The Moon as a Stepping Stone to Human Mars Missions

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Abstract

Human space mission designers stretching back to von Braun and beyond have envisioned the moon as a waypoint to the more challenging missions to Mars. The moon is seen as a potential proving ground for technologies, equipment and operations, and a venue upon which to learn the art of surface exploration. Mars missions are years in duration with very limited Earth return opportunities, but the moon provides the opportunity to perfect exploration concepts while being only a few days from Earth. Though the environment and gravity differ from Mars, and will thereby not provide a perfectly analogous environment, the remoteness, limited logistics, and harsh conditions on the Moon provide an environment that can be used to stress many systems that will be used or will be extensible to hardware and operations that will be used on Mars.

This paper begins by describing the systems, or options for systems, that together comprise a human Mars architecture. With this human Mars operational concept as a basis of comparison, each of these systems is analyzed in the context of a range of potential exploration missions that first targets lunar exploration experience, examining how the lunar experience can be best used to prepare for the eventual human mission to Mars. The paper concludes with a concise summary of specific areas that have the strongest applicability between exploration experience on the lunar surface and extensibility to human Mars exploration.

Nomenclature

CH_4	Methane
km	Kilometer
km/s	Kilometers per second
kWe	Kilowatts Electric
m	Meters
n/a	Not Applicable
O_2	Oxygen
s	Second
t	Ton (metric)
sol	One Mars day (24 hours 39 minutes)
Xe	Xenon

Acronyms/Abbreviations

ALARA	As Low as Reasonably Achievable
BoC	Basis of Comparison
EDL	Entry, Descent and Landing
EVA	Extra Vehicular Activity
GER	Global Exploration Roadmap
ISRU	In-Situ Resource Utilization
ISS	International Space Station
MAV	Mars Ascent Vehicle
NASA	National Aeronautics and Space Administration
NRHO	Near Rectilinear Halo Orbit
ROI	Regions of Interest
SEP	Solar Electric Propulsion
SPE	Solar Proton Event
SLS	Space Launch System

1. Introduction

Strategies for exploring deep space with humans have continued to evolve over the past several decades. Since its inception, NASA mission planners and designers have assessed various exploration strategies ranging from quick "flags and footprints" sorties, to field stations, to more robust human outposts and even settlements. These study concepts have included various destinations with most focus on the Moon, Mars and occasionally near-Earth asteroids. Through all of these studies there has emerged a common thread that a stepwise progression of exploration capabilities which gradually expands the distance and time of human exploration endeavors is required. This history of studies also debated the specific exploration path that should be taken, the scope and duration of each of the steps along the path, and how those sequential steps can be sustained and stitched together to best meet technical and national needs, goals, and objectives.

Beginning in 2017, the United States began operating under Space Policy Directive 1, which provides for a U.S.-led, integrated program with private sector partners for a human return to the Moon, followed by missions to Mars and beyond. [1] The policy grew from a unanimous recommendation by the new National Space Council. This renewed focus on the Moon has reinvigorated the question of how the Moon can serve as a venue to develop and demonstrate key exploration capabilities, gain knowledge, or reduce risks to future human missions to Mars. Although this question is not new, significant progress has been made since the previous NASA programs that studied the "Moon as a testbed for Mars" question was raised. [2,3,4,5,6] The ISS continues to demonstrate our ability to support humans continuously in space, technologies have advanced, robotic missions have and continue to provide a wealth of information about these future exploration targets, and human space mission concepts continue to mature. Given that the new U.S. space policy has now defined the path (lunar missions first leading to human Mars missions in the future), the focus of the assessment described in this paper was aimed at providing an update in identifying areas where crewed lunar missions could provide applicability toward future human Mars missions.

2. Assessment Approach

Determining how future human lunar missions can reduce risks and demonstrate performance characteristics of systems and operations necessary for a future Mars mission is a complex endeavor. Understanding potential Moon-Mars relationships must be based on both understanding the Mars mission concept (representing the end use case) as well as the lunar mission concept which precedes the subsequent Mars mission. For this assessment, a notional "basis of comparison" Mars architecture described in Section 3, is used as the future Mars mission concept. Four different scopes of lunar mission activities were then considered with respect to this Mars mission - the lunar missions ranged from lunar orbit only with no human landings on the surface to a long-term lunar field station, and illustrated four very different points on a lunar mission continuum. These four example lunar mission concepts are described in further detail in Section 4. Utilizing a range of lunar mission concepts provides better understanding of how each could benefit future exploration endeavors thus aiding in the decision-making process for both future lunar and Mars missions. The key capabilities required for each of these four lunar mission concepts were then assessed against the basis of comparison Mars architecture. For this assessment emphasis was placed on finding areas of natural overlap for various lunar mission concepts, and no attempt was made to force specific Mars testbed activities into lunar missions.

Since both the lunar and Mars mission scenarios are still in formulation and continue to evolve, applicability assessments described herein were viewed for the most part qualitatively from a system capability and risk reduction perspective. That is, emphasis was placed on determining how well the assumed lunar system itself, or fundamental knowledge which would be obtained by conducting the lunar mission, would feed forward to future Mars missions. The assessment team avoided questions like "*must a specific system be tested on the moon before it can be used for Mars?*" This assessment was thus predominately a qualitative activity, one that did not try to apply numeric evaluation and scoring methodologies, but rather one which would bin the applicability of each lunar capability into one of three distinct rating categories:

- ○ **Little or none**: Within this rating level it was viewed by the assessment team that even though the capability may play a very important role in lunar exploration, the specific system or capability in question provided very little or no feed-forward to the Mars basis of comparison architecture.
- ◖ **Somewhat**: With this rating level the capability was viewed as being on the path to Mars, but differences in the capability performance level, operational characteristics, or environment would require modification and additional testing would be required before it would be fully applicable to a Mars mission.
- ● **High**: This capability was viewed as being directly on the path to future human Mars missions as is, or with few to no modifications and emphasis would be on certification to the Mars environment and operational requirements.

It should be noted that the relevance scores provided exhibit a highly coupled relationship between the assumptions made in terms of both the lunar and Mars mission and system concepts. If any of the assumed capabilities are developed differently than what was assumed here, either lunar or Mars, the resulting relevance would need to be re-evaluated and changed accordingly.

