Human Mars Mission Design – The Ultimate Systems Challenge

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Abstract

A human mission to Mars will occur at some time in the coming decades. When it does, it will be the end result of a complex network of interconnected design choices, systems analyses, technical optimizations, and non-technical compromises. This mission will extend the technologies, engineering design, and systems analyses to new limits, and may very well be the most complex undertaking in human history. It can be illustrated as a large menu, or as a large decision tree. Whatever the visualization tool, there are numerous design decisions required to assemble a human Mars mission, and many of these interconnect with one another. This paper examines these many decisions and further details a number of choices that are highly interwoven throughout the mission design. The large quantity of variables and their interconnectedness results in a highly complex systems challenge, and the paper illustrates how a change in one variable results in ripples (sometimes unintended) throughout many other facets of the design. The paper concludes with a discussion of some mission design variables that can be addressed first, and those that have already been addressed as a result of ongoing National Aeronautics and Space Administration (NASA) developments, or as a result of decisions outside the technical arena. It advocates the need for a “reference design” that can be used as a point of comparison, and to illustrate the system-wide impacts as design variables change.

Keywords: Mars, Mission Architecture, Systems Engineering

Nomenclature

AU	Astronomical Unit
kWe	Kilowatt-electric

Acronyms/Abbreviations

Delta-V	Change in Velocity
DRA	Design Reference Architecture
EDL	Entry, Descent and Landing
EVA	Extravehicular Activity
EZ	Exploration Zone
IMLEO	Initial Mass to Low Earth Orbit
Isp	Specific Impulse
ISRU	In Situ Resource Utilization
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
MAV	Mars Ascent Vehicle
MLP	Mobile Launch Platform
PLSS	Portable Life Support System
RF	Radio Frequency
ROI	Region of Interest
SLS	Space Launch System
SME	Subject Matter Expert
TMI	Trans-Mars Injection
VAB	Vehicle Assembly Building

1. Introduction

NASA came into existence in 1958, and soon after its inception its engineers began imagining design solutions for sending human crews to the planet Mars. Even before NASA, visionaries like Werner von Braun were calculating, dreaming, and documenting how humans could one day venture to our most Earth-like neighbor. Von Braun’s *Das Marsprojekt* [1] provided the first technical end-to-end design of a human Mars mission, and it set the standard for how human exploration missions would be analyzed.

NASA’s early human Mars mission concepts were constructed following the same logic of von Braun’s analyses, concentrating mostly on the propulsive solutions for departing Earth, injecting to Mars, landing, and returning to Earth. Early studies paid relatively little attention to the comfort of the human explorers or the details of what tasks these explorers would be doing once they arrived on the planet. As the 1960s progressed, NASA’s human Mars studies became increasingly refined as mission planners absorbed Apollo flight experience and hardware designs and the first robotic missions began returning data from Mars. The 1960s ended with Werner von Braun again advocating Mars exploration, this time addressing the Space Task Group and championing a human mission to be flown in 1982. As NASA entered the 1970s, human Mars missions took a back seat to post-Apollo long-duration flights in Earth orbit and robotic exploration of the red planet, and it would not be until the 1980s that human Mars mission planning emerged again.

Human Mars architectures proliferated in the 1980s, and have continued until present day [2]. Beginning with the Case for Mars conference and the Planetary Society, human Mars mission planning has continued with architectures of increasing complexity as part of the US government space initiatives, independent reports, and commercial Mars architecture studies.

The common thread throughout all of this work is a series of choices that must be made, among a legion of options, to link the pieces of each human Mars mission architecture. Von Braun's initial focus on launch, propulsion and trajectory choices captured a large part of the essential physics, and subsequent studies filled in additional layers of nuance.

2. Design Choices

A myriad of decisions must be made before a human mission to Mars can be accomplished. These begin with 'big picture' architecture decisions, such as the primary focus of the mission and processes needed to leverage the costs, and drill all the way down to cargo handling procedures, trash disposal, and many others. In fact, a matrix of these top-level decisions offers up to 5.3 x 10^{37} possible combinations. Of course, a selection in any one category could narrow the choices in a number of others, but the possibilities are nevertheless staggering. A copy of the entire decision matrix, as it is now known, is shown in Table 1, but it will evolve as different designs and processes are matured.

Table 1. Mars Mission Decision Matrix

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**
Flags & Footprints / Lewis & Clark	Opposition Class - Short Stay (1-60 sols)	Robotic / Telerobotic	Continual Control	Low Cost / Gradual Build-Up	None	Space Launch System (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	Entry, Descent and Landing (EDL) and Ascent	Combination	Combination	Combination	10 m Diameter, Long Length	8	6 per year
Primary Activity: Human Expansion		Human Settlements			Surface Systems				12 m Diameter	10 +	
		Human Colonization			Infrastructure for Permanent Habitation						

Table 1. Mars Mission Decision Matrix (continued)

