Human Exploration Missions to Phobos Prior to Crewed Mars Surface Missions

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Abstract— **Phobos is a scientifically interesting destination which offers engineering, operational and public outreach activities that could enhance subsequent Mars surface missions. A Phobos mission would serve to facilitate the development of the human-based Mars transportation infrastructure, unmanned cargo delivery systems, as well as habitation and exploration assets that would be directly relevant to subsequent Mars surface missions. It would also potentially provide for low latency teleoperations (LLT) of Mars surface robots performing a range of tasks from landing site validation to infrastructure development to support future crewed Mars surface Missions.**

A human mission to Phobos would be preceded by a cargo predeploy of a Phobos surface habitat and a pressurized excursion vehicle (PEV) to Mars orbit. Once in Mars orbit, the habitat and PEV would spiral to Phobos using solar electric propulsion (SEP)-based systems. When a crewed mission is launched to Phobos, it would include the remaining systems to support the crew during the Earth-to-Mars orbit transit and to reach Phobos after insertion into a high Mars orbit (HMO). The crew would taxi from HMO to Phobos in a spacecraft that is based on a MAV to rendezvous with the predeployed systems. A predominantly static Phobos surface habitat was chosen as a baseline architecture. The habitat would have limited capability to relocate on the surface to shorten excursion distances required by the PEV during exploration and to provide rescue capability should the PEV become disabled.

PEVs would contain closed-loop guidance and provide life support and consumables for two crewmembers for two weeks plus reserves. The PEV has a cabin that uses the exploration atmosphere of 8.2psi with 34% oxygen. This atmosphere enables EVA to occur with minimal oxygen prebreathe before crewmembers enter their EVA suits through suit ports, and provides dust control to occur by keeping the suits outside the pressurized volume. When equipped with outriggers, the PEV enables EVA tasks without the need to anchor. Tasks with higher force requirements can be performed with PEV propulsion providing the necessary thrust to counteract forces.

This paper overviews the mission operational concepts, and timelines, along with analysis of the power, lighting, habitat stability, and EVA forces. Exploration of Phobos builds heavily on the development of the cis-lunar proving ground and significantly reduces Mars surface risk by facilitating the design, development and testing of habitats, MAVs, and pressurized rover cabins that are all investments in Mars surface assets.

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1. INTRODUCTION

The Evolvable Mars Campaign (EMC) is a capability-driven strategy to identify the exploration framework needed to ultimately place humans on the surface of Mars [1-3]. Within the EMC, human exploration of Mars' moons Phobos and Deimos is being considered as an intermediate step that would help develop and utilize many elements of the Mars surface transportation, exploration, and habitation infrastructures, while minimizing the development of additional infrastructure unique to the Mars' moons. Phobos is scientifically interesting in and of itself. For example, it likely houses samples of ejecta from Mars' surface [4] and possibly materials from the asteroid belt [5] , and studying its terrain could provide insights into the evolution of Mars. Crews operating on the surface of Phobos for a conjunction-class mission (between 300 and 550 days in Mars' vicinity [6]) may benefit from a reduction in cumulative radiation exposure, of up to 34% relative to a high Mars orbital mission [7]. Crews operating from Phobos (or elsewhere in the Mars vicinity) also have the potential to exploit low-latency teleoperations (LLT) of Mars surface assets to validate landing sites and perform other mission-critical tasks in preparation for human Mars surface missions [8] .

2. SUMMARY OF ARCHITECTURE CASES AND ASSESSMENT METHODOLOGY

Previous work conducted by the Human Spaceflight Architecture Team (HAT) systematically developed, evaluated, and compared Phobos mission architectural options for the purpose of determining the most effective and efficient architecture for performing a reference program of scientific exploration [7]. Variations in the (1) number of crewmembers sent to the Phobos surface, (2) duration of time spent on or near (i.e., orbiting) Phobos, (3) crew taxi transportation vehicles between high Mars orbit (HMO) and the Phobos surface, (4) surface habitats, mobility units, and exploration systems, (5) cumulative radiation exposure, and (6) total architectural mass were considered [7]. This section contains a brief summary of that study (referred to as the Phase One study), and the next section (Section 3) contains a description of the down-selection process used to define the current architecture.

Phase One Mission Architectures

The Phase One trade study assessed conjunction-class mission opportunities to Phobos (approximately 500 days' duration in the Mars system) between the years 2022 and 2045. A four-person crew was assumed to travel from Earth to a one-sol HMO in a Mars transit vehicle (MTV). From HMO, either two or four crewmembers were transported to Phobos space (i.e., to a Phobos distant retrograde orbit [DRO] or to the Phobos surface) via a crew taxi vehicle. The duration of time spent in Phobos space was evaluated between 5 and 500 days, with the assumption that any remaining mission time would be spent in the MTV in HMO. Multiple Phobos habitat locations (orbital versus fixed surface versus mobile surface) were traded in terms of the required round-trip delta-V and transfer time, station-keeping delta-V, and cumulative radiation protection.

One strategy employed during the Phase One study was to pursue architectural options that incorporated a common habitable airlock, which could be shared among the various transportation vehicles and habitats to facilitate redundancy and reusability. This enabled design commonality among the potential HMO-to-Phobos crew taxi, Phobos and Mars habitat and exploration rover, Mars descent vehicle, and Mars ascent vehicle (MAV).

Three different crew taxi cabins were evaluated: a minimalist taxi design, a taxi/lander design, and a pressurized excursion vehicle (PEV) design. Design differences governed the extent to which the taxi cabin could be used for additional mission functions, such as for Phobos or Mars surface exploration, Mars descent, or Mars ascent. The PEV concept consists of a core cabin that houses various work packages to support scientific exploration and short-term crew habitation. It can be outfitted with different mobility systems depending on mission needs, such as a reaction control system (RCS) mounted on a sled under the vehicle or mechanical propulsion "hopper" (derived from the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) [9]) for surface transport. The Phase One study considered a PEV with an astronaut positioning system (i.e., a robotic arm with a portable foot restraint (PFR) mounted to the front of the vehicle), an unpressurized exploration vehicle, and an EVA jetpack as potential work platforms for surface operations. Habitat and logistics module (LM) masses, volumes, and configurations for the 5-to-500 day range of mission durations were developed as part of a broader study of EMC habitation sizing, modularity, and commonality [10, 11]. The habitats were assumed to be predeployed by a solar electric propulsion (SEP) tug spacecraft [12]; the SEP would also provide solar power to the habitat.

While the specific scientific sites that may be explored are not yet known, the Phase One study included eleven representative regions of interest (ROI) on the Phobos surface for the purpose of developing representative mission content and EVA timelines to compare the different architectures. The locations of these ROIs are depicted in Figure 1 [13]. Each ROI was 1 km in diameter and contained five science sites, each 30 m in diameter. For the purpose of considering traverse plans, the maximum distance between ROIs was 10 km. A standard circuit of tasks to be performed at each site, including verbal site descriptions, photographic documentation, and various types of geological sampling, was assumed to quantify science productivity for each architecture.

The Phase One study resulted in six primary candidate architectures for surface exploration of Phobos: (1) a single PEV for crew taxiing, surface mobility, and short-duration surface habitation, (2) two PEVs for increased surface operations redundancy and flexibility, (3) two PEVs plus a DRO habitat for longer stays in Phobos space, (4) two PEVs plus a fixed surface habitat for longer stays on the Phobos surface, (5) a minimal-mass taxi/lander for short-duration surface operations, and (6) a minimal-mass taxi plus mobile surface habitat for enhanced surface exploration and longer stays on the Phobos surface. Table 1 describes these architectures, including the number of crewmembers to be sent to Phobos, the duration of time spent in Phobos space, the hardware and associated masses pre-staged to both HMO and Phobos space, the percentage of achievable science sites, and any Phobos-specific elements (i.e., hardware to be developed specifically for Phobos [as opposed to Mars] surface operations). For calculations of the mass and percentage of science sites achieved, either 50 or 500 days on the Phobos surface was used in the model, as described in row three of Table 1. Note that for the two-PEV-plus-DRO-habitat architecture, the crew is anticipated to perform multiple short-duration trips to the Phobos surface from the DRO habitat; for all other architectures, row three of Table 1 refers to the time spent on the Phobos surface. Numbers in brackets are for two separate 500-day missions to the Mars system; all of the mass for both missions is expected to be pre-staged before the first mission. Science productivity, described in row eight of Table 1, refers to completing all tasks at each of the 55 sites (11 ROIs x 5 sites per ROI). Because both the surface of Phobos and orbit around Phobos offers protective radiation shielding, the radiation exposure computations (row thirteen of Table 1) were based on more detailed mission timelines which included anticipated time in HMO, Phobos DRO, and on the Phobos surface, derived from opportunistic launch dates from Earth and corresponding mission durations between 2022 and 2045. Notably, architectures that include Phobos surface habitats offer substantial reductions in cumulative radiation exposure, relative to architectures spent fully in HMO.