Lastly, since lunar missions do not require all of the same operational needs as future human Mars missions, not all of the capabilities necessary for Mars were considered in this Moon-Mars applicability assessment. For instance, neither planetary aerodynamic deceleration, or production of oxygen from the atmosphere, to name a few, were considered because either the lunar mission does not require that capability, or the capability is not feasible on the Moon. Resulting lunar capabilities which were key and considered applicable were grouped into those associated with space transportation systems and support (section 5), human health and performance (section 6), and surface activities and systems (section 7).

3. The Mars Basis of Comparison

Throughout the past three decades, NASA has continued to maintain a set of evolving design reference architectures for the human exploration of Mars. [7,8,9,10,11,12] These reference architectures, sometimes referred to as reference missions, provide potential visions of human exploration of Mars which are based on the best estimates of the concepts at the time of publication. These architecture descriptions provide a common framework for integration between multiple agency efforts including Mars robotic missions, research that is conducted on the International Space Station (ISS), systems concept and technology development efforts, discussions with commercial and international partners, as well as to inform evolving future lunar exploration missions and systems.

In the context of determining how potential lunar exploration missions can feed forward to future exploration strategies, the Mars end goal must first be defined – a Mars reference. The description in this section, and also captured in Table 1, provides the high-level characteristics of one potential human Mars architecture, herein referred to as the "Basis of Comparison (BoC) Architecture." Although the Mars basis of comparison architecture continues to evolve, the description below provides a snapshot of the representative architecture used in this analysis to assess the feed-forward applicability various lunar mission concepts to this Mars vision.

The BoC Mars architecture focus on the long-term human exploration of the surface of Mars. This strategy concentrates all surface assets at a single location within a specified Exploration Zone – the region where activities of human missions will take place. [13,14] With this single site strategy, assets on the surface could be reused by subsequent crews, much like how the ISS has served to support multiple crews for nearly two decades in Low-Earth orbit. Initial missions to the surface of Mars will be expeditionary in nature, with astronaut crews on the surface of Mars for up to 500 days at a time, with uncrewed operations between visits. The exploration strategy will emphasize routine exploration by the crew utilizing Extravehicular Activity (EVA) spacesuits as well as long-range roving via pressurized rovers at ranges up to 100 km distant from the outpost. This type of operation would be similar to early exploration of the Antarctic, where explorers utilized "field stations" for their seasonal visits to the continent. In this same way, a Mars surface field station will be the base camp for early Mars explorers. The Mars surface field station will develop over time, with subsequent missions delivering additional supplies to expand the station's capabilities. [15,16]

Buildup of the Mars field station will begin with dedicated cargo missions, each of which deliver the necessary surface assets including surface power systems, the Mars ascent vehicle, In-Situ Resource Utilization (ISRU) systems necessary for producing oxygen for Mars ascent, surface habitation, logistics, and surface mobility systems such as long-range pressurized and short-range unpressurized rovers. Each of these systems will be put into operational service with a combination of autonomous capabilities, supervision from operators on Earth, or potentially teleoperated from orbit if crew were present at the time of the cargo vehicle arrival.

Heavy lift launch vehicles, such as the Space Launch System (SLS), augmented with commercial launch vehicles where appropriate, will be used to deliver both the Mars-bound payloads, Mars transfer vehicle, and the necessary propellants to cislunar space, such as to the Lunar Orbiting Platform-Gateway as described in 0, for aggregation and checkout prior to departure for Mars. The Mars transfer vehicle propulsion system assumed for the basis of comparison architecture is based on a reusable hybrid solar electric propulsion (SEP)/chemical system. [17,18,19] High-power hybrid solar electric/chemical propulsion stages, which are identical for both crew and cargo missions, will be fueled, and rendezvous with their cargo in cislunar space before departing for Mars. [20,21,22]

Initial missions will rely on oxygen generated from the Martian atmosphere for the propellant oxidizer for the Mars Ascent Vehicle (MAV), and for oxygen to supplement the field station's life support systems. ISRU could be evolved to include the use of Martian water for the generation of rocket fuel (CH_4) and additional life support consumables when sufficiently large and accessible deposits of water ice deposits are identified. [23,24,25,26,27,28]

Entry, descent and landing systems will be needed to navigate the thin Martian atmosphere and land the 22 metric tons of useful payload precisely at pre-selected exploration zones. [29,30] To deliver the MAV, other cargo elements, and the crew to the surface, an Entry/ Descent/ Landing (EDL) system is required for each vehicle going to the Martian surface. Large aerodynamic decelerators, such as the Hypersonic Inflatable Aerodynamic Decelerator (HIAD), produce large drag area to take advantage of the thin atmosphere of Mars. [31] Rocket propulsion is still required for the terminal portion of descent to the surface, with cargo and crew both utilizing conventional chemical rockets and precision soft landing systems to land approximately 1 km from the field station to minimize blast ejecta damage. [32]

Modular habitats will provide the volume for the crew to sleep, eat, exercise and work on the Martian surface. [33,34,35,36] Habitation elements will be delivered with each crew landing, and over time the habitation volume of field station will increase to allow more room for enhanced laboratory and science operations. Pressurized connections between habitats, rovers, and even the MAV will allow pressurized transfer of crew and supplies among pressurized elements without the need for EVA, and without introducing Martian dust into the crew's environment [37].

Surface power will be provided by modular array of 10 kWe fission power units (Kilopower) that will allow the surface field station to be located at any Martian latitude and will provide the ability to perform ISRU operations and support crew activities around-the-clock, regardless of seasonal variations in day/night cycle or dust storm interference. [38,39] [40,41,42]

4. Example Lunar Missions Considered

The recent US Space Policy Directive sets a near-term course back to the Moon while retaining Mars as the long-term goal. The details of the future approach for human lunar exploration are still under investigation by NASA, international partners, industry and academia. The current lunar strategy begins with the deployment of a Lunar Orbiting Platform – Gateway (referred to as "gateway" and further described in Section 0), in cislunar space orbiting the Moon. The missions which follow, including those to the lunar surface, are still under study. In order to determine the potential applicability of future lunar missions to human exploration of Mars in an era of an evolving lunar exploration strategy, the assessment team felt that it was more appropriate to examine a range of potential lunar mission concepts, each of which would provide differing degrees of applicability toward future Mars missions, rather than picking one lunar concept. Table 2 provides an overview of the key characteristics of various lunar mission concepts considered for this

Table 1 Characteristics of the Mars basis of comparison architecture.