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
Distant Retrograde Orbit (DRO)	Cis-Lunar Habitat	< 50 mt	Take Orion to Mars	Yes	Direct Entry	All Chemical / Cryogenic	All Chemical / Cryogenic	Nitrogen Tetroxide (NTO) / Hydrazine	Monolithic Transit Hab	600 days	2	Deep Space Gateway (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	All Chemical / Storable	All Chemical / Storable	Liquid Oxygen (LOX) / Methane	Modular Transit Hab	1000 days	3	DSG > 2-year Flyby > Short-Stay Surface
Low Earth Orbit (LEO)		100 - 200 mt			Lunar Orbit Capture	Nuclear Thermal Rocket (NTR)	NTR	LOX / Hydrogen	Combination	1200 days	4	DSG > 3-year Orbital > Long-Stay Surface
High Earth Orbit (HEO)		> 200 mt				Solar Electric Propulsion (SEP)	Hybrid SEP / Chem				5	DSG > 3-year Orbital > Short-Stay Surface
						Hybrid SEP / Chem	Hybrid SEP / Hypergols				6	
						Hybrid SEP / Hypergolic Propulsion (Hypergols)	Split SEP / Chem				> 6	
						Split SEP / Chem	Quantum Vacuum Plasma Thruster (Q-thruster)					
						Q-Drive	SEP / Chem / Aerobrake					
						SEP / Chem / Aerobrake	NEP					
						Nuclear Electric Propulsion (NEP)	Bimodal NTR					
						Bimodal NTR						

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	NRHO		Landers		Combination
Combination	Areosynchronous						Other		HEO		Earth Return Propellant		
Lunar First													
Areosynchronous													
Mars Flyby													
Backflip													
Grand Tour													
Fast													

Table 1. Mars Mission Decision Matrix (continued)

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 Mars Orbiter Laser Altimeter (MOLA)	< 100 m
Active	Artificial Short Arm	Medical	2037	Long Stay (300+ sols)	3	20	20 mt lander: 6.7 - 40.0 mt	Mid Lift-to-Drag (L/D)	Polar	0 km MOLA	100 m - 1 km
	Artificial Long Arm	Dust	2039		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		
					6	27	27 mt lander: 9.0 - 54.0 mt	All Propulsive	Southern Hemisphere		
					> 6	30	30 mt lander: 10.0 - 60.0 mt		Different for each mission		
						40	40 mt lander: 13.3 - 80.0 mt				

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		All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE)	
Water from Regolith	Combination	Rigid				90 sols	Drilling / Geophysical Tests	Full-Scale Life Science	> 90% Closed				Other	
Water from from Subsurface Ice		Local Features and Resources				300 - 500 sols								
Fabrication / Manufacturing						500 - 1000 sols								
Combination						> 1000 sols, overlapping crews								
Export														

3. Interconnections and Complexity

As shown above, human exploration of Mars may represent one of the most complex systems-of-systems engineering challenges that humans will undertake. The distance, energy, and time required to transport the mission crew from the surface of the Earth to Mars and back results in a complex, highly integrated architecture of new technologies and systems that must work together seamlessly. An example of Mars architecture interconnectivity between major system elements and choices is depicted in Figure 1. This figure shows where design relationships between system choices exist for various systems and subsystems of a typical Mars architecture. In this figure, larger nodes indicate where more interconnectivity between design choices exists. These types of relationship diagrams can be useful since they show at a glance which nodes may drive the overall architecture more than others. Two elements of a typical Mars architecture, the ascent vehicle and habitat, are further discussed below to illustrate the complex interconnectivity between Mars architecture systems.

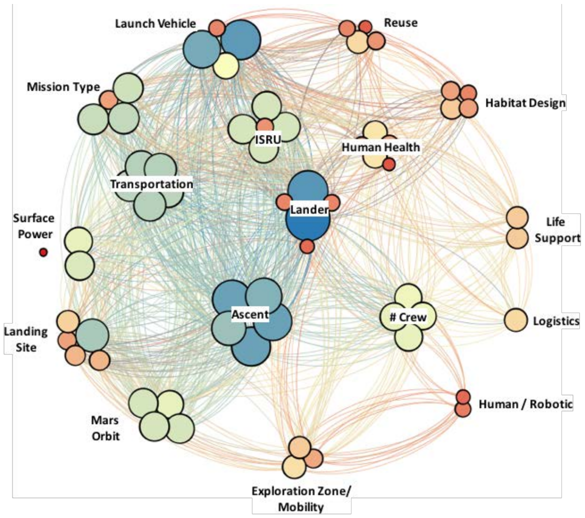

Figure 1. Example Mars architecture interconnectivity.

3.1 Interconnections – Mars Ascent Vehicle

Perhaps one of the challenges that has the most impact on the architecture of a round-trip mission to Mars and back is that of ascending from the surface of Mars. Ascent represents a significant challenge and is, in fact, more difficult and potentially riskier than previous Apollo missions (Table 2).

Typical key characteristics for the Mars Ascent Vehicle (MAV) include long periods of dormancy, both in transit and on the surface, operability with limited maintenance and repair opportunities, large propellant loads with the desire for those propellants to be produced from local resources on Mars, large crew size, and the capability of seamlessly operating with the rest of the systems of the architecture in multiple environments. [3] Additionally, it must be configured in a way that minimizes the landed center of gravity and allows for crew access.

Table 2. Ascent Vehicle Comparison – Moon (Apollo) vs. Mars.

