

Human Exploration of Phobos

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Abstract—This study developed, analyzed, and compared mission architectures for human exploration of Mars’ moons within the context of an Evolvable Mars Campaign. **METHODS:** All trades assumed conjunction class missions to Phobos (approximately 500 days in Mars system) as it was considered the driving case for the transportation architecture. All architectures assumed that the Mars transit habitat would remain in a high-Mars orbit (HMO) with crewmembers transferring between HMO and Phobos in a small crew taxi vehicle. A reference science/exploration program was developed including performance of a standard set of tasks at 55 locations on the Phobos surface. Detailed EVA timelines were developed using realistic flight rules to accomplish the reference science tasks using exploration systems ranging from jetpacks to multi-person pressurized excursion vehicles combined with Phobos surface and orbital (L1, L4/L5, 20 km distant-retrograde-orbit [DRO]) habitat options. Detailed models of propellant mass, crew time, science productivity, radiation exposure, systems and consumables masses, and other figures of merit were integrated to enable quantitative comparison of different architectural options. Options for pre-staging assets using solar electric propulsion versus delivering all systems with the crew were also evaluated. Seven discrete mission architectures were evaluated. **RESULTS:** The driving consideration for habitat location (Phobos surface versus orbital) was radiation exposure, with an estimated reduction in cumulative mission radiation exposure of up to 34% (versus a Mars orbital mission) when the habitat is located on the Phobos surface, compared with only 3% to 6% reduction for a habitat in a 20-km DRO. The exploration utility of lightweight unpressurized excursion vehicles was limited by the need to remain within 20 minutes of solar particle event radiation protection combined with complex guidance, navigation, and control systems required by the nonintuitive and highly-variable gravitational environment. Two-person pressurized excursion vehicles as well as mobile surface habitats offer significant exploration capability and operational benefits compared with unpressurized extravehicular activity (EVA) mobility systems at the cost of increased system and propellant mass. Mechanical surface translation modes (ie, hopping) were modeled and offered potentially significant propellant savings and the possibility of extended exploration operations between crewed missions. Options for extending the use of the crew taxi vehicle were examined, including use as an exploration asset for Phobos surface exploration (when combined with an alternate mobility

system) and as an EVA platform, both on Phobos and for contingency EVA on the Mars transit habitat. **CONCLUSIONS:** 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.

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1. INTRODUCTION

Human exploration missions to the moons of Mars have been proposed as an intermediate step for eventual Mars surface missions [2, 3]. As explained by Korsmeyer et al. [4], human missions to Mars’ moons would result in the development and operation of new technologies, systems, and ops concepts, many of which will be required for eventual Mars surface missions, without the added complexity and risk associated with Mars descent, ascent, and long-duration surface systems and operations. The opportunity to perform low-latency teleoperation (LLT) of robotic Mars surface systems could provide significant benefits not only for scientific exploration purposes, but also in the scouting and preparation of landing sites in

advance of human surface missions [4, 5]. The manufacture, transportation, and transfer of propellant, oxygen (O₂), and/or other products produced via in-situ resource utilization (ISRU) on the Mars surface could significantly decrease the mass that must be landed to support human surface missions; however, these tasks are complex, mission critical, and in some cases must be performed before any human landings have occurred. The capability to perform low-latency teleoperations in support of ISRU could mitigate some of the associated risks and decrease the level of autonomy required of the ISRU systems [5]. Although Phobos and Deimos differ significantly from each other with respect to the latitudes, duration, and frequency with which line-of-sight to Mars is achievable, both moons offer frequent and operationally useful periods of time and latitudes within which low-latency teleoperations of Mars surface assets could be performed [6]. Selection of specific landing sites on each moon and/or use of communication relays would further increase teleoperations capabilities. Low-latency teleoperations may also include collection and launch of Mars samples into Mars orbit for retrieval and return as part of a human mission to Mars' moons.

The aforementioned benefits of a human mission to Mars' moons can also be said of human Mars orbital missions or even, to a lesser extent, a Mars fly-by mission [4]. Indeed, for the purposes of this study, it is assumed that crewmembers are first transported in a Mars transit vehicle (MTV) on a conjunction class trajectory and inserted into a one-sol high-Mars orbit (HMO) where the MTV would remain until the Earth-return transit is initiated. The primary benefits of then sending crewmembers from HMO to Phobos or Deimos in a smaller crew-taxi spacecraft are that 1) meaningful scientific exploration of Mars' moons can /be performed by humans [4, 7] and 2) the radiation dose to which crewmembers are exposed may be significantly reduced compared with HMO because of the shielding effect of the moons [6].

This paper describes a study to systematically develop, analyze, and compare several different human Phobos mission architectures within the context of the Evolvable Mars Campaign (EMC) [8] being developed by NASA's Human Spaceflight Architecture Team (HAT). Specifically, architectures were evaluated that incorporated different crew sizes, mission durations, crew taxi concepts, habitat concepts and locations, and EVA mobility systems. Figures of merit focused on radiation dose, scientific exploration productivity, and mass estimates of systems, propellant, and logistics. Mission architectures were also qualitatively evaluated in terms of the potential for systems to be multi-use and evolvable, consistent with one of the key strategic principles of the EMC [8].

This paper is comprised of eight parts. Section 2 describes the primary trades, assumptions used, and seven specific mission architectures that were quantitatively evaluated. Section 3 provides additional details of exploration system concepts that were considered, compared, and down-

selected for use within the seven overall mission architectures. The representative regions of scientific interest, subsites, and standard set of scientific exploration tasks used in this study are described in Section 4. Section 5 describes analysis of Phobos surface translation techniques and Delta-V requirements that were incorporated into an integrated model along with crew time and consumables estimates from detailed EVA timelines, which are described in Section 6. Results of the quantitative comparison of mission architectures are presented and discussed in Section 7 along with a qualitative assessment of the potential for commonality and evolvability of the Phobos mission architecture elements within the EMC. Conclusions are in Section 8.

2. PHOBOS MISSION ARCHITECTURE CASES AND ASSUMPTIONS

This paper describes the results of a single phase of study of Mars mission architectural options within the EMC framework. All trades assumed conjunction class missions to Phobos (330 to 550 days in Mars system) as it was considered the driving case for the transportation architecture. The HAT is undertaking more detailed analysis of Phobos and Deimos mission architectures at the time of writing. Ongoing work also includes analysis of human assisted sample return options and development and testing of LLT systems and ops concepts.

Mission Architecture Cases

Seven mission architecture cases are summarized in this section and shown in Table 1. Detailed explanations of the exploration systems and down-select process that resulted in the seven mission architectures are provided in Section 3.

Table 1 – Mission Architecture Cases A-G. PEV is the pressurized excursion vehicle, described below and in Section 3.

	Case A	Case B	Case C	Case D	Case E	Case F	Case G
Crew Size	2		4				
Duration (days)	5-50			50-500 (x2)			
Crew Taxi	Lander-Taxi	PEV-Taxi with Detachable Service Module			Minimalist Taxi		
Pre-Staged Habitat	None		Orbital	Fixed Surface	Mobile Surface		
Prestaged PEV	No		Yes			No	
EVA Mobility	Booms	PEV				Booms	

Crew Size—It was assumed in all mission architectures that a four-person crew transits from Earth to a one-sol HMO [9, 10]. However, it is assumed in Cases A and B that only two of the four crewmembers transit in a crew taxi from HMO to Phobos, with two crewmembers remaining in HMO. In all other cases the full four-person crew transits to Phobos.

Phobos Mission Duration—All seven mission architecture cases were evaluated over a range of possible durations for which crew could stay on or near (ie, orbiting) Phobos. In

all cases, the remainder of time spent in the Mars system was assumed to be spent by crews in the MTV in HMO.

Conjunction class mission opportunities to Phobos between 2022 and 2045 were evaluated. The transportation architecture and trades are described in detail elsewhere [9, 10].

Crew Taxi—The vehicle used to transport crewmembers between HMO and Phobos is referred to as the crew taxi. For the study described here, three different crew-taxi cabin configurations were evaluated: a minimalist design, a lander-taxi design, and a pressurized excursion vehicle (PEV) design, with differences among the trade options affecting the extent to which the crew taxi could be used for mission functions in addition to taxiing of crew between HMO and Phobos. Details of the crew-taxi options are included in Section 3.

Habitats—It was assumed that a predeployed habitat would be required to support Phobos missions in excess of 50 days duration. All such habitats were assumed to be predeployed by a solar electric propulsion (SEP) tug spacecraft [9, 10], which would also be used to provide solar power for the habitat. Options for orbital (Case D) as well as fixed (Cases E and F) and mobile (Case G) versions of a Phobos surface habitat were considered. Cases A-C, with durations of 5 to 50 days, used the crew-taxi vehicle or a prestaged PEV for habitation purposes.