Architecture Characteristic			Mars Mission Basis of Comparison Architecture
General Description	Objectives	Primary Mission Objective	Long duration exploration of one site on Mars
		Secondary Mission Objective	Emphasis on affordability and sustainability
		Mission Campaign Strategy	1st crewed mission to orbit, 2nd to surface
		Mission Cadence	Crew trip to Mars every other opportunity (~52 months)
	Mission Description	Mission Type	Conjunction Class - Minimum Energy
		Total Transit Time (out + back)	650 - 800 days
		Duration at Destination Time	300 - 400 days
		Total Mission Time	1050 - 1100 days
		Crew Size	4
		Cargo Deployment	Pre-deployed before crew departs Earth
		Mars Capture Method (Cargo)	Propulsive capture into Mars orbit
		Mars Ascent Propellant	Cryogenic O_2/CH_4
		Interplanetary Propulsion	Hybrid Solar Electric / Chemical
		Departure Aggregation / Staging	Lunar Near Halo Orbit / High Earth Orbit
ARCHITECTURAL ELEMENTS	Surface	Surface Site Location	Build up single site (Jezro Crater as reference location)
		Surface Power	Fission (4 each @ 10 kWe + 1 spare)
		Mobility	Pressurized Rover (100+ km range)
		In-Situ Resources	O_2 from the atmosphere to fuel the ascent vehicle
		Reuse	System lifetime 15 years.
		Redundancy	Built up as outpost grows
	Planetary Access	Mars Entry, Descent & Landing Technique	Supersonic Retropropulsion - Inflatable Aero - No staging
		System Design Commonality	Common for Crew and Cargo
		# of Descent Systems per Crew Mission	3
		Descent System Payload Capacity	22 t
		Descent System Mass at Launch	52.7 t
		Mars Orbit Insertion Method	Propulsive Capture
		Descent Design Altitude	0 km
		Precision Landing Accuracy	< 50 m
		Mars Ascent Propellant	ISRU (O_2 for ascent, CH_4 from Earth)
	Space Transportation	Mission Type	Conjunction Class Minimum Energy
		Reuse	Reused 3 times
		Crew Mission Cadence	Crew trip every-other opportunity
		Propulsion System Type	Hybrid Solar Electric / Chemical (500 kWe)
		System Performance	Power = 500 kWe, SEP Isp = 2600 s, Chemical Isp = 350 s
		Refuel Capability	Xe, CH_4, O_2
		Orion Use	To cis-lunar and back
		Propellant Type & Load	Xe (26 t) / O_2/CH_4 (26 t)
	Staging	Vehicle Assembly and Reuse Point	Cis-Lunar: NRHO 1,500 km x ~70,000 km
		Departure Strategy	Dual lunar gravity assist
		Crew Ingress / Departure Point	High Earth: 400 km x 384,000 km
		Crew Return Point	Propulsive Capture to High-Earth Orbit
	Launch	Cargo Launch Vehicle	SLS 2B (45 t to Trans-Lunar Injection)
		Crew Launch Vehicle	SLS 2B (Orion + 13 t cargo)
		Average SLS Launch Rate	2.3 Launches per year
		SLS Launch Surge Rate	3 Launches per year
		SLS Payload Shroud	10 m diameter x 19.2 m length
		Commercial Launch	Opportunities possible and under investigation

analysis. These lunar mission concepts, largely based on previous studies and analyses, range in scope, scale, and key capabilities. Each of these four lunar mission concepts are further described in the following paragraphs.

4.1. Lunar Orbiting Platform-Gateway

This lunar-orbit only mission advances NASA's plans of extending human presence beyond low-Earth orbit. In the next few years, the first launches of the Space Launch System and Orion crew vehicle will ferry humans into deep space for the first time in over four decades. During these early exploration missions, astronauts will begin to live and work for extended durations in the deep space environment where they will incrementally build operational experience and test the systems required for long-duration missions to Mars. NASA's concept for these first missions in Phase 1 – an exploration phase characterized by the demonstration of exploration systems – involves deployment of a Lunar Orbiting Platform-Gateway in cislunar space. [43,44,45] While the gateway can be constructed in various sequences depending on mission plans, NASA analysis teams have concluded that gateway will most likely be composed of four functional capabilities: a solar electric power propulsion element (~ 50 kWe), short-duration habitats, logistics modules, and an airlock/node. As currently envisioned, the gateway will be placed in an elliptical Near-Rectilinear Halo Orbit (NRHO) [46] via a combination of commercial launches and payloads co-manifested with launches of the SLS/Orion exploration systems. The current gateway strategy evolves to be able to support four crew for or up to 42 days during each visit in cislunar space, with no crew actually landing on the surface of the Moon. During each stay in lunar orbit the crew will perform technology evaluations, support operational maintenance of the gateway, conduct operational activities including Mars transfer vehicle checkout, refurbishment of returning Mars vehicles, and facilitate scientific exploration such as tele-robotically operating robotic systems on the surface of the Moon.

4.2. Sortie Class

Missions in this class of lunar exploration were assumed to be similar to the Apollo missions conducted from 1969-1972 whereby two to four crew would explore the lunar surface out of their lander for short durations. Each mission was envisioned to explore distinct separate sites on the Moon with the crew conducting short-range exploration close to the landing site via EVA suits and unpressurized rovers utilizing only systems brought with the them (no pre-deployment of cargo). For this mission concept, space transportation system assumptions similar to those of the gateway-class missions were assumed including SLS/Orion crew and cargo transport; gateway serving as an operational node prior to descent to the surface; cryogenic oxygen/methane descent and ascent propulsion with a refuelable/reusable ascent stage; and all Earth-based propellants (no-ISRU).