Driving Characteristic	State of the Art (Apollo)	Example MAV
Crew size	2	4-6
Ascent Delta-V	2 km/s	4-6 km/s
Ascent Time	2 hours	24-72 hours
Dormant Duration	4 days	~2000 days
Propellant Load	2.5 mt	33-38 mt
Propellant Type	Earth Storable	Soft Cryogenic
External Interfaces	Minimal	Multiple
Mission Mode	With crew	Pre-deployed
Communication Delay	2.5s	480-2400 s
Power Generation	Internal	External

When put into context with the remainder of the systems that must be transported to the surface of Mars, previous analyses [4] have indicated that the MAV represents the largest indivisible item to be landed and has complex interconnectivity with many components of the overall architecture. Figure 2 shows those major elements having strong connectivity with the MAV. [5] [6] Some of these complexities and interrelationships between elements are listed below.

- Launch Vehicle – the throw capacity along with the available launch vehicle shroud diameter places significant constraints on the ascent vehicle size (mass and volume).
- Mission Type – drives the dormant and active times, thus driving overall system reliability.
- Transportation – the design of the MAV, especially the system wet mass, is driven by the propellant choice and whether or not In Situ Resource Utilization (ISRU) is incorporated. This decision then drives lander size, transport element capability, and delivery time to Mars, as well as potential commonality with other elements of the architecture, such as the descent system or the in-space transportation elements.
- ISRU – the ability to produce propellants locally on Mars as opposed to bringing them from Earth drives the size and need for cryogenic propellant, landing site selection, and power generation capabilities.
- Human health – crew time as well as habitation functions drive the size of the ascent cabin,

which then drives the overall ascent stage size and propellant need.

- Surface power – the design of the MAV, such as the choice of fuel type, can drive not only ISRU, but also the power needs for propellant conditioning.
- Number of crew – drives the overall size of the ascent cabin and resulting vehicle size.
- Mars orbit –the staging orbit used for the in-space transportation system significantly drives the ascent vehicle size; higher orbits desired for the in-space transportation system require more ascent delta-V, resulting in more propellant and volume. The orbit choice also impacts operational aspects such as launch windows and options for early ascent from the surface.
- Exploration Zone/Mobility – drives the crew's ability to don and doff Extravehicular Activity (EVA) suits, dust and planetary protection, and surface mobility, including pressurized rovers and access systems such as pressurized tunnels.
- Landing Site –drives ISRU options. Additionally, landing site latitude drives MAV performance, and landing site slope affects the MAV's ability to lift-off from the lander launch platform.
- Lander – the lander delivery capability, including mass and volume, is a significant driver for MAV capability and configuration.

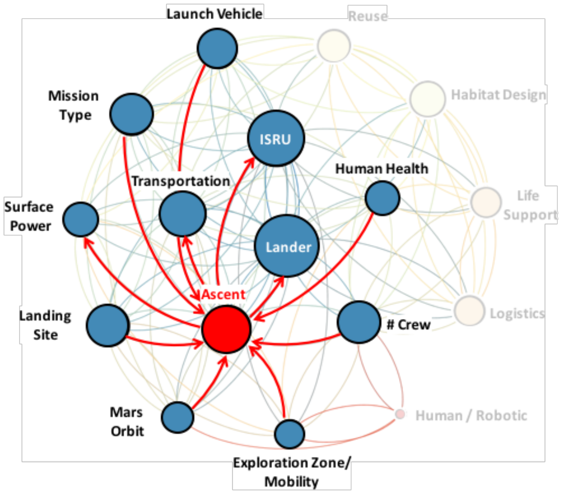

Figure 2. Mars ascent architecture interconnectivity.

3.2 Interconnections – Habitation

Support of the crew during long-duration Mars missions provides another good example of interconnectivity between the various architectural elements. [7] [8] Architecture solutions that can reduce the total mission duration, and thereby reduce crew exposure to the deep-space environment, are highly desired. But expected propulsion capabilities and the physics and phasing required for round-trip Mars missions mean that durations will remain long, typically years in length. Therefore, the habitat drives many aspects of a typical Mars architecture (Figure 3).

- Mission Type – the type of mission drives the overall mission timeline and the resulting time required to get to Mars, explore, and then return to Earth. This mission time has a significant impact on the overall habitat design, mass and volume.
- Launch Vehicle –constraints including the throw mass, volume, and launch rate drive habitat design considerations such as monolithic or modular design, rigid or inflatable structures, or the number of pressurized elements.
- Number of crew – drives the overall volume and logistics mass required.
- Lander – for surface habitats, the lander delivery capability, including mass and volume, is a significant driver for surface missions.
- Reuse – the decision on whether or not to reuse the habitat drives the mission type, logistics and launch support strategies.
- Human Health – key driving aspects include radiation protection and medical and physiological countermeasures, as well as other overall human factors.
- Life Support – as expected, the closure of the life support system significantly drives the consumables quantity, but it also drives other salient features of the habitat design, such as layout, to enable maintenance and repair of key life support systems throughout the mission.
- Logistics – logistics supply and disposal strategy affects habitat design and layout.

