The Fifth Community Workshop on Achievability and Sustainability of Human Exploration of Mars: Three Scenarios for the 2030s (AM V)

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Sponsored by Explore Mars, Inc. & the American Astronautical Society

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THE SUMMARY OF

The Fifth Community Workshop on Affording, Achieving, and Sustaining Human Mars Exploration

Beginning in December 2013, Explore Mars, Inc. and the American Astronautical Society jointly sponsored annual community-based workshops, known as the *Achieving Mars* (AM) workshops, on major aspects of human exploration of Mars, including science goals (AM III), priority technology investments (AM IV), and development of architectures to achieve different "end states" of human exploration of the Mars system within the decade of the 2030s (AM V). A major goal of these workshops from their inception has been to involve the broad U.S. space exploration community – NASA, industry, and academia – together to provide decision-making input to national space policy. The final reports of the first five workshops are hosted on the Explore Mars, Inc. website at https://www.exploremars.org/affording-mars .

Over the past few years NASA and multiple other organizations have produced a large number of plausible scenarios for human exploration of Mars in the 2030s. In general, however, these scenarios have been developed independently. The fifth *Achieving Mars* invitation-only workshop (AM V) held in December 2017, in contrast, brought much of the human exploration community together to develop three distinctly different human Mars exploration architectures. Subject matter experts identified areas of commonality, as well as areas where opinions differ and important decisions need to be made among the three.

Three different "end states" for human exploration of Mars were adopted at AM V and an architecture was developed that sought to achieve each of those end states under common ground rules and constraints. The three end states were

1. Initial exploration analogous to the Apollo Program or the Lewis and Clark "Corps of Discovery"
2. Semi-permanent base or "field camp" on the martian surface, analogous to early Antarctic exploration
3. Building toward sustained, permanent habitation analogous to current Antarctic exploration

Three teams, both during the workshop and over the months that followed, developed and critiqued the distinct architectures in detail that achieved the three end states. They were guided by a handful of ground rules and assumptions:

- The initial human mission to the vicinity of Mars will take place by about the mid-2030s.
- SLS and Orion will be available during the time period considered here, so will not be assessed in depth in this workshop.
- Early and focused technology investment will be identified, including precursors and demonstration missions.
- Partnerships (international, industrial, commercial, academic) will be an essential component.
- The role of lunar surface operations with astronauts and robots will be assessed.
- The role of a cis-lunar habitation and operations facility will be assessed.
- Community engagement will be essential.
- Research and development will continue on ISS at least through the mid-2020s.
- Budgets available for human exploration of Mars will be assumed to grow approximately with inflation. If additional funding appears to be required above that, plausible sources of the funding will be identified.
- No technological "miracles" or, if so, clearly identify and justify them.

In addition to major exploration timelines and milestones, major elements of the architecture and an annual and total cost for each of the three architectures are presented in the final report.

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Workshop Sponsors

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Executive Summary

In late 2017, approximately 60 government, industry, and academic professionals in human exploration technologies and operations, scientific exploration of Mars, and senior management met for three days in Washington, DC to begin to assess in depth three distinctly different scenarios for the human exploration of the Red Planet by the end of the 2030s. Significant work continued for many weeks after the close of the workshop.

The three scenarios were chosen to span a plausible range of missions that might be carried out over the next two decades: (1) a series of short-stay sorties, (2) a “long-stay” science-oriented mission, and (3) a “long-stay” mission that begins to significantly build up infrastructure for sustained human occupation. Ground rules for the missions included a realistic long-term budget, cost-limited technology developments, use of the International Space Station and the Space Launch System, and opportunities for commercial and international participation.

Each of the scenarios identified priority technology developments, key elements necessary for success (e.g., number of launch vehicles, crew size, use of ISS and the Gateway, rendezvous in space), a year-on-year cost estimate, and the role of science exploration.

The findings and observations of this lengthy assessment activity are discussed at length in the body of this report and included for all three teams:

- All three teams agreed that the first surface mission was feasible to be flown no later than 2037.
- The destination should be the Martian surface.
- All missions should be flown using conjunction-class trajectories. The long-duration stay in the Martian system was key to the exploration objectives.
- So-called “split missions” are desired to deliver cargo ahead of the crew. Rendezvous/transfer activities should occur in Mars orbit.
- All landers should be pre-deployed to Mars orbit, but Earth-return propellant should be delivered with the crew and should not be separately pre-deployed.
- International and/or commercial launch vehicles could be considered.
- Launch vehicles will require a minimum of 8.4-meter diameter payload fairings for most Mars architecture elements, with 10-meter diameters needed for most Mars landers.
- All teams favored the use of aerocapture or aerobraking for Mars orbit capture.
- A crew should consist of 4 – 6 members
- Landers need <100 m landing accuracy
- Landing zone surveys should be conducted both from orbit and robotically.
- Surface science operations should focus on field work within the 100 km Exploration Zone.
- A deep-space/cislunar habitat (aka, Gateway) should be designed eventually for missions of 1000 days or more, analogous to human missions to Mars.
- Radiation issues should be handled passively.
- Crew health should be maintained using zero-g exercise countermeasures (as on ISS). All teams assumed that the crew health issues associated with a 1000+ day free space mission (e.g., Mars orbit) can either be mitigated or the risks accepted.
- Modular surface habitats were seen as adequate, with large monolithic habitats or those constructed from local resources or features not required.
- All types of robotics should be employed.

Background: The AM Workshop Process and Initiation of AM V

The *Achieving, Affording, and Sustaining Human Exploration of Mars Workshops* were initiated in early 2013 with the purpose of involving representatives of the broad community of technologists, engineers, scientists, and policymakers in assessing and developing scenarios, technology investment plans, and goals for the human exploration of Mars.

To continue to build a broadly based consensus on the future of human space exploration, the *Fifth Community Workshop on Achievability and Sustainability of Human Exploration of Mars* (AM V), organized by Explore Mars, Inc. and the American Astronautical Society, was held at the Washington Plaza Hotel, Washington, D.C., December 5-7, 2017.

Approximately 60 invited professionals from the industrial and commercial sectors, academia, and NASA, along with international colleagues, participated in the workshop. These individuals were chosen to be representative of the breadth of interests in astronaut and robotic Mars exploration.

AM V built upon the four previous *Affordability and Sustainability Workshops* (i.e., AM I–IV; https://www.exploremars.org/affording-mars). Those previous workshops assessed and reported on multiple scenarios for human exploration of Mars. For that reason, our organizing committee concluded that the 2017 workshop would concentrate specifically on distinct scenarios specifically intended to affordably achieve three different "end states" for human operations on the Martian surface. Included in each scenario, each of which was developed and critically reviewed during the workshop and which is reported on here, are significant milestones, major elements of the scenario, priority early developments, and the realism of the affordability of the scenario.

The output of the workshop consists of findings and observations presented to space agency leadership, to policymakers, and at professional conferences.

Guiding Workshop Assumptions and Ground Rules

The three teams, both during the workshop and over the months that followed, developed and critiqued the three architectures that achieved the three end states. They were guided by a handful of ground rules and assumptions:

- The initial human mission to the vicinity of Mars will take place by about the mid-2030s.
- Budgets available for human exploration of Mars will be assumed to grow approximately with inflation. If additional funding appears to be required above that, plausible sources of the funding will be identified.
- The Space Launch System (SLS) and Orion will be available during the time period considered here, so will not be assessed in depth in this workshop.
- Early and focused technology investment will be identified, including precursors and demonstration missions.
- Partnerships (international, industrial, commercial, academic) will be an essential component.
- The role of lunar surface operations with astronauts and robots will be assessed.
- The role of a cislunar habitation and operations facility will be assessed.
- Community engagement will be essential.
- Research and development will continue on the International Space Station (ISS) at least through the mid-2020s.
- No so-called technological "miracles" are permitted or, if so, clearly identify and justify them.
- In addition to major exploration timelines and milestones, major elements of the architecture and an annual and total cost for each of the three architectures will be presented in the final report.

The Three “End States” for Human Exploration of Mars: Points of Agreement and Points of Departure

The workshop organizers adopted for this workshop three “end states” intended to represent distinct points along a continuum of options for human Mars exploration (Figure 1): an Apollo-style architecture, a science-oriented “field camp” architecture similar to early Antarctic exploration, and an architecture that laid the groundwork for permanent human habitation. Workshop participants were divided into three teams, each challenged to define a human Mars architecture that concluded with one of the “end states”:

1. The “sortie-class” concept is for initial human Mars exploration with a series of near-term affordable missions, first to Mars orbit, followed by a series of sortie missions to the Martian surface with crews of four. This approach would initially utilize proven technologies and vehicles that are currently under development by NASA, U.S. commercial aerospace, and international partners.
2. The second “end state” assessed was to send humans to a temporary field station on the surface of Mars from which the crew would conduct scientific research, analogous to early human exploration of Antarctica. This field station was not intended to be the final end state for human visits to Mars. The development of the field station could feed forward into scenarios for permanent human habitation, but was not required to accomplish it. Our field station architecture begins with a program to maximize the usefulness of lunar missions for future Mars development.
3. Our third team assessed what mission architectural elements would be needed to support the long-term goal of permanent human habitation of Mars. It was the strong consensus of the team that the audacious goal of permanent presence should be the end state needed to guide an overall Mars investment strategy and to minimize sustaining costs. The team recognized that the fundamental source of enterprise sustainability required for permanent human habitation is both a critical mass, as well as a broad portfolio of international and commercial partners. Although the team believes in the importance of sustained presence as the long-term goal, the team also felt that an incremental and iterative architecture is needed, which places a priority on getting to the Martian system sooner rather than later, thus letting resulting lessons learned from initial voyages inform subsequent engineering developments. Such a strategy not only has the advantage of ensuring engineering investments are those that are needed, but also amortizes costs over a longer period of time. An initial orbital mission – or possibly several – is a key element of an iterative strategy.

As each team defined its architecture, its members were making numerous decisions related to space transportation, surface access, surface systems, and dozens of other variables that define a human Mars architecture. As part of each team’s deliverables, they captured these choices on a large matrix of design variables supplied to them by the workshop organizers. Their responses to this matrix, in addition to the detail captured in each of the architecture descriptions, were compiled and compared. Our side-by-side comparison provides insight into the architectural design variables that were common to all architectures as well as those design variables that differed across architectures.

The “common” design variables provide useful insight into a number of core decisions that applied across the wide breadth of human Mars architectures, and which can form the core of any mission architecture. Just as importantly, the design variables that provided unique responses to each architecture provide insight into architecture choices that vary as a function of end state.

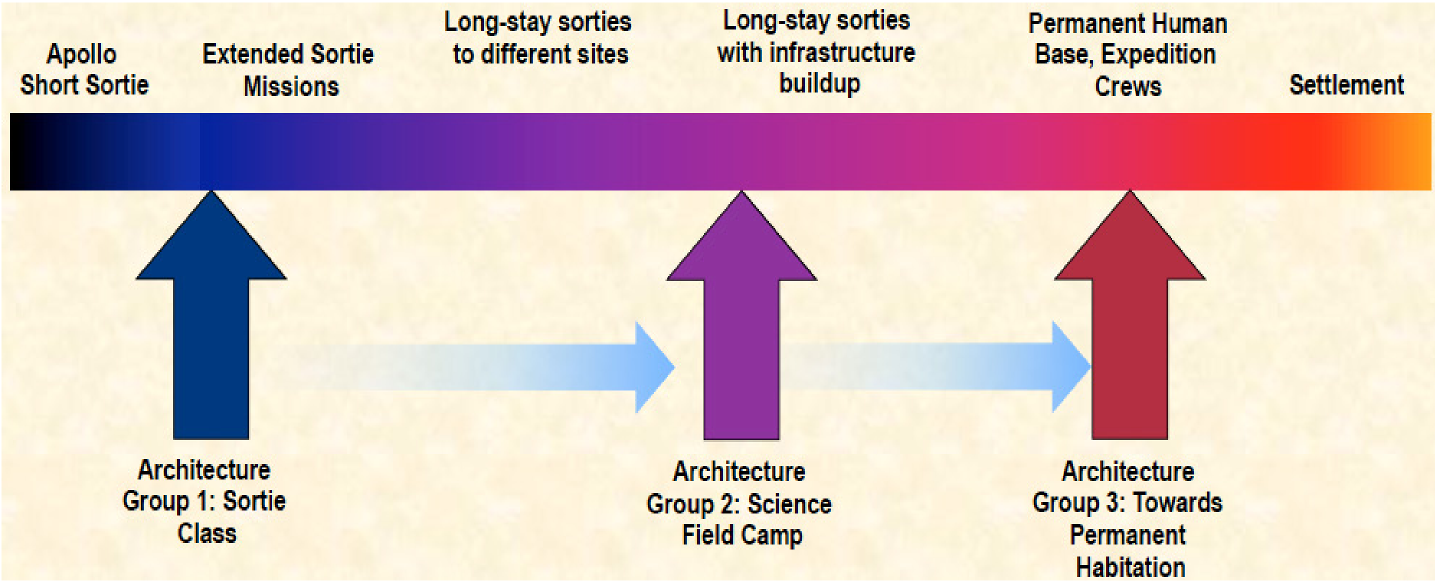


Figure 1. The three scenarios adopted here shown on the continuum of "end states" for human exploration of Mars.

Figures 2 through 6 below capture the architectural choices made by each of the three teams. The color coding indicates the specific endpoint that these teams were designing towards.

Apollo-Class	Research Base / Antarctic Field Analog	Primary Activity: Human Expansion

Mission Architecture / End State						Transportation					
						Earth-to-Orbit					
Primary Program Focus	Mission Class	Level of Human Activity	Earth Based Mission Support	Cost Emphasis	Reusability	Crew Launch Vehicle	Propellant and/or Logistics Launch Vehicle	Element Launch Vehicle	Launch Vehicle Shroud Size / SLS 2B Fairing	Earth-to-Orbit Flights per Expedition	Launch Vehicle Rate
Apollo-Class	Opposition Class - Short Stay (1-60 sols)	Robotic / Telerobotic	Continual Control	Low Cost / Gradual Build-Up	None	SLS/Orion	SLS	SLS	8.4 m Diameter, Short Length	2	1 per year
Research Base / Antarctic Field Analog	Conjunction Class - Long Stay (300+ sols)	Expeditions	Moderate Intervention	High Cost / Gradual Build-Up	In-Space Habitation	International	International	International	8.4 m Diameter, Long Length	4	2 per year
Primary Activity: Science & Research	All-Up vs. Split Mission	Human-Tended	No Daily Intervention	Low Cost / Fast Build-Up	In-Space Transportation	Commercial	Commercial	Commercial	10 m Diameter, Short Length	6	3 per year
Primary Activity: Resource Utilization		Continuous Presence	Minimal	High Cost / Fast Build-Up	Tradeable: EDL and Ascent	Combination	Combination	Combination	10 m Diameter, Long Length	8	6 per year
Primary Activity: Human Expansion		Human Settlements			Surface Systems		None		12 m Diameter	10 +	
		Human Colonization			Infrastructure for Permanent Habitation						

Figure 2. Human Mars architecture decision matrix (1 of 5)

Transportation												
Cis-Earth Infrastructure							Deep Space					
Initial Orbit	Long-Term Staging	Supporting Space Infrastructure Mass	Orion	In-Space Refueling	Earth Return Mode	Cis-Lunar Propulsion	Mars Orbit Propulsion	Chemical Propellant	In-Space Habitation	In-Space Habitat Duration	No. of Crew to Orbit	Pathway
DRO	Cis-Lunar Hab	< 50 mt	Take Orion to Mars	Yes	Direct Entry	All Chemical / Cryogenic	All Chemical / Cryogenic	NTO / Hydrazine	Monolithic Transit Hab	600 days	2	DSG > 2-year Flyby > Long-Stay Surface
Near Rectilinear Halo Orbit (NRHO)	No Cis-Lunar Infrastructure	50 - 100 mt	Leave Orion in Orbit	No	Earth Orbit Capture LDHEO	All Chemical / Storable	All Chemical / Storable	LOX / Methane	Modular Transit Hab	1000 days	3	DSG > 2-year Flyby > Short-Stay Surface
LEO		100 - 200 mt			Cis-Lunar Orbit Capture	NTR	NTR Trade	LOX / Hydrogen	Combination	1200 days	4	DSG > 3-year Orbital > Long-Stay Surface
HEO		> 200 mt				SEP	OCT				5	DSG > 3-year Orbital > Short-Stay Surface
Cis-Lunar Space						Hybrid SEP / Chem	Hybrid SEP / Chem				6	DSG > Cis-Lunar > Short Surface > Long Surface
						Hybrid SEP / Hypergols	Hybrid SEP / Hypergols				> 6	
						Split SEP / Chem	Split SEP / Chem					
						Q-Drive	Q-Drive					
						SEP / Chem / Aerobrake	SEP / Chem / Aerobrake					
						NEP	NEP					
						Bimodal NTR	Bimodal NTR					

Figure 3. Human Mars architecture decision matrix (2 of 5)

Transportation													
Deep Space												Earth Return	
Destination	Mars Parking Orbit	Mars Orbit Insertion - Cargo	Mars Orbit Insertion - Crew	Mars Orbit Operations	Mars Descent Propellant	Ascent Vehicle Propellant - From Earth	Ascent Vehicle Propellant - From ISRU	MAV Payload Up	Earth Capture Orbit	Earth Return Scheme	Mars Pre-Deployment	Descent to Earth's Surface	Earth Entry Vehicle
Mars Orbit	1-sol	Propulsive	Propulsive	Minimal	Storables	Cryogenic	LOX Only	0 kg	Direct Entry (with Transit hab flyby)	Direct Entry	Consumables	Direct	Orion
Phobos	5-sol	Aerobrake	Aerobrake	Rendezvous / Transfer	Cryogenic	Hypergol	LOX Methane	250 kg	DRO	Propulsive Capture	None	Separate System	Commercial
Mars' Surface	500 km Circular	None	None	Vehicle Refurbishment		Other	LOX/Hydrogen	> 250 kg	NHRO		Landers		Combination
Combination	Areosynchronous	Aerocapture					Other	100 kg	HEO →		Earth Return Propellant		
Lunar First							None		Cis-Lunar		Unpressurized Rover		
Areosynchronous											Science Equipment		
Mars Flyby													
Backflip													
Grand Tour													
Fast													

Figure 4. Human Mars architecture decision matrix (3 of 5)

Human Health			Surface								
Radiation	Countermeasures	Design Considerations	First Surface Mission Date	Crew Surface Stay Time	No. of Crew to Surface	Lander Payload Size (Metric Tons)	Landed Mass per Crewmember (Metric Tons)	Lander Entry Type	Landing Location	Lander Altitude	Landing Accuracy
Passive	Zero-G w/Exercise	Psychology	2035	Short Stay (1-60 sols)	2	18	18 mt lander: 6.0 - 36.0 mt	Blunt Body	Near Equator	- 6 km MOLA	< 100 m
Active	Artificial Short Arm	Medical	2037	Long Stay (300+ sols)	3	20	20 mt lander: 6.7 - 40.0 mt	Mid L/D	Polar	0 km MOLA	100 m - 1 km
	Artificial Long Arm	Dust	2039	Variable Short → Long	4	22	22 mt lander: 7.3 - 44.0 mt	Inflatable	Mid-Latitude	+ 2 km MOLA	> 1 km
			2041 +		5	25	25 mt lander: 8.3 - 50.0 mt	Deployable	Northern Hemisphere		
			2033 Orbital		6	27	27 mt lander: 9.0 - 54.0 mt	All Propulsive	Southern Hemisphere		
			Scales with Budget		> 6	30	30 mt lander: 10.0 - 60.0 mt		Different for each mission		
					All (4 or 6)	40	40 mt lander: 13.3 - 80.0 mt		Near Water (Subsurface Ice)		

Figure 5. Human Mars architecture decision matrix (4 of 5)

Surface														
ISRU	Power	Habitat Type	Life Support	Planetary Outpost	Excursion Radius/ Exploration Zone	Length of Surface Stay	Planetary Sciences	Laboratory Sciences	ECLSS	Trash	Robotics	Landing Zone Surveys	Cargo Handling	Surface Communication
None	Solar	Monolithic	Open	Different for Each Expedition	< 10 km	7 sols	Teleoperation of Instrument/ Networks	None	Open	Containers	Low Latency Telerobotics	Orbital	Crane/ Hoist	Line of Sight
Demonstration Only	Nuclear	Modular	Closed	Single Outpost	10 - 100 km	14 sols	Recon Geology / Geophysiology	Basic Analysis / No Lab	50 - 75% Closed	Recycle	Autonomous	Robotic	Ramp	Relay Satellite
Atmospheric Oxygen	RTG	Inflatable		Multiple Outposts	> 100 km	30 sols	Field Work	Moderate Geochemical + Life Science	75 - 90% Closed	Combination	Crew Partnered		ATHLETE	
Water from Regolith	Combination	Rigid			Walk Back	90 sols	Drilling/ Geophysical Tests	Full-Scale Life Science	> 90% Closed		All		Other	
Water from from Subsurface Ice	Fuel Generator	Local Features and Resources				300 - 500 sols							Humans	
Fabrication / Manufacturing		Ascent Stage				500 - 1000 sols							TBD	
Combination						> 1000 sols, overlapping crews								
Export														

Figure 6. Human Mars architecture decision matrix (5 of 5)

Points of Agreement: Architectural Design Decisions Common to All Architectures

A number of workshop "input" assumptions were identified as common design choices from each of the architecture teams, including the use of Orion and SLS. However, some specific challenges for both of these programs were common across architectures, including evolution of the Orion crew complement from 4 to 6, and the need for a 10 meter-diameter launch fairing on the cargo version of the SLS to support Mars entry, descent, and landing (EDL) systems.