4.3. Global Exploration Roadmap Class

Over the past several years agencies participating in the International Space Exploration Coordination Group (ISECG) continue to advance a long-range international exploration strategy to expand human presence into the Solar System. [47,48] The third edition of the Global Exploration Roadmap, (GER) [49] released January 2018, reaffirms the interest of 14 space agencies to expand human presence into the Solar System, with the surface of Mars as a common driving longer-term goal. It reflects a coordinated international effort to prepare for space exploration missions beginning with the International Space Station (ISS) and continuing to the lunar vicinity (e.g. the gateway), the lunar surface, then on to Mars. The GER concept consists of a series of missions to the lunar surface with four crew to explore the lunar surface and prepare for Mars. [50] It was also assumed for this analysis that the gateway will serve as an operational node for all subsequent lunar surface missions considered including lunar lander support as well as crew and payload transfer activities. Each mission will utilize the SLS/Orion for delivery of the crew to the gateway in cislunar space where the crew will transfer to their awaiting lunar lander. Although specific system trades continue to be conducted, for this analysis it was assumed that the lunar lander systems would be of a Mars-forward design consisting of cryogenic oxygen/methane for both the descent and ascent stages. It was further assumed that the ascent stage was capable of being refueled at the gateway and reused for subsequent lunar missions and all propellants for both the descent and ascent stages are brought from Earth – that is no lunar derived In-Situ Resource Utilization (ISRU) derived propellants would be utilized. Pre-deployed assets on the surface of the moon, consisting of a Kilopower fission system and pressurized rovers, would be capable of supporting four crew for up to 42 days on the surface. With this strategy, the pressurized rovers serve as both habitation and regional-scale exploration capabilities. A key aspect of the GER strategy is the ability to relocate the surface assets to a new exploration site between crew missions, thus expanding the overall exploration range on the surface of the Moon. It should be noted that the capabilities describe here are assumed for GER-class missions, and if these assumptions are changed, for instance a non-cryogenic propulsion system for the lander, the resulting Mars-forward applicability described in sections 5–7 would need to be re-evaluated.

4.4. Lunar Field Station Class

Lunar Field Station-class missions provide a more robust exploration capability at a single site on the surface of the Moon. Much like future Mars missions, dedicated lunar cargo missions would be conducted to pre-deploy critical surface assets such as Kilopower fission power systems, long-duration habitation, logistics, and surface mobility such as pressurized rovers to a predesignated landing site. [51,52,53] Each of these systems is offloaded and emplaced on the surface and put into operational service with a combination of autonomous capabilities, supervision from operators on Earth, or potentially teleoperated from orbit by crew onboard the gateway. While on the lunar surface, the crew would live out of the pre-deployed habitation systems for up to six months per crew rotation and utilize the pressurized rovers to conduct long-range regional exploration around the lunar field station. For this mission concept, space transportation system assumptions similar to those of the gateway-class missions were assumed including SLS/Orion crew and cargo transport; gateway serving as an operational node prior to descent to the surface; and cryogenic oxygen/methane descent and ascent propulsion with a refuelable/reusable ascent stage. Although it was assumed that local resources derived from the surface of the Moon, such as trapped water ice in permanently shadowed regions, would not be used for these lunar missions, the lunar field station missions would include technology and operational demonstrations of consumable production and handling.

5. Space Transportation Systems and Support

The transportation of crew and cargo between Earth and Mars is a key challenge in the development of a viable human exploration strategy for Mars. Efficient and cost-effective methods which balance the technologies required, risks exposed, and complexity of operations are key considerations in measuring viable future exploration approaches. As summarized in Table 3, missions in cislunar space can serve as an important step in developing and demonstrating future Mars transportation systems and concepts depending on the approaches considered. The relevance ratings below are based on the mission and concept capability assumptions discussed previously in sections 3 and 4.

5.1. Elliptical Orbit Rendezvous

The reference parking orbits for both the lunar gateway (near-rectilinear halo orbit) and the Mars basis of comparison (5-sol elliptical) are both highly elliptical with nearly the same period. Since these non-circular parking orbits will require new deep-space rendezvous techniques, missions to the lunar gateway could serve as an excellent venue to perfect deep-space advanced navigation and rendezvous techniques which will be required at Mars. Accordingly, all of the lunar missions considered for this assessment exhibit high relevance to future Mars missions.

5.2. Deep Space Logistics & Operations

The Mars BoC operational concept is envisioned to use the gateway in cislunar space as the aggregation point for Mars-bound crew transportation systems including launch, assembly, and checkout of the Mars transfer vehicle. In addition, a key element of the Mars BoC architecture is the return of the Mars transfer vehicle back to cislunar space at the end of a Mars mission for refurbishment, refueling, and reuse. This need drives the overall Mars logistics and operational capability needs to be very similar to those that will be required for gateway and other cislunar missions. Logistics, crew transport and other operational considerations should be very similar.

5.3. Heavy-Lift Launchers

The assumed architectures for both the lunar and Mars exploratory missions include heavy-lift launch of both crew and cargo as a key capability for delivery of systems to cislunar space. For this analysis the SLS was assumed to provide that need augmented with commercial vehicles as appropriate. Analysis associated with the Mars BoC architecture has shown that the ability to inject a minimum of 45 t cargo (or 13 t of cargo when co-manifested with the Orion) to trans-lunar injection, 10 m diameter shroud, and, depending on the role of commercial launch providers, a peak launch rate of up to three per year delivery capability is required. For the lunar missions considered here, the SLS will need the ability to throw heavy payloads onto a trans-lunar trajectory as well. This could include either the Orion with approximately 10 t of co-manifested cargo on crew missions, or a dedicated cargo element of 40 t. Since the lunar mission concepts considered for this analysis show an evolutionary path to meeting future Mars mission needs, it was determined that the heavy lift launchers would have a high relevance for all lunar missions considered here.

Table 2 Range of lunar mission assumptions.