Pressurized Excursion Vehicles—As described in Section 3, a variety of exploration system concepts were considered and assessed for their applicability to human Phobos missions. The PEV concept is a small pressurized vehicle that could function as an EVA worksystem and short-term habitation, while also being potentially adapted for use as a crew taxi. Variations on the PEV concept could also be applicable to other missions within the EMC framework. Cases B-E used a PEV to support Phobos exploration operations.

EVA Mobility—The range of options considered for EVA mobility are described in Section 3. The assessment and down-select process, which was informed in large part by test data from previous work evaluating EVA worksystems for near-Earth asteroids, resulted in the assumption that a PEV would provide EVA mobility and worksite stabilization in Cases B-E and EVA booms would be utilized in Cases A, F, and G [11, 12].

3. EXPLORATION SYSTEMS CONCEPTUAL DEVELOPMENT AND DOWN-SELECT

A variety of exploration system concepts were developed for habitation, transportation, and performance of scientific exploration tasks. Concepts took into account the very low but non-negligible gravity on Phobos, equivalent to approximately 0.06% of Earth's gravity, as well as uncertainty regarding surface composition and soil

mechanics. An analysis performed using the Copernicus trajectory design and optimization system [13] indicated significant variation in gravitational effects across Phobos, with escape velocities of approximately 3 m/s at the sub-Mars and anti-Mars points (Figure 1).

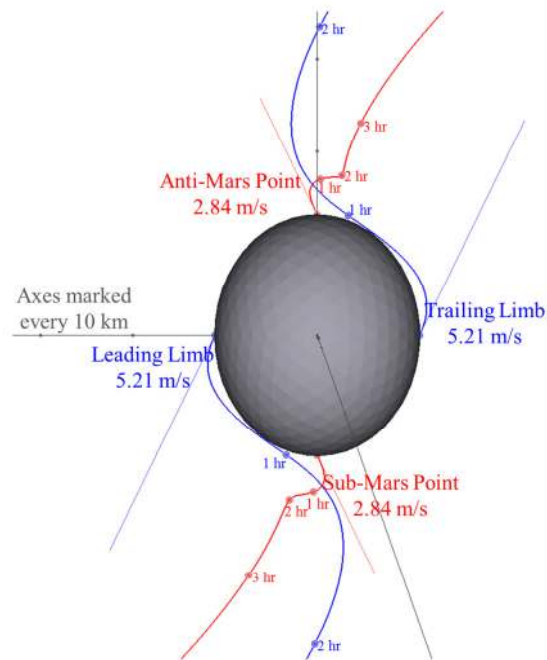


Figure 1 – Low energy escapes from Phobos surface.

In addition to conceptual system design efforts within NASA, a student design class at Rhode Island School of Design participated in the ideation and conceptual development of multiple concepts over the course of several months.

This section describes the subset of exploration system concepts that were down-selected and details the combinations of these systems and associated assumptions that were defined as the seven specific mission architectures that were quantitatively and qualitatively evaluated and compared.

EVA Booms and Translation Aids

Following from previous work by our team on EVA techniques for exploration of near-Earth asteroids, the approach of using deployable booms and/or tensioned “translation lines” was considered for cases in which a surface habitat or lander was assumed to provide a stable base on the Phobos surface. One or more rigid, possibly telescoping or folding booms would be extended away from the base, allowing EVA astronauts to tether to the boom and translate along it to sites of interest. Lines tensioned between booms or possibly anchored into the Phobos surface could provide additional translation and stabilization options.



Figure 2 – An EVA boom concept being evaluated in simulated weightlessness [1].

Although test data suggest that this approach can provide acceptable translation and worksite stabilization to perform most scientific exploration tasks [1, 11, 12], the clear limitation of such an approach is the limited range that is achievable away from the central base, probably on the order of tens of meters. However, when combined with a mobile base this approach was considered a potentially viable low-mass option and was assumed to be used, with a 15-m range from the central base, in mission architecture Cases A, F, and G.

EVA Jetpack

It is assumed that EVA crewmembers on Phobos would, at a minimum, have a jetpack similar to the simplified aid for EVA rescue (SAFER) that is intended for contingency use to enable return to a vehicle or habitat following unintended separation. An EVA jetpack intended for nominal use on Phobos would likely have similarities with the manned maneuvering unit (MMU) [14] but would incorporate increased Delta-V capability and be designed for operations in close proximity to the Phobos surface. To address concerns regarding contamination of scientific samples with jetpack thrusters, models were developed for a jetpack using nitrogen (N_2) and Tridyne propulsion options (Figure 3) to provide 30 m/s (100 ft/s) of Delta-V. Concepts were designed to be compatible with current rear-entry exploration EVA suit concepts. Estimated masses of the EVA crewmember and jetpack concept were 180 kg (suit plus crewmember) and 115 kg (jetpack), respectively.

Worksite stabilization during performance of scientific exploration tasks was a primary concern with the EVA jetpack concept. Data from near-weightless testing in multiple simulation environments have indicated that only simple tasks such as float sampling can be performed acceptably using an EVA jetpack system [1, 11, 12]. Frequent contact between suit and surface is also likely, causing safety and suit maintenance concerns, and possibly affecting integrity of sites of scientific interest. To develop notional EVA timelines for the exploration system concepts

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(Section 6), it was assumed that EVA crewmembers using jetpacks would be able to anchor to the surface to provide the required stabilization for core sampling, rock chip sampling, and instrument deployment tasks. As a baseline, anchoring was assumed to require 2 minutes of EVA time per anchor whenever required for a particular task. The feasibility of anchoring technologies was not evaluated during this study.

The limited ability to translate with payloads, tools, and samples also affects jetpack utility, although a teleoperated or autonomously operated cargo carrier – possibly based on the same jetpack system – could be used to assist EVA crewmembers using jetpacks. For timeline purposes, it was assumed that crew using EVA jetpacks could translate with samples and equipment weighing up to 6.8 kg (~ 15 lb) and with a volume of up to 0.056 m³ (~ 2 ft³).

The achievable range using an EVA jetpack is also limited. The assumption that crewmembers must always maintain access to solar particle event (SPE) protection within 20 minutes limits the maximum range to approximately 1 km from a radiation shelter such as a habitat, assuming 0.1 m/s² acceleration capability and 1 m/s allowable translation rate during contingency return. A maximum translation rate of 0.3 m/s (~1 ft/s) was assumed for nominal operations to protect against the possibility of hitting the surface at rates exceeding the impact capabilities of the suit or the possibility of achieving escape velocity.

The highly variable and counter-intuitive gravitational environment demonstrated by our analysis of surface-to-

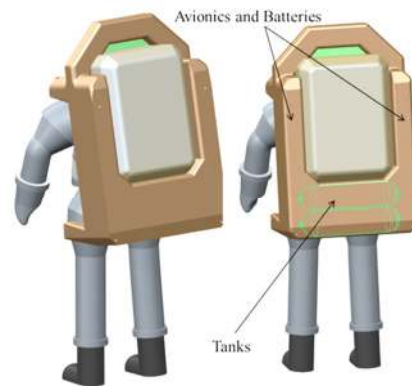


Figure 3 – EVA jetpack concept.

surface translations and low-energy escape trajectories suggests that complex guidance, navigation, and control (GN&C) systems will be required. Although no detailed assessment of GN&C systems and packaging was performed, it is likely that such systems would be challenging to accommodate within a jetpack design. The required capability to perform contingency rescue of EVA crewmembers would likely incur additional complexity. Furthermore, the development of jetpack technology is not directly evolvable to Mars surface missions.

Coupling EVA jetpacks with a mobile habitat or PEV (described later in this section) would mitigate some but not all of the EVA jetpack concept's limitations.

Unpressurized Exploration Vehicle

Some of the aforementioned limitations of EVA jetpacks could be mitigated by an unpressurized exploration vehicle (UEV) that would provide similar propulsion capability but provide additional options for incorporating GN&C as well as other instrumentation, payloads, and collected samples. However, further knowledge of Phobos surface properties and the efficacy of anchoring technologies is required to evaluate the extent to which a UEV could be sufficiently stabilized to enable acceptable performance of exploration tasks. The estimated wet mass of the UEV concept in Figure 4 is 260 kg, (including 30 m/s Delta-V, nitrogen propulsion), which is unlikely to provide adequate inertial mass to provide meaningful reaction forces for an EVA astronaut performing tasks such as drilling or large payload deployment.



Figure 4 – Unpressurized exploration vehicle concept.

It was assumed that crewmembers on a UEV could translate with samples and equipment up to 13.6 kg (~ 30 lb) and 0.11 m³ (~ 4 ft³) and could detach from the UEV during EVA to perform tasks as needed. Crewmembers were assumed to wear an EVA jetpack for contingency return should the UEV fail. A 2-minute anchoring task was assumed to precede the same sampling tasks as described for the EVA jetpack.

