Human and Robotic Exploration Missions to Phobos prior to Crewed Mars Surface Missions

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***Abstract*— Phobos is a scientifically significant destination that would facilitate the development and operation of the human Mars transportation infrastructure, unmanned cargo delivery systems and other Mars surface systems. In addition to developing systems relevant to Mars surface missions, Phobos offers engineering, operational, and public engagement opportunities that could enhance subsequent Mars surface operations. These opportunities include the use of low latency teleoperations to control Mars surface assets associated with exploration science, human landing-site selection and infrastructure development, which may include in situ resource utilization (ISRU) to provide liquid oxygen for the Mars Ascent Vehicle (MAV).**

A human mission to Mars' moons would be preceded by a cargo predeploy of a 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 based systems, with the habitat descending to the surface and the PEV remaining in orbit. When a crewed mission is launched to Phobos, it would include the remaining systems to support the crew during the Earth-Mars transit and to reach Phobos after insertion in to Mars orbit. The crew would taxi from Mars orbit to Phobos to join with the predeployed systems in a spacecraft that is based on a MAV, dock with and transfer to the PEV in Phobos orbit, and descend in the PEV to the surface habitat.

A static Phobos surface habitat was chosen as a baseline architecture, in combination with the PEV that was used to descend from orbit as the main exploration vehicle. The habitat would, however, 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. To supplement exploration capabilities of the PEV, the surface habitat would utilize deployable EVA support structures that allow astronauts to work from portable foot restraints or body restrain tethers in the vicinity of the habitat. Prototype structures were tested as part of NEEMO 20.

PEVs would contain closed loop guidance and provide life support and consumables for two crew for 2 weeks plus reserves. The PEV has a cabin that uses the exploration atmosphere of 8.2 psi with 34% oxygen, enabling use of suit ports for rapid EVA with minimal oxygen prebreathe as well as dust control by keeping the suits outside the pressurized volume. When equipped with outriggers and control moment gyros, the PEV enables EVA tasks of up to 8 pounds of force application without the need to anchor. Tasks with higher force requirements can be performed with PEV propulsion providing the necessary thrust to react forces.

Exploration of Phobos builds heavily from the developments of the cis-lunar proving ground, and significantly reduces Mars surface risk by facilitating the development and testing of habitats, MAVs, and pressurized rover cabins that are all Mars surface forward. A robotic precursor mission to Phobos and Deimos is also under consideration and would need to launch in 2022 to support a 2031 human Phobos mission.

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1. INTRODUCTION

The Evolvable Mars Campaign (EMC) is a technology capability driven strategy to identify the exploration framework needed to ultimately place humans on Mars' surface [1-3]. Within the EMC, human exploration of the moons of Mars is being considered as an intermediate step resulting in the development and operation of new technologies, operations concepts, and systems. Previous work conducted by NASA's Human Spaceflight Architecture Team (HAT) evaluated several architectural options for a mission to Phobos [4]. Seven architectures were proposed in that study, this paper will describe the current baseline down selected from those cases and the rationale for doing so.

Exploration of Mars' moons provides significant benefits towards successfully completing a Mars surface mission in addition to the scientific exploration that will be conducted on Phobos. Missions to Phobos provide opportunity for crews to more effectively scout potential Mars surface landing sites, and perform mission critical tasks via Low Latency Teleoperations (LLT) from Phobos surface, a Phobos distant retrograde orbit (DRO), and/or while en route to the moon. Crews can oversee tasks such as in-situ resource utilization (ISRU), assembly and operational verification of Mars surface components, and more quickly operate robotic rovers on Mars surface[5].

This paper describes the current mission architecture for Phobos surface exploration. The paper is comprised of 8 parts. Section 2 describes the past efforts to define several mission architectures, primary trades, assumptions used and preliminary operations concepts for exploration and EVA on Phobos. Section 3 outlines the current baseline mission timeline and operational scheme for conducting exploration over the course of the mission following crew landing on Phobos surface. Section 4 provides analysis related to force loading crewmembers and vehicles may experience while performing Extravehicular Activity (EVA) on Phobos. Section 5 provides an examination of the solar power capability on Phobos surface and impacts to mission design. Section 6 discusses the overall Phobos mission architecture and its place within the EMC as an intermediate step towards Mars surface operations. Conclusions are in Section 7.

2. SUMMARY OF ARCHITECTURE CASES AND ASSESSMENT METHODOLOGY

Previous work conducted by the HAT described seven mission architecture cases [4], which have since been evaluated for their feasibility across several criteria including crew size, number of vehicles required, launch payload capacity needed to deliver assets to Martian space, and operational and exploratory capability in order to establish the baseline architecture described in this paper. A summary of the seven cases evaluated in [4] is presented in Table 1 .

Table 1 Mission Architecture Cases A-G. PEV is the pressurized excursion vehicle, described below.

	Case A	Case B	Case C	Case D	Case E	Case F	Case G
Crew Size	2		4				
Duration (days)	5-50			50-500			
Crew Taxi	Taxi/ Lander	PEV with Detachable Service Module				Minimal Taxi	
Pre-Staged Habitat	None			20km DRO	Fixed Surface		Mobile Surface
Pre-Staged PEV	No		Yes			No	
EVA Mobility	Booms	PEV				Booms	

Mission Architecture Evaluation Criteria

Mission architectures are created and evaluated based on three main criteria: Crew Size, Mission Duration, and Vehicles needed. For crew size it was assumed in all mission architectures that a four-person crew transits from Earth to a one-sol High Mars Orbit (HMO) with varying numbers of crewmembers remaining in HMO or descending to Phobos surface depending on the mission. The mission duration was evaluated for a variety of different lengths, with the remainder of time spent in the Mars system assumed to be spent by crews in the Mars Transit Vehicle (MTV) in HMO.

