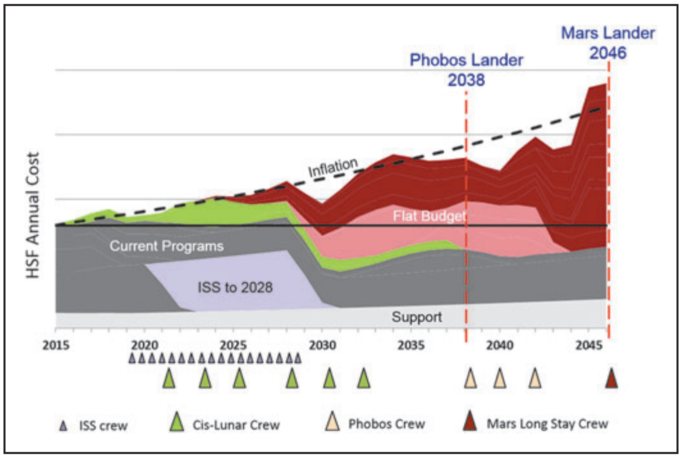


Fig. 2. NRC cost profile, budget-constrained case.

MISSION TO PHOBOS

The Phobos mission concept is illustrated in *Figure 4* and described in more detail in Price et al.[3] Key attributes of the campaign would include:

- proving out the method for getting to Mars orbit and back;
- serving as a precursor to Mars landing campaigns;
- using four SLS launches;
- prepositioning assets in Mars system using SEP tugs prior to crew arrival; and
- round-trip mission length of about 2.5 years, including about a 300-day stay at Phobos.

Each of the four SLS Block 2 launches and the mission phases are described in the following sections.

Launch #1: The SLS would inject a 100 kWe SEP Tug and its payload to Earth escape. The payload would be two in-space chemical stages to be prepositioned for use later in the campaign: (1) A Phobos transfer stage (PTS) to get a crewed Orion from high mars orbit (HMO) to Phobos and later back to HMO, and (2) A trans-earth injection (TEI) stage for returning crew to Earth at the conclusion of Mars operations. The SEP tug would transfer its payload to HMO with a trip time of about 3.8 years.

Launch #2: This SLS launch would be similar to Launch #1 except that the SEP payload would be the Phobos Habitat. The SEP tug would preposition the habitat on Phobos and remain with the habitat to provide power and the capability for relocation. The habitat would be a common design with the deep space habitat (DSH) that transfers the crew to Mars and back.

Launch #3: The payload for this launch would be: (1) the DSH and (2) the Mars orbit insertion (MOI) stage. The SLS would launch this payload to High earth orbit (HEO) where it would loiter and wait for the crew arriving on the fourth launch.

Launch #4: An Orion with a crew of four would be launched to HEO to dock with the DSH and MOI stage. The exploration upper stage (EUS) would have sufficient propellant remaining to perform the trans-mars injection (TMI) burn to send the combined vehicle stack to Mars. The transit time would be about 200–250 days, and then the MOI stage would be used to inject the crewed assembly into HMO.

Mars orbit and Phobos mission phases: Meeting up with the chemical stages pre-positioned by Launch #1, the vehicles would be reconfigured in HMO so that the TMI stage is docked to the DSH, and Orion with crew is docked with the Phobos transfer stage. The Phobos transfer stage would take the Orion and crew to the Phobos habitat, already put in place by Launch #2.

After arrival at the Phobos habitat, the transfer stage would be docked in a parking location on the habitat, and the Orion

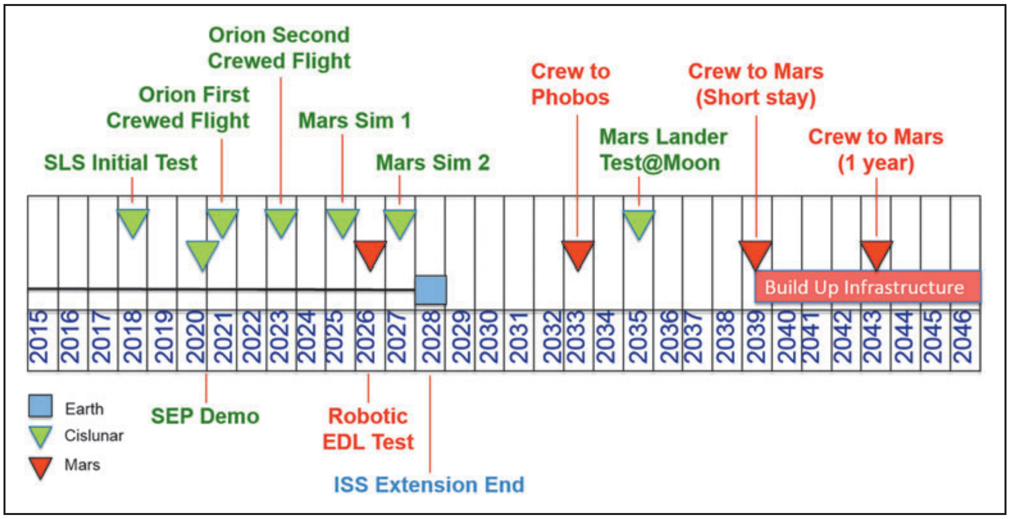


Fig. 3. Example program timeline.