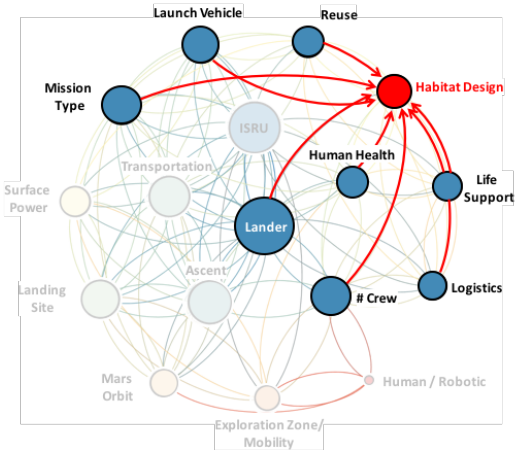

Figure 3. Mars habitat architecture interconnectivity.

4. Key Design Influences

The previous section illustrates how every architecture is interconnected throughout the human

Mars mission design, and uses the MAV and habitat as illustrative examples. Experience has shown that, of the many architectural decisions, a small number emerge as the decisions that most broadly influence human Mars mission architecture. These design decisions often "frame" the architecture, and are sometimes given as constraints to designers, rather than as open design variables.

4.1 End Game

Perhaps the most fundamental impact on Mars mission architecture is whether a human Mars mission is intended as an Apollo-type sortie, an expedition to establish a scientific field station, or the beginning of a permanent human settlement. A short stay "flags and footprints" mission may provide only limited mission return, but may be attractive because the price tag and time commitment are modest as compared to a permanent installation that requires future sustaining missions. Many architectural technical decisions hinge on the long-term vision and commitment for the activities to be carried out on Mars, with flow-down impacts to much of the Mars surface architecture, operational concepts, and technology needs.

4.2 Earth to Orbit Transportation

A great deal of human space exploration investment is made in the quest to reduce mass and risk. Entire technology programs are undertaken with the goal of reducing the ultimate mass of human Mars mission payloads launched from Earth – this is due to the fact that current launch economics accounts for the largest fraction of overall mission costs. Efforts have continued over the past decades to lower the cost of delivering payloads to space, but these efforts have not yet succeeded to the point where payload mass can be decoupled from launch costs.

If, at some point in the future, launch costs decline precipitously, entirely new space exploration architectures will emerge. Mission architectures, spacecraft designs, and technology programs will no longer be focused on metrics such as the reduction of initial mass to low Earth orbit (IMLEO), and launch mass would no longer be a proxy for mission cost. Such a scenario would only be possible if current launch costs decline by another one or two orders of magnitude, but if such a scenario did occur it would transform the very nature of space exploration.

4.3 In-Space Transportation

Current in-space propulsion is based on decades-old chemical and emerging electric propulsion technologies, augmented with recent incremental advances in efficiency. The balance of thrust and specific impulse (Isp) continue to dominate the mission designer's choice of propulsion system, and that choice has fundamental linkages into trip times, flight dynamics, arrival and departure orbits, launch packaging volume, and launch mass. Low Isp, high thrust systems can provide impulsive "kicks" that shorten trip times at the expense of mass; electric propulsion can provide more efficient use of fuel mass at the expense of transit time duration. Other in-space propulsion systems such as nuclear thermal propulsion provide moderate thrust and higher efficiency, but come with launch packaging and development challenges.

The choice of in-space propulsion system has a large "systems" effect on the overall Mars architecture. In addition to the factors discussed above, the mission designer may choose to split cargo and crew propulsion to take advantage of less mass efficient, but shorter, transit time options for crew transit and longer, more efficient systems for cargo. Hybrids that combine the best features of several propulsion systems also open intriguing design options.

4.4 Landing Site Selection

Landing site selection will influence virtually every aspect of Mars surface architecture as well as EDL constraints. Landing site selection will impact the choice of parking orbit for orbital mission assets and the amount of plane change necessary to access the sites. Landing site selection will also affect the choice of surface power systems, with solar power becoming less available as latitude increases. Additionally, the landing site may likely affect the availability of local resources, with valuable resources such as water being more available at higher latitudes. The choice of landing site will also be impacted by the "end game" discussed above, with certain landing sites being more desirable for exploration missions, and others more suited for visits over multiple expeditions.

4.5 Space Resource Utilization

Every space mission to date has relied on supplies launched from Earth. A fundamental shift in space exploration will occur as humans begin to utilize resources from space to reduce the dependence on Earth. ISRU will, literally, change the equations of how humans explore space – by producing needed consumables such as water, oxygen, and rocket fuels, the efficiency of human Mars missions will increase dramatically. Ultimately, less of these products will need to be shipped from Earth, reducing payloads, lander size, entry vehicle requirements, in-space transit mass and launch mass. Readily available supplies of resources and consumables may also decrease mission risk, enable alternate propulsion options, and enable expanded use of ISRU materials for advanced uses such as radiation shielding and habitat construction. ISRU use may also require that higher levels of power may be required for resource extraction, production and storage.

5. Starting Point

To form a starting point for a basis of comparison for a crewed Mars mission architecture, decisions must be made to convey a logical sequence of trades and design choices. The approach to developing ground rules for such trades includes selecting the crucial technical considerations for both Mars transportation and Mars surface infrastructure. A discussion should include assessments of the trades for each critical component of the architecture, the practicality of the choice, and a strong rationale as to why a given choice was made. A list of trades follows, along with the preferred options obtains by discussion with Mars mission subject matter experts (SMEs).