For both the jetpack and UEV concepts, constant thruster firing (rather than anchoring) to enable performance of tasks was not considered a practical solution; analysis showed that the 30 m/s capacity of the UEV concept would be exhausted after completion of only 3 sample collection tasks, assuming that each task required constant thrusting with 22 N (5 lbf) for 2 minutes.

Pressurized Exploration Vehicle

The PEV concept is an evolution of the lunar electric rover concept developed for lunar surface habitation and exploration during the Constellation program [11, 12, 15-

18], and which was more recently adapted and evaluated for exploration of near-Earth asteroids [1, 19, 20]. The PEV concept consists of a core cabin that can be kitted with work packages and mobility systems depending on mission needs. The PEV core cabin is nominally sized to accommodate 2 crewmembers for up to 14 days or up to 50 days if augmented with a pair of inflatable logistics modules. Rapid EVA egress and ingress is enabled via 2 suit ports and an exploration atmosphere of 56.5 kPa (8.2 psi), 34% O₂, 66% N₂ [18]. The ability to rapidly egress and ingress the vehicle is assumed to enable single-person EVAs in the vicinity of the PEV, with contingency rescue capability being provided by the PEV pilot [1, 19]. Thermal control is maintained using a radiator combined with a water-filled fusible heat sink, which also functions as protection against SPE radiation.

For operations on and near Phobos the PEV would use a reaction control system (RCS) sled mounted to the cabin. In this study, the RCS sled provided 200 m/s of Delta-V using hydrazine (N₂H₄) propulsion (Isp = 225 s) with refueling capability. The RCS sled could potentially be augmented with a mechanical propulsion system, referred to as a “hopper”, which would use electromechanical actuators to propel the PEV vertically and possibly horizontally to reduce the consumption of propellant required for Phobos surface exploration. This is discussed further in Section 5. A crew taxi based on the PEV cabin with a detachable SM is described later in this section.

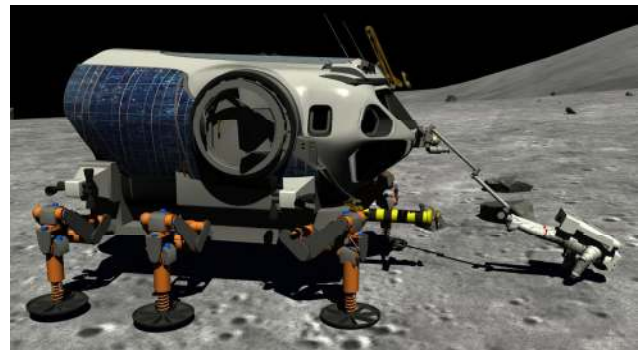


Figure 5 –Simulation screen capture showing PEV with hopper system and astronaut on an APS.

A robotic arm with a foot restraint, referred to collectively as an astronaut positioning system (APS), would be mounted to the front of the vehicle to provide a work platform for an EVA astronaut (Figure 5). Data from multiple test environments has shown an APS to be the only totally acceptable way to perform all tested exploration tasks due to the stabilization that it provides coupled with ability to translate with multiple payloads and scientific samples [1, 11, 12]. The infrequent need to recharge or resupply coupled with the SPE protection and pressurized safe-haven that the PEV provides means that exploration range of any single PEV excursion is limited primarily by the availability of an alternate safe haven in the event that

the PEV becomes immobilized or suffers another significant failure. This contingency rescue capability could be provided by a second PEV-class vehicle (as in the lunar conops [16]) or it could be provided by a crew taxi, mobile habitat, or possibly combined with EVA jetpacks.

Consistent with PEV operational assumptions for near-Earth asteroids [1, 19], assumed maximum translation rates were 0.1 m/s (~0.3 ft/s) when < 5 m from the surface and 0.6 m/s (~2 ft/s) when > 5 m from the surface; assumed nominal rate was 0.3 m/s (~1 ft/s). Assumed sample and equipment payload capacity was 454 kg (~1,000 lb) and 1.0 m³ (~35 ft³).

The PEV was assumed to land on the Phobos surface before performing each exploration task. The mass of the PEV, estimated at 7,689 kg (dry, including hopper) for the Phobos configuration, was assumed to be adequate to provide reaction forces to allow exploration tasks to be performed without anchoring or constant thrusting. At the time of writing, analysis is being performed to quantify the force profiles and corresponding RCS and / or control moment gyroscope reactions that would be required to enable acceptable performance of EVA exploration tasks.

The mass and cost of developing and delivering a PEV to Phobos were the primary limitations identified with the approach. Another potential limitation of the PEV concept as evaluated is that propellant mass calculations assume Hydrazine as the propellant. Although the extension of the EVA astronaut in front of the PEV would reduce potential pluming in the immediate vicinity of EVA task locations, it is possible that contamination could result. The ability to mechanically translate and brake using a hopper would reduce or eliminate possible contamination.

Phobos Habitats

An orbital habitat (Figure 6) would not require landing structure or the protection against the dusty Phobos surface environment that would be essential for a Phobos surface habitat and may also be required for crew-taxi vehicles docking to a surface habitat. Other potential benefits include improved line-of-sight with Earth, Mars, Phobos, and the Sun for improved communications, teleoperations, surveying, and/or solar power generation purposes. Surface habitats (Figure 7) are likely to provide improved radiation protection and may require less crew time and propellant to explore the Phobos surface compared with exploration based out of an orbital habitat.

Habitat and logistics masses, volumes, and configurations for a range of mission durations and locations (orbital versus fixed surface versus mobile surface) were developed as a part of a broader study of EMC habitation sizing, modularity, and commonality [21, 22] and these habitat concepts were incorporated into different Phobos mission architectures as described later in this section. However, an analysis was first conducted to compare and down-select

from the large number of potential locations for an orbital habitat. In addition to reviewing the work of Wallace et al. [23], an analysis was performed using the Copernicus trajectory design and optimization system [13] to evaluate a range of specific options for orbital habitat locations including Phobos-Mars L1, L4, L5, and distant retrograde orbits (DROs) at a range of distances and inclinations relative to Phobos. An extensive analysis of orbital considerations for Phobos missions was performed; a summary of the considerations and conclusions is included here and in Table 2.

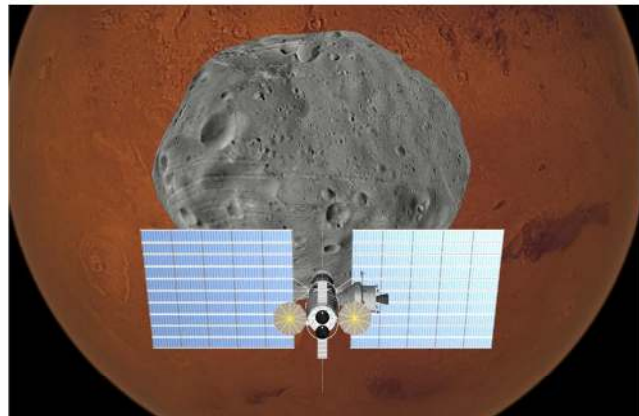


Figure 6 – Simulation screen capture showing Phobos orbital habitat.

Daily radiation doses associated with different habitat locations were also calculated using OLTARIS (on-line tool for the assessment of radiation in space), a web-based radiation transport tool with human models [24], from which values were calculated of effective dose equivalent, which is a measure relevant to understanding biological effects such as cancer incidence risk. Phobos exposure was modeled as lunar surface 1 AU galactic cosmic rays (GCR) during 1977 solar min (DSNE) and 1991 solar max (lunar surface simulates neutron backscattering from the regolith). Spacecraft hull and subsystems were approximate by 20 g/cm² aluminum. Mars and Phobos were assumed to block GCR from those angles completely, which when viewed from the sub-Mars point on Phobos corresponds to 50% of



Figure 7 – Phobos surface habitat concept with top-mounted crew taxi and service module (Cases F and G).

Table 2 – Transfer time, transfer Delta-V, and radiation dose comparison of habitat locations.

Location	Roundtrip Transfers		Station-keep Delta-V per Day	Effective Dose Equivalent (mSv/day)			
	Delta-V (m/s)	Time (hrs)		1977 Solar Min	1991 Solar Max	Percent of Free Space	
Free Space				0.826	0.399	100.0%	100.0%
L1 (1- 10 m Position Error)	7.9	3.7	0.22 - 1.30	0.623	0.300	75.3%	75.3%
L4/L5	64.0	141	Very Low	0.798	0.385	96.6%	96.6%
20 km DRO	24.6	4.1		0.763	0.368	92.4%	92.4%
150 km DRO, 0 incl.	63.8	10.0		0.797	0.384	96.4%	96.4%
150 km DRO, 10 deg incl.	76.9	10.9		0.798	0.385	96.5%	96.5%
200 km DRO, 0 incl.	82.1	10.1					
200 km DRO, 10 deg incl.	99.4	11.0					
Phobos Surface			0.401	0.196	48.5%	49.1%	
Phobos Surface w/ 10 deg Crater Rim			0.326	0.159	39.4%	39.9%	
Mars Surface			0.332	0.173	40.2%	43.3%	
Lunar Surface			0.430	0.210	52.0%	52.7%	

the sky being blocked by Phobos itself and 3.4% of the sky (or 6.8% of remaining sky) being blocked by Mars.