would dock to an entry hatch to the habitat (*Fig. 5*). The crew would live in the habitat for about 1 year and perform an extensive science mission there, including extra vehicular activities (EVAs) on the surface. Science observations and goals for crewed Phobos exploration have been described by Abercromby et al[4]. While at the Phobos base, the Martian moon would provide radiation shielding for at least half of their exposure field of view to the space environment.

At the conclusion of their Phobos stay, the crew would redock with the parked transfer stage and use the remaining propellant to return in the Orion to HMO to dock with the transit habitat and the TEI stage, potentially stopping at Deimos on the way back. The Phobos habitat would remain in place for potential reuse.

Return phase: At the conclusion of the 500-day stay in the Mars system, the TEI stage would be used to send the Orion and DSH on a return trajectory to Earth. After about a 250-day transit, the crew would perform a direct Earth entry and landing in the Orion crew module (CM).

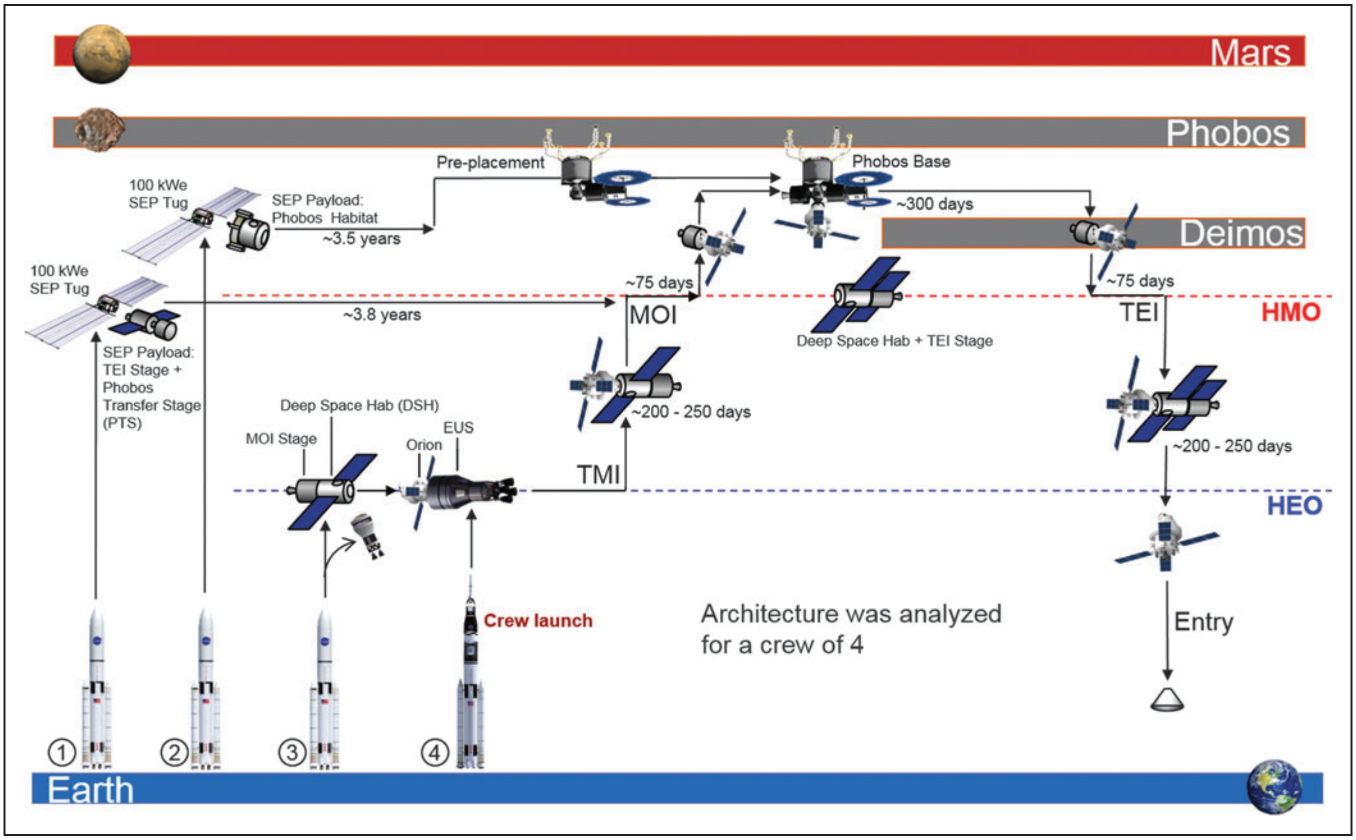


Fig. 4. Phobos mission architecture.