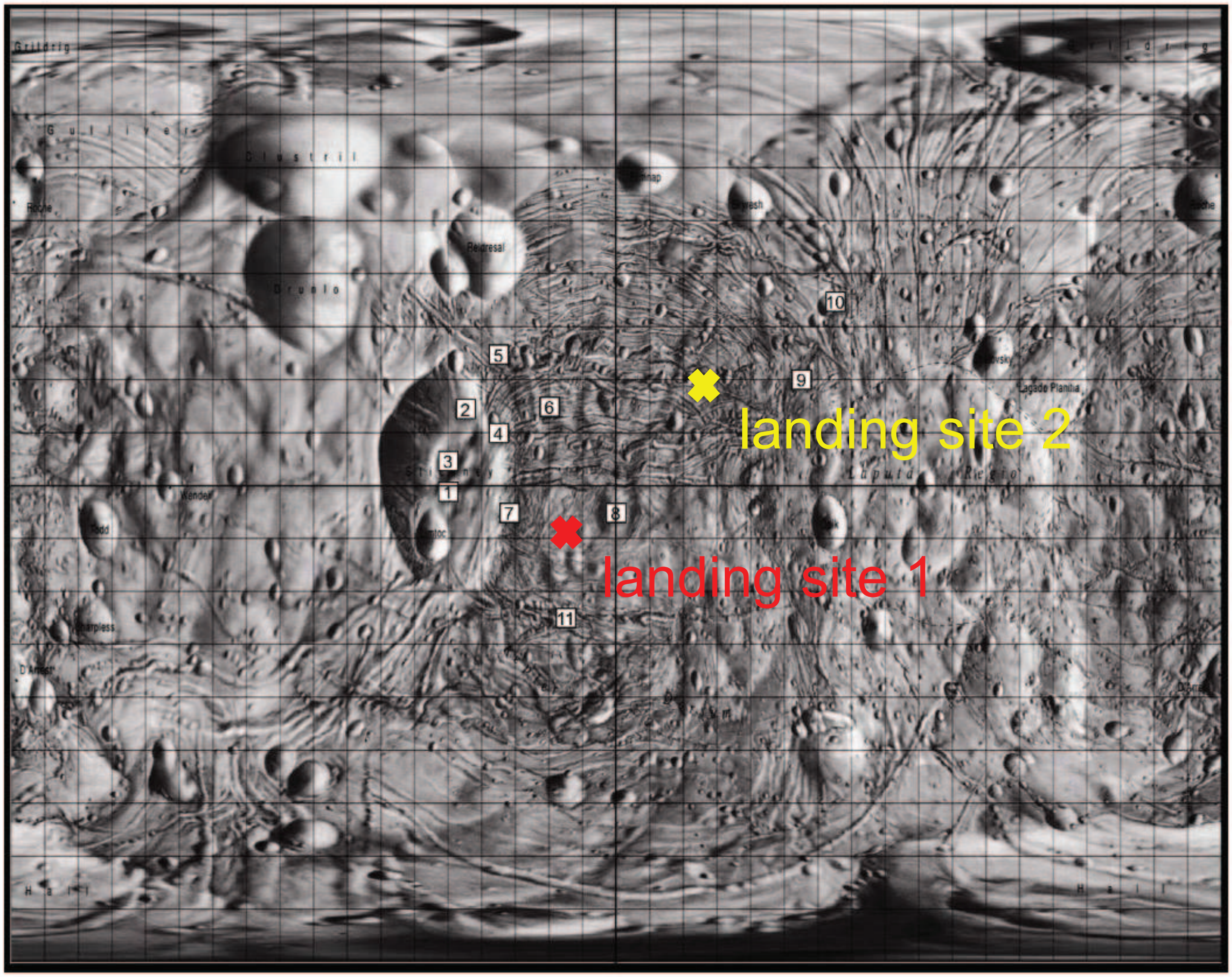
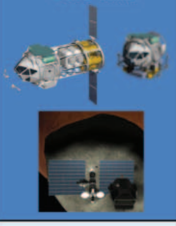
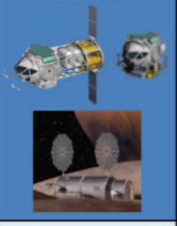


Figure 1. Mercator-style projection of the Phobos surface highlighting eleven scientific regions of interest. Two potential habitat landing sites are shown from which PEV exploration excursions may be performed (see section 4).

Table 1. Summary comparison of the Phase One Phobos mission architectures. Numbers in blue refer to two separate 500-day crewed missions to the Mars system. PEV = pressurized excursion vehicle, RCS = reaction control sled, SM = service module, LM = logistics module.

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%

Down-selection of the Phase One Mission Architectures

After the Phase One study was completed, the HAT further examined the minimal taxi with a mobile habitat (Figure 2) for exploration architecture as a promising candidate for a Phobos surface mission. In this scenario, the crew would transfer from HMO to Phobos in a MAV-derived taxi, hereafter referred to as the *Phobos taxi*, which includes a cabin with suit ports for low overhead, high frequency EVA, and dust control. . The Phobos taxi would dock directly to the mobile surface habitat and remain with the habitat throughout the mission. One advantage of this approach is that the Phobos taxi, habitat, and all four crewmembers are kept together at all times. Furthermore, with the Phobos taxi docked to the habitat, the crew could abort back to the MTV in HMO at any time.

Incorporating a mobile habitat facilitates surface exploration without the need to develop and deliver a PEV-class vehicle. The taxi/habitat stack would move to each exploration ROI using its RCS and would also be capable of ambulating within the 1 km diameter of each ROI. The four crewmembers would operate in extravehicular (EV) / intravehicular (IV) pairs. The habitat would operate at 14.7psi / 21% O_2. The proposed protocol would have EV crewmembers “camp out” in the taxi at the exploration atmosphere of 8.2 psi/34% O_2, enabling 15 min EVA prebreathe protocols during periods of high frequency EVA [14]. Upon exiting the taxi via the suit ports [14], the EV crew would work from portable foot restraints (PFRs) and/or body-restraint tethers (BRTs) that slide along 7.62 m (25 ft) outriggers deployed from the habitat. Strategically locating these outriggers on either side of the habitat, combined with the weight of the habitat, chemical/solar electric propulsion delivery vehicle, and taxi, would provide adequate stabilization to counteract more than 800lb of force (e.g., including the force produced by an EV crewmember performing surface core drilling) without toppling the taxi/habitat/propulsion vehicle system. Tethers and/or jetpacks could enable exploration beyond the range of the outriggers (see Section 8 for detailed explanation and analyses of similar outriggers on a PEV). Upon completion of an EVA, the EV crewmembers would clean their EVA suits and then ingress the mobile habitat through the suit ports and taxi-to-habitat airlock. Upon completion of all EVA activities at the current ROI, the taxi/habitat stack would move to a new exploration ROI and the EVA cycle would repeat.

Disadvantages of this particular architecture, however, are that (1) the ten ROI-to-ROI RCS relocations of the crewed taxi/habitat stack would require an estimated 4250 kg of propellant and introduce additional risk relative to a stationary habitat and that (2) trafficability concerns surrounding movement of the entire stack would limit exploration of scientifically interesting areas, such as crater walls or areas with high densities of boulders, and would introduce additional risk compared to a smaller more robust PEV. . These considerations drove the selection of the current architecture, which consists of a predeployed, predominantly stationary surface habitat with a PEV and MAV-based Phobos taxi.

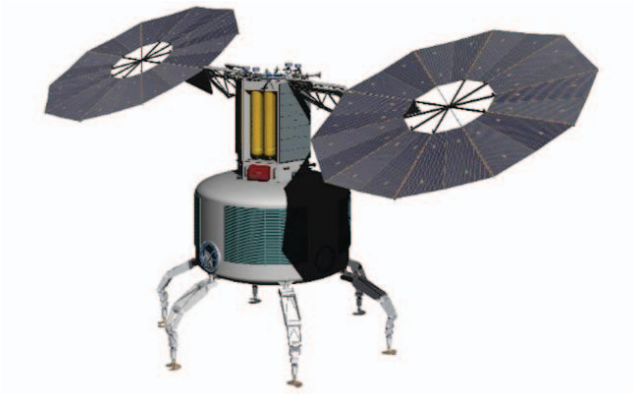


Figure 2. Illustration of the mobile habitat with the chemical/solar electric propulsion delivery vehicle attached. The habitat is equipped with legs capable of hexapodal translation across Phobos surface.

3. CURRENT PHOBOS MISSION ARCHITECTURE

The current down-selected architecture includes a predeployed, predominantly stationary surface habitat, PEV (Figure 3) and MAV-based Phobos taxi, which would consist of a simple MAV cabin without suit ports. The surface habitat has sufficient RCS propellant to support one surface relocation, one rescue of a failed PEV, and one contingency launch and rendezvous docking with the Phobos taxi. Within this architecture, two options were evaluated with respect to the utilization of the Phobos taxi. In both options, Phobos taxi is predeployed to HMO and the surface habitat/PEV stack with a chemical/SEP hybrid delivery vehicle is predeployed to Phobos space.

In option 1, the PEV, with its own RCS sled, would undock from the habitat/PEV stack and insert into a 20-km DRO around Phobos, while the habitat with the hybrid delivery vehicle would land on the Phobos surface. A successful landing of the Phobos habitat would be a prerequisite for the crewed MTV to perform the trans-Mars injection (TMI) burn. Once the crewed MTV arrives in HMO, all four crewmembers would transfer into the Phobos taxi. The crewed taxi would then transfer from HMO to the 20 km Phobos DRO and rendezvous and dock with the PEV. The crew would transfer into the PEV and perform a deorbit burn to dock with the Phobos surface habitat. After performing the initial habitat activation and checkouts, the crew would begin surface exploration.

In option 2, the entire habitat/PEV stack is landed on the Phobos surface. A successful stack landing would be a prerequisite for the crewed MTV to perform the TMI burn. Upon arrival of the MTV in HMO, the crew would transfer into the Phobos taxi, deorbit to the Phobos surface, and dock directly to the habitat.

Option 1 encompasses simpler landing dynamics and simpler surface-relocation and rescue-scenario maneuverability than option 2, which includes a larger habitat/PEV/taxi stack with an offset center of gravity (see Section 7 for further explanation and analyses). Option 1 also lowers the risk of environmental damage to the Phobos taxi, which could result from interactions with the Phobos surface caused by docking and exploration operations in option two. The Phobos taxi, which remains in the 20-km DRO in option 1, can also serve as a communications relay. A disadvantage of option 1, however, is that the Phobos taxi is not routinely accessible to the crew for regular inspection and maintenance. Having the Phobos taxi in the 20 km DRO also complicates crew abort scenarios, which would require the crew to ingress the PEV, launch into the DRO, and successfully rendezvous and dock with the taxi before returning to the MTV in HMO (by comparison, in option 2, the crew simply ingresses the Phobos taxi on the surface and aborts directly to HMO). Option 2 also has the advantage of additional habitable volume for contingencies during surface operations (e.g., habitat leak).

