Strategic Implications of Phobos as a Staging Point for Mars Surface Missions

Bret G. Drake
The Aerospace Corporation
2310 E El Segundo Blvd
El Segundo, CA 90245
bret.g.drake@aero.org
bret.g.drake@nasa.gov

Michelle A. Rucker
NASA Johnson Space Center
2101 NASA Parkway
Houston, TX 77058
michelle.a.rucker@nasa.gov

Alicia Dwyer Cianciolo
NASA Langley Research Center
1 NASA Drive
Hampton, VA 23681
alicia.m.dwyercianciolo@nasa.gov

Abstract— As human exploration endeavors begin to set sights beyond low Earth orbit to the surface of the Moon, exploration of the surface of Mars continues to serve as the "horizon destination" to help focus development and research efforts. One Mars exploration strategy often discussed is the notion of utilizing the moons of Mars, namely Phobos, as an exploration destination prior to Mars surface missions. The premise behind this is that staging missions from Mars' moons as well as exploring the moons themselves would be less costly and risky. However, understanding potential advantages of Phobos staging and exploration must be done in the context of the overall end-to-end Mars surface exploration needs, goals, objectives, campaign approach, and systems required. This paper examines the strategic implications of utilizing the moons of Mars as a potential location for exploration of Mars. Operational concepts utilizing both Phobos and Mars orbital strategies will be examined to understand the architectural impacts of this staging strategy. The strategic implications of each operational concept are assessed to determine the overall key challenges and strategic links to other exploration destinations. Results from this analysis indicate that, if the objective is to conduct Mars surface missions, utilizing Phobos as an exploration destination adds little benefit toward the goal of exploration of Mars.

TABLE OF CONTENTS

1. INTRODUCTION

The President's Space Policy Directive-1 [1] provides the direction for NASA to more effectively organize government, commercial and international efforts to develop a sustainable presence on the Moon and beyond. Human exploration of the Moon is part of a larger, sustainable exploration campaign extending from low-Earth orbit to the surface of Mars, and deeper into space. In addition, human exploration of Mars has continued to foster strong bipartisan congressional support with the NASA Authorization Act of 2008 [2] and the NASA Authorization Transition Act of 2017 [3] which specifically call for human missions to the surface of Mars as the horizon goal to focus NASA's exploration development efforts.

While exploration of the surface of Mars has maintained strong support throughout the modern era of human exploration planning, missions to the moons of Mars, Phobos and Deimos, have at times also been injected into strategic planning discussions [4-20], often because Phobos and Deimos are presumed to be a "cheap and easy" first step to Mars exploration. Assessments of conducting human exploration of the moons of Mars have ranged from full up architecture and system concept definition to others which are more pedestrian, only providing casual mention of the potential strategic value of Mars moon exploration. Comprised within many of these studies are stated underlying rationales and motivations for human exploration of Phobos and Deimos. Typical rationales include the assertion that human missions to Phobos and/or Deimos would:

- serve as a catalyst for future human exploration;
- be easy missions to conduct because they side-step the need for a Mars lander or ascent vehicle;
- function as a platform for low-latency telerobotic exploration of Mars;
- help certify human exploration systems;
- serve as a staging point for surface missions;
- represent a low-cost entry point for exploration of Mars; and
- ease the transportation burden through in-situ propellant production.

When formulating exploration concepts, it is important to view the entire exploration campaign to understand how each

978-1-7821-2734-7/20/$31.00 ©2020 IEEE ....

progressive step, vehicle element, and operational construct fits within the entire system-of-systems architectural strategy. That is, missions to Phobos should not be viewed independently as standalone endeavors, but rather should be viewed from the perspective of how they advance the overall exploration goals. As discussed earlier, human exploration of the surface of Mars has retained strong and lasting consensus as a national goal and thus should comprise a strong focus of the exploration efforts. Therefore, missions which may precede Mars surface missions should be assessed in how well they advance that overarching goal. More specifically, if a human mission to Phobos and/or Deimos were conducted prior to a Mars surface mission, the question of how well it feeds forward to the goal of humans on Mars should be a key consideration.

This paper will examine the strategic implications of human exploration missions to the moons of Mars, Phobos[1] and Deimos, as potential destinations on the way to the surface of Mars. This discussion will begin with a brief discussion of the moons' characteristics followed by an overview of example exploration strategies of the martian system. That discussion will include a range of Phobos exploration concepts as well as exploration of the surface of Mars. These mission approaches are discussed to provide context for the rationales of human exploration of Phobos.

2. THE MOONS OF MARS: PHOBOS AND DEIMOS

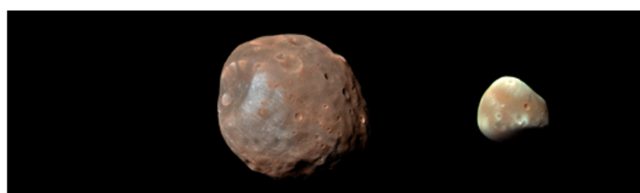
The origin of Phobos and Deimos continues to be highly debated with theories ranging from these bodies being captured asteroids to the idea that they could have coalesced from debris still in orbit after Mars formed, or perhaps that Mars was once surrounded by many Phobos and Deimos-sized bodies during its formation, with only these two remaining today [21]. Spectroscopically both Phobos and Deimos appear to be similar to C or D-type asteroids (carbonaceous chondrite). The moons are shaped like ellipsoids and are tidally locked with Mars, keeping one face toward the planet. Since Phobos is at a location of very strong tidal forces (inside Roche's limit) it will either disintegrate into a ring or crash into Mars in about 100 million years. The surface of Phobos is cratered (indicating it is greater than 3 billion years old) and scored by deep linear groves like those seen on Vesta that point along its orbital motion. Deimos has a smoother surface, perhaps indicating extensive regolith. The densities of these moons are too low to be solid rock with porosities of 20 to 30% (supporting the non-asteroid origin) and both bodies have very low surface gravity (measured in thousandths of a g). Observations are consistent with both moons being rubble piles. There is a significant range in the size of material on their surface and there has been speculation of dust rings circling both bodies, but the rings have never been observed. Both satellites are in nearly circular orbits almost exactly in Mars' equatorial plane. These orbital characteristics are important factors since those orbits will drive the overall transportation and system architecture as discussed further in Section 3. Figure 1 provides some basic characteristics of Phobos and Deimos.

3. EXPLORING THE NEIGHBORHOOD OF MARS

Round-trip missions to Mars, either to the surface or to the moons of Mars, will require a series of complex maneuvers. As shown in Figure 2, round-trip Mars missions are typically conducted in four phases comprised of: 1) uncrewed operations of launch and assembly of the transportation vehicles including pre-deployment of mission assets (denoted blue), 2) transfer of crew from Earth to Mars orbit (denoted green), 3) exploration of Mars (Phobos option denoted gray and Mars surface denoted orange), and 4) return of the crew back to Earth (again denoted green). While the entire Mars operational sequence is important, this paper will focus predominately on the options for exploring the neighborhood of Mars, namely the surface of Mars, with an understanding of how Phobos may fit into that campaign strategy.