The vehicle used to transport crewmembers between HMO and Phobos is referred to as the crew taxi. For the study described in [4], 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. By the time of the writing of this paper, the current understanding is that a vehicle based on the Mars Ascent Vehicle (or a common cabin structure) would be used for the PEV and any ascent/descent module needed for Phobos space. This places a Phobos mission in line with the Evolvable Mars Campaign (EMC) and helps to drive design and development of the MAV.

The PEV concept is a small pressurized vehicle that could function as an EVA work system 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. The PEV is an evolution of the lunar electric rover concept developed for lunar surface habitation and exploration during the Constellation program, and which was more recently adapted and evaluated for exploration of near-Earth asteroids [6]. The PEV is augmented with a mechanical propulsion system, hereafter referred to as a "hopper", and is derived from the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) [7]. 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 4).

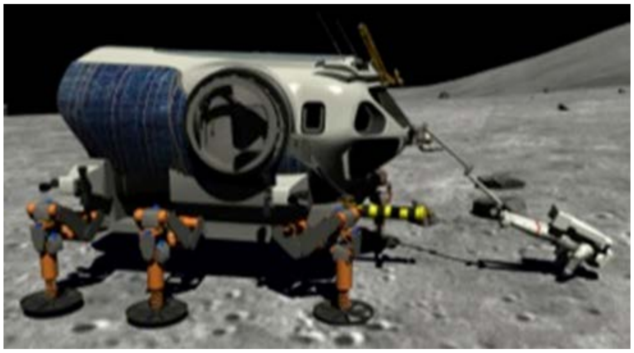


Figure 1 Simulation screen capture showing PEV with hopper system and astronaut on an APS.

Lastly, several habitat options were investigated, included mobile and static habitats to support missions varying in length from 50-500 days. All such habitats were assumed to be predeployed by a solar electric propulsion (SEP) tug spacecraft [8], which would also be used to provide solar power for the 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 [9, 10] and these habitat concepts were incorporated into the different Phobos mission architectures.

Exploration Regions – 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 described in Section 7. However, to enable development of representative mission content, 11 representative regions of scientific interest were identified. The regions are: 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. Region locations are shown in Figure 1, and each region is assumed to contain 5 subsites in which a previously described standard battery of EVA tasks will be performed [4].

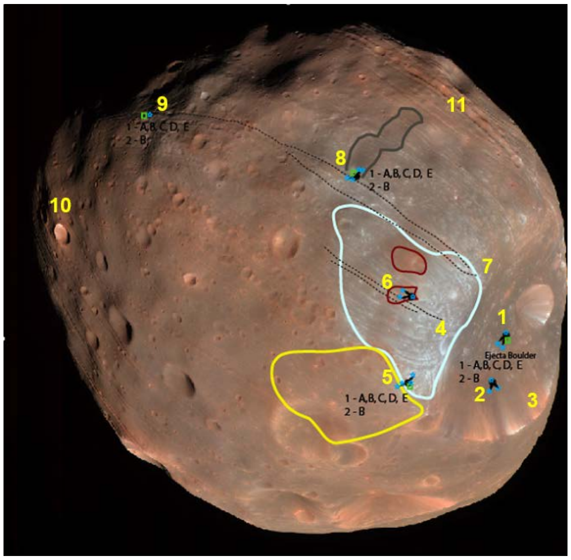


Figure 2 11 example regions of scientific interest used in evaluation of mission architectures.

3. DOWN SELECTED PHOBOS MISSION ARCHITECTURE AND BASELINE OPERATIONS

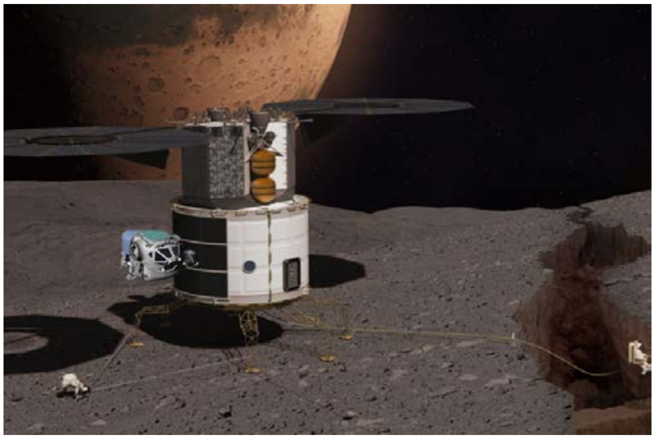


Figure 3 Graphical representation of the habitat on Phobos with the PEV docked. Crewmembers will work from tethers and booms to evaluate EVA systems and train in Phobos gravity at the start of the surface mission.