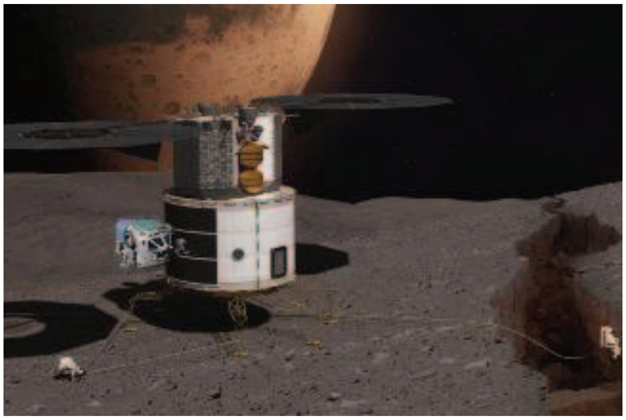


Figure 3. Illustration of the surface habitat on Phobos with the PEV docked. Every three weeks, two crewmembers would perform two-week exploration excursions in the PEV.

A hybrid option to reduce some of the risks and maintain some of the safety margins mentioned above would be to begin the mission using option 1, with the Phobos taxi remaining in Phobos DRO and the crewed PEV landing and docking with the surface habitat. Once surface operations are successfully underway, the Phobos taxi could be deorbited and berthed to the surface habitat, thereby enabling more routine inspection and maintenance, increased habitable volume, and a simpler abort profile. To minimize the complexity of maneuvering the entire habitat/PEV/taxi stack, taxi deorbiting and berthing could occur halfway through the mission after the habitat relocation has been completed. The possibility also exists of launching the PEV to DRO to perform inspections and maintenance on the Phobos taxi; this would be advantageous during extended exploration excursions, when, for example, an ascent to the DRO could be part of a longer excursion to a distant region.

Relocating the habitat mid mission minimizes the excursion distances between the habitat and the PEV. This both reduces propellant usage and simplifies the rescue of a failed PEV with the habitat. The need to relocate the habitat for rescue operations could be eliminated if crews could perform an EVA to return to the habitat.

Human Powered Walk-back

The low-gravity (.006 m/s^2) nature of Phobos could provide the potential for some form of human powered walk back from a failed PEV to the habitat. Human powered methods might be safer techniques than the exclusive use of jet packs, which have the potential to achieve escape velocity; this introduces additional risks [7], particularly with the non-uniform gravity levels and un-intuitive Phobos orbital mechanics. A reliable walk back technique could eliminate the need for the habitat to perform a rescue and possibly the need to relocate the habitat midway through the mission to maintain safe excursion distances for the PEV as more distant regions are explored. An initial analysis of a human powered walk-back traverse, using a jumping technique, was performed assuming application cases of 50 to 180 lbs of force applied over a 0.2 s period, at a 45^{o} angle of departure. The resulting idealized walk-back times and trajectories are shown in Table 2 and Figure 4, respectively. For example, using this approach a 180 lb jump results in traversing 100 m in approximately 4 min, which leads to walk-back times of over 3.5 hr for a 5 km traverse. It is unlikely that a crew member would be able to perfectly execute these jumps in the desired direction. There would also possibly be dissipation of energy from currently unknown soil mechanics, and this combination could result in much longer walk back times that could exceed the nominal 6.5 hours life support [15].

Table 2. Expected return times (h:mm:ss) from various distances away from the habitat using human powered locomotion.

		Distance from Habitat (m)					
Force Applied (0.2 sec)	Velocity (m/s)	100	500	1000	2500	5000	10000
180lb	0.54	0:04:20	0:21:42	0:43:24	1:48:30	3:36:59	7:13:59
150lb	0.45	0:05:12	0:26:02	0:52:04	2:10:11	4:20:22	8:40:44
100lb	0.3	0:07:49	0:39:04	1:18:08	3:15:19	6:30:38	13:01:15
50lb	0.15	0:15:38	1:18:10	2:36:21	6:30:52	13:01:45	26:03:30

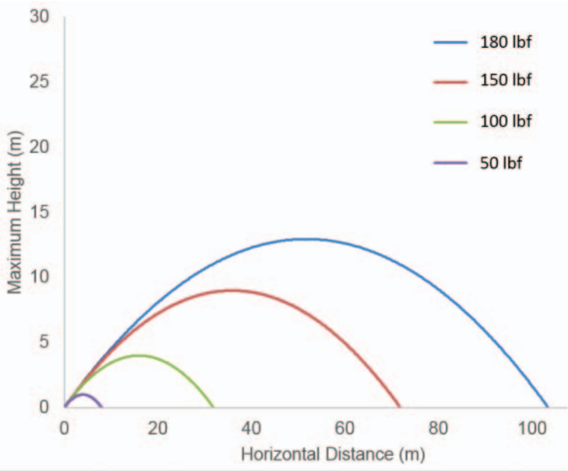


Figure 4. Trajectory plots of a 45^{o} jump on Phobos for various force applications. All forces are applied for 0.2 seconds.

This analysis suggests that a different walk-back method be investigated. A potentially more efficient means might be to translate in a prone position, much the same way crewmembers perform micro-gravity translations on the International Space Station (ISS) [15]. On ISS, crew members apply small forces with their hands in a prone position and staying low to the surface. On Phobos crewmembers would translate much the same way, building up velocity with repeated low force applications against the surface, and increasing their traverse speed gradually over time. Previous modeling efforts suggest this approach could be valid and could result in minimum translation speeds of 0.13 m/sec [16]. This is much lower than micrgravity translations on ISS which can be up to 0.61 m/sec [17, 18]. If translation speeds of 0.61m/sec could be achieved, walk backs from 5 km would take an estimated 2.5 hours, which is less than 50% of the nominal portable life support system capability.

The uncertainty in the efficacy and efficiency of these translation methods suggests that some combination of human powered walk back combined with the use of a self-aid for EVA rescue (SAFER) jetpack for attitude control could be a viable walk back technique. Evaluations of these walk-back methods are planned in the future using the Active Response Gravity Offload Systems system at the Johnson Space Center. It is also anticipated that these techniques would be evaluated early in the mission with astronauts tethered to the PEV to better understand walk back contingencies and to develop flight rules regarding maximum excursion distances of the PEV from the habitat.

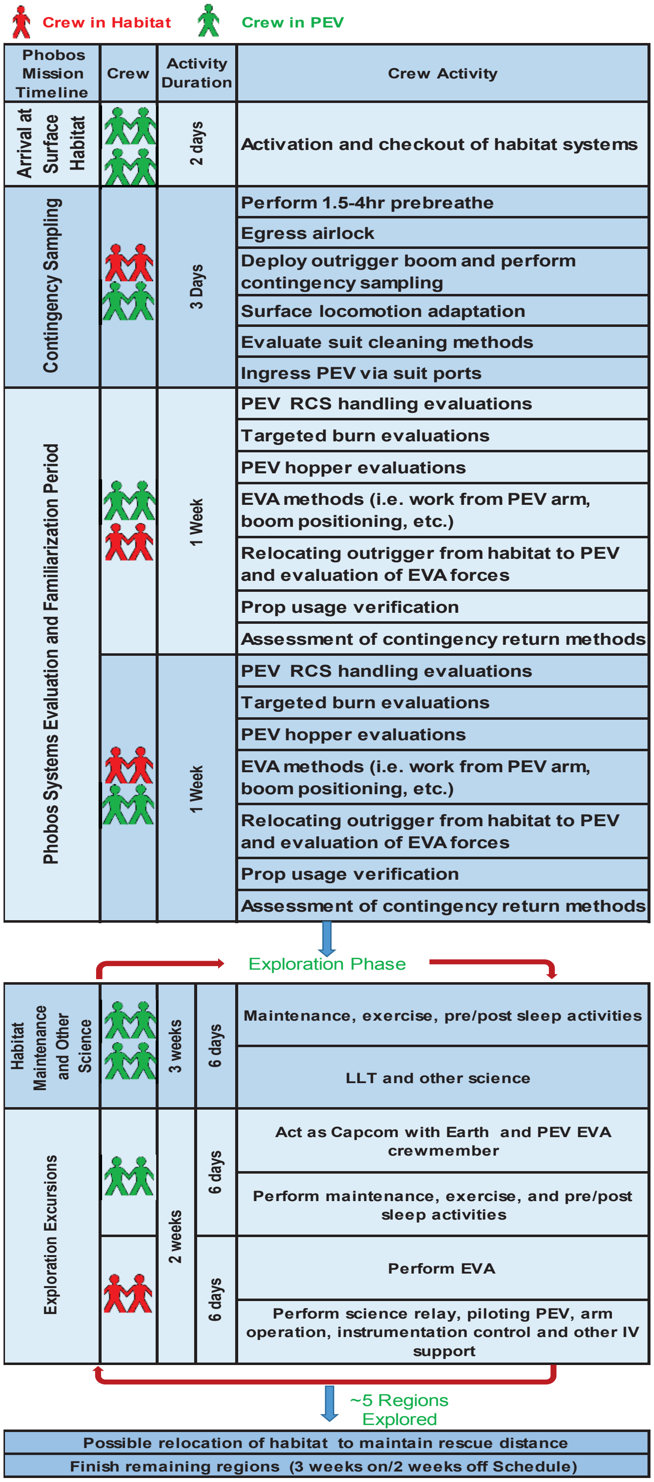
4. PROPOSED MISSION OPERATIONS & TIMELINE

The current mission architecture outlined in this paper is designed to support a 500-day mission in Phobos space with four crewmembers.

A proposed Phobos surface mission operations concept and timeline has been developed for this architecture and mission length (Figure 5). After arriving at the surface habitat, all four crewmembers would spend two days activating and inspecting the habitat systems. Once activation and checkout is complete, preparation for a contingency sampling EVA would begin. Two EV crewmembers would don EVA suits in the habitat and begin a prebreathe protocol, which would be either the 4hr ISS in-suit light exercise (ISLE) prebreathe protocol for a 4.3-psi EVA, or a 1.5-hr resting prebreathe protocol to perform a 6-psi EVA [19]. The EVA suits will be capable of both pressures via a variable pressure regulator [20]. The crewmembers would then egress the habitat airlock, deploy the habitat outriggers, and perform a contingency surface sample collection. Next, they would translate to the docked PEV, ingress the PEV via the suit ports, and begin a one-week evaluation and familiarization period within close proximity to the habitat. During this time the handling qualities of the PEV RCS and hopper systems would be evaluated with manual flying and targeted burns to verify their guidance, navigation, and control (GNC) algorithms. RCS propellant usage and hopper efficiencies would also be characterized. EVA methods would be assessed, including work from the astronaut positioning system with PFR and from outriggers on the PEV. Finally, contingency walk back methods would be evaluated with a crewmember tethered to the PEV during translations.