For the purposes of comparison with estimated Mars surface exposure, the Mars surface case was modeled as Mars surface GCR during 1977 solar min (DSNE) and 1991 solar max and calculations accounted for atmosphere and Mars surface neutron backscattering. The same assumptions for spacecraft hull and subsystems effects were used as for Phobos.

Mars-Phobos L1 Habitat—Mars-Phobos L1 is approximately 3.5 km off surface of Phobos and provides rapid access to the Phobos surface with little propellant. Furthermore, being positioned between Mars and Phobos and the relative proximity to the Phobos surface results in almost a 25% reduction in estimated radiation exposure for each day spent at L1 compared with a day in free-space. As reported by Wallace et al. [23], the cost of station-keeping at L1 depends on the navigational accuracy of the spacecraft (see Table 2), but for a spacecraft that could be required to remain at L1 for thousands of days to support multiple human missions, the propellant cost of station-keeping could be significant. However, we considered the even more significant result of our analysis of L1 to be that the failure to perform a station-keeping maneuver – which are required every 1 to 4 hours – can result in impact with the Phobos surface within 4 hours. The frequent station-keeping burns required at L1 would also necessitate frequent attitude adjustments or additional thrusters if the SEP is to be used for station-keeping.

Mars-Phobos L4/L5 Habitat—Mars-Phobos L4 and L5 are 9,377 km distant from the center of Phobos and from the center of Mars. Their locations provide constant line-of-sight with the sub-Mars point and could be used to extend communication windows with Earth and with Mars surface assets. Our analysis indicated that these locations would provide stable, safe parking orbits for habitats and would require minimal station-keeping. However, transit to Phobos would require on the order of 1 to 3 days each way, depending on Delta-V budget and, although Mars reduces radiation exposure by an estimated 3.4% compared with free

space, the distance of L4 and L5 from Phobos precludes any meaningful radiation shielding from Phobos itself.

Phobos Distant Retrograde Orbit Habitat—A large range of quasi-stable DROs, including inclined DROs, were considered (Figure 8). DROs with nadir radius of roughly 200 km and larger can maintain a near constant sun angle on Phobos for long periods and, when inclined, large radius DROs may offer safety benefits in loss of control scenarios because of the tendency of DROs to depart along-track if sufficiently perturbed; departing down-track from a coplanar DRO could result in impact with Phobos whereas a DRO with sufficient inclination could avoid such a possibility. Benefits of smaller radius DROs are that the time and Delta-V to transfer between the DRO and the Phobos surface are lower and radiation protection is marginally improved. As can be seen from Figure 8, smaller radius inclined DROs may also be good surface survey orbits. Round-trip transfers between a 20-km DRO and the Phobos surface take approximately 4.1 hours and 24.6 m/s Delta-V. Orbit maintenance would likely be minimal; however, high accuracy relative navigation and fine control effectors would be required.

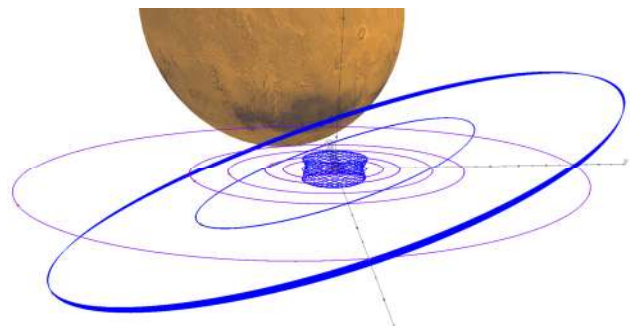


Figure 8 – A range of coplanar and inclined DROs were evaluated.

Surface Habitat—It is clear from inspection of radiation dose estimates in Table 2 that Phobos surface habitats offer significantly greater radiation protection; Phobos blocks approximately 50% of GCR, and even more if the habitat

can be located within a topographic low such as a crater. For this study it was assumed that a fixed habitat would be located at the sub-Mars point, which would ensure line-of-sight with Mars while also increasing radiation protection versus locations without full visibility of Mars' disc. A detailed assessment of thruster sizing and propellant mass for landing on Phobos was performed over a range of possible habitat masses but is not described in this paper.

While surface habitats offer radiation shielding benefits, they can also introduce challenges. Power systems, illumination, and communications constraints – studied in detail by Pratt and Hopkins [6] – were not evaluated in this study and are being incorporated into follow-on analyses at the time of writing. In this study it was assumed that a fixed surface habitat (Cases E and F) would utilize the 150kW to 400 kW arrays of the SEP used for predeployment [9, 10], combined with adequate energy storage to accommodate night (average 3.8 hours) and eclipse (maximum 54 minutes) periods.

Surface habitats were assumed to incorporate landing legs. The design and estimated mass of 500 kg was based on utilization of robotic arm technology derived from an asteroid redirect mission [25]. The landing legs were also considered potentially evolvable to PEV mobility systems on Phobos or Mars [26]. Incorporating mobility into a surface habitat was assumed to require additional propellant, the mass of which was calculated using Copernicus and incorporated into the mission architecture figures of merit described in Section 7. As with the PEV concept, it is possible that lander legs could be designed to mechanically hop or walk a habitat to reduce or eliminate propellant usage and plumbing surface translations [26]. Studies were conducted using the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system [27] as a basis for spring-loaded feet in a hopper system.

EVAs originating from a surface habitat in the absence of a PEV (ie, Cases F and G) were assumed to use EVA booms and translations lines as described earlier in this section.

Crew Taxi

The vehicle used to transport crewmembers between HMO and Phobos is referred to as the crew taxi. A roundtrip transfer between a 1-sol HMO and Phobos including rendezvous and docking requires approximately 1,020 m/s of Delta-V, which is provided by an SM. For cases in which a habitat or PEV has been predeployed, the crew taxi is assumed to dock to that system carrying only the minimal consumables to support crew for approximately 24 hours. All other consumables are predeployed with the habitat or PEV. When no predeployment mission is assumed (Cases A and B), all consumables are transported with the crew taxi with inflatable logistics modules used to provide additional volume for 25 to 50-day missions.

The sizing and design of the crew-taxi cabin and SM is the subject of an ongoing detailed trade study. For the study described here, crew-taxi SM wet masses were estimated parametrically based on the assumption of a pump-fed LOX Methane engine, and three different crew-taxi cabin configurations were evaluated: a minimalist design, a lander-taxi design, and a PEV design.

Minimalist Crew Taxi—This option is a minimum mass vehicle designed for crew transportation between HMO and a Phobos habitat and not designed for Phobos surface proximity operations or exploration. The estimated mass was 2,930 kg for the cabin and 10,804 kg for the SM wet mass.

Lander-Taxi— This alternative would transport a two-person crew from HMO to Phobos orbit using a detachable SM. The SM (estimated 14,286 – 17,830-kg wet mass) remains in Phobos orbit while the lander-taxi (estimated 4,331 kg) descends to the Phobos surface and is used as a minimal volume habitat and EVA airlock for up to 50 days. The lander-taxi is sized to relocate to 11 different sites across Phobos (see Section 4), incorporates EVA booms, and operates as an airlock for EVAs. The SM would incorporate additional logistics for lander-taxi resupply to enable durations of over 14 days.

PEV-Taxi—This option is similar to the lander-taxi with the difference that the PEV-Taxi incorporates suitports and an RCS sled with sufficient propellant to enable its use (without SM attached) as a fully capable PEV for Phobos surface exploration. The estimated mass of the PEV-Taxi cabin and SM interface was 6,228 kg with a SM wet mass of 18,383 kg to 25,464 kg, depending on the mass of inflatable logistics modules being transported.



Figure 9 – PEV- Taxi concept with detachable service module and inflatable logistics modules.

