Manned Sample Return Mission to Phobos: a Technology Demonstration for Human Exploration of Mars

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***Abstract*— In order to reduce the knowledge gap associated with long-duration human exploration of Mars, a manned precursor mission destined for one of the Martian moons is currently considered a feasible option for testing and demonstrating critical technologies within the Martian system. The 2013 Caltech Space Challenge, a student mission design competition held at the California Institute of Technology, addressed the interest in human precursor missions. Two teams of 16 students, with varying backgrounds and nationalities, were allocated five days to design a mission to land at least one human on a Martian moon and return them, along with a sample, safely to Earth with a launch date no later than January 1, 2041. This paper provides an overview of Technology Advancing Phobos Exploration and Return (TAPER-1), the manned Phobos sample return mission devised by Team Explorer. As the first manned mission to the Martian system, TAPER-1 is designed as an opposition class mission to Phobos, carrying four astronauts, with a launch date in April 2033, and a nominal time of flight of 456 days. In addition, this paper demonstrates the feasibility and value of exposing students to the process of rapid mission design.**

TABLE OF CONTENTS

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1. INTRODUCTION

Given its proximity to Earth, an upcoming target for both manned exploration and possible colonization is Mars. Despite its inherent allure as a feasible destination for manned missions, there are numerous multidisciplinary difficulties associated with travelling to and operating a direct mission to the Martian surface. A precursor mission to one of Mars' moons, Phobos or Deimos, may be an important step to understand how to operate within the Martian system. Due to the gap in knowledge about the compositional, radiation, and space-weathering environment, as well as the origin of the Martian moons, further characterization of these bodies would increase the likelihood of successful manned missions to Mars. A precursor mission to a Martian moon could allow for testing and verification of key technologies and operational processes, reducing the risk to the human crew during subsequent longer duration Mars missions. By addressing the corresponding critical gaps in science, technology and policy, a precursor mission would enable future manned exploration of Mars. Useful infrastructure could also be established through precursor missions. It is within this context, that the authors of this paper present a manned mission to Phobos, named TAPER-1, resulting from a rapid mission design exercise conducted during the 2013 Caltech Space Challenge.

The TAPER-1 mission is a single component in a multi-mission program that acts as an intermediate step towards the ultimate goal of human Mars exploration. Phobos is selected as the target moon for TAPER-1 since it appears to have more geologically interesting features than Deimos, including Stickney Crater and a system of surface grooves [1], [2]. As the first manned mission to the Martian system, TAPER-1 is designed as a short-stay mission to Phobos, with a launch date of April 6, 2033 and a nominal time of flight of 456 days. The mission consists of six launches into a low Earth assembly orbit, followed by departure along an interplanetary trajectory to Phobos. Once in the vicinity of Phobos, two of the four crew members explore the surface and perform scientific experiments to provide insight into the origin and evolution of the moons, and assess the feasibility of using the moons for in-situ resources during future manned missions to Mars. After approximately one month in the Martian system, all four crew members then complete the outbound interplanetary trajectory return to the Earth via direct entry. Following completion of the manned mission, weather stations, seismic network stations and robots remain on the surface of Phobos to perform extended science, further reducing the scientific knowledge gap prior to a manned mission to Mars.

Throughout the remainder of this paper, the mission objectives, science drivers, timeline, spacecraft components, operations, and human factor issues are presented. In addition, the programmatic aspects of the mission are also considered, including cost, risk, political sustainability and public awareness and outreach.

2. Mission Overview

"He who receives an idea from me, receives instruction himself without lessening mine; as he who lights his taper at mine, receives light without darkening me".

-Thomas Jefferson

The mission devised by Team Explorer for the 2013 Caltech Space Challenge is envisioned as a single component in the multi-mission program named TAPER. This program consists of two components: a robotic precursor mission, TAPER-0, which would provide crucial information about Phobos and the Martian environment; and a manned mission, TAPER-1.

The goal of the TAPER-1 mission is to significantly reduce critical technology, science, and policy gaps, thereby enabling future manned missions to Mars. In order to achieve this goal, a primary objective of TAPER-1 is to demonstrate the ability to safely transport humans in a long duration mission, and return them safely with samples from the surface of Phobos. Additionally, TAPER-1 would allow for the development of key technologies vital to human operations in the Martian environments. By performing scientific observations and activities on the surface of Phobos, TAPER-1 is intended to further humanity's understanding of both the Martian system and the solar system. Secondary objectives for the TAPER-1 mission include identifying and collecting Martian materials that may have accumulated on Phobos via natural means or were delivered by supportive robotic operations.

As a whole, the TAPER program is intended to foster both international collaboration and public support. Given the context of the TAPER program as a precursor to Martian exploration, it is considered a priority to explore collaboration between American and international space agencies and the private sector, thereby forging partnerships that would enable subsequent manned interplanetary missions of longer duration and higher complexity than otherwise feasible. It is assumed that TAPER would be the first program to send humans to the Martian system, following missions to the International Space Station (ISS) and exploration of cislunar space in the 2020s: a likely scenario that is consistent with various human space exploration proposals [3]–[5]. Given this assumption, the division of responsibility among the entities participating in the TAPER program would be based on the Technology Readiness Level (TRL) of various components following the completion of stepping stone missions in the Earth-Moon system. In particular, it is envisioned that national space agencies would be responsible for developing riskier components that have a low TRL at the beginning of the TAPER program, while private spaceflight companies would be responsible for developing higher TRL components that are cost-effective. In addition, particular importance is placed on promoting the exploration of the Martian system to members of the public via outreach programs that are discussed in Section 8. Although these outreach activities cater to the general public, a number of initiatives are targeted towards supplementing and promoting the education of students in STEM fields.

TAPER 0: The Precursor Mission

Prior to the manned mission, additional knowledge about Phobos is required in order to reduce the risk to the astronauts and to increase the success of human operations on the surface of Phobos. The robotic precursor mission, TAPER-0, is designed to address these critical knowledge gaps. It is intended that through the robotic mission, further knowledge would be obtained about the topography, gravitational field, radiation environment, and regolith properties of Phobos. Accordingly, better characterization of Phobos would improve the design and utilization of instruments, experiments and operations during the manned mission, thereby reducing risk to the astronauts and increasing the likelihood of TAPER-1 satisfying the primary mission objectives. A byproduct of a robotic precursor mission is the analysis of design parameters selected for TAPER-1, allowing for validation and improvement of the engineering design. TAPER-0 may also provide a testbed for limited, robotic in-situ resource utilization (ISRU) techniques, prior to their implementation by the astronauts during TAPER-1.

TAPER 1: The Main Mission

The design of TAPER-1 meets two important goals: reducing risk to the human crew, while simultaneously incorporating numerous technologies and operations that would be utilized on a human mission to the surface of Mars. Although specific design choices are explored in later sections of this paper, Figure 1 depicts the overall architecture of TAPER-1, including launch and rendezvous in the Earth vicinity, operations in the Martian system, and return to Earth.

TAPER-1 is designed to depart the Earth during the 2033 launch opportunity, with a backup launch window in 2035. During the nominal and backup launch windows, the effective radiation dose due to galactic cosmic rays is near a local minimum, thereby reducing the radiation risk to the crew [6]. Given this design choice, a nominal launch window for the manned component of TAPER-1 is selected to be one week around April 6 2033, based on a tradeoff between ΔV, time of flight (TOF), and launch C3, explored further in Section 4. The TAPER-1 mission requires a total ΔV of 10.5 km/s and a time of flight of 456 days, leaving the assembly orbit on April 7 2033 and returning to the Earth via direct entry on July 6 2034. The resulting trajectory for TAPER-1 reflects the decision to design an opposition class or short-stay mission, in order to reduce the health risks to the human crew, and the longevity requirements on various subsystems. In addition, the short duration of 30 days in the Martian system is considered sufficient to achieve both the scientific and mission objectives of the TAPER-1 mission.

Prior to the crew launch, five additional launches are used to insert the unmanned mission components into Low Earth Orbit (LEO) for rendezvous and assembly. In addition to the crew vehicle (CV), the unmanned components are assembled to form the Deep Space Vehicle (DSV). Rendezvous of the unmanned components of the DSV in LEO is considered more favorable than assembly in either the Martian system or in a Highly Elliptical Orbit (HEO); this decision is discussed further in Section 5. As depicted in Figure 1, four of the unmanned launches will insert a nuclear thermal rocket (NTR) propulsion system into LEO using NASA's Space Launch System (SLS). The fifth launch, using a SpaceX Falcon Heavy launch vehicle, inserts both the Deep Space Habitat (DSH) and the Phobos Surface Explorer (PSE) into LEO. The DSH is the spacecraft that the astronauts live in during transit between the Earth and Phobos. An inflatable DSH by Bigelow is selected for TAPER-1; the rationale for this design choice is explained in Section 5.

The PSE, modeled after NASA's Space Exploration Vehicle (SEV), is a two-stage vehicle that the astronauts would use during the surface expedition on Phobos. Unlike the SEV, the PSE possesses a habitable first stage, named the P-Hab, which would be left behind on Phobos to serve as a station for future missions in the Martian system. Only the remaining stage, named the PSE Separator (P-Sep), would ferry the two astronauts back to the DSV, prior to disposal in a graveyard orbit, as illustrated in Figure 1. While its life support would need to be restocked for each use, leaving the P-Hab on Phobos would provide valuable communications access to the Martian surface, establish infrastructure that encourages future missions, allow for continued science observation, and aid in developing reusable technologies for long duration Mars missions. The PSE concept devised in this paper closely mimics the capabilities that a Mars ascent vehicle would need in NASA's Human Exploration of Mars Design Reference Architecture 5 [7]. This inspired the propulsion system of the PSE to also be powered by methane and liquid oxygen (LOX), which are propellants that could possibly be made on Mars using ISRU [7].