5.1 Transportation Trades

Current trades and design choices must start with the elements which are currently under development, namely the crew and cargo variations of the Space Launch System (SLS) launch vehicles, the Orion spacecraft (which will serve as the primary mode of crew transportation between Earth and cis-lunar space), and the Deep Space Gateway. These current elements influence certain key transportation trades:

5.1.1 Transportation Mission Architecture

The required mission elements can all be sent to Mars on the same injection opportunity, arriving at Mars at nearly the same time. Alternately, some of the crew-support elements can be pre-deployed to Martian orbit or the surface several years prior to crew arrival. Having all elements arrive at approximately the same time at Mars minimizes the in-space lifetime requirements. However, element failure (either the element itself or transportation) can have an unrecoverable effect on the mission, since no replacement can be immediately dispatched from Earth. A “pre-deployment” strategy can ensure functioning elements prior to crew arrival and can “level” the launch campaign at a cost of less-frequent missions. In addition, pre-deployment of surface assets can allow ISRU production in advance of the crew’s arrival.

The SME preferred option consists of Mars surface equipment and crew landing systems being pre-deployed the injection opportunity prior to crew arrival. This allows verification of arrival and correct functionality prior to crew departure from Earth. In addition, pre-deployed elements can take advantage of more efficient (but slower) transits to Mars than utilized by the crew delivery.

5.1.2 Transfer Habitation Functionality

The in-space crew habitat could also perform the function of surface habitat. Alternatively, specialized habitats can be designed for either in-space or surface functionality, with transfer of crew from one to the other in the Mars system. Unique development costs could be reduced by combining in-space and surface habitat designs. However, disparate operational environments (e.g., thermal, gravity, acceleration) and functionality (e.g., EVA support, science) may make common development/design challenging. Some space transportation options suggest integrating the transportation system and habitation vehicle, further complicating common design.

The option to optimize habitats for in-space and surface applications is favored by the SME community. The unique environments and functionality indicate that a common design and development would be difficult. Operationally, the crew would be transferred to the surface habitat in Mars orbit and descent/land in it.

5.1.3 Entry, Descent and Landing (EDL) Commonality

Mars EDL systems could be tailored for individual payloads or a common system could be designed to handle most/all required surface payloads. Mars EDL system designs are generally dependent upon landed payload mass and volume. Uniquely tailoring an EDL system for each payload could result in a lowest mass system, but a “common” EDL system could reduce development costs.

Mars EDL systems are generally regarded as high-cost, high-risk developments. Analysis indicates that crew and surface cargo delivery can be manifested into similar payload mass volume envelopes. The SMEs prefer a common EDL system for all surface payloads, MAV and crew descent/landing.

5.1.4 Mars Rendezvous Orbit

The split-mission strategy (see section 5.1, “Transportation Mission Architecture”) implies that a rendezvous location in the Mars system is necessary for crew transfer to the landing system, and, potentially, to the integration of the return propulsion systems. This rendezvous location has conflicting implications for in-space and surface systems. High Mars orbit is preferred for systems that transit to/from Earth, since it reduces the propulsion requirements (i.e., propellant mass) for those systems. Low Mars orbit is preferred for the ascending MAV to minimize MAV propellant requirements. Individual orbits could be optimized for each, but would necessitate a specialized vehicle to transfer crew between high and low orbits.

Use of a high Mars orbit to reduce propulsion requirements for systems that transit to/from Earth is favored by the SMEs. ISRU production of MAV propellant greatly reduces the impact of high orbit on the MAV mass. The necessity for a unique crew orbital transfer vehicle is viewed as undesirable and has been eliminated by this choice.

5.1.5 Earth Departure Aggregation Orbit

Some of the Mars mission payloads (e.g., crew transit spacecraft) are too large for direct injection to Mars with a single SLS launch. Aggregation/assembly somewhere in Earth orbit or the Earth-Moon system is therefore necessary. The optimal location depends upon in-space and launch vehicle propulsion system characteristics and could potentially impact other exploration objectives.

A Low Earth Orbit (LEO) assembly orbit maximizes the SLS payload, but high-thrust, high efficiency propulsion is needed for the Trans-Mars Injection (TMI) maneuver which, for chemical systems, implies cryogenic oxygen/ hydrogen. The technology development for storage of these "hard" cryogens over times needed for aggregation/assembly is not currently planned. An option is to "immediately" utilize the oxygen/hydrogen performance of the SLS upper stage and boost the payloads to a higher orbit, where the TMI requirements are greatly reduced.

High Earth Orbit or cis-lunar locations are consistent with electric propulsion capabilities (the currently preferred propulsion option, see section 5.6, "In-Space Propulsion"), both for TMI and for Earth return.

The staging orbit must also be consistent with SLS and Orion capabilities for crew delivery (and retrieval, see section 5.7, "Earth Return"). And finally, there may be other exploration requirements and mission objectives that influence the assembly/aggregation location (e.g., lunar exploration, asteroid retrieval, etc.).

SMEs agree that a cis-lunar location - currently a "Near Rectilinear Halo Orbit" which meets electric propulsion departure/ return capabilities, SLS/Orion access and a potential staging point for lunar surface missions – is the optimal choice.