Additionally, all three mission scenarios had in common:

- All teams agreed that the first surface mission was feasible to be flown **no later than 2037**.
- The destination should be the Martian surface. Preliminary astronaut missions to cislunar space, lunar surface, Venus, flyby of Mars, or Phobos missions were considered unnecessary, largely because Mars is vastly different from these other venues. In addition, robotic demonstration and precursor missions appear able to carry out desirable missions in advance of humans to Mars.
- All missions should be flown using **conjunction-class trajectories**. The long-duration stay in the Martian system was key to the exploration objectives, and even the Apollo-class architecture that only planned to stay on the surface for 14 sols[1] supported conjunction-class missions, using the remaining time in Mars orbit to achieve additional priority goals (e.g., telerobotic exploration on the surface or construction of infrastructure).
- **Split missions** are desired to deliver cargo ahead of the crew. Rendezvous/transfer activities should occur in Mars orbit. For each expedition, at least four Earth-to-Orbit flights are required, at a rate of 2 or more per year. There was no expectation of a high-cost/fast buildup program.
- All landers should be pre-deployed to Mars orbit, but Earth-return propellant should be delivered with the crew and should not be separately pre-deployed.
- **International and/or commercial** launch vehicles could be considered. Propellant, logistics, and elements could be launched on any combination of SLS, international, and commercial vehicles.
- Launch vehicles will require a minimum of **8.4-meter diameter** payload fairings for most Mars architecture elements, with **10-meter diameters** needed for most Mars landers.
- All teams favored the use of **aerocapture or aerobraking** for Mars orbit capture.
- A crew should consist of **4 - 6 members**
- Landers need **<100 m landing accuracy**
- Landing zone surveys should be conducted both from orbit and robotically
- **Earth-based mission support** (mission control) should be used differently than it is today, with only moderate oversight of crew activities and monitoring of the mission. Continual Earth-based mission support is neither possible nor required, although a minimum to moderate amount of support is desired.
- **Relay satellites** should be used for surface communication.
- **Surface science operations** should focus on fieldwork within the 100 km Exploration Zone.
- A **deep-space/cislunar habitat** (aka, Gateway) or its follow-on facility should be designed eventually for missions of 1000 days or more, and was seen as requiring no more than 50 mt of supporting deep space infrastructure.
- **Radiation** issues should be handled passively.
- **Crew health** should be maintained using zero-g exercise countermeasures (as on ISS). All teams assumed that the crew health issues associated with a 1000+ day free space mission (e.g. Mars orbit) can either be mitigated or the risks accepted.
- **Modular surface habitats** were seen as adequate, with large monolithic habitats or those constructed from local resources or features is not required.
- **All types of robotics** should be employed, with science goals an important component.
- A number of workshop "input" assumptions showed up as common design choices from each of the architecture teams, including the use of Orion and SLS. However, some specific challenges for both of these programs were common across architectures. This included evolution of the Orion crew complement from 4 to 6, and the need for a 10-meter diameter launch fairing on the cargo version of the SLS to support Mars EDL systems.

[1] A sol is one solar day on Mars (24 h 39 m).

Points of Departure: Architectural Design Decisions Vary Across Architectures

In contrast to the architectural decisions shown in Figures 2 thru 6 that are common across architectures, several others stand out as having little or no commonality among them. Most obvious is the length of the surface mission, which is tied directly to the three end states: 14-sol sorties, 90- to 500-sol science research missions, and >1000-sol human expansion missions.
Others include:

- **The potential dates for conducting an initial mission are inversely proportional to the mission's scop**e:
  - The simpler sortie-type mission targets 2033 for a crewed mission to Mars orbit and a two-week sortie mission to the Martian surface in 2037.
  - The Research Base prefers 2035 or 2037 missions, although is realistically targeting the 2040s, dependent on NASA's lunar mission timeline and available budgets.
  - The Human Habitation architecture did not target a specific date, but instead states that the timeline would scale with available budget.
- **Build-up of mission capabilities corresponds to the scope of the mission endpoints as well**. The sortie architecture goes directly to a short surface stay, the Research Base architecture favors an evolutionary buildup from short to longer-duration surface missions, as does the Human Habitation architecture.
- **Use of in-situ resource utilization (ISRU) for propellant varies among the architectures.** The more limited sortie missions do not utilize ISRU, the Research Base architecture prefers LOX-based ISRU, evolving to propellants, and the Human Habitation architecture embraces the full suite of ISRU products.
- **Landing sites.** The location of the landing site is not considered to be a major decision point for the Apollo-style scenario, since this scenario proposes simple science sorties targeting different sites for each mission. The Research Base architecture would seek a mid-latitude site, but the Human Habitation scenario considers the location of the landing site to be primary to its mission, desiring a single landing site with the availability of multiple resources, including water, carbon dioxide, radiation protection, construction and additive manufacturing raw materials, and power availability.

Observations

Design of a feasible mission for landing humans on the Martian surface should include the points of agreement outlined above, regardless of the final mission type. For example, the reference architecture should be based on a conjunction-class, long-stay mission, with the Martian surface as the primary destination, and the first crew landing planned for no later than 2037. SLS (with a 10-meter fairing for landers) and Orion should be the vehicles used, with at least two launches per year. Crews should consist of 4 - 6 crewmembers, with at least four going to the surface. A human Mars orbital mission might be included within a scenario of a series of sorties, although the goal of human Mars exploration should be landing humans on the Martian surface.

Landing zone surveys should be conducted from orbit initially by robots and, subsequently, by crews. Landers need to have a landing accuracy of <100 m. All operations require at least one cargo lander to be pre-deployed before crew arrival, and landers should be sized to carry at least 20 mt of payload, including consumables, science equipment, and rovers. Relay satellites can be used for surface communication. Crew surface science operations should focus on fieldwork and employ all types of robotics as well as the teleoperation of instruments for long-term studies.

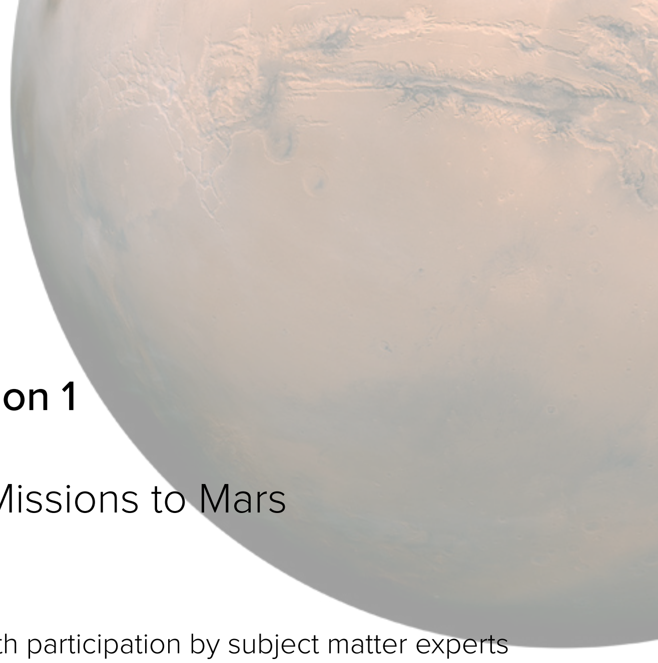
Regardless of the final operational and timing decisions, the architectural concepts as described in this report, along with previous studies, provide a common foundation for a reference architecture that is both viable and achievable, and should be considered as part of all future reference missions.

Comparison of AM V Architectures With Previous Work

Extensive design work on the three scenarios described here permitted a comparison with prominent architectures developed and widely discussed over the past several years, specifically NASA's DRA 5.0 (NASA SP-2009-566) and the recent Evolvable Mars Campaign (e.g., https://www.nasa.gov/sites/default/files/files/3-EMC_for_NAC_Research_SubCom_Moore.pdf. Comparison among these architectures is summarized on the following table.

Comparison of Mars Architectural Philosophies

DRA 5.0: Minimize risks and exposure of crew/cargo to the deep space environment with short duration transits separated by a long surface stay. Three crewed missions in 10 years with overlapping pre-deployed cargo missions.	**EMC :** Progressive expansion of capabilities through the cis-lunar "Proving Ground" to a sustainable human presence on Mars with reasonable extension of ISS, SLS, Orion and DSG. Emphasis on affordability and sustainability.	**AM V Team 1:** Focused on sortie-class missions to different sites on Mars, with very limited surface infrastructure. The architecture is readily evolvable to long surface stays with the on-ramping of additional cargo landers with habitats and other equipment.	**AM V Team 2:** Looked for ideas to enable an "enterprise sustainable" architecture for an initial human Mars Field Station. Does not necessarily represent completed trades.	**AM V Team 3:** Focused on laying groundwork for a permanently habited Mars base. Initial missions intended to select ideal surface base location. Tech development focuses on fault tolerance and scalability
Key Architectural Similarities				
Conjunction Class – 900-1000d	Conjunction with depart & arrival windows to 1200d	Conjunction Class	Conjunction Class	Conjunction Class
Pre-deployment of cargo	Pre-deployment of cargo	Pre-deployment cargo	Pre-deployed cargo on a range of lander sizes	Pre-deployed cargo on a range of lander sizes
Long surface stay	Evolve to long surface stay	Evolve to long surface stay	Long surface stay	Evolve to Long surface stay
Round-trip crew vehicle	Round-trip crew vehicle (hybrid SEP/Chemical option)	Round-trip crew vehicle (Orion direct Earth entry)	Round-trip crew vehicle	Round-trip crew vehicle
Key Architectural Differences				
Crew of 6	Crew of 4	Crew of 4	Examine crew of 6	Crew of 6
Cost profile – high peak	Cost profile – long medium	Cost profile – stay within ISS-type budget	Cost profile – long medium	Cost profile – follows ISS budget until emplacement of base structures (2040's)
In-space prop: fast transit, NTR	In-space prop: Minimum energy SEP/Chemical, Chemical, NTP	In-space prop: International partner supplied traditional hypergolic bipropellant	In-space prop: NTP, Minimum energy SEP/Chemical, Chemical	In-space prop: International partner supplied bipropellant or cryogenic LOx/CH_4
All crew to surface	1^{st} crew to orbit, 2^{nd} to surface	1^{st} crew to orbit, 2^{nd} to surface	No orbital only missions; All crew to surface	1^{st} mission orbital, 2^{nd} mission with opportunity for surface sortie. 3^{rd} & 4^{th} missions with two surface sorties
Vehicle assembly in LEO	Vehicle assembly in cis-lunar, HEO departure and arrival	Vehicle assembly in HEO, HEO departure, direct entry Earth return	Vehicle assembly in cis-lunar, HEO departure and arrival	Vehicle assembly in cis-lunar, HEO departure and arrival
Max launch cadence – 6/yr.	Max launch cadence – 2/yr. (1 crew and 1 cargo)	Max SLS launch cadence – 2/yr., plus commercial	Launch cadence depends on commercial landers	Launch cadence depends on commercial landers
Crew trip to Mars each opportunity	Crew trip to Mars every other opportunity	Crew trip to Mars every other opportunity	Aim for frequent opportunities	Crew trip to Mars every other opportunity
Minimize crew space exposure	Crew 1100 days in space ok	Crew away from Earth for 950 days	Minimize crew space exposure (surface stays + NTP)	Crew 1100 days in space
Redundant surface systems possible	Single string of elements	Single set of human-rated elements, lander abort to orbit capability	Modular habs and labs likely have redundancy	Redundant surface systems; pressurized rover is initial habitat
Each landing site different for science	Single site build-up infrastructure	Initially to different sites, later to a single site	Single site with broad science exploration	First missions will recon sites- depending on success of 1^{st} mission, subsequent missions either return or lander elsewhere
ISRU (O2 for ascent)	ISRU (O2 for ascent)	No ISRU for initial missions	ISRU O2, but also include H2O as early as possible	ISRU O2, but also include H2O as early as possible
All systems expended	Reuse of habitat, transportation, surf. Sys.	All systems expended, but transit habitat and SEP tug can be returned for repurposing, surface systems reused	Reuse of habitat, transport, and surface & examine MAV reuse	MAV designed to be reused



AM V Breakout Session 1

A Series of Sortie-Class Human Missions to Mars

Abstract

A community architecture was developed in a three-day workshop with participation by subject matter experts in the NASA and industry human spaceflight field. The concept is for the initial human exploration of Mars with a series of near-term affordable missions, first to Mars orbit, followed by a series of sortie missions to the Martian surface with crews of four. This approach would initially utilize proven technologies and vehicles that are currently under development by NASA, U.S. commercial aerospace, and international partners.

An initial flight rate of a crewed Mars mission every four years could be achieved with no more than two Space Launch System (SLS) launches per year, along with commercial cargo deliveries to high Earth orbit and/or cislunar space and also commercial deliveries to Mars. This architecture would have the flexibility to expand in scope, add surface habitats for year-long stays, on-ramp new technologies, and evolve to support a semi-permanent base on Mars.

The initial architecture would have a Mars transit stack assembled at the cislunar Gateway (or in high elliptical Earth orbit) consisting of a Deep Space Habitat (DSH), Mars Orbit Insertion stage, Trans-Earth Injection stage, Earth Departure Stage (EDS), and an Orion vehicle with a crew of four. Except for the EDS, all propulsion systems would need to be long-duration systems and would have storable NTO/MMH[2] propellants.

For surface access, a single lander with a fully fueled Mars Ascent Vehicle (MAV) would be separately delivered by two SLS launches and aerocaptured into High Mars Orbit (HMO) to await the crew. A MAV Boost Stage (MBS) would be delivered with a commercial launch, using a solar electric propulsion tug to provide transit to HMO. The MBS would aerobrake to Low-Mars Orbit (LMO) to be pre-positioned for boosting the MAV later in the mission.

After transferring the crew from Earth to HMO, the stack would rendezvous with the lander for crew transfer. The lander would de-orbit and perform entry, descent, and landing, and the crew would conduct a two-week mission on the surface, similar in scope to an extended Apollo 17-type mission. A separate robotic sky crane lander, similar to that used for the Mars Science Laboratory (MSL), would deliver a one-ton class unpressurized rover with seats and other science equipment that would be pre-positioned for the crew to use. At the conclusion of the surface mission, the MAV would launch the crew to LMO to dock with the MBS and then continue to HMO to transfer to the transit stack. The crew would spend the remainder of their stay in HMO, teleoperating assets on the surface, including the rover. Upon Earth return, the crew would perform direct entry with Orion.

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[2] (di) nitrogen tetroxide/monomethylhydrazine

Primary Objective

The primary objective of this example concept is to execute human missions to Mars at the earliest possible date within the constraints of:

1. Maximizing crew safety as the highest priority
2. Not requiring large increases in NASA's current human spaceflight budget, adjusted for inflation
3. Achieving significant scientific and exploration objectives
4. Providing a credible path for expanding the scope to on-ramp new technologies and capabilities, as available, and building toward extended surface stays on Mars at a semi-permanent base

Major Milestones

Major milestones in this example are:

1. DSH design shakedown at the Gateway in 2029
2. Propulsion stage shakedown burns to completion in cislunar space
3. Possible lunar landing test of the Mars lander design in 2031
4. Crewed mission to Mars orbit in 2033.
5. Crewed two-week sortie mission to the Martian surface in 2037
6. New missions to the surface every four years with longer surface stays

Guiding Principles

This example program architecture would meet the Congressional direction for humans in the Mars vicinity by the 2030s. It would also address the National Space Council's guidance to return to the Moon as a stepping stone to Mars.

In meeting strategic principles for sustainability, this example architecture would

1. Be implementable in the near-term within the buying power of current budgets[3]
2. Support publically engaging scientific exploration and human activities on Mars
3. Apply high-Technology Readiness Level (TRL) systems for near-term missions and provide on-ramps for advanced technologies [e.g., fission power, in-situ resource utilization (ISRU)] as available and affordable
4. Provide near-term missions with an incremental buildup of capabilities for more complex missions over time
5. Provide opportunities for U.S. commercial businesses to develop Mars mission services and lower the cost of NASA's exploration program
6. Provide a mission architecture that is resilient to anomalies and flexible to evolve space infrastructure and eventually build up infrastructure on the Martian surface
7. Provide opportunities for international partnerships
8. Establish a regular cadence of crewed missions, first to the Moon, and then to Mars

[3] As an example: The 2033 crewed mission to Mars orbit listed as Major Milestone #4 above assumes that funding to complete a Mars lander will not be available until sometime later in the 2030s.

Required Developments

This example architecture assumes the availability of the International Space Station (ISS), SLS, Orion, and supporting robotic missions, as well as the use of the Gateway for testing technologies and Mars vehicles. It also assumes the development of an advanced solar electric propulsion (SEP) space tug (NASA Solicitation NNH16ZCQ001K-PPE 2017) and a DSH (NASA Solicitation NNHZCQ001K-HABITAT 2016) that can support missions of up to 1000 days. Beyond these developments, which are already planned by NASA and being studied through current industry contracts, there are only two other vehicle developments that would be needed to execute the initial Mars missions:

1. Current technology in-space propulsion stages using traditional space-storable bipropellants, possibly using the already developed RS-72 U.S./European engine
2. A crewed Mars lander with a fully fueled MAV capable of delivering a crew of four to the Martian surface, providing a surface stay of about two weeks, and launching the crew to LMO to dock with a chemical boost stage that would deliver the crew to HMO

Architecture and Vehicles

This example system architecture is similar to the Lockheed Martin Mars Base Camp (Cichan et al. 2017) concept. It would utilize an "all-up" vehicle stack that would not require meeting up with any other vehicles to return the crew to Earth. The vehicle stack would transport a crew of four from an elliptical High Earth Orbit (HEO) to HMO on a conjunction-class mission and return the crew to Earth with the option for direct entry in an Orion capsule for an ocean landing, similar to the Apollo mission returns from the Moon.

The Mars Base Camp concept consists of two sets of identical vehicles to provide block redundancy at the vehicle level. For our community-developed architecture, this was modified to eliminate the dual-vehicle set approach, but still maintain human-rated double-fault-tolerant vehicle designs. Higher TRL systems were used to reduce up-front cost and risk (e.g., biprop rather than LOX/LH2 propellants). This was achieved by adopting some of the concepts in the JPL Minimal Mars Architecture (Price et al., 2015).

The Minimal Mars lander design (Price et al., 2016) was used in this example concept to minimize up-front cost and risk. The departure vehicle stack is shown in Figure 1. The DSH concept is based on a large body of previous studies and is currently in a development study phase by NASA (Simon et al., 2017).