After the first pair of EV crewmembers completed the one-week evaluation period, they would clean their EVA suits and ingress the habitat airlock. The second pair of EV crewmembers would then undergo a similar one-week evaluation and familiarization period in the PEV. After completion of these evaluations, flight rules, procedures, and detailed exploration traverse plans would be updated as necessary; these would be coordinated with ground mission support (on Earth) over the following weeks.

The mission would then enter a nominal exploration pattern, which would begin with all four crewmembers at the habitat for three weeks. During this time, the crew would have 6 hrs per day to conduct LLT of Mars and Phobos (and possibly Deimos) surface exploration assets and other science activities (described in Section 5), and 6 hrs per day to perform pre/post-sleep activities, exercise, and general maintenance and housekeeping tasks. After this three-week period, two EV crewmembers would ingress the PEV and perform a two-week exploration excursion, while the other two IV crewmembers remain in the habitat supporting the excursion and corresponding EVAs, as well as conducting other in-house habitat tasks. The two EV crewmembers would alternate roles as PEV pilot and EV crewmember, with each EVA crewmember performing one 4-hr EVA per day, six days per week. The IV crewmembers may alternate roles in 6-hr shifts between serving as science capsule communicator (CapCom) between an Earth-based science support team and the PEV crew, and performing exercise and general housekeeping activities; both habitat crewmembers may be needed during certain portions of the PEV exploration excursion, including during EVA. Previous analog field studies conducted with communication latency (between Earth and Mars), including the NASA Research and Technology Studies (RATS) and NASA Extreme Environment Mission Operations (NEEMO), have clearly demonstrated the benefit of one or two IV crewmembers supporting EVAs, freeing the PEV crewmembers to focus on piloting and EVA tasks [18] [21]. After the PEV returns from its two-week excursion, all four crewmembers would remain at the habitat for three weeks, thus restarting the nominal exploration pattern.



Phobos Mission Timeline	Crew	Activity Duration	Crew Activity
Arrival at Surface Habitat	🟩🟩🟩🟩	2 days	Activation and checkout of habitat systems
Contingency Sampling	🟥🟥🟩🟩	3 Days	Perform 1.5-4hr prebreathe
			Egress airlock
			Deploy outrigger boom and perform contingency sampling
			Surface locomotion adaptation
			Evaluate suit cleaning methods
			Ingress PEV via suit ports
Phobos Systems Evaluation and Familiarization Period	🟩🟩🟥🟥	1 Week	PEV RCS handling evaluations
			Targeted burn evaluations
			PEV hopper evaluations
			EVA methods (i.e. work from PEV arm, boom positioning, etc.)
			Relocating outrigger from habitat to PEV and evaluation of EVA forces
			Prop usage verification
			Assessment of contingency return methods
	🟥🟥🟩🟩	1 Week	PEV RCS handling evaluations
			Targeted burn evaluations
			PEV hopper evaluations
			EVA methods (i.e. work from PEV arm, boom positioning, etc.)
			Relocating outrigger from habitat to PEV and evaluation of EVA forces
			Prop usage verification
			Assessment of contingency return methods

Exploration Phase

Habitat Maintenance and Other Science	🟩🟩🟩🟩	3 weeks	6 days	Maintenance, exercise, pre/post sleep activities
				LLT and other science
Exploration Excursions	🟩🟩	2 weeks	6 days	Act as Capcom with Earth and PEV EVA crewmember
				Perform maintenance, exercise, and pre/post sleep activities
	🟥🟥		6 days	Perform EVA
				Perform science relay, piloting PEV, arm operation, instrumentation control and other IV support

~5 Regions Explored

Possible relocation of habitat to maintain rescue distance

Finish remaining regions (3 weeks on/2 weeks off Schedule)

Figure 5. Proposed Phobos surface mission timeline.

This pattern of three weeks in the habitat (with all four crewmembers) and two weeks in PEV (with two crewmembers) would continue until approximately five regions have been explored (Figure 1). The habitat would then be relocated to be closer to the more distant exploration regions to minimize PEV excursion distances, thus reducing PEV propellant usage and increasing the safety margin for a PEV rescue scenario.

Low-Latency Teleoperations

Over the course of a 500 day Phobos mission using the proposed mission operations timeline, greater than 1800 hours will be available for LLT. This would be achieved at the rate of 6 hrs per day during the three-week time periods when all four crew are in the habitat. Continuous LLT communications with Mars surface assets from Phobos could be enabled through the use of communication relays in orbit around Mars [22, 23].

To date, all robotic planetary exploration has been performed under the constraints of high latency communications (i.e., 4-22 min each way between Earth and Mars). The high latency from Earth to planets such as Mars has historically necessitated automation or high-latency commanding as the methods of performing robotic tasks [24]. Currently, opportunities exist within the EMC for potentially mission-enhancing, low-latency teleoperation of robotic assets by human crews [25].The one-way speed of light latency would range from 20 ms at Phobos to up to 1 s at high Mars orbits [22].

In order to optimize the use of Phobos crew time for controlling Mars surface assets, the EMC has begun a study and testing program to understand the functional requirements of future LLT rovers and work systems, that will be designed to take full advantage of the benefits of LLT. The characteristics of these LLT rovers and work systems will be highly dependent on the tasks they perform and how those tasks are designed. For these reasons the study is looking across the EMC architecture (i.e., cis-lunar, lunar surface, Phobos-Deimos, and Mars surface) for candidate tasks. Categories of tasks that will be under consideration during the analysis range from landing site/outpost validation (e.g., hazard assessment, resource assessment, science assessment), outpost setup and integration (e.g., lander offloading, transporting/deployment, assembly, activation, integration), and science operations (e.g., reconnaissance, science acquisition, sample analysis).After initial task identification, a set of selection criteria will be used to identify the most appropriate candidate tasks to be performed via LLT. Examples of selection criteria include: the probability of task success increases with LLT, enabling of tasks not practical without LLT, and risk reduction for critical tasks with LLT.

These range of tasks can broadly be divided into exploration/science tasks, and Mars base infrastructure development tasks, which include offloading and transport of payloads and various assembly, maintenance and inspection tasks. The exploration/science rover tasks will incorporate various instruments and sensors that will have a range of processing times that will influence the time line, along with the speeds that the rovers are operated. It will be important to sequence these tasks to take maximize LLT productivity. It is also likely that this future generation of LLT rovers will be operated a speeds much higher than current high latency planetary exploration rovers. These higher speed rovers will have very different duty cycles than conventional rovers, with the LLT rovers being operated for shorter times at higher speeds and then having to recharge. The transport costs of these rovers will be a function of the total mass and velocity of the rover.

To better understand the relationship between transport costs and duty cycle, rovers ranging from 500 to 2000 kg gross vehicle mass (GVM) were evaluated at various traverse speeds . Selection of the mass range was based on the mass of previous Mars surface rovers including the Mars Science Laboratory, whose GVM is approximately 900 kg, including an instrument complement of approximately 80 kg [26]. Preliminary estimates performed during the initial phase of the EMC LLT study show possible necessary science instrument mass increases of 45%. Assuming a linear increase in GVM with instrument mass provides an estimate of approximately 1300kg. Rovers to support Mars surface infrastructure development tasks may require larger GVM [27]. Transport cost estimates included driving speeds ranging from 1 to 3 mph with the assumption that the average drive time in a 6 hr crew LLT period would be 3 hrs, with the remaining 3 hrs spent doing detailed observations, sampling, and analysis. A rolling resistance of 0.15 (dimensionless), gravity of 3.7 m/s^2, and a hotel load (i.e., speed-independent minimum power draw to keep systems operating) of 40 W were assumed, as a conservative starting point. The time required to recharge the rover's batteries was then approximated assuming net charging rates of 60 W and 120 W per hour, associated with conventional radioisotope thermal electric generators. Table 3 shows estimated number of hours required to recharge the rover's batteries based on traverse speed, rover mass, and assumed net charging rate. Figure 6 estimates the minimum net charging power needed for a rover to be fully charged, within the 18 hour duty cycle making it available for daily 6 hour crew LLT shifts.

Table 3 shows that battery recharge times range from 4 to 38 hours, based on a 120W charging power.. Furthermore, some of the instrument analysis tasks may require considerable processing time. These considerations suggest that a large single rover may not take full advantage of crew time for LLT, depending on its translation speed .For these reasons, consideration should be given to utilizing two or more rovers or utilizing higher powered radioisotope thermoelectric generators, if available. This would enable increased time efficiency of operations, as some rovers could be recharging while others are being used to perform LLT tasks during the 3 week periods that the Phobos crew is available to perform LLT. Consideration should also be given to having a low mass, low hotel load, high powered long range scouting rover.

Table 3. Estimated time required (hours) to recharge rover batteries as a function of rover mass, traverse speed, and charging power above hotel load.

Rover traverse speed ->		1 mph		2 mph		3 mph	
Power above hotel load ->		60 W	120 W	60 W	120 W	60 W	120 W
Total Rover Mass (kg)	500	8	4	14	7	21	10
	1000	14	7	27	13	39	20
	1500	21	10	39	20	58	29
	2000	27	13	51	26	76	38

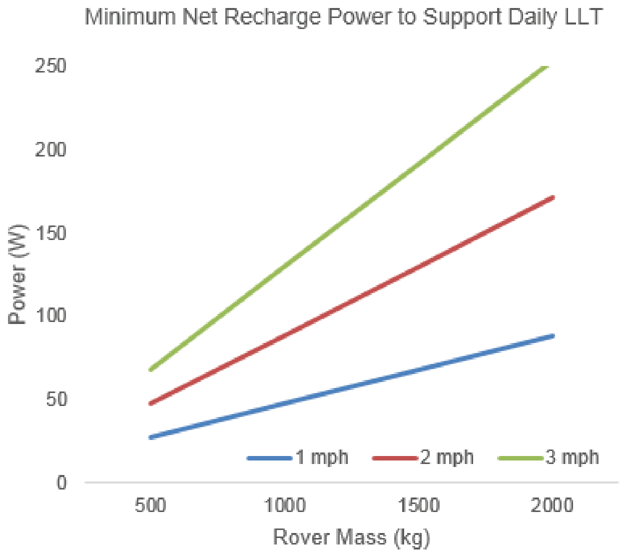


Figure 6. Minimum recharge power needed to sustain a daily LLT schedule.