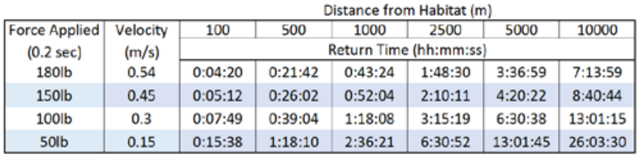
Overall mission timeline

The baseline mission architecture outlined in this paper is a 500 day mission with four crewmembers that requires a predeployment of a habitat to Phobos surface and PEV to Phobos DRO (depicted in Figure 2), with the MAV acting as a taxi to ferry the crew from the Mars Transit Vehicle to the PEV.

Following the arrival at the habitat on Phobos surface by the crew in the PEV, crewmembers will don suits via suit ports and deploy outriggers to perform contingency sampling on the surface. Subsequently crewmembers will perform a two day activation and checkout period of the habitat hardware and systems, before beginning a two week training with the PEV within SAFER distance of the habitat (~500m). A pair of crewmembers will each spend one week in training over the two weeks, alternating weeks. Functions assessed may include PEV RCS handling, PEV hopper handling, EVA methods (working from PEV, boom positioning, etc.), evaluation of tolerable force loads on booms both from PEV and habitat, verification that actual propellant usage is within estimates, and performance of an assessment of human locomotive capability as it pertains to self-rescue.

The low gravity nature of Phobos provides the possibility for the crew to translate on the surface in the event of a PEV failure without the use of propellant, which may offer a favorable trade for mass savings and offer more safety margin in both the ability of the crew to self-rescue back to the habitat, and removing the need for the habitat to relocate and rescue the two crewmembers from the failed PEV. Prior modeling efforts have shown that the preferred method of locomotion in a low gravity environment is in a prone position with achievable traverse rates on the order of 0.13m/s [11]. This position is similar to crawling along the bottom of a pool in near neutral buoyancy making it possible to train future crewmembers in proper techniques for optimal low gravity movement. A preliminary analysis of an ideal Phobos traverse was conducted and provided early confidence that a human powered self-rescue may be possible. A table of these results and expected return times to the hab for an applied force by the crewmember at various velocities is presented in Table 2.

Table 2. Expected return times for various distances from the habitat. Forces are applied at an optimal take off angle of 45º for 0.2 seconds.



		Distance from Habitat (m)					
Force Applied (0.2 sec)	Velocity (m/s)	100	500	1000	2500	5000	10000
		Return Time (hh:mm:ss)					
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

Assuming that system checkouts, and Phobos surface mobility and EVA operations training are successfully completed, crews will begin the exploration phase of the timeline. The four crewmembers will spend three weeks in the habitat performing maintenance and exploration EVA preparations. These three weeks will also provide approximately 6 hours per day for LLT and other science. Every three weeks, 2 crew will explore a scientific region in the PEV for a two week excursion. The general concept for exploration activity is to have one habitat crewmember act as the CapCom with Earth and the PEV EVA crewmember (6hrs/day), one habitat crewmember performing maintenance and other science (6hrs/day), one PEV crewmember performing EVA (4 hrs. /day), and one PEV crewmember performing exploration science, piloting the PEV and performing other functions related to IV support (6 hrs. /day).

This pattern of three weeks in habitat (4 crewmembers) and 2 weeks in PEV (2 crewmembers) will continue until approximately five regions have been explored. Based on current architecture and mission timelines, it may be necessary to relocate the habitat once approximately five regions are explored in order to maintain a minimum safe distance between it and the PEV at a region should a PEV failure occur and a rescue by the habitat becomes necessary.

Habitat relocation and PEV EVA operations are highly dependent on propellant and power capacity. The current assumption is that the PEV will traverse from region to region in a hub and spoke style, with excursions back to the habitat at the conclusion of each two week EVA. As part of this study the use of the PEV hopper to traverse from region to region versus the use of propellant exclusively was examined. Figure 3 plots the mass trades for using the hopper to travel between regions, and to explore the region sites against using propellant exclusively to complete all excursions.

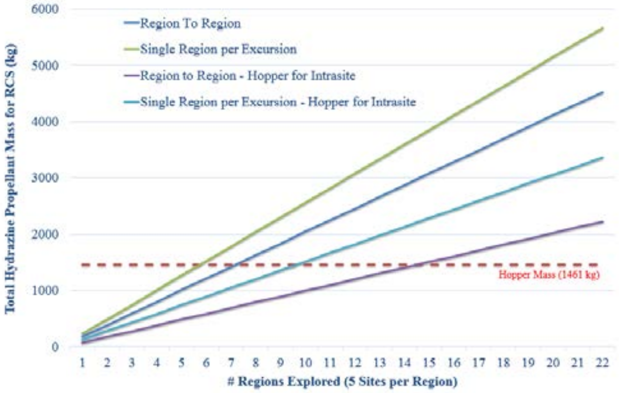


Figure 4 Total hydrazine propellant mass needed to complete exploration of up to 22 regions on Phobos surface if the hopper legs on the PEV are used versus a propellant exclusive operation mode.

While hopping from region to region results in the best trade for mass, there is the added cost of transit time that hopping results in. Time of flight becomes a hindrance to utilizing the hopper exclusively and thus the HAT concluded that propellant be used to transit between regions and the hopper be used to visit the five sites within each region.

Ultimately the driving factor for the method of exploration, be it hub and spoke, or region to region transits will come from the power requirements of the PEV. If it becomes necessary to refuel the PEV two week excursions will likely become three day missions with transits to and from the habitat for refueling. Power capability is described in Section 5, and is taken into consideration in Section 6 where the overall architecture mass is examined against the launch capability present for a mission in the 2030s.

