CALTECH
SPACE CHALLENGE

TAPER

Technology Advancing Phobos Exploration and Return

March 29, 2013

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Glossary

$AODCS$	Attitude and Orbit Determination and Control System
$ARED$	Advanced Resistive Exercise Device
$CHECS$	Crew Health Care System
CHX	Heat Exchanger
$COPV$	Composite Overwrapped Pressure Vessel
CSA	Canadian Space Agency
CTS	Crew Transport System
CV	Crew Vehicle
DSH	Deep Space Habitat
DSV	Deep Space Vehicle
$ECLSS$	Environmental Control and Life Support System
EDC	Electrochemical Depolarized CO2 concentration
EP	Electric Propulsion
EPT	Electric Propulsion Tank
ESA	European Space Agency
$ELISSA$	Environment for Life Support System Simulation and Analysis
EVA	Extra Vehicular Activity
$FTMW$	Fourier-Transform microwave
$GCMS$	Gas Chromatograph Mass Spectrometer
GCR	Galactic Cosmic Rays
GER	Global Exploration Roadmap
$GLCS$	Gravity Loading Countermeasure Skinsuit
GNC	Guidance Navigation and Control
$HEFT$	Human Exploration Framework Team

HEO	High Earth Orbit
$IMLEO$	In-mass LEO
IR	Ionizing Radiation
$ISRU$	In-situ Resources
ISS	International Space Station
$JAXA$	Japanese Exploration Agency
KSC	Kennedy Space Center
LEO	Low Earth Orbit
$LIFE$	Living Interplanetary Flight Experiment
LOX	Liquid Oxygen
$LIBS$	Laser-induced Breakdown Spectroscopy
LSS	Life Support System
MRO	Mars Reconnaissance Orbiter
$NASA$	National Aeronautics and Space Administration
$NCPS$	Nuclear Cryogenic Propulsion Stage
NEA	Near Earth Asteroid
NEO	Near Earth Object
$NERVA$	Nuclear Engine for Rocket Vehicle Application
NTR	Nuclear Thermal Rocket
PBR	Particle Bed Reactor
PSE	Phobos Surface Explorer
$PSEP$	PSE Separator
REE	Rare Earth Elements
SEV	Space Exploration Vehicle
$SFWE$	Static Water Feed Electrolysis

SLS	Space Launch System
SPE	Solar Particle Event
STK	Satellite Toolkit
$TAPER$	Technology Advancing Phobos Exploration and Return
TCC	Trace Contaminant Control
TMI	Trans-Mars Injection
TOF	Time of Flight
TRL	Technology Readiness Levels
$VPCAR$	Vapour Phase Catalytic Ammonia Removal

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Abstract

This document provides a programmatic roadmap for the planning, design and development of the “Technology Advancing Phobos Exploration and Return” space mission (TAPER). The derivation of the science traceability matrix and mission objectives will be discussed, as well as the objectives and timelines. To fulfill mission objectives, the mission design and associated technologies will be discussed.

1 Introduction

1.1 Problem Statement

In March 2013, the Engineering and Applied Science Department at Caltech hosted the Caltech Space Challenge, a 5-day student space mission design competition consisting of 32 undergraduates and graduates with varying backgrounds and nationalities split into two teams of 16. Teams were given the following problem statement:

"In 5 days, each team is challenged to design a mission to land humans on a martian moon, either Phobos or Deimos, and return them along with a sample safely to Earth. The launch date of the mission may be no later than January 1st, 2041."

The following questions, as well as tens of sub-questions, are presented as key aspects to be considered when designing the mission:

Q1: What is the proposed work about?

Q2: Why should the proposed work be undertaken?

Q3: How will the proposed work be accomplished?

Q4: What will be learned and what will the benefit(s) be if the project is successful?

Q5: How will the results change in the future?

Only this mission needed to be developed, while any precursor missions deemed necessary could be explained using general justifications. Also, the mission design must allow for extravehicular activity (EVA) on Phobos surface for means of sample collecting and return. It was also defined that the astronauts could only land in one of the Martian moons.

The following report details Team Explorer's solution to this problem statement, which is presented as a conceptual roadmap for the mission design and the context in which it is undertaken.

Appendix A provides a complete breakdown of all questions, short responses to each question, and leads the reader to the sections of this document which are relevant to each question.

1.2 Inspiration

"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 symbolism of our chosen program name, Technology Advancing Phobos Exploration and Return, or TAPER, is inspired by the above quote. It is clear that this mission is proposed as part of a larger vision for the exploration and colonization of Mars. As will be stated, TAPER's goal is to support future manned missions to Mars, providing knowledge to others in the same spirit of Thomas Jefferson's message.

1.3 Context

1.3.1 The Current and Future State of Space Exploration

The context of the current state and future of space exploration for this mission is primarily understood from three documents: the final report of the Review of U.S. Human Spaceflight Plans Committee [1], the National Space Policy of the United States of America [2] and the Global Exploration Roadmap [3]. All these documents are largely similar in their proposals of the future of human exploration over the next few decades. They outline the Mars as the ultimate goal, while identifying many possible destinations and missions to serve as intermediary steps.

The proposed mission exists within this larger context: beginning with the completion of exploitation of the International Space Station (ISS) in low-earth orbit (LEO) through 2020; then exploration first in the Cis-Lunar environment in the 2020s; followed optionally by operations at Near Earth Asteroids (NEA); and then missions to the martian system, and ultimately the surface of Mars itself.

The National Space Policy specifically states as one of its goals “By the mid-2030s, send humans to orbit Mars and return them safely to Earth” while the Global Exploration Roadmap states “Some agencies are studying human missions to the martian moons, Phobos and Deimos......these missions may also provide the opportunity to demonstrate similar capabilities as those required for asteroid missions.”

It is with these statements firmly in mind that a mission is proposed, as part of a larger program, to accomplish the objective of sending humans to a martian moon and returning them safely with martian system samples.

1.3.2 Major Contributors

1.3.2.1 Space Agencies

Although several viable program leader architectures exist, the National Aeronautics and Space Administration (NASA) is proposed as the primary administrator and executor of the TAPER program due to their extensive history in space and vision for the future of human spaceflight. However, the potential involvement of other space agencies should not be minimized; the European Space Agency (ESA), the Japanese Exploration Agency (JAXA), the Canadian Space Agency (CSA) and Roscosmos are among several agencies with extensive human spaceflight experience that all offer valuable knowledge and resources. Therefore, TAPER will be an international cooperation in a similar spirit to the International Space Station, though, the decision to select certain components for the mission will be driven mainly by cost and performance as opposed to inclusivity.

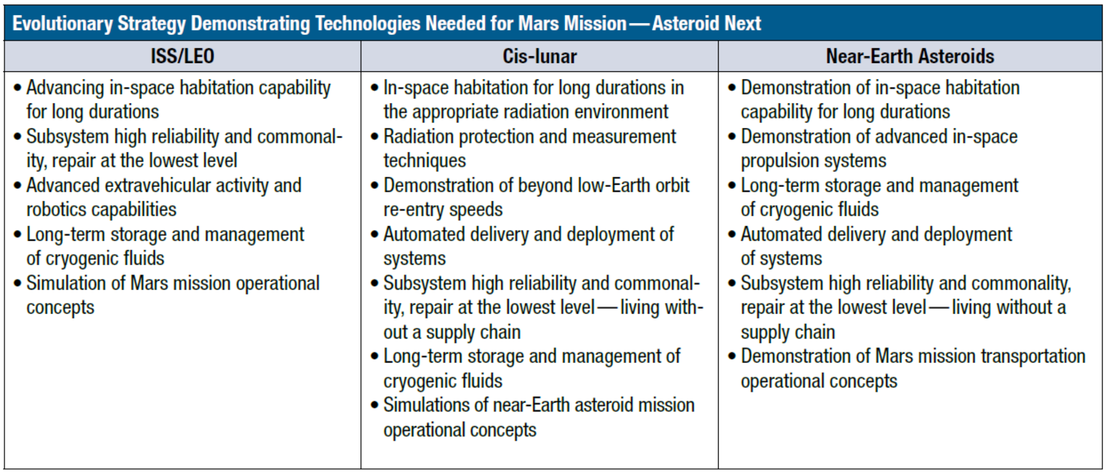
1.3.2.2 The Private Space Industry

Due to the efforts of NASA and other space agencies to help private space companies develop safe, reliable, and cost-effective transportation vehicles, a number of companies have grown to become important players in the field of space exploration, including Space Exploration Technologies Corporation (SpaceX), Bigelow Aerospace, and Astrium among others. It is now reasonable to depend on companies like these to develop and manufacture high TRL components for future missions at a cheaper price, allowing NASA and other space agencies to focus on vital components with lower TRL and higher risk. Examples of relatively high Technology Readiness Level (TRL) components would be launch and entry vehicles, while examples of low TRL components would be in-space propulsion and landers.

NASA's continuing budget struggle requires a strict monetary focus towards the development of select critical technologies. Space Launch System (SLS) and Orion, the launch and entry vehicles currently under development at NASA, are exciting projects that enable NASA to explore beyond the solar system farther than ever before. However, it begs the question of why NASA would fund these projects while simultaneously funding the development of launch and entry vehicles in the private sector (e.g. Falcon Heavy and Dragon) that will most likely evolve to have the same functionalities someday for cheaper. TAPER seeks to avoid such redundancies and allocate resources more effectively to create the most feasible and cost-effective solution.

1.3.3 Step Towards Human Exploration of Mars

The Global Exploration Roadmap (GER) [3] provides a list of key technologies that need to be developed before a human mission to the martian surface, and how they can be demonstrated in mission scenarios at a variety of destinations as shown in Fig. 1.1. Any mission to a martian moon as a precursor to the martian surface would have to contribute to the demonstration of these capabilities and technologies.



Evolutionary Strategy Demonstrating Technologies Needed for Mars Mission—Asteroid Next

ISS/LEO	Cis-lunar	Near-Earth Asteroids
• Advancing in-space habitation capability for long durations • Subsystem high reliability and commonality, repair at the lowest level • Advanced extravehicular activity and robotics capabilities • Long-term storage and management of cryogenic fluids • Simulation of Mars mission operational concepts	• In-space habitation for long durations in the appropriate radiation environment • Radiation protection and measurement techniques • Demonstration of beyond low-Earth orbit re-entry speeds • Automated delivery and deployment of systems • Subsystem high reliability and commonality, repair at the lowest level—living without a supply chain • Long-term storage and management of cryogenic fluids • Simulations of near-Earth asteroid mission operational concepts	• Demonstration of in-space habitation capability for long durations • Demonstration of advanced in-space propulsion systems • Long-term storage and management of cryogenic fluids • Automated delivery and deployment of systems • Subsystem high reliability and commonality, repair at the lowest level—living without a supply chain • Demonstration of Mars mission transportation operational concepts

Figure 1.1: List of technologies from the GER.

2 TAPER Program Overview

The TAPER program is established to provide a supportive knowledge-building environment to ensure the completion of the Phobos sample return mission. The goal of TAPER is to bridge critical policy, technology, and science gaps and demonstrate the capability for future human exploration of Mars through sending an international crew to one of the Martian moons.

While the current global context is a good support for such a mission, the current state of scientific knowledge and technology do not fully support the feasibility of a single mission to a martian moon. This is why the primary mission must be undertaken as part of a larger program, transforming the single mission into a primary or ultimate mission that is preceded by a number of precursors, either at the moon or during robotic missions to the martian moons. This multi-stage approach will close those knowledge and technology gaps, provide flexibility in mission design and allow the primary mission to be reduced in scope.