As an effort to understand the interrelationships between latency time (which could vary based on Phobos location and communications relays), driving speeds, and terrain factors, a high fidelity physics mobility simulator has been developed based on the JPL ATHLETE[9], and representative Mars surface terrain. Latency times of 0,250,500,750, and 1000 ms with be evaluated at different speeds and terrains. The testing will provide initial data to further inform the characteristics for future LLT rovers that could be controlled from Phobos, during transit to Mars as well from earth.

5. PEV PHOBOS TRAVERSE ANALYSIS

Habitat relocation and PEV EVA operations are both highly dependent on propellant and power capacity. This section focuses on PEV operations; however, high-level estimates of propellant for habitat relocation are included in Table 5. The current assumption is that the PEV will traverse from region to region in a hub-and-spoke style (see Figure 1 for potential habitat landing sites, from which each region would be traveled to), with trips back to the habitat at the conclusion of each two-week excursion. While hopping from region to region would be the most mass efficient, so no propellant is required by the hopping system, there is a cost of longer transit times. With the assumption of perfect hopping efficiency, simulation estimates for region-to-region translations show they could take up to four hours. Those times could increase to tens of hours if the hopper energy is dissipated by soft surface soil mechanics; at that point, PEV power and consumables would limit exploration productivity. For these reasons, it was concluded it would be more mass efficient to use propellant for region-to-region translations, and hopping for intra-region (inter-site) exploration.

Figure 7 compares the total hydrazine propellant mass required to travel to multiple regions within an excursion (region to region) with the propellant mass to travel to a single region per excursion (thereby requiring multiple round trips to and from the habitat to explore multiple regions), with and without the use of the hopper for intra-region exploration.

The 22 potential regions explored consists of two visits to each of the eleven regions of interest. The mass of the hopper system is estimated to be 1461 kg [28]. With hopping only, the hopper paid for its mass within 5-7 regions (cross-overs between the horizontal hopper line and the top two sloped lines on Figure 7); however, with the hybrid approach the hopper pays for its mass within 9-14 regions (cross-overs between the horizontal hopper line and the bottom two sloped lines on Figure 7). If only one mission of eleven regions is planned, the hopper may not be as advantageous, although it would provide a redundant translation capability should the RCS system fail. Furthermore, the hopper would provide locomotion for additional exploration using the PEV with high-latency commanding from Earth for ongoing exploration after the crew departs.

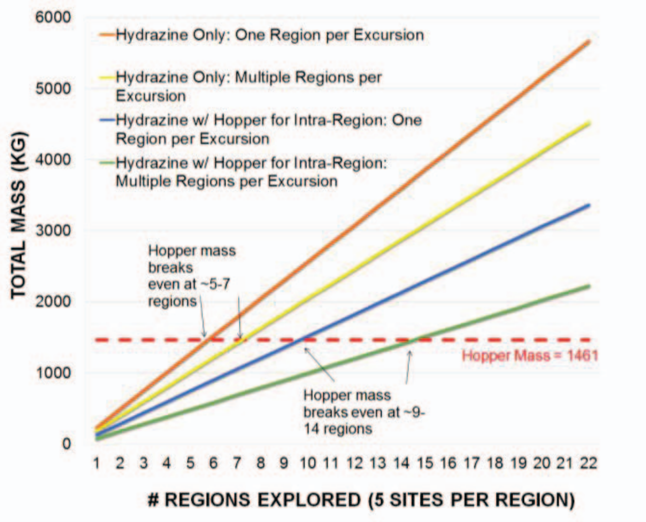


Figure 7. Total hydrazine propellant mass required to complete exploration of up to 22 regions (two visits to each of the eleven ROIs) on the Phobos surface with and without the use of a hopper for intra-region translation. The red dashed line represents the mass of the hopper. Note that these cases are not equivalent in terms of transit times, as using the hopper requires longer times.

In addition to propellant usage, PEV power generation and storage are also limiting factors for traverse planning. If the PEV's solar arrays and batteries are not capable of supporting two-week excursions, the PEV would need to return to the habitat for recharging, which would require additional propellant. PEV power generation and storage capabilities are described in the following section.

6. POWER AND INCIDENT SOLAR RADIATION ANALYSIS

Incident solar radiation plays a crucial role in power and thermal subsystems for solar-powered vehicles, such as the PEV and the habitat. A thorough understanding of solar radiation on Phobos will allow engineers to appropriately size solar arrays and batteries. A study using a high-fidelity computer simulation to investigate the lighting conditions, specifically incident solar radiation, on the Phobos surface over one Martian year was performed to provide these recommendations. The computer simulation was developed using NASA Johnson Space Center's in-house simulation tools to: (1) model the states of the Sun, Earth, Mars, and the moon using the JPL DE405 model [29], (2) model the orbit of Phobos, its surface, and its gravitational field, and (3) model the occultation of Phobos' surface due to solar eclipse by Mars and self-shadowing [30]. Here we focus on the impacts of lighting on exploration capabilities and the effects of power on mission timelines and operations.

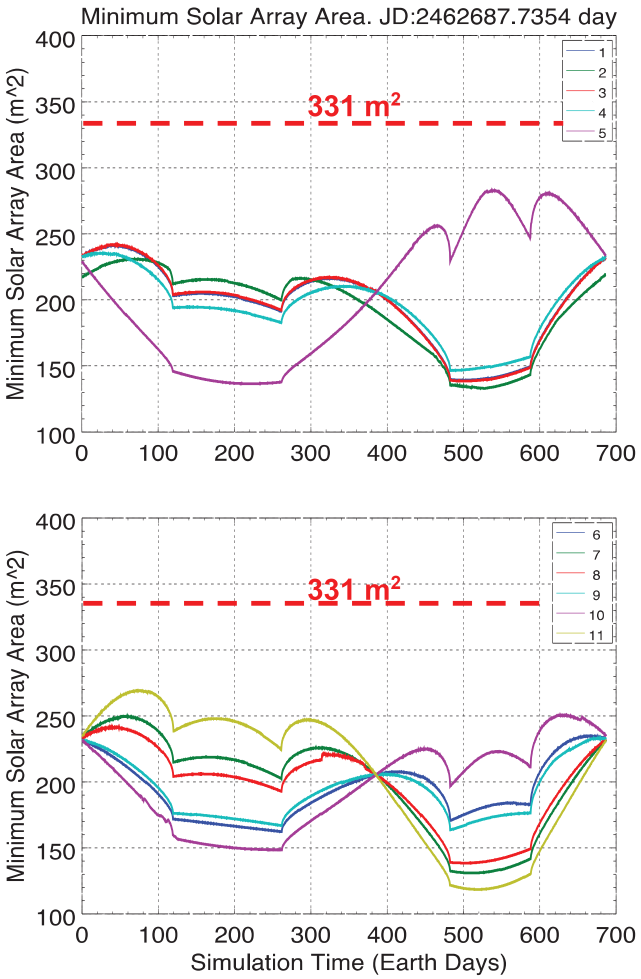


Figure 8. Minimum Sun-tracking solar array size needed to sustain a 15-kW power load for the habitat at each of the eleven regions of interest.

The eleven regions of interest (Figure 1) were evaluated over the course of the simulated Martian year in terms of the minimum solar array area needed to sustain specific power loads for the habitat and PEV. In general, many of the regions provided the necessary incident solar radiation to use the solar arrays for power generation for both the habitat and PEV. However, sites 5, 6, 10, and 11 pose more of a challenge for a fixed solar array on a PEV due to their surface location with respect to the Sun. Sites 5, 6, 10, and 11 do not receive as high an intensity of sun exposure over the course of the year and would require larger arrays on the PEV if they are not explored during the most advantageous season. Further details are provided in the following sections on habitat and PEV power analysis.

Habitat Power Analysis

Using this model, we evaluated the 331-m^2 solar arrays associated with the 150 kW (at 1 AU) SEP delivery vehicle, assuming a 30% solar array efficiency, an average 15-kW power draw needed to operate the habitat, and 80% maximum battery discharge percentage. Figure 8 shows the minimum solar array area needed to continuously power the habitat, at each of the eleven regions, as a function of mission duration, accounting for seasonal variations. All sites were shown to have reasonable margins for solar array size if solar tracking arrays are used. If the Chem-SEP Hybrid delivery vehicle, with 435 kW is used, it will provide even greater power margins. The analysis can also be used to determine a preferred sequence for region-to-region excursions that would maximize the opportunity for power and sun exposure during the year; this sequencing is left as future work.

PEV Power Analysis

PEV power requirements were assessed with the same model and assumptions discussed in the previous sections. **Error! Reference source not found.** shows the solar array size necessary to visit all eleven science regions during some portion of the year. Four different PEV power loads and assumptions of fixed and solar tracking arrays were modeled. The average power generation requirement of 1.67 kW in the table over a 24-hr period resulted from assuming the PEV required 3 kW for nominal operations, 8 hr per day, and that the PEV would be powered down to the 1-kW hotel load (the minimum power to keep the mission critical systems operating) for the remaining 16 hr per day. It was also assumed that the PEV would have 120 kWh of energy stored in onboard batteries, and that the solar tracking arrays would be deployed anytime the PEV was stationary (but retracted during translation). Assuming 30% solar array efficiency, Table 4 shows that 43 m^2 fixed solar tracking arrays would provide sufficient power generation for the PEV to perform up to two-week excursions to all eleven science regions. However, the PEV could not perform two-week excursions to any region at any time of the year. Therefore, upgrading to solar tracking arrays and planning the sequence in which to explore the regions would need to be performed; alternately, the duration of excursion to some regions would have to be adjusted to be less than two weeks.