Base on this mission architecture the MAV is placed in HMO and is not deorbited to Phobos surface at any point in the mission. This carries with it many advantages related to protecting the MAV and ensuring a safe return of crewmembers. By keeping the MAV in orbit you lower the risk and complication related to landing the habitat and provide the habitat with a more stable load configuration on the ground. There is also no risk of the MAV being inadvertently damaged by surface operations and any dust or debris that is released from the surface via those operations. Despite these advantages there are still concerns related to leaving the MAV in orbit, primarily that it is remote and not available for routine inspection by the crew during the 500 day Phobos mission. Additionally abort scenarios become complicated in that the crew must transfer the PEV to DRO and then dock it with and transfer to the MAV.

If these concerns place the crew in too high of a risk posture it may be beneficial to alter the baseline operational concept to have the habitat land with the PEV prior to crew arrival, with the crew descending to Phobos surface in the MAV and docking it with the hab. This places the MAV in a position to be routinely inspected, provides simpler abort scenarios for the crew, provides additional habitable volume, and acts as a redundant communications system. However there still remains the risk to the MAV from Phobos surface operations, having the MAV docked to the habitat complicates any relocations that the habitat may need to undertake, and habitat-PEV docking scenarios will also be complicated by the structural configuration of the habitat with the MAV attached.

4. WORKING AND TRANSLATING ON PHOBOS

EVA Force Analysis

In the low gravity environment of Phobos surface EVA, astronaut surface mobility and ability to perform tasks will pose a great challenge [11]. Reaction of a PEV on the surface of a small planetary body to a small force generated by extra-vehicular activity (EVA) sampling tasks was investigated to better understand these dynamics and assess the ability of crewmembers to perform EVA on Phobos surface. In this case, a small force is generated by an astronaut taking a soil sample while attached to a positioning arm attached to the PEV. The questions addressed were if the PEV will be lifted by this force and, if so, what the duration of the contact time (amount of time that EVA force can be applied before the astronaut is not able to reach the surface) is for each force case. Additionally, the study determined whether outriggers (coming off the back and both sides of the vehicle) improve the performance during EVA. EVA force cases were run through an Octave designed model, with the following assumptions:

1) Gravitational acceleration is perpendicular to the surface of the planetary body
2) Local frame is fixed on the planetary body.
3) Mass of outriggers on PEV is neglected.
4) PEV, EVA supporting structure, and outriggers are assumed to be rigid bodies.
5) EVA application point, vehicle's center of mass, and pivot point are coplanar in the x-z plane of the vehicle's structure frame.
6) Astronaut is placed at the end of a robotic arm and has a reach of 2ft

The force required to lift the PEV corresponds to the gravitational force on the vehicle. On Phobos, the lowest total surface acceleration is 0.004m/s^2, near the sub-Mars point [12]. This lowest surface gravity represents a worst case analysis and was used to generate the results. A free body diagram of the model is shown in Figure 5.

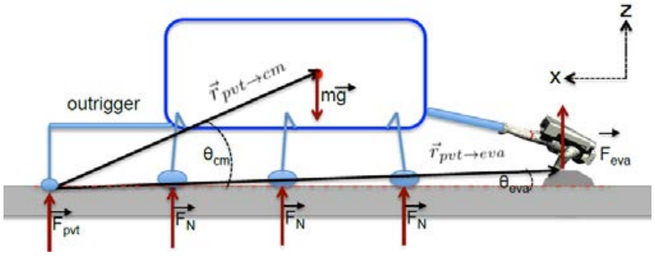


Figure 5. Free body diagram of the PEV on a flat surface.

The model was used to evaluate the approximately 7000kg PEV on Phobos with the assumptions previously described. Generally speaking, forces that are below 4 lbf will not tilt the PEV. In cases where a large force is applied (e.g. working with a core sample drill), if approximately 80lbf of force is applied the PEV will reach a topple point and will not return to the surface in the original orientation. Figure 6 shows the results for a various EVA forces applied across 4 metrics: 1) Maximum tilt angle, the angle the structure tilts in relation to the force applied by the astronaut; 2) Contact Time, the time the astronaut can remain in contact with the surface before the 2ft reach limit is exceeded; 3) Distance lifted, the vertical distance the structure is lifted from the ground plane; 4) Settling time, roundtrip time for structure to return to the surface.

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. With outriggers, the moment arm for gravity torque is larger. Therefore, the maximum tilt angle and settling time can be reduced. Also they allow larger EVA contact force to be applied before PEV starts to tilt or topple. Performance could be improved if an active torque was produced through active attitude control to counter the produced torque from the applied force. In terms of