The sixth and final launch is allocated to launching both the CV and the crew. The CV houses the astronauts during ascent from Earth at the beginning of the mission and during descent towards Earth at the end of the mission. In order to minimize risk to the crew, the final launch would not occur until the assembly of the NTR, DSH, and PSE is completed, which may place constraints on the launch window [8]. The selected CV is the SpaceX Dragon Rider due to the relatively lower development cost and higher TRL. Once assembled, the DSV (consisting of the NTR propellant stack, the DSH, the PSE, and the CV) departs LEO and travels along an interplanetary trajectory to Phobos. After completion of this trajectory arc, the crew inserts into the final orbit in the Phobos vicinity. Two astronauts then board the PSE and head towards the surface of Phobos, targeting the landing sites that are detailed in Section 3.

The astronauts' expedition lasts almost a month, and utilizes support from the two astronauts remaining onboard the DSH, which travels along a low-inclination parking orbit near the Mars-Phobos L_1 Lagrange point. The activities during the surface expedition on Phobos are designed to meet the mission and science objectives, while the versatile capabilities of the PSE enable the astronauts to explore multiple sites and perform a variety of operations. The knowledge gained during surface operations is intended to contribute to future missions to the Martian system. At the conclusion of the Phobos surface expedition, the P-Hab is anchored to the surface of Phobos in order to create a permanent station and return to the DSV in the P-Sep. This concept is depicted in Figure 1. The P-Sep would then be sent into a graveyard orbit, allowing the crew to return to the Earth together on an interplanetary trajectory aboard the DSV. At the end of this trajectory arc, the crew would board the CV to reenter the Earth's atmosphere on July 6, 2034.

In combination, the two missions comprising the TAPER program provide invaluable information about the Martian system. Through testing of key technologies and surface operations, the TAPER program reduces critical knowledge gaps, therefore reducing the uncertainties and risks of future manned missions, including exploration of Mars and long duration interplanetary missions. In addition, the TAPER program provides a permanent station in Phobos, enabling new opportunities for tele-robotic operations.

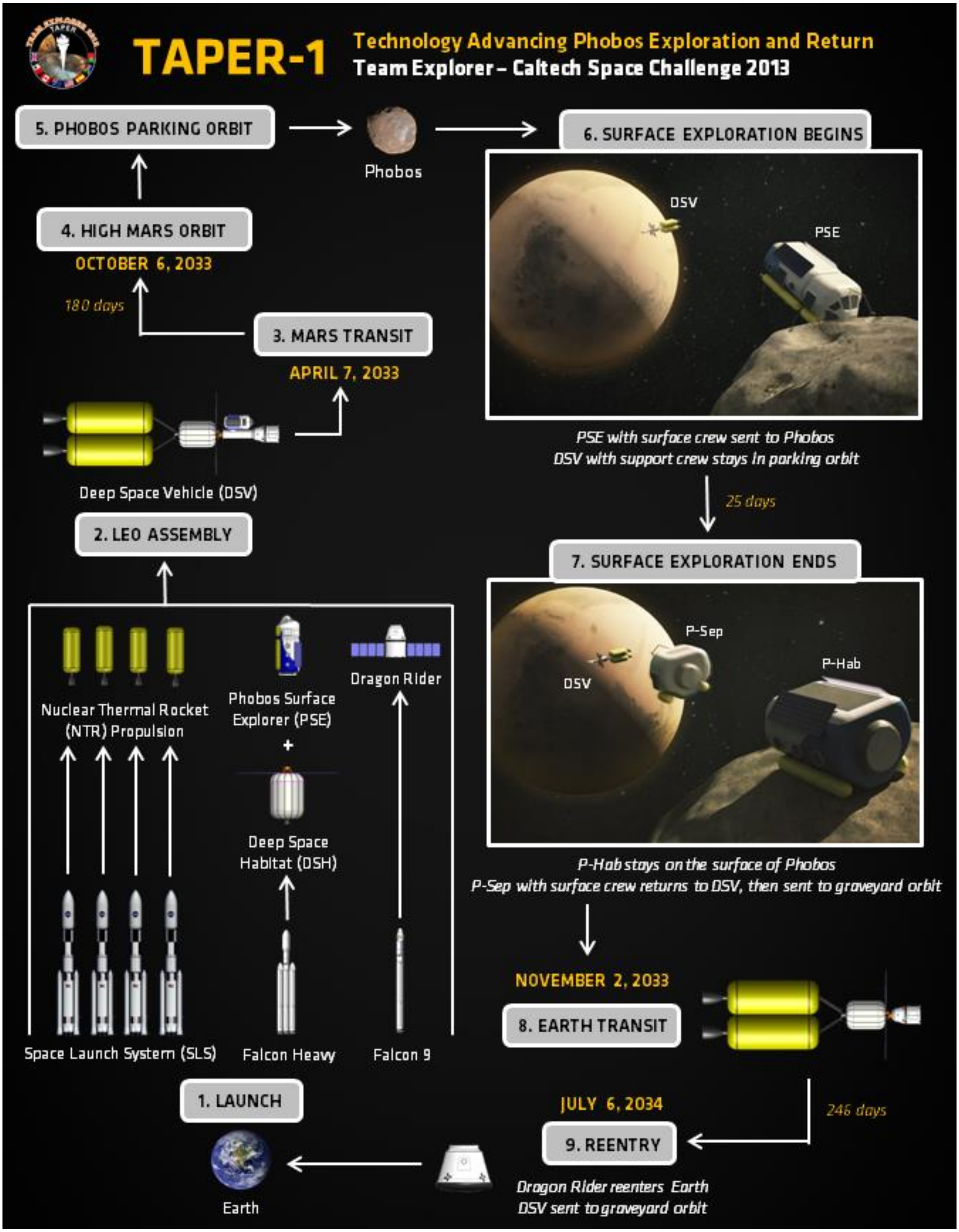

Figure 1 - TAPER 1 mission sequence summary

3. SCIENCE

Phobos provides an excellent target for scientific investigation within the Martian system. Despite decades of remote observations, the origin and evolution of this small solar system body remain unresolved [9]. In-situ and returned sample investigation may be the only methods to definitively answer these fundamental scientific questions about the origin of the Martian system. In addition, Phobos' relatively low density suggests that its interior is either highly porous [10], or it contains low-density material, particularly water ice [11]. The presence of water would allow the possibility of using the moon as an important source for ISRU during future missions to the Martian system. Thus, scientific exploration of Phobos may determine whether water or other additional in-situ resources are present to support future missions to the Mars system.

Science Objectives

The scientific objectives for in-situ science are derived from the primary mission objectives, and they are summarized in the science traceability matrix, included in Appendix A. Three main scientific objectives for in-situ science are identified as follows:

Objective 1: Investigate the origin and evolution of the Martian moon to better understand the Martian system—Three hypotheses exist concerning the origin of Phobos: (1) formation through capture of primitive bodies from the outer solar system, (2) formation through co-accretion with Mars, or (3) formation by impact into differentiated Mars. Each of these origin hypotheses would result in a different composition of Phobos [12]. An investigation to unambiguously determine the composition of Phobos through analysis of collected samples may provide insight into which of these hypotheses is most likely. Additional measurements to determine the moon’s interior structure could further constrain its possible formation by indicating whether the body is an unconsolidated rubble pile or partially differentiated small body. Investigation of the interior structure of Phobos may also elucidate if there is ice deep in the subsurface, which could indicate that the formation of Phobos occurred in the outer solar system, rather than in the vicinity of Mars. Additional measurements and collection of Phobos regolith samples may provide information about the evolution of the moon through the geologic processes shaping the moons’ surface over time.

Objective 2: Assess availability of in situ resources for possible future use in manned Mars missions—Although remote measurements have yet to definitively identify the presence of in-situ resources on Phobos' surface, both the low bulk density and grooves of Phobos suggest that it may contain frozen volatiles under the surface [1]. The detection and characterization of such material is, therefore, a high science priority for this mission, intended to support future manned exploration of Mars. Additional materials that could potentially be mined for ISRU such as clays, magnesium, rare earth elements, methane and ammonia may also exist on the surface or subsurface. If these materials are present, they could be analyzed and characterized, and their locations could be well identified.

Objective 3: Understand the current environment of Phobos in the context of the Martian system to support architecture for future manned Mars missions—Due to its location, Phobos has a unique dust and radiation environment. Characterizing this environment is an important goal, as it may support future missions to the Martian system. Additionally, space weathering of the surface of Phobos has likely been influenced by the moon's unique environment, and analysis of returned samples from the surface may improve characterization of space weathering processes that occur on other bodies in the solar system.

Additional Science Objectives—Two optional and relatively inexpensive objectives for in-situ high return science may also be identified: investigation of the compositional relationship between Phobos and Deimos, and identification and collection of any Martian samples ejected onto the surface of Phobos.