At the highest level, TAPER is envisioned to meet the following objectives:

(a) Demonstrate the ability to safely transport humans to and return from the Martian system;

(b) Develop key technologies and operations vital to human Mars exploration;

(c) Learn more the solar system to better understand the past, present, and future of our planet Earth, and humanity's role in the universe;

(d) Foster international collaboration in preparation for eventual missions to Mars.

Complementary activities within the program prior to TAPER seek to answer scientific questions and develop technologies to support the mission.

As shown in Fig. 2.1, it has been determined that a precursor mission is necessary to fill specific knowledge gaps before the manned mission at LEO or the moon. While the next twenty years will likely see significant advancement in these domains, the necessity of this information is such that no assumptions of external knowledge-sharing missions can be made. The following sections detail general objectives that must be met in technology demonstrations and a robotic precursor mission (TAPER 0) in order to proceed to the main mission (TAPER 1).

TAPER - The Road Map to Mars

Technology Advcancing Phobos Exploration and Return (TAPER) is a concept program that aims to bridge the policy, technology, and science gaps for manned exploration of Mars by sending a crew to a Martian moon.

Figure 2.1: The Road Map to Mars.

2.1 Technology Demonstrations

The first steps in closing the knowledge gaps require the utilization of current space research facilities and activities, such as exploring habitation environments on the International Space Station.

2.1.1 Knowledge Gaps

Table 2.1 provides a list of technologies that Engineering assumes will achieve reasonable TRL levels before the expected 2033 launch time frame, either through LEO demonstrations or lunar missions. While the state of these technologies is quite low, it is believed that these technologies will be reasonably achievable within the launch time frame.

The zero-boil-off technology needs to be advanced to make the long term storage and use of the Nuclear Thermal Rocket (NTR) engine feasible for the TAPER 1 mission. A PBR type nuclear reactor level also needs to be demonstrated. The

Technology	Current TRL
Zero-boil off for cryogenic propellant	2
Development of a Particle Bed Reactor type Nuclear Thermal Engine	3
Composite propellant tanks	3
In orbit assembly	2

Table 2.1: List of technologies assumed to achieve reasonable TRL before the expected 2033 launch time frame.

Particle Bed Reactor (PBR) type reactor was chosen for this mission due to the higher specific impulse, and the low mass achievable for the same power density as a Nuclear Engine for Rocket Vehicle Application (NERVA) type reactor.

While the state of these technologies is quite low, it is believed that these technologies will be achievable within the launch time frame. These technologies were taken from the In-Space Propulsion Systems Roadmap published by NASA.

2.1.2 Expected Research

LEO technology demonstration missions will be used to gain a greater understanding of the long-term physiological and psychological effects of microgravity. An extended human presence onboard the ISS and/or extreme Earth analogue(s) will be used to finalize crew selection and test revolutionary medical techniques. This includes monitoring the extended health of the astronauts, the efficiency of the different countermeasures, the tele-operations of surgical procedures and testing new clinical medicine techniques.

Extended operations in LEO will also be used to validate the in-situ food production and waste management techniques needed for a human mission to Phobos. This will also be extended to further validate the proposed schedule, workload and decision making structure for a human mission.

Additionally, the LEO environment will address the engineering challenges of the manned Phobos mission. This includes the in-orbit demonstration and validation of all proposed rendezvous and docking activities, and in the integration and test of the proposed propulsion system. This includes the nuclear thermal propulsion for the Earth-Phobos transit. Key technologies pertaining to the material and subsystem selection of advanced solar panels (i.e. battery capabilities), communication (i.e. antenna design, the expansion of bandwidth) and composite structures will also be assessed.

2.2 Precursor Mission: TAPER 0

2.2.1 Technology Demonstrations

Robotic precursor missions to Phobos include both remote sensing and in-situ measurements. Each precursor activity would be based on a Discover Class (500 M$) mission. In descending orders of priority, these robotic missions would address the following themes:

1. Map the global topography of Phobos.
2. Measure the gravitational field in the local vicinity of Phobos.
3. Assess the radiation properties in the local vicinity of Phobos.
4. Map and assess the geotechnical and mechanical properties of the regolith on Phobos.
5. Examine the mechanical and electrostatic properties of the dust and regolith on the surface of Phobos.
6. Search for subsurface ice and other volatile products.
7. Search for subsurface ice and other volatile products.
8. Map the global mineralogical and chemical composition of Phobos.

All mapping operations will be conducted at a high resolution. These themes could be achieved by the operations of: high resolution imaging, laser altimeter, gravitometer, an advanced broad energy Mars radiation environment experiment, an in-situ lander with cone penetrator, radio science, ground penetrating radar, acoustics mapping, human factor experiments, neutron spectrometer, a thermal infrared spectrometer and a UV/IR spectrometer. This is, however, a preliminary list, which is not considered to be exhaustive. Heritage can be taken from DAWN, Hayabusa-(2), Mars Odyssey, Mars Express, the Mars Exploration Rovers, and the Mars Science Laboratory.

These eight themes will be used to maximize the scientific and engineering mission performance of the TAPER mission, and to reduce the operational risk, complexity and cost of the manned mission to Phobos. This includes the analysis and confirmation of the proposed trajectory, orbital element of Phobos, landing sequence/sites, and the extended surface operations for the manned mission. Surface operations include the refinement of the proposed anchorage technique, mobility approaches, EVA activities (planning, schedule, operations) and understanding how the transit and local environment (radiation, dust/regolith) will affect the crew, instrumentation and spacecraft. This also includes the timely, independent prediction of the solar particles and galactic cosmic ray events, and in the validation of safe haven mitigation techniques and technologies. This could be achieved through dedicated human science experiments. The synergy between robotic and human exploration will also be addressed.

3 TAPER 1 Mission Overview

3.1 Mission Statement

The mission of TAPER 1 is to send an international crew of four to Phobos and return them safely with surface samples to serve as precursor to the human exploration of Mars.

3.2 Primary Objectives

In light of its mission, TAPER 1's primary objectives are the following:

- Demonstrate the ability to send humans to the martian system and return them safely with samples of the environment.
- Assess the feasibility of Phobos as resources for future missions to the Martian surface.
- Investigate the origin and evolution of the moons to better understand the Martian system.
- Understand the current environment of Phobos in the context of the Martian system to support architecture for future manned Mars missions.
- Establish infrastructure on Phobos to support future manned exploration of both Phobos and Mars.

3.3 Secondary Objectives

The secondary objectives are key points of interest for the TAPER mission; however, should any one of these not be met, the mission will not be considered to have failed. The secondary objectives are to:

- Investigate the compositional relationship between the two moons of Mars

- Find and collect any martian material which may have collected on the Martian moons
- Demonstrate technology readiness for tele-operations of in-situ science instruments on Phobos

3.4 Requirements

The mission requirements of TAPER 1 are derived directly from the mission objectives. These break down the broad goals outlined above into definite, measurable requirements against which the compliance of the proposed mission design can be judged. The full list of requirements are available in Appendix C while just the first level is shown below.

1. Demonstrate the ability to send humans to the martian system and return them safely with sample of the environment.
    1.1. The human crew shall travel to Phobos and return.
    1.2. The human crew shall remain safe for the mission duration.
    1.3. The mission shall comply with all planetary protection guidelines.
    1.4. There should be contingency of launch opportunities in case of mission delay.
    1.5. Key technologies relevant to future missions to the surface of Mars shall be demonstrated.
    1.6. Demonstrate the ability to mitigate psychological and physiological effects of deep space flight to and from the martian system.
2. Assess the feasibility of Phobos and/or Deimos as resources for future missions to the martian surface.
    2.1. Determine is the volatile content of the moon’s surface and subsurface.
    2.2. Detect and quantify any mineable material including magnesium, methane, ammonia, clays and Rare Earth Elements (REE).
3. Investigate the origin and evolution of the moons to better understand the martian system.
    3.1. Identify diverse suite of rocks and regolith to be collected and returned for detailed laboratory investigation.

  3.2. Determine composition in situ of rocks and regolith from diverse and well characterized locations.

  3.3. Constrain internal structure of Phobos.

  3.4. Characterize Phobos regolith and processes that may have modified it over time.

4. Understand the current environment of Phobos in the context of the martian system to support architecture for future manned Mars missions.

  4.1. Characterize effects of space weathering on the Phobos' regolith.

  4.2. Understand how radiation is attenuated and blocked on the surface over time.

  4.3. Quantify amount of dust fall and frequency of micrometeorite impacts on Phobos.

3.5 Mission Architecture

The diagram in Figure 3.1 details the general mission architecture for TAPER 1. The mission is a manned short-stay, Martian moon surface-sample-return mission that satisfies all the mission objectives detailed earlier in this section and is the result of a number of mass trade studies detailed later in this report.

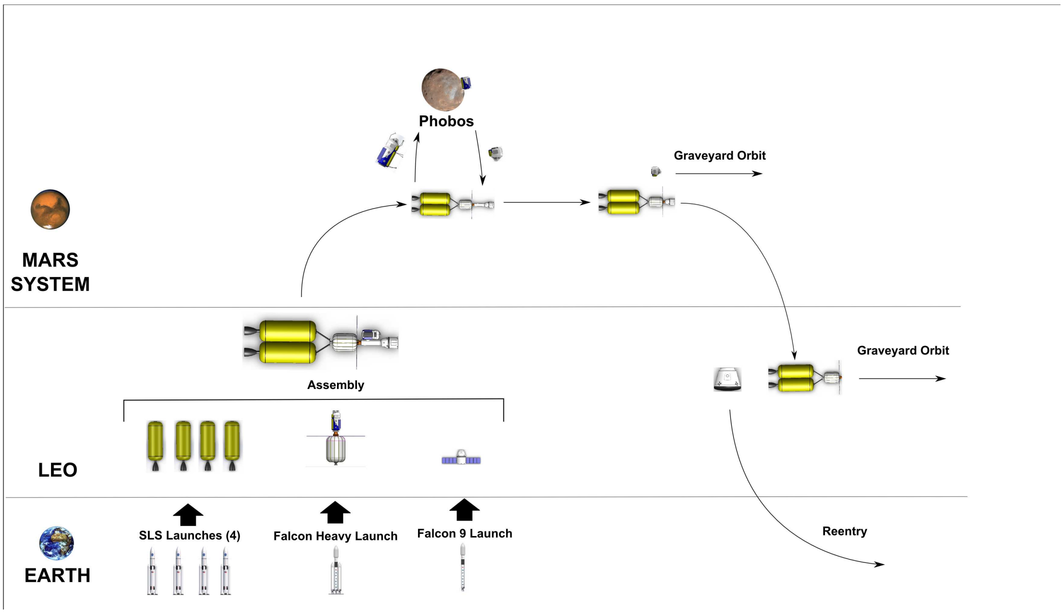


Figure 3.1: BAT diagram for TAPER 1 mission.

Key design choices include an “everything-in-one-stack” vehicle assembled in LEO, as opposed to pre-deployed elements that will assemble with the crewed vehicle a few years later. It was decided that sending any critical components in earlier launches would be too risky, since this is intended to be the first manned mission into deep space (beyond the moon). However, such operations for future missions will still be prepared for with rendezvous and docking sequences performed between the exploration vehicle and the deep space vehicle in this mission, which are much simpler and have less risk.

Another important design choice was a Phobos exploration vehicle capable of leaving the habitable section behind to act as a Martian moon base for future Martian missions. While life support for the habitat will need to be restocked for each use, it provides valuable communications access to the Martian surface and allows for continued science observation after the surface mission is complete.