There could be several options for implementing the Earth Departure Stage(s), since the in-space duration of these stages is much less than the Mars Orbit Insertion (MOI) or Trans-Earth Injection (TEI) stages. A commercial system, such as the planned ACES (Barr et al., 2015), could provide this function. A space-storable stage, weighing about 60 t, could also be an option, and it could be delivered to HEO either commercially or with SLS. Another option could be two of the in-space propulsion stages, with some propellant off-loaded. The latter option could be delivered to HEO either commercially or with SLS.

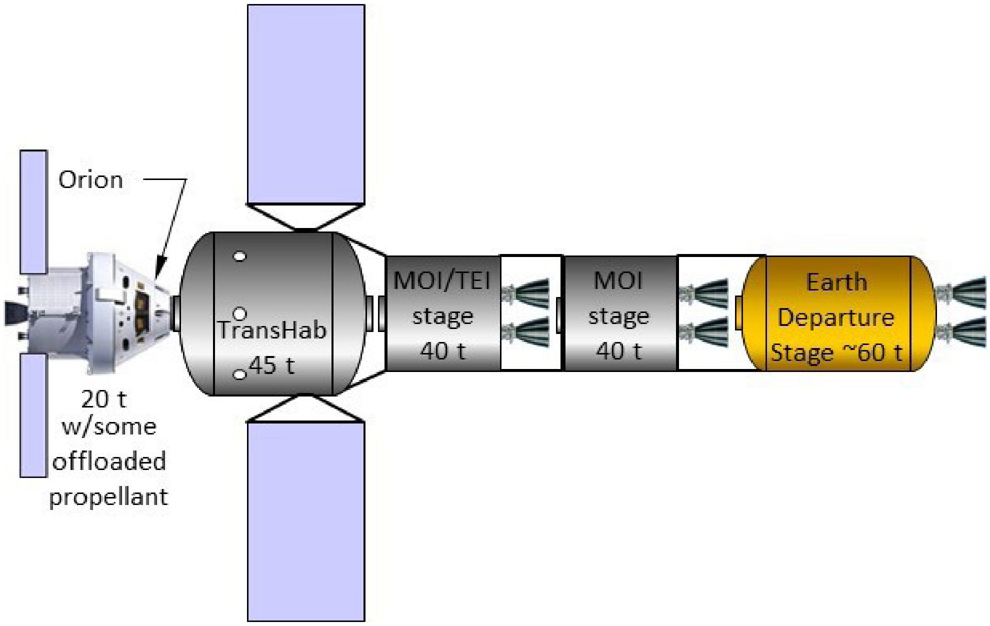


Figure 1. High elliptical Earth-orbit departure configuration for crew

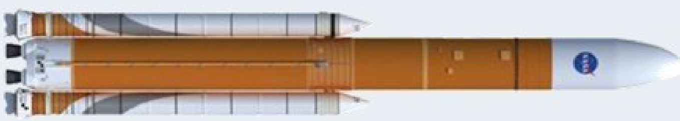
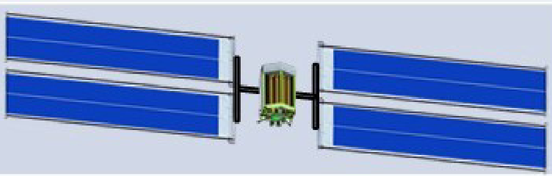
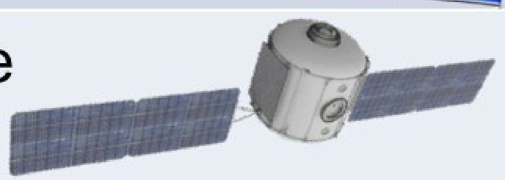
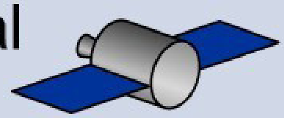
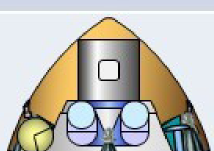
Vehicles		# Vehicles per Mission	Production Rate
Orion		1	1 every 4 years
SLS		5	1.25 per year
SEP Tug ~125 kWe		1	1 every 4 years
Deep Space Habitat		1	1 every 4 years
In-Space Chemical Propulsion Stage		4	1 per year
Mars Lander		1	1 every 4 years

Figure 2. Basic vehicle set for example architecture

Concept of Operations

The mission sequence for a first orbital mission to Mars is shown in a bat chart in Figure 3. This would be for a conjunction-class trajectory, and the 2033 opportunity was chosen for the example program timeline. A bat chart for a first Mars landing mission is shown in Figure 4. The 2037 opportunity was chosen for this example.

A notional SLS launch scenario is shown in Figure 5. The approximately 10 t MBS would be injected to Mars with a commercial launch vehicle and a 125 kWe SEP tug. The EDS launches could be candidates for commercial launches rather than SLS. Besides potentially reducing costs, utilizing commercial launches could free up available SLS launches for other purposes while staying within an expected SLS launch rate of about two per year. This could possibly allow for the Mars mission flight rate to be later increased to a new crewed mission every 26-month Mars opportunity.

SLS payload launch concepts for the landed mission example are shown in Figure 6.

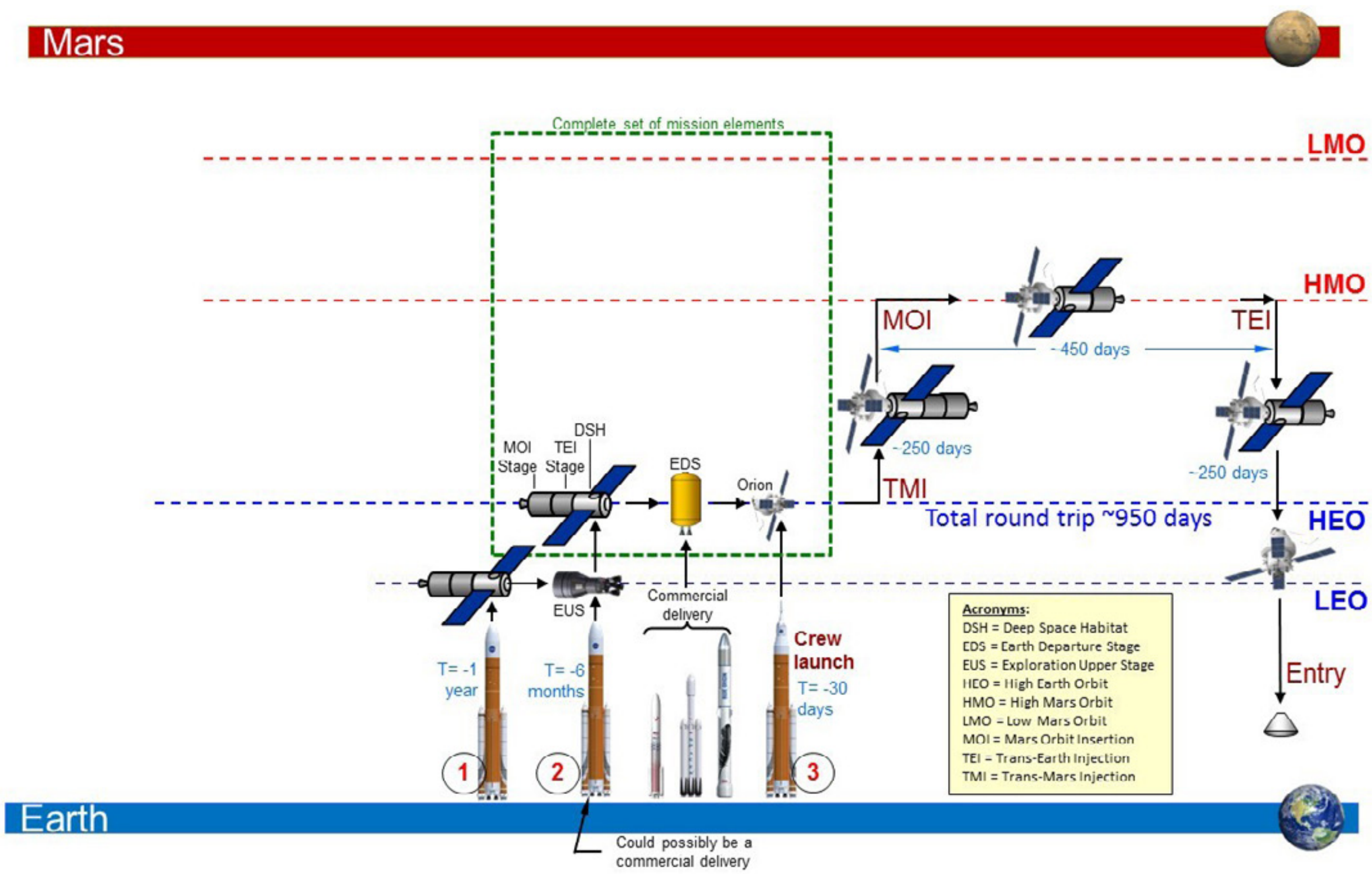


Figure 3. Sequence for High Mars Orbit (HMO) mission concept, possibly in 2033

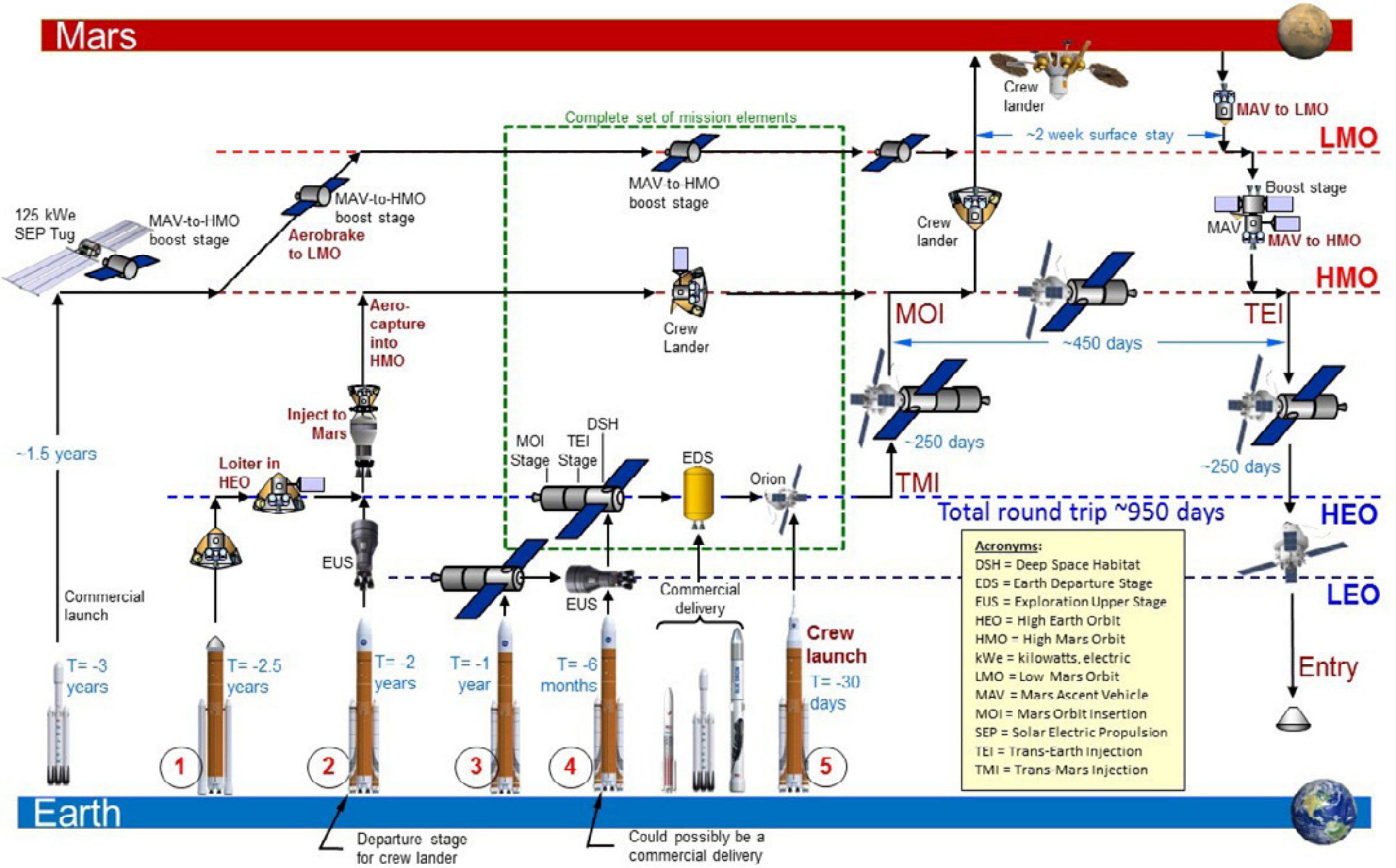


Figure 4. Sequence for Mars landing sortie mission concept, possibly in 2037

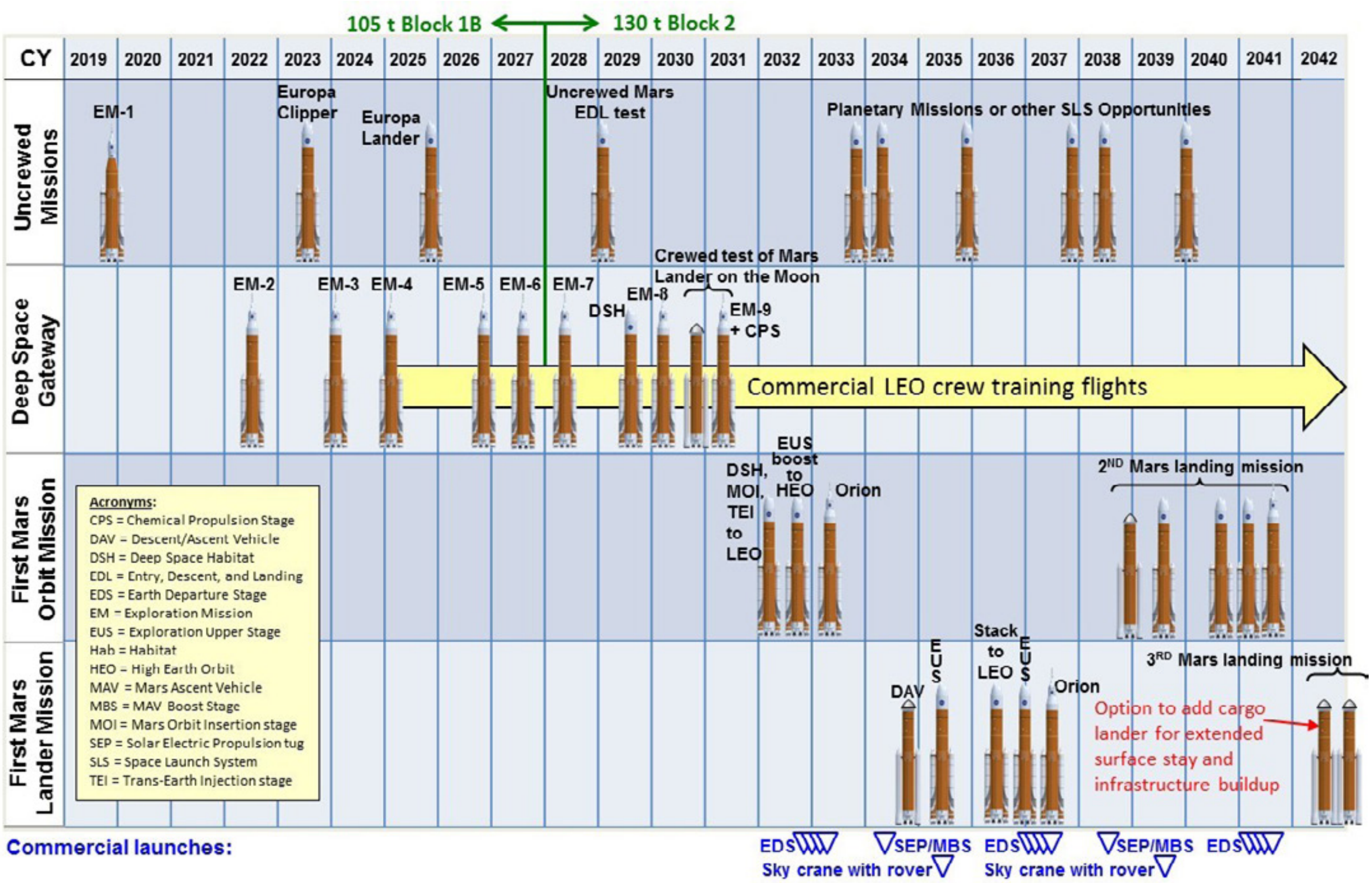


Figure 5. Notional SLS flight scenario to support the example program architecture concept

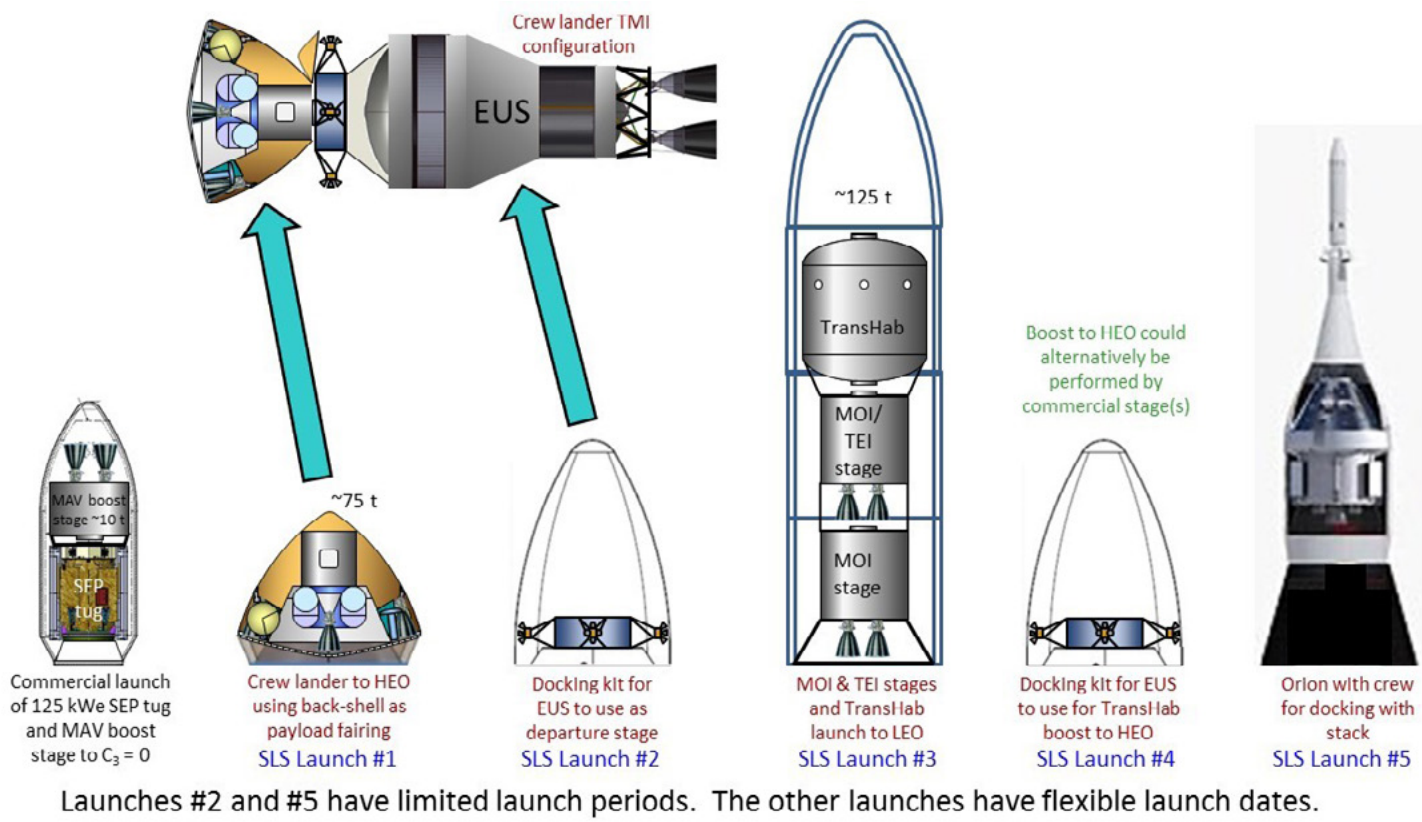


Figure 6. Payload configuration concepts for SLS launches to support a crewed Mars landing mission

The initial example architecture could be upgraded as more advanced technologies become available and affordable. These upgrades would be prioritized to provide for 1) greater crew safety and comfort, 2) higher performance, 3) expanded mission duration and scope, and 4) utilization of non-terrestrial resources if there is a solid business case for doing so. Some examples of upgrades could be 1) transition to cryogenic in-space propulsion stages (e.g., LOX/LH2), 2) transition to more capable lander vehicles, 3) growing food on Mars to improve crew support capabilities and morale, 4) utilization of in-situ resource utilization (ISRU) for crew resources (e.g., oxygen and water), and 5) transition to in-situ propellant production (ISPP).