Landing Sites

Three landing sites are identified based on their ability to fulfill the defined scientific objective, and are indicated in Figure 2. A fourth landing site is identified as the P-Sep's permanent settlement, which may be used for future Mars missions. All four locations are listed in Table 1. These landing sites could be adjusted to better fulfill the mission objectives if precursor science measurements indicate more favorable landing sites.

Each of the first three landing sites provides unique geologic topographies and access to samples that may help address mission goals. The Stickney Crater site (site A) may represent an area that contains material originating from the interior of Phobos. The second location (site B) is located in the blue spectral unit, and differs in color from the rest of Phobos' redder surface [13]. Samples collected at site B may provide an important contrast to the red samples that cover a majority of the moon. The third location, in the red spectral unit, may help provide an understanding of the overall composition of Phobos.

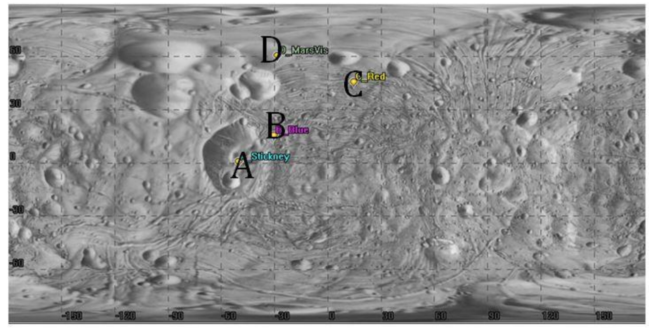

Figure 2 - Selected landing sites on Phobos

Table 1 – Landing sites and their coordinates

Site Identifier	Site Location	Coordinates
A	Stickney crater	0^{o} N, 50^{o} W
B	Blue spectral unit	15^{o} N, 30^{o} W
C	Red spectral unit	45^{o} N, 15^{o} E
D	Mars visible	60^{o} N, 28^{o} W

The fourth landing site is selected due to its communications benefits. The PSE is intended to permanently land in this location to act as a communications relay since the location has permanent visual contact with Mars. Site D is also exposed to constant sunlight during the Martian summer, which increases the PSE's power production to sustain its communication functionality.

In Situ Science Instruments

The instrument platform is designed to accomplish the mission's in situ science objectives by taking into account the synergy between robotic and human exploration. The science package is summarized in Table 2, and it contains the following major components: 1) equipment for human sample collection, 2) mobile science platforms, 3) seismic network stations, 4) space environment monitoring, and 5) margin for additional science instruments.

Equipment for Sample Collection—The astronauts on the surface of Phobos are provided with two robonauts (100 kg each) to aid in mobility within the microgravity environment [14]. Each robonaut carries sample collection tools similar to those used by the Apollo astronauts on the Moon [15] (scoops, rakes, hammers, hand lenses, documentation cameras, and tongs), as well as sample boxes, cores, and bags. The sample containers are expected to comply with planetary protection requirements. The sample collection strategy is summarized in Table 3, and it includes a 50% mass increment for educational and public outreach purposes, international cooperation, as well as target of opportunity. Surface samples do not need to be stored cryogenically during the return trip to Earth, since temperatures on Phobos' surface can reach upwards of 340 K [16], whereas core samples should be cryogenically stored to prevent any potential volatiles from sublimating.

Mobiles science platform—Five mobile robotic platforms, nicknamed "Phobots", support astronauts exploring the landing sites by roving around the vicinity and performing in situ operations, with one Phobot per landing site plus two additional to allow multiple Phobots to investigate particularly interesting sites and/or provide redundancy. The Phobots are semiautonomous robots that can be controlled by the crew that remain in orbit. Additionally, the Phobots are able to take advantage of human intelligence to make decisions about locations to investigate. Since the Phobots carry science instruments, they provide geological context for the retuned samples.

Table 2 – In situ science instruments

In Situ Major Components	Equipment/Instruments	Quantity	Mass [kg]
Sample collection equipment (425 kg)	Robonauts	2	100
	Tongs, rake, dust cooper, hammer, hand lens, camera	1	25
	Sample boxes, cores, bags	1	200
5 Mobile Science Platforms (Phobots) (10 kg each)	Raman/LIB Spectrometer	1	3
	Multispectral imaging system	1	0.5
	Neutron spectrometer	1	3
	Visible/Near-Infrared Spectrometer	1	0.75
	Chassis and communications	1	2.75
Seismic Network Stations	Small networks deployed towards landing	5	1
3 Space Weather Stations	Plasma Wave System	1	3
	Micrometeorite Detector	1	3.5
	Dust Particle Detector	1	3
	Structure and Communications	1	3
Margin for additional Instruments		-	300
Total mass (20% margin)			**1000**

Seismic network stations—Chipsats ('satellite-on-chip'), [17] are intended for deployment during Phobos arrival, thereby forming a seismic network to provide information about the interior of Phobos during and after surface operations [18], [19].

Space environment monitoring station—A space environment monitoring system is expected to be deployed at each landing site. This equipment can monitor Phobos' unique space environment and can remain operational after surface operations end.

Margin for Additional Science Instruments—Space is allocated for extra science instruments that may be considered useful based on findings from the precursor mission. For instance, if observations from TAPER-0 reveal that Phobos has ice deposits at a depth on the order of 10 to 100 meters below the surface, a specially-designed deeply penetrating drill may be required to access the potential in-situ resource. Additional ideas for opportunistic science that could be used to fulfill this margin, but are not critical to meeting science objectives, include a phased array radar to scan the ground and map local soil strata, composition, and conductivity; rubidium clocks to accurately measure Phobos' time and position; a cosmic ray ground array to analyze galactic cosmic rays up to the appropriate GeV energy range; or a large optical telescope to survey Mars' surface in finer detail.

Table 3 – Sample collection strategy

	Rock Samples	Core Samples	Soil scoops
Required samples per site	30	10	5
Number of sites	3	3	3
Minimum mass per sample(kg)	0.2	1.5	0.1
Total mass (kg)	18	45	1.5
Total mass (kg) (50% margin)	27	67.5	2.25

Additional Science Instruments

Remote sensing instruments to support mission objectives and high-return science remain in orbit during surface operations. These instruments are summarized in Table 4**.** The orbiting astronauts can supervise the astronauts that are on the surface of Phobos using high-resolution color cameras to monitor their safety, document their operations, and provide photos for public outreach. Improved radar technology may allow for detailed subsurface mapping, which may help identify locations rich with subsurface volatiles. Low, mid, and high energy particle range detectors can help observe space weather and complement ground observation detectors. Additionally, five small, light, and relatively inexpensive CubeSats [20] (2 kg each) may be sent to Deimos to provide definitive identification of Deimos' composition. Finally, a small science instrument may be dedicated to fulfilling public outreach requirements.

Opportunities during transit

In flight sample analysis—In order to maximize science return from the returned samples and to give crew members a task to complete during the long journey back to Earth, astronauts are tasked with preliminary analyses of the approximately 100 kg of samples during the journey home, prior to any detailed analyses on Earth. Findings from this investigation may help sample storage facilities on Earth understand any potentially hazardous materials they may encounter and design necessary measures to mitigate risk. A mass of 200 kg and 2000 W of power is allocated for the DSV to support analysis of samples en route to Earth. These parameters are selected based on their similarity to the current science payload of the Curiosity Mars Rover. The proposed instrument package includes 1) a Fourier-transform microwave (FTMW) spectrometer, to look for exotic states of matter; 2) a gas chromatograph mass spectrometer (similar to SAM on Curiosity) to detect volatiles and organics and also determines chemical composition; 3) a nano SIMs for high resolution, high precision isotopic imaging and compositional analysis; 4) X-ray diffraction to provide mineral identification, and 5) a tunable laser spectrometer to measure isotopic ratios in evolved gases.

Radiation experiments—An experiment derived from Phobos-LIFE (Living Interplanetary Flight Experiment, originally designed for Phobos-Grunt) can be used as an in-flight test to assess interplanetary survivability of hardy Earth-based microorganisms in a deep space environment.

Table 4 – Remote sensing science instruments

Orbital Remote Sensing Instruments	Mass [kg]
High resolution color imaging system	10
Radar	15
Low/Middle/High energy range particle detector	2/4/2
5 CubeSats sent to Deimos	2 each
Dedicated instrument for outreach	10
Total Mass (20% margin)	65

Samples to be tested include triplicate versions of several dozen types of organisms representative of archaeal, eukaryotic, and bacterial domains of life. Two sealed units may be tested in transit to Phobos and back; the first unit is solely exposed to radiation on the DSV during travel, the second unit is exposed to additional radiation on the surface of Phobos. Ideally, these units are compared to concurrent samples both on Earth and in near Earth Orbit. In addition, dosimeters may be used to measure radiation exposure of both the astronauts and living biological samples (cultivated from an in-flight photobioreactor) throughout the journey.

In transit astrophysics—Outreach opportunities exist for the general scientific community to propose experiments and develop instrumentation for use onboard TAPER-1.