Pre-Deployment of Mission Assets

Previous Mars architecture assessments have shown that the mission approach of pre-deploying cargo ahead of the crew is an advantageous strategy (Drake [22], Craig [15, 16]). With this "forward deploy" strategy a portion of each mission's assets would be sent to the vicinity of Mars prior to the crew. While this forward deploy strategy adds additional operational time to some of the systems, it provides some unique advantages over the strategy where all the necessary assets are transported with the crew. That is, this strategy would:



Characteristic	Phobos	Deimos
Periapsis	9,234 km	23,456 km
Apoapsis	9,518 km	23,471 km
Inclination	1.093°	0.093°
Eccentricity	0.0151	0.00033
Orbital Period	7 h 39 min	30 h 19 min
Size	27 x 22 x 19 km	15 x 12 x 11 km
Mean Density	1.876 gm/cm^3	1.471 gm/cm^3
Surface Gravity	0.0006 g's	0.0003 g's
Escape Velocity	11.39 m/s	5.6 m/s

Figure 1. Key characteristics of Phobos and Deimos.

[1] Within this text the term Phobos is often used in a singular generic sense to refer to the moons of Mars, both Phobos and Deimos, and is not meant to exclude potential mission to Deimos as well

- allow for verification and checkout of many of the Mars systems prior to departure of the crew from Earth, thus reducing crew and mission risk;

- result in lower overall mission mass by allowing cargo to be transported on lower energy trajectories;

- facilitate advanced operational strategies such as the generation of ascent propellants prior to committing the crew to the surface; and

- allow the crew to fly on faster, higher-energy trajectories, thus minimizing their exposure to the hazards associated with deep-space inter-planetary travel.

For the mission and systems concepts considered within the assessments for this paper, the pre-deploy strategy is assumed for all mission concepts. The specific systems which are pre-deployed are dependent on the capabilities required for the destination and operational concept as described in the following sections.

Transportation of Crew to Mars Orbit

As depicted in Figure 2, for any round-trip mission to Mars a series of maneuvers are required for both the arrival and departure of the crew vehicle. Qu, et al [23] provides an excellent overview of some of the considerations for optimization of the parking orbits for Mars missions. From this study, as well as others, it has been shown that an optimum strategy for human Mars missions is to capture the crew vehicle into a highly elliptical parking orbit high in the gravity well at Mars. This high parking orbit, combined with the forward deployment strategy, provides a mass efficient strategy for human exploration of Mars. This efficiency stems from mass optimization of the parking orbits for both the crew and cargo transfer vehicles which align with an optimum split of mission functions of the various systems required to implement the overall exploration strategy. In essence, previous studies have determined that the lower mass strategy is to capture the Mars transfer vehicle into a high-Mars orbit, typically a 1 to 5-sol orbit[2] as shown in Figure 3. This high-parking orbit strategy keeps the heavy transit vehicle and habitat high in the gravity well, thus reducing the total delta-v, and subsequently reducing the propellant required. This "gravity well" effect can be seen in the mass trends illustrated in Figure 4, which shows the significant mass savings of keeping the Mars transit habitat high in the gravity well as opposed to transporting it down to Phobos or low-Mars orbit and back up for departure. With this strategy, transportation of the crew from this high-Mars parking orbit to the desired exploration destination (Phobos or the surface of Mars) would then be conducted by smaller systems as described in subsequent sections.

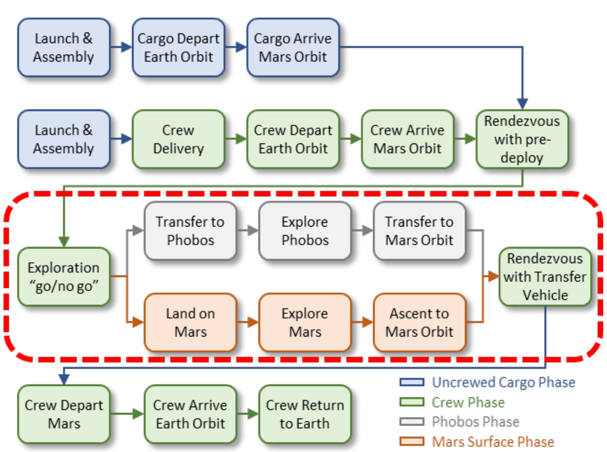
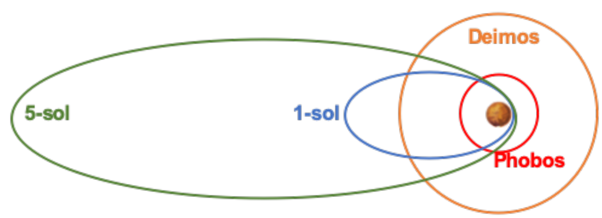


Figure 2. Typical crew Mars mission major event sequence.

Human Exploration of Phobos

As part of NASA's Evolvable Mars Campaign studies in 2016, Gernhardt, et al [18] conducted an excellent assessment of some of the key considerations and alternative strategies for the human exploration of Phobos. For the range of exploration strategies considered the assessment teams concluded, consistent with the gravity well effect described above, that capturing into a high-Mars orbit with transfer of the crew to Phobos via a separate short duration vehicle (taxi) was the optimum approach. This taxi strategy is common with other Phobos exploration assessments, including those conducted by Cichan [19] and Price [17]. With this crew to Phobos transfer strategy defined, exploration of Phobos can then be characterized by two distinct methods: "Short Duration" and "Long Duration Habitation".

Orbit	Periapsis	Apoapsis	Inclination	Period
Phobos	9,234 km	9,518 km	1.093°	8 hr
Deimos	23,456 km	23,471 km	0.093°	30 hr
5-sol	3,647 km	122,847 km	As needed	125 hr
1-sol	3,647 km	37,297 km	As needed	24.7 hr
Low Mars*	3,897 km	3,897 km	As needed	2 hr



* Low Mars orbit not depicted

Figure 3. Orbits of various Mars staging locations.

[2] A 1-sol orbit has a period equal to the average length of a martian sidereal day of 24 hours 37 minutes 22 seconds.

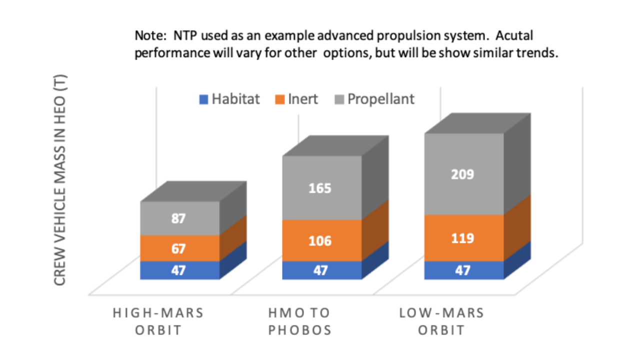


Figure 4. Example total crew vehicle mass for various Mars orbits.