Architecture Decision Process and Rationale

The decision process we used in the AM V Breakout Group 1 considered and traded a number of alternatives, driven by the main objectives of safely transporting crews to Mars and back while staying within NASA's current human space flight budget, adjusted for inflation. We leveraged previous extensive architecture studies, specifically the Lockheed Martin Mars Basecamp and the JPL Minimal Architecture, as foundational parts of the community architecture in order to produce a credible product within the limited time that was available for the workshop. There was some discussion about program evolution and expansion beyond the first sortie missions, but most of these concepts were deferred, given our time constraints.

Many of our key decisions were driven by reducing development and mission risk, by development and mission cost, and by development schedule:

1. Common NTO/MMH in-space chemical propulsion with non-reusable systems for the initial missions.
2. A 125 kWe-class SEP tug used for delivery of the MAV boost stage is a reasonable next step from the Gateway Power and Propulsion Element, with acceptable development risk. It enables launch by a commercial vehicle, rather than SLS, that is not tied to the narrow conjunction-class departure periods. By budgeting some additional xenon propellant, it could be utilized to retrieve Mars vehicles (e.g., DSH, MOI/TEI stages) for return to the Gateway or HEO for reuse, or alternatively to LEO for easy commercial access crew training.
3. Pre-deployment of lander in HMO.
4. Crew travel to Mars orbit with everything needed for their return. Crew would transfer to the lander in a one-sol Mars orbit.
5. A robotic unpressurized rover with seats for crew transportation and science equipment would be pre-deployed via a Mars Science Laboratory (MSL) class sky crane system. This could potentially be a commercialized service. The rover would also be capable of teleoperation from Mars orbit for site reconnaissance and science, or operation from Earth in the absence of a crew.
6. Orbital mission first, followed by a landing mission two opportunities later.
7. After initial operational capability is in place and a budget "wedge" opens up, expand the cadence of flights and/or add cargo landers with pressurized rover, consumables, and other science equipment.
8. Single lander for the initial sortie missions, with the addition of a second lander for a longer stay on the third mission or later, as budgets permit.
9. Maximize simplicity with only four vehicle types needed for the orbital mission. Use SLS and Orion. The Exploration Upper Stage (EUS) would be upgraded for an on-orbit loiter time of ~10 - 12 days so that it could dock in space and perform propulsive maneuvers for the lander and for the crew transit vehicle stack.
10. For surface missions, use a large-scale lander, based on existing experience, with NTO/MMH propellants for descent and ascent. A fully-fueled MAV would provide abort-to-orbit capability to LMO. A commercial or international boost stage would provide for ascent from LMO to HMO in the MAV. The boost stage should have adequate deltaV to provide for orbit phasing as needed to provide flexibility in supporting the MAV ascent.

Initial Performance Capabilities

We selected the following performance capabilities and implementations for this example architecture:

- NTO/MMH, storable bipropellant, possibly using existing-design RS-72 engines with 340 Isp and no cryogenic support overhead. This provides a similar system performance to LOX/methane when the penalties of cryogenic overhead are considered.
- 5 SLS launches per landing mission, depending on commercial capabilities
- 6 commercial and/or international launches per landing mission, depending on commercial capabilities
- 1 commercially developed medium duration (< 90 days) upper stage for Earth departure that could be cryogenic or space storable bipropellants

Technology Requirements

This example architecture would require only a few major new technology developments:

- 1,000 day environmental control and life support system (ECLSS) for the DSH
- Supersonic retro-propulsion for EDL with 250 kN-class engines throttleable to 50%
- 125 kWe-class SEP
- Aerocapture with traditional heatshields (dual-use could be an attractive option, but is not required)

Risk Assessment

We constructed our architecture example with the goal to reduce as much as possible development risks and in-flight mission risk. We chose existing technologies and straightforward testable design approaches to reduce the risk of cost overruns and program cancellation.

The following contingency and abort capabilities could be available:

- The crew stack could abort back to Earth for one to two weeks after TMI, depending upon the launch year.
- The crew stack could be on a free return trajectory to abort back to Earth if MOI was in jeopardy.
- The MAV concept would have abort-to-orbit capability during EDL and after landing
- Orion could function as a temporary lifeboat in the event of other vehicle anomalies
- Orion could provide emergency EVA capability as was planned for the canceled Asteroid Redirect Mission (ARM).

The following descope options could be available for the example program to address development and/or cost risks:

- Descope Mars EDL demo to a high Earth atmospheric test
- Mars lander testing in LEO rather than a crewed lunar landing test
- Testing the DSH in LEO with commercial crew rather than at the Gateway
- Descope the first Mars orbit mission in 2033 to a flyby
- Descope the crew size from 4 to 3 and/or the landing crew size from 4 to 3 or 2

Utilization of Earth/Moon Orbital Infrastructure

The ISS and the Gateway would be utilized for technology and vehicle testing and qualification for missions to Mars. A crewed lunar landing test could provide flight-like qualification of the flight system, terminal descent and landing, surface deployments, surface operations, mission operations, ascent preparations, and the Mars Ascent Vehicle.

The Gateway would not be required as a staging point for the operational missions to Mars. The concept is for the operational missions to be staged without supporting infrastructure in HEO, but the Gateway could be utilized if it presents advantages. Transfers between this facility and high elliptical-Earth orbit typically require very little deltaV, but require additional time, which could increase the duration of the missions.

Opportunities for International and Commercial Partnerships

International partners could reduce NASA's cost by providing essential mission elements such as the chemical propulsion stages, the pressure vessels for the Deep Space Habitats, Mars surface systems, and other elements. International partners could also provide essential modules for the Gateway and provide their own crewed lunar landers to gain surface mission flight experience and perform lunar exploration.

Commercial launch vehicles and in-space propulsion stages could potentially reduce the program cost. Commercial vehicles could be used to resupply the Gateway, provide privately funded lunar landers, and provide supplies and logistics to the Martian surface. Commercial crew vehicles to LEO could also provide important crew training at lower cost than SLS/Orion with more frequent flights to enable having a larger pool of trained astronauts to support missions to Mars.

A potential future commercial profit-driven cislunar economy could be leveraged to lower the cost of launches and increase the flight rate of crewed Mars missions, building on this more minimal initial architecture, and accelerating the pace of establishing infrastructure and expansion of a human presence on the surface of Mars.

Cost Estimate

A cost assessment for the AM V Breakout Group 1 community architecture was performed by Robert Shishko at NASA JPL using a cost tool that was developed in a collaboration between the Aerospace Corporation and JPL. The cost estimates were intended to include the costs associated with a Mars program that would be *in addition* to NASA's human spaceflight budget.

These costs do not include NASA's current programs such as SLS, Orion, ISS, mission operations, and Center support costs. We assumed that the SLS program will develop the Block 2 version and will provide two launches per year. The estimates do not include the development and operation of the Gateway, assuming that it would be covered in budget line items separate from the human Mars Program. The estimates assume that the biprop in-space chemical propulsion stages for the Mars missions would be provided by international partners. The estimates do include Mars vehicles tested at the Gateway and a crewed lunar landing test of the Mars lander design.

The total estimated budget is shown in Figure 7. The estimates are in real year dollars, assuming an annual inflation rate of 2.6%.

The costing methodology was developed by the Aerospace Corporation and updated in a collaboration between the Aerospace Corporation and JPL. The methodology and cost estimates are comparable to the National Research Council (NRC) Pathways study (NRC 2014). The cost methodology is also comparable to that used in a 2017 assessment by the NASA Office of Inspector General (NASA OIG 2017). The estimate suggests that the example program could be implementable with an annual cost, in comparable year dollars, to that of the ISS. The total cost of the program over 25 years, in comparable year dollars, is also similar to that of ISS. ISS has been a successful and sustainable program at this level of expenditure, and the Mars program would be expected to have a high level of public excitement and compelling scientific discovery to also be sustainable. Other important factors in sustainability are international and commercial partnerships. It should be noted that the validity of the cost model and the fidelity of this estimate do not represent the rigor and validation that would be required for any cost commitments.

Conclusion

We present here a community-based architecture that was developed in a three-day workshop with participation by subject matter experts in the NASA and industry human spaceflight field. We drew upon a large body of previous studies and a set of vehicles and technologies that are well understood. This example program architecture has some attractive advantages. It could represent a near-term, low-risk approach for human exploration of Mars in the 2030s with a budget similar to that of the International Space Station. Although the architecture was intended to be minimal in scope for the initial missions, it would have the capability to evolve and expand to support extensive long-stay human exploration of Mars, the incorporation of more advanced technologies and in-situ resource utilization, and the eventual buildup of a capable international base.

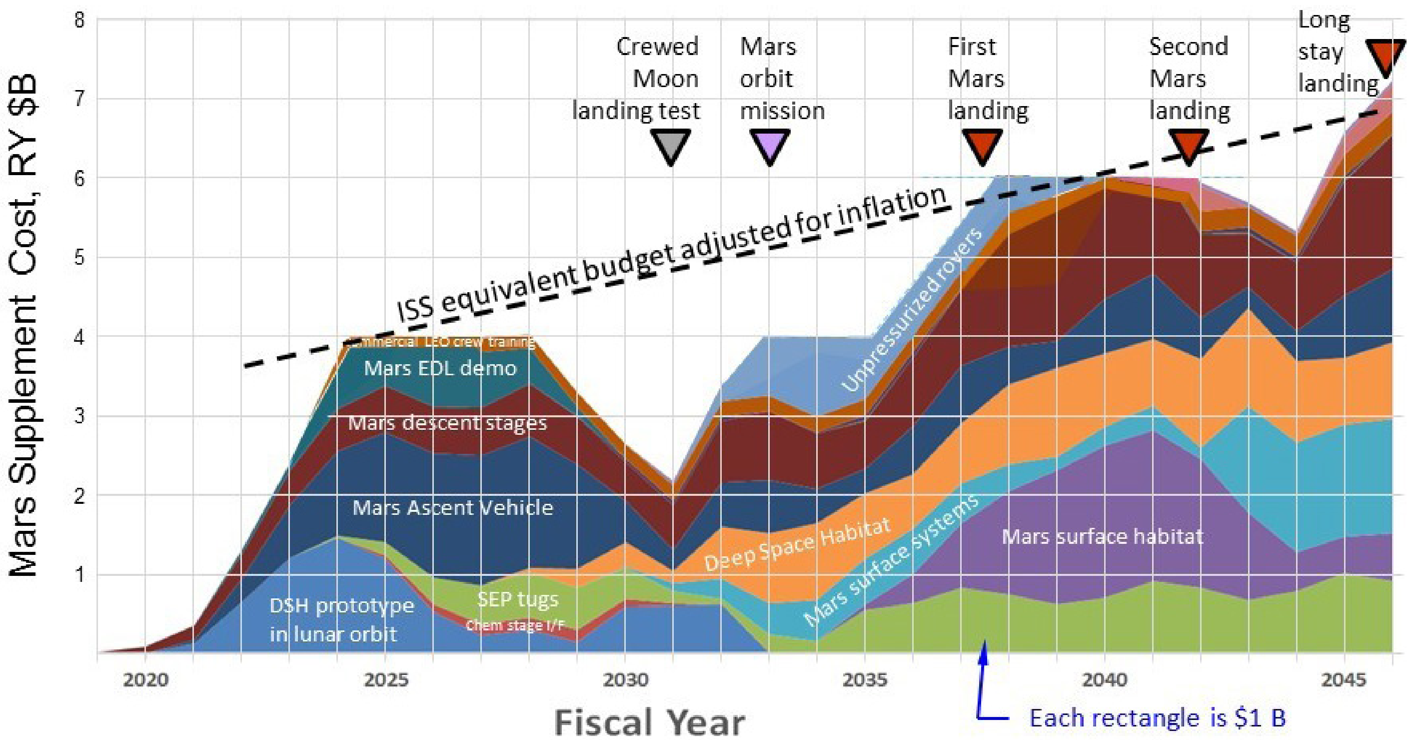


Figure 7. Estimated cost of the example architecture and schedule

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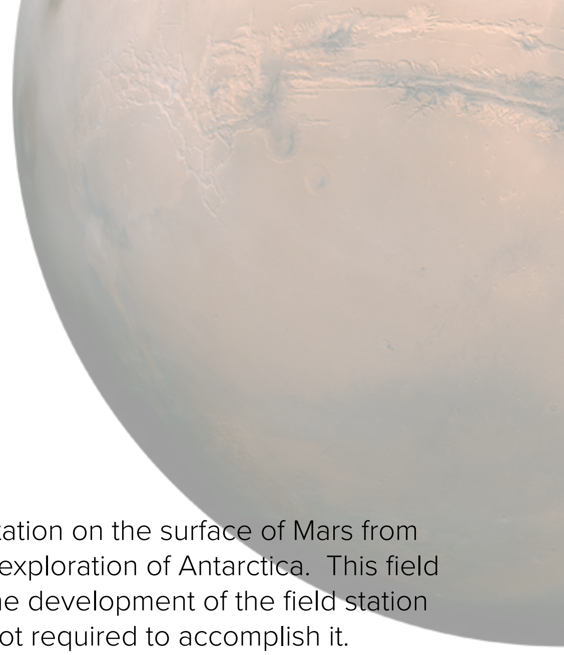

AM V Breakout Session 2

Research Station on Mars

Abstract

The second “end state” assessed was to send humans to a temporary field station on the surface of Mars from which the crew would conduct scientific research, analogous to early human exploration of Antarctica. This field station was not intended to be the final end state for human visits to Mars. The development of the field station could feed forward into scenarios for permanent human habitation, but was not required to accomplish it.

Our field station architecture begins with a program to maximize the usefulness of lunar missions for future Mars development. We believe that this requires that a joint Moon-Mars program office be established that has responsibility for implementing Mars missions and has the authority to make decisions. This is critical because the definition of the Mars elements determines what technologies and demonstrations are most useful at the Moon. This is not, however, intended to limit lunar activity to only what is useful for Mars, as economic expansion beyond low Earth orbit is seen as a benefit to the affordability of future missions. A program that includes lunar and Mars elements is naturally more costly than only doing one or the other. We conclude that coordinating the two reduces the overall life cycle cost for accomplishing both programs by providing double value from initial investments, and smooths the cost profile of the Mars mission across a longer period of time while getting value and results from active use of the earliest developed components.

For a field station mission, small crews use reusable transit vehicles to reach Mars and visit a location on the Mars surface with reusable habitation and scientific assets that are built up over time. This location should be one that seems a viable option for permanent human habitation, but does not necessarily represent a commitment to that location. Some of the elements needed for the mission almost certainly require use of the Space Launch System (SLS) Block 2 capabilities (such as the Mars Ascent Vehicle). However, we posit that modular systems with smaller habitat or science elements would enable more diverse participation in launch, landing, and providing modules for the mission. It may also provide more flexibility to evolve desired science or exploration capabilities between the first and last crews. The field station science and exploration objectives should be planned so that they can be accomplished within the hardware life of the key reusable pieces of infrastructure (habitat, human rovers, etc.). The next generation of missions should use new elements for permanent human habitation.

Our work builds on the designs carried out as part of the Evolvable Mars Campaign (EMC; e.g., https://www.nasa.gov/sites/default/files/files/3-EMC_for_NAC_Research_SubCom_Moore.pdf). The NASA work under EMC was directed toward a very similar end state, but performed under different constraints and optimized for slightly different goals. Integration of lunar activities, commercial opportunities, flexible modular campaign design, and reusable elements are all modifications that attempt to make the Mars mission more sustainable in various ways. Our team re-examined the EMC architecture trades, focusing on key goals to achieve enterprise sustainability, such as enabling more commercial and international participation, and examining whether and how to integrate technology demonstration and operations development in cis-lunar space or other lunar mission activities.

The table in our earlier section on scenario “end states” compares the characteristics of our architecture with that of NASA’s Design Reference Architecture 5 and the agency’s more recent EMC.

Primary Objectives and National Priorities

Our architecture was developed under the guiding principles of enabling human assisted science on the surface of Mars and to prepare for future sustained human habitation on the surface.

After discussion of the definition of a "Field Station" and possible operations that could occur in such a mission, our team determined that the primary objectives of the mission enabled by our architecture include:

1. Learning how to live and work sustainably on the surface of Mars via the natural evolution of activities with human experience and feedback
2. Developing and testing the technologies required for future permanent human habitation on the surface of Mars, which may not be critical for initial human scientific investigation
3. Defining and locating the desirable characteristics of an Exploration Zone in preparation for future human activities
4. Evaluating the viability of biology (human, agricultural, or extant microbes) in the Martian environment
5. Performing meaningful science to understand the Martian environment and the effects of long- term habitation in space and at Mars on human health.

Our architecture expands permanent human presence beyond low Earth orbit (LEO) by developing and testing the technologies and operations necessary for long-term human habitation, not only beyond the surface of the Earth, but on the surface of the Moon and in deep space. Fulfilling this goal will require the involvement of international, academic, and industry partners to develop mission elements. Collaboration can include everything from research objectives to hardware. In doing so, our architecture will expand the capabilities of human explorers and drive the demand for future industries.

Our architecture incorporated policies from the National Space Council that direct NASA to return to the lunar environment before continuing to Mars missions. Our architecture uses the Moon as a testing ground for key technologies and operations specifically to enable future human and robotic Mars missions. These include, but are not limited to, the engines for the Mars Ascent Vehicle (MAV), the propulsion and habitation system for the Mars Transfer Vehicle (MTV), and the concept of operations for semi-autonomous human operations beyond LEO. This architecture also relies on commercial partners to provide flexibility in terms of launch and landing options for the many pieces of a Mars mission. Those capabilities and business cases will be developed as part of the lunar missions.

In many ways, the objectives outlined above are what make this architecture an affordable and sustainable enterprise. We frame human exploration of Mars not only as an incredible scientific and technological achievement, but also as part of enabling commercial and international participation beyond LEO. Costs of Mars missions will be lowered by encouraging a multiplicity of launch and landing vehicles provided by international or commercial partners, investing in efficient and potentially reusable assets, and guiding the development of lunar assets such that they are applicable and enabling for Mars missions. But, most importantly, we will demonstrate that human spaceflight activities are continuously accelerating our species towards the stars.

Enterprise Sustainability and Affordability

Our team was strongly motivated by the discussion of the many principles that can contribute to enterprise sustainability. Eight principles were outlined during the AM V workshop that summarize an approach that can make this effort affordable and sustainable. We attempted to address each of them in our architecture.

Fiscal Realism: Implementations in the near-term use the buying power of current budgets and in the longer term using budgets commensurate with economic growth. Our option sets the scope, scale, and schedule of the effort to live within current budgets, but also assumes leveraging contributions that can be made by partners and innovations from the commercial sector. These factors drive this option towards an affordable approach.

Scientific Exploration: Exploration enables science and science enables exploration. We assume investments currently being made in robotic vehicles for the scientific exploration of Mars will be leveraged to enable more refined and more extensive scientific exploration by human crews on Mars.

Technology Push and Pull: Our approach assumes near-term robotic and human missions will emphasize application of high-Technology Readiness Level (TRL) technologies, but also assumes sustained investments in technologies and capabilities that overcome the challenges of future missions.

Gradual Build Up of Capability: We assume that a defined cadence of compelling and integrated human and robotic missions will be created that provides for a sustainable incremental buildup of capabilities and enables more complex missions over time.

Economic Opportunity: Our approach assumes proactively creating opportunities for U.S. commercial business to further enhance their experience and business base.

Architecture Openness and Resilience: We assume multi-use, evolvable space infrastructure, minimizing unique developments, with each mission leaving something behind to support subsequent missions. These features contribute to a resilient architecture.