Overall, it is a simple mission that is feasible with current and developing technologies that serves as a vital stepping stone towards manned Mars exploration. Among other aspects, the propulsive system used to reach the Martian system and lessons learned from the operations on the surface of Phobos will be very applicable to future missions.

3.6 Major Design Choices

3.6.1 Phobos vs. Deimos

Choosing the Martian moon destination for the manned sample return mission (TAPER 1) required assessment of the implications for both the mission at hand and future missions to the Martian system. Therefore, the development of technology used on this mission should be beneficial to future missions to the Martian system. Also, an interesting idea that would be a logical next step would be landing empty habitats on the Martian surface and assembling the habitats using tele-operations from the surface of a martian moon, making the establishment of permanent architecture on the surface of Phobos an appealing idea.

Phobos was decided to be the favorable choice for a number of reasons. Since Phobos is the closer of Mars two moons, it has a much shorter communication gap to the Martian surface and requires less communication capabilities. Also, Phobos has a greater likelihood that it would contain subsurface volatiles, which would be investigated as a possible in-situ resource for future manned exploration of the Martian system. Deimos has superior line-of-sight to Earth, but communication to a satellite in Mars orbit that is connected to Earth would be much more logical. Deimos also has longer communications access to assets on the Martian surface and spends twice as much time with constant sunlight on Phobos, but the geological science appears to be much more interesting than Deimos.

Among Phobos' number of scientifically interesting targets is the $\sim$9 km diameter Stickney impact crater that may expose material from Phobos' deep interior. Spectral heterogeneity on the observed on the moons surface suggests Phobos may be composed of materials having multiple compositions and/or different degrees of space weathering, and in situ investigation of these differing spectral units would allow for a definitive characterization of these two materials and great knowledge of space weathering processes in the Martian system. Finally, there is a greater likelihood of finding Martian ejecta on the surface of Phobos than Deimos, which provides the opportunity for additional opportunistic science.

3.6.2 Conjunction vs. Opposition Class

The choice between a conjunction class mission (long Mars stay) and an opposition class mission (short Mars stay) is the next key trade in our mission concept. Conjunction class missions have Mars vicinity stays in the range of 330-560 days, while opposition class missions have stays in the range of 30-60 days [4].

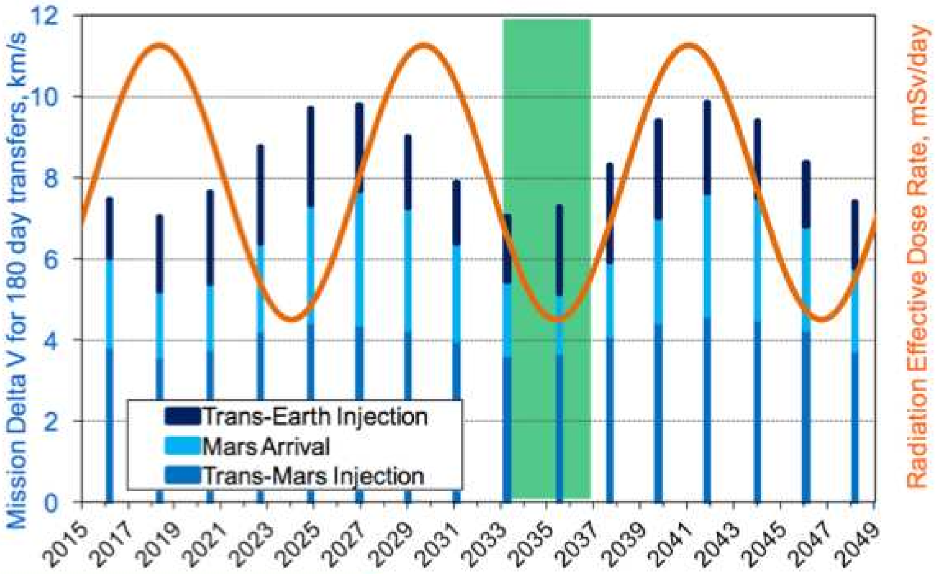
Longer stays offer additional time for surface operations and science and allows more flexible mission operations planning. Conjunction class trajectories also have lower ΔV requirements for interplanetary transfer. However, longer stays increase the risk of subsystem failures, the exposure of the crew to radiation, and negative health effects on the crew such as psychological stress and bone loss, which should especially be avoided as much as possible on the first manned deep space mission.

An opposition class mission is chosen for this mission design. Opposition-length stays are sufficient for achieving the primary mission objectives, while reducing overall mission risk and risk to crew safety. Both mission classes equivalently demonstrate the ability to send and return humans from the martian system as well as allow investigation of the health effects of deep space travel. A stay on the order of 30 days of in-situ science was also deemed to be adequate to achieve the scientific goals of this mission. While opposition class trajectories have higher ΔV

requirements, such trajectories are technically feasible at a reasonable cost. Also, with the demonstration of propulsive technology being one of the key objectives for this mission, the additional ΔV could be a productive challenge.

3.6.3 Launch Dates

Two primary factors drive the launch dates: effective radiation dose, tied to solar cycles; and ΔV requirements. Figure 3.2 shows two ideal opportunities: one in 2033, and a backup in 2035, based on estimations from a study by Lockheed-Martin [5]



Selected Crew Launch Year: 2033
Backup Crew Launch Year: 2035

Josh Hopkins. "Deimos and Phobos as Destinations for Human Exploration." Accessed: 27 March, 2013.

Figure 3.2: Mission ΔV and radiation estimates for different launch dates.

The primary mission is set to launch based on a 32-day interplanetary transfer window from 1st April 2033 to 2nd May 2033. Should significant delays occur, a secondary 15-day transfer window in 2035 exists from 6 August 2035 to 20 August 2035. The design targets the end-dates of this 2035 window.

3.6.4 Vehicle Selection

3.6.4.1 Deep Space Habitat

The trade space for the deep space vehicle included both hard shelled structures and inflatable structures. Specifically, the vehicles considered were:

- Hard-shelled:
  - NASA Human Exploration Framework Team (HEFT) Phase II, a conceptual study for a new deep space habitat;
  - ISS-based HAB/MPLM, a conceptual study for a deep space habitat based on the International Space Station;
- Inflatable:
  - Bigelow Aerospace Sundancer, a privately-developed inflatable habitat expected to be tested at the International Space Station shortly.

The major selection criteria between these three vehicles were their habitable volumes and masses. HEFT, HAB/MPLM and Sundancer have 71.8m3, 108.3m3 and 180 m^3, respectively. Their masses, in the same order, are approximately 18, 35 and 9.1 tons, respectively. Since the Sundancer is an upgraded version of Bigelow Aerospaces Genesis module which has been demonstrated in space, a high TRL by launch time is assumed. Given these benefits, the Sundancer is selected. The Bigelow Aerospace's inflatable habitat concept is illustrated in Fig. 3.3.

Figure 3.3: Bigelow Aerospace's Inflatable Habitat Concept.

3.6.4.2 Crew Vehicle

A number of crew vehicles are currently being developed which shall ensure the viability of the mission. The following vehicles were considered, and are presented in Fig. 3.4.

- Orion Multi-Purpose Crew Vehicle (MPCV) (NASA/Lockheed) [6]
  - Number of Crew: 2-4
  - Total Mass: 21250 kg
  - Volume: 8.95 m^3
  - Life: 21-210 days
  - Development cost thus far: \$6.4+ billion
- Dragon Rider (SpaceX) [7]
  - Number of Crew: 1-7
  - Total Mass: 4200 kg
  - Volume: 10 m^3
  - Life: 1 week to 2 years
  - Development cost thus far: \$524 million
- CTS-100 (Boeing) [8]
  - Number of Crew: 1-7
  - Total Mass: 10000 kg
  - Volume: TBD
  - Life: 210 days
  - Development cost thus far: \$600.9 million

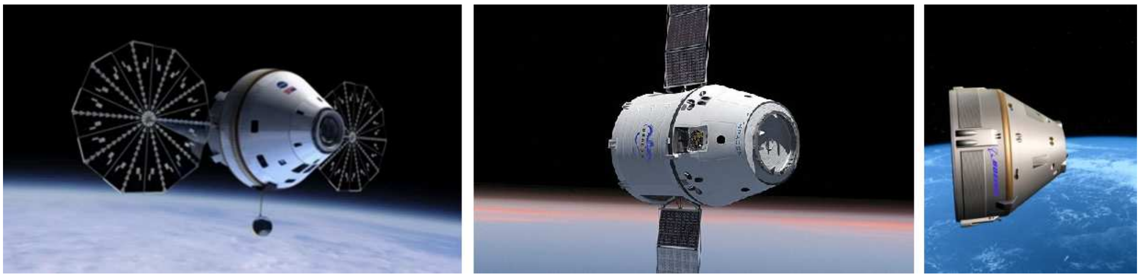


Figure 3.4: Considered crew vehicles (Orion, Dragon and CTS-100).

Dragon Rider was ultimately the vehicle chosen for this mission due to the relatively low development cost, the success rate of Dragon Cargo, and its current design with a Mars mission already in mind.

3.6.4.3 Phobos Explorer

The vehicle used to explore the surface of Phobos included a trade study between the Space Explorer Vehicle (SEV) concept in Fig. 3.5 and a new innovative concept that has all the functionalities of an SEV, except for being modular. The SEV is currently designed to accommodate 2 astronauts for 30 days, has a predicted wet mass of about 17000 kg, and can store 1000 kg of payload for sample return. It also allows for vehicular exploration, robotic exploration, EVA via suit-port. As for the modular SEV concept, the habitat with EVA capabilities, robotic explorer, vehicular explorer, and ascent capabilities would each be separate components that can be connected together. All the components would stay on the surface of Phobos, while the ascent component would be capable of staying behind on Phobos. This would establish functional architecture on the surface of Phobos for future missions.

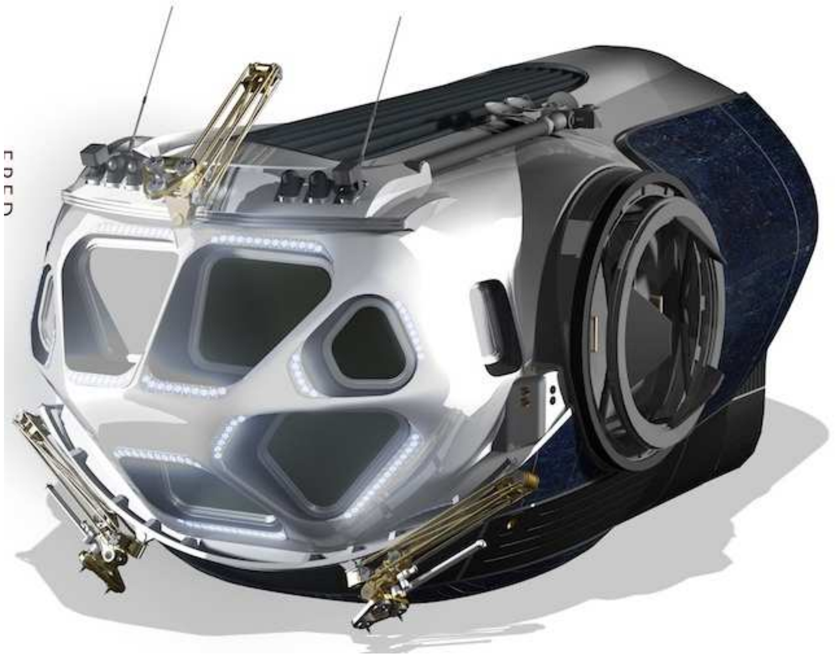


Figure 3.5: NASA's Space Exploration Vehicle (SEV) Concept.