Phobos Short Duration Approach – The emphasis of this strategy is to minimize time spent and complexity of operations required to explore Phobos by incorporating a small taxi transfer vehicle along with the necessary "Phobos-unique" exploration systems required to accomplish short-duration exploration as depicted in Figure 5a. With this strategy the Phobos exploration systems and taxi would be pre-deployed to the Mars vicinity prior to the crew leaving Earth.[3] Once in Mars orbit the crew would use the taxi to transfer from high-Mars orbit to Phobos, explore the moon, and then return to high-Mars orbit. This taxi must be capable of not only transporting the crew, but must also support the mission crew for the duration of exploration (typically 14-50 days) and be capable of operation in the low gravity environment there. This short stay approach is also consistent with the strategy proposed by Cichan [19], with the use of a modified Orion vehicle serving as the taxi and as the Phobos exploration vehicle. It should be noted that the low-gravity on the surface of Phobos poses some significant challenges which require new Phobos-unique systems. As described by Cichan, *"In the low gravity environment of Phobos and Deimos, care must be taken to avoid kicking or pluming the surface with thrusters as this will propel surface material into orbit or escape velocities."* Thus, Phobos-unique exploration systems and operational concepts, such as very low-gravity surface mobility, anchoring, and dust mitigation techniques, which are not needed for the eventual Mars surface mission, are required to properly explore this small body.

Phobos Long Duration Approach – With this strategy, emphasis is placed on maximizing exploration of Phobos, including duration. This approach is facilitated by the pre-deployment of a long-duration habitat to Phobos prior to crew departure from Earth, ensuring that the necessary assets are in place before committing the crew to Mars orbit, as shown in Figure 5b. Once in high-Mars orbit the crew would utilize the pre-deployed taxi to transfer from the Mars transit vehicle to the emplaced habitat, followed by subsequent long-duration exploration. This exploration would be further advanced with the incorporation of habitat mobility and anchoring systems to allow a range of potential sites to be explored during the long stay on Phobos.

Within each of these broad operational concepts additional options have been considered, focusing predominately on how incorporation of alternative exploration systems impacts the overall mission complexity and mission return. Figure 6 provides a good overview of a range of options considered, including factors such as the number of short-duration exploration vehicles, location of the habitat, and required mobility and exploration systems. The long-duration habitation strategy was the preferred Phobos exploration approach for both the Gernhardt [18] and Price [17] study teams.

Human Exploration of Mars Surface

As shown in Figure 7, human exploration of the surface of Mars follows similar cargo pre-deployment followed by a destination exploration phase. For Mars surface missions, payloads are pre-deployed by dedicated landers prior to crew departure from Earth. For a typical Mars surface mission, two landers would pre-deploy assets on the surface of Mars. These assets include the required power, ascent vehicle, in-situ resource production or ascent propellants, mobility, habitation and logistics. A third lander is pre-deployed to Mars orbit. This vehicle serves as the crew lander, which

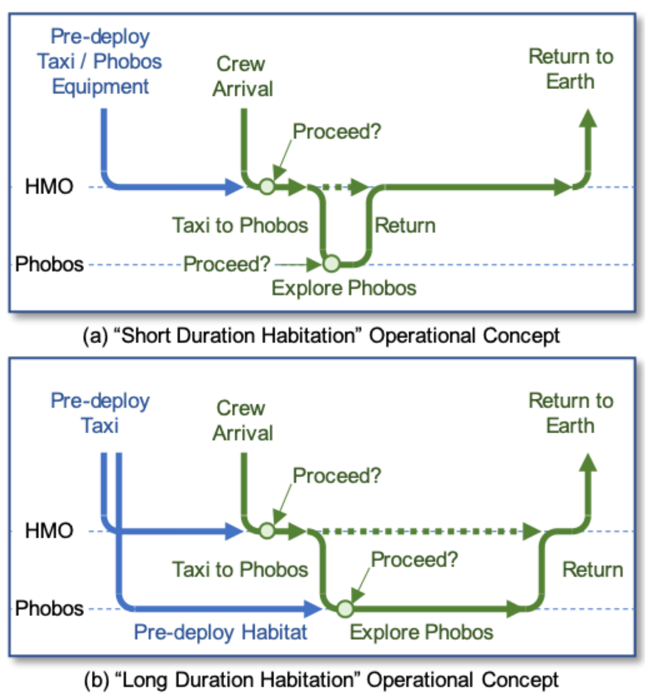


Figure 5. Example operational concepts for human exploration of Phobos.

[3] Cichan, et al suggest transporting the Orion modified vehicle (taxi) with the crew. While this eliminates a pre-deployment mission, transporting the taxi with the crew will add additional mass to the crew transfer vehicle.

	Short Duration	Short Duration	Long-Duration Habitation	Long-Duration Habitation	Short Duration	Long-Duration Habitation
Phase One Phobos Mission Architectures	**1x PEV (as Taxi)** 	**2x PEV (1 as Taxi)** 	**2x PEV (1 as Taxi) + DRO Hab.** 	**2x PEV (1 as Taxi) + Fixed Surf. Hab.** 	**Minimal Taxi/ Lander** 	**Minimal Taxi + Mobile Surf. Hab.** 
Crewmembers to Phobos Space	2	4	4	4	2	4
Duration in Phobos Space (days)	50	50	500 [1000]	500 [1000]	50	500 [1000]
Pre-Staged to HMO	PEV Taxi, RCS Sled, SM, LMs	PEV Taxi, SM	PEV Taxi, SM	PEV Taxi, SM	Minimal Taxi/Lander, SM, LMs	Minimal Taxi, SM
Mass to HMO (kg)	35,703	25,305	25,305	25,305	24,303	13,579
Pre-Staged to Phobos Space	–	PEV, RCS Sled, LMs	PEV, RCS Sled, DRO Habitat	PEV, RCS Sled, Fixed Surface Habitat	–	Mobile Surface Habitat (incl. propellant)
Mass to Phobos Space (kg)	–	11,021	33,536 [45,246]	34,040 [45,602]	–	32,000 [43,943]
Science Sites Achieved (%)	100	100	100 [200]	100 [200]	20	100 [200]
Phobos-Specific Elements	RCS Sled, optional Hopper	RCS Sled, optional Hopper	RCS Sled, optional Hopper	Habitat landing legs, RCS Sled, optional Hopper	Minimal Taxi/Lander legs	Habitat landing legs
Duration in HMO (days)	286-496	286-496	0	0	286-496	0
Duration in Phobos DRO (days)	4	4	302-512	4	4	4
Duration on Phobos Surface (days)	50	50	28	326-536	50	326-536
Reduction in Cumulative Radiation Exposure Relative to HMO	3%	3%	4-6%	20-33%	3%	20-33%
Total Pre-deployed Mass (kg)	35,703	36,326	58,841	59,345	24,303	45,579