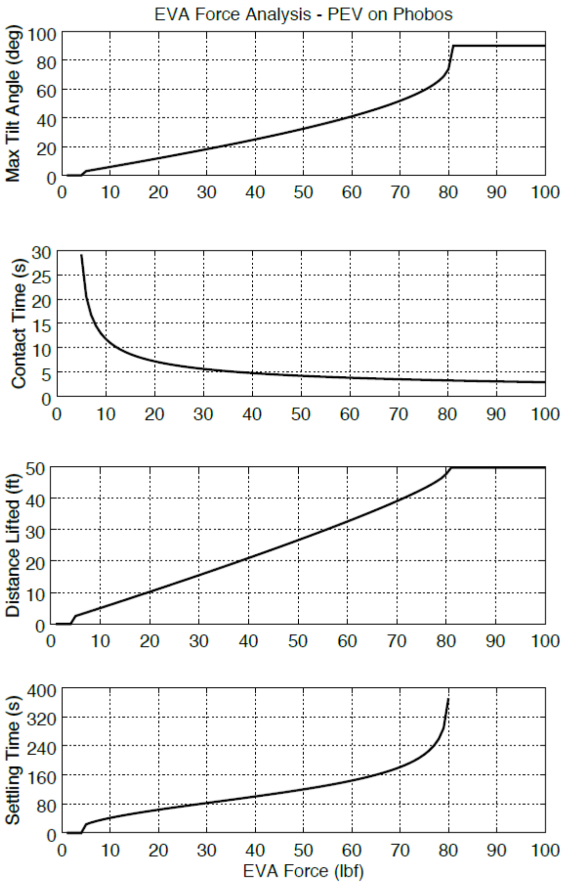


Figure 6. PEV force analysis for various metrics. Saturation points are observed beyond 80lbf indicating that the PEV has toppled.

performance improvements, rotation could be reduced or eliminated through active control and the maximum time of force application can be increased by applying the EVA force closer to the vehicle's center of mass.

Phobos Habitat Docking Analysis

Docking a PEV with the habitat on Phobos may result in unfavorable stability scenarios as the mass properties of the HAB stack will change after docking with the PEV and the momentum of PEV due to docking will cause HAB-PEV stack to rotate as well as translate. The HAB-PEV stack static stability after the docking, the static stability margin changes, and the dynamic response of HAB-PEV after docking were investigated as part of this study through an Octave designed model. A preliminary static and rotational dynamic analysis for PEV docking on Phobos with the habitat was conducted with primary results indicating that the stability margin (horizontal distance from center of mass to the nearest leg) increased after the PEV docked with the HAB when vehicle is on a negative ground slope, but decreased when the vehicle is on a positive ground slope. A free body diagram of the model is illustrated in Figure **7** where x-y-z represents the local reference frame and x'-y'-z' represents PEV's structure frame.

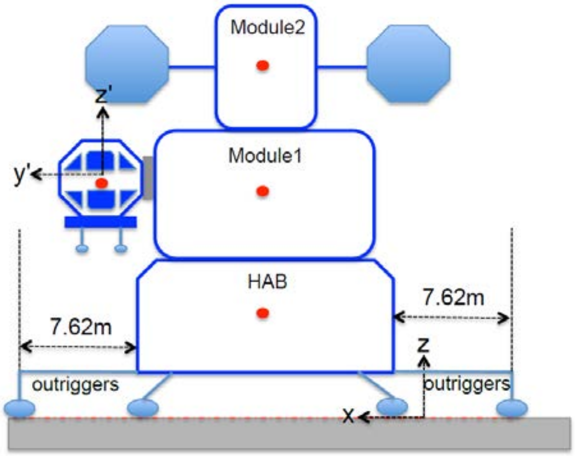


Figure 7 Free body diagram of HAB-PEV stack on level ground with 25ft (7.62m) outriggers deployed.

With a docking speed under 10 cm/s, a seven ton PEV does not significantly de-stabilize a 30 ton HAB when the docking is performed on a relatively flat surface. The results also indicated that the maximum tilt angle and settling time increases and the HAB-PEV structure is more likely to topple when docking occurs on a slope with a negative ground slope angle. It was also found that performing PEV docking on a relatively flat surface (between -10 and +10 degrees) is preferred; as it maintains both the static and dynamic stability of the vehicle. Docking at a steeper ground slope angle is only possible with the addition of 25ft outriggers in a similar deployment described in the EVA force analysis. Data with the outriggers is presented in Figure 8 and Figure 9. While this is a simplified look at the docking dynamics it does present a risk should docking fail with the PEV on an attempt. The tilt and return of the habitat structure (possibly with a MAV docked, adding to instability) will only further complicate docking procedures and could endanger the crew. The HAT recommends that berthing be the docking methodology for PEV-habitat interactions. Where the PEV robotic arm grapples onto the structure of the habitat and then brings the PEV in to mate with the habitat. Due to the low gravity nature of Phobos, docking from any height off the surface will require use of propellant and significant automatic and pilot control of the vehicle. Berthing using the PEV arm also has the possibility to greatly reduce the static instability that could be caused by a missed PEV docking attempt, however further analysis is needed to address both docking dynamics and static stability should the MAV also be attached to the habitat on Phobos surface.

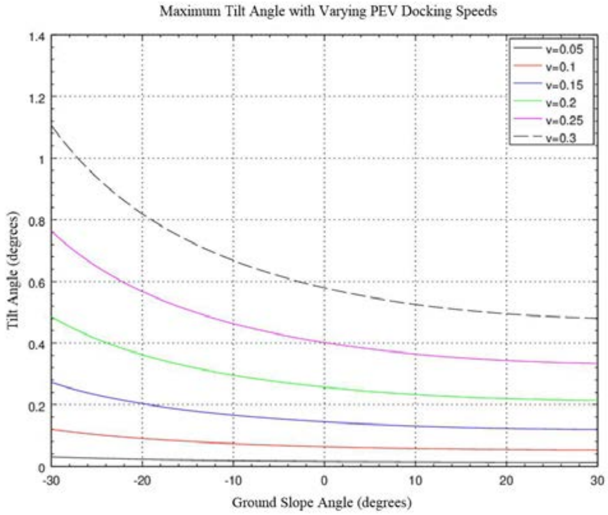


Figure 8 Tilt angles for a 30 Ton habitat on varying ground slopes at varying PEV docking speeds.