After a risk analysis, the mobility, power requirements and mass/size of such a modular vehicle made it an inferior choice. The ability to establish permanent architecture on Phobos for future missions was still desired though. Therefore, the advantages of both designs were merged with a new 2-stage SEV concept. During exploration, the 2-stage SEV would have all the exploration capabilities of the SEV. However, at the end of the surface expedition, the first stage (which includes all the capabilities of a surface base, including habitability and communication) can be separated and left behind while the second stage would ascend and meet the deep space vehicle for the return trip.

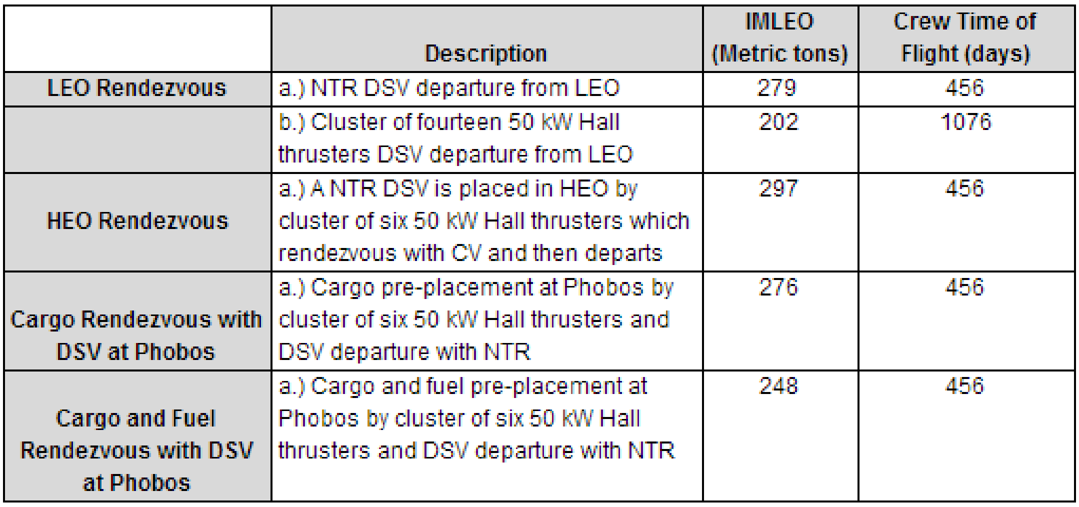
3.6.5 Propulsion System Selection

The propulsion system is selected through a trade study. Rendezvous operations utilizing combinations of different propulsion systems is studied. Considered operations include but are not limited to:

1. LEO rendezvous of all components.
2. Rendezvous of crew vehicle with Deep Space Vehicle (DSV) in High-Earth Orbit (HEO).
3. Rendezvous of cargo with DSV at Phobos
4. Rendezvous of cargo and fuel with DSV at Phobos

Trade study results show that the optimal choice for this mission is to utilize Nuclear Thermal Rockets and rendezvous all components in LEO. A brief summary of this trade study is shown in Figure 3.6.

The gains from the efficiency of electric propulsion are minimized by the choice of an opposition class mission which requires short transit times. The increase in



	Description	IMLEO (Metric tons)	Crew Time of Flight (days)
LEO Rendezvous	a.) NTR DSV departure from LEO	279	456
	b.) Cluster of fourteen 50 kW Hall thrusters DSV departure from LEO	202	1076
HEO Rendezvous	a.) A NTR DSV is placed in HEO by cluster of six 50 kW Hall thrusters which rendezvous with CV and then departs	297	456
Cargo Rendezvous with DSV at Phobos	a.) Cargo pre-placement at Phobos by cluster of six 50 kW Hall thrusters and DSV departure with NTR	276	456
Cargo and Fuel Rendezvous with DSV at Phobos	a.) Cargo and fuel pre-placement at Phobos by cluster of six 50 kW Hall thrusters and DSV departure with NTR	248	456

Figure 3.6: Summary of Propulsion Trade Study.

risk due to the reduction of abort options as a result of fuel preplacement at Phobos outweighs the reduction of initial mass in LEO (IMLEO). The LEO rendezvous utilizing NTR is the best choice due to low risk, operational simplicity, and comparable IMLEO. A majority of propulsion and rendezvous options do not show significant improvement of IMLEO which merit the complexity of rendezvous.

Data found in this table is approximated from a number of reference articles [4, 9]. Orbit transfer ΔV values for finite time, spiral burns are approximated by data from references and circular orbit transfers.

The NTR presents a significant political issue as the only radioactive propulsion systems. It must then be assumed that the NTR can be jettisoned into an orbit which meets international standards on safe disposal of radioactive material.

4 Science

4.1 Context

In addition to its position as a stepping stone for future Mars exploration, Phobos provides an excellent target for scientific investigation. Despite decades of remote observations, the origin and evolution of this small solar system body remain unresolved [10], and in situ and returned sample investigation may be the only method to definitively answer these fundamental scientific questions about the moon.

Beyond fundamental science questions, Phobos' relatively low density suggests either (a) that the moon is highly porous [11] or (b) contains low density material, particularly water ice, in its interior [12]. The notion buried water ice exists on Phobos presents the possibility of using the moon as an important source for in situ resource utilization (ISRU) for astronauts on future missions to the martian system. Scientific exploration of the body would help to address whether these materials are present and to provide the availability to search for additional materials to be mined to support ISRU.

4.2 Science Objectives for Surface Operations

The scientific objectives for in situ science are derived from the primary mission objectives and are summarized in the science traceability matrix, Table 4.1. Objectives for additional high-return science investigations that could be accomplished during in situ investigation of Phobos surface but are not critical to achieve the overall mission objectives were identified, as well as science that could be conducted during the transit to/from Phobos was also considered.

Science Related Mission Objectives	Measurement Objectives	Measurement Requirements	Instrument Requirements
Investigate the origin and evolution of the moons to better understand the Martian system	Identify diverse suite of 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 on Phobos (red and blue units), preferably three	Return samples to be analyzed by techniques on Earth, including XRD, isotopic/ age dating analyses, etc
	Determine 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), preferably three	Raman/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
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	Raman/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
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

Table 4.1: Science traceability matrix for major Phobos in situ science.

4.2.1 Mission Critical Science Objectives

Science related mission objective 1: Investigate the origin and evolution of the martian moons to better understand the martian system.

Three hypotheses exist pertaining to Phobos' origin: (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 results predicts a different composition for Phobos, and an investigation to unambiguously determine Phobos' composition through in situ analysis and analysis of returned samples will provide insight into which of these hypotheses is most likely. Additional measurements to determine the moons' interior structure could further constraint its possible formation by indicating whether the body is an unconsolidated rubble pile or partially differentiated small body. Investigation of Phobos' interior structure may also show whether there is ice deep in the moons' subsurface, indicating formation in the outer solar system rather than at Mars. The presence of water ice may also be utilized as an in situ resource for future missions, which overlaps with science related mission objective 2. Additional measurements and collection of Phobos regolith samples will provide information about how the moon has evolved through the geologic processes that shaped the moons surface over time.

Science related mission 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 any possible in-situ resources on Phobos' surface, the moon's low bulk density and mysterious grooves feature suggest it may contain volatiles frozen in its subsurface. The detection and characterization of any such material is therefore a high science priority for this mission meant to support future manned exploration of Mars. Additional materials that could potentially be mined for ISRU such as clays (suggested to present by Phobos presumed CM chondrite type composition), magnesium, rare earth elements, methane and ammonia may also exist on the surface or subsurface, and it is also a high priority to detect the locations of and characterize these materials should they be present.

Science related mission objective 3: Understand the current environment of Phobos in the context of the Martian system to support architecture for future manned Mars missions.

Phobos' location in martian orbit results in the moon existing in a unique dust and radiation environment. Characterizing this environment is an important goal as it will support architecture for future missions to the martian system. Additionally, space weathering of Phobos' surface has likely been influenced by the moon's unique environment, and analysis of returned samples from the surface will allow a better characterization of space weathering processes that occur on a solar system body other than our moon.

4.2.2 Additional high-priority science objectives

Objectives for in-situ high-return science that are not required to meet the overall mission objectives but that are achievable for minimal extra cost are:

- Investigate the compositional relationship between the two moons of Mars
- Identify and collect any martian samples ejected to the surface of Phobos

4.3 Landing Sites

Three landing sites were identified based on their ability fulfill the defined scientific objectives; a fourth landing site was identified as the PSEP's permanent settlement, which can be used for future Mars missions (see Table 4.2). These landing sites are meant as guidelines, but may be adjusted to better fulfill the mission objectives if precursor science measurements indicate more favorable options.

Site Identifier	Site Location	Coordinates	Distance from Previous Site [km]
A	Stickney crater	50 deg W, 0 deg N	0
B	Blue spectral unit	30 deg W, 15 deg N	6
C	Red spectral unit	15 deg E, 45 deg N	11
D	Mars Visible	28 deg W, 60 deg N	9

Table 4.2: List of landing sites identified and their coordinates based on the scientific objectives.

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 Phobos' interior. The second location (site B), is located in the blue spectral unit, differs in color with the rest of Phobos' redder surface. These samples inherent difference will provide an important contrast to the red samples that cover a majority of the moon. The third location, in the red spectral unit, will help provide an understanding of Phobos' overall composition.

The fourth landing site was chosen because of the communications benefits. The PSE will permanently land there to act as a communications relay by the mission's end. The location can view all of Mars, which may aid any future Mars surface missions. The location also will be exposed to constant sunlight during a martian summer, which will maximize the PSE's power production to sustain its communication functionality.

4.4 Science Payload

4.4.1 In situ instruments

The instruments needed to fulfill in situ science objectives are summarized in Table 4.3.

Surface science equipment	Heritage	Quantity	Mass [kg]
Sample collection equipment		1	425
Robonauts		2	100
Tongs, rake, dust scooper, hammer, hand lens, documentation camera		1	25
Sample boxes, cores, bags		1	200
Mobile Science Platforms (Typical payload below) - "Phobot"		5	10
Raman/LIBS Spectrometer	JPL Raman/LIBS in development	1	3
Multispectral imaging system	Rosetta Landing Imaging System (ROLIS)	1	0.5
Neutron spectrometer	Dynamic Albedo of Neutrons	1	3
Visible/Near-Infrared Spectrometer	Comet Infrared and Visible Analyzer System (CIVA)	1	0.75
Chassis and Communications		1	2.75
Seismic network stations		25	1
Small networks deployed towards landing	JPL in development	5	1
Space weather stations		3	12.5
Plasma Wave System	FPMS		3
Micrometeorite Detector	METEOR		3.5
Dust Particle Detector	DIAMOND		3
Structure and Communications			3
Margin for inclusion of additional instruments determined necessary by precursor science			300
Total mass (including 20% margin)			1005

Table 4.3: In situ science instruments

The instrument platform is designed to take into account the synergy between robotic and human exploration that will be available during this mission and contains five major components:

1. *Equipment for human sample collection:* This includes two robonauts to aid in mobility in the microgravity environment, sample collection tools modeled after those used by the Apollo astronauts (scoops, rakes, hammers, tongs, hands lense, documentation camera), and sample boxes, cores, bag. These sample containers will comply with planetary protection requirements and may be somewhat mass heavy. The sample collection strategy is summarized in Table 4.4. Core samples will be stored in a cryogenic cooler for the trip back to Earth to minimize any potential alteration due to sublimation of any volatiles. Surface samples do not need to be cooled as the surface temperature of Phobos can range near 300 K.