Notes: PEV Pressurized Excursion Vehicle (a multi-purpose vehicle capable of supporting the crew for short durations)
RCS Reaction Control Sled (provides attitude and some translational control)
SM Service Module (used for major translational maneuvers such as from high-Mars orbit, to Phobos, and back)
LM Logistics Modules (pressurized module for storing necessary consumables and supplies)

Figure 6. Summary of Phobos exploration concepts (adapted from Gernhardt, et al).

not only transports the crew to the surface, but also provides the crew support functions necessary to readapt to a gravity environment after their long zero-g transfer to Mars.[4] Once in orbit, the crew transfers to their lander, descends to the surface and conducts exploration of the surface of Mars. It is desired to spend as much time as possible exploring, but the actual surface duration is typically driven by the assets which can be pre-deployed ahead of the crew; more assets provide more time to explore. At the end of the surface mission, or any time during the stay in the event of an emergency, the crew transfers to the ascent vehicle and then to the loitering Mars transfer vehicle in high-Mars orbit for subsequent return to Earth.

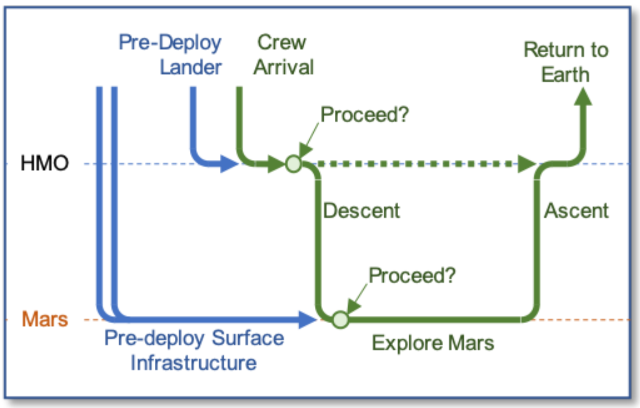


Figure 7. Human exploration of Mars operational concept.

4. EXAMINING THE RATIONALES FOR PHOBOS

Often when exploration of Phobos is inserted into the discussion as a strategy for future human exploration, it is done from a Mars moon-centric perspective. That is, Phobos exploration is considered independently and considerations for subsequent exploration objectives, namely exploration of the surface of Mars, are often neglected. This underlying tone is expressed in the recent National Academies review of human space exploration [26]: *"A crewed mission to Phobos and Deimos in Mars orbit would include many elements of a crewed mission to Mars but without the challenge of EDL [entry, descent and landing] and ascent from Mars."* While it is true that exploration missions to Phobos or the surface of Mars retain many operational and system commonalities (specifically getting into Mars orbit and back), viewing a specific mission alone (e.g. Phobos) without the broader context of the overall strategic goals and objectives (Mars surface), is misleading. Thus, it is important to understand the overall exploration context before judgements can be made as to the value of any specific stage in the exploration pathway. The review of the various rationales for human exploration of Phobos discussed below are provided with the overarching context of how Phobos missions would benefit exploration of the surface of Mars. That is, since human exploration of the surface of Mars continues to retain strong public interest, it is assumed in the following discussion that Mars surface exploration should be a key element of any future exploration strategy.

Low-Latency Teleoperations

Some mission planners have proposed that one of the primary objectives of conducting human missions to Phobos is to remotely operate assets on the surface of Mars, thus eliminating the challenging aspects of crew landing and ascent from the martian surface. This is a classic risk/return proposition – a claim that sufficient value can be gained without the risk of surface access. However, crew landing on Mars cannot be ignored since it remains a key policy and exploration objective. Exploration planners have typically viewed human exploration of Mars as being a collaboration of humans and robots working together. This human-robotic collaboration is the core strategy of exploration today, whereby human operators on Earth are controlling robotic systems both in orbit and on the surface of Mars. Since these operators control the robotic assets from the Earth, they must unfortunately also combat the high latency associated with the two-way communication delays between Earth and Mars. This round-trip time delay is dependent on the relative locations of the Earth and Mars in their respective orbits during the mission and can vary from 6-44 minutes round-trip.

As humans venture further into deep-space, the value proposition of the incorporation of low-latency teleoperations has emerged. Low-latency operations are typically defined as those where the operator is near the controlled asset, so the communication delay is within the typical response time of the human operator. This "cognitive timescale" is considered to be less than 0.5 seconds, but will vary depending on the specific task to be performed [24]. Depending on the tasks and response timescales required, the concept of "telepresence" emerges. As described by Lupisella [24], telepresence *"can be seen as a special case of LLT [low-latency teleoperations] in which a remote human operator is more fully "present" in the environment of the asset, enabling highly complex and rapid decision-making for time-critical tasks that require uniquely human judgment (e.g. quick science judgments for highly dynamic phenomena). Telepresence, with the right data, tools and low-latency, can facilitate a strong sense of presence at locations of interest, allowing rapid, complex decision-making that could be as effective as being there."*

Here on Earth there are examples where teleoperations are showing great benefits. For instance, remotely operated vehicles continue to serve as the prime enabler for complex operations in the deep-sea industry. These robotic systems can accomplish tasks in the dangerous high-pressure deep-

[4] Other mission options, where the crew lands with a fully fueled ascent vehicle, have been also proposed (Price [17]) and are still under consideration, but have been found to require additional Mars assets (intermediate crew taxi vehicle) and larger landers.

sea environment with their human operator safely on board the support ship. With the human operator at the helm, these vehicles can accomplish complex tasks and remain on station for long durations, extending through many daily shifts of their sea-top operators. Likewise, remotely piloted aircraft have proven to be vital assets over the course of America's operations in forward operating theaters [25]. Operation of these aircraft is typically accomplished with two crews: 1) the support crew who reside in the country where the aircraft is launched, landed, and maintained, and 2) a mission flight crew which receives "handover" after launch of the aircraft for the actual mission execution. These mission control crews operate the vehicle via satellite signals from the continental United States with support from the ground team or traditional ground force. It should be noted that emphasis in cases here on Earth, both in sea and air, the operator remains in a safe location while controlling the robotic asset. That is, risk is focused predominately on the potential loss of the robotic asset or unintentional collateral damage during the complex operations, not on the mission crew. The crew remains safe, while their robotic counterpart takes the risk. That is not the case for Phobos missions and will be an important distinction discussed later.

Some mission planners have suggested that low-latency teleoperations should be a prime focus of initial operations and exploration of Mars, specifically when missions to Phobos or only Mars orbit are contemplated. With the astronaut near Mars, on Phobos, Deimos, or in Mars orbit, robotic assets could be controlled on the surface of Mars. Lupisella [24] provides an excellent assessment of the types of potential tasks that the astronaut crews could perform via teleoperations, including tasks such as *"(1) landing and outpost site assessment and validation, (2) landing and outpost site surface preparation, (3) outpost setup and integration, (4) outpost operations, and (5) science operations, including sample acquisition and analysis as well as 'crew-assisted sample return.'"* However, entry, descent, and landing is still required for those, often human scale, teleoperated assets, and thus the challenge of landing large payloads on Mars cannot be avoided.