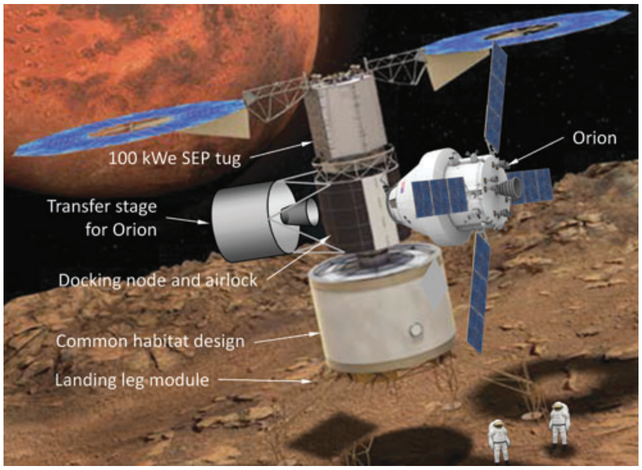


Fig. 5. Phobos base concept.

Potential reuse: If there is adequate mass margin, a small amount of additional Xenon propellant in the SEP tugs would enable them to be returned to Earth orbit or lunar orbit for possible refurbishment, refueling, and reuse. Additionally, if a deflection maneuver is performed on the returning deep space habitat, it could potentially be recovered by one of the returning SEP tugs and also returned to Earth or lunar orbit for possible reuse.

Other options were considered for a Mars orbiting mission. One option focused on teleoperation of robotic assets without crewed Phobos exploration. This would likely result in a lower cost mission. A short-stay variant of this option was also assessed, spending only about 1 month in Mars orbit before heading back to Earth, but this requires an extra Earth return stage and a Venus gravity assist, which presents thermal control risks. Options for crewed retrieval of robotically orbited Mars samples have been studied, and that could be part of the mission if additional delta V can be allocated for the crewed Mars orbital operations.

MARS LANDER CONCEPT

The lander concept (see *Fig. 6*) used in this example is a 12 m diameter traditional blunt-body entry vehicle with a heat shield that is scaled up from the Mars science laboratory (MSL) design. There would be no parachutes or deployable aerodynamic decelerators. The lander would perform a lifting descent and be steered to a precision landing. At about Mach 2, supersonic retro-propulsion (SRP) rockets would be ignited to perform the final descent and landing. Supersonic retropropulsion has been validated to some extent by Space X in their flight tests to return their first stage boosters for reuse. The upper atmosphere conditions for a portion of the Space X SRP profile are a good analog for the Mars atmosphere during SRP for a lander.

The propellants in this concept would be MMH and MON-25, using current technology pump-fed engines similar to the RS-72[5] or the Proton 3rd stage engine. It is assumed that some significant engine development work or modifications would be required. The lander would have about a 75-ton entry mass and deliver a useful landed payload mass of about 23 t. Because of its size, the lander would be launched in a "hammerhead" configuration on the SLS. Its ogive-shaped back shell would also serve as the launch fairing. This basic lander design would be used for both crew and cargo landers to the martian surface in the mission sets described here.

The lander design was assessed with a Monte Carlo simulation of the entry, descent, and landing (EDL) profile using the scenario depicted in *Figure 7*. The design was shown to close within the parameters of the simulation. A representative EDL profile is shown in *Figure 8*. In this chart,

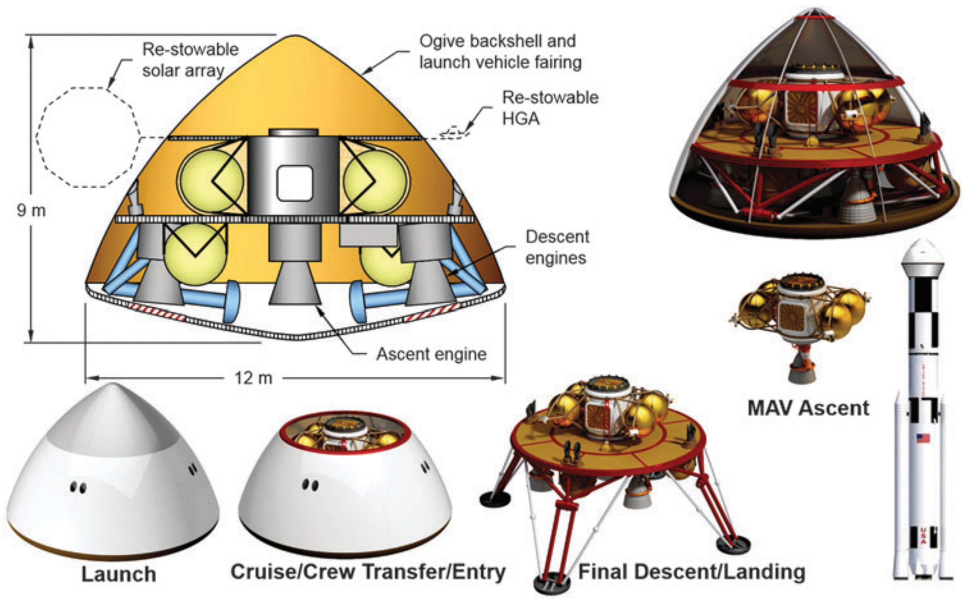


Fig. 6. Blunt-body Mars lander concept.