5.1.6 In-Space Propulsion

The choice of in-space propulsion will affect mission performance, development costs and risk. Trades among propulsion technologies include:

1. Traditional in-space chemical propulsion (e.g., space-storable) has insufficient performance for crewed Mars missions. The technology for long-duration in-space storage of high-performance chemical "hard cryogens" (oxygen/hydrogen) is not currently available. Development of this technology could affect the attractiveness of this option.
2. "Soft-cryogens" (e.g., oxygen/methane) may provide a reasonable compromise among efficiency, thrust and space-storability. Moderate levels of cryo-cooling may allow long duration (years) storage.
3. Electric propulsion has space-storable propellant, is highly efficient, and shares applicability with advanced robotics missions, but for power levels consistent with photovoltaic systems, it exhibits relatively low thrust levels.
4. Nuclear thermal propulsion exhibits high thrust and high efficiency, but again requires a "hard cryogen" propellant and introduces the cost/risk/political challenges associated with nuclear systems.

SMEs prefer solar-powered electric propulsion for the interplanetary cruise with integrated oxygen-methane propulsion for orbit injection maneuvers. This provides good balance between efficiency and development effort. Oxygen-methane is also preferred for MAV propulsion (consistent with Mars ISRU), so engine commonality is a possibility. The performance of this combination may result in a non-staging, reusable propulsion system for round-trip crewed Mars missions.

5.1.7 Earth Return

Crew return following the Mars mission can be via a direct-return to Earth in an Orion-style entry vehicle. Alternately, the transit habitat can brake into the Earth-Moon system and the crew can be retrieved via a vehicle launched from Earth. Direct entry from the returning interplanetary trajectory requires transporting the entry vehicle round-trip to the Mars system and back. This implies additional propellant requirements on the transit spacecraft and unique lifetime and environmental requirements on the entry vehicle (e.g., years in deep space). In addition, Earth entry velocities returning from Mars are typically higher than returning from Earth-Moon space, implying more stringent heat shield requirements. However, decelerating the transit habitat also implies additional propellant requirements. The severity depends on the transit propulsion efficiency and the target location in Earth-Moon space.

Because the proposed solar-electric in-space propulsion system (see "In-Space Propulsion" above) is highly efficient and because reuse of the transit spacecraft is an architectural goal, consensus of the SMEs is for the transfer vehicle to be decelerated into the Earth-Moon system. The target orbit (see "Earth Departure/Aggregation Orbit") allows combinations of lunar gravity assists, low-thrust and high-thrust for efficient capture. Crew retrieval would be via

Orion/SLS launch after the crew returns to Earth-Moon space. This should require no augmentation to Orion currently planned capabilities.

5.1.8 Launch Vehicle Cadence

The SLS launch cadence is not an architectural trade. The constraints are based on the SLS Program capabilities. The SLS Program has access to a single launch pad and a single Mobile Launch Platform (MLP). This implies that a launch must occur and the MLP be returned to the Vehicle Assembly Building (VAB) before the stacking of the subsequent launch vehicle can commence. Engine, booster and stage production capability are currently limited to supporting two flights per year. Two SLS launches per year marginally supports one Mars surface mission every 52 months. A launch cadence of up to three per year would add resiliency and contingency to crewed Mars mission needs, but would still likely still only support missions every 52 months.

5.2 Mars Surface Strategy Trades

When considering the trade options, it is important to understand how the options govern other components of the overall architecture (e.g., how EDL vehicle sizing governs the SLS launch cadence). Furthermore, transportation mission architecture trades can influence the Mars surface strategy and the asset deployment sequence. Key Mars surface strategy trades include:

5.2.1 Single Central Site vs. Multiple Dispersed Sites

When multiple crewed Mars surface missions are envisioned, each landing could target the same site, or instead target multiple, geographically diverse sites. Multiple sites could provide access to, and investigations of, widely diverse geology and climates, but each mission would essentially be “starting over” as far as surface infrastructure is concerned. Concentrating multiple missions at a single, localized location would allow a build-up of exploration infrastructure, allowing more comprehensive local exploration and resource utilization.

Experts agree that establishment of a single location for a sequence of missions with robust surface mobility is the best option. Strategic location combined with regional mobility, on the order of 100 km. per traverse, could provide sufficient exploration potential and geological diversity. Robust habitation, power, and resource utilization capabilities should result due to sequential buildup of deployed assets.

5.2.2 Surface Mobility Capability

Mars surface mobility capabilities can range from crew in spacesuits travelling only a few kilometers (as with the early Apollo lunar missions) all the way to extended durations using pressurized rovers capable of 100’s of kilometers in traverses.

Crewed surface mobility utilizing only spacesuits is constrained by the operational limitations of the suit’s portable life support system (PLSS) and the endurance of the crewmember; ranges of only a few kilometers are likely to result. Crew incapacitation and incapability to return to the habitat is a risk.

Unpressurized rovers similar to the ones utilized by the later Apollo missions can extend traverse distances to 10’s of kilometers due to their speed and the reduction in crew fatigue. Excursion time is still constrained by the PLSS and “crew-in-suits” limitations, and the maximum traverse radius may still be limited to crew “walk-back” distance in the event of rover breakdown.

Pressurized rovers can extend exploration duration to weeks and distance to 100’s of kilometers, but represent a much greater investment in mass and power. Dual rover operations can provide rescue/backup in case one rover breaks down.

Studies show that dual pressurized rovers with ~100 km of roving capability per traverse provide the best overall capabilities. Long duration surface missions run the risk of depleting exploration productivity in a short time without extended surface ranging capability.