Hopkins and Pratt [13] provide an excellent discussion of the communication strategies for controlling surface assets from both Phobos and Deimos. With these strategies, the thought is that the crew would remain "safe" at Phobos or Deimos and complex surface tasks could be conducted remotely. Table 1 provides an overview of some key orbital parameters, including approximate communication coverage for various locations near Mars. Hopkins argues that due to the long dwell times, superior communication coverage, and solar illumination, Deimos offers a superior location for teleoperation of surface assets as compared to Phobos. But examination of Table 1 shows that neither Phobos or Deimos provides significant advantages over high-Mars orbit from a communications and low-latency teleoperations perspective. In fact, high-Mars orbit provides latencies consistent with human "cognitive timescale" while providing good communication coverage. High-Mars orbit also provides easier and lower cost (in propellant) round-trip transportation as well as opportunities for landing and ascent, as discussed later. Regardless of the teleoperation venue, whether on Phobos, Deimos, or in Mars orbit, the premise that low-latency teleoperation is a safe strategy, much like remote operations conducted at sea and in the air here on Earth, is fundamentally flawed. The only way to achieve low latency for Mars is to reduce the round-trip communications time by placing the operator at Mars. To do that the crew will be exposed to all the risks of launching, traveling to and living in deep-space, and returning to Earth. The suggestion that accepting all of those risks for the mere purpose of reducing the communication lag is insufficient and cannot serve as a prime rationale for a human mission to Phobos.

That is not to say that low-latency teleoperations do not play a role in human exploration of Mars. On the contrary, mission planners have long suggested that upon arrival at Mars the crew will communicate with the pre-emplaced surface assets to ensure their operability prior to landing. In addition, while on the surface, remote operations of systems from within the surface habitat and pressurized rovers is assumed to be an integral part of advanced exploration concepts. This strategy is most important for hazardous operations, such as operating near nuclear power systems, or for scientific exploration such as the exploration of "special regions" – areas where human related contamination must be minimized. Low-latency teleoperations will end up being a key element of future human exploration of Mars, but it cannot serve as a primary objective or sole operating concept if human surface exploration remains an important objective.

Table 1. Comparison of various Mars orbital parameters.

Characteristic	Phobos	Deimos	High-Mars
Periapsis (km)	9,234	23,456	3,647
Apoapsis (km)	9,518	23,471	37,210
Inclination	1.093°	0.093°	Varies
Orbital Period (hrs)	7.65	30.32	24.65
Orbital Velocity (km/s)	2.13	1.35	Varies
Two-way Com. (ms)	40	134	2-226
Time Between Passes (hrs)	6.9	71.8	Varies

Phobos as a Staging Point to the Surface

As discussed in Section 2, Phobos and Deimos provide a stable, repeatable, predictable location deep in the gravity well of Mars and this distinction has motivated some mission planners to suggest Phobos should be used as a staging point for Mars surface missions. Although this sounds like a good strategy, the orbits of these moons inject unique challenges which make them far less attractive than suggested.

Getting to Phobos – As discussed in Section 3 and depicted in Figure 4, transporting mission elements, such as the crew habitat and landers, to Phobos will require much larger transportation vehicles due to the low, circular, and equatorial nature of the orbit of Phobos. Although Figure 4 shows the impact for the crew vehicle, similar mass impacts will occur for the cargo transportation systems, especially if reusability of those systems is desired. Thus, utilizing Phobos as a staging location will place additional burden on the in-space transportation systems, namely increased propellant, to transport the mission elements deep into and out of the gravity well of Mars to access Phobos.

Departing and Returning to Phobos – Here again, the circular nature of the orbit of Phobos poses additional challenges for the Mars landers and ascent vehicles for missions staged from that location. Cianciolo [27] and Polsgrove [28] provide initial estimates of the performance characteristics of both Mars descent and ascent stages. A summary of the descent and ascent change in velocity (delta-v) and durations are provided in Figure 8. The shorter orbital period of Phobos (7hr 39m) will result in shorter descent and ascent times, which would enable smaller crew cabins for those mission phases. However, since the orbit of Phobos is circular and nearly equatorial, the descent and landing maneuvers will significantly increase, especially for landing sites which are not located on the equator of Mars. Figure 8 shows that the total descent delta-v could increase from 67%-230% for 40° latitude sites as compared to the high-Mars orbit case. This large increase in descent delta-v would dramatically increase the resulting size of the landers or the corresponding decrease in payload which could be delivered to Mars. It must be noted here that it was assumed, consistent with the analysis conducted by Qu [23], that the orbital parameters for both the low and high-Mars orbit cases could be tailored via proper trajectory design and timing such that these orbits could facilitate a co-planar descent maneuver without any needed plane change. Since Phobos is in a fixed orbit which cannot be changed, that strategy is not possible, and thus plane changes must be performed during descent from Phobos for any non-equatorial landing sites. These studies have also shown that choosing the right time for ascent as well as implementation of intermediate orbit phasing strategies will facilitate ascent from varying landing sites and thus no large plane change would be required during ascent. It is interesting to note that with these reasonable ascent timing and phasing strategies, the ascent delta-v is remarkably similar for both high-Mars orbit and Phobos.

Table *2* provides a comparison of some of the key mission characteristics for both high-Mars orbit and Phobos, showing a distinct advantage of high-Mars orbit staging for Mars surface exploration. Therefore, Phobos should not be considered a staging location for future Mars surface missions.

Phobos Missions as Risk Reduction

Many strategic assessments and studies over the years have suggested that a human mission to Phobos can serve as a vital test of the round-trip transportation systems necessary for future human Mars missions. That view considers the round-trip from Earth orbit to Mars orbit, including Phobos, and back to be a viable risk reduction strategy prior to committing the crew to the descent and ascent required for Mars surface access. For instance, Abercromby [14] concludes his assessment with the statement *"Human exploration of Phobos offers a scientifically meaningful first step towards human Mars surface missions that develops and validates transportation, habitation, and exploration systems and operations in advance of the Mars landing systems."* Likewise, the Planetary Society [29] states that a Mars orbit/Phobos mission *"[v]alidates method[s] for getting to Mars orbit and back."* It is true that a mission to Phobos would facilitate the development of many of the same systems and operational concepts required to get to Mars orbit and back for a Mars surface mission. That is, a human mission to Phobos requires similar round-trip transportation systems to get to Mars orbit and back as those required for Mars surface missions. But what must be made clear from a vehicle certification and risk perspective is that Mars missions can be very unforgiving. Shortly after leaving Earth orbit the ability to abort the mission and return to Earth is very limited and the return time is commensurate with the time of the declared abort, if not longer. Free return aborts are typically not available and powered aborts are measured in durations of many months or even years. System redundancy and reliability, along with strategies to mitigate in-flight component failures, become driving parameters in vehicle and system designs. This is especially important since logistics supply must be well-planned, and routine logistics and supply delivery strategies, such as those which are the lifeblood of the International Space Station Program, are non-existent. All the required repair and maintenance supplies must either be anticipated and taken with the crew, or pre-deployed. Prior to committing to leaving Earth orbit, the mission and engineering teams must have full confidence in the ability of all the required systems to perform the mission and support the crew for the entire round-trip mission, nearing three-years in duration. Thus, the human round-trip transportation system must be fully validated and certified prior to the first long-duration Mars mission, regardless if the target destination is Phobos, Deimos, the surface, or just Mars orbit. Studies such as those done by Price [17] and Duggan [30] provide good examples of a stepwise progression of mission sequences and tests on the path towards Mars, including ground tests, missions in cis-lunar space, uncrewed transportation, and landing tests. Due to the lack of aborts and long-duration nature, a human mission to Phobos should not be viewed as a "certification flight" prior to subsequent Mars landing missions.