Table 4. Minimum solar array size requirements for varying PEV power loads to visit eleven science regions.

Average Power Draw per day (kW)	Array Size (m^2) Fixed	 Solar Tracking
1.67	43	28
3	77	52
4	102	69
5	128	85

Alternative Energy Storage Technologies

While still under investigation and in an early prototype state, rechargeable nanoelectrofuel technologies could provide power and energy storage to the PEV and reduce dependency on solar arrays. In these nanofluid flow batteries, the energy is stored in nano phase salts dissolved in water, with one tank containing positively charged nano particles and the other tank with negatively charged particles which combine in a half cell reversible reaction to produce power. [31]. The nano electrofuel can have a specific energy of up to 600 Wh/kg compared to Li-ion batteries with approximately 200 Wh/kg.

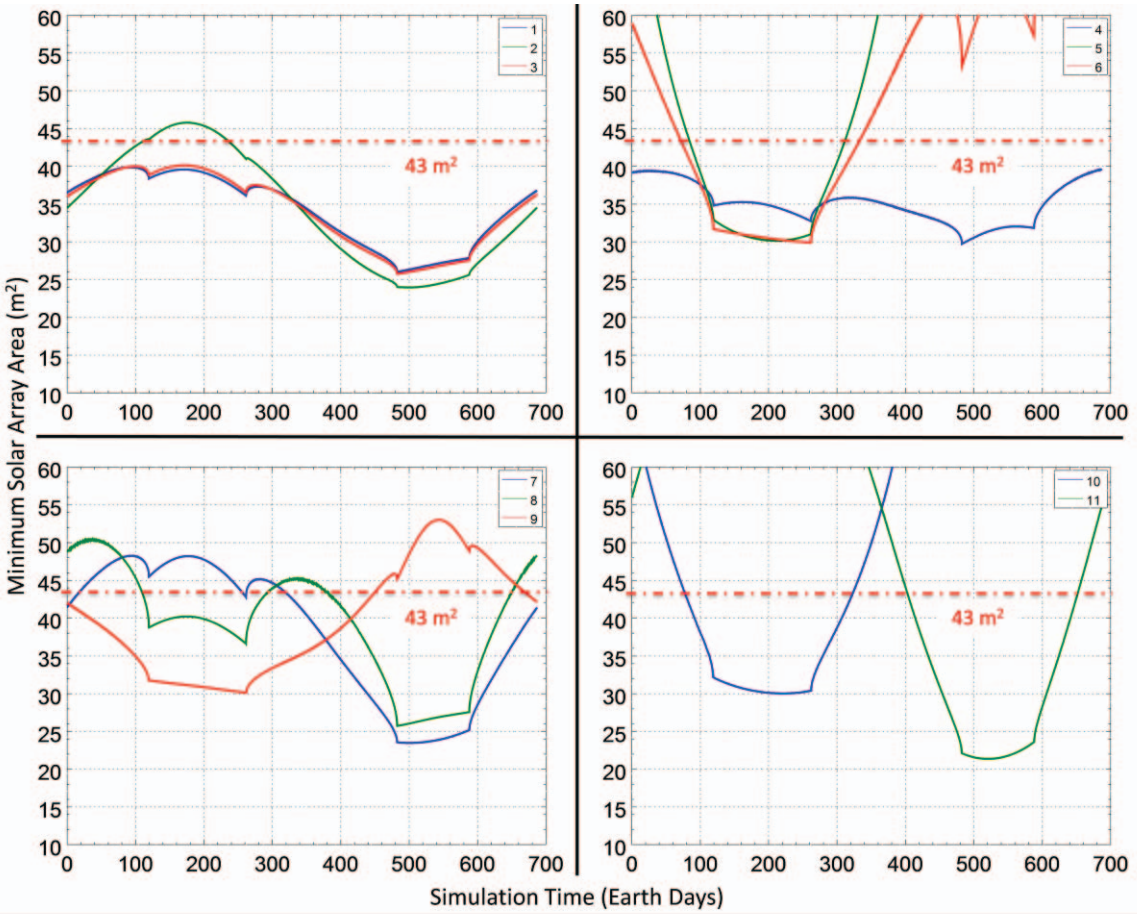


Figure 9. Minimum solar array area needed to power a PEV at the eleven regions of interest if fixed solar arrays of $43m^2$ are used as a worst case.

The discharged nanofluid can either be recharged in place or pumped out and replaced with charged nanofluid. The recharge times are faster than recharging lithium ion batteries and are unlimited in terms of the number of recharge cycles [32]. While this still requires a power source to recharge, the potential for increased energy storage means fewer solar arrays are needed.

Nanoelectrofuel technology could provide an attractive supplement to PEV batteries, as the PEV's design already incorporates 500 pounds of water which serves as both radiation protection for solar particle events (SPEs), and as a fusible heat sink to supplement passive radiators during peak power loads. This water could potentially be infused with the charged nanoparticles providing energy storage in addition to the SPE protection and thermal control function.

If the 500 lb of water already in the PEV were infused the charged nano-particles that would provide up to three days of energy to operate the PEV. Additional nanofluid could extend PEV excursions to seven or more days without the use of solar arrays for recharging enabling excursions into regions with low sunlight. Further analysis of this alternative power generation and energy storage technology is left as future work.

7. HABITAT DOCKING FORCE ANALYSIS

Docking the PEV with the habitat on the Phobos surface may result in unfavorable stability scenarios as the momentum exchange due to the docking of the PEV may cause the habitat-PEV stack to rotate and translate. The habitat-PEV dynamic response after docking was investigated as part of this study. A preliminary static and rotational dynamics analysis was conducted for the PEV docking with the habitat. A free body diagram of the model is illustrated in Figure 10, where x-y-z represents the habitat structure frame and x'-y'-z' represents PEV's structure frame. Figure 11 describes the maximum tilt angles induced on a 30-T habitat (with 25-ft outriggers deployed) on varying ground slopes by a 7-T PEV docking at speeds between 0.05 and 0.3 m/s. For docking speeds less than 0.1 m/s, the PEV does not significantly destabilize the habitat when docking is performed on a relatively flat surface (e.g., between −10 and +10°). However, when docking is performed with the habitat on a positive ground slope (meaning that the PEV is traveling uphill toward a habitat tilted toward it), the stability margin (i.e. horizontal distance from the center of mass to the nearest landing leg contact point) increases; when docking is performed with the habitat on a negative ground slope, the stability margin decreases.

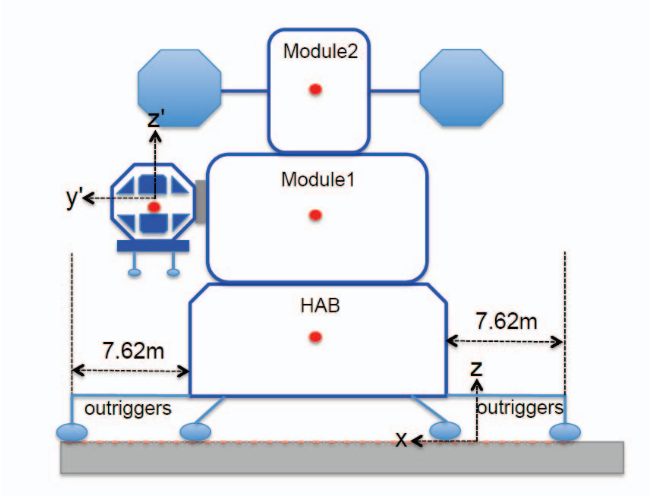


Figure 10. Free-body diagram of habitat-PEV stack on level ground with 25-ft (7.62-m) outriggers deployed.

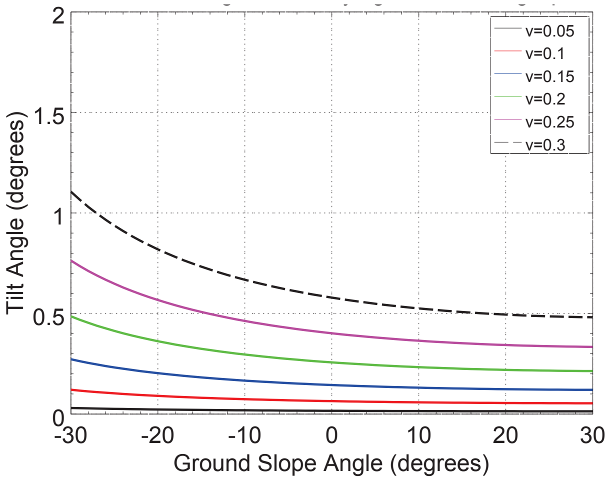


Figure 11. Tilt angles for a 30T habitat on varying ground slopes at varying PEV docking speeds (m/s).

Figure 12 illustrates the time it takes for a 30-T habitat (with 25-ft outriggers deployed) on varying ground slopes to settle after a 7T PEV docks to it at speeds between 0.05 and 0.3 m/s. Faster docking speeds and more negative ground slope angles lead to longer settling times. For example with a docking velocity of 0.2 m/s, that habitat would tilt approximately 0.25 degrees on level ground and require approximately 15 s to settle. In general, performing PEV docking on a relatively flat surface and at slower speeds is preferred, as it reduces habitat displacement dynamics . The configuration of the habitat requires docking to the side hatches, requiring constant up firing pulses to be performed to offset the effects of gravity, this combined with cross coupling within the RCS control system results in a challenging piloting task which introduces the risk of a failed docking and increases propellant usage. With a failed docking attempt, the habitat will be displaced, and then return over a period of seconds, resulting in complicated docking dynamics, that might introduce the risk of inadvertent contact, resulting in potential damage to the PEV, habitat and docking system. For these reasons we concluded that berthing should be the nominal docking method. To berth, the PEV would use its robotic positioning arm to grapple the habitat. Once grappled, the robotic positioning arm would then slowly berth the PEV to the side hatch. Berthing should reduce propellant usage, increase the reliably of mating the PEV to the habitat, and reduce the static instability caused by a docking attempt [33].