5.2.3 ISRU Emphasis

Utilization of Martian resources can greatly reduce mission mass delivery requirements, but imply the upfront need for ISRU technology development, equipment delivery, and increased surface power. In addition, landing site selection may be restricted if localized resources are required. Recent robotic missions have indicated that substantial subsurface water ice may be accessible. However, this would require additional infrastructure and power and would to some extent impose location constraints on the exploration site.

SMEs favor a strategy to extract oxygen from atmospheric carbon dioxide for production of MAV ascent oxidizer starting with the first crewed mission. The resulting mass reduction more than offsets the mass of the production equipment and the needed power generation can also be utilized by other surface elements. Extraction of water from subsurface ice could follow if outpost activities expand.

5.2.4 Crew Size

The number of crewmembers on a Mars mission has implications for mission productivity, transportation, mass and power requirements. Mars missions will likely be international in composition and partner representation on the crew may feature heavily in the level of the partners’ participation.

Larger crew size implies a more robust skill mix and "redundancy" in case of incapacitation of a crewmember. However, a larger crew also implies increased habitation volume and mass, more consumables and more power.

The SMEs felt that, as with ISS, the initial crew size would be limited (4 crewmembers) with expansion (6+) as additional habitation, power and resources become available (see above trade on "Single Site vs. Multiple Sites" and subsequent trade on "Surface Habitation Architecture"). This would allow participation by international crew members reflecting the level of contributions.

5.2.5 Surface Power Systems

Power capacity and generation options on the Martian surface have implications for ISRU production rates, the number of crewmembers that can be supported, resiliency to environmental extremes, and system development costs. Photovoltaic systems have relatively low development costs, but the low solar insolation on the Martian surface (1.4 to 1.6 AU from the sun, varying elevation) implies large array sizes, and the probability of dust storms make power storage requirements nearly impractical (tau levels of 4 or 5 have been recorded). Nuclear power systems provide constant output and are independent of solar insolation, but may have high development and production costs.

The Use of nuclear "kilopower" units (up to 5 units of 10 kWe each) is preferred by the SMEs. A major consideration was the above mentioned probability of dust storms during long surface missions, along with the ability to remotely site multiple units without long cable runs.

5.2.6 Earth Communication

Techniques for communication between the Martian surface and Earth have implications on data rates, availability, and requirements for relays. Direct Martian surface-to-Earth communications will experience long periods of unavailability (>12 hrs/day) due to Mars rotation and data rate limitations due to the requirement for radio frequency (RF) links. Properly positioned orbital relay(s) can provide higher percentage communications coverage and higher data rates but required dedicated satellite(s) and deployment(s).

Areosynchronous relays satellite(s) with RF link to the surface outpost and laser communications to Earth, enabling nearly constant communications coverage and high data rates, seems to be the best option.

5.2.7 Surface Habitation Architecture

Long duration surface habitats can be deployed prior to crew arrival with the crew landing in the MAV. Alternately, the surface habitat can transport the crew from Mars orbit to the surface. Having habitation operational upon arrival of the crew offers considerable advantages, as the crew may well be suffering from microgravity deconditioning. Descent aborts using the MAV are generally not feasible, especially if ISRU production of propellant is envisioned, so crew descent/landing in the MAV provides little advantage. In addition, the MAV tends to have limited functionality and habitability due to mass constraints, so it is less than an ideal environment for the crew to readapt from deconditioning. Landing in a habitat that can be readily made functional avoids the need for the crew to don/doff spacesuits, perform surface traverses, etc.

The SME preferred option consists of the crew descending and landing in a surface habitat which can be configured for surface operations immediately post-landing, reducing the physical stresses to the deconditioned crew. A pre-deployed functional habitat provides backup and enhanced surface capabilities (lab, EVA support, etc.).

5.2.8 Transfer amongst Surface Elements

Crew transfer amongst a surface habitat, pressurized rover and MAV can be accomplished via suited EVA or in "shirt-sleeves" via pressurized connections. Pressurized access to the MAV from the pressurized rover via a pressurized tunnel allows lighter, smaller volume pressure suits for descent/ascent.

The SME community has determined that pressurized access between the surface habitat and a pressurized rover, allowing simplified and time-efficient transitions to surface mobility operations, is the best choice. Subsequent EVAs would utilize the pressurized rover egress system (e.g., suitlock). Lightweight tunnel design concepts appear attainable.

5.2.9 Spacesuit Commonality

Requirements exist for crew pressure suits which encompass Mars descent/ascent (within the habitat or MAV) and Mars surface activities. A question exists as to whether a single suit design can accommodate all requirements. A single suit design could reduce development costs and total mass/volume required for the mission; however, the operational requirements are significantly different between landing/ascent and surface operations. A Mars surface suit/PLSS is expected to require significant stowage volume as it may include hard elements. Since the pressurized volume of the MAV will likely be extremely limited and the environmental requirements (MAV depressurization) significantly less demanding, separate suit designs may be more advantageous.

Specialized entry/launch pressure suits for the MAV volumetric constraints and environment are preferred by the SMEs. Transfer from/to the MAV would be accommodated by pressurized access via rovers and pressurized tunnels (see "Transfer amongst Surface Elements").