4. TRANSIT

The opposition class trajectory followed by the DSV is designed to deliver the crew to the vicinity of Phobos, provide a safe parking orbit for the two astronauts that do not visit the surface, and safely return all four crew members to the Earth via direct entry. Given that TAPER-1 is manned, the trajectory design for this mission addresses the critical tradeoff between the time of flight, ΔV and reentry velocity, all primarily driven by the two interplanetary components of the transfer. The inbound interplanetary transfer is designed to connect the initial LEO rendezvous orbit to an intermediate high Mars orbit, while the outbound trajectory departs from the Martian system and returns the crew to Earth via direct entry. In addition, a final orbit in the Martian system is selected through consideration of the Phobos landing sites and the potential for additional scientific observations or remote tele-operation of robotic systems on the surface of Mars. The resulting trajectory, described in detail within this section, is characterized by a total TOF of 456 days, with approximately 30 days spent in the Martian system, and a total ΔV of 10.5 km/s, satisfying engineering requirements from the propulsion, science and human factors subsystems.

Interplanetary Transfer Arcs

Following the rendezvous of each component that is launched into a 300 km altitude LEO, the assembled DSV departs along an outbound interplanetary trajectory. For the nominal and backup launch years, a set of Lambert arcs is computed to connect the Earth and Mars, located using ephemeris states, for each possible combination of departure and arrival dates. The resulting heliocentric transfer solutions provide an initial approximation of the total ΔV (the sum of the trans-Mars injection and Mars orbit injection maneuvers), TOF and final approach velocity associated with each interplanetary arc, thereby facilitating the selection of a launch window. Accordingly, an initial guess for this segment of the trajectory is obtained and corrected in STK to target the desired boundary conditions: for example, a LEO departure and high-Mars orbit arrival [21].

For the 2033 launch year, the computed solutions are analyzed to determine a nominal launch window and approximate flight times for the outbound interplanetary transfer. Analysis of the computed solution set reveals a local minimum in the total ΔV for a subset of arcs with a flight time of approximately half a year. This minimum also occurs at a similar location to the local minimum in the C_3 at Earth departure, a parameter used for selection of an appropriate launch vehicle. Consequently, a nominal outbound interplanetary trajectory arc is selected with a LEO departure date of April 7 2033, an approximate TOF of 180 days and a total ΔV of 5 km/s, which includes the TMI and MOI manuevers. This conic arc also possesses an Earth departure C_3 of 8.43 km^2/s^2. The crew is nominally launched into LEO the day prior to the trans-Mars injection, which may occur within a one-week launch window around the nominal departure date. The length of this launch window is selected through consideration of variations in the properties of the transfer arc and geometrical constraints on the assembly orbit, imposed by the prior launches into LEO for the unmanned components of TAPER-1 [8].

In order to return the crew safely to Earth from within the Martian system, an inbound interplanetary arc is also selected, with the departure dates constrained to occur at least 20 days after the arrival of the crew into the Martian system, allowing sufficient time for the scientific objectives of the mission to be satisfied. Through identification of the local minimum in the ΔV and the velocity at Earth arrival, November 2 2033 is selected as the nominal departure date from the Martian system, with direct Earth entry occurring on July 6 2034. The trans-Earth injection maneuver for this outbound arc is approximately 4.22 km/s, while the time of flight is 246 days. Upon arrival at Earth, the crew experiences a reentry velocity of 15.9 km/s, which may either be within the expected limitations of reentry vehicle thermal protection systems in 2033, or could be reduced using optimization methods. Figure 3 depicts the two interplanetary transfer arcs between Earth and Mars, as viewed in a Sun-centered inertial frame. Analysis of this figure reveals that the selected interplanetary trajectory crosses the orbit of Venus. Accordingly, the ΔV for the inbound transfer arc could be reduced in further studies by exploiting the gravity of Venus.

A similar analysis is performed for 2035, which is designated as the backup launch year. Identification of the local minimum of the Lambert arc solutions that correspond to shorter flight times allows for selection of the nominal backup Earth departure date as August 14 2035. Accordingly, a backup crew launch would nominally be scheduled for August 13 2035, with an allowed launch window of approximately one week. In addition, for the inbound transfer, the crew is estimated to depart the high-Mars orbit on March 11 2036 and return to the Earth on October 30 2036.

Intermediate Mars Orbit

Given the rapid design of the TAPER-1 mission, an intermediate orbit in the Martian system is selected based on studies in existing literature. In particular, a high Mars orbit is employed [22]. This orbit possesses an apoapsis radius of 37000 km, a periapsis radius close to the radius of Phobos, and zero inclination with respect to the orbital plane of Phobos. Since the apoapsis of the high Mars orbit lies beyond the orbit of Deimos, opportunistic flybys of Deimos may allow the crew to perform additional scientific observations. This intermediate orbit is connected to the Phobos-vicinity parking orbit through the application of maneuvers at successive apses. Summing the cost of these maneuvers for both approach to and departure from the parking orbit, the total ΔV for transit within the Martian system is equal to 1.2 km/s.

Phobos Vicinity Orbit

Since the Phobos landing locations, selected in Section 3, always face Mars, a Mars-Phobos L_1-centered orbit is employed as a parking orbit. In this system, the L_1 Lyapunov orbits that do not intersect the surface of Phobos have amplitudes normal to the Mars-Phobos line that are approximately 15 km or less. Sample members of the family that do not intersect Phobos are depicted in red in Figure 4 in a Mars-Phobos rotating frame. In this plot, L_1 is displayed as a black diamond and Phobos is conservatively portrayed as a circle with radius equal to the maximum surface altitude of Phobos; both objects lie on the *x*-axis, which is directed along the Mars-Phobos line. Although these orbits possess unstable modes in the orbital plane of Mars and Phobos, some members of the family have stable motion normal to the orbital plane. In addition, halo orbits are formed through a bifurcation from the L_1 Lyapunov orbits that do not intersect the surface of Phobos. Thus, in the ephemeris model, the desired L_1-centered orbit may be designed to resemble a three-dimensional, low inclination L_1 quasi-periodic orbit.

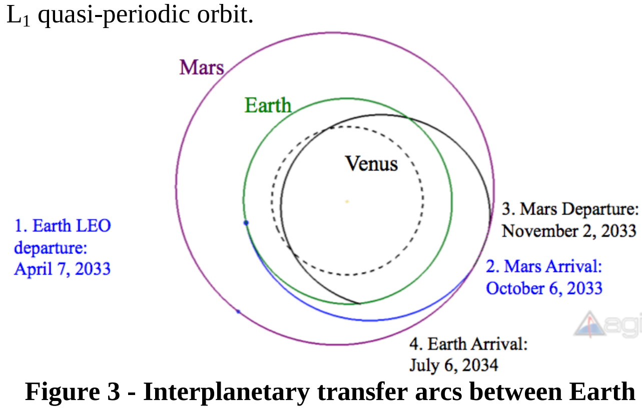

Figure 3 - Interplanetary transfer arcs between Earth and Mars, as viewed in a Sun-centered inertial frame.

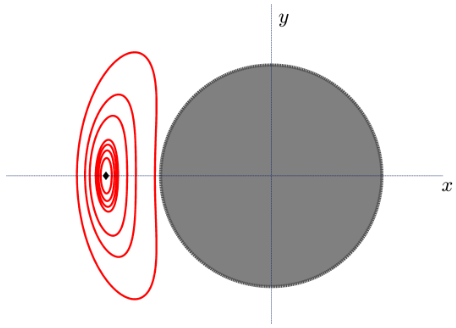

Figure 4 - Sample L_1 Lyapunov orbits in a Mars-Phobos rotating frame, with the origin at the center of a circle with radius equal to the Phobos mean radius.

The two astronauts that are not bound for the surface of Phobos remain on the parking orbit for 24 days until November 1 2033. Based on the range of the periods of these orbits in the Mars-Phobos system, small correction maneuvers could occur every few hours at the crossings of the Mars-Phobos line, estimated to accumulate a ΔV on the order of 100 m/s. In addition, given the relative location of this orbit within the Martian system, the crew may tele-operate a rover on Mars or a set of small CubeSats located within their line of sight. This parking orbit, therefore, allows for both small station-keeping maneuvers and the potential for TAPER-1 to fulfill additional scientific objectives, further reducing the knowledge gap associated with operating in the Martian system.

Abort Scenarios

Mechanical or other failures may occur at any time during this mission; however, primary abort scenarios may be identified and potential solutions suggested. An error during or following the trans-Mars injection would most likely occur during the beginning of the interplanetary trajectory and an abort trajectory may be constructed using a Lambert arc terminating at the Earth [23]. Given the orbital geometry, such a maneuver may be expensive and would require consideration of the remaining fuel and any restrictions on the duration of the return flight. If a thrusting failure occurs when the crew is in the Martian system, the astronauts could potentially remain in a stable Mars-centered orbit, returning home on the nominal Mars departure date without landing on the surface of Phobos.

5. SPACECRAFT

The design of the DSV assembly, which transports the crew between the Earth and Phobos, is primarily driven by the scientific and operational requirements. Prior to discussion of the design of the components of the DSV, it is important to note the different configurations of the DSV at various stages of the TAPER-1 mission. During the outbound leg, from Earth to the Martian system, the DSV consists of the DSH, PSE (P-Hab and P-Sep), CV and NTR propulsion system, as depicted and labeled in Figure 5. Since the P-Hab is designed to remain on the surface of Phobos after the crew has completed surface operations, and the P-Sep is sent to a graveyard orbit, the configuration of the DSV upon departure from the Martian system is different to that of the outbound leg. Accordingly, the DSV consists of the DSH, the NTR propulsion system, and the CV during the inbound transit. The design process for each component is presented in this section, in addition to the robotic assistance and Environment Control and Life Support System (ECLSS). This section concludes with a mass and power budget.