4. REFERENCE SCIENCE / EXPLORATION REGIONS, SITES, AND TASKS

Questions that could be researched during human and robotic exploration of Phobos and Deimos include: What is the composition of both moons? What are their origins? Are

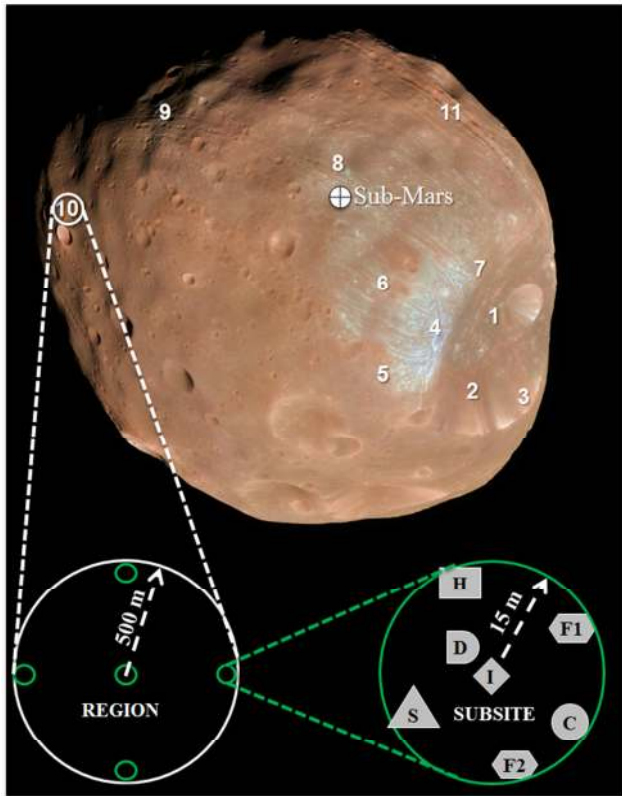


Figure 10 – Example regions of scientific interest (white) used in evaluation of mission architectures.

Each region consisted of five sub-sites (green) consisting of two float samples (F1, F2), a hammer chip sample (H), a core sample (C), a soil sample (S), and deployment and retrieval of an instrument array (I) and a drill (D).

they related to Mars? Are Phobos and Deimos related to each other? And if so how? How have these bodies evolved over time? What are the internal structures of Phobos and Deimos?

The actual regions of scientific interest, the specific sites that would be visited, and the tasks that would be performed are not yet known and would be informed by a team of scientists using high-resolution data from one or more robotic precursor missions. However, to enable development of representative mission content and subsequent comparison of mission architectures, 11 representative regions of scientific interest were identified for detailed investigation. The regions, as shown on Figure 10, are as follows: 1) Floor of Stickney Crater; 2) Side wall of Stickney Crater; 3) Far rim of Stickney Crater; 4) Overturn of Stickney Crater and grooves; 5) Overlap of yellow and white units; 6) Overlap of red and white units with grooves; 7) Opposite rim of Stickney and start of grooves; 8) Brown outlined unit and mid-point of grooves; 9) End point of grooves; 10) “Young” fresh crater; 11) Deep groove structure.

For consistency, each of the 11 regions was assumed to be 1 km in diameter and contain 5 subsites of 30 m in diameter. A standard circuit of tasks was assumed to be performed within each region as shown in Figure 10. The standard circuit tasks are the same as those that have been previously tested in simulated weightlessness in NASA’s Neutral Buoyancy Laboratory, active response gravity offload system (ARGOS, shown in Figure 2) [28], NASA Extreme Environment Mission Operations (NEEMO) [11, 12], and in virtual reality (VR) environments [1].

Upon arrival in a region, a near-field survey task would be performed during which crewmembers would translate to all five subsites to provide verbal descriptions and photo-documentation but without performing any sample collection. The standard circuit of tasks would then be performed at each of the five sub-sites.

It is understood that the actual tasks performed and the size, number, and distribution of regions could differ significantly; however, the consistent selection of representative regions, sites, and tasks enabled systematic comparison among mission architectures and enabled use of EVA performance and operations concept data from previous RATS and NEEMO studies of near-Earth asteroid operations concepts and mission architectures [1, 11, 12]. Future testing is planned to better understand the effects of variable illumination and gravitational effects during exploration at different locations and times.

5. PHOBOS SURFACE TRANSLATIONS

The time and Delta-V required to reach the 11 reference science regions was estimated using Copernicus [13]. Estimates were calculated for surface-to-surface translations between regions as well as transfers between surface regions and an orbital habitat in a 20-km DRO. Estimates based on all 11 regions are shown in Table 3.

Shorter-range intraregion translations of 5 to 500 m were simulated by the NASA Exploration Systems Simulations (NExSyS) project. The NExSyS Phobos surface operations simulation is an integrated simulated Mars-Phobos dynamic environment that supports the study of complex crew/vehicle interactions and translations within Phobos’ complex surface acceleration field. The translational accelerations of a spacecraft near the surface of Phobos are complicated by the irregular shape of Phobos, the low orbital altitude of Phobos and the fact that Phobos is node-locked into a synchronous orbit. The simulation models Phobos’ irregular gravity field with a polyhedral gravity model based on shape and assuming a uniform density. The gravity gradient effects (tidal accelerations) across Phobos are captured as part of the modeling of Phobos’ orbit and Mars’ gravity field. The centrifugal accelerations due to Phobos’ 7.5 hour rotation rate are also captured.

The implications of local variations in the Phobos surface acceleration field were incorporated into Delta-V estimates

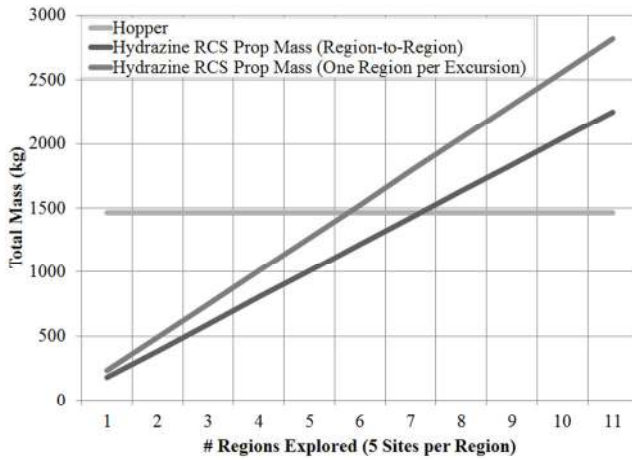


Figure 11 – Hydrazine RCS vs. hopper efficiency comparison for PEV exploration of science regions.

for surface translations by looking at three representative locations on the surface of Phobos: the sub-Mars point, the orbital leading point, and the north pole. Directional dependencies were also considered (ie, east-west, north-south, +/- x and y). Distance effects were also considered (5 to 500 m). The model computed the required velocity to make defined translations. For use in the integrated model, described in Section 7, mean values were calculated (Table 3).

Knowledge of the surface properties of Phobos is necessary to accurately assess the feasibility of a mechanical hopper for surface-to-surface translations. Specifically, the magnitude and direction of propulsion and the corresponding braking that can be mechanically provided are unknown. A hybrid approach using both mechanical and RCS propulsion is possible and could provide benefits in terms of propellant mass savings as well as reducing pluming of the surface. As a preliminary assessment of the potential mass savings, a conceptual design of a hopper system and associated mass estimate were produced (shown in Figure 5). The estimated mass of 1,461 kg was then compared with the propellant mass required to translate to each of the 55 sites in 11 different regions and perform the near-field survey and standard circuit of tasks described in Section 4. Propellant mass was estimated using the Delta-V estimates listed in Table 3 and was calculated 2 different ways: first, assuming that a PEV translated sequentially to each of the 11 regions and 55 sites, and second, assuming that the PEV returned to a fixed habitat at the sub-Mars point after exploring each region. Both estimates are shown on Figure 11 and compared with the fixed mass of the hopper system. Assuming 100% efficiency of the hopper system (ie, no propellant is required for surface translations) it can be seen that the mass of the propellant exceeds the mass of the hopper after exploration of 6 to 8 of the reference exploration regions.

6. EVA TIMELINES

EVA task timelines were created to understand the required U.S. Government work not protected by U.S. copyright

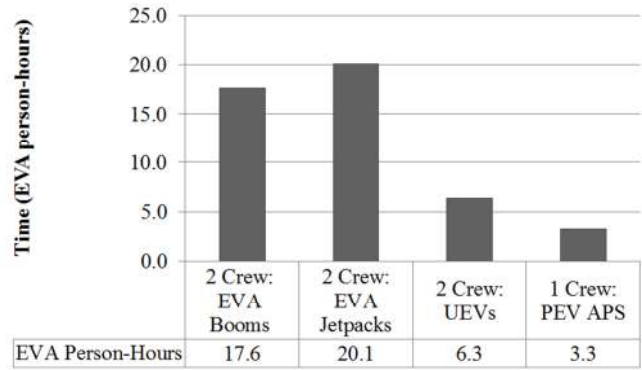


Figure 12 – Comparison of total EVA person-hours to perform a standard circuit of EVA exploration tasks.

time, propellant, support equipment, and other operational constraints and considerations associated with performing the near-field survey and standard circuit of exploration tasks using different exploration system concepts. Timelines were created for EVA booms, EVA jetpacks, UEV, and PEV concepts. Timelines incorporated assumptions

Table 3 – Time and Delta-V estimates (mean, standard deviation, maximum, and minimum) for translations between Phobos surface regions.