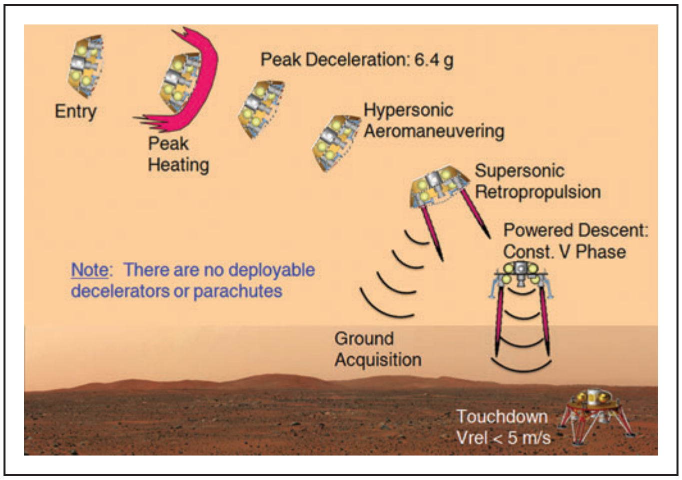


Fig. 7. Entry, descent, and landing (EDL) scenario for 75 t entry mass blunt-body lander.

time moves from right to left. The vehicle enters the Mars atmosphere in the upper right, follows the curve, and then lands on the surface on the lower left corner of the plot. Contours of Mach numbers and dynamic pressure are indicated on the plot, along with tick marks for every 10 seconds of time.

The EDL case considered here did not include any deployable parachutes or decelerators. It is possible that the use of an inflatable aerodynamic decelerator, perhaps an advanced version of that being developed by the low density supersonic decelerator (LDSD) program, could improve the performance of a lander in this class.

The Mars ascent vehicle (MAV) would use the same propellant type and the same engine type as the descent stage. It would provide a single-stage ascent to a low mars orbit (LMO). There the MAV would dock with a prepositioned boost stage to perform a second set of burns to take the MAV to HMO and transfer the crew back to Orion and the DSH. Since this MAV concept carries a full propellant load, the lander could potentially perform abort-to-orbit at some points in the EDL profile and also after landing. Note that using a two-step ascent—first to LMO and then boosted to HMO—avoids taking extra propellant to the surface, enabling a more mass-efficient and smaller lander and ascent vehicle.

The MAV crew cabin in this example is mass limited, and there is a tradeoff between the number of crew members it can support versus the number of days of life support consumables it can carry. The 23 t MAV is estimated to be able to support a crew of two for about 28 days or a crew of four for about 6