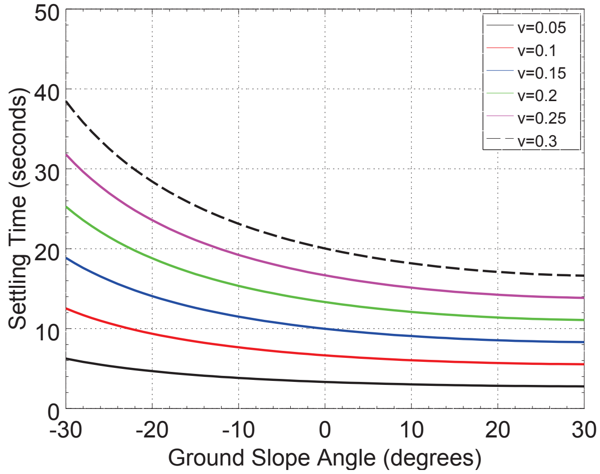


Figure 12. Settling time for a 30-T habitat after PEV docking at varying speeds (m/s).

8. EVA FORCE ANALYSIS

In the low-gravity environment of Phobos, forces associated with performing EVA tasks, such as sample collection and surface core drilling, will need to be reacted and to provide a stable work platform. The feasibility of anchoring on Phobos remains a large uncertainty, as little is known about the soil mechanics. Furthermore, the low gravity levels result in a very low soil mass, which limits the forces anchors can support. Instead of anchoring a vehicle, using outriggers allows a larger EVA contact force to be applied before the vehicle will begin to tilt. One type of outrigger support system was evaluated under simulated Phobos gravity during the NEEMO 20 mission in July 2015 (Figure 13) [21].

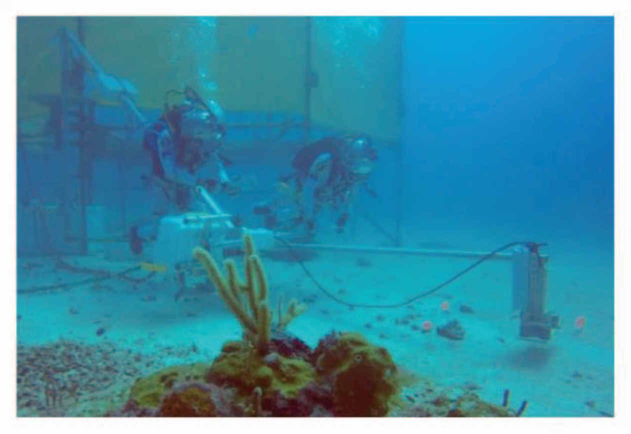


Figure 13. Crewmembers adjusting outrigger boom during NEEMO 20 mission prior to sampling.

NEEMO 20 evaluations were focused on the kinematics and general usability of the outrigger as a work platform that encompassed a PFR, a BRT, and a sliding tool/sample bag stanchion system. The NEEMO 20 crewmembers rated the kinematics and usability of the outrigger system as acceptable with no recommended improvements (Figure 14). These tests did not address the dynamics associated with this type of work platform at the Phobos gravity level; those tests are planned in the future using the Active Response Gravity Offloading System (ARGOS) at NASA Johnson Space Center.

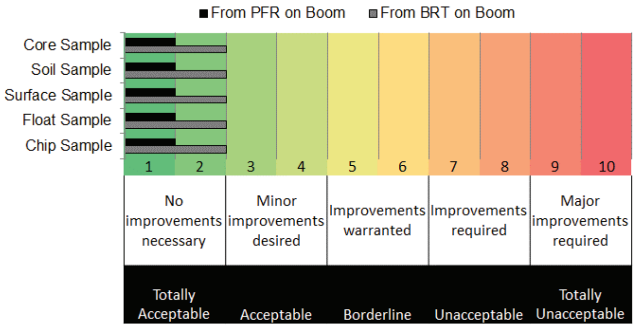


Figure 14. Acceptability ratings associated with performance of different forms of sampling from the outrigger boom during NEEMO 20 using the portable foot restraint (PFR) and body restraint tether (BRT).

For this paper, the reaction forces of a PEV on the surface of Phobos in response to forces generated by EVA sampling tasks were modeled. The model described the reaction of the PEV to forces generated by an astronaut on the end of a positioning arm on the front of the PEV (Figure 15). The model calculated when the PEV would be tilted off the surface, how long the crewmember would remain in contact with the surface after a force is applied, how long it would take for the vehicle to settle, and at what point the vehicle would topple. The model made the following assumptions:

- Gravitational acceleration was perpendicular to the surface of the planetary body.
- The local reference frame was fixed on the planetary body.
- The PEV, EVA supporting structure, and 25-ft outriggers were assumed to be rigid bodies,
- The mass of the PEV was 7 T.
- The mass of the outriggers was neglected.
- The EVA application point, the vehicle's center of mass, and the pivot point were coplanar in the x-z plane of the vehicle's structure frame.
- A 6-ft crewmember was assumed to have a 2-ft reach, and was placed at the end of a 10-ft positioning arm.

The force required to lift the PEV corresponds to the gravitational force on the vehicle. On Phobos, the lowest total surface acceleration is 0.004 m/s^2, near the sub-Mars point [34]. This lowest surface gravity represents a worst-case analysis and was used to generate the results.

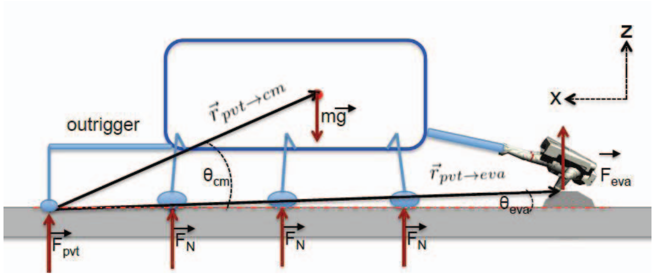


Figure 15. Free body diagram of the PEV on a flat surface.

Figure 16 shows the maximum tilt angle (i.e., the angle the PEV tilts in relation to the force applied by the astronaut), contact time (i.e., the time the astronaut can remain in contact with the surface before the 2 ft. reach limit is exceeded) distance lifted (i.e., the vertical distance the structure is lifted from the ground plane), and settling time (the round-trip time for the structure to return to the surface) for EVA forces up to 100 lbf. For example, if the crewmember applied a 20lb normal force, the PEV would tilt up to approximately 12°, and the crewmember would lose contact with the surface after approximately 7 s, be lifted 10 ft. off of the surface, and take over 1 min to regain contact with the surface.

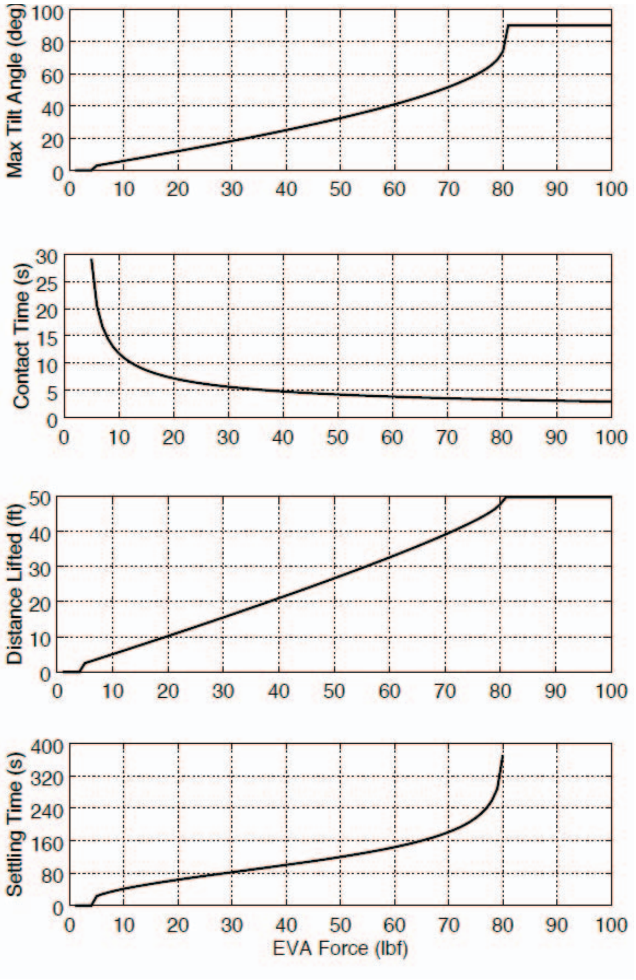


Figure 16. PEV force analysis (lbf) for various metrics. Saturation points are observed beyond 80 lbf, indicating that the PEV would topple at forces greater than 80 lbf.

At the full 10 ft extension of the positioning arm, forces below 4 lbf will not tilt the PEV regardless of force application duration. When the arm is fully retracted, forces up to 8 lbf will not tilt the vehicle. It is estimated that many sampling tasks, such as picking up a float sample or performing surface tape samples, soil scoop samples, or chip samples, will result in small transient, off-surface normal forces that will likely not tilt the vehicle beyond the 2 ft reach of the crewmember; however, the quantitative characterization of actual EVA forces associated with these sampling tasks has not yet been performed and is planned as forward work. Some EVA tasks, such as large core drilling, will certainly result in high forces that will cause the vehicle to tilt. However, the model estimates that it would take an 80 lbf to topple the vehicle. In general, an EVA force that is greater than the weight of the vehicle will lift the PEV in the weak gravitational environment of Phobos. For tasks resulting in high forces, the PEV RCS system would be programmed to fire and counteract the forces, thus limiting the tilt and translation of the vehicle. Importantly, the EV crewmember will be receiving continuous motion feedback resulting from their application of forces, and should be able to adapt their techniques to minimize displacements off the surface. For example soil samples could obtained with a shorter more tangential application versus perpendicular force application.