Propulsion System

The propulsion system for TAPER-1 is designed to simultaneously reduce both cost and mission duration in response to budgetary requirements and human factors considerations. In order to select the type of propulsion system, a trade study of different rendezvous architectures is conducted, including rendezvous in LEO, in HEO, or in the vicinity of Phobos. The parameters used are Initial Mass in LEO (IMLEO) and the crew TOF. In particular, IMLEO reflects the number of launches required, which dominates the mission cost. Note that the data used in this trade study are obtained from existing literature [22], [24], [25] and consider initial mass estimates due to the iterative and rapid nature of the design of TAPER-1.

The results of this trade study, displayed in Table 5, reveal an appropriate choice for the assembly orbit, and subsequently, the propulsion system. Through analysis of Table 5, it is clear that the advantages of using solar electric propulsion are mitigated by a large increase in the time of flight, and it is not considered feasible for the crew and spacecraft to withstand for the duration of the TAPER-1 mission. Furthermore, pre-placement of fuel at Phobos reduces aborts options, thereby unacceptably increasing the risk of mission failure. One combination of propulsion type and rendezvous orbit that appears most appropriate within the set of scenarios examined is the use of Nuclear Thermal Rocket (NTR) and assembly in LEO. This combination possesses the lowest risk, highest operational simplicity and a reasonable IMLEO. In particular, a Particle Bed Reactor NTR system is selected over a Nuclear Engine for Rocket Vehicle Application (NERVA) variant for this mission due to the estimated mass savings [26]. Note that political issues must be addressed prior to the utilization of NTR due to the risk of radioactive pollution. Specifically, the NTR propulsion system must be jettisoned to meet international standards for safe disposal of radioactive material and planetary protection standards.

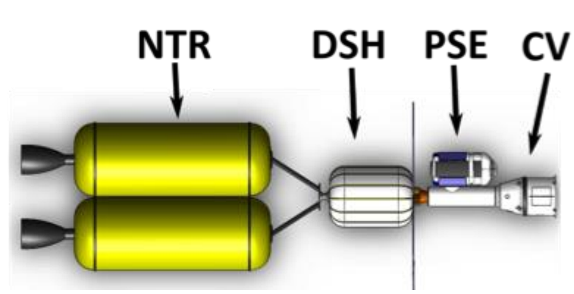

Figure 5 - Outbound DSV assembly

Table 5 – Propulsion Trade Study

Description	IMLEO (mT)	Crew TOF (days)
LEO rendezvous of components, then departure of DSV with NTR	279	456
LEO rendezvous of components, then departure of DSV with cluster of 50 kW Hall thrusters	202	1076
Partial NTR-DSV placed in HEO by cluster of 50 kW Hall thrusters, then rendezvous with CV and depart	297	456
Cargo placed at Phobos by cluster of 50 kW Hall thrusters and DSV departure from LEO with NTR	276	456
Cargo and NTR fuel preplaced at Phobos by cluster of 50 kW Hall thrusters and DSV departure with NTR	248	456

Crew Vehicle

The primary function of the crew vehicle is to serve as a command module for the DSV and as a reentry vehicle at the conclusion of the TAPER-1 mission. As a secondary function, the crew vehicle may also be used as a lifeboat and storm shelter for the astronauts in case of catastrophic mission failure or random solar events. For the TAPER-1 mission, the crew vehicle is selected from a list of currently developed spacecraft, including the Orion Multipurpose Crew Vehicle, the Dragon Rider, and the CTS-100 [27]–[29]. As the result of a trade study, the Dragon Rider capsule from SpaceX is selected due to the low development costs, the current success of the Dragon Cargo vehicle, its capability to hold the four astronauts comprising the crew of TAPER-1, and the possibility of using this capsule in subsequent Mars missions.

Phobos Surface Explorer

Another component of the DSV is the PSE, which is a two-stage SEV comprised of the P-Sep and P-Hab. The P-Sep, portrayed in the bottom left of Figure 6, enables crew mobility on the surface and returns the astronauts to the DSV upon completion of surface operations on Phobos. The P-Hab, depicted on the bottom right of Figure 6, provides a living and working environment for the astronauts during the 30-day Phobos surface exploration. The PSE habitat (P-Hab) is designed to remain on the surface of Phobos as a permanent base, while the P-Sep returns to the DSV.

The features of the P-Sep are designed to enable thorough exploration of the surface of Phobos, while simultaneously creating a permanent infrastructure. First, the propulsion system of the P-Sep is a LOX/Methane engine that is sized for ascent and descent based on currently available propulsive systems. In addition, the P-Sep has three robotic arms and a sample collection compartment. Robotic arms are also present on the P-Hab to allow the habitat to clamp to the surface of Phobos. Other features of the P-Hab include suit ports for use during EVAs, a docking port to enable access to the remainder of the DSV, and robotic exploration tools.

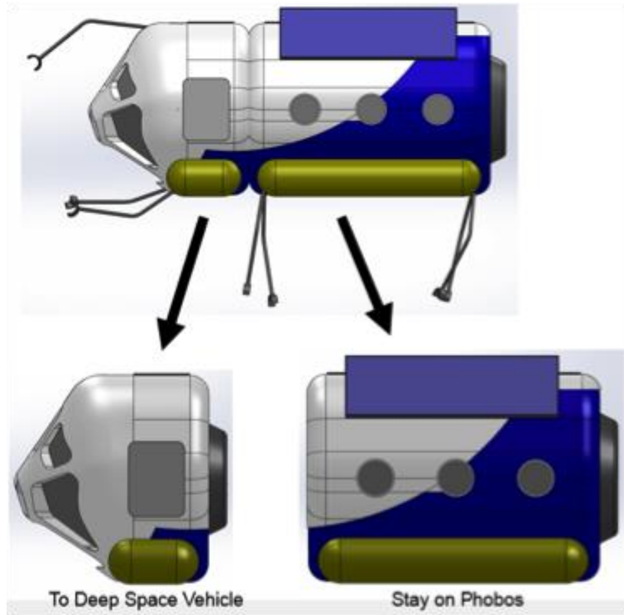

Figure 6 - PSE Design Concept

Deep Space Habitat

The DSH is used by the crew as a living and working space for the duration of the mission. As a result of this operational requirement, the first design choice for the DSH is the type of structure. Both hard-shelled and inflatable structures are considered in a trade space that includes the NASA HEFT Phase II, the ISS-based HAB/MPLM, and the Bigelow Aerospace Sundancer, which, respectively, have 71.8 m^3, 108.3 m^3, and 180 m^3 habitable volumes and weigh 18 tons, 35 tons, and 9.1 tons [30], [31]. In this trade study, the Sundancer possesses the largest habitable volume and lowest weight. Additionally, the Sundancer is an upgraded version of the Bigelow Aerospace Genesis module which has been demonstrated in space. These factors lead to the selection of the Bigelow Aerospace Sundancer as the DSH.

The internal layout of the DSH is divided into the following major sections: avionics, ECLSS, storage, crew quarters, galley stowage, work stations, hygiene, exercise space. A cross sectional view of the internal DSH layout is shown in Figure 7. The volumes included in this design are derived from NASA heritage listed within the Human Integration Design Handbook [31].

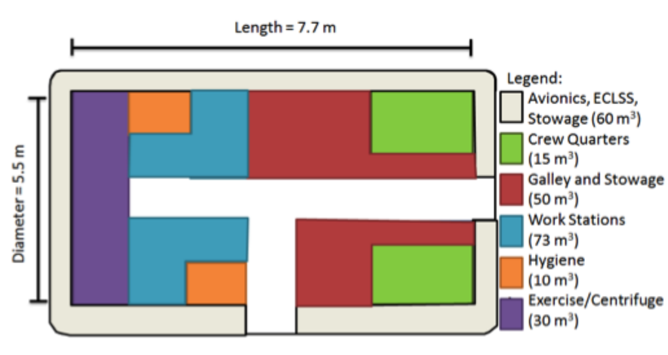

Figure 7 - DSH Layout

ECLSS

ECLSS maintains a habitable environment within the spacecraft through a closed loop where some of the consumables are recycled to conserve mass. The ELISSA (Environment for Life Support System Simulation and Analysis) software, developed at the Institute of Space Systems, University of Stuttgart, was used to simulate this life support closed loop system in the DSH for a 443 day long duration mission to Phobos. The final mission duration is 456 days, but these results may be easily extrapolated to the next 13 days. Figure 8 shows the ECLSS architecture chosen for the DSH [32].

The simulation constructed using ELISSA is based on a crew of four astronauts living in the DSH for a mission duration of 443 days in a habitable volume of 180 m^3. This simulation is considered conservative because for 30 days, two astronauts will leave the DSH to explore the surface of Phobos. Throughout this simulation, ELCSS atmospheric requirements include 101.1 KPa, 293 K, 21% partial pressure of O_2, 41% relative humidity, partial pressure of CO_2 must be less than 2.5%, and sufficient water and food must be provided. For the simulation, ELISSA combined the following four subsystems:

- *Air*—3 Static Feed Water Electrolysis (3 kg of O_2 generated/day, TRL=8); 2 Electrochemical Depolarized Concentrator for CO_2 removal (TRL=6); 2 Trace Contaminant Control (TRL=8), and 1 Heat Exchanger (TRL=8).