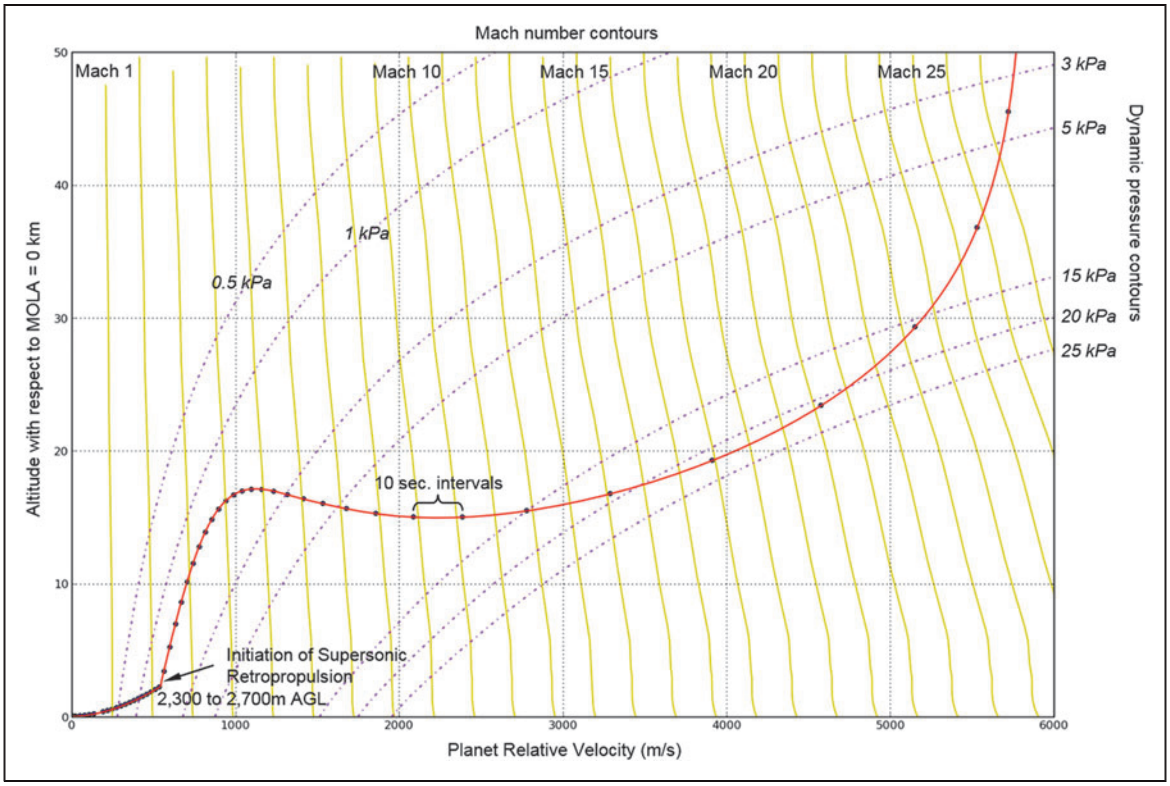


Fig. 8. Sample EDL profile for 75 t entry mass blunt-body lander.

days. The lander and MAV concept shown here requires further study and refinement to provide a higher fidelity validation of its mass and performance.

SHORT-SURFACE-STAY MARS LANDING CAMPAIGN

The Mars landing campaign would use six SLS launches, four of which have high heritage to the Phobos campaign described earlier, using proven vehicles and mission profiles. As depicted in *Figure 9*, the SEP cargo missions would be very similar to those in the Phobos campaign (*Fig. 4*), except that on Launch #1 the Phobos transfer stage would be replaced with a similar MAV boost stage. On Launch #2, the Phobos habitat would be replaced by a cargo version of the DSH that would be used to resupply the crewed habitat in HMO. The crew delivery to HMO (Launches #5 and 6) would also be identical to the Phobos campaign (Launches #3 and 4).

The new feature for the landing campaign is the delivery of the Mars lander to HMO through two launches (Launches #3 and 4 in *Fig. 9*). A dual SLS launch scenario would be used to inject the 75 t lander on a trajectory to Mars. Upon arrival, aerocapture would be used to place the lander in HMO. The lander would then wait in HMO for the arrival of the crew.

Once in HMO, the crewed vehicle integrated stack would dock with the habitat consumables resupply vehicle that had been previously placed in HMO and restock the DSH. The spent MOI stage would be replaced with the fresh TEI stage. The crewed vehicle stack would also rendezvous and dock with the lander.

For this short-surface-stay mission, two of the crew would transfer to the lander, and the other two crew members would remain in the DSH in HMO. The lander would be deorbited and perform its EDL to the martian surface. The EDL phase of the mission is shown in *Figure 6*.

The first landing mission would be a short-stay visit, similar to Apollo 17 in scope. At the conclusion of the surface mission, the crew would use the MAV to launch to LMO. The MAV would dock with the prepositioned boost stage and use that to raise the orbit to HMO to rendezvous and dock with the DSH and Orion for crew transfer. From this point on, the mission profile would be identical to the earlier Phobos mission.