All human missions to Mars contain within them discrete "go/no go" decision points which serve as risk posture gates. At each gate the mission support team and the crew will develop a consensus on whether or not the mission should proceed from its current mission phase (risk posture state) to the next. This mission risk posture decision process will be much like the launch commit criteria polling that is done to support each launch here on Earth. Only when all systems are "go" will the mission proceed further. For human Mars missions there are typically five key risk posture decision gates: 1) commit to launch, 2) commit to leave Earth orbit toward Mars (this is perhaps the most significant decision gate, since quick return to Earth after the trans-Mars injection has been completed is difficult and thus the crew must proceed to Mars at this point or soon after), 3) commit to Mars orbit insertion (a decision gate here only exists if a powered or free-return option has been pre-planned into the mission, which is rare), 4) commit to transfer to the exploration destination (for the discussion in this paper that means Phobos or the Mars surface), and 5) decision to continue with the destination exploration phase. The mission phases associated with returning the crew to Earth typically do not contain key architectural decision gates, since safe return of the mission crew along the nominal path is typically the only option. Figure 5 and Figure 7 show where decision gates associated with exploration of Phobos or the surface (gates four and five) are in the respective mission phases in the vicinity of Mars.

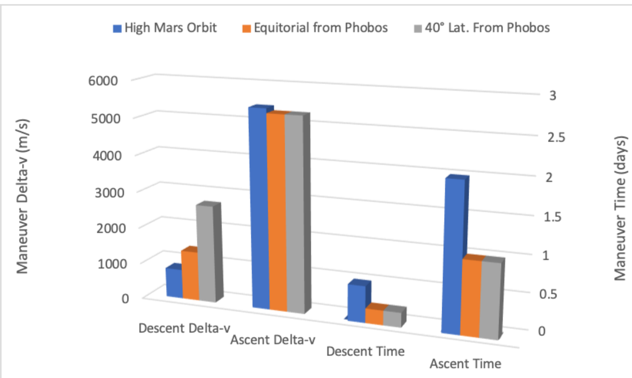


Figure 8. Landing and ascent maneuvers and times for various staging orbits.

Table 2. Key figures of merit for using Phobos as a staging location.

Consideration for Mars	High Mars Orbit	Phobos
Deep Space Transport Propellant	✓	
Complexity of Orbital Operations	✓	
Number of Transportation Systems	✓	
Range of Landing Sites	✓	
Descent and Landing Propellant Load	✓	
Ascent Propellant Load	Similar	Similar
Time of Descent		✓
Time of Ascent		✓

✓ Indicates areas with a distinct advantage.

So how would a mission to Phobos help reduce the risk for Mars surface missions or serve as a test or certification step? It doesn't. Both missions to Phobos and the surface of Mars must safely arrive in Mars orbit after successfully passing through risk decision gates 1-3. Up to the point where the decision must be made to explore Phobos or Mars, they are the same and there is no distinction between them. The decision to explore Phobos or the surface of Mars are made as separate and distinct risk decision gates and are not related. Thus, prior to the decision to proceed with the exploration of Phobos, a mission to Phobos would not in itself retire any risks that a mission to the surface of Mars would, up to the point of proceeding with the landing. Proceeding to either Phobos or the surface of Mars introduces additional destination unique risks.

Phobos Challenges as Compared to Mars Surface - Exploration of Phobos introduces unique challenges and risks which would not be present for Mars surface missions.

- Zero-gravity Exposure: Phobos missions will be conducted entirely in zero-gravity. Durations for Mars missions typically range from 600 to over 1000 days. Thus, the amount of time in free space for Phobos missions is significant and will represent a major challenge for the human health community. (For reference, Mars surface missions can result in up to 300-500 days on the surface, resulting in 25%-56% less time in free space).

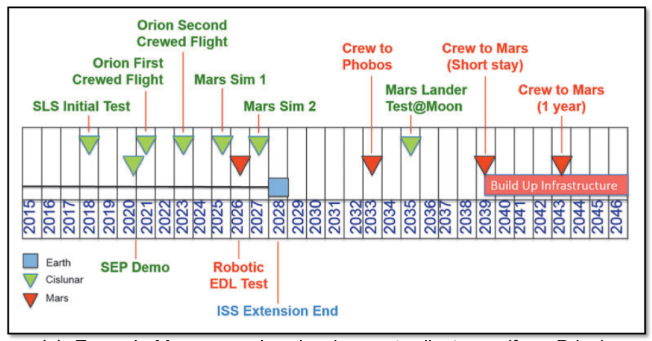
- Radiation Exposure: Measurements conducted on the surface of Mars obtained by the Radiation Assessment Detector instrument have provided a good estimate for the expected radiation dose that the crew will be exposed to. [31] Studies on the effectiveness of different spacecraft materials on reducing the radiation dosage to the crew have indicated that while statistically significant improvements in protection from galactic cosmic radiation can be obtained with high hydrocarbon materials, shielding thickness beyond 20 g/cm^2 has limited effect on shielding performance. [32] In fact, the planet itself will provide the crew the best shielding due to the mass and atmosphere of Mars. Thus, for the Phobos or Mars surface exploration missions, crew radiation exposure will be reduced by spending more time exploring the planetary body and less time in free space. Hence the desire to follow the "long duration habitation" strategy for exploring Phobos and the surface of Mars.

- Transit to the Destination: It is often claimed that Phobos missions are "less risky" than Mars surface missions because they avoid the tricky entry, descent, landing, and ascent phases. However, as long as exploration of the surface of Mars remains a key strategic objective, the Mars landing and ascent phases cannot be avoided; a mission to Phobos only delays the eventual need to land on Mars. Both missions to Phobos and Mars have unique challenges associated with getting to the exploration destination. Phobos missions will require the incorporation of a dedicated Phobos crew-taxi which must support the crew for multiple days and perform the necessary translational maneuvers (on the order of two km/s). Due to the low surface gravity of Phobos the arrival phase will be more analogous to "rendezvous" as opposed to "landing" on the surface of Mars. Phobos transfers are done via propulsive maneuvers in free space, whereas Mars surface access introduces additional challenges, including hypersonic and transonic entry phases, descent, and landing, followed by Mars ascent. Landing on Mars is much different than Phobos, thus a Phobos mission would not reduce the associated risks for Mars surface landing. Surface landing risk is better mitigated using a series of dedicated crew-size cargo landers – essentially the forward deploy cargo missions.