5.2.10 Mars Ascent Vehicle Scale

The Mars surface cargo will influence the size and complexity of the EDL system. Dividing the cargo into smaller landed packages may drive the scale of the EDL to have commonality with that of Mars robotic missions, which could lead to lower or shared development costs. The crew habitation elements can conceivably be subdivided for entry and landing then assembled on the surface, but with increased operational complexity. Consumables, power systems, rovers, etc. can be distributed onto smaller landers. The MAV represents the largest "indivisible" payload and even then, one could envision landing the propellant separately and transferring it into the MAV on the surface, or producing it in situ, although this obviously has safety and operational complexity implications.

The SME prefer the option of landing the MAV fueled (for oxygen-methane, the methane makes up ~25% of the propellant mass) and producing the oxidizer in situ. This was deemed to be a good trade between mass and surface operational complexity. This results in a landed mass of 20-25 metric tons.

6. Basis of Comparison

The previous sections have described the complex network of interconnected design choices, systems analyses, technical optimizations, and non-technical compromises that must be considered when planning a viable human mission to the surface of Mars. NASA continues, along with their partners and stakeholders, to conduct or sponsor studies of human exploration beyond low-Earth orbit, taking various pathways through this complex network. These studies are being used to understand requirements for human exploration of the Moon and Mars in the context of other space missions and research and development programs. To anchor a "basis of comparison" for exploring other paths within the mission design menu/tree that might explore new technologies, alternate cost or risk postures, or new additions to the design option space, NASA periodically defines a design reference architecture (DRA). These DRAs are not intended to be the program plan for human exploration of the Moon and Mars, but instead are meant to provide a viable end-to-end reference against which other concepts can be compared. The results from these comparisons are then used by NASA to:

- Derive technology research and development plans;
- Define and prioritize requirements for precursor robotic missions;
- Define and prioritize potential flight experiments and human exploration mission elements, such as those involving the International Space Station (ISS), lunar surface systems, and space transportation;
- Open a discussion with international partners in a manner that allows identification of potential interests of the participants in specialized aspects of the missions;
- Provide educational materials at all levels that can be used to explain various aspects of human interplanetary exploration; and to
- Describe to the public, the media, and other federal government organizations the feasible, long-term visions for space exploration.

To guide studies over the next several years, NASA will establish a set of ground rules and assumptions to examine one particular approach to the human exploration of Mars that will form the basis for the next Design Reference Architecture.

One principal example of these ground rules and assumptions is a choice to concentrate all surface assets needed to support human exploration at a single location and then send all crews to this site for all missions that make up the DRA. This contrasts with the scenario considered in Design Reference Architecture 5.0 (DRA 5.0), in which a campaign of three missions sends crews to three separate stand-alone locations on Mars.

NASA introduced the concept of an Exploration Zone (EZ) and a Region of Interest (ROI) as a mechanism to help organize the key criteria used to identify candidate sites on Mars for this single base of operations for human crews. NASA will use the EZ concept as part of a multi-year effort to determine where and how humans could explore Mars. In the near term, this process includes: (a) identifying locations that would maximize the potential science return from future human exploration missions, (b) identifying locations with the potential for resources required to support humans, (c) developing concepts and engineering systems needed by future human crews to conduct operations within a candidate location, (d) identifying key characteristics of the proposed candidate locations that cannot be evaluated using existing data sets, thus helping to define precursor measurements needed in advance of human missions, and (e) using the resulting surface exploration strategy to help drive the overall transportation and operational exploration architecture. This choice of a single surface site has already resulted in an important observation, in that the EZ lends itself to a "field station" approach for development of a centralized habitation zone / landing site. In this context, a working definition of a "field station" is as follows. [9]

> Field stations create a bridge between natural environments and (Earth-based) research laboratories. Research laboratories offer considerable power to conduct analyses in a predictable environment and to infer cause and effect from manipulative experiments, but they may miss factors that turn out to be critical in a natural environment. Field studies can encompass the full range of relevant interactions and scales, but they are not as tightly controlled. By offering access to both laboratories and field environments, Field Stations combine the best of both worlds.

This is but one example of observations and recommendations that will become apparent as more of the options discussed above are examined in the context of a full human exploration architecture and as technological innovations emerge. The roadmap that NASA and its partners will follow through cis-lunar space to pioneer Mars will emerge from this work.

7. Conclusions

A human Mars architecture is a complex, interconnected series of choices. While every architectural decision is important to the definition of the overall architecture, not all architectural decisions carry the same "weight" in terms of the other architecture variable that they affect. In particular, the choice of the Mars surface "end state", the economics of Earth launch, the choice of in-space transportation technology, the choice of Mars landing site, and the use (or not) of local resources have the greatest impact across the overall architecture.

The human Mars architecture can be thought of in two parts – transportation from Earth to Mars (and back, in the case of an exploration crew), and operations in the gravity well, including landing, surface operations and ascent. Each these two parts are shown in this paper in two ways – first as tables of options, and later as a discussion of those decisions that could serve as a starting point for an architecture that incorporates current technology work, Mars science, and agency options for operations in cis-lunar space. Taken together, compelling human Mars architectures begin to emerge from the multitude of design options. Work is continuing at NASA to explore innovative human Mars mission design options, and to establish a set of mission design decisions that can be used as a basis of comparison for future studies.

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