- *Water management*—2 Vapor Phase Catalytic Ammonia. Removal to produce potable water (250 kg/day per unit, TRL=6); 2 Air Evaporation System for urine treatment (TRL=3).

- *Food*—1200 kg of dehydrated food (maximum intake per person = 0.56 kg/day).

- *Waste Management*—2 Sabatier Reactors for CO_2 reduction ($CO_2+4H_2 \rightarrow CH_4+2H_2O$); 2 Pyrolysis units for CHF reduction (TRL=4).

The total mass estimation of the life support system (LSS) is around 8000 kg (empty mass (3420 kg) + product mass (3000 kg) + hardware mass (1670 kg)), and the total volume occupied by the system is 12.5 m^3.

Figure 9 shows the evolution of the major LSS factors during the Phobos mission. These include O_2, CO_2, H_2O and food remaining on board during the 443 days. All levels are within the nominal range during the mission and some food is still remaining on board after coming back to Earth, assuring some extra resources for eventual contingencies and maintenance of an adequate astronaut comfort level. These results leave margin to reduce consumption of resources in an emergency situation. For instance, laundry could be potentially suppressed, reducing the H_2O consumption by 12 kg/day per astronaut.

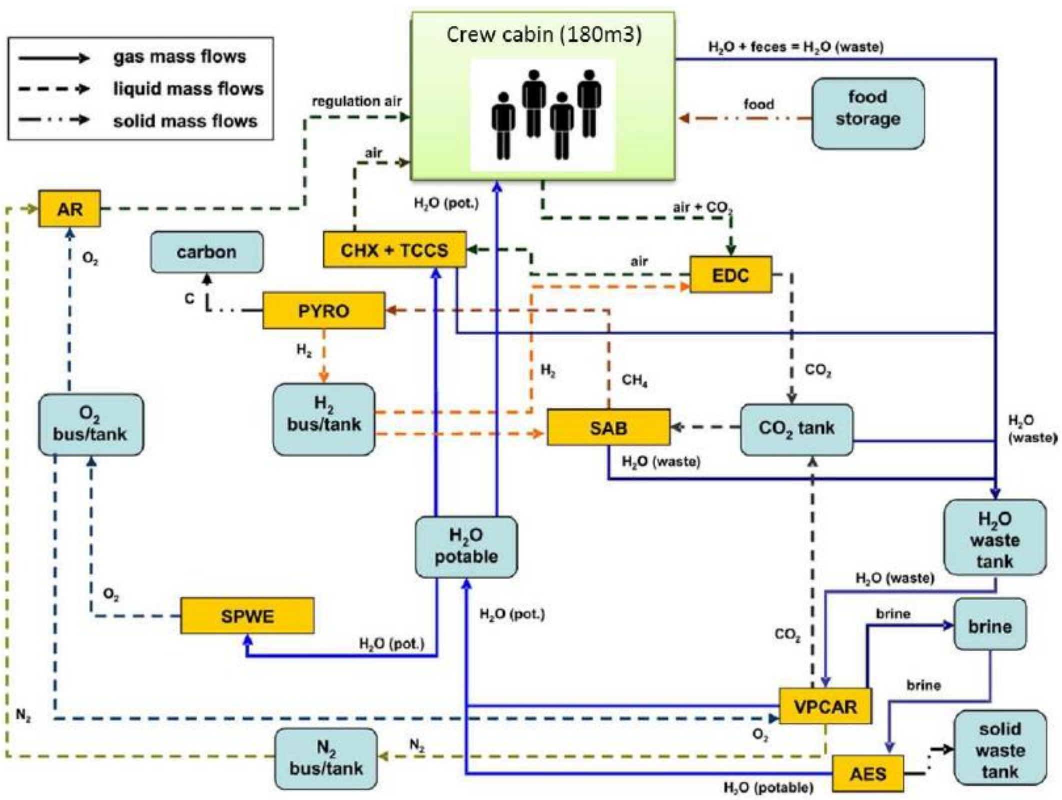

Figure 8 – ECLSS architecture (adapted from [32])

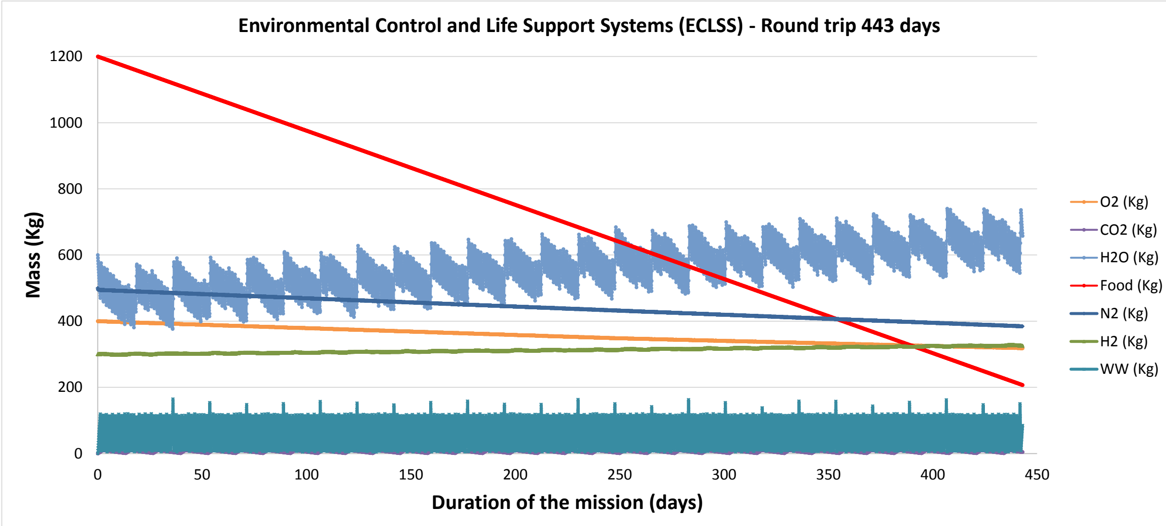

Figure 9 – DSH ECLSS parameters during the round trip mission

Robotic Assistance

Rovers deployed on the surface of Phobos during the mission are intended to fulfill several roles. Functions of these robots include scouting other sites while the astronauts are at the first site, retrieval of samples from areas inaccessible to the astronauts in the PSE, and providing a larger field of vision to the astronauts on the ground when accompanying them to sites. The robots also permit testing of new robotic technology which is designed to operate in milli-gravity environments and difficult terrain.

A robotic design proposed in [33] is adapted for the mission requirements of TAPER-1. The original design envisages a mother spacecraft ("Phobos Surveyor") which deploys a number of rovers, named "Phobots" in the TAPER program, to the surface while the crew is orbiting Phobos. A graphical depiction of the proposed operational use of Phobots is provided in Figure 10. The robots are small, multi-faceted spacecraft/robot hybrids with internal actuation and external spikes. Mobility is achieved through tumbling and hopping, at a speed of approximately 180 m/hr. Instruments onboard the Phobots include a stereo-vision camera with multispectral filters, a microscope, a Raman/LIBS spectrometer, a neutron spectrometer and a visible/near-infrared spectrometer. The envisaged total power consumption is 15 W, which includes the actuator, onboard computer, communication and instrumentation. The Phobots would be powered by a combination of solar panels and batteries. To ensure a maximum mass of 10 kg per Phobot, the instruments could be distributed evenly amongst the individual robots.

The robots may act as Mobile Science Platforms (MSP) or scouts, close to or far from the astronauts on the ground, with two operational modes. In the first mode, the robots accompany the astronauts in the P-Sep, acting as scouts by providing a better vision of the terrain. They also provide better maneuverability when targeting samples that are difficult to reach. In the second mode, the robots are used to explore designated sites not yet visited by the astronauts, to start conducting measurements and identifying sample collection areas, thereby aiding surface operations.

Mass Budget

An overview of the mass budget for the DSV is shown in Table 6. Note that all subsystem masses have been increased by 10% and the propulsion system sized according to this mass. This margin was added to the IMLEO, while a margin of almost 50% was added to the ΔV requirements.

Power Budget

The approximate power budget for the TAPER-1 mission is determined using the maximum power that each subsystem requires, with the results displayed in Table 7. In this table, the power source indicates the means by which power is produced for the respective subsystem, with some power sources shared between subsystems. In addition, a margin is applied to each subsystem in order to ensure additional power availability for off-nominal operating conditions.