	Rock Samples	**Core Samples**	**Soil scoops**
Required collected qty per EVA site	30	10	5
Number of EVA sites	3	3	3
Minimum mass (kg)	0.2	1.5	0.1
Total mass (kg)	18	45	1.5
Total mass with 10% E/PO, 20% international cooperation, 20% target of opportunity	27	67.5	2.25

Table 4.4: Sample collection strategy

2. *Mobile science platform (Phobots):* Five mobile science platforms, dubbed Phobots, will be deployed at each of the three landing sites (one per landing site plus two spares to allow multiple Phobots to investigate particularly interesting sites and/or allow for redundancy). The purpose of these mobile platforms will be to perform in situ science to provide context for collected samples as well as provide the ability to investigate a greater surface area of Phobos than would be allowed for by the astronauts alone. Results from the Phobots can also be used to guide astronauts to collect particularly interesting samples. The Phobots will be semiautonomous robots that can be controlled by the crew remaining in orbit in order to demonstrate ability for tele-operation of mobile machines and take advantage of human intelligence to make decisions about where to investigate. The mass of the Phobots will be limited to 10 kg to allow mobility, and the instruments suggested in the table above will allow for complete compositional and morphological characterization for the area.

3. *Seismic network stations:* Provided by ChipSats deployed during entry to Phobos, this network will provide information about Phobos' interior and can remain active after surface operations end.

4. *Space environment monitoring stations:* One station to be set up at each landing site, these contain equipment to monitor the unique space environment around Phobos and can remain active after surface operations end.

5. *Margin for additional science instruments determined necessary be precursor science:* This has been allocated to account for additional instruments that may be deemed useful on findings from the precursor missions. For example, if investigation reveals Phobos has ice deposits at a depth on the order of 10s to 100s of meters below the surface, it would be desired to bring a specially-designed deeply-penetrating drill to access this potential in-situ resource for sample return to Earth. If precursor science missions demonstrated unexpected properties of the Phobos regolith this also leaves margin for adapting the equipment to a better, more suitable environment.

Additional ideas for opportunistic science that could be used to fulfill this margin, but are not critical to meeting science objectives, include:

- Phased array radar (∼square km array; estimated mass of 100 kg - includes antenna elements, cable, power supply, amps, electronics). This can be used as ground-penetrating radar to scan the ground and image it, mapping local soil stratas, conductivity, and composition in the low Hz to GHz band.
    - This could also double as a receive antenna for a steerable radio telescope. It would be powered with an Advanced Stirling Radioisotope Generator (∼20 kg, included in total mass estimate)
        - ∗ Dependent on location on Phobos, this may also be used as a radio telescope pointed heavenward, and/or an upward pointing radar with steerable beam. Finally, it could be used at a later date to help guide spacecraft as a beacon, or serve as cosmic light house of sorts.
- Rubidium clocks (∼1/4 kg) can serve as a stable time base and allow one to send data-rate pulses back to earth for obtaining high-precision fixes on Phobos location to measure small orbital changes. These could also be calibrated with identical clocks on Earth to potentially support relativistic experiments.
- Cosmic ray ground array comprised of particle detectors serving as a mean to analyze galactic cosmic rays up to energies in the GeV range.
- Large optical telescope that could resolve finer details on Mars.
- Interferometer - Phobos could be an advantageous location for radio astronomy as it is well away from the RF soup near the Earth.

4.4.2 Additional science instruments

Instruments to support mission objectives and high-return science will also be included on the component of the mission that remains in orbit during surface operations. These instruments are summarized in Table 4.5.

Orbital Remote Sensing Instruments	**Heritage**	**Mass [kg]**	**Power [W]**
High resolution color imaging system	Dawn framing camera	10	20
Radar	Sharad	15	40
Middle energy range particle detector	Maree	4	7
Low energy range particle detector		2	2
High energy range particle detector		2	2
Cubesats sent to Deimos (x 5)		2	2
Dedicated instrument for outreach		10	10
Total (incl. 20% margin)		69.6	97.2

Table 4.5: Remote sensing science instruments

The rationale for inclusion of each of these instruments is as follows:

- **High resolution color camera:** This camera will be able to image the crew on the surface of Phobos to monitor safety and provide public outreach photos.

- **Radar:** Although radar investigations will be included in precursor science experiments, it is expected that significant advances in radar technology may allow for more detailed mapping of the subsurface, while could aid in selecting an in situ investigation site likely to be rich in subsurface volatiles.

- **Low, mid, and high energy particle range detectors:** Detectors to observe space weather that will be used synergistically with ground observation.

- **Cubesats sent to Deimos:** Five small, light, and relatively inexpensive cubesats will be sent to Deimos to provide definitive identification of Deimos composition. The science value returned from this relatively inexpensive addition to the payload is high, and it would be criminal not to take advantage of having the nearby crew vehicle to support cubesat operations.

- **Dedication instrument for outreach:** Will include a small science instrument dedicated to fulfilling public outreach requirements. This instrument can either be designed by members of the public or used to fulfill science requests sent in by the public.

4.5 Opportunities for Science while in Transit

4.5.1 In-flight sample analysis

Requirements necessitate the return of ∼100 kg of sample for analysis, yet mass is available for a greater amount of sample to be brought back from Phobos although not necessarily returned to Earth (limited by mass allowed in crew return vehicle). 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 will begin preliminary analyses of the ∼100 kg of "opportunistic" samples during the journey home. If any of these samples proves to be extraordinary, it will be allocated to be returned to Earth for more detailed analysis. Findings from this investigation will additionally help sample storage facilities on Earth understand any potentially hazardous materials they may encounter and design necessary measures to mitigate risk.

It is assumed that technology will develop substantially in the next 20 years allowing sample analysis instruments to be lighter weight and require less power. A mass of 200 kg and 2000 W of power has been allocated in the DSV to support analysis of samples for triage en route to Earth. These values were chosen based on their similarity to the current science payload of the Curiosity Mars Rover. An instrument package has been proposed which will allow for isotopic and compositional analysis (including capability to detect organics and volatiles and isotopic ratios) in order to identify outstanding samples to be delivered to Earth for additional analysis. These instruments include:

- **Fourier-transform microwave (FTMW)** spectrometer to look for exotic states of matter. Having identified chemistry through other instruments on board, the FTMW spectrometer would enable one to see if rotational spectra and bond length of elements on distant planets are as expected compared to known earth values. Additionally, would allow for highly accurate determination of the structure of any odd/interesting molecules.
- **Gas Chromatograph Mass Spectrometer** - like SAM instrument on Curiosity, can detect volatiles and organics in particular, determines chemical composition by heating sample and observing gas absorption lines.
- **Nano SIMs** for high-resolution, high-precision isotopic imaging and compositional analysis.

- **X-ray diffraction** - compositional analysis to provide definitive mineral identification.
- **Tunable Laser Spectrometer** - Can measure isotopic ratios in evolved gases.

4.5.2 Radiation experiments

Two tests have also been proposed to better understand the effects of radiation exposure in the deep-space environment with the primary purpose of validating contemporary knowledge of radiation effects on tissues and biological organisms.

- New-LIFE is an experiment derived from Phobos-LIFE (Living Interplanetary Flight Experiment, originally designed for Phobos-Grunt) to be used as an in-flight test to assess interplanetary survivability of hardy earth-based microorganisms in a deep-space environment. Samples to be tested will include triplicate versions of several dozen types of organisms representative of archaeal, eukaryotic, and bacterial domains of life. Two sealed units will be tested in transit to Phobos and back, the first solely exposed to radiation on the DSV during travel, the second additionally exposed to radiation on the surface of Phobos. Ideally, these units will be compared to concurrent samples both on Earth and in near Earth Orbit. This experiment could provide an education/public outreach opportunity.
- Dosimeters will also be used to measure radiation exposure of both the astronauts and living biological samples (cultivated from an in-flight photobioreactor) throughout the journey.
- Additional experiments designed to test the effects of long duration spaceflight on humans are described in section on human factors.

4.5.3 In transit astrophysics

One test is devised to examine astrophysics:

- Provide outreach opportunity for the general scientific community to propose experiments and develop instrumentation for observations of Earth as an exoplanet.

5 Operations

5.1 Phase I: LEO Assembly Operations

Due to launch mass and volume constraints, the DSV is segmented across six launches and assembled in a 300 km circular low Earth orbit (LEO). The initial four launches transport propellant tanks on SLS cargo missions. The fifth launch transports the DSH and PSE. The final launch, which occurs at T-0, transports the four crew members to the DSV assembly in a modified Dragon capsule aboard a Falcon 9.

After rendezvous and final assembly, the DSV performs a trans-Mars injection (TMI) maneuver, beginning the Phobos interplanetary transit. This nominally occurs one day following crew launch. The TMI must occur in a 32-day departure window from 1st April 2033 to 2nd May 2033, with a nominal TMI date for optimal ΔV of 7 April 2033. A contingency departure window exists in 2035 from 6 August 2035 to 20 August 2035.

5.2 Phase II: Phobos Transit Operations

The DSV performs the trans-martian injection burn at LEO periapsis nominally on 7 April 2033. It travels on the interplanetary trajectory for 180 days until 6 October 2033. It then performs a plane change and enters a 9,376 - by - 37,000 km radius high Mars orbit. On 6 October 2033, it performs a maneuver to raise periapsis to Phobos orbit. On 7 October 2033, it performs an injection burn to enter a Lyapunov orbit about the Mars-Phobos L_1 point.

5.2.1 Crew Activities

A typical day will include a variety of activities including scheduled work, exercising, eating, and sleeping (Fig. 5.1). Daily planning will include a variety of tasks that need to be completed and the astronaut can choose the order. The scheduled work will include assessing the condition of the spacecraft, conducting science experiments, performing outreach activities, maintenance, and preparation for key mission events. During the onboard task list the crew will be able to participate in recreational reading, video games, and skill training. A typical day on the outboard section of the mission would look like Fig. 5.2.

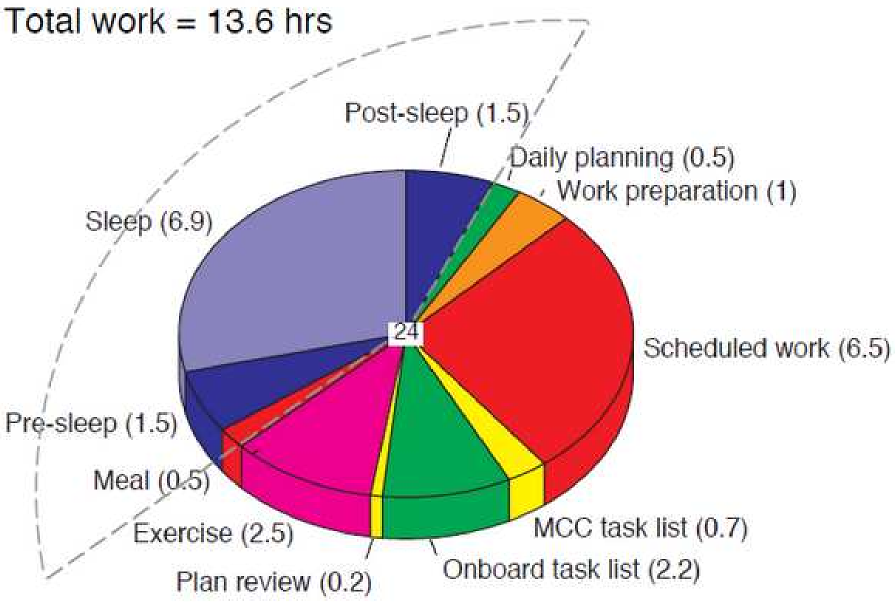


Figure 5.1: Template for a typical day crew schedule.