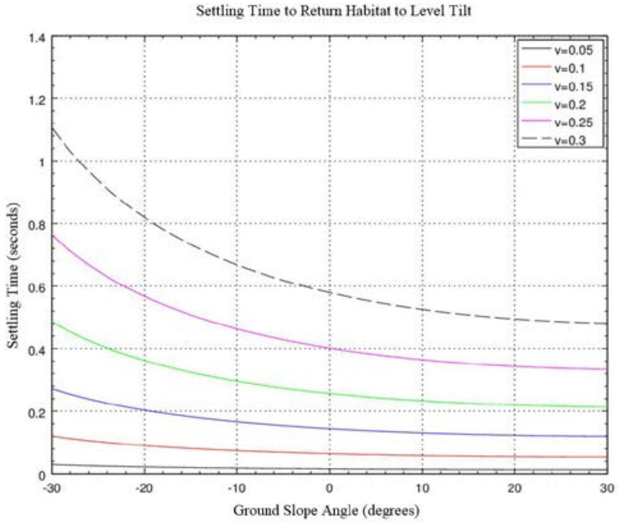


Figure 9 Settling time for a 30 ton habitat following PEV docking at varying velocities.

5. PHOBOS POWER AND LIGHTING ANALYSIS

To ensure the success of a Phobos mission, solar radiation plays a crucial role in power and thermal subsystems for a solar-powered vehicle such as the PEV and habitat. A thorough understanding of solar radiation on Phobos allows engineers to appropriately size the solar arrays and the batteries for the power subsystem. A study using a high fidelity computer simulation to investigate the lighting conditions, specifically solar radiation, on the Phobos surface over one Martian year was conducted by the HAT. The computer simulation was developed using JSC's in-house simulation tools in order to: (a) model the states of the Sun, Earth, Mars, and the Moon using JPL DE405 model; (b) model the orbit of Phobos, its surface, and its gravitational field; (c) model the occultation of Phobos' surface due to solar eclipse by Mars and self-shadowing. Details of this model are presented in [13], this paper will focus on impacts of lighting to exploration capability and effects of power on mission timelines and operations.

The 11 regions previously described were evaluated for 1 Martian year, for the minimum solar array area needed to sustain a certain power load for the habitat and PEV. Figure 10 shows the location of the 11 regions on a Mercator style projection of Phobos. Overall it was found that many of the sites provide the feasibility to use solar arrays for power generation, however Sites 5, 6, 10, and 11 pose more of a challenge for a fixed solar array due to their surface location with respect to the Sun (5, 6, 10 being in the northern hemisphere, and 11 in southern hemisphere). 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 very large arrays if they are not reached during the proper season.

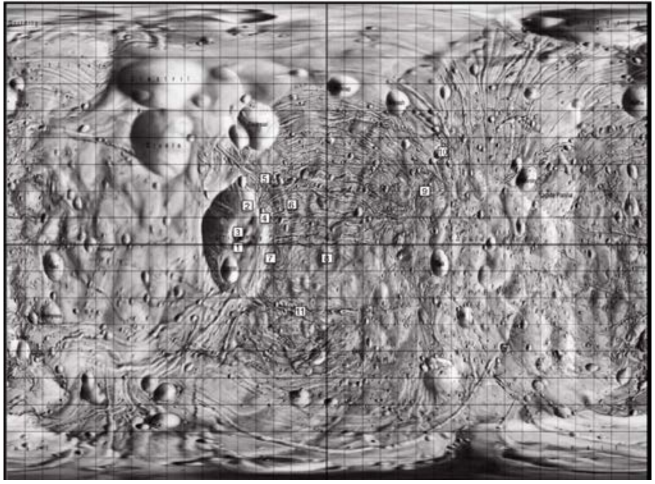


Figure 10 Mercator style projection of Phobos surface, with 11 regions of scientific interest.

Habitat Power Requirements

Using this model, and assuming a 30% solar array efficiency with a 10 kW power draw, the minimum solar array size for the habitat at the 11 scientific regions was evaluated. All sites are all within reasonable tolerances for a solar array size if solar tracking arrays are used. It is also possible to infer a preferred region to region excursion timeline in order to maximize the opportunity for power and sun exposure during the year Figure 11 and Figure 12.

PEV Power Requirements

Assuming a 30% solar array efficiency it was found that it is possible to safely perform excursions to all scientific regions outlined in this architecture with the PEV. However, certain regions are not accessible year round and there may be times where longer or shorter exploration excursions than the planned two weeks are possible. To examine a worst case, a fixed solar array was evaluated for the PEV across the same Martian year as the habitat for a 1.67 kW power load.