Translation Distance (m)	Delta-V (m/s)				Time (mins)			
	Mean	SD	Max	Min	Mean	SD	Max	Min
5	0.32	0.04	0.36	0.26	0.0	0.1	1.0	0.6
15	0.56	0.06	0.62	0.45	1.3	0.2	1.7	1.0
100	1.44	0.16	1.60	1.16	3.3	0.7	4.6	2.5
500	3.23	0.36	3.58	2.60	6.5	0.8	8.6	5.3
Region-to-Region	18.0	5.3	27.4	6.9	109	24	128	45
Orbit-to-Region	13.3	0.8	14.5	12.2	86.6	12.6	110.7	72.6
Region-to-Orbit	13.3	0.6	14.4	12.5	13.3	0.6	14.4	12.5

regarding worksite setup/cleanup times, anchoring times, translation times, don/doff times, checkout times, and task completion times that varied among exploration systems and were informed by previous analog testing results [1, 11, 12].

Analysis showed that EVA jetpacks required a mid-EVA return trip to the habitat to stow samples and retrieve other tools as required. This return trip was not required for UEVs due to their increased stowage capacity. Longer EVAs were assumed for jetpacks and UEVs (6.5 hours) versus PEVs (4 hours) due to inefficiencies in translating back to the habitat via jetpack and UEV.

The EVA person-hours required to complete all exploration tasks at a single subsite (excluding near-field survey of region) is compared for the four EVA exploration systems in Figure 12. Minimization of EVA time reduces consumables usage, extends EVA suit life, and reduces the likelihood of suit-induced physiological trauma [29]. The outputs of the EVA task timeline models including EVA consumables and propellant usage were used as inputs to the overall mission timelines and integrated model described in Section 7. Two crew using EVA booms were assumed for

Cases A, F, and G. Single-person EVAs using the APS on a PEV were assumed for all other cases. A maximum of 24 hours of EVA per crewmember per week was assumed.

7. COMPARISON OF MISSION ARCHITECTURES

Following the concept development, analyses, down-select, and mission architecture definitions described in the previous sections, an integrated model was created that combined Delta-V, logistics and consumables masses, system masses, radiation exposures, EVA crew times, and exploration productivity based on the identified regions of scientific interest, and completion of associated standard circuit tasks and near-field surveys. Propellant mass estimates assume that all translations are performed using hydrazine RCS propulsion ($I_{sp} = 225$ s). This section describes and compares the estimates of radiation exposure, masses, exploration productivity, and also includes a qualitative assessment of the commonality and evolvability of the different mission architectures within the EMC.

Exploration Productivity

The number of subsites explored is shown in Figure 14 as a function of elapsed time spent in the Phobos vicinity for each of the seven mission architectures. From Figure 14 it can be seen that 100% of the reference exploration content was completed within 50 days for all mission architectures except Cases A and F. In Case A the minimal lander had adequate propellant to reach all 11 reference regions of scientific interest but used EVA booms to explore only 1 subsite per region. In addition to the high overhead and consumables usage for each EVA egress-ingress cycle, the lack of a suit port or suit lock for dust protection and the inability to perform suit maintenance in the Apollo-style Taxi-Lander would make it unlikely that 11 EVAs could be safely performed by each crewmember as is assumed in the 50-day version of Case A.

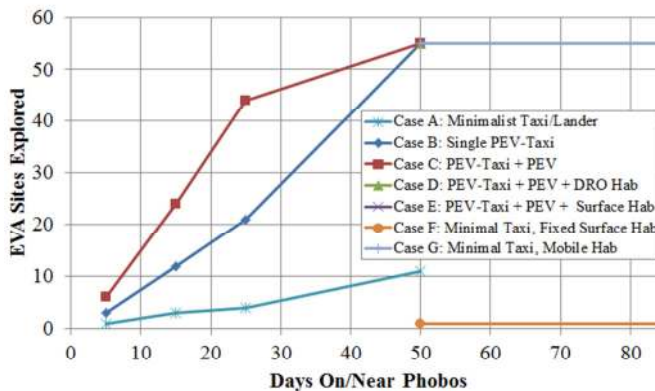


Figure 14 – EVA productivity (sites explored) versus Phobos mission duration for Cases A-G.

Case F assumes a fixed habitat and a minimalist crew taxi, which represents the lowest mass option of the long-duration mission architectures but was assumed to use EVA booms and provide exploration only in the immediate

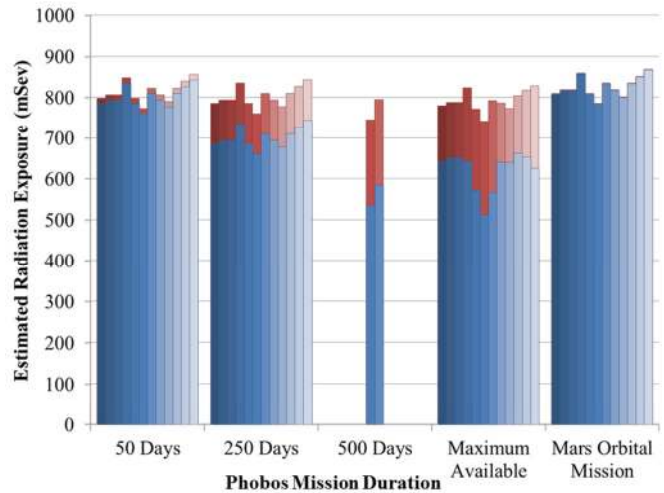


Figure 13 – Estimated cumulative radiation exposure for end-to-end mission architectures for 12 mission opportunities between 2022 and 2045. Estimates for Case D (20 km DRO habitat) are shown in red.

Table 4 – Maximum Phobos mission duration and estimated radiation exposure (averages and ranges). Percent reduction in cumulative radiation exposure compared with Mars orbital mission also shown.

Habitat Location	Days in Free Space	Days on/near Phobos	Cumulative Radiation (mSev)	% Radiation Reduction vs. HMO
HMO	999 (950-1050)	0	826 (785-868)	-
Surface	586 (400-660)	405 (322-542)	623 (514-663)	25% (20-35%)
20 km DRO			791 (741-828)	4% (4-6%)

vicinity of the habitat. EVA jetpacks or UEVs could provide a limited, but possibly worthwhile, increase in exploration capability.

The inclusion of a second fully-capable PEV in Cases C-E would provide increased redundancy and rescue capability including the possibility of a redundant method of return to HMO; however, it was not required to accomplish the reference exploration objectives defined in this study. Limited EVA consumables, propellant, and possibly EVA suit design life rather than crew time are likely to limit exploration productivity. As previously described in Section 5, a mechanical hopper system estimated at 1,461 kg could reduce overall propellant mass and increase exploration capability, possibly even allowing for continued teleoperation between crewed missions.

Radiation Exposure

The effective radiation shielding provided by different locations in the Mars-Phobos system are described in Section 3. However, because a large fraction of an overall mission would be spent in free space transiting between

Earth and Mars, the actual reduction in cumulative radiation exposure for the overall mission will not be as significant as shown in Table 2. The estimated cumulative radiation exposure for mission doses were calculated based on cumulative time spent in Earth-Mars transit, High Mars Orbit, 20-km Phobos DRO, and on Phobos surface for 10 mission opportunities between 2022 and 2045. Cumulative radiation exposure was estimated for missions lasting 50 to 500 days and for Phobos missions based primarily in a 20 km DRO (mission Case D) versus Phobos missions based primarily on the Phobos surface (all other mission cases). Results are shown in Figure 13. To estimate the radiation benefits of Phobos missions compared with a simpler Mars-orbital mission, cumulative radiation exposure was also estimated for each mission opportunity assuming that

crewmembers remained in HMO and spent no time on or near Phobos. Note that only 2 mission opportunities provided for a full 500 days on Phobos; the maximum possible Phobos vicinity stay for each mission opportunity was calculated and is also included in Figure 13 and Table 4 for comparison purposes.