	Lunar Missions Assumptions			
Lunar Attribute	Gateway-Only	Sortie-Class	GER-Class	Lunar Field Station
Human lunar surface mission?	No	Yes, Multiple Sites	Yes, Multiple Sites	Yes, Multiple Sites
Number of crew to the surface	0	2 - 4	4	4+
Surface exploration duration	n/a	3-5 days	42 days	6 months
Pre-deployed assets?	No	No	Yes	Yes
Surface exploration strategy	Earth or Gateway tele-operated robotic science & demonstrations	Unpressurized rover	Pressurized rover	Pressurized rover
Descent/ascent propulsion stage type	n/a	Cryogenic (O_2/CH_4) lander / ascent	Cryogenic (O_2/CH_4) lander / ascent	Cryogenic (O_2/CH_4) lander / ascent
Transportation system reuse	n/a	Ascent Stage	Ascent Stage	Ascent Stage
Surface power	n/a	n/a	Kilopower	Kilopower
Surface habitation	n/a	n/a	n/a	Habitat
Surface resources	n/a	n/a	n/a	ISRU
Surface exploration range	n/a	<10 km per site	100 km per site	100 km from base
Other common assumptions	All options assume gateway node, heavy lift launch, and 11 km/s Earth return velocities			

Table 3 Moon-Mars relevance for space transportation capabilities.

Capability	**Applicability to Mars Missions**			
	Gateway Only	**Sortie-Class**	**GER-Class**	**Lunar Field Station**
Elliptical Orbit Rendezvous	●	●	●	●
Deep Space Logistics & Operations	●	●	●	●
Heavy-Lift Launchers	●	●	●	●
Earth Entry at Lunar-Return Velocities	●	●	●	●
High-Power Electric Propulsion	◖	◖	◖	◖
In-Space Refueling (Xe)	●	●	●	●
Cryogenic Propellant Descent/Ascent Stage	○	●	●	●
Lander Cryogenic Propellant Management	○	●	●	●
In-Space Refueling (O_2/CH_4)	○	●	●	●
Hazard Avoidance / Precision Landing	◖	●	●	●
Deep Space & Surface Navigation & Communication	◖	◖	●	●

Moon-Mars Relevance Rating: ○ Little or none ◖ Somewhat ● High

5.4. *Earth Entry at Lunar-Return Velocities*

All of the lunar missions considered for this assessment result in Earth-return entry speeds of approximately 11 km/s when returning from cislunar space, such as from the gateway. The operational concept for the Mars BoC utilizes cislunar space as the staging node for both outbound and returning Mars vehicles. That is, upon return from Mars, the inbound Mars transfer vehicle propulsively decelerates back into cislunar space, with the crew subsequently returned with the same entry requirements as the lunar missions assumed here. Thus, there is a high degree of relevance between the lunar and Mars mission Earth return concepts.

5.5. *High-Power Electric Propulsion*

The Power and Propulsion Element of the assumed gateway is expected to utilize Solar Electric Propulsion (SEP) for station-keeping and potentially for major orbital transfer maneuvers. As currently envisioned, this system would have a power generation capability of approximately 50 kWe total power for both the SEP system and gateway operational elements. The Mars BoC reference utilizes SEP as well for the interplanetary transfers, but the power level for the Mars SEP would be an order of magnitude larger, approximately 675 kWe array power / 400 kWe power to the thrusters. Although all of the lunar missions considered here utilize the gateway as an operational node, improvements in the SEP system including power generation, conditioning, propellant capacity, and perhaps electric thruster design, would be required to meet future human Mars mission needs.

5.6. *In-Space Refueling (Xe)*

The Mars BoC architecture's interplanetary vehicle considered for this assessment, a hybrid SEP/chemical propulsion system, utilizes Xenon (Xe) as the working propellant for the electric thrusters and cryogenic O_2/CH_4 for the chemical system. It was also assumed that the Mars SEP vehicle would return to the gateway for refurbishment and refueling for use on the next Mars bound mission. In addition, as currently envisioned, the gateway Power and Propulsion Element is currently planning for a Xe refueling capability as well, thus since all lunar missions considered here utilize the gateway as an operational node, though different in scale there is a high degree of relevance between the lunar and Mars Xe refueling concepts.

5.7. *Cryogenic Propellant Descent/Ascent Stage*

The Mars BoC architecture utilizes cryogenic O_2/CH_4 engines for the Mars descent stage. In addition, the BoC ascent stages also utilize cryogenic O_2/CH_4 to take advantage of Mars ISRU opportunities for mass reduction. Although vehicle and technology trades continue to be conducted, cryogenic O_2/CH_4 engines are emerging as a desirable for lunar landers, particularly ascent if they are based from higher energy orbits, such as the gateway near-rectilinear halo orbit. Since, for this analysis, it was assumed that the lunar propulsion systems would be of a Mars-forward design consisting of cryogenic O_2/CH_4 for both the descent and ascent stages, it was found that there would inherently be a high degree of relevance between the lunar and Mars descent/ascent propulsion systems. It should be noted that the use of cryogenic O_2/CH_4 for lunar missions was assumed here, and if that assumption is changed, the relevance score would also change accordingly to be somewhat, or most likely, not applicable for all lunar surface missions.

5.8. *Lander Cryogenic Propellant Management*

The BoC architecture's Mars descent stage and ascent stages must keep cryogenic O_2/CH_4 stored and conditioned for many months in space and on Mars. Since it was assumed that the lunar stages would be of a Mars-forward design utilizing O_2/CH_4, the lunar stages need to keep the propellants conditioned during transit and while at the gateway between missions which could last months in duration. In addition, during extended surface missions, the propellants will need to stay conditioned on the lunar surface. These combined lunar lander needs indicate that for all lunar surface missions considered in this analysis, there is a high degree of relevance to Mars missions. As mentioned above, if the assumptions associated with the lunar lander or ascent stage propellants are changed, the relevance would also change accordingly.

5.9. *In-Space Refueling (O_2/CH_4)*

Vehicle reusability is emerging as a desirable goal for space systems, namely as one potential way to reduce the cost of exploration. The hybrid SEP/chemical transportation system used as the reference for the Mars BoC option involves refueling the crewed Mars transfer vehicle with He and O_2/CH_4. Due to the projected cost of lunar landers many study options are examining reusable and refuelable O_2/CH_4 lander stages. For this analysis it was assumed that the lunar ascent stage would return to the gateway in cislunar space and would be refurbished and refueled for subsequent use. Thus, the ability to transfer propellants for lunar landed system, namely O_2/CH_4, was found to be highly applicable to future Mars missions. As mentioned previously, if the assumptions associated with the lunar ascent stage propellants or its ability to be reused are changed, the relevance along with the relevance in other categories would also change accordingly.