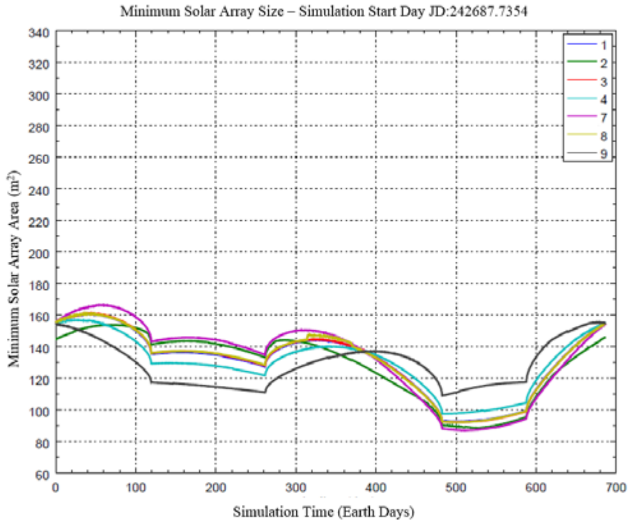


Figure 11 Minimum sun tracking solar array size needed to sustain a 10kW power load for sites 1-4 and 7-9 for the habitat on Phobos.

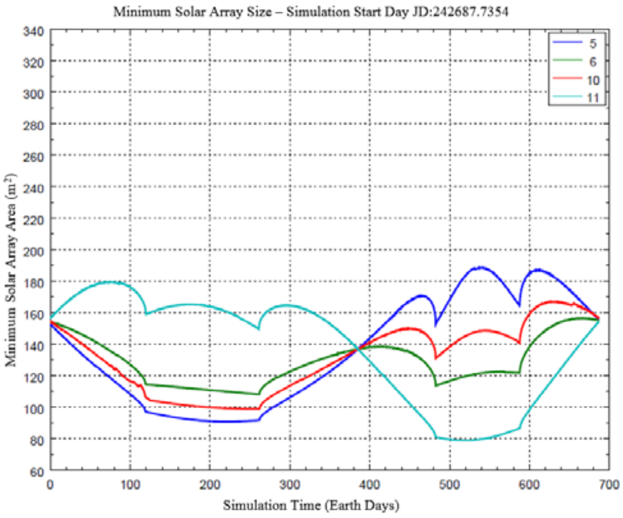


Figure 12 Minimum sun tracking solar array size needed to sustain a 10kW power load for sites 5-6 and 10-11 for the habitat on Phobos.

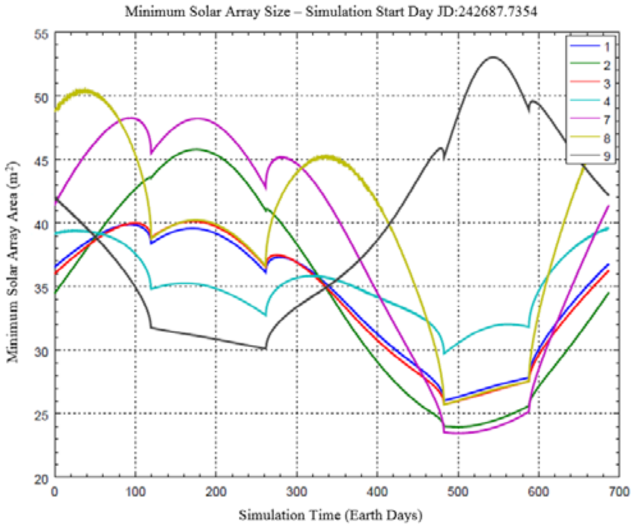


Figure 13 Minimum fixed solar array size needed to sustain a 1.67kW power load for sites 1-4 and 7-9 for the PEV on Phobos.

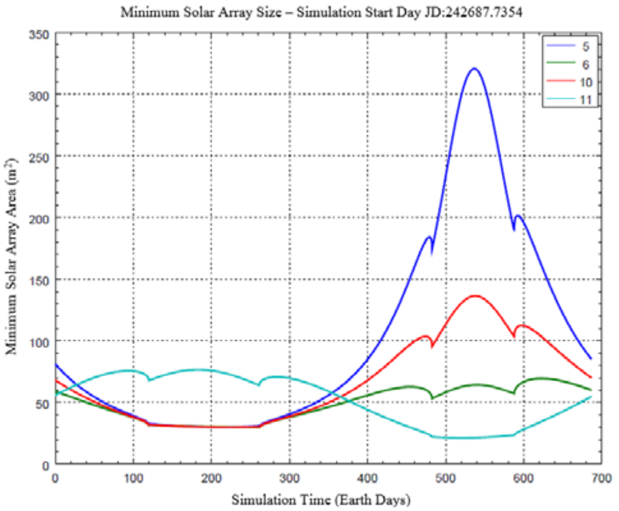


Figure 14 Minimum fixed solar array size needed to sustain a 1.67 kW power load for sites 5-6 and 10-11 for the PEV on Phobos.

Mission planning to reach these regions will require additional analysis of lighting, transit times, instruments power requirements, among other systems. To better evaluate possible mission timeline constraints both fixed and solar tracking solar arrays were analyzed, with results for minimum solar array size needed presented in Table 3 for various power load requirements. This size represents the minimum array area needed for every site during some portion of the year. As shown in **Figure 14**, site 5 for example is only achievable for only ~300 days following the Martian spring equinox (day 0, **Figure 14**) with these PEV solar array sizes.

Table 3. Solar array size (m^2) requirements for varying PEV power loads.