From inspection of Figure 13 it is apparent that short-stay (50 days or fewer) missions on or near Phobos provide only minimal radiation protection compared with a Mars orbital mission, assuming that all other mission time would be spent in a 1-sol Mars orbit and in Earth-Mars transit. Significant radiation benefits of as much as 35% (Table 4) may accrue during longer stay missions to Phobos but these benefits are greatly diminished to only 4% to 6% if the

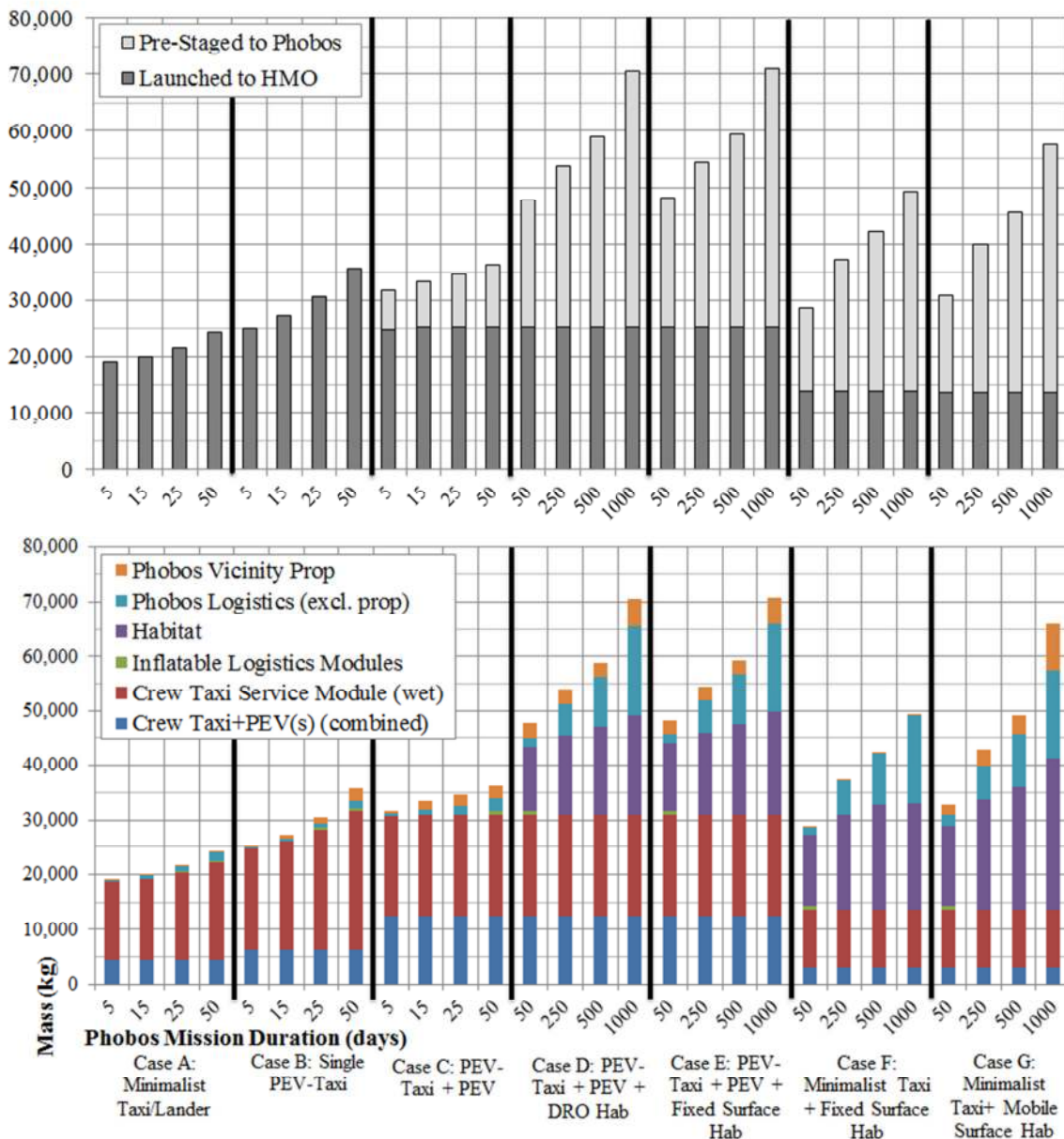


Figure 15 – Mass estimate comparison for Cases A-G.

Phobos mission is based out of an orbital habitat rather than a habitat on the Phobos surface.

As described in Section 3, protection against SPE radiation must also be considered and is likely to affect selection and operation of exploration systems. A mobile radiation shelter – whether in a habitat, PEV, or even an unpressurized shelter – will likely be necessary to ensure access to SPE protection within 20 minutes at all times.

Total Architecture Masses

The overall mass estimates for each mission architecture are shown in Figure 15. The mass of payloads predeployed in advance of the human mission is indicated in the top half of the figure and ranged from 28,462 kg (Case F) to 34,040 kg (Case E) for a 500 day mission.

Cases A and B have the benefit of not requiring any pre-deployed payloads. However, because they require that all systems and logistics be transported from HMO to Phobos, it can be seen that the total mass increases rapidly with increases in mission duration when compared with Case C in which a predeploy mission is used. The mass of a PEV-Taxi, estimated at 6,331 kg, compared with a minimal taxi (2,930 kg) or even the Taxi-Lander (4,331 kg) requires a significantly larger SM due to the gear ratio for transportation between HMO and Phobos. The gear ratio makes predeployment of assets to Phobos using slower but higher-efficiency spacecraft such as SEP tugs an extremely valuable capability and allows for the use of a minimal crew taxi. A modular approach in which a PEV-Taxi can be kitted with a prestaged RCS sled upon arrival in Phobos orbit would allow for a reduced mass crew taxi compared with a fully-capable PEV, while preserving the ability to use the crew taxi for exploration on Phobos and also as a habitable airlock on the MTV during transit between Earth and Mars. A preliminary concept for a standard interface is currently being developed, which would allow for in-space change-out of mobility systems, payloads, and even crew cabins to provide increased options for reusability and evolvability within the EMC.

As previously noted the second PEV included in Cases C-E provides safety and redundancy benefits but is not required to accomplish the reference exploration tasks. As such, if only considering mass and exploration productivity, a minimal crew taxi could be used instead of the PEV-Taxi, an estimated difference of 17,379 kg including SM.

The orbital habitat in Case D requires much higher mass than the short-stay mission architectures (Cases A-C) without offering increased exploration capability. Compared with the fixed surface habitat (Case E) the mass of propellant required to transfer back and forth between DRO and the surface is offset by the additional mass required for the habitat to land and operate on the Phobos surface. However, Case E provides the same exploration capability as Case D while offering far superior radiation protection.

The lowest mass option that provides meaningful radiation protection benefits is the minimalist taxi and fixed surface habitat (Case F). Although the exploration productivity provided by this architecture is the lowest of all the architectures, it would provide a low-mass, long duration Phobos mission option that could be well-suited for teleoperation of robotic assets on Phobos, Deimos, and the surface of Mars.

Incorporating mobility into a surface habitat (Case G) offers benefits by avoiding the need to develop and deliver a PEV class vehicle yet still providing the ability to explore all of the reference exploration regions. However, the frequent relocation necessary to accomplish the reference exploration tasks requires a large quantity of propellant (1,850 – 3,538 kg) with more propellant being required to move the larger habitats and increased logistics that are necessary for longer duration missions. Even the ability to relocate far fewer than the 55 times assumed in Case G could offer benefits in varying habitat location to optimize radiation shielding (eg, in a crater), illumination, and/or communications capability as has been described elsewhere [6]. Mechanical translation of the habitat, either by hopping or by walking, using a system such as ATHLETE [26, 27] is currently being evaluated and would have the added benefit of direct applicability to Mars surface operations.

Coupling a mobile habitat with EVA mobility systems such as the UEV or EVA jetpacks could reduce the extent of habitat relocation that is required, although the aforementioned limitations of these systems for performance of some EVA exploration tasks may limit their utility. Data from analog testing [1, 19, 30] suggests that the quality of science may also be reduced compared with using a PEV due to reduced surveying and sensor deployment capability.

Including suit ports on a mobile habitat would provide important dust protection, reduce the consumables and crew

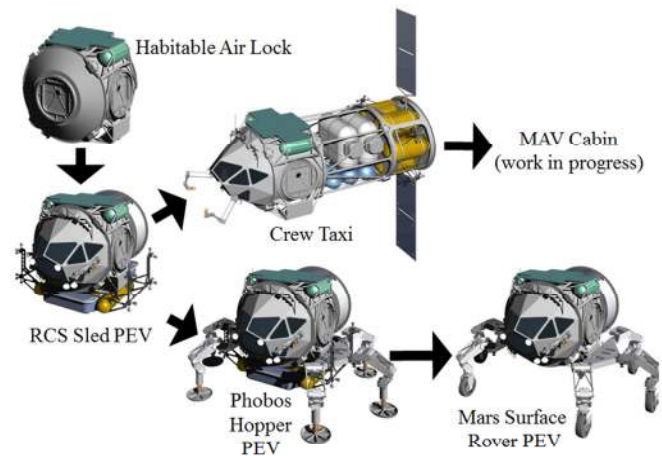


Figure 16 – Modular vehicles provide options for reusing and evolving systems within the EMC.

time for egress and ingress, and ensure that EVA systems and operations on Phobos are applicable to planetary surface missions [15-17, 31]. It is possible that a PEV-Taxi without an RCS sled could be used as an EVA module attached to a mobile habitat. Although not providing the same capability as a fully mobile PEV, it could provide the exploration atmosphere [18], dust protection, SPE radiation protection, and EVA support systems necessary to enable efficient EVA egress and ingress from a mobile habitat. Although less desirable, a PEV cabin without suit ports could be utilized as a low-mass crew taxi while also serving as a habitable airlock both for a Phobos habitat and for the MTV.