5.10. *Hazard Avoidance / Precision Landing*

It is expected that lunar landing missions could utilize the same or nearly the same set of autonomous precision landing and hazard avoidance technologies (sensors, algorithms, and avionics) as Mars landing missions, specifically for the terminal landing phase. Autonomous capabilities will be even more critical with Mars missions since the crew will be deconditioned by months in microgravity and the crew must rely more heavily on autonomous systems. Repeated landings at the same landing site can significantly improve precision landing performance over time, by using surface assets as navigation beacons. These missions can also improve the understanding of plume ejecta during landing which could damage pre-deployed or existing surface assets. For these reasons, even though the lunar landing systems will have some different challenges that may drive different component performance requirements from what is needed on Mars, there would still be high relevance especially for the terminal landing phase of the missions. Lastly, since for this analysis it was assumed that robotic exploration of the lunar surface would be conducted from the gateway, it was believed that some of the precision landing and hazard avoidance technologies could be demonstrated on smaller robotic landers, thus providing some relevance to Mars missions for gateway-only missions.

5.11. *Deep Space & Surface Navigation*

All human deep space missions are beyond the Global Positioning System and the Tracking Data and Relay Satellite System umbrella thus putting heavy reliance on the Deep Space Network. Twenty-four hours a day, seven days a week, high-bandwidth communications and navigation functions may stress the Deep Space Network's capabilities. As mission durations increase, especially with the presence of crew, the volume of data transmitted will increase dramatically. The longer duration GER-Class and lunar field station missions will move these requirements toward those of years-long Mars missions, thus indicating high relevance for future Mars missions.

6. Human Health and Performance

As humans extend their reach beyond low-Earth orbit eventually to the surface of Mars, they will be exposed to the hazardous environment of deep space for lengthy periods; consequently, protective measures must be devised to ensure crew health and maximize mission success as well as the long-term health of the crew after the mission. The health and safety of crew members while they travel to and from the Mars and inhabit its surface are key near-term research concerns. The ISS is currently serving as a vital test facility for research that demands long exposures to the reduced-gravity in space. That research, along with information gained with future missions in cislunar space, is forming the foundational data necessary to extrapolate and infer what will be necessary for future Mars missions. The relevance of future lunar missions in paving the way to Mars for several human health and performance key characteristics are provided in Table 4 and discussed further in this section. In many cases the level of feed-forward care available to the crew will be highly dependent on the level of capabilities which would be available by the lunar mission flown, with greater capabilities providing greater feed-forward. For more information on the overall key risks for human health, refer to the Human Research Roadmap. [54]

Table 4 Moon-Mars relevance associated with human health and performance.

Capability	Applicability to Mars Missions			
	Gateway Only	Sortie-Class	GER-Class	Lunar Field Station
Flight Medical Capabilities	◖	○	◖	◖
Radiation Exposure	◖	○	◖	●
Cognitive or Behavioral Conditions	◖	○	◖	●
Long-Term Medication Storage	●	○	◖	●
Food System	◖	○	◖	●

Moon-Mars Relevance Rating: ○ Little or none ◖ Somewhat ● High

6.1. Flight Medical Capability

The need for advanced medical care for crewmembers becomes increasingly necessary as mission remoteness and durations increase; the ability for timely and repeated logistics delivery are limited; and the ability for aborts with quick return to Earth diminish. For the Mars BoC transits, Mars orbit and Mars surface phases, where mission durations are measured in years and opportunities for timely medical evacuation is are essentially non-existent, advanced medical care will be required.

Level of care is a term used in terrestrial medical settings to refer to the amount and type of medical care rendered based on perceived need and the ability of the provider. The levels of care for human space flight systems are defined in the NASA Spaceflight Human System Standard, Volume 1: Crew Health (NASA_STD_3001, Vol 1). The primary drivers for level of care are mission destination (LEO vs. outside LEO) and mission duration. As these parameters increase, the required level of medical capability and the associated medical diagnostic and treatment modalities also increase. Timely medical evacuation requires return to definitive care within hours, which is currently not feasible for mission destinations outside of LEO. For the Sortie-class missions, the manifested medical capability will be significantly different than for a Mars mission, making the feed-forward applicability low. Longer mission durations outside of LEO have a higher degree of feed-forward for Mars, with the medical capabilities for a long duration lunar field station having the most applicability.

6.2. Radiation Exposure

As envisioned within the context here, the gateway will not contain a crew landed component, but the gateway will provide a Solar Proton Event (SPE) shelter within the integrated stack in cislunar space. This shelter may involve utilizing the Orion capabilities or another shielded storm shelter area within the gateway based on the "As Low as Reasonably Achievable" (ALARA) principle. Since all of the lunar missions considered for this analysis utilize the gateway as a staging node, the knowledge gained regarding deep space SPE shielding is expected to be somewhat relevant to future human Mars exploration missions. Protection from Solar Proton Event (SPE) on the surface may be difficult to implement in lander-only scenarios such as the Sortie-class missions envisioned here, however a SPE shelter, evacuation strategy, or risk acceptance strategy must be in place. Longer duration GER-Class and field station missions will need to address this threat with a SPE shelter within the pressurized rovers when on long-duration roves or other strategies must be in place when timely retreat to a surface habitat is not possible. Fixed-location habitats, such as with the lunar field station or Mars surface habitats, will most likely implement more extensive techniques, including use of in situ materials to provide added shelter from SPEs.

6.3. Cognitive or Behavioral Conditions

Long-duration missions such as those to Mars place the crew in isolated, confined and extreme environments, thus increasing the possibility that adverse cognitive or behavioral conditions will occur. These conditions have the potential to adversely impact crew health and performance should these fail to be detected and treated in flight. Due to preflight screening, known countermeasures, and the limited duration of Sortie-class missions, it is not expected that these missions will feed-forward to the longer duration Mars missions. Missions of longer duration, coupled with the radiation environment and distance from earth, such as gateway or GER-class missions, may provide feed-forward information on the behavioral performance of exploration crewmembers on the individual and team level and the impact of radiation on cognition and performance. Longer-duration missions such as those associated with the lunar Field Station are expected for provide a higher degree of feed-forward to Mars.