9. MISSION ARCHITECTURE MASSES AND DELIVERY CAPABILITY

The preceding sections of this paper have described the overall mission architecture, operational concepts, and timelines, as well as an analysis of power, lighting and stability for the habitat and PEV. These analyses have informed the conceptual design of all of the elements that would make up a human Phobos mission. This section describes the mass estimates (Table 5) and delivery capabilities (Figure 17) to support such a mission. The mass estimates for the habitat, Phobos taxi, and logistics were based on parametric models that have been developed and utilized for this and other architectural studies [7, 35]. The mass of the PEV was based on a detailed mass equipment list derived from a combination of subsystem schematics and functional prototypes of various PEV subsystems, including the cabin structure, avionics, hatches, life support systems (including waste control and food systems), fusible heat sink, pressure control system, suit ports, and displays and controls.. Estimates for habitat and PEV propellant usage were based on the Copernicus and NASA Exploration Systems Simulations models (NExSyS) models [36]. The total mass estimate for the habitat, cargo, propellant, PEV, and Phobos taxi is approximately 56,550 kg.

Figure 16 shows the cargo payload delivery capability using a chemical/SEP hybrid delivery vehicle for launch dates in the 2030s [6, 37]. These numbers assume that the delivery vehicle drops off the taxi in HMO and then uses the SEP to spiral the HAB and PEV to Phobos orbit. Launch opportunities in 2030 and 2033 provide a cargo delivery capacity of 78,372 and 72,737 kg, respectively, resulting in mass margins of 16 to 22 T. The payload delivery capability for the 2035, and 2037 launch dates is reduced to 60 T, which closes with mass margins reduced to 4 to 5 T.

Table 5. Mass Equipment List for the estimated habitat and associated exploration systems mass for a 500 day Phobos surface mission.

Estimated Mars Moons System Masses (kg)	
Phobos Habitat Components	
Habitat (dry)	18212
Landing gear	470
Additional RCS hardware	270
Other attitude control (e.g., CMG)	150
Supplemental GN&C	75
Outriggers/Booms	115
Cargo	
Logistics (500 days at Phobos)	10106
ECLSS fluids/gases	613
Propellant	
DRO to Surface, Region to Region Transfers, and contingencies (Habitat)	1000
PEV Excursions, DRO to Surface transfers, and contingencies	1265
Exploration Systems	
PEV	7422
Phobos Taxi	17000
Total Mass - Habitat and Systems	**56548**

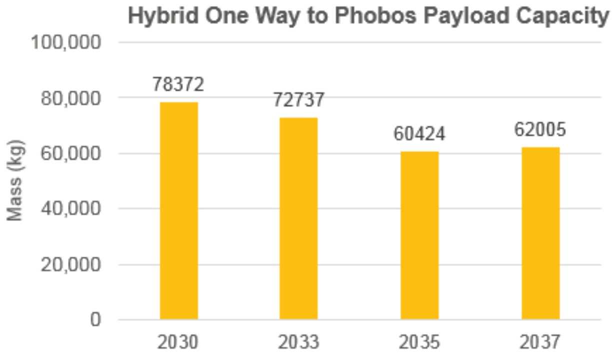


Figure 17. Cargo payload masses for various launch years to Phobos.

Our Phobos mission architecture development and associated analyses show that a human Phobos mission is a realistic opportunity that closes with mass margins, incorporates credible EVA exploration techniques that do not require anchoring, provides the exploration capability to address 100% of the reference science objectives, and results in a 34% reduction in radiation exposure [7] compared to an equivalent duration HMO mission. It also provides in excess of 1800 hrs of crew time for LLT of Mars surface assets to perform exploration science and prepare for a future human Mars surface mission. Through this architecture development we have demonstrated that Phobos is a viable human target and an opportunity for a mission to Martian space as early as 2030.

10. PHOBOS: AN INVESTMENT TOWARD MARS SURFACE MISSIONS

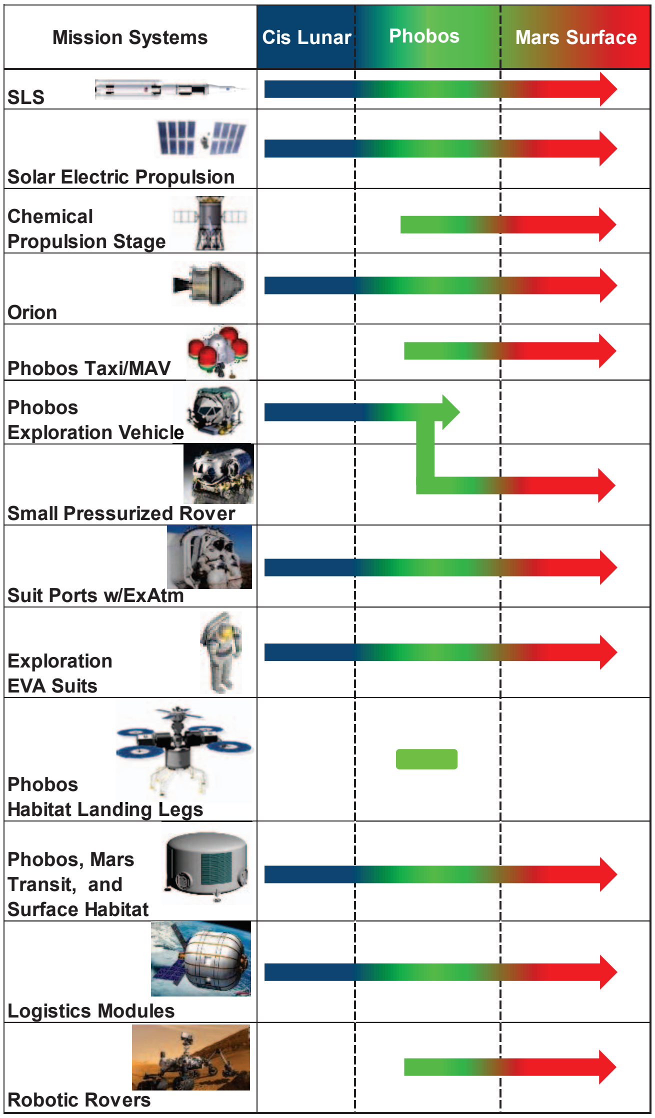
The Phobos architecture developed in this study was conducted under a ground rule to minimize any Phobos-unique elements and stress the development of transportation and exploration assets that would be directly relevant to a future Mars surface mission. This Phobos architecture builds heavily on the cis-Lunar proving ground activities and then develops and tests the Mars transportation infrastructure, including the crewed MTV and the cargo delivery vehicles that would be needed to support a Mars surface mission. It would additionally develop and validate the cis-Lunar aggregation methods for these systems. It also develops the habitation systems that would be used for the Mars transit vehicle, and the Phobos and Mars surface habitats. The Phobos taxi, based on the MAV second-stage propulsion system and would serve to validate the design and operation of the MAV. The Phobos PEV would incorporate the same cabin, and utilize the same exploration atmosphere and suit ports that would be used for the Mars surface rover. The EVA suits, dust mitigation and control systems would be largely common with the Mars surface EVA system, and would provide the opportunity to evaluate and refine the techniques that would be used on Mars' surface.

The capability of performing LLT of Mars surface rovers from Phobos would enhance the Mars surface mission by validating landing sites and possibly enabling development of some of the Mars surface infrastructure. The Phobos mission would also serve to validate and refine both science and engineering mission operations techniques that address the effects of time delay. The only Phobos unique elements of this architecture would be the Phobos habitat landing legs (which could be derived from the asteroid redirect mission [38]), the PEV RCS sled, and hopper legs. Figure 6 illustrates the systems evolution and commonality from the cis-Lunar proving ground to the Mars surface.

It is recognized that the Phobos mission development and execution will take time and have costs that could potentially be spent on a Mars surface mission. However, a Mars surface mission requires additional expensive, low technology readiness level (TRL) elements including, but not limited to: Mars surface landers and the associated entry, descent, and landing (EDL) technologies, Mars surface power and distribution systems, lander offloading systems, in-situ resource utilization (ISRU) systems, and surface mobility systems. It is also recognized that operating within a constrained budget environment, NASA and its international partners will want to have a steadily evolving pace of spaceflight activities that culminate in a Mars surface mission, and the Phobos mission provides that framework, analogous to what Gemini did for the Apollo Program [39].

Additionally, a Phobos Mission offers numerous public engagement benefits, including the fact that Phobos is only 9000 Km from Mars and that Mars will loom large over the horizon of all the Phobos exploration and public outreach and engagement activities.

Table 6. Systems Evolution and Commonality from the Cis Lunar proving ground through Phobos to Mars surface.



Mission Systems	Cis Lunar	Phobos	Mars Surface
SLS	━━━	━━━	━━➜
Solar Electric Propulsion	━━━	━━━	━━➜
Chemical Propulsion Stage		━━━	━━➜
Orion	━━━	━━━	━━➜
Phobos Taxi/MAV		━━━	━━➜
Phobos Exploration Vehicle	━━━	━━➜	
Small Pressurized Rover		━━━	━━➜
Suit Ports w/ExAtm	━━━	━━━	━━➜
Exploration EVA Suits	━━━	━━━	━━➜
Phobos Habitat Landing Legs		━	
Phobos, Mars Transit, and Surface Habitat	━━━	━━━	━━➜
Logistics Modules	━━━	━━━	━━➜
Robotic Rovers		━━━	━━➜

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11. BIOGRAPHY

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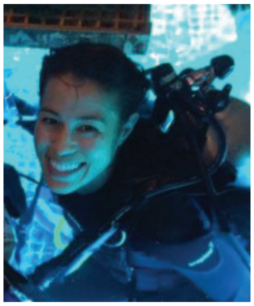

Kara Beaton *received her bachelor's and master's degrees in aerospace engineering from the University of Illinois and Massachusetts Institute of Technology, respectively. She completed her doctoral studies in biomedical engineering at the Johns Hopkins University School of Medicine. She has extensive experience with operationally driven aerospace and biomedical research with the US Navy, NASA, and various clinical laboratories. She is currently a research engineer in the EVA Physiology Laboratory at JSC, where she is involved in the Exploration Analogs and Mission Development and the Mars Moons Human Spaceflight Architecture teams.*

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Steve Chappell attended the University of Michigan and earned a bachelor's degree in aerospace engineering. He also earned master's 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.

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