Table 6 – Mass Budget

Component	Mass (t)
NTR Propulsion System	184
PSE	16.4
DSH	25.2
CV	9.5
Crew	0.6
Total	235.7

Table 7 - Power Budget

Vehicle	Power (kW)	Power Source
PSE	9.0	Solar and Li-Ion Batteries
DSH	18.5	Solar
CV	2.0	Solar
Total	29.5	Solar and Li-Ion Batteries

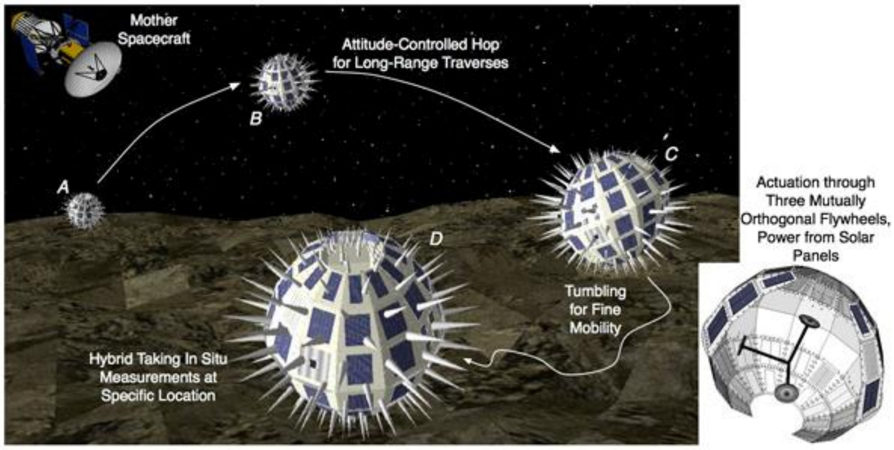

Figure 10 - The mission architecture of the "hedgehog" robots [33]

6. Crew Operations

Interplanetary Transfers

A typical day for the crew during the interplanetary transfers includes scheduled work, exercising, eating, and sleeping. Scheduled work includes assessing and maintaining the performance of the spacecraft, conducting scientific experiments, making outreach communications to Earth, and preparation for key mission events. The crew is also allocated time for reading, video games, and skill training.

Phobos Surface Operations

The two crew members landing on Phobos have as a primary objective to retrieve surface, core, and dust samples. The astronauts spend the 24-day Phobos surface mission inside the PSE, and are able to make limited excursions of up to 8 hours in duration in the P-Sep. The first EVA is planned on the third day on Phobos, although additional EVAs may occur in subsequent days, either intentionally or when robotic access is limited. A nominal schedule based on a deep drill science payload is presented in Table 8. On the other hand, the two crew members remaining in the DSV are engaged in other tasks, including the support of the surface operations, the tele-operation of the Phobots rovers when necessary, and the conduction of additional physiological and biological experiments.

Sustained Phobos Operations

Three operational space weather stations and the seismic network stations remain on the surface of Phobos following completion of the TAPER-1 mission. The weather station includes a plasma wave system, a micrometeorite detector, a dust particle detector, and a communication system. The Phobots, depending on their available end-of-life power, may also be operational. The selected landing sites are at most 3 km away from areas where there is constant sunlight [6], so that the Phobots would be able to periodically pause data collection and recharge their batteries in a sunlit area. These systems would extend scientific operations and support future exploration of the Martian system.

Table 8 – Nominal schedule during surface operations

Mission Day	Activities Planned
Day 0	PSE separates from DSV and begins transit to Phobos surface
Day 1	Reach Landing Site A
Day 2	Install permanent Martian moon surface science equipment at Landing Site A
Day 3	First planned EVA. Explore vicinity of Landing Site A.
Days 4-8	Drilling operations at Landing Site A
Days 9-10	Collect drill and other rock samples from Landing Site A
Day 11	Reach Landing Site B
Day 12	Install permanent Martian moon surface science equipment at Landing Site B
Days 13-14	Core for and collect samples from second site while in PSE or P-Sep.
Day 15	Reach Landing Site C
Day 16	Install permanent Martian moon surface science equipment at Landing Site C
Day 17-18	Collect samples at landing Site C
Day 19	Reach Landing Site D
Day 20-21	Install permanent Martian moon surface science equipment at Landing Site D
Day 22	Collect samples at Landing Site D.
Day 23	P-Sep rendezvous with orbiting DSV
Day 24	Mission ends. Preparation of transfer to Earth

7. HUMAN FACTORS

Crew Size and Selection

In order to increase the possibility of mission success, astronaut candidates are selected such that they are able to handle high-stress and high-risk situations, and confined isolation, all present during a long duration space mission. Screening for these candidates is intended to be based on physiological [34] and psychological [35] testing. Depending upon the political and ethical environment in the 2030s, genetic testing may potentially be used to screen astronaut candidates [34]. The crew for the Phobos mission is selected to consist of four astronauts of mixed gender, since analogue Antarctic studies have shown that mixed crews have an increased productivity and elevated mood [36]. Despite an odd crew size would be desirable to avoid decision making process, and even crew size has been selected primarily because of mass constraints. In addition, it has been suggested that a four-member crew is desirable over three, in order to minimize psychological issues derived from such a small number of astronauts [37]. In addition, the crew is also intended to have a very clear hierarchy in order to avoid complications during the decision-making process. The suggested roles of the crew are chief commander/pilot, flight surgeon, mission specialist/geologist, and a mission engineer.

Radiation Protection

Ionizing radiation is the primary concern for human health during long duration space missions. In order to mitigate the acute and long term effects of radiation, the upper limit of the radiation dose is selected to be a 3% fatal cancer risk. Based on calculations performed by Cucinotta, the maximum duration a male over the age of 45 can stay in space is approximately 526 days [38]. Females over the age of 55 can be in space for a maximum of 472 days. These results are based on the following assumptions: 20 g/cm^3 of aluminum shielding, storm shelter for a solar particle event (SPE), and launch during solar maximum [38], [39]. In order to minimize radiation exposure, a low z-material called Vectran is used as the structural material of the inflatable spacecraft. It is produced by “poly condensation of a 4-hydroxybenzoid acid and 6-hydorxynaphthalene-2-carboxyl acid”, and studies have shown that it can shield against micrometeorite and orbital debris (MMOD), and it has good thermal control capabilities [40]. NASA uses this material in their current spacesuit, the Extravehicular Mobility Unit, and in the fabric used for the airbags on the rovers Mars Pathfinder, Spirit, and Opportunity [40].

Passive shielding is also employed in TAPER-1 in the form of an integrated ECLSS. This system provides life-sustaining technologies to the crew while lining the cabin walls with water, liquid hydrogen and other biological materials. Several additional technologies could also be tested for radiation protection during the journey.

Physiology

In long duration space missions the human body undergoes many changes due to the microgravity conditions, including bone loss, muscle atrophy, orthostatic intolerance, motion sickness, and neurovestibular effects [41].

Bone loss contributes significantly to the physiological deconditioning that occurs during spaceflight, occurring primarily due to the absence of skeletal loading in microgravity [41], [42]. Bone loss usually begins at the lumbar spine and becomes significant in the lower extremities [41]. These observations are reasonable, considering that astronauts use their upper limbs to move around the spacecraft, and their lower extremities for stabilization. Other factors that affect the human skeleton are low light levels, high concentration of CO_2, dietary factors (calcium and vitamin D), and genetic factors. In addition, skeletal unloading conditions lead to a significant loss of calcium in the bones and a substantial increase in the risk of kidney stone formation [41], [42]. Muscles are also highly affected by microgravity, in particular the antigravity muscles, which are involved in maintaining stability in the Earth gravity environment. Previous studies have shown that the changes in muscle volume after long duration spaceflight can be as high as -20% for the iliopsoas (or dorsal hip muscles) and -19.6% for the soleus (back part of the lower leg) [41]. Muscles also lose mass and strength. Muscle atrophy is caused by two major factors: the lack of activity that decreases the protein synthesis, and inadequate caloric intake. Other factors include oxidative stress (balance between oxidants and antioxidants) and hormonal influences [41]. The cardiovascular system is also highly affected by long duration spaceflight. The human body adapts to the new environment and produces changes in blood volume, aerobic capacity and cardiac mass. Shortly after reaching orbit, there is a significant fluid shift from the lower to the upper body, producing a “puffy” face. Furthermore, these changes could potentially present problems after flight, such as orthostatic intolerance. In addition, astronauts can suffer motion sickness in space, mainly caused by conflicting cues provided by the vestibular system and other senses [41].

Countermeasures—Bone remodeling is highly dependent on the mechanical loading applied on the skeleton [43]; thus, the DSH is designed to include a short radius centrifuge to create static loading. The gravity gradient created by the centrifuge is an excellent countermeasure for bone loss, muscle atrophy and cardiovascular changes in microgravity. In addition, a cyclometer could be included in the centrifuge to improve the aerobic capacity and cardiovascular effects of astronauts, as depicted in Figure 11. In addition, the DSH is designed to also include a treadmill and a resistance device similar to the Advanced Resistive Exercise Device exercise machine currently used in the ISS. The treadmill provides peak loads on the human body, which are important for bone remodeling, and the resistance exercise machine has been proved to be the best countermeasure for muscle atrophy.

Other countermeasures derive from concepts for Intravehicular Activity, providing continuous loading or resistance on the human body. Exoskeletons can provide continuous resistance to the wearer in order to improve muscle atrophy. The Gravity Loading Countermeasure Skinsuit (GLCS) is a countermeasure garment to produce a continuous static loading profile on the wearer body similar to the loading profile induced by gravity on Earth, gradually increasing the loading in the z axis (see Figure 11) [42]. Some of these concepts still present engineering challenges since the technologies have TRLs of 2/3; however, they are likely to be ready within the next 20 years.

Finally, astronauts may take the appropriate drugs in order to counteract weightlessness physiological effects. Bisphosphonates have been proved to decrease bone loss, but long terms effects need to be further investigated before the space mission. Human parathyroid hormone can also increase bone formation in space. Human physiology characteristics should be carefully monitored in order to personalize and adjust the countermeasure program for each one of the astronauts. Monitored parameters include weight, anthropometric measurements (leg volume, calf circumference), urinary calcium excretion and serum levels, and cardiac activity [41].