Commonality and Evolvability

Systems that should be considered for commonality between the MTV and a Phobos mission include habitation systems, life support systems, inflatable logistics modules, and the crew taxi, which could provide contingency EVA capability as a habitable airlock for the MTV during outbound and inbound transits, transport crew between HMO and Phobos, and possibly provide nominal EVA capability on Phobos either as an EVA module on a habitat or as a PEV. A crew-taxi design that could be adapted for use as a Mars ascent vehicle (MAV) from Mars surface is currently being evaluated. A PEV design incorporating the exploration atmosphere, suit ports, and suit port compatible EVA suits would be directly applicable to use as a pressurized rover on the surface of Mars, either using a wheeled chassis or possibly using a mobility system evolved from an ATHLETE-class Phobos hopper. A previously mentioned standard interface aims to provide the capability to reuse modules for different purposes or to replace or upgrade parts of a modular system. Further development and evaluation of the standard interface concept is underway at the time of writing.

The modular approach to enabling evolvable systems is illustrated in Figure 16 with a class of spacecraft based around a low volume module on the order of 10 to 15 m³ in volume, which provides EVA capability and can accommodate 4-suited crewmembers for short transits, 2-unsuited crewmembers for weeks at a time, or in the minimalist case could even serve as a logistics module [*"Space Technology Advancement & Readiness (STAR) Node," NASA, Internal White Paper, April 18 2013*]. A design exercise by space architects and human factors engineers examined the possibility of using the same 10 to 15-m³ module as a repeating element in long-duration habitation capability found that – although possible – the small diameter of the repeating pressure vessel led to significant inefficiencies in mass and overall functionality compared with use of a larger diameter pressure vessel. However, an approach of developing two classes of core modules that could be outfitted for different mission applications was considered potentially viable. The smaller class of vehicle, as described above, could augment larger habitation systems based around a common core module that is outfitted as necessary for Earth-Mars transit, Phobos

surface habitation, or Mars surface habitation. Appropriate sizing and outfitting of the larger core module is currently being evaluated with the goal of developing a larger core exploration module that can be augmented with logistics versions of the smaller module to accommodate any duration of exploration mission without over-sizing the module for shorter-duration missions.

8. CONCLUSIONS

Human exploration of the moons of Mars as an intermediate destination on the path to eventual exploration of Mars itself appears to offer meaningful scientific, engineering, operational, and public engagement benefits; however, further analysis and data from robotic precursor missions is required to better understand the environment, the risks and benefits of such a mission, and its role within a broader Evolvable Mars Campaign.

While this study represents only a preliminary assessment of a small subset of many possible mission architectures, several important observations and recommendations can be made:

1. Short stay (Cases A-C) and/or orbital-based Phobos missions (Case D) fail to take advantage of the significant radiation protection that is provided by Phobos; even in a low (20 km) DRO there is much less protection than on the surface. A reduction in cumulative mission radiation exposure of up to 34% (versus a Mars orbital mission) is estimated when the habitat is located on the Phobos surface, compared with only 4% to 6% reduction for a habitat in a 20-km DRO.
2. The ability to use longer-duration but higher-efficiency (eg, solar electric propulsion) uncrewed missions to predeploy a habitat, consumables, and exploration systems in advance of a human mission allows for a minimalist mass crew taxi and SM, saving as much as 17,379 kg compared with a PEV-taxi. However, further analysis is required to evaluate the mass, cost, and operational implications of a PEV-Taxi that also provides EVA capability while on Phobos.
3. Pressurized excursion vehicles and mobile surface habitats offer significant exploration capability and operational benefits compared with unpressurized EVA mobility systems at the cost of increased system and propellant mass. Two PEVs would offer increased redundancy and contingency rescue capabilities but, unlike lunar or Mars surface exploration, are unlikely to increase exploration productivity or efficiency on Phobos.
4. Further analysis and testing is necessary to identify low-mass methods for increasing EVA exploration range and capability from a mobile habitat to reduce the propellant mass and risk associated with frequent habitat relocations.

5. The possibility of acute radiation exposure during an SPE is likely to affect the utility of EVA jetpacks or other unpressurized exploration vehicles. Unless significant radiation shielding is incorporated into those vehicles, EVA crew would likely be required to remain within 20 minutes of a radiation safe-haven (ie, habitat or pressurized exploration vehicle). Exploration utility of lightweight unpressurized excursion vehicles may also be limited by the need for complex GN&C systems to operate within the nonintuitive and highly-variable gravitational environment of Phobos.
6. Exploration EVA suits, suit ports, and life support systems capable of providing the exploration atmosphere (56.5 kPa, 34% O₂, 66% N₂) and the associated dust protection, consumables and crew time savings, and single-person EVA capability are likely to significantly enhance human exploration of Phobos and will be directly applicable to Mars surface missions.
7. Mechanical surface translation modes (ie, hopping) offer potentially significant propellant savings and the possibility of extended exploration operations between crewed missions using technologies that may be applicable to Mars surface systems. Further simulation and assessment of these technologies is warranted.
8. The implications of orbital, spatial, and seasonal variation in illumination, surface properties, and other environmental factors requires further analysis. Robotic precursor data will eventually be required to characterize the gravitational field, identify regions of scientific interest and hazards, characterize soil mechanics for analysis of hopper efficiency and dust environment, and to identify and characterize any useful materials that could be used for demonstration of *in situ* resource utilization.
9. A pair of core exploration module designs of different sizes may offer the opportunity of sensible commonality, reuse, and evolution of systems across multiple mission destinations within the Evolvable Mars Campaign. A smaller version 10-15 m³ in volume would provide EVA capability, accommodate 4-suited crewmembers for short transits, 2-unsuited crewmembers for weeks at a time, or simply be used as a logistics module. One or more variations of the smaller module would augment larger habitation systems based around a common core module that is outfitted as necessary for Earth-Mars transit, Phobos surface habitation, or Mars surface habitation. A standard interface could further increase options for reuse, evolution, repair, and upgrading of exploration systems.

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Biography



Andrew Abercromby received an M.Eng. in Mechanical Engineering from the University of Edinburgh in 2002 during which he worked on X-38 in the Flight Mechanics Laboratory at JSC. He earned a Ph.D. in Motor Control from the University of Houston while working in the JSC Neurosciences Laboratory

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Steve Chappell attended the University of Michigan and earned a bachelor's degree in Aerospace Engineering. He also earned masters and doctoral degrees from the University of Colorado in Aerospace Engineering Sciences, researching human performance and spacesuit systems in

simulated reduced gravity. His career has spanned many areas of engineering and science, including work on embedded software for fighter aircraft, satellite ground systems development, and earth-observing satellites systems engineering. Currently, in addition to helping lead the Mars Moons Human Spaceflight Architecture Team, his work has been focused on optimizing human and system performance for the next-generation of space exploration. He has extensive experience leading and taking part in research in multiple exploration analog environments including arctic, desert, underwater, alpine, and partial gravity simulators.



Michael Gernhardt is a NASA astronaut who has been a mission specialist on four Space Shuttle missions. He has a bachelor's degree in physics from Vanderbilt University as well as master's and doctorate degrees in bioengineering from the University of Pennsylvania. He is the manager of the NASA JSC EVA Physiology Laboratory, project lead for the EAMD team, and the lead for the Mars Moons Human Spaceflight Architecture Team.



David Lee received a B.S. in Aeronautical Engineering from Wichita State University in 1989. He has been with the Johnson Space Center for 27 years. He has worked in a number of areas, including thermal resource planning for the International Space Station and ascent debris radar for the Space Shuttle program. His

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A. Scott Howe is a licensed architect and robotics engineer at NASA's Jet Propulsion Laboratory. He earned PhDs in industrial and manufacturing systems engineering from Hong Kong University and in architecture from University of Michigan. Dr. Howe spent 13 years of practice in Tokyo, Japan, and taught for 6 years at Hong Kong University. He specializes in robotic construction and currently is on the NASA development team building long-duration human habitats for deep space and permanent outposts for the moon and Mars. Dr. Howe is also a member of the JPL All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system development team, Asteroid Redirect Mission (ARM) capture mechanism team, and Mars Sample Return (MSR) Orbiter design team.

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