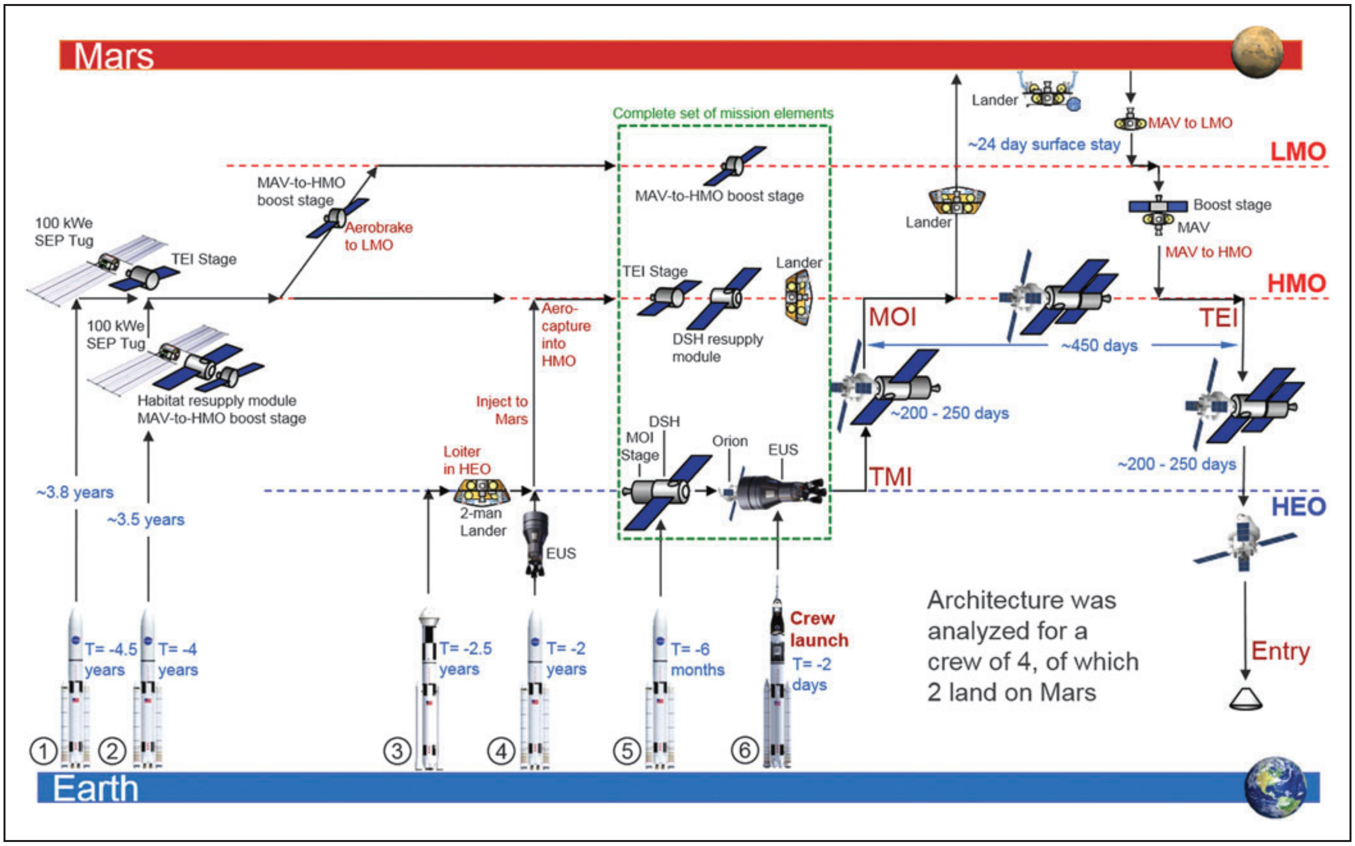


Fig. 9. Mars short-surface-stay mission architecture.

LONG-SURFACE-STAY MARS LANDING MISSION CONCEPTS

For the subsequent campaigns, a full crew of four would land on Mars and spend over 300 days on the surface. For these missions, a surface habitat and a cargo lander would be pre-placed at the landing site (using similar 23 t landers) to support the crew. This campaign would require two additional landers (thus, four additional SLS launches relative to the short-stay campaign), bringing the total SLS launches for this campaign to 10. Each lander would be delivered in a manner almost identical to the crewed lander, with the exception that they could use direct entry and avoid aerocapture as an intermediate step. The crewed segments of the mission would be identical to the previous short-surface-stay mission, except that the full crew would go to the surface. This launch campaign would be implemented with a steady cadence of one SLS launch every 6 months. The exception is that once every 2 years, two SLS launches would need to occur within one month of each other. Additional ground infrastructure at the Kennedy Space Center would be required to support those biennial extra launches, and that capability would be needed by about 2040. The profile for this campaign is shown in *Figure 10*.

TOWARD A PERMANENT OUTPOST

In a continuing program of human Mars exploration using this example architecture, a new crew of four could be sent to Mars every 4 years along with two cargo landers. Over time, infrastructure could be built up for an expanding base on Mars. In addition to consumables, the cargo landers could bring exploration equipment such as pressurized rovers, advanced surface power systems, science equipment, drilling equipment, *in situ* resource utilization (ISRU) packages, and additional habitation volume. As the Mars base expands, some crew would stay for the minimum cycle time of about 350 days, but others could possibly stay for a much longer time and wait for the next Earth return opportunity. In this way, the base could eventually be permanently occupied and evolve toward increasing self-sufficiency.

THE VEHICLES

The vehicles and number of units that would be needed for the first Mars landing mission are shown in *Figure 11*. The SLS and Orion are under development, and the SEP tug development is planned for a technology demonstration mission. The DSH is under study, and NASA has plans for its development