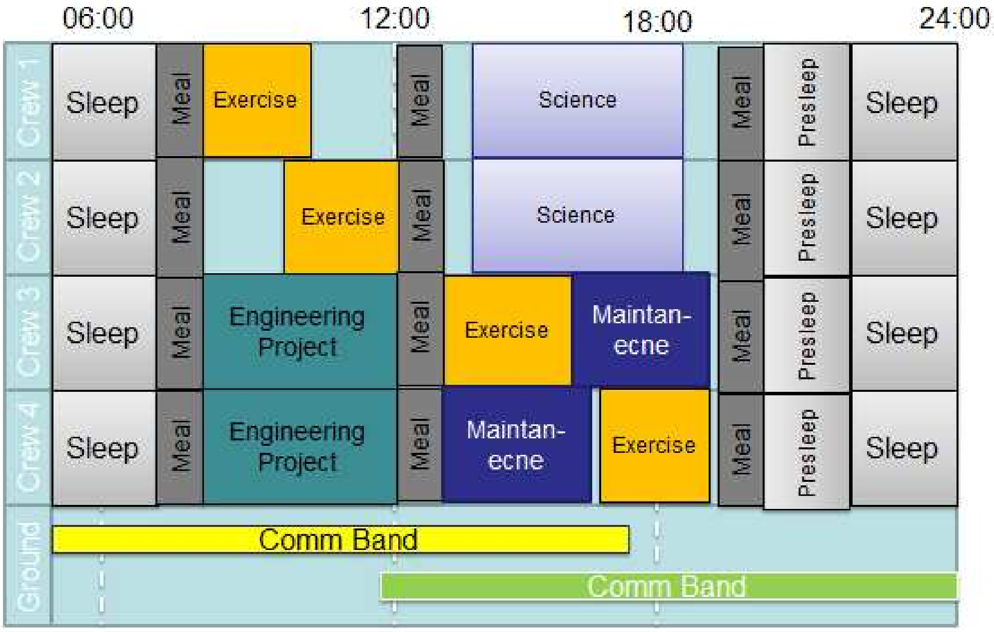


Figure 5.2: Template for a crew work break down for a typical day.

5.3 Phase III: Phobos Vicinity Operations

The objective of the Phobos vicinity operations is to land on the surface of the martian moon and retrieve geological samples while ensuring astronaut safety. Once in the Mars-Phobos L_1 Lyapunov orbit, the PSE will undock from the DSV with two crew nominally on 8 October 2033. The two vehicles will be separated for a planned period of 30 days. While in Phobos orbit, two crew will continue to conduct physiological and biological science, as well as telerobotic operation of several rovers that will land with the PSE on the surface. Figure 5.3 gives a representation of what an example work day would look like while performing surface operations. The goal of both modes of exploration are to fulfill the scientific objectives of the flight, collecting and detailing samples from the martian moon.

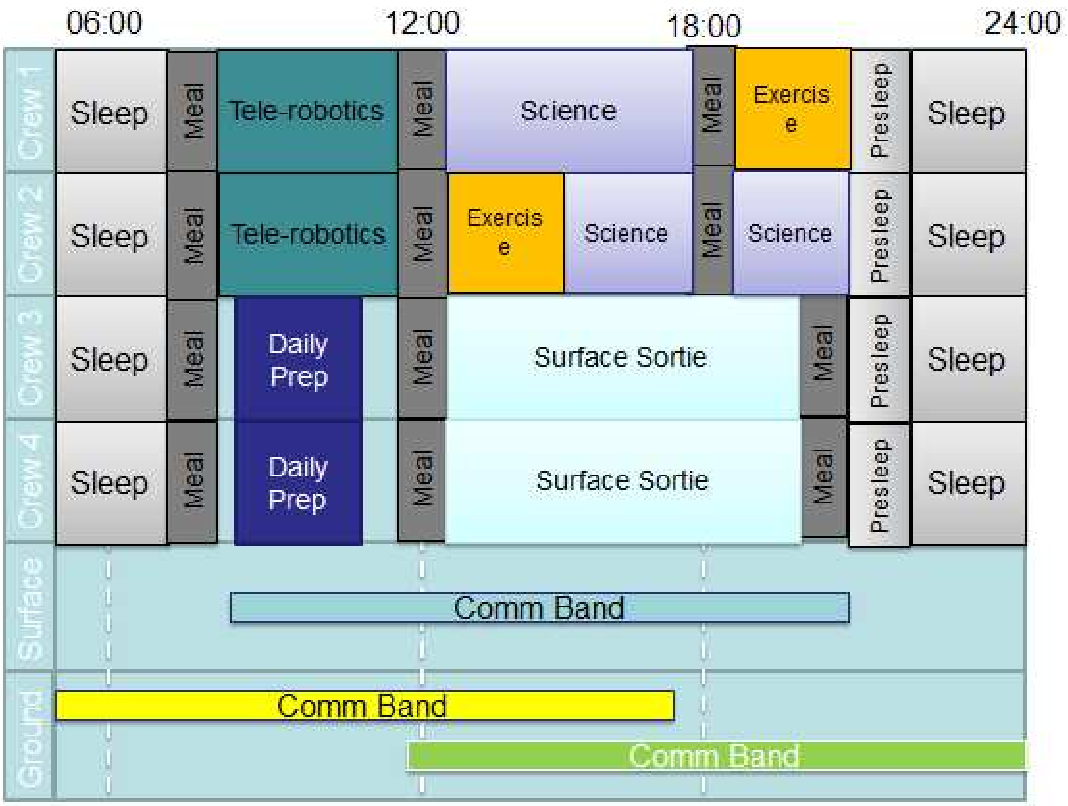


Figure 5.3: Template for a crew schedule day during surface operations.

5.3.1 Surface Control Operations

The Mars-Earth trajectory allows for 24 Earth days around Phobos before the crew must take the return trajectory path to Earth. The PSE will enable two astronauts to closely approach and interact with Phobos surface to conduct scientific experiments and obtain core and dust samples (see rendering in Fig. 5.4). The PSEP will also allow astronauts maneuverability around the chosen landing site. Astronaut EVA is only necessary when robotic maneuverability is limited to reduce sample contamination and astronaut risks. The PSEP returns to the PSE within eight hours of leaving the PSE to reduce astronaut risk during missions as well. The schedule below in Earth days is for the astronauts on the surface and assumes a deep drill was selected to be included the science payload based on precursor science. The first activities occur nominally on 8 October 2033 (TS) and the last activities occur nominally on 1 November 2033.

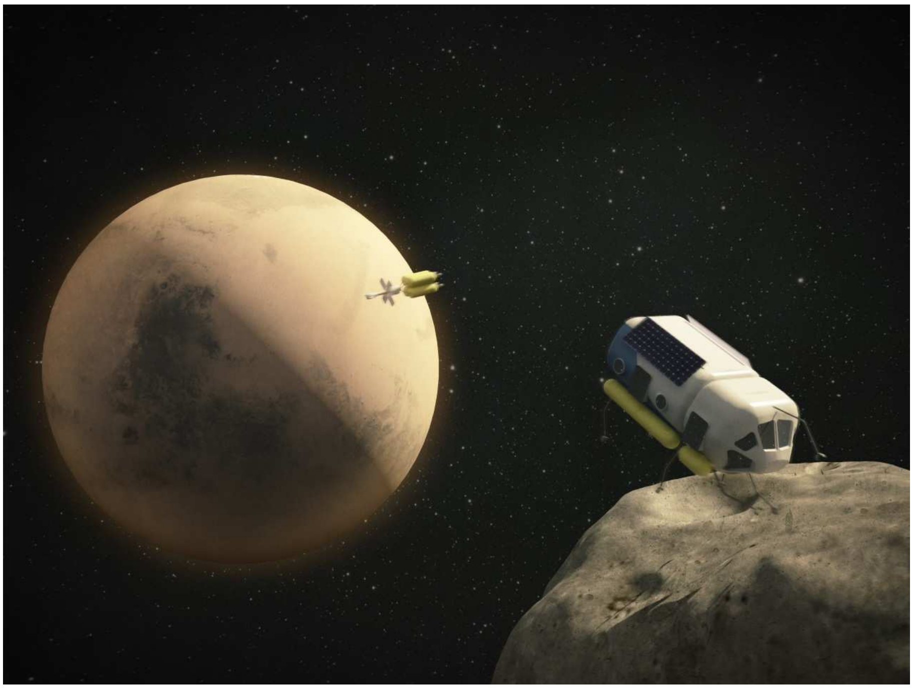


Figure 5.4: Rendering of PSE surface operations (Photo credit: Victor Dang).

T_S+1: Reach selected landing site and attach to Phobos surface at Landing Site A.
T_S+2: Install permanent martian moon surface science equipment while in PSEP.
T_S+3: First planned EVA. Explore vicinity of Landing Site A. First human contact with a martian moon.
T_S+4-8: Setup the martian Moon deep drill and begin drilling operation from PSE.
T_S+9-10 Collect drill and other rock samples.
T_S+11: Detach PSE from martian moon surface and travel to Landing Site B.
T_S+12: Install permanent martian moon surface science equipment while in PSEP.
T_S+13-14: Core for and collect samples from second site while in PSE or PSEP.
T_S+15: Detach the PSE from martian moon surface and travel to Landing Site C.
T_S+16: Install permanent martian moon surface science equipment while in PSEP.
T_S+17-18: Collect samples from third site.

T_S+19: Detach the PSE from martian moon surface and travel to Landing Site D.
T_S+20-21: Secure PSE onto martian moon surface and install permanent martian moon surface science equipment while in PSEP.
T_S+22: Collect samples from fourth site.
T_S+23: Drive PSEP to rendezvous with orbiting DSV.
T_S+24: Crew prepares to exit Mars orbit.

If the precursor mission determines that the drill operation is not achievable or cannot be accomplished in the provided time frame, then a fourth landing site will be selected.

5.3.2 Remote Control Operations

The schedule below is for the two astronauts in the DSV in Earth Days. They will support ground operations on a continuous basis. While the two astronauts in the PSE complete EVA activities, the first and second astronaut will be tele-operating mobile science platforms (Phobots) to search for interesting Phobos exploration sites and provide context for collected samples. The robots will carry scientific payloads to complete their missions.

T_S+1: Land the PSE on Phobos surface.
Day 2-17: Deploy Phobots at the beginning of activities at each landing sites. Teleoperate Phobots to collect geologic context for collected samples and identify potentially interesting samples for future collection.
T_S+18-20: Finish Phobot investigation of landing sites and continue to explore Phobos surface.
T_S+21-22: Prepare spacecraft for sample accommodation and for Earth return trip.
T_S+23 Astronauts on the ground come back.
T_S+24: Crew prepares to exit Mars orbit.