Global Collaboration and Leadership: We assume that our approach will lead to substantial new international and commercial partnerships, in part leveraging current International Space Station partnerships, although also building new cooperative ventures for exploration.

Continuity of Human Spaceflight: Our approach builds upon current efforts to establish a regular cadence of crewed missions to cis-lunar space during ISS lifetime, building an uninterrupted expansion of human presence into the solar system.

Adopted Assumptions

The AM V workshop provided an opportunity for many points of view to be discussed, but obviously did not include time for deep engineering analysis. Team 2 made several key assumptions about policy or engineering decisions that informed our architecture:

1. We assumed that the nature of a field station is that the location is semi-permanent, with elements that are reused, and with growing capability over time. Researchers on Earth have proven the value of having humans “in the field”, even in challenging environments. The location selected for our field station should have both good scientific value and potential for permanent human habitation to gather the most relevant lessons during this period. But it does not represent a commitment to that location or to any particular design and architecture for future permanent human presence on Mars.
2. We assumed that NASA would pursue sending humans to cis-lunar space. Development of the Gateway and lunar surface activities would be pursued by NASA, with commercial and international participation. These missions would likely delay the initial Mars mission, compared to options Team 1 explored. However, they provide opportunities for technology demonstration, and thus independent technology demonstrations or initial Mars orbital missions if demonstrations are not necessary.
3. We assumed, based on feedback from industry partners at the workshop, that smaller payload sizes for launch vehicles and landers would reduce the barrier to participation from industry and international partners. We also assumed that industry requires a continuous and near-term cadence of opportunities and reasonable expectation that multiple providers can be involved in future missions in order to invest their own funds into developing capabilities.

Concept of Operations

The major mission elements of our architecture include the following key elements and activities:

1. Lunar Activities
    a. In order to provide value to the Mars missions, all lunar activities and technologies would be prioritized by their applicability to Mars missions. In turn, this requires an assumption that NASA would create a program authority with the ability to direct the development of all future human exploration activities in order to ensure continuity of purpose and design. Another primary assumption is that after significant investment in lunar activities combined with key Mars precursor missions, it is unnecessary to perform an orbital mission at Mars before reaching the surface.
    b. Lunar activities would include commercial or international launch and landing of payloads. These may start small, but should quickly be driven to larger-scale capability that could use elements (engines, landing structure, navigation, power) relevant to small payloads for the human Mars missions. An example is the possible demonstration of a small nuclear power reactor on the Moon to enable commercial landers to survive the lunar night, which uses the same reactor technology as needed to power pre-crew ISRU propellant production on Mars. Other examples include utilizing the same propellant in lander or ascent vehicles, or building structural elements that can be certified to both sets of requirements.
    c. Operations in cislunar space should utilize propulsion elements intended for the Mars missions. Our team recommended nuclear thermal propulsion (NTP) technologies for transit of crew and some cargo to Mars. With commitment to development, the first demonstration of NTP technology should be accomplished during this period of initial cislunar activity; that is, around the middle of the next decade. After demonstration, it can be used for maneuvering elements in cislunar space, or delivering scientific missions to Mars.

2. Robotic Precursors
    a. Robotic precursors to Mars will perform scientific investigations based on Decadal Survey science priorities. However, such precursors should also help with site selection and resource identification for the human mission. They can also be used to deploy assets such as communication satellites or even infrastructure for Mars orbit aggregation points. These missions should be performed using in-space propulsion elements, entry, descent and landing technology, and ascent technology that is intended for use in the future human Mars mission, even if they add risk to the science missions. These capabilities are expected to be able to deliver larger payloads to Mars orbit and to the Mars surface, which provides more opportunity for science investigations and preparation for human missions.

3. Aggregation Points
    a. An aggregation point in cislunar space may enable reuse of Mars transit vehicles, and in-space propulsion. Thus, like EMC, this architecture assumes use of an aggregation point in cislunar space. Based on NASA plans, that presumably is the Gateway. The team did not perform detailed analysis on ideal orbits for departure, capture, or refurbishment and crew transfer activities.
    b. Reusability was seen as an important cost driver that could be leveraged to make a more sustainable Mars architecture. We were very interested in exploring the reusability of the Mars Ascent Vehicle. Several concepts were discussed, including reusing the ascent stage but providing a new lander to return it to the Mars surface each time, or refueling the vehicle in Mars orbit so that it could provide its own landing. (Both cases assume ascent fuel is produced by ISRU on the Martian surface). These cases would potentially benefit from an aggregation point in Mars orbit.

4. Launch Vehicles
    a. The precursor activities and field station operations would be supported by a multiplicity of vehicles (NASA, international partners, commercial). An upgraded SLS capability is assumed to be needed for the largest payloads as it was in EMC, but detailed analysis was not performed to compare Block 1B versus Block 2. Smaller payloads could be launched on commercial or international vehicles. If highly capable in-space propulsion is reusable, then these payloads could be aggregated together for transit to Mars, or delivered separately if there are multiple in-space propulsion capabilities developed by industry and international partners.

5. Orbital and Surface Communications Assets
    a. We assume that an areo-synchronous node for communication with Earth is required, and likely delivered as part of a precursor mission.
    b. Local surface relays for line-of-sight communication would be established at the field station. Robotic deployment could be used to connect the field station with any rovers or scientific assets that are relatively nearby, but not crew-tended.

6. Mars Transfer Vehicle with Habitat
    a. This element is assumed to be much like the EMC solution, and is reusable with refurbishment and restocking at Gateway. The lifespan of the MTV Habitat is one of the primary drivers to determine the limit on the number of potential missions to the field station.

7. Crew and Cargo Lander
    a. An approximately 20 mt payload capability for large items (e.g., MAV) is assumed. Technologies for entry, descent and landing were not selected in this analysis.
    b. Smaller payload capability options provided by partners or commercial vendors are used for precursors and for delivering assets and resupply to the field station.

8. Surface Habitation
    a. The capabilities of the field station will evolve over multiple missions. Pressurized modules would be based on modular and flexible units. A habitable volume would be the first module required, and a science module of some kind is also assumed. Over multiple missions, science modules (pressurized laboratories or robotic capabilities) can be deployed at the habitat or nearby.

9. Surface mobility
    a. Rovers to transport humans and highly capable and durable spacesuits are assumed to be needed for this architecture to maximize scientific exploration from a single field station site. These capabilities could evolve over time, using payloads delivered by the smaller landers, from unpressurized to pressurized rovers with multi-day capability, or the addition of safe-havens with consumables or shelter farther and farther from the field station habitat.

10. ISRU and Power
    a. The eventual goal of sustained human presence mandates a dependence on ISRU for breathable oxygen and ascent propellant. This architecture emphasizes the utilization of both atmospheric CO_2 and water (potentially from regolith or subsurface ice).
    b. The goal to access, acquire, and process regolith or subsurface ice is a significant mission driver that impacts equipment (e.g., diggers, movers, haulers) and power. Power requirements for processing CO_2 or H_2O and then liquifying and storing the products will likely be in the 10s of kilowatts.
    c. The presumption that subsurface ice is prevalent in the northern latitudes could determine the preferred landing location and power generation approach. Northern latitudes tend to favor nuclear power due to the reduced solar flux, greater seasonal flux variation and longer night period.
    d. A small nuclear reactor (e.g., Kilopower) provides continuous day/night power with low mass and volume (a 10 kW unit weighs about 1500 kg), and can be used effectively at any surface location on Mars. The reactor is largely unaffected by seasonal temperature variations or dust storms. Technologies like these are also useful for the long day-night cycle on the Moon, and therefore are broadly useful. By integrating design considerations of lunar and Martian missions, using them to enable missions in the northern Martian latitudes is not a penalty specifically attributable to that mission or architecture decision.

11. Mars Ascent Vehicle
    a. The EMC architecture determined that using fuel generation from resources on Mars provided an important reduction in the mass of the MAV, which was the largest indivisible payload. We also assume that ISRU is enabling for this architecture to reduce costs and to develop self-sufficiency that will be important for the future permanent human presence on Mars. Because the location of the

field station should be chosen based in part that it is a strong candidate for the first permanent human settlements, it should have water resources available. Our architecture also included substantial mass delivery capabilities for precursor and science missions, which should provide opportunities to validate the “Ground Truth” of water resource availability and make sufficient preparation for including water and atmosphere based processes for ISRU.

b. Reusability was seen as an important element of enterprise sustainability. Reusing components either reduces cost, or enables new science and exploration capabilities to be delivered with the resources that would have been spent on repeated builds. Reusing the MAV seemed to be an option that had not been thoroughly explored by other studies. While technically challenging, it would be an important step toward developing affordable permanent settlement on Mars, since we assume that the base is permanent, but that individual crewmembers still rotate and return to Earth after a period of time on Mars. With reusable MAVs, ascent capabilities can be provided for the number of crewmembers returning to Mars orbit each time, which may not be a constant number.

The figure below attempts to illustrate how the design elements come together across the campaign. Gateway missions in cislunar space are assumed to occur independently, but emphasis is placed on commonality between landers to the Moon and Mars, and the use of a variety of launch vehicles. Mars precursor missions and demonstrations of NTP technology above and beyond assumed Gateway missions are also included. Finally, delivery of key elements for the human Mars mission (Mars ascent vehicle, surface habitation) and the first crew rotation are illustrated.

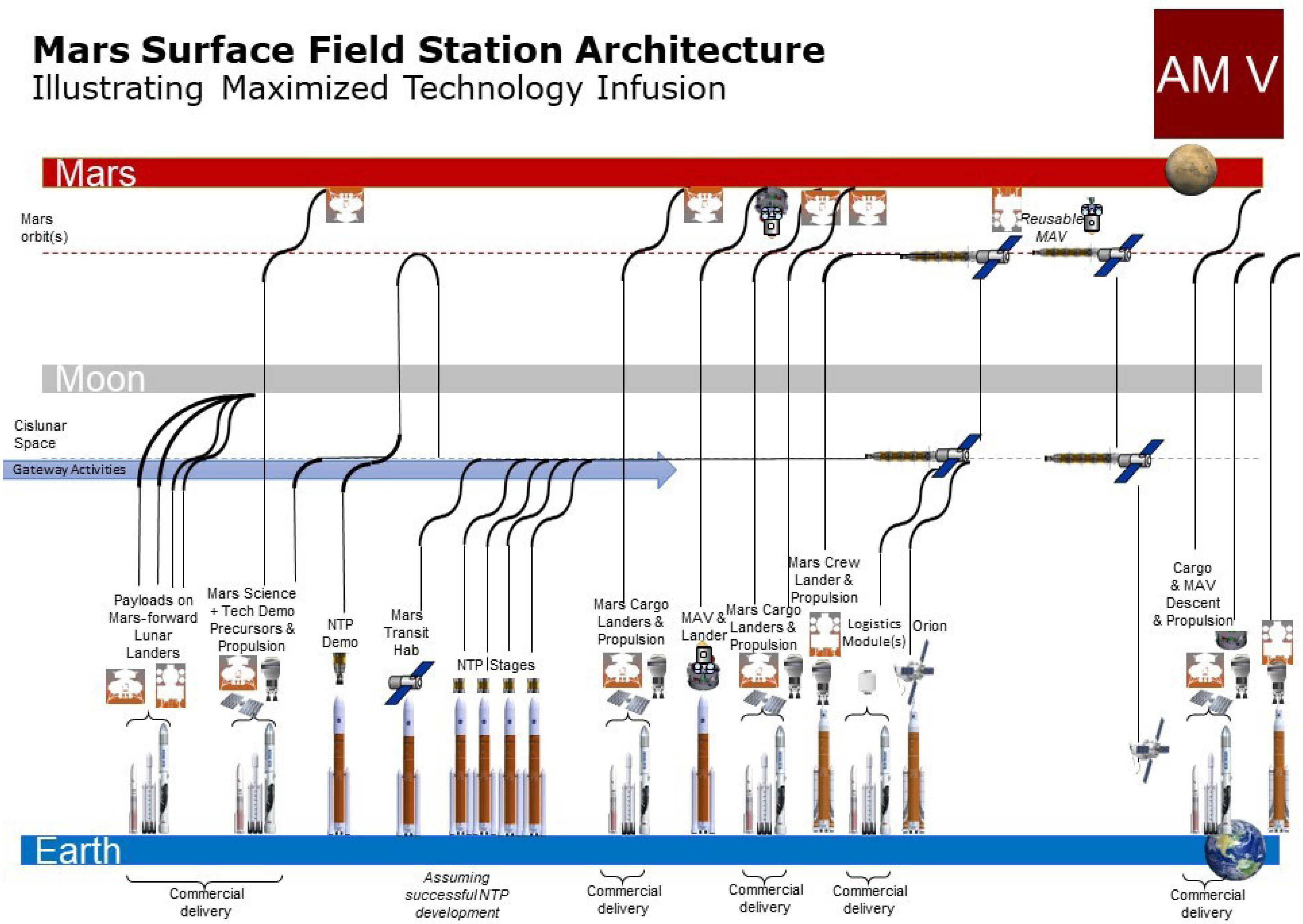

Figure 1. Representation of mission elements including launches from Earth, cislunar activity, lunar surface activity, and both robotic and human Mars missions

A tentative timeline of major events by decade includes

- Most key architecture decisions will need to be made in the early 2020s,
- Technology development for activities at the Moon will continue into the 2030s, and
- Humans will arrive in the Martian system sometime in the 2040s.

Without significant increases to the current budget, sending humans to Mars by 2033 while simultaneously carrying out *significant* activities on the surface of the Moon is an unrealistic proposition without resources in excess of a simple extrapolation of NASA's current human spaceflight budget.

These missions are necessarily preceded by robotic precursors, designed with the explicit purpose of identifying and then verifying resources and science objectives. Landing site location will largely be dependent upon the findings of these robotic precursors. They will also serve as subscale demonstrations of key mission elements such as ISRU, landers, surface power, and potentially the MAV. As these robotic precursor missions are underway, the development, testing, and deployment of mission elements that do not depend on the results of the robotic precursor missions, such as the in-space habitat, the in-space propulsion system, and the logistics vehicles will need to commence. We will also need to investigate human mission elements and operations using analog missions with long stays on the ISS or Gateway and fieldwork in Mars-like environments on the Earth.

The next steps will include the development and testing of human-rated surface assets, pre-emplacement of mission-ready assets, and practice missions with human crew aboard the Gateway, perhaps in conjunction with the actual MTV. It is essential that pre-emplacement of mission elements on the surface of Mars begins long before the crew arrives in order to validate the technologies the crew will depend upon on the surface. Only after these steps are completed can a crew launch and depart for Mars on the MTV. Our architecture anticipates crewed missions at every other launch opportunity. These will be 1,100-day conjunction-class missions with 500-day surface stays. Multiple missions to the surface will be carried out over the course of a decade, or until major mission elements (e.g., the surface hab, the MTV, etc…) need to be replaced. At that point the opportunity to improve upon the design of these major elements and chose a permanent location for future human settlement will become available.

A draft timeline for our activities leading up to the first human Mars missions is outlined in Figure 2.

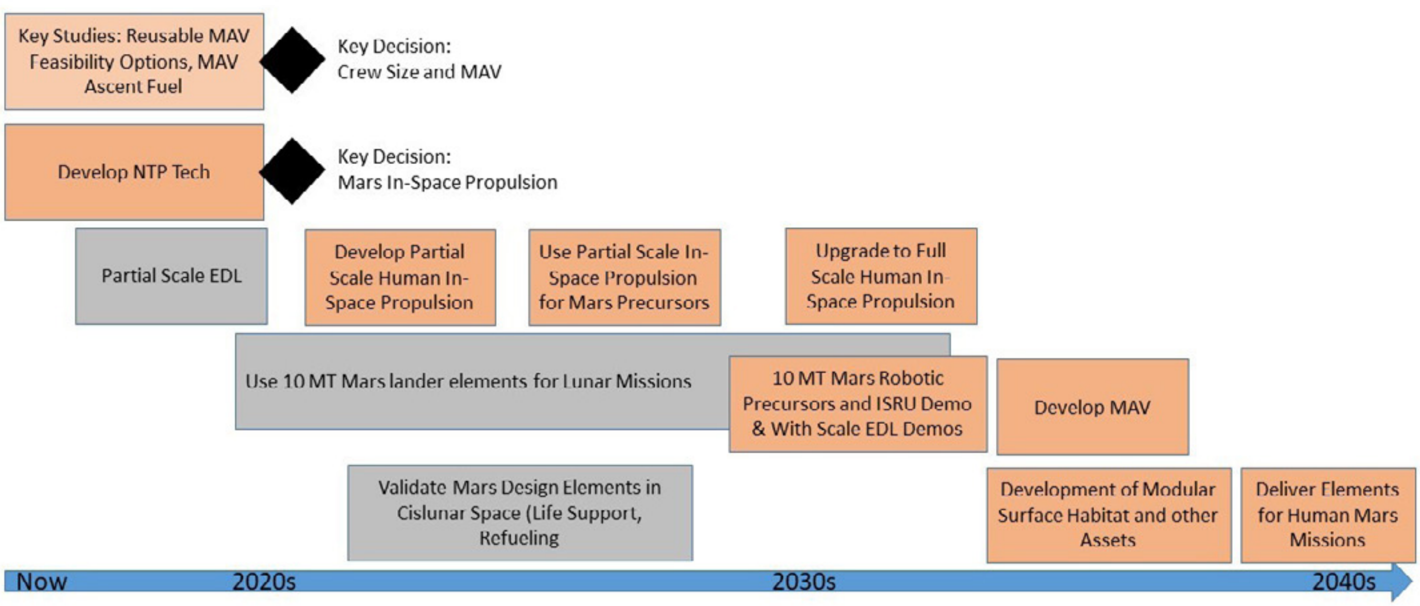

Figure 2. Timeline for key activities

Plausible system upgrades pending availability of funding, technology readiness

Our team identified several key technology areas that should be emphasized. In order to reduce long-term cost, our architecture considers phasing in more efficient technologies as they became available even in the lunar missions, and then implementing them for Mars missions. To a large extent, these should be considered the baseline with an option to descope if development shows they are not viable. Key technologies include nuclear thermal propulsion (NTP) and reusable MAVs. Water and atmosphere ISRU and nuclear power are also important, and are both lower risk and more important to include for performing the mission. Investing in the development of these technologies is a necessary step to ensure that our architecture is sustainable in the long term and leads toward a sustainable permanent human presence on Mars. This is an example where flexibility will be a key feature of our architecture.

We cannot know with certainty if the above technologies will be ready for the first human missions to Mars. Our architecture may need to evolve over the course of its lifespan to adapt to the introduction of more attractive technologies. In part, this is why modularity works to the advantage of these plans.

Our decision-making process

Decisions on architecture and elements were predicated on the following:

Plan ahead: No redesigning/recertifying new/different assets than what is necessary for permanent presence. Also, design lunar elements to feed forward as much as possible to Mars designs,

Evolvable infrastructure: engineering elements that get the job done, although not necessarily the 'final' Mars mission infrastructure,

Lessons learned: using our opportunities in space and on the Earth's surface to learn how to explore and live beyond Earth (e.g., engineering, ISRU, science, etc…), and,

Flexibility of purpose: recognize that our base may not be the 'final' location and decide when/where to relocate as hardware life comes to an end and/or replacement is needed.

There are several key decision points guided by the above principles. The most pressing among them as outlined include:

- **By the early 2020s,** decide whether to commit to the full-scale development of NTP or "big" solar electric propulsion (SEP) for use as the propulsion system on the MTV. Given the necessary development times for these technologies, failing to commit to one in the near-term will delay the implementation of the technology in the long-term.
- **By the early 2020s,** decide what size crew to send to Mars. Crew size, whether 4 or 6 (or even 5 or 7), affects the development and construction of major mission elements including the MTV, the MAV, and the crew lander. These are key driving elements for EDL technology, and important targets for finding commonality with lunar landers, so those decisions are necessary to pursue near-term activities. It will also impact the kinds of science our crews are able to pursue while on mission and the logistics strategy for maintaining them in-transit and on the surface.
- **By the early 2020s**, decide if NASA is going to perform human missions to the lunar surface, and if so, by the mid 2020s, decide who is building the human Lunar Ascent Vehicle (LAV). This will impact the timeline of development for the MAV.
- After initial robotic precursor missions provide ground truth on available resources at candidate landing sites on Mars, a decision is needed on whether to fully embrace a Mars descent/ascent propulsion system that is compatible with Martian ISRU, and what propellants. Choosing propellant from Earth or ISRU propellant changes the architecture and launches dramatically. Some discussions suggest starting with hypergolic propellants and phasing in of ISRU, but this is effectively two entirely different developments of Mars capabilities, including in-space transport and descent and entry capabilities, and not affordable. Choosing methane or hydrogen also has large implications for any lunar activities

Elements specifically intended to enable affordability and enterprise sustainability

Our primary means of making a crewed mission to Mars affordable is the incorporation of a diversity of launch and landing vehicles, using commonality of design and lunar activity to make them commercially viable.