6.4. Long-Term Medication Storage

Since resupply opportunities will be limited for Mars missions, in-flight consumables and medications may need to be stored for periods of three years or more. Given the hostile space environment, long-term radiation exposure may diminish the stability and effectiveness of pharmaceuticals, resulting in a reduced ability to treat medical conditions with associated acute or chronic health consequences and/or performance impacts. Since the strategy for gateway and GER-class missions is to periodically revisit the exploration outpost, it is possible to position medicines for long durations providing some feed-forward research on the ability to store these critical pharmaceuticals for long periods. The long duration lunar Field Station missions provide the best Mars analog, with the shorter duration Sortie-class missions providing little opportunities for future Mars missions.

6.5. Food System

Shelf life and resupply limitations associated with a Mars mission with challenge the delivery of a safe, nutritious, and acceptable food system. The impact of the radiation environment on the shelf-life of the prepackaged food system is unknown. Bioregenerative food systems may augment prepackaged food systems, but the technical feasibility of such systems is also unknown. Missions to the lunar vicinity provide opportunities to test new approaches and technologies for food storage and delivery. Although the current food system is expected to be acceptable for short-duration of Sortie-class missions, the extended durations of gateway and GER-class missions will provide important data and research opportunities with the longer duration Field Station-class missions providing the highest Mars feed-forward relevancy.

7. Surface Systems and Activities

The Mars BoC architecture envisions the emplacement of a surface field station which would provide the necessary capabilities for the crew to conduct range of scientific investigations and applied technological research. This strategy for the exploration of the surface of Mars will require new concepts and capabilities some of which could be tested on the surface of the Moon. Table 5 provides a summary of the anticipated relevance between differing lunar mission concepts and the Mars basis of comparison architecture. It should be noted here that it was assumed that gateway-only missions would not include a human surface exploration component and consequently surface exploration activities would be limited to the operation of pre-deployed small lunar robotic systems - either by Earth-bound operators or from the gateway crew while is in cislunar space. Thus, many of the gateway-only systems and capabilities associated with this category were not applicable for future Mars missions. The other lunar mission concepts analyzed provide differing capabilities resulting in differing relevancy toward Mars. In essence, since the Mars BoC architecture envisions a robust surface exploration capability to take advantage of the long-stay transportation architecture, those lunar concepts with more surface capabilities feed forward towards Mars better.

Table 5 Moon-Mars relevance for surface systems and activities.

Capability	Applicability to Mars Missions			
	Gateway Only	Sortie-Class	GER-Class	Lunar Field Station
Routine Surface EVA & Local Mobility	○	◖	◖	●
Regional-Scale Surface Mobility	○	○	●	●
Dust Mitigation (Equipment)	○	◖	◖	◖
Fission Nuclear Surface Power (kWe-class)	○	○	◖	●
Robotic Teleoperation, Site Preparation	◖	◖	●	●
Modular Habitation Systems	◖	○	○	●
Surface Science Operations & EVA Support	○	◖	●	●
Planetary In-Situ Resource Utilization	○	○	○	◖

Moon-Mars Relevance Rating: ○ Little or none ◖ Somewhat ● High

7.1. Routine Surface EVA & Local Mobility

The Mars BoC architecture assumed strategy provides the ability to support the crew for multi-month surface missions with frequent EVA and local roving capability from the pre-deployed field station. While the Sortie and GER-class missions may require advances in EVA mobility and environmental resilience such as the mass and maintenance required for the portable life support systems, it will likely take more significant fixed infrastructure such as those associated with a longer duration lunar field station to demonstrate the more robust operation and maintenance capabilities required for future Mars missions.

7.2. Regional-Scale Surface Mobility

The exploration strategy defined by the Mars BoC architecture describes multi-month surface missions with regional roving capability (300-400 days on the surface with the ability for the crew to explore 100+ km from the field station). Since, by definition, the analogous systems and operational experience exist for the lunar GER-class and lunar field station scenarios, these two mission classes are believed to be highly relevant to future human Mars missions. Whereas neither the gateway-only nor Sortie-class missions provide regional-scale human exploration capabilities.

7.3. Dust Mitigation (Equipment)

While it is believed that the dust on Mars will be easier to handle than on the moon, all lunar surface scenarios could improve understanding of techniques to mitigate the effects of dust on surface systems including EVA space suits, mobility systems such as pressurized rovers, habitat hatches and seals, and deployed infrastructure. The difference in Martian dust characteristics and its airborne transport make these techniques only partially applicable.

7.4. Fission Nuclear Surface Power (kWe-class)

The Mars BoC architecture utilizes "KiloPower" fission power systems to establish a surface infrastructure for power-intensive systems such as ISRU, regional-scale rover recharge and habitation systems. Photovoltaic solar systems do not work well on Mars due to the size of array needed and the effects of dust and dust storms which are present on Mars.[55] Sortie-class lunar missions have modest power requirements and could be conducted with batteries or fuel cells contained within the lunar lander and thus pre-deployed power systems are not required. Although GER-class missions could be conducted using solar systems with batteries for nighttime storage, the GER raises the possibility of utilizing pre-deployed fissions systems for rover recharge and other surface operations, thus indicating some forward applicability to Mars for that power concept. Lunar field station activities would likely need fission systems for similar continuous high-power operations and survival through the lunar night, thereby demonstrating a key Mars capability need.

7.5. Robotic Teleoperation, Site Preparation

Buildup of the Mars BoC field station begins with dedicated cargo missions, each of which deliver the necessary surface assets including surface power, the Mars ascent vehicle, ISRU systems, surface habitation, logistics, and surface mobility systems. Each of these systems is put into operational service with a combination of autonomous capabilities, supervision from operators on Earth, or potentially teleoperated from orbit if crew were present at the time of the cargo vehicle arrival.[56] A lunar base would likely benefit from similar capabilities and these could be performed in an analogous manner from the gateway. The GER strategy involves intense teleoperation of the regional rovers between crew missions from either the Earth or gateway. Thus, these autonomous or tele-robotic operations of both the lunar field station and GER-class exploration scenarios are viewed to be highly applicable to future human Mars missions.