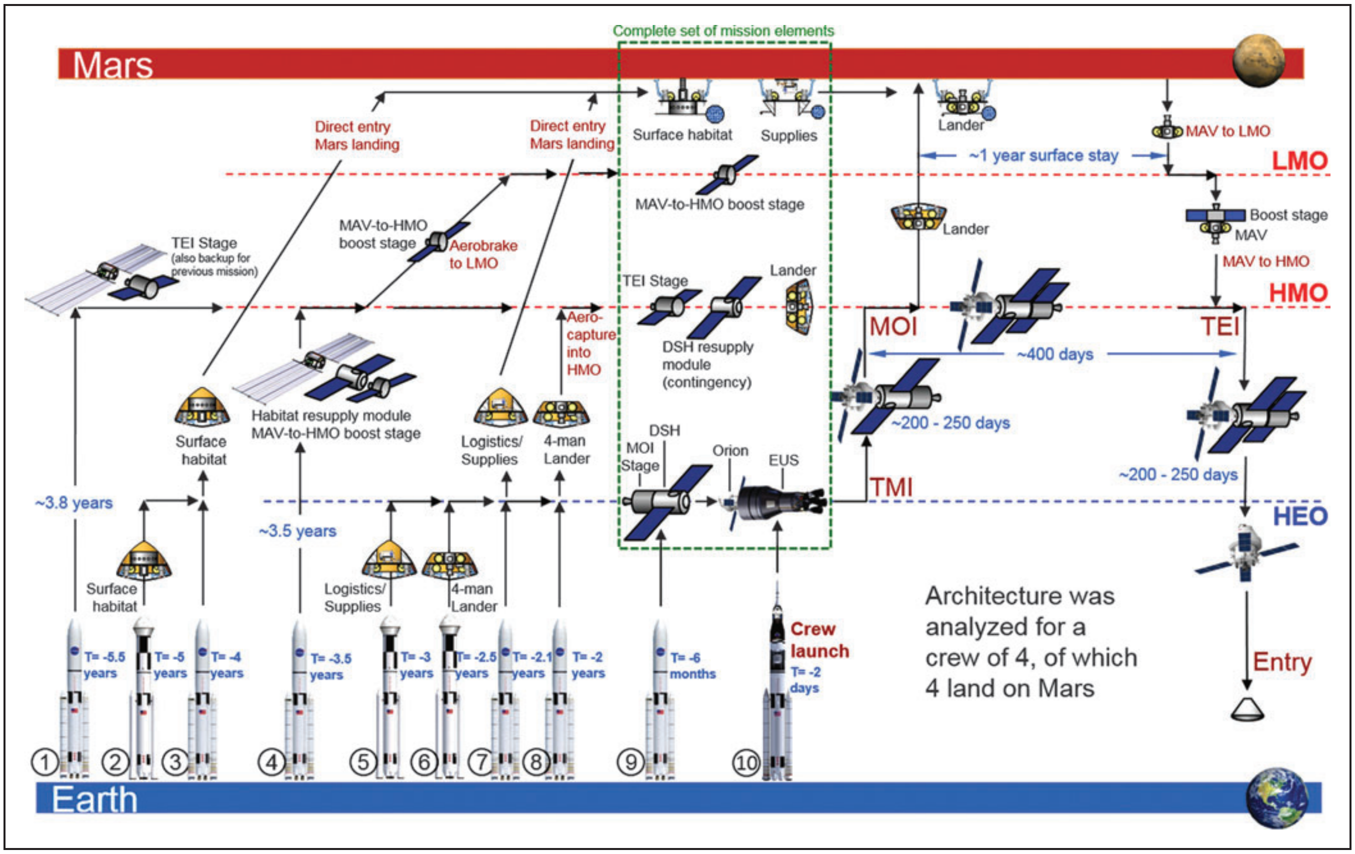
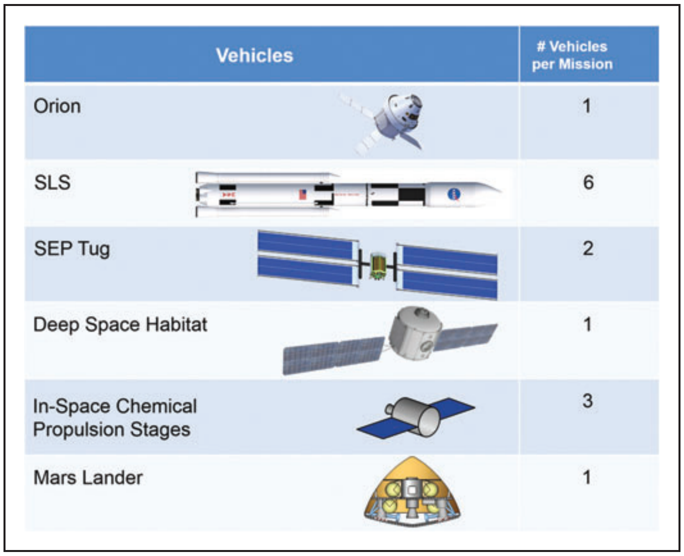


Fig. 10. Mars long-surface-stay mission architecture.



Vehicles	# Vehicles per Mission
Orion	1
SLS	6
SEP Tug	2
Deep Space Habitat	1
In-Space Chemical Propulsion Stages	3
Mars Lander	1

Fig. 11. Example vehicle set for human Mars missions.

in the early 2020s. The lander was described earlier. The chemical-in-space propulsion stages would be a new development, but a low-risk, high-TRL approach could be used. In this architecture example, these units would be conventional bi-prop systems similar in size and performance to the Titan 2 second stage. We have assumed that they would use MMH/MON-25 propellants and the same type engines as the descent and ascent stages of the lander.