Encouraging the commercial development of a Mars lander rated up to 10 mt to complement the development of a NASA supported lander capable of delivering 20 mt to the surface (primarily for the MAV) is a key feature of our architecture. Developing a smaller lander allows for greater flexibility when it comes to the payloads we will be delivering to the Martian surface. Smaller elements such as science labs, rovers, and consumables can be delivered to the surface without having to launch them on an SLS. It also means that not all elements have to be designed and delivered at the same time to efficiently use a 20-ton lander.

Additionally, if NASA chooses to go to the Moon's surface, the development of the MAV can be spread across the budget of multiple programs. Building the LAV such that it shares specific elements with a future MAV will allow it to serve as a sub-scale technology demonstration mission for future Mars missions. This shifts some of the cost of development towards lunar activities, while reducing Mars mission costs by saving on development and testing costs for Mars missions. Having more, smaller payload deliveries also allows more flexibility and broader participation in Mars surface elements.

Plausible technology capability performance upgrades, pending availability of funding

The major technologies required for our architecture are very similar to those required for EMC, but several key upgrades were discussed and all are plausible. NTP would provide flexibility in mission architecture, improve abort options, shorten transit times, and improve delivery capability, which could be important for sustainability as goals and desired capabilities change over time. The reusable MAV also appears to be an avenue toward making human Mars missions more affordable, and to build up capability for future permanent human presence on Mars. This is considered feasible because the vehicles do not have to actually be reused in initial missions if the capability to refuel or be refitted with a new descent lander stage cannot be provided yet, or the risk is considered too high. ISRU utilizing water and atmosphere on Mars with location-independent surface power is also included. Since our timeline includes many precursor missions before human missions to Mars, there is time to prove the water resources are available at the desired landing site(s), and perform technology demonstration missions on Mars.

Required major technologies and elements

- 1,100 day-class ECLSS systems for transit and surface
- 10 ton-rated Mars cargo lander
- Mars Ascent Vehicle
- 20 ton-rated crew lander
- In-space propulsion: Development of NTP should be pursued, but the architecture is not reliant on it. At least one large-scale in-space propulsion system must be developed.
- Mars atmospheric ISRU is required; Development of water and atmosphere ISRU should be pursued as the initial baseline, but the architecture is not reliant on it
- Small nuclear power reactors (e.g., Kilopower) that generate long-duration (10 yrs or more) continuous day/night power and are not sensitive to landing location, seasonal sunlight/temperature variations or dust storms.
- Crew surface mobility capable of 100 km excursions from lander
- Planetary space suit

Major risks associated with team's approach

The greatest risks associated with our team's approach are affordably funding the development of a commercial/international cargo lander that has relevant Mars capabilities.

Given how critical a multiplicity of launch and landing capabilities are to the sustainability of our architecture, if a smaller Mars landing vehicle is not developed and key elements are not used in a commercially viable way at the Moon, the scope of capabilities that can be delivered to the surface will be limited. That being said, our architecture is feasible with only one landing vehicle, but such would require designing each mission element with the mass/volume constraints of the 20-ton lander in mind. Doing so would also require more SLS launches and the costs associated with them, and mean that fewer commercial providers are involved.

There are several other critical risk points across the course of our architecture that could determine the success or failure of the mission, but these are very similar for many architectures for human Mars missions. Primary among these is the first crewed launch from the surface of Mars. The MAV is expected to land at Mars to begin its fueling process far in advance of the crew. It will then sit in the harsh Martian environment for the time it takes to be completely fueled plus the crew's total time on the surface. When the crew straps in to leave the planet the MAV must fire and proceed to orbit without error. Unless we are to build a test stand on Mars, this will be the first time the MAV has been fired since it left Earth.

Another critical risk point comes as the crew is landing. The lander needs to achieve a very accurate landing near the infrastructure required to support the crew on the surface. Without additional power supplies (from either surface infrastructure or onboard power reserves at the cost of extra weight) the crew, whose bodies will be extremely fatigued from the eight-month trip in microgravity, will be hard pressed to reach a more sustainable safe-haven. This risk can be mitigated by the pre-emplacement of materials on the surface, which also serve as validation of the pinpoint landing capabilities, and through the use of autonomous, possibly pressurized, rovers that may be able to retrieve and support the crew on their way to a more permanent habitation module. To understand the full implications of this risk requires studying how astronauts recover from time in microgravity with limited interaction from ground control.

A less-critical risk is that of delaying a human mission to Mars. Depending on how long NASA spends practicing at the Moon, and how much money is available for the simultaneous development of multiple systems, the first Mars missions may be delayed beyond 2040.

Despite the risks outlined above, we believe our architecture avoids some of the cost risks normally associated with Mars architectures by shifting development cost of Mars technologies onto lunar activities.

Role of the ISS, cis-lunar Gateway, and lunar surface

1. The ISS is still an important testbed for microgravity technologies needed for the Mars Transit Vehicle, such as life support and research into human health for the microgravity transit mission.
2. An upgraded and longer-duration Gateway may serve an important role in our architecture as an aggregation point for the reusable Mars Transit Vehicle. It also provides research opportunities related to radiation. The Gateway also serves as an aggregation point for lunar surface activities. Commercially viable lunar surface activity is an important part of this architecture that the Gateway helps enable.
3. Our architecture attempts to make Mars missions more affordable by spreading development costs over time. Rather than having capabilities sit dormant (and then potentially not be ready when needed for Mars), or trying to do missions before capabilities are ready (such as Mars orbital missions only), lunar surface activities provide value for the earliest developed capabilities.

Capabilities suitable for partner contribution

1. Government: NASA, DoD: Our architecture assumes that an upgraded SLS-class vehicle is still necessary for the largest elements of the mission. We assume that this is not a vehicle that industry or other partner nations will develop without NASA as a funding customer.
2. International: This architecture provides a great deal of flexibility for international partners to provide important elements. Surface elements could be provided for research goals, or where the nation has goals in developing technology and align well with a stand-alone element, such as life support in a human rover, or power systems that are also applicable to Earth operations.

3. Commercial: Our architecture increases mission opportunities with lunar activity and Mars precursors that attempt to create and sustain a reasonable cadence of NASA-funded missions utilizing commercial capability. With a feasible business case for providing those capabilities, industry would be more willing to develop the capabilities and keep costs reasonable to compete for future business. With affordable, capable systems, other customers may be interested in also using those systems for lunar missions or other deep-space activities.

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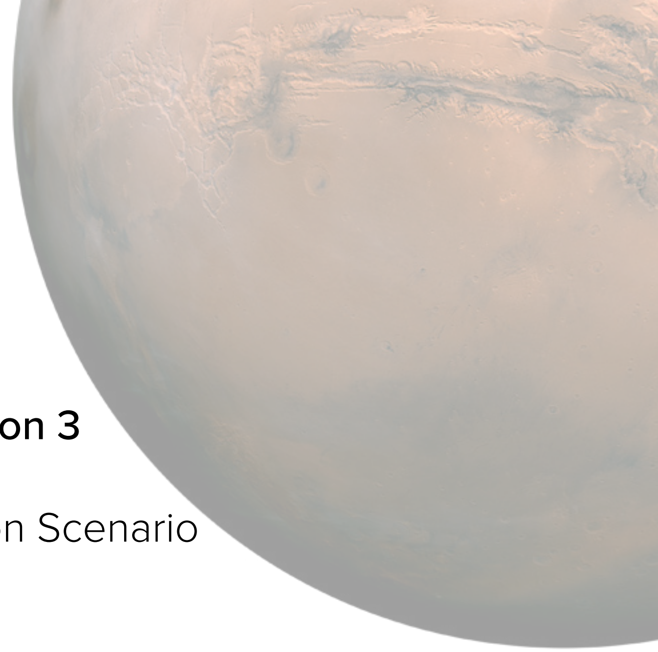

AM V Breakout Session 3

Permanent Human Habitation Scenario

Abstract

It was the strong consensus of Team 3 that the stretch goal of permanent presence on Mars should be the end goal to which we strive, and that such a goal is needed to inform/guide our overall Mars investment strategy and to minimize sustaining costs. To this end, the team felt that an incremental and adaptable architecture is needed, placing priority on getting to the Martian system sooner rather than later and letting resulting lessons learned from initial voyages inform subsequent engineering developments and mission objectives.

Such a strategy not only has the advantage of ensuring that engineering investments are those that are needed, but it also allows for amortization of costs over a longer period of time as well as crew insertion with an emphasis on safety. An initial orbital mission – and possibly several – followed by short-term surface stays are key elements of such an iterative strategy. It is essential to have a healthy respect for what we do not know about Mars and ease our way into learning how to live and work there. Correct base selection is much more important for achieving long-term presence than it is for the sortie-class and research base end states. The selected site must have sufficient scientific opportunity to warrant such an extended presence, and availability and use of resources will be required to reduce the dependency on supplies arriving from Earth and therefore lower the cost of permanent presence on Mars. Performing adequate and even iterative reconnaissance in advance to pick a good site becomes more critical. When we achieve long-term presence is not as important as methodically, safely and sustainably working towards the end goal: to make sure that we are able to stay on Mars for as long as we want.

The fundamental source of enterprise sustainability required for permanent human habitation is a broad portfolio of international and commercial partners. The modular architecture is best supported by a similarly modular and diverse supply chain, thus, it is imperative that we view our partners as true collaborators who have major roles and bear risk accordingly. Our team envisioned a more aggressive use of ISS to support exploration to enable the “sooner rather than later” approach. A cislunar human habitation and transportation system, commonly referred to as the Gateway, was also felt to be a critical element in an overall Mars strategy. Sorties to the lunar surface were not viewed as required, though they could be advantageous in a couple of key areas so long as the overall goal of achieving the first initial human missions to Mars was not materially delayed.

Our team was convinced that, with a flexible and iterative approach, this architecture would not necessarily cost more than the others for a given time-frame, and that such an approach may, in fact, be the only way to achieve the dream of human habitation of Mars.

1. Primary Objectives

The primary objective[4] of Architecture 3 is to establish a permanent human presence on Mars that substantially involves international, academic, and industry partners. The architecture that our team developed will

- Enable a capability for human habitation on Mars and a thriving space economy in the 21st Century,
- Maximize the role that human exploration of space plays in advancing overall knowledge of the universe, and
- Explore the viability of and lay the foundation for sustainable economic activities in space.

The NASA Authorization Act's policy guidance and the HEOMD Strategic Principles[5] for Sustainable Exploration serve to both shape and be figures of merit for architectures. Table 1 is an assessment of Architecture 3 against these figures of merit. Most have been addressed by our architecture explicitly while several are architecture-independent.

Table 1. Architecture 3 Assessment

Figure of Merit	Architecture Assessment
NASA Authorization Acts Long Term Goals and Key Objectives	
• Expand permanent human presence beyond LEO with international, academic, and industry partners	Addressed explicitly
• Enable the extension of human presence throughout the solar system	Addressed explicitly
• Enable human habitation on another celestial body and a thriving space economy	Addressed explicitly
• Sustain the capability for long-duration presence in low-Earth orbit	Not addressed, but not impacted
• Determine if humans can live in an extended manner in space with decreasing reliance on Earth	Addressed explicitly
• Identify potential roles that space resources may play to meet national and global needs and challenges	Not addressed, but not impacted
• Explore the viability of and lay the foundation for sustainable economic activities in space	Addressed explicitly
• Advance overall knowledge of the universe	Addressed explicitly
• Support United States' national and economic security and global competitive posture	Addressed implicitly

[4] Our primary objective responds directly to policy guidance in the bi-partisan NASA Authorization Act of 2010 (REF: https://www.nasa.gov/pdf/649377main_PL_111-267.pdf) as refined by the NASA Transition Authorization Act of 2017 (REF: https://www.congress.gov/bill/115th-congress/senate-bill/442), which mandates the Long Term Goals and Key Objectives of the NASA human space flight and exploration efforts.
[5] Reference: https://www.nasa.gov/sites/default/files/atoms/files/2018_strategic_principles.pdf

• Inspire young people in their educational pursuits	Addressed implicitly
• Build upon the cooperative framework established by the ISS	Addressed explicitly
• Achieve human exploration of Mars with stepping stone approach	Addressed explicitly
HEOMD Strategic Principles	
• Fiscal Realism	Addressed explicitly
• Scientific Exploration	Addressed explicitly
• Technology Pull and Push	Addressed explicitly
• Gradual Build Up of Capability	Addressed explicitly
• Economic Opportunity	Addressed explicitly
• Architecture Openness and Resilience	Addressed explicitly
• Global Collaboration and Leadership	Addressed explicitly
• Continuity of Human Spaceflight	Addressed explicitly

2. Guiding Principles

This scenario uses a set of guiding principles that result in permanent presence. The detailed guiding principles are:

1. No technology development is wasted: Everything feeds towards permanent presence
2. Modularity is important in all aspects of Mars mission elements
3. Single fault tolerance
    - a. We can tolerate one major failure and still achieve mission success
4. Extensive commercial and international involvement assumed, even in the critical path
5. Diversity of supply chain is high priority for mission success particularly given constraints of synodic launch windows: “If you miss the launch window you are down 26 months”
6. Assume six-person crew
    - a. Majority of human spaceflight experience is built around 3 or 6 person crews
    - b. Assume 3-person landers and MAVs
        - i. To protect single fault tolerance for mission success on short stay missions, two landers/MAVs are needed
            - 1. Also allows validation of 2 different sites, if necessary
            - 2. Allows two sorties (e.g., a “red” team followed by a “blue” team)
        - ii. Include a single lander and MAV on second orbital mission
            - 1. If lander and MAV check out and other TBD criteria are met, there is an option for a short-stay landing
        - iii. Also reduces total mass for any given lander
            - 1. More landers are required, but mass and packaging are more manageable.

      As we step towards permanent presence, 3-person steps in crew-size are more manageable than 4- or 6-person increments, providing a smoother ramp.
7. Orbital Missions assumed initially
    - a. With options to go to surface if TBD criteria are met
    - b. May be several orbital missions
8. Human presence on orbital missions will support second, redundant round of Mars sample return and analysis en route home
9. MTV is the safe-haven and ride home
    - a. MTV remains human-tended for initial missions to Mars
        - i. Reduces dormancy challenges. Systems that are uncrewed for extended periods of time, but required for subsequent use, pose a huge risk to campaign success if there are no crew onboard to prevent propagation of issues becoming catastrophic loss.
        - ii. Keeping the MTV tended reduces the complexity of the most critical mission component.
10. MTV is more complex than simply a habitat
    - a. A laboratory module which can function as a backup habitat in case habitat is compromised.

    b. Airlocks needed to support in-transit EVA
        i. Support science mounted externally
        ii. Exterior access in case of major malfunctions which require EVA to repair
    c. Robotic arm to support major malfunction repairs.
11. Initial missions on the surface will be short stay
    a. Surface presence should be considered dangerous until proven otherwise
        ii. There is no experience with human Mars surface operation, although decades of experience in orbit
        iii. Surface is assumed unsafe until it is better understood
    a. With options to extend later surface stays if TBD criteria are met
    b. May be several short stay missions before long stays are attempted
    c. Humans will support landing site assessment and verification
    d. Humans will support assembly and checkout of Mars Base components (Hab/Lab)
12. Rovers are a higher priority than habitat/laboratory, etc.
    a. Rovers provide rescue capability
        i. For example, if the crew does not land in the right place, the rover can come to them.
    b. At least two rovers for redundancy
        i. Rovers could be delivered by commercial/international partners
13. Not looking for complete reusability for initial landers/MAVs: incrementally build to full reusability
14. LOx/Cryo propellant engines for MAV
    a. Reduce propellant via LOx ISRU production
        i. For example, for a 4-person MAV, reduces need for 28 metric tons of mass to the surface.
    b. Cryo Propellant ISRU is deferred until water resources are verified
        i. Human surface crews are assumed to help with verification and setup of production equipment.

The goal of permanent human presence results in a number of key architecture differences, as compared to the other AM V scenarios:

- Flexible mission objectives
- Modularity and diversity of supply chain are critical
- Protection against failure modes to ensure mission success
- Commercial and international partnering is key: Partners should be on critical path
- Six-person crews with three-person landers/MAVs
- Martian surface treated as dangerous until mastered
    - Mars Transfer Vehicle is treated as the safe haven
    - Mission sequence builds from orbital missions through short stays to permanent presence
- Pressurized rovers are a critical initial element
- Heavy emphasis on utilizing local resources (ISRU)

Cislunar activities will demonstrate technologies and operations for crewed Mars exploration and so need to be feed-forward to Mars exploration. The Gateway is critical for aggregation, resupply, and refurbishment for the Mars Transfer Vehicle. Development of liquid oxygen and cryogenic fuel (hydrogen or methane) engines should be common to minimize development efforts and establish run times on the engines. Lunar ascent vehicles can probably be feed forward, at least for the non-aerodynamic deceleration phases. The Gateway's Power and Propulsion Element (PPE) and habitat are logical components of the Mars Transfer Vehicle. Ideally, they should be the same to minimize development costs, and establish sufficient run times to understand mean times between failures and therefore Martian resupply requirements. The Mars Transfer Vehicle though will be more than a habitat and a PPE. Compact nuclear power on the Moon is also enabling for Mars. Rovers are critical for Mars. It is not clear yet that lunar ISRU is viable – reserves are unproven – and that any associated technologies must feed forward to Mars ISRU applications.

3. Concept of Operations

Major Milestones and Mission Sequence

The campaign to reach the end state of permanent human habitation consists of three phases that provide for crew safety and affordability. The mission phases and key activities during that phase are:

1. Robotic Exploration to Select Landing Site (see Figure 1):
   Placing the initial uncrewed infrastructure in low-Mars orbit, in high-Mars orbit, and on the Martian surface, for navigation, communication, space weather, site selection, and ending with a sample return mission that also supports scientific investigations.
   a. Commercial launches, direct to Mars
   b. One low-Mars orbit optical / synthetic aperture radar spacecraft survey
   c. Two high-Mars orbit navigation / communications / space weather spacecraft
   d. One ground-truth rover
   e. One sample-return mission
2. Crewed Orbital & Sortie Missions to Confirm Landing Site (see Figure 2):
   Establishing an initial orbiting base about Mars where crew may safely conduct further surveys of the human exploration zone (EZ) as needed and assist via teleoperations the build-up of surface assets once the resources and hazards are verified.
   a. Mixture of SLS and commercial launches, cislunar aggregation
   b. Initial habitation infrastructure in Mars orbit
   c. First crews to Mars orbit, with potential first visits to the EZ anticipated to be short stays in pressurized rovers.
3. Buildup of Surface Assets Following Site Selection (see Figure 3):
   The initial build-up of surface assets to support a crew, including the insertion of the initial surface crew upon verification of operational safety metrics for the surface systems.
   a. Mixture of SLS and commercial launches, cislunar aggregation
   b. Initial surface infrastructure at verified landing site
   c. Crews to the Martian surface for short stays in a habitat at verified landing site, assisting in infrastructure buildup.

Beyond Phase 3:
Bringing crews to Mars faster than we bring them home, for long, overlapping stays which maintain permanent presence.

Relying on robotic vehicles wherever possible reduces the number of crews necessary to be exposed to radiation and microgravity. Establishing the reality of resources and hazards at the proposed human exploration zone prior to any build-up of infrastructure there ensures that all resources are available for the crews at the site and hazards are minimized.