7.6. Modular Habitation Systems

The Mars BoC field station relies on a gradual build-up of habitable elements, which include crew descent modules, pressurized rover cabins, and empty logistics containers that are used to expand the habitable volume. Modular support systems and operational procedures that ensure critical services such as power, thermal control, or life support are efficiently distributed across several modules could be developed on either the gateway or lunar field station missions. Such systems would be reusable over the long-term, but the modular aspect could make them easily replaced or upgraded on later missions.

7.7. Surface Science Operations & EVA Support

The primary objectives for the BoC Mars architecture focus on the long-term human exploration of the surface of Mars. The long surface missions implied by BoC architecture would necessitate fixed-location habitation which would include systems and capabilities for EVA, life support, science, etc. in a partial gravity environment. With this strategy regional exploration using pressurized rovers from a field station consisting of multiple pressurized elements is assumed. Long duration surface missions with regional mobility offer potential for extensive planetary surface science and in situ analysis. While Sortie-Class missions could provide local sample collection and deployment of small science packages, the in situ analytical capability would most likely be limited. The GER-class and lunar field station missions could more closely resemble Mars BoC-type surface science capabilities, thus being highly relevant to Mars.

7.8. Planetary In-Situ Resource Utilization

The Mar BoC ISRU strategy is an evolutionary one staring with the production of oxygen from the atmosphere, evolving later to the potential production of fuel and other resources from water ice trapped in the subsurface. While the ISRU resources and extraction processes are likely different between the moon and Mars, some of the product preparation and storage processes such as cryogenic liquefaction and storage may be similar. While there are known useful resources on Mars, namely oxygen in the atmosphere, there are still uncertainties with the quantity, quality, location, and overall characteristics of potential resources on the Moon. Thus, for the lunar missions assumed here, only the lunar field station were considered to have the capabilities which may begin to demonstrate, though not necessarily use in the critical path of crew return, locally produced resources, giving the lunar field station only partial feed forward to Mars.

8. Conclusions

Since both the lunar and Mars mission scenarios are in early formulation, the applicability findings detailed above are primarily qualitative from a system capability and mission risk reduction perspective. That is, emphasis was placed on determining how well the assumed lunar system itself, or fundamental knowledge which would be obtained by conducting the lunar mission, would feed forward to future Mars missions. This assessment did not try to apply numeric evaluation and scoring methodologies, but rather identified the applicability of each lunar capability. It should be noted that findings are highly dependent on the assumptions made in terms of both the lunar and Mars missions and system concepts. If any of the assumed capabilities or systems are changed to be different than what was assumed here, either lunar or Mars, the findings would need to be re-evaluated. Although the assessment described here was predominately strategic and further detailed studies are required, some high-level findings emerge as related to the scope of lunar missions considered.

Gateway Only: The findings indicate that gateway missions can provide good in-space transportation feed forward to human Mars missions, but much of that is driven by the specific gateway design assumptions made. The choice of an elliptical orbit at the Moon provides good operational similarities to future Mars missions rendezvous strategies. And, as long as the gateway continues along the path to implement higher power solar electric propulsion concepts with the capability to be refueled, it can serve as a good technical demonstration of the more complex and higher power transportation systems required for Mars. However, since the gateway-class missions are limited in crew duration and are orbit only missions, that is they do not contain a lunar surface exploration component other than small robotic missions, many key challenges associated with human health and surface operations for Mars missions will remain.

Sortie-Class: Since it was assumed here that all lunar missions would utilize the gateway as a staging node on the way to the Moon, Sortie-class missions exhibit the same in-space transportation operational and electric propulsion relevancy as gateway missions, with the addition of lander and ascent stage feed-forward. This lander/ascent stage feed forward is predominately related to the assumption that the lunar lander systems would implement a cryogenic (O_2/CH_4) propulsion system which will be key in demonstrating these capabilities for Mars. This is an important assumption. If it is decided that non-cryogenic propellants would be used for lunar missions, then then the applicability to Mars would be more limited. However, regardless of the propulsion choice landing human-scale systems on the Moon can provide good feed forward in helping mitigate the Mars challenges associated with terminal descent, hazard avoidance, and plume ejecta. Though not identical to Mars, understanding the basic physics and operational constraints and strategies for landing on the Moon will represent vital steps toward Mars. Lastly, even though the Sortie-class missions do include a surface component, the short duration of the operations and reduced surface infrastructure limit the applicability to Mars from a human health and surface systems perspective.

GER-Class: GER-class missions which provide medium duration stays on the surface of the Moon (42 days) provide even more value in terms of applicability of demonstrating the critical systems and reducing risks for future human Mars missions. In fact, given the anticipated investments required as compared to the relevancy toward Mars obtained, GER-class missions may provide the better return on investment of the lunar mission concepts considered here. They provide a broad range of applicability across all sectors: transportation, human health, and surface systems and activities. Additional relevancy for GER-class mission can be gained by increasing the duration of stays on the surface (along with the required infrastructure) and demonstration of other advanced concepts necessary for Mars such as the use of locally produced ascent propellants for crew return.

Lunar Field Station: Due to the scope and scale of the lunar field station concept considered, missions of this class provide the broadest feed-forward toward future Mars missions. They drive the capability needs for all sectors providing greater linkages toward Mars, with the limiting factor related mostly to the difference in environments between the Moon and Mars. The capabilities required for the longer duration field station class missions drive for more robust capabilities and require additional investments to implement. Although missions of this class can provide additional feed-forward to Mars, these capabilities come at an additional cost and implementation time, thus further cost/benefit assessments on the lunar field station concepts are warranted to determine if the extra benefit of longer stay lunar field station missions is worth the cost and extended schedule.

The findings presented here demonstrate that as we venture back to the Moon with the explicit intent of moving forward to more distant and challenging missions such as Mars, it is important continually look toward the future and make sure that near-term decisions related to the Moon feed forward to those future Mars needs. In many cases that may necessitate following a non-optimum and, most possibly slightly more expensive in the near-term lunar exploration path which will still lead to Mars. Perhaps of most interest is that the assessment showed that conducting a full-up long-duration Mars dress rehearsal on the Moon (e.g. the lunar field station as described here) may not be required prior to committing to a human Mars mission. In fact, more modest operations on the Moon such as the GER-class missions, can provide key Mars capability development and risk reduction. A human return to the Moon in its essence can, if done correctly, serve as an excellent down payment to Mars.

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