The vehicle masses used in the mission design analyses are listed in *Table 1*.

Table 1. Vehicle Mass Table

Mission Element	Mass Allocation, t
Orion command module	10
Orion service module	5
Orion service module propellant	4
Deep space habitat	30
Mars orbit insertion (MOI) stage	30
Trans-Earth injection (TEI) stage	26
Orion Phobos transfer stage	14
Phobos habitat	25
Phobos landing legs, docking node, exploration equip.	12
Mars lander descent stage	52
Mars ascent vehicle	23

AFFORDABILITY SANITY CHECK

Since affordability was established as a metric for this architecture, we sought a first look cost sanity check. We concluded that for a relative comparison on affordability with the recently completed NRC report, the approach we have outlined should be evaluated by the same organization, with the same individuals using the same process and the same cost databases that were previously used. For this reason, the Aerospace Corporation performed this part of the study. Their analysis took into account the technology readiness levels of the vehicles and components used in the architecture. The results of their assessment, shown in *Figure 12*, suggest that the approach outlined here might be affordable within the current HSF annual budget adjusted for inflation with an ISS wedge opening in 2028. Additionally, because this approach uses elements with a higher technology readiness, it is reasonable that the cost risk will be lower and the schedule confidence higher. However, it should be noted that while this provides a good basis for a relative comparison with the NRC pathways, a much more detailed exercise is needed to establish a higher fidelity cost estimate for budget commitment.

CONCLUSIONS

Annual budget constraints need to be considered as a design requirement for human journey to Mars architectures since it is likely that the NASA budget will not see a dramatic increase beyond adjustments for inflation. This in turn requires a phased approach toward establishing a permanent outpost on Mars to allow the technical risk and the required funding to be spread out and still deliver significant and

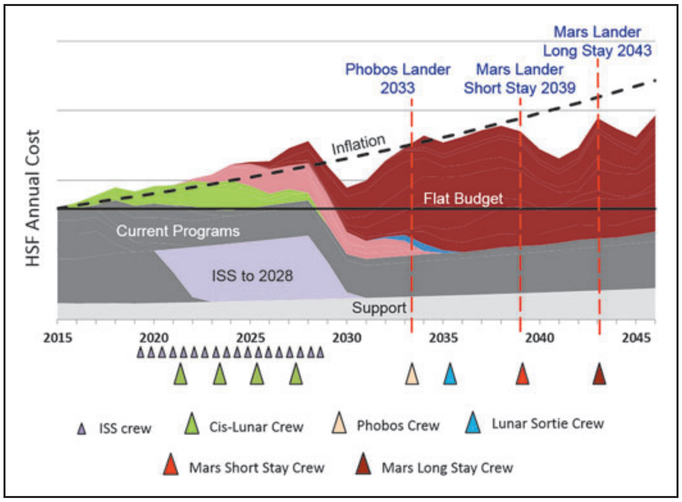


Fig. 12. Budget profile for example minimal mission set.

publicly engaging milestones along the way. One such approach is presented here as an example. It is a minimal architecture that relies on assets already under development or planned by NASA. A series of missions in cislunar space would lead to a Phobos lander in 2033 to be followed in short order by a dress rehearsal landing on the Moon, and then by a crew to the surface of the red planet by 2039.

We hope that the ideas and principles introduced here in whole or in part can be a useful input to the process of structuring an implementable human journey to Mars in our lifetime.

ACKNOWLEDGMENTS

The humans-to-Mars community is small, and ideas are readily shared and build on each other. This JPL internal study has evolved over the past 2 years and, along the way, has been shared with others both inside and outside of NASA whose comments and critiques have helped us improve on the concept. In turn, this study has spawned similar ideas within other teams who have adopted aspects of this architecture.

We would like to acknowledge contributions of colleagues Nathan Strange, Damon Landau, Ryan Wooley, Rob Manning, Mark Adler, Ian Clark, Bobby Braun, Rob Grover, Evgeniy Sklyanskiy, Steve Sell, Bob Shisko, and Raul Polit-Casillas. Finally, we acknowledge the Aerospace Corporation, specifically Torrey Radcliffe and Randy Persinger, who undertook the cost assessment of this architecture on the same basis as used for the NRC study.

The research described in this article was carried out at the Jet Propulsion Laboratory, California Institute of Technology, using JPL internal funds. The Jet Propulsion Laboratory is under a contract with the National Aeronautics and Space Administration. Copyright 2015 California Institute of Technology. U.S. government sponsorship acknowledged.

AUTHOR DISCLOSURE STATEMENT

The authors declare no conflict of interest regarding this study.

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Address correspondence to:
Hoppy Price
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive, M/S 301-170S
Pasadena, CA 91109

E-mail: Humphrey.W.Price@jpl.nasa.gov