Our stepwise approach to selecting a site and then building up infrastructure also benefits affordability by phasing activities over time to stay within budgets and minimizing the risk of needing to select a different surface site. Placing assets in Mars orbit is far cheaper than placing them on the surface. Placing assets in cislunar space costs the least, transporting them to Mars orbit costs more, and then placing them on the Mars surface from Mars orbit costs the most.

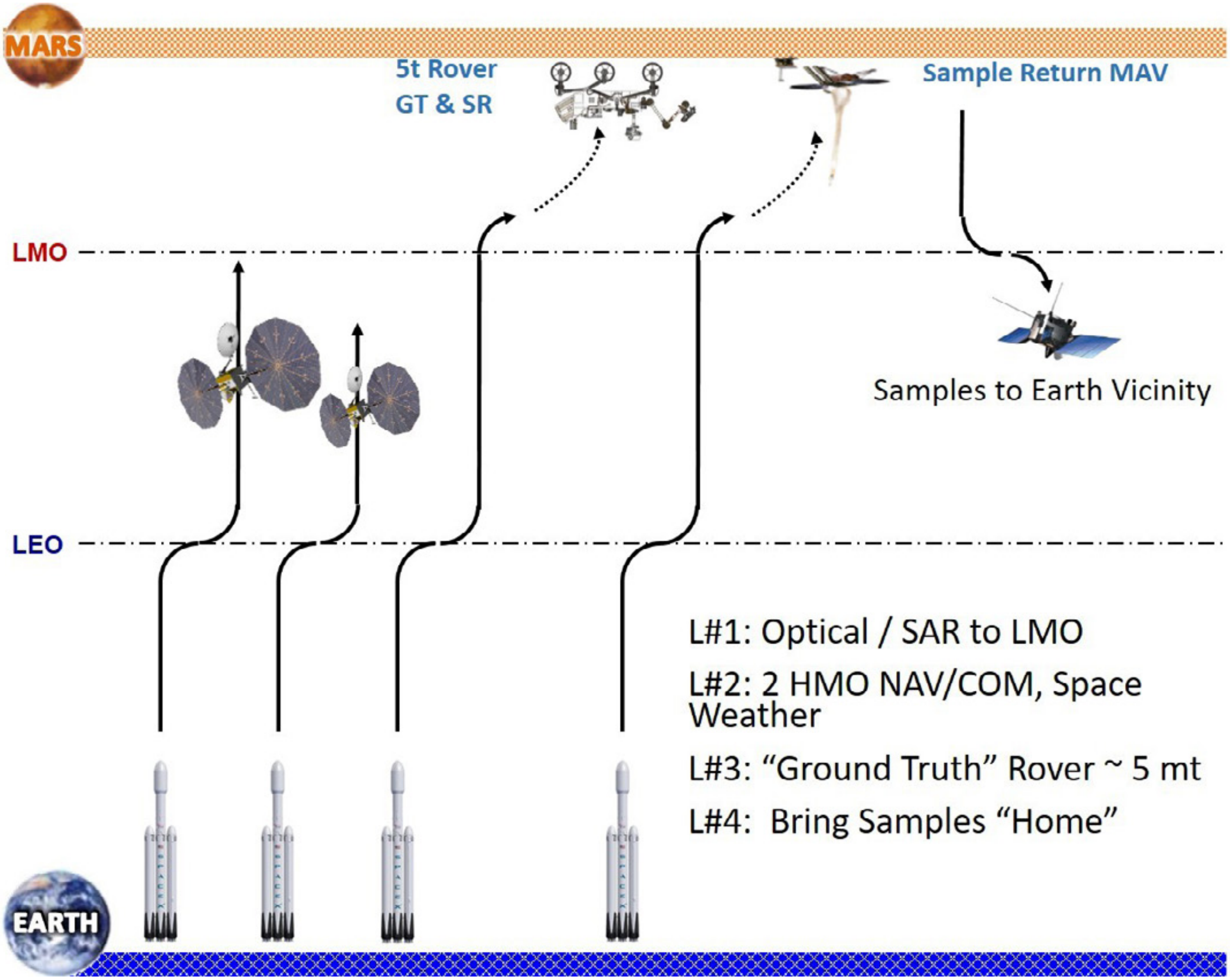

Figure 1. Phase 1: Robotic Exploration to Select Landing Site

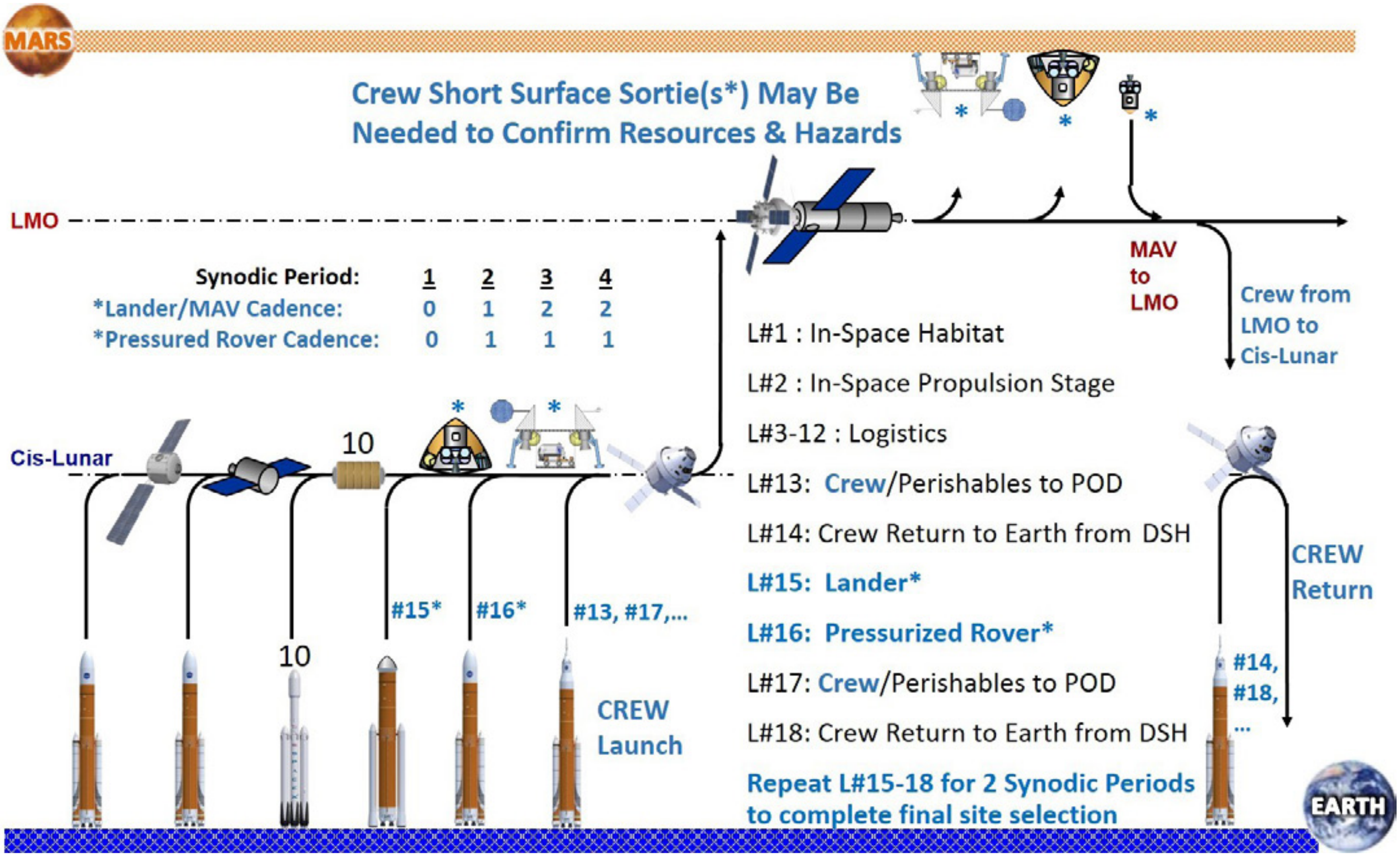

Figure 2. Phase 2: Crewed Orbital Mission to Confirm Landing Site

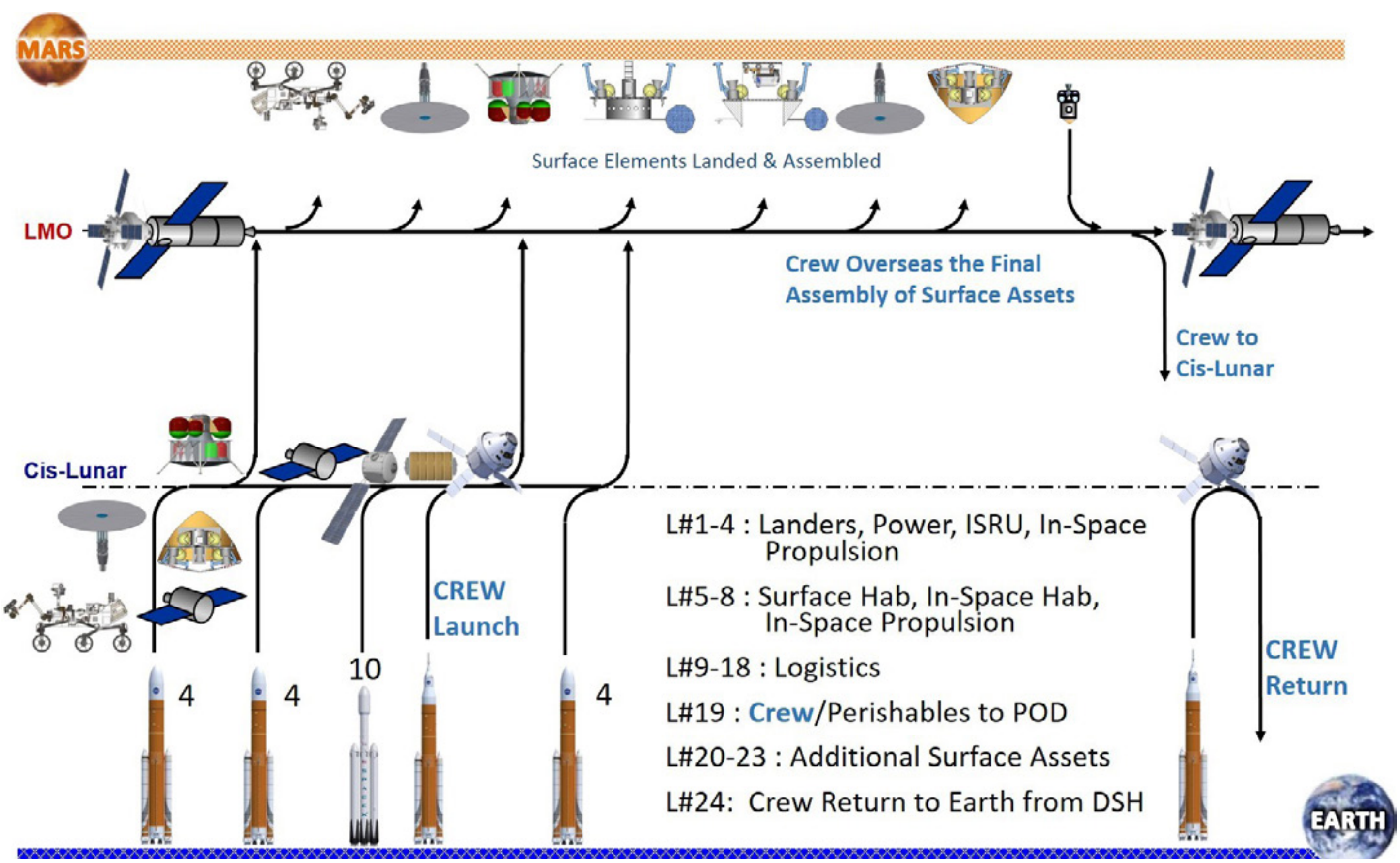

Figure 3. Phase 3: First Crews to Mars Surface Missions

Plausible System Upgrades

The first priority on upgrades is to implement those technologies and capabilities that increase safety, reduce cost of permanent presence on the surface, and lead to Earth-independence. Reusable landers like Hercules (Arney, et al., 2015) that utilize Mars in-situ resource utilization (ISRU) fuel is only the beginning. Reusable interplanetary transportation, as well as increased commonality across all mission elements, will help drive down costs. The Hercules design originally conceived for only entry, descent, and landing (EDL) at Mars has variants that make it viable for other mission elements, such as lunar EDL, interplanetary transportation and habitation, and orbiting nodes including safe haven (Komar D. R., 2017). The Hercules also offers entry aborts to both orbit and the surface, as well as launch abort at Mars (Komar & et. al., 2018).

Additive manufacturing using plastics will likely lead to uses of the ISRU metals as well as repurposing any materials brought from Earth. However, there is the challenge of producing energy on the surface of Mars. Becoming energy-rich is vital to safe permanent presence. Habitation systems will also be upgraded as crew protection requires a mixture of underground habitation shielded from harmful galactic cosmic rays (GCR) and surface greenhouses that require access to sunlight and energy to run growing lamps and water pumps.

Landing Site Criteria and Selection

For the objective of permanent habitation, maximizing the number of vehicles and other assets that are reused was a key decision, although perhaps the most important aspect is the availability of the resources, primarily water ice, carbon dioxide, and regolith including some minerals and volatiles. These are valuable ingredients to feedstock for in situ construction and additive manufacturing on Mars and lead to emplacement of radiation protection shielding, fission and exhaust blast berms, landing pads, launch pads, driveways, and habitable and unpressurized structures. This living off the land approach will require easy access to large amounts of power that can scale over time with growth of crew number on the surface and the assets required to support crew.

The landing site needs to be rich in usable resources, so our phased plan focuses on determining the availability and accessibility of those resources, and then building up the surface infrastructure to take advantage them. Determining the availability of resources also has overlap with scientific objectives. The build-up of safe surface assets is the costliest portion of the mission. It will be even more costly if we learn later that we picked the wrong landing site. Hence, the goal of Phase 2 is to ensure that the correct site has been selected prior to making that huge investment.

These are some of the uncrewed assets and capabilities that need to be considered or demonstrated prior to or during Phase 2:

- High-bandwidth communication
- Navigation
- Space weather warning system
- Mars surface weather
- Precision landing

In order to provide greater flexibility on each mission, we decided on a mission crew size of 6 astronauts. Each mission will carry with it a pair of 3-person landers, rather than a single monolithic lander. This allows two surface sorties, with the second surface crew capable of investigating an alternative landing site if the first crew finds the primary landing site to be insufficient.

Affordability and Sustainability

For a long-term scenario focusing on permanent human presence, key strategies to enable sustainability are scaling the timeline to the available budget and remaining flexible as the scenario grows. The other fundamental source of enterprise sustainability required for permanent human habitation is a broad portfolio of international and commercial partner stakeholders. While it is hard to predict the exact contributions from each partner, their contributions both increase the affordability by spreading the costs across many organizations and increase the sustainability by providing broad, diverse support for the campaign. The architecture needs to be designed to encourage partner stakeholders to contribute through open standards, flexibility, and a clear, stable mission sequence.

Using ISRU and a reusable lander can lead to sustainable human presence on the surface of Mars. As shown in Figure 4, the initial 12 SLS launches positions the campaign to begin selecting the level of ISRU that stakeholders are willing to fund, including the reusable lander (Komar D. R., 2017). This decision point allows the program an opportunity to reconsider earlier decisions prior to making additional investments. This is critical to achieving an acceptable risk posture with the least amount of funding.

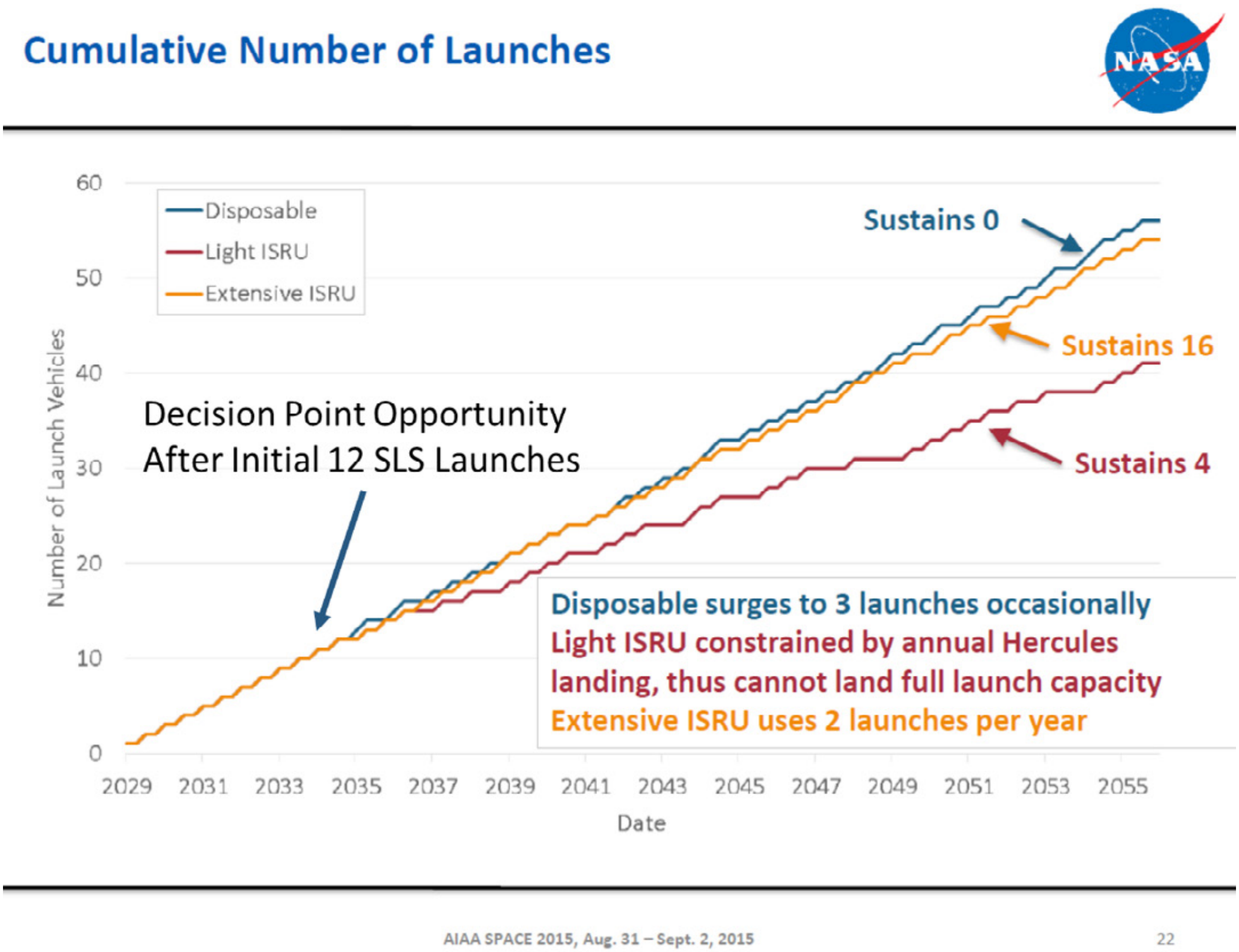

Figure 4. Decision point at which the magnitude of ISRU is decided

4. Required Major Technologies and System Elements Performance Capabilities

The required major technologies for the scenario, in a priority order that reflects the time of first use, are:

1. Commercial and/or international launch vehicles
2. Robotic Mars orbital and surface assets
3. Human-rated, high-mass transportation to deep space (SLS and Orion)
4. Deep-space habitation (i.e., the Gateway or equivalent)
5. Surface power
6. Surface ISRU
7. Reusable, refuelable Mars lander and ascent system
8. Surface habitation

The SLS is assumed as the launch vehicle for large elements and for crew launch. Orion is assumed as the vehicle for crew ascent, travel to cislunar space, and re-entry at Earth. In-space habitation systems for the journey to and from Mars, and while in Mars orbit, would require near closed-loop life support systems, high-efficiency propulsion systems, and high reliability and maintainability. We also propose development towards reusable, refuelable lander and ascent vehicle that can travel between Mars orbit and the surface and back, which is shown in Figure

The principle elements of the surface architecture are the propellant ISRU system, the surface power system, the habitation system, and the other ISRU systems.