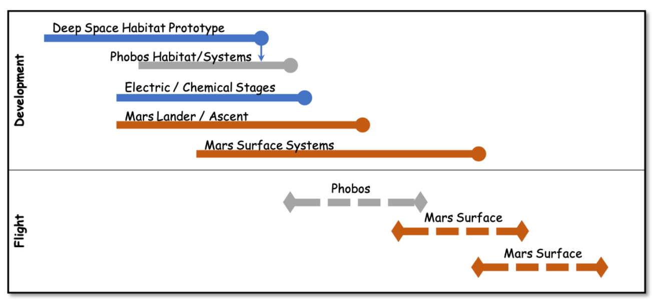
- Phobos-unique challenges: Abercromby [14], Gernhardt [18] and Hopkins [13] describe many of the operational and system concepts necessary for exploring the very low gravity of Phobos. Uncertainty in the surface composition combined with the low-gravity environment will require the incorporation of Phobos-unique exploration concepts and systems. Analyses by Abercromby [14] show that escape velocities from the surface of Phobos are on the order of only 3 m/s, depending on the location.[5] To operate on Phobos, unique systems such as jetpacks, booms, mobility legs, or anchoring systems, to name just a few, must be included in the operational concept. Likewise, in this low gravity environment, care must be taken to minimize pluming or disturbing the surface, since disturbed surface dust will take a long time to settle back down, complicating the operations. These Phobos-unique systems and operational concepts have little feed-forward to Mars surface missions, and thus will represent one-time Phobos-specific investments.

The Cost and Schedule of Phobos Exploration

Other often cited rationales for human exploration of Phobos are the purported cost-effectiveness, specifically from a budget-smoothing perspective, and the schedule relief of development of the Mars landers and associated surface exploration systems. That is, a Phobos mission would provide a significant exploration achievement while "buying time" for development of the necessary Mars surface exploration systems. As discussed previously, a human mission to Phobos will require the development and pre-deployment of Phobos-unique systems including habitation, a crew taxi, science equipment, and anchoring and mobility methods. These systems must be designed, developed, tested, launched, transported, and emplaced at the proper location prior to the crew leaving Earth orbit. These, along with the required launch and mission support efforts, represent unique one-time costs. Even if these systems and procedures can potentially be derived from other required Mars exploration systems, their development will put additional pressure on the overall exploration budget. Price, et al [17] describe an example integrated Mars architecture analysis conducted by the Jet Propulsion Laboratory in 2015. This architecture described one approach for a stepwise exploration methodology which included development and testing of the necessary operational systems, including International Space Station technology development and risk reduction, deep-space transportation system development and testing, robotic testing of Mars landers, and crew testing of prototype deep space habitation systems. The resulting schedule milestones from the JPL study is reproduced in Figure 9. Panel (a) provides the key campaign milestones, and panel (b), derived from panel (a), shows the resulting development and flight schedules needed to meet those key campaign events. As can be seen from examination of this figure, development and testing of the required Phobos exploration systems (shown in gray), along with the actual mission execution, occurs in parallel with the critical Mars surface access and surface systems development. Development of these systems at the same time will place additional budget and execution pressure, either increasing the required budget or delaying the Mars surface missions, pushing them further to the right in time.



(a) Example Mars campaign development milestones (from Price).



(b) Corresponding development and flight schedules.

Figure 9. Example Mars campaign schedule.

5. SUMMARY

Human exploration of Mars has continued to maintain strong political and public interest support and should be used as the horizon destination to help focus research and systems development. Human exploration beyond low-Earth orbit to the Moon, and eventually to the surface of Mars, should be accomplished through a series of sequential missions. In order to be affordable and sustainable, each stage should strategically reduce risk and help develop fundamental capabilities and operational concepts for subsequent phases.

[5] For reference, if you jump off Phobos with only half the speed of a typical high-jump here on Earth, you would escape into space.

While a human mission to Phobos would be significant in the representation of the ability of humans to venture out farther in space than at any point in history, as discussed in the manuscript, a mission to Phobos should not be viewed as a validation of a round-trip mission to Mars orbit and back. Mars missions are very unforgiving with limited abort options, long duration, and limited logistics supply opportunities. The risk profile for a human mission to Mars orbit and back is the same whether the intended exploration destination is Phobos or the surface of Mars. Thus, a Phobos mission provides no further Mars orbit risk reduction benefits, yet it introduces additional Phobos-unique risks (i.e., very low gravity exploration) and new exploration systems such as a crew taxi, a Phobos-tailored habitat, reduced gravity mobility, and Phobos exploration gear. The fixed circular orbit of Phobos does not serve as a good staging location for missions to the Mars surface. Insertion of a Phobos mission before a mission to the surface of Mars will burden the overall required budget and delay the ultimate goal of getting to Mars.

In his testimony in 1990 before the U.S. House of Representatives, Dr. Franklin Martin, then Associate Administrator of NASA's Office of Exploration, provided a concise summary of what was known regarding human missions to Phobos at the time: "*Now, we could go to Phobos in a rather inexpensive way in terms of mass [in] low-Earth-orbit to get there, because you don't have to go down in to the gravitational field of Mars. You don't have to pay the price of landing on Mars in terms of mass and getting off the planet. The gravitational field on Phobos is about a 1000th of what it is here in this room. So, it is a relatively easy place to get to. Phobos to go somewhere else, it's a little limited. … But to me, going to Phobos without a commitment to go on to Mars is a little like taking your kids to Orlando and not taking them to Disney World. Mars is Disney World… We need to analyze that and make sure we understand what's going on.*"[33] Since Dr. Martin made this statement, analysis included in this paper and the cited references shows that Phobos is not easy, nor risk free, and not on the path to the surface of Mars. If a mission to Phobos is considered further as a strategic destination for human exploration, it must stand on its own merits in terms of risk and return on investment, and not as a rationale for getting to Mars. It must provide unique value on its own beyond the limited applicability to Mars surface missions. In fact, a detour to Phobos will add cost and delay surface access with no clear reductions in risk to future Mars surface missions.

REFERENCES

[1] The White House, "Space Policy Directive 1, Reinvigorating America's Human Space Exploration Program," 11 December, 2017.

[2] "National Aeronautics and Space Administration Authorization Act of 2008," Public Law 110-422, 15 October, 2008.

[3] "National Aeronautics and Space Administration Transition Authorization Act of 2017," Public Law 115-10, 21 March, 2017.