Clinical Medicine

The TAPER-1 mission employs the medical system that is currently used and operated on the ISS called the Crew Health Care System. However, several improvements are made to address medical anomalies, including telemedicine, 3D metal printing, and a surgical suite. Making use of telemedicine, crew members can diagnose themselves, analyze the symptoms, and use the necessary materials to regain optimal health. A touch screen tablet could wirelessly communicate with biological sensors and compare the measurements with preloaded data for health monitoring. After a proper diagnosis is confirmed, the device may provide step by step directions that show the crewmember how to carefully execute the necessary protocol. In addition, a 3D metal printer could be used to fabricate special surgical hardware, as needed. To minimize health complications precautionary surgery is also recommended.

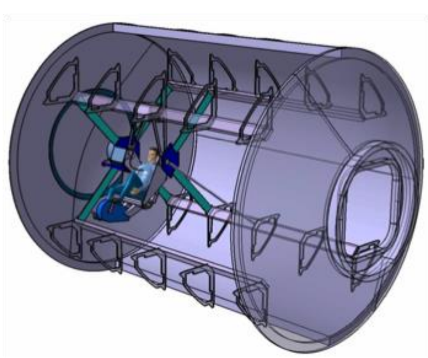

Figure 11 - Short radius centrifuge combined with exercise (left, credit ESA); and a prototype of the Gravity Loading Countermeasure Skinsuit (right)

8. PROGRAMMATIC CONSIDERATIONS

Cost

Cost estimates for manned Mars system exploration in literature range widely: from tens of billions to hundreds of billions USD [44]–[46]. The principal source of cost uncertainty is the low TRLs for key components. While it is impossible to narrow the total cost estimate within the scope of this study, certain aspects have been identified as primary cost drivers.

Technology development is one primary cost driver. For instance, development of a Nuclear Cryogenic Propulsion Stage (NCPS) is estimated at four billion USD as quoted by media sources [47]. Since this development encompasses the simple solid core reactor type, it is assumed that the development of the Particle Bed Reactor type used in this mission will be similarly costly. Launch costs are another primary cost driver. The use of the Space Launch System is estimated at 2.5 billion USD per launch [5], and subsequently total cost of upwards of ten billion USD for the mission. Overall, these primary cost drivers ensure a lower limit of several tens of billions in USD.

Risk

The program-level risks are largely split into two categories: political and financial. The program has been designed to fit within a larger international context for space exploration (as laid out by the Global Exploration Roadmap [4]). Within this framework, international pressure inhibits withdrawals from such financial and political obligations and minimizes the negative effects if one nation does withdraw.

If the TAPER program is found to be infeasible, possible de-scope options and takeaways include: a) use of developed knowledge and hardware for a mission to a Near Earth Asteroid (NEA); b) use of precursor science data for future missions to the Martian system; c) benefit of technology development for future missions and industry partners; d) lessons learned from design and development of the missions.

Political Sustainability

The potential multi-decade development timeline for TAPER encompasses several political cycles, and policy fluctuations must be expected. Pragmatic, flexible approaches to budgeting and schedule are required to ensure the impact of potential funding reductions is minimized. As with the mitigation of political and financial risk, international cooperation creates an obligation between the partners, which likely supersedes any one nation's politics. This has had a positive effect on the political sustainability of the International Space Station program, and would likely influence the TAPER program similarly.

Public Relations and Outreach

International programs require strong and consistent public support from all members and thus, TAPER's success hinges on public engagement from each contributing nation. It is expected that the key players in the TAPER program would maintain their current outreach programs, but further public outreach may be required to meet public relations needs. The following are suggestions for specific outreach concepts that take advantage of the unique opportunities the TAPER mission provides.

International CubeSat Design Competition—Five CubeSats are required for the Deimos flyby aspect of the mission. An international competition is proposed to challenge schools and universities to develop the CubeSats required for the mission. This challenge would be similar to other competitive CubeSat development challenges, such as QB50, which have proven educational merit and significant public attention. The winning CubeSats would be launched as part of the TAPER program, subject to extensive design review and verification.

External Biology Experiment—As previously discussed in the Science section, the response of biological matter to the deep space environment is a key question the TAPER program plans to explore. In an effort to educate future scientists and engineers about the effects of deep space flight, a competition to design an external biology experiment is proposed. Much like the 2012 YouTube SpaceLab competition, the proposed External Biology Experiment Challenge would invite students to consider the scientific thought process while providing an opportunity to have their experiments fly in space.

Vehicle Naming—Similar to the public outreach initiative which led to the naming of the Mars Science Laboratory as the Curiosity Rover, each major segment of the TAPER program could be named as part of an international competition, open to the public.

Astronaut Interfacing—Currently, astronauts onboard the ISS participate in teleconferences with students across the world to share their experiences and excite the public about space exploration. It is expected that teleconferencing advances could lead to an entirely new method of interfacing with the astronauts. One potential option would be to have members of the public challenge an astronaut in a (likely space-related) computer game.

Online Education—Leading up to TAPER-1, each space agency involved could ask project scientists and engineers to teach online courses related to the subjects involved in the mission. These project members could give short online lectures using services like edX or Coursera. The online education format provides students with intimate access to key mission figures; this would be a major motivational boost for the students to pursue STEM education.

9. SUMMARY

This mission is framed in the context of the future human exploration of the Martian system. TAPER addresses some of the key roadmap gaps, both scientific and technological [4]. Moreover, the science objectives proposed by TAPER explore deeper scientific questions about not only Phobos itself, but also the Martian system. Although the proposed mission requires significant innovation in both minor and major technologies, current TRLs combined with ongoing research programs suggest that these technologies will be available for the TAPER mission. Furthermore, by testing and developing these technologies on a more accessible target such Phobos, technology for future Mars missions can be better designed and developed.

Although involvement of the general public was addressed in previous sections, it cannot be overstated that the relationships between the project contributors and the general public play a critical aspect to the overall success of the project. A mission to the Martian system is of such high stature that the entire world will be both watching with bated breath and expecting the successful outcome of the mission. Furthermore, the relevancy of the TAPER program must be demonstrated throughout its duration. The specialized technologies developed to support TAPER must encourage growth in technologies used day-to-day by the general public. The knowledge gained by TAPER must be properly disseminated throughout the globe, not simply privy to those scientists involved in the project.

Finally, this research effort has been completed in the context of a rapid mission design exercise during the second Caltech Space Challenge, held in 2013. Sixteen students with different backgrounds and nationalities designed this manned mission to Phobos, supported by experts from Jet Propulsion Laboratory and Caltech, in a time span of five-days. This work contained within this paper demonstrates the value of exposing students to the rapid mission design process through the use of a concurrent engineering approach. In particular, Team Explorer gained an appreciation and understanding of both the challenges and merits of rapid mission design.

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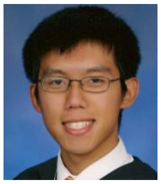

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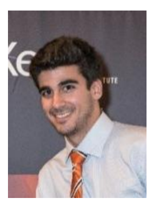

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APPENDIX A

Science Traceability Matrix for major Phobos in situ science

Science Related Mission Objectives	Measurement Objectives	Measurement Requirements	Instrument requirements
Objective 1: Investigate the origin and evolution of the Martian moon to better understand the Martian system	Identify diverse suite of rocks and regolith to be collected and returned for detailed laboratory investigation	Rock and soil samples must be collected from at least two locations on Phobos (red and blue units), preferable three	Return samples to be analyzed by techniques on Earth, including XRD, isotopic/age dating analyses, etc
	Determine the composition in situ of rocks and regolith from diverse and well characterized locations	Rock and soil samples must be investigated from at least two locations on Phobos (red and blue units), preferable three	Rama/LIBS, Visible/Near infrared spectrometer measurements; Multispectral camera to identify spectrally unique areas and provide context
	Constrain internal structure of Phobos	Seismic measurements locations across Phobos	Deployable seismometers
	Characterize Phobos regolith and process that may have modified it over time	In situ science to characterize grain size, distribution, roundness; investigation of returned core samples	Hand lens, corer and scoop to bring back regolith samples
Objective 2: Access availability of in situ resources for possible future use in manned Mars missions	Determine the volatile content of the moon's surface and subsurface	Measure regolith water content in situ, collect sample cores from any areas identified by precursor as potential for having subsurface water	Rama/LIBS, VNIR spectrometer, Neutron spectrometer, drill for areas identified by precursor mission as potential for subsurface ice; deep drill if indicated necessary by precursor science
	Detect and quantify any mineable material including magnesium, methane, ammonia, clays, REE	Understand the composition of the surface	Raman/LIBS, APXS, Visible/Near infrared spectrometer measurements
Objective 3: Understand the current environment of Phobos in the context of the Martian system to support architecture for future manned Mars missions	Characterize effects of space weathering on the Phobos regolith	Collect core samples from at least three locations on each of two sites	Returned samples: XRD, isotopic and age dating analysis, GCMS, etc.
	Understand how radiation is attenuated and blocked on the surface over time	Measure fluxes and energies of particles received at Phobos surface	Plasma wave detector; energetic particle detector for low energy particles
	Quantify amount of dust fall and frequency of micrometeorite impacts on Phobos	Measure dust fall on Phobos	Dust detector