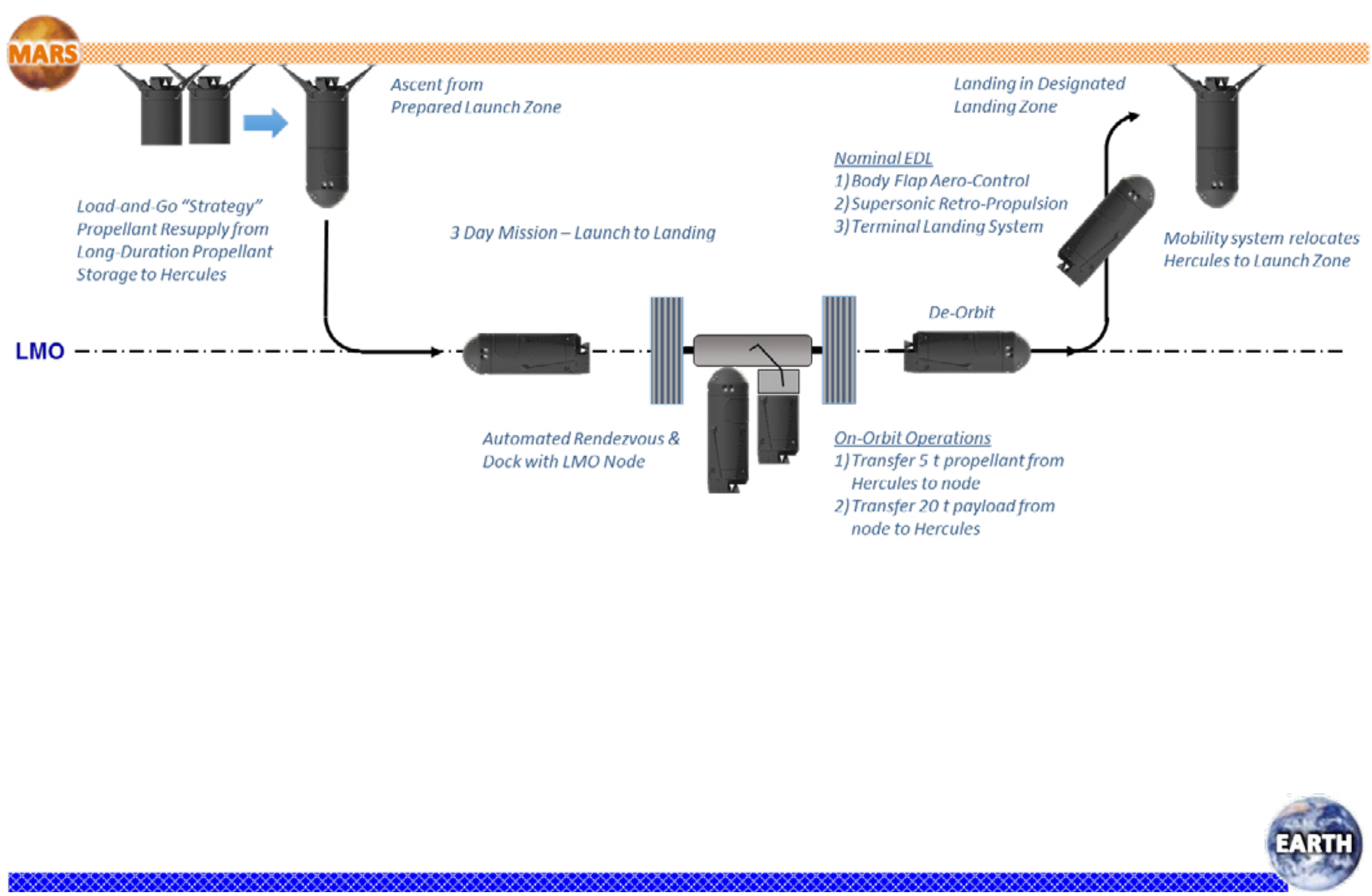

Figure 5. Reusable, Refuelable Lander and Ascent Vehicle

Propellant ISRU

Previous studies have identified methane and oxygen, produced from Martian carbon dioxide and a source of hydrogen, as a potential propellant that can be manufactured on Mars, leading to significant reductions in landed mass on Mars. The Sabatier process converts carbon dioxide and hydrogen to methane and water. The water can then be electrolyzed into oxygen, stored for eventual use, with hydrogen recycled back to the Sabatier reactor. We assume in this study that the ISRU plant is located near a significant quantity of high-concentration water (~40%) in the regolith. This water provides the initial source of hydrogen.

Surface Power

Due to the hundreds of kilowatts required for the ISRU and other systems on the surface of Mars, we assumed nuclear power as the baseline technology for providing electrical power in this study. This assumption is consistent with the trade studies discussed in Design Reference Architecture 5 (NASA Mars Architecture Steering Group, 2009). The surface power system consists of the nuclear reactor itself, power conversion system, power management and distribution system, and radiators.

Habitation

Two types of habitats are used by the crews on the surface of Mars: initially, pressurized rovers serve as mobile habitats, and only after the final site selection is made and heavier assets are deployed is a dedicated surface habitat module landed. The rovers will serve as habitats for the three-person short stays until site validation is complete. Additionally, the rovers can serve as mobile life boats which can come to the astronauts if they land off target. Each Mars mission after the first orbital mission will carry a pressurized rover with it, to gradually build up mobile, flexible assets on the surface. Once the final site is selected, a larger, permanent surface habitat will be deployed to support humans for long stays leading to permanent presence.

Other ISRU

As the initial capabilities are deployed and operated, there exist opportunities to further reduce the dependency on supply from Earth. Transition to partial food production on Mars would be beneficial. Plastics (polyethylene) can be produced from methane manufactured on Mars. These plastics can then be used with advanced manufacturing processes (e.g., 3-D printing) to produce spare parts on demand.

Plausible Technology Capability Performance Upgrades

Surface power and propulsion upgrades would improve the scenario in the long term. The surface power concept selected in reference 2 was a nuclear device providing 110 kWe and weighing 12.1 t, which is an improvement over current concepts. Even more advanced nuclear technology, such as Nuclear Thermionic Avalanche Cells (NTAC) could also provide surface power and power rovers and habitats (Choi & Mankins, 2017). The standoff distance requirement is anticipated to be far less than traditional fission reactors.

Nuclear thermal propulsion could also reduce transit times (Borowski, McCurdy, & Packard, 2014). Initial assessments by NASA Langley Research Center suggest that NTAC may enable fast transits via high thrust as well as high I_{sp} for VASIMR and Hall propulsion concepts at alpha values (kg/kw) far lower than possible with fission reactors or MHD (magnetohydrodynamic) power concepts (Chang Diaz, 2013).

5. Major Risks

There are a few technical risks that will need to be addressed in the development and demonstration of the systems. A high-reliability, near-closed-loop life support system for the in-orbit and surface habitation systems is required to keep the logistical supply chain manageable. Systems on the ISS are demonstrating increasing loop closure and reliability, but they are not Mars-class yet. Long-duration exposure to microgravity and radiation affect crew performance (NASA, 2014), but there are no Mars analog mission results available for guiding architectural design. Systems to generate propellant, water, and oxygen while on the surface of Mars are necessary. Numerous ground demonstrations have been completed, and the Mars 2020 rover is carrying an ISRU experiment, although more development and demonstration are required. These ISRU systems require high power, and small nuclear fission reactors are the best choice to allow for reliable power, even in higher Mars latitudes and likely dust storms. These power systems would have heritage from small naval nuclear reactors but are a new-development item. Mars entry, descent, and landing has been demonstrated at the one metric-ton class for scientific missions, but tens of metric tons are required. Mars ascent has not yet been demonstrated.

From an operational perspective, this scenario is very dependent on site selection. There would be significant consequences to the schedule if during initial exploration the crew determines that resource availability is insufficient for a permanent presence and a new site would need to be selected. From a political perspective, permanent presence is a long-term endeavor. Funding instability will have significant impacts. Given that achieving major program milestones is very dependent upon funding level, there is a risk that funding instability will result in infrequent missions, which are hard to sustain politically.

6. Role of ISS, Cislunar Space and Lunar Surface

In general, we see significant opportunities for accelerating the exploration of Mars using ISS and a mid-2020s Gateway in cislunar space. ISS is an under-utilized exploration asset at present. The Gateway is a mandatory element to support Mars missions as a capability for aggregation of exploration program elements. Our team concluded that human sorties to the lunar surface are not required in advance of the exploration of Mars, although such missions can be instructive, bearing in mind inescapable differences between the Moon and Mars. The following tables outline how our team sees these different regions of space enabling humans-to-Mars.

Table 2. ISS/LEO Roles

ISS/Low Earth Orbit	
Should	Can leverage if activities underway there
ECLSS – Closed Loop	
Analog missions (in space, e.g., Scott Kelly's mission) of 12 months or longer with multiple crewmembers	Tele-operations
Analog missions that connect to an Earth-based Mars analog to understand physical, psychological and productivity recovery times from having been in zero g.	Human-rate other exploration sub-systems and modules in space. In other words, take full advantage of having a robust platform now in zero g and in a vacuum. Start developing lifetime tests to understand how the systems will perform on actual missions to Mars.
Commercial partnership rehearsals	

Table 3. Gateway Roles

Gateway	
Should	Can leverage if activities underway there
Human operations with > 1 day away from Earth	First part of deep-space logistics supply chain for supporting Mars missions
Full deep-space radiation environment	Telerobotics
Mars Transfer Vehicle assembly, integration and resupply.	Lunar sample return
Commercial partnership rehearsals	Mars sample return: inspection and quarantine (if needed).
	Technology demonstrations such as for cryogenic fluid management

Table 4. Lunar Surface Roles

Lunar Surface	
Should	Can leverage if activities underway there
Assess reality of potential resource feedstocks (robotically; uncertain whether human astronauts needed at this time)	Teleoperations
Human presence on lunar surface to build expectations. Could be private US companies or international partners, while NASA prepares for Mars.	Pressurized rovers
Cultural and political goal would be for everyone looking at the Moon to know that humans are there.	Some ISRU
	Low-g habitat
	Psychological, emotional, and other crew health experience (far side of Moon, L2)
	Surface operations
	Partnership rehearsals
	Sample return process
	Propellant/water production for Mars missions, if feedstocks are verified and shown to be economically viable

7. Capabilities Suitable for Partner Contributions

Our team not only identified significant opportunities for commercial and international participation, but also believes that those partnerships will be enabling for a sustainable exploration of Mars. For commercial partnering, the lessons learned from ISS are critical. We fully anticipate the logistics to a Gateway will be key to not only reducing costs, but also for enabling new industries and increasing overall system redundancy through a diverse supply chain that can withstand failure.

A key component will be propellant delivery, given the large amounts of propellant necessary for Mars missions. Eventually, we foresee this propellant delivered from Earth. When/if water feedstocks are proven in sufficient abundance on the Moon, the Martian moons or Mars itself, we anticipate that commercial interests will be key for efficiently extracting these resources. Critical for establishing these industries is having a credible, multi-decade, and substantial requirement for, in this case, propellants. We foresee commercial launch providers not only delivering logistics, but also modules.

We anticipate this model being extended sooner rather than later to the Martian system, initially to Mars orbit and then to the Martian surface. Key here is having defined standards and an aggregation node in high-Earth orbit and/or cislunar space, and in the Martian system to allow other partners to fully participate in the exploration of Mars. In this paradigm, the government creates an anchor-tenant function. The government also does basic research and development to establish the viability of market, such as surveying for the existence of resources in accessible and sufficient quantities to allow commercial interests to be successfully involved.

Working with other countries is also key. We must harness the ideas, energy, and resources that 71 countries with active space programs potentially bring to the exploration of Mars. Such partnerships not only provide additional diversity of ideas and systems and therefore improve the ability to withstand failure, but also as governmental entities, they will be able to help underwrite basic research and development. This will be enabling for their commercial interests as well as ours, to move deeper into the Solar System.

Regardless of whether it is a commercial or an international partner, it is important to empower them to manage their contributions. For commercial companies delivering propellant, NASA would not direct them how to manage every segment of their operation, but rather agree to buy propellant successfully docked to a node in the Martian logistics system. If the partner does not arrive successfully, they do not get paid. While there may be risks in putting a partner in the "critical path", there are ways to reduce that and give the partner real ownership for their contribution. Perhaps a commercial or an international partner could deliver a second rover to the Martian surface. If they arrive on time, then we have a backup a rover; if they do not, then we just work with the primary rover. In other words, the partner is delivering key functionality, but the whole mission does not depend on it. Even placing a partner in the critical path, may be acceptable, if there is a satisfactory alternative, should they not deliver.

In turn, from the perspective of sustainability it is important to recognize the importance to international space exploration for NASA, playing the role of "anchor tenant," to itself be a reliable partner. Many smaller space agencies will be relying on NASA to deliver on its stated goals, as was the case sufficiently often with ISS. ISS has also taught us that working with partners is not only important for all of the reasons above, but it also leads to so many more stakeholders being involved. This, in turn, ensures the sustainability of the exploration of Mars and its ultimate permanent habitation.

8. Cost Estimate

A cost assessment for the AM V Breakout Group 3 community-derived architecture was performed by Robert Shishko at NASA JPL using a cost tool that was developed in collaboration between the Aerospace Corporation and JPL. The cost estimates were intended to include the costs associated with a Mars program that would be in addition to NASA's human spaceflight budget. These costs do not include NASA's current programs such as SLS, Orion, ISS, mission operations, and center support costs. The estimate assumed that the SLS program will develop the Block 2 version and will provide two launches per year. The estimates do not include the development and operation of the Gateway, assuming that it would be covered in budget line items separate from the human Mars program. The estimate assumes that in-space propulsion stages for the Mars missions would be provided by international partners. *In reality, a guiding principle for this team is to scale the timeline of the mission to meet the available budget.*

The total estimated budget is shown in Figures 6 through the year 2046 for consistency with the estimates for the other 2 end goals presented above. However, launches and assets are required beyond 2046 to achieve the first long-stay crew arrival on the Martian surface in 2051. The costs of those additional assets that occur up until 2046 are included in the cost estimate shown in Figure 6. The estimate is in real year dollars, assuming an annual inflation rate of 2.6%. The costing methodology was developed by the Aerospace Corporation and updated in a collaboration between the Aerospace Corporation and JPL. The methodology and cost estimates are comparable to the National Research Council (NRC) Pathways study (National Research Council, 2014). The cost methodology is also comparable to that used in a 2017 assessment by the NASA Office of Inspector General (NASA Office of the Inspector General, 2017).

The cost estimate, with international partners providing in-space propulsion, suggests that the example program could be implementable with an annual cost, in comparable year dollars, below that of the ISS, up until the second crewed mission to the Martian system, and then staying close to the ISS budget during subsequent landings. Not included herein but available upon request, a cost estimate representing LOx/methane in-space stages paid by NASA shows that the program could be executed at approximately the same cost as the ISS, until the first orbital mission to Mars in 2033. This comparison underscores the importance of international partners to sustainability. In both estimates, the costs ramp up as we develop and deploy the technology required for permanent habitation of the Red Planet.

We emphasize that the validity of the cost model and the fidelity of this estimate do not represent the rigor and validation that would be required for any cost commitments.

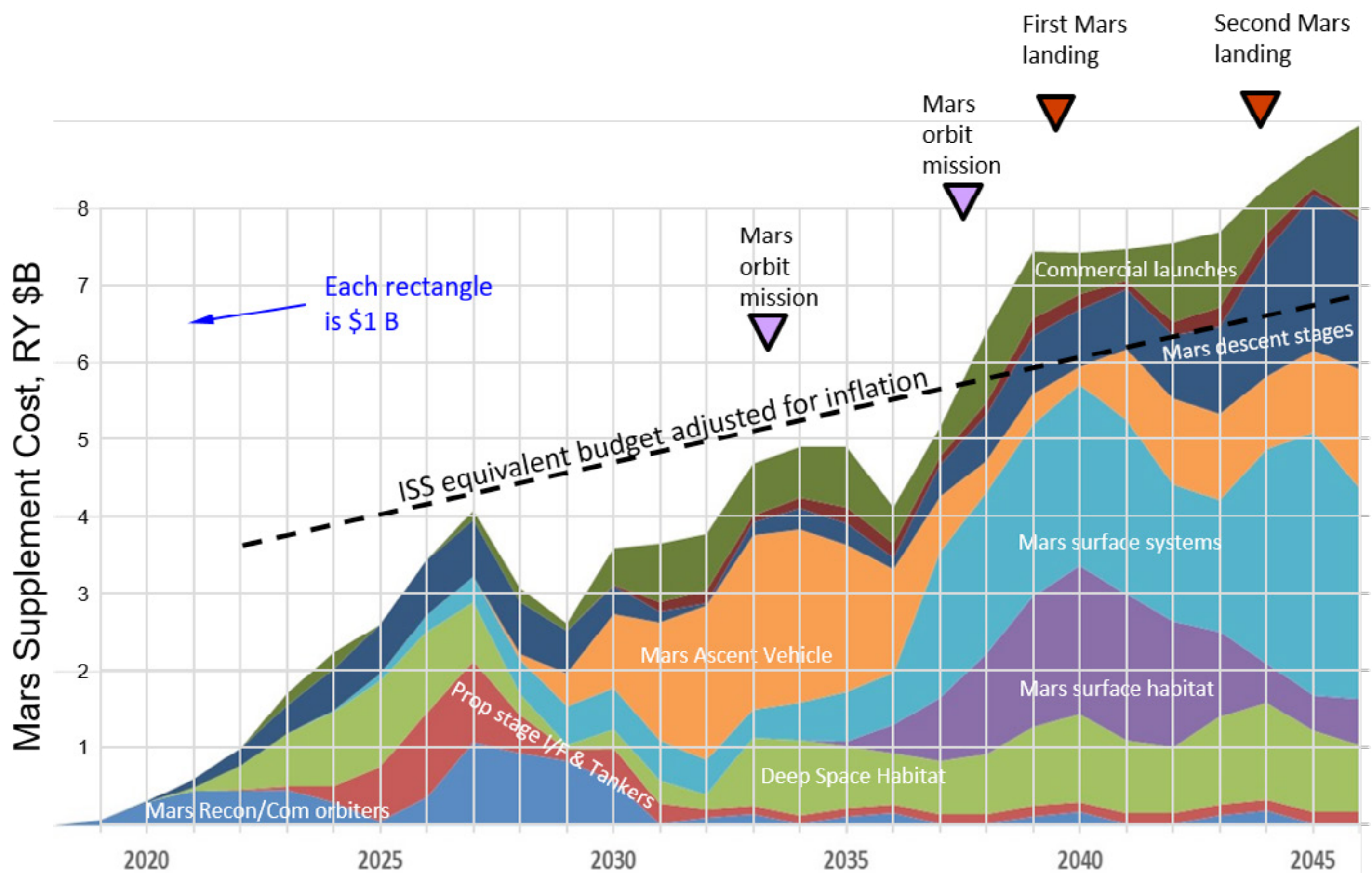

Figure 6. Cost estimate based on the initial long stay occurring in 2051 and International Partners contributing the in-space propulsion element. ("Dance Card" shows launch in 2050 of first long-stay crew).

9. Summary

The architecture developed by Team 3 is intended to achieve the following goals derived from the 2010 and 2017 NASA Authorization Acts:

1. Enable a capability for human habitation on Mars and a thriving space economy in the 21st Century,
2. Maximize the role that human exploration of space plays in advancing overall knowledge of the universe, and
3. Explore the viability of and lay the foundation for sustainable economic activities in space.

- The following key architecture points will allow advancement towards permanent presence on Mars while staying within realistic budgetary and technological constraints:
  - Step-wise approach with flexible mission objectives
  - Robotic reconnaissance
  - Orbital missions with options for short sortie
- Surface missions with options to extend
- No technology development is wasted
- Modularity and diversity of supply chain are critical
- Protection against failure modes to ensure mission success
- Commercial and international partnering is key: Partners should be on critical path
- Prioritization of site selection and verification
- Six-person crews with three-person landers/MAVs
- Martian surface treated as dangerous until mastered
  - Mars Transfer Vehicle is treated as the safe-haven
  - Mission sequence builds from orbital missions through short stays to permanent presence
- Pressurized rovers are a critical initial element
- Heavy emphasis on utilizing local resources (ISRU)

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