[4] Singer, S. F., "The Ph-D Proposal: A Manned Mission to Phobos and Deimos", Case for Mars, P. Boston, ed., AAS 81-231, pp. 39-65, 1981.

[5] O'Leary, B., "Phobos & Deimos as Resource & Exploration Centers," Case for Mars II, C. McKay, ed., AAS 84-164, pp. 225-245, 1985.

[6] Adelman, S. J., B. Adelman, "The Case for Phobos," Case for Mars II, C. McKay, ed, 1985, AAS 84-165, pp. 245-252, 1985.

[7] "The Case for Mars: Concept Development for a Mars Research Station," JPL Publication 86-28, 15 April, 1986.

[8] "Beyond Earth's Boundaries, Human Exploration of the Solar System in the 21st Century," NASA, 1988.

[9] NASA Office of Exploration FY1988 Annual Report, Technical Memorandum 4075, 1989.

[10] NASA Office of Exploration FY1989 Annual Report, Technical Memorandum 4170, 1989.

[11] O'Leary, B., International Manned Missions to Mars and the Resources of Phobos and Deimos, Acta Astronautica, Vol. 26, No. 1, pp. 37-54, 1992, 0094-5765/92.

[12] Hopkins, Joshua B., and Pratt William D., "Comparison of Deimos and Phobos as Destinations for Human Exploration and Identification of Preferred Landing Sites," AIAA 2011-7140, AIAA Space 2011 Conference & Exposition, 27-29 September 2011.

[13] Hopkins, Josh, "Deimos and Phobos as Destinations for Human Exploration," Caltech Space Challenge, March 2013.

[14] Abercromby, Andrew, F., J., et al., "Human Exploration of Phobos," IEEE Aerospace Conference, 2015.

[15] Craig, Douglas A., et al., "Pioneering Space Through an Evolvable Mars Campaign," American Institute of Aeronautics and Astronautics, AIAA 2015-4409, 2015.

[16] Craig, Douglas Al, et al., "The Evolvable Mars Campaign – Study Status," IEEE Aerospace Conference, 2015.

[17] Price, Hoppy, et al., "A Minimal Architecture for Human Journeys to Mars," New Space, Many Ann Liebert, Inc. Vol. 3, No. 2, 2015.

[18] Gernhardt, Michael L., et al., "Human Exploration Missions to Phobos Prior to Crewed Mars Surface Missions," IEEE Aerospace Conference, 2015.

[19] Cichan, Timothy, et al., "Mars Base Camp: An Architecture for Sending Humans to Mars by 2028," IEEE Aerospace Conference, 2017.

[20] "Humans Orbiting Mars, A Critical Step Toward the Red Planet," The Planetary Society, 2018.

[21] Craddock, Robert A., "The Origin of Phobos and Deimos", 25th Lunar and Planetary Science Conference, February 1994.

[22] Drake, Bret G., "Human Exploration of Mars, Design Reference Architecture 5.0," NASA-SP-2009-566, 2009.

[23] Qu, Min, et al., "Optimizing Parking Orbits for Roundtrip Mars Mission, AAS, 2017.

[24] Lupisella, Mark L., et al., "Low-Latency Teleoperations and Telepresence for the Evolvable Mars Campaign," IEEE Aerospace Conference, 2017.

[25] Kowalski, Jordan, Captain, USAF, "The Future of Remotely Piloted Aircraft in Special Operations, Methods to Improve AFSOC MQ-9 Effectiveness for Supporting Special Operations," Air Force and Staff College, Wright Flyer Paper No. 60, Air University Press, Maxwell Air Force Base, Alabama, 2017.

[26] "Pathways to Exploration, Rationales and Approaches for a U.S. Program of Human Space Exploration," Committee on Human Spaceflight, Aeronautics and Space Engineering Board, Space Studies Board, National Research Council, 2015.

[27] Cianciolo, Alicia D. and Brown, Kendall, "Impact of Utilizing Phobos and Deimos as Waypoints for Mars Human Surface Missions," AIAA Aerospace Conference, AIAA 2015-4411, 2015.

[28] Polsgrove, Tara P., et al., "Human Mars Ascent Vehicle Configuration and Performance Sensitivities," IEEE Aerospace Conference, 2017.

[29] Hubbard, Scott, et al., "Humans Orbiting Mars: A Critical Step Toward the Red Planet," The Planetary Society Workshop Report, 2017.

[30] Duggan, Matthew, Engle, James, and Moseman, Travis, "An Extensible and Affordable Exploration Architecture," IEEE Aerospace Conference, 2017.

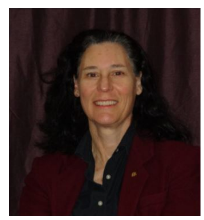
[31] Hassler, Donald M., et al., "Mars' Surface Radiation Environment Measured with the Mars Science Laboratory's Curiosity Rover," Science, Vol 343, 2014.

[32] Cucinotta, Fancis A., et al., "How Save is Safe Enough? Radiation Risk for a Human Mission to Mars," PLOS One, Volume 8, Issue 10, October 2013.

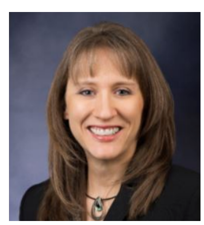
[33] Martin, Franklin D., sworn testimony, 1990 NASA Authorization: Hearing Before the Subcommittee on Space Science and Applications of the Committee on Science, Space, and Technology, House of Representatives, volume 2, 1990.

BIOGRAPHY

Bret G. Drake *currently serves as the Associate Director of the Space Architecture Department for the Aerospace Corporation where he leads system engineering and programmatic assessments of advanced space systems. Previously at NASA, Bret led design and analysis studies of human exploration in missions to the Moon, Near-Earth Objects, and Mars.*



Michelle Rucker *received a B.S. (1984) and M.A. (1986) in Mechanical Engineering from Rice University and has been with NASA for 29 years. She currently serves as the lead of the NASA Mars Integration Group at the Johnson Space Center. She began her NASA career as a test engineer at the White Sands Test Facility before moving on to roles as a deputy subsystem manager for the International Space Station, EVA and Spacesuit Systems Deputy Branch Chief, and Altair Lunar Lander Test and Verification Lead.*



Alicia Dwyer Cianciolo *is an aerospace engineer at the NASA Langley Research Center. She specializes in developing simulations to analyze vehicle flight through different atmospheres in the solar system. Primarily focusing on Mars over the past 15 years, she has worked on several missions to the planet including the Odyssey and Reconnaissance Orbiter aerobraking operations, the Exploration Rovers, and as a member of the Entry, Descent and Landing Team that successfully landed the Curiosity Rover on Mars in August of 2012. She is currently supporting NASA's the next lander mission to Mars, InSight, and is working to analyze entry technologies that will enable human exploration of the planet. She holds a Bachelor of Science degree in Physics from Creighton University and a Master of Science degree in Mechanical Engineering from The George Washington University.*