5.4 Phase IV: Earth Return Operations

On 1 November 2033, the PSEP will transport the two surface crew members back to the DSV (see rendering in Fig. 5.5). To leave Phobos, the DSV will perform an apoapsis-raising burn on 1 November 2033. Next, the DSV performs a periapsis

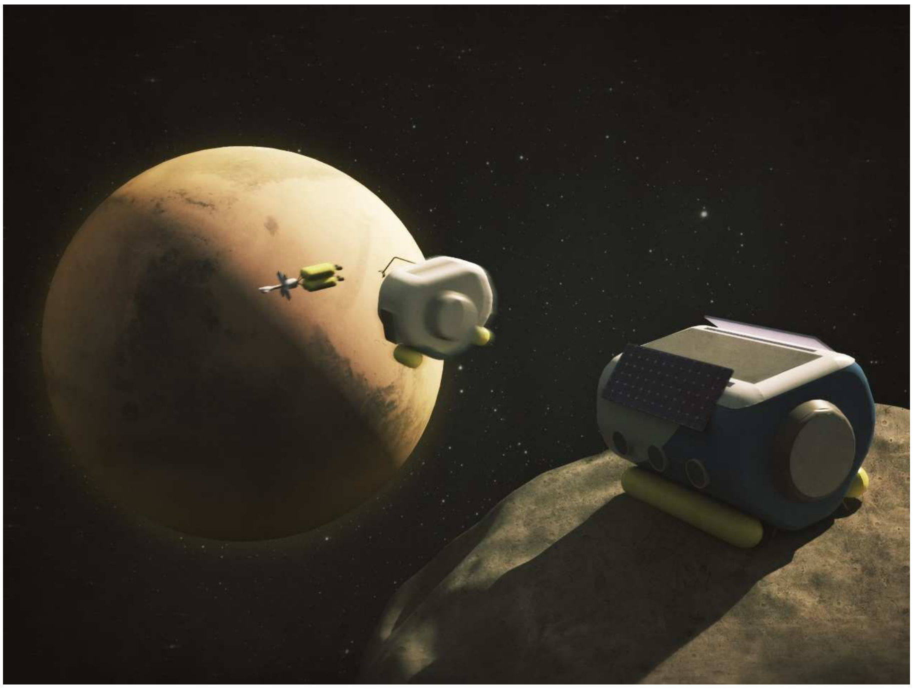


Figure 5.5: Rendering of PSEP returning to DSV, leaving the PSE Habitat behind on the surface of Phobos (Photo credit: Victor Dang).

lowering burn on 2 November 2033 to enter a high Mars orbit. Then, on 4 November 2033, the DSV executes a trans-Earth injection to return to the Earth. The DSV will return to Earth vicinity on 6 July 2034. The Dragon crew module will separate from the DSV and undergo direct Earth entry at a velocity of 11.3 km/s. The DSV will be captured in a graveyard orbit about the Earth.

5.5 Phase V: Sustained Phobos Science

Three operational space weather stations and twenty-five seismic network stations will remain on the surface of Phobos. The weather station includes a plasma wave system, a micrometeorite detector, a dust particle detector and a communication system. This will be used to extend the surface scientific operations of the mission. The Phobots, depending on their available end-of-life power, may also be operational. These continued activities will develop the Mars-Moon space heritage. This will support the overall development of the wider TAPER program. Future activities include Mars surface ISRU and assembly, Mars Sample Return and Manned Mars Exploration.

6 Engineering

6.1 Launch

6.1.1 Overview

The launch vehicles selected for the TAPER 1 mission were constrained by the dimensions of the current launch vehicles payload dimensions and the availability to launch into LEO. With the proposed mission, one Falcon 9, one Falcon Heavy, and 4 SLS launch vehicles will be used. The SLS launches will be responsible for transporting propellant tanks into LEO prior to the launch of the crew capsule while Falcon Heavy and Falcon 9 will be responsible for transporting the DSV and crews Dragon module separately. These launch vehicles currently meet the requirements of this mission, however other commercial or government options can be considered based on an increased performance to help achieve mission success.

6.1.2 Launch Vehicle(s)

Three different launch vehicles were chosen based on their launch properties for each part of the mission. The SLS launches shall use the Kennedy Space Center (KSC) infrastructure that is currently in NASAs mission. The Falcon 9 and Falcon Heavy will be in operation during the current launch frame, and have been chosen to meet the mass requirements of those separate launches. These launches represent those which meet meet the required mass to LEO, and which do so at minimal cost. Table 6.1 outlines the constraints and the characteristics of the payloads for each launch vehicle used for the TAPER 1 mission.

Item	Heritage	Constraints	Dimensions Needed
DSV and PSE	Falcon Heavy	D: 5.2 m x 13.9 m LEO mass: 53000 kg	D: 5 m x 13 m Mass: 42500 kg
DSV Propellant (4)	HHLV Block 1	D: 7.5 m x 24 m LEO mass: 81000 kg	D: 3.7 m x 22 m Mass: 67145 kg
Crew	Falcon 9	D: 5.2 m x 13.9 m LEO mass: 10450 kg	Mass: 10100 kg

Table 6.1: Constraints and characteristics of the payloads of each launch vehicle used for the TAPER 1 mission.

6.2 Transit

A critical component of the mission design is the selection of a trajectory that delivers the crew to the surface of Phobos and returns them safely to Earth. This section details each segment of the outbound (Earth to Phobos) and inbound (Phobos to Earth) trajectories and the rationale behind the trajectory design. A higher level summary of each portion is shown below in Figures 6.1 and 6.2. The result is a trajectory that possesses a total of flight (TOF) of 456 days, with 30 days spent in the Martian system, and a total ΔV requirement of 13.5 km/s, satisfying the requirements from other subsystems, including propulsion, human factors and science.

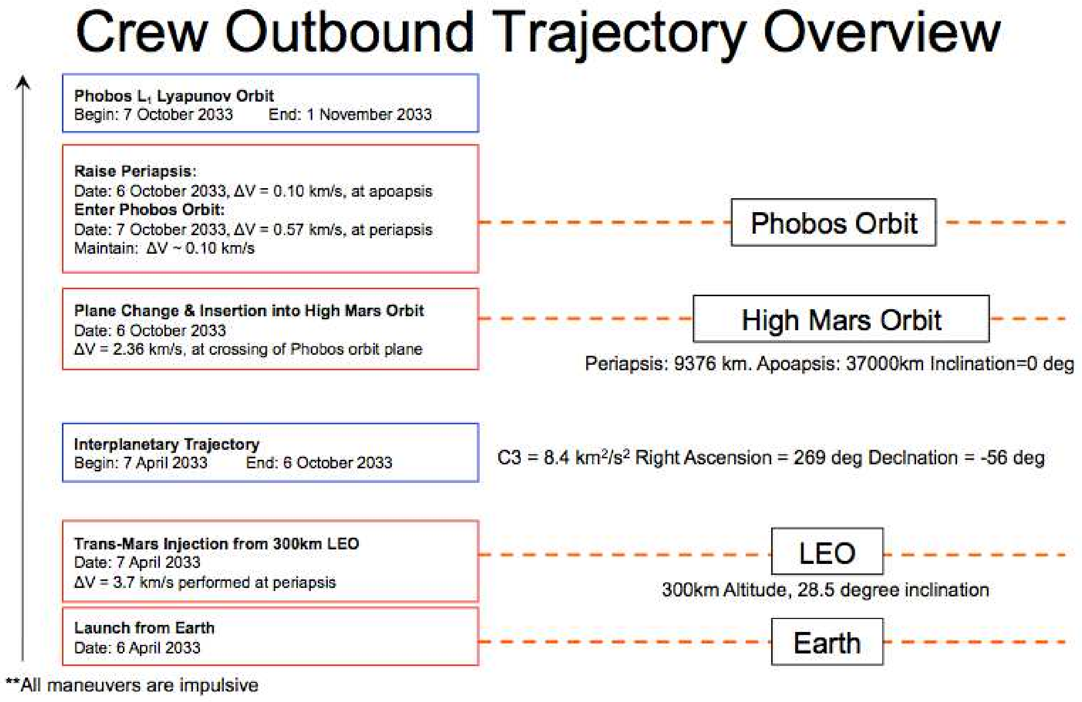


Figure 6.1: Overview of outbound crew trajectory.

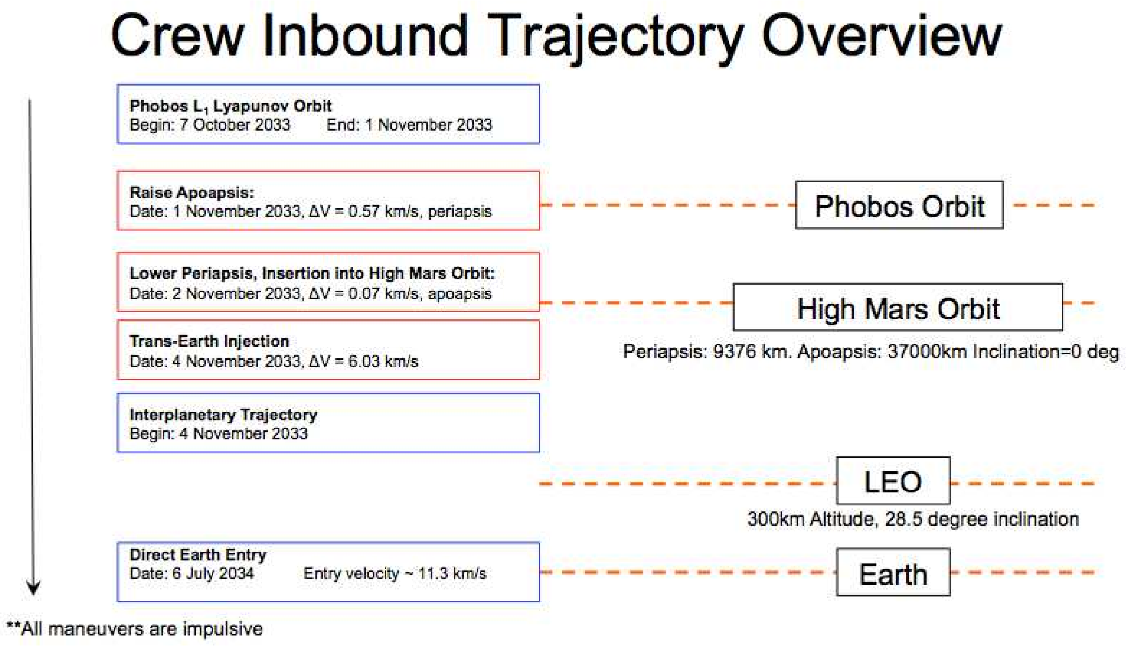


Figure 6.2: Overview of inbound crew trajectory.

6.2.1 Outbound Crew Trajectory

6.2.1.1 Interplanetary Trajectory

Subsequent to a rendezvous in a 300 km altitude low earth orbit (LEO), the crew depart upon an interplanetary trajectory. In order to ensure that the crew arrive at Mars, the geometry of Earth and Mars in their heliocentric orbits is used to determine suitable launch dates and flight times. For the appropriate launch year, a set of interplanetary Lambert arcs is computed using initial conditions spanning each day in the year and flight times between 100 days and 1 year. As an initial approximation tool, Lambert arcs are computed to connect the ephemeris states of Earth at each potential departure date and Mars at each possible arrival date. The ΔV requirements for each transfer are obtained by applying an impulsive maneuver at the boundaries of each Lambert arc. Note that the resulting maneuvers do not represent the exact ΔV required to perform an interplanetary transfer since the spacecraft will be located in orbits about Earth and Mars, not at their locations at some epochs. This methodology merely serves as initial approximation to choose a launch window and obtain an initial guess for higher fidelity models employed later in the design process.