Power (kW)	Array Size	
	Fixed	Solar Tracking
1.67	43	28
3	77	52
4	102	69
5	128	85

6. PHOBOS ARCHITECTURE MASSES AND DELIVERY CAPABILITY

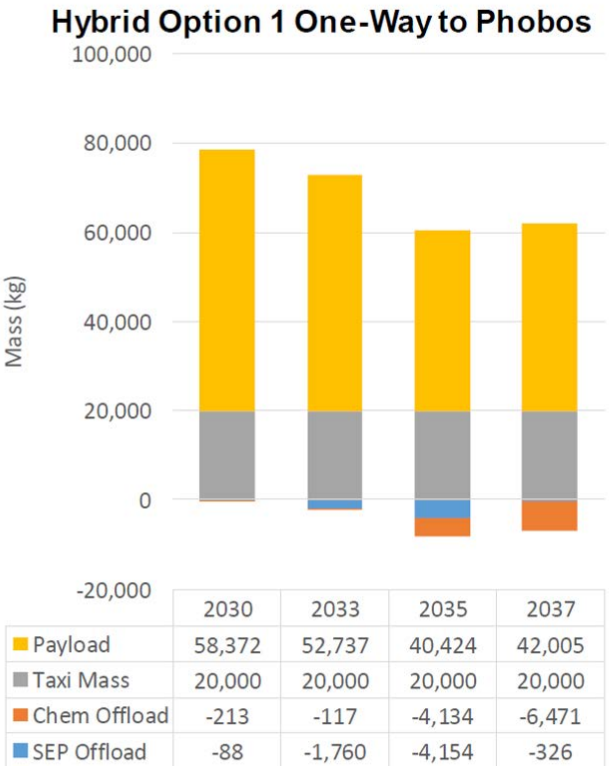
Following the down-selection and mission architecture definition a Master Equipment List (MEL) was developed to estimate the overall Phobos systems requirements and compare it against the payload capabilities for various launch windows in the 2030s. The current baseline architecture for a human mission to Mars' moons requires a cargo predeploy of a 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 based systems, with the habitat descending to the surface of Phobos and the PEV remaining in orbit. When a crewed mission is launched to Phobos, it would include the remaining systems to support the crew during the Earth-Mars transit and to reach Phobos after insertion in to Mars orbit.

Using the integrated model described in [4], which combines 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, a mass estimate for the habitat and PEV was created and is shown in Table 4, and are within the launch capability for various mission years outlined in Figure 15.

Table 4. Master Equipment List for the estimated habitat mass and associated exploration systems mass needed in Martian space for completion of a 500 day Phobos surface mission. All masses here are estimated based on the current state of knowledge of the HAT on these systems.

Estimated Mars Moons System Masses	
Major Components	**Mass (kg)**
Hybrid Propulsion Module (dry)	20405
Habitat (dry)	18212
Landing gear/Mobility	470
Additional RCS hardware (prop in PM tanks)	270
Other attitude control (e.g., CMG)	150
Supplemental GN&C	75
Outriggers/booms	115
Cargo	
Logistics (500 days)	10106
Non-Propellant	613
ECLSS fluids/gases	613
Propellant	
Remaining Xenon	960
Remaining Chemical	640
DRO to Surface, Region to Region Transfers	1000
Exploration Systems	
PEV	7422
MAV (as taxi)	5752
Total Mass - Habitat and Systems	**66653**

These mass estimates for the baseline Phobos architecture can vary depending on the mission timeline and power needs for exploration of the different regions of interest. If for example we are power limited due to low intensity periods of the year as described in Section 5, this will require added mass for propellant to move the PEV to and from the habitat for refueling during a two week EVA excursion. The propellant needed to traverse from region to region with the PEV while using the hopper for intrasite relocation is approximately ~1125 kg. However if the PEV is power limited that mass climbs to 5250 kg (3 day missions, requiring 2 roundtrip trips to the habitat and scientific region). While the MEL lists all Phobos system masses, the delivered habitat and PEV mass is ~41000 kg. Based on this, and the possibility the crew is power limited, the overall mass of this architecture falls in the ~45000 kg to ~50000 kg which is well within the payload capability for several launch windows in the 2030s.



	2030	2033	2035	2037
🟨 Payload	58,372	52,737	40,424	42,005
▨ Taxi Mass	20,000	20,000	20,000	20,000
🟧 Chem Offload	-213	-117	-4,134	-6,471
🟦 SEP Offload	-88	-1,760	-4,154	-326

Figure 15 Cargo Payload options for various launch years to Phobos space. Several launch opportunities in the 2030s can carry the mass of the down selected Phobos mission architecture habitat, PEV, and associated logistics.

7. CONCLUSIONS

The current baseline architecture for a 500 day Phobos mission provides the opportunity for meaningful scientific, engineering, operational, and public engagement benefits. Further analysis and data from robotic precursor missions is still required to better understand the environment and better define scientific regions of interest, the risks and benefits of such a mission, and its role within a broader Evolvable Mars Campaign. Such a precursor mission architecture is currently being developed by the HAT and a robotic precursor mission to Phobos and Deimos is under consideration for a launch time in the 2020s. Based on the preliminary analysis presented here, a mission to Phobos will be an integral intermediate step on the path to Mars surface exploration. Placing a crew in Martian space allows for both human exploration of Phobos and provides ample opportunity for more rapid exploration of Mars surface via LLT and other robotic assets. Exploration of Phobos also builds heavily from the developments of the cis-lunar proving ground and significantly reduces Mars surface risk by facilitating the development and testing of habitats, MAVs, and pressurized rover cabins that are all Mars surface forward.

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