For the 2033 launch year, the resulting ΔV and TOF estimates are analyzed to determine the departure dates and flight times for the interplanetary transfer. Figure 6.3 represents an approximation to the total ΔV (in km/s) required by the outbound interplanetary trajectory for the appropriate departure dates and times of flight.

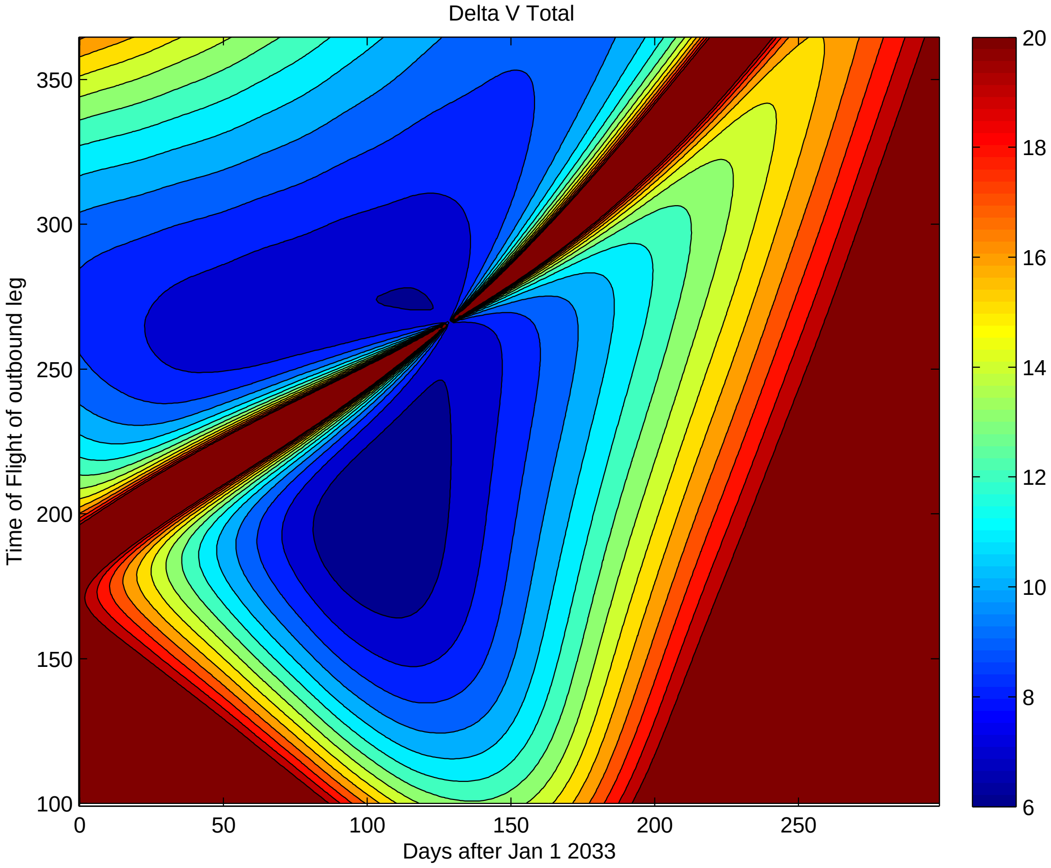


Figure 6.3: Total ΔV (in km/s, depicted in the colorbar) for Lambert Arc solutions in the year 2033 for flight times from 100 to 365 days, connecting the states of Earth and Mars.

Most noticeably, a local minimum, colored blue, occurs for flight times close to 180 days in the months of March and April in 2033. This minimum also corresponds to a local minimum in the C3 (in km^2/s^2) at Earth departure, as shown in Figure 6.4. Knowledge of this parameter is required for selection of a launch vehicle. Thus, for a TOF of 180 days, a nominal Earth departure of April 7 2033 is selected, with the crew launched one day earlier on April 6 2033. For this departure, the transfer arc reaches the Martian system on October 6 2033. By analyzing variations in the approximate ΔV for this arc, which dominates the ΔV requirements for the outbound portion of the mission, a departure window is chosen from April 1 2033 to May 2 2033. The bounds of this launch window result in a total ΔV for the transfer arc of approximately 6.8 km/s, which has been identified by the engineering subsystems as an acceptable upper limit.

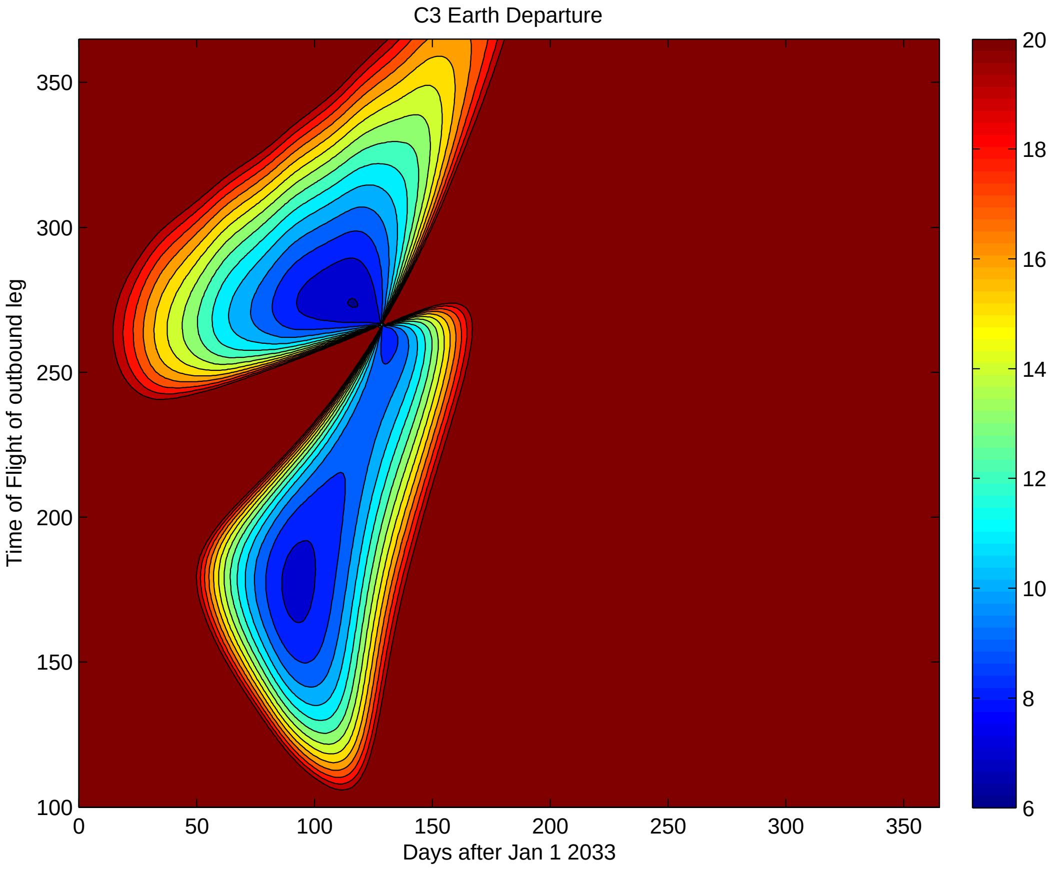


Figure 6.4: C3 (in km^2/s^2, depicted in the colorbar) at Earth departure for Lambert Arc solutions in the year 2033 for flight times from 100 to 365 days, connecting the states of Earth and Mars.

A similar analysis is performed for the backup departure window of 2035. Figure 6.5 represents the total ΔV (in km/s) at Earth departure for Lambert arc solutions connecting the states of Earth and Mars. By locating the local minima that correspond to shorter flight times, a nominal backup Earth departure date of August 14 2035 is identified. Accordingly, a backup crew launch would nominally be scheduled for the day before, on August 13 2035. Using the aforementioned launch window analysis methodology, the crew could launch for a LEO departure window between August 6 2035 and August 20 2035.

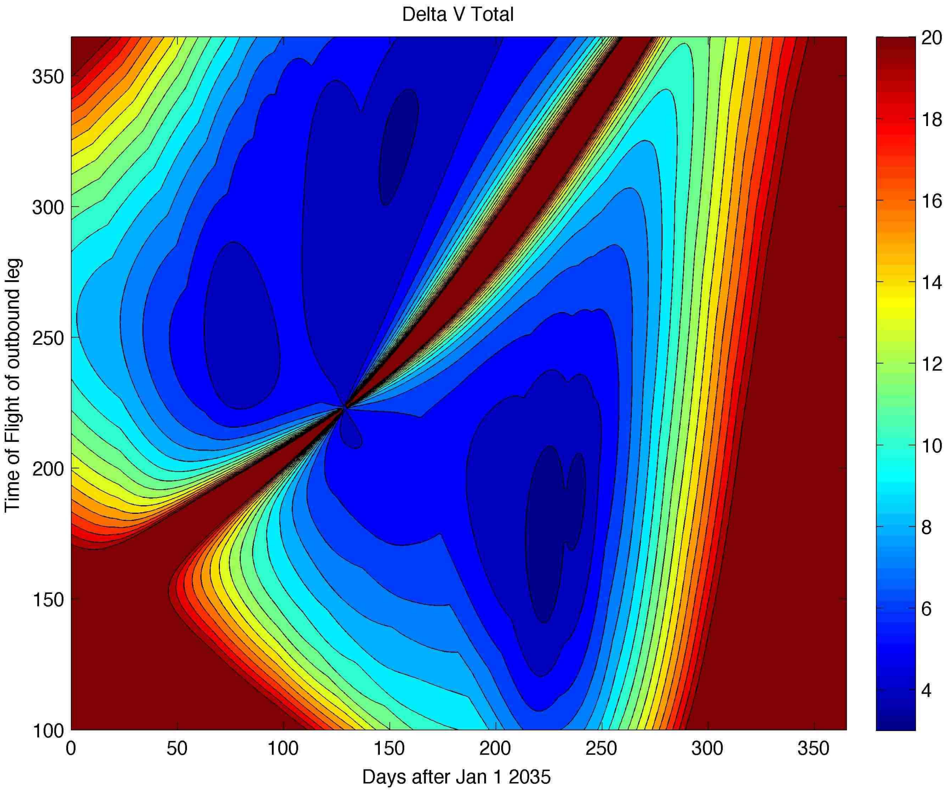


Figure 6.5: Total ΔV (in km/s, depicted in the colorbar) for Lambert Arc solutions in the year 2035 for flight times from 100 to 365 days, connecting the states of Earth and Mars.

An inbound interplanetary transfer must also be computed to return the crew safely to Earth from within the Martian system. Figures 6.6 and 6.7 represent the total ΔV (in km/s) and velocity (in km/s) at Earth arrival for Lambert arc solutions connecting the states of Mars and Earth to return the crew after a 2033 launch.

Locating the local minimum that provides a sufficient time for the crew to perform scientific and other activities on the surface of Phobos, a Mars departure of November 2 2033 is chosen, with a return time of flight of 246 days. The crew, therefore, spends 30 days within the Martian system. This appears to be within the allowable flight time specified by the human factors subsystem. In addition, for this return transfer trajectory, the Earth arrival velocity is close to a local minimum. The value of this minimum, approximated at 11 km/s, is within the limits allowed by current reentry vehicles. Performing the same analysis for the backup 2035 launch window, and referencing Figure 6.8, the crew is estimated to return to Earth on October 30 2035.

The initial epoch for the trans-Mars injection burn and the selected time of flight are used to target a interplanetary transfer that connects a 300 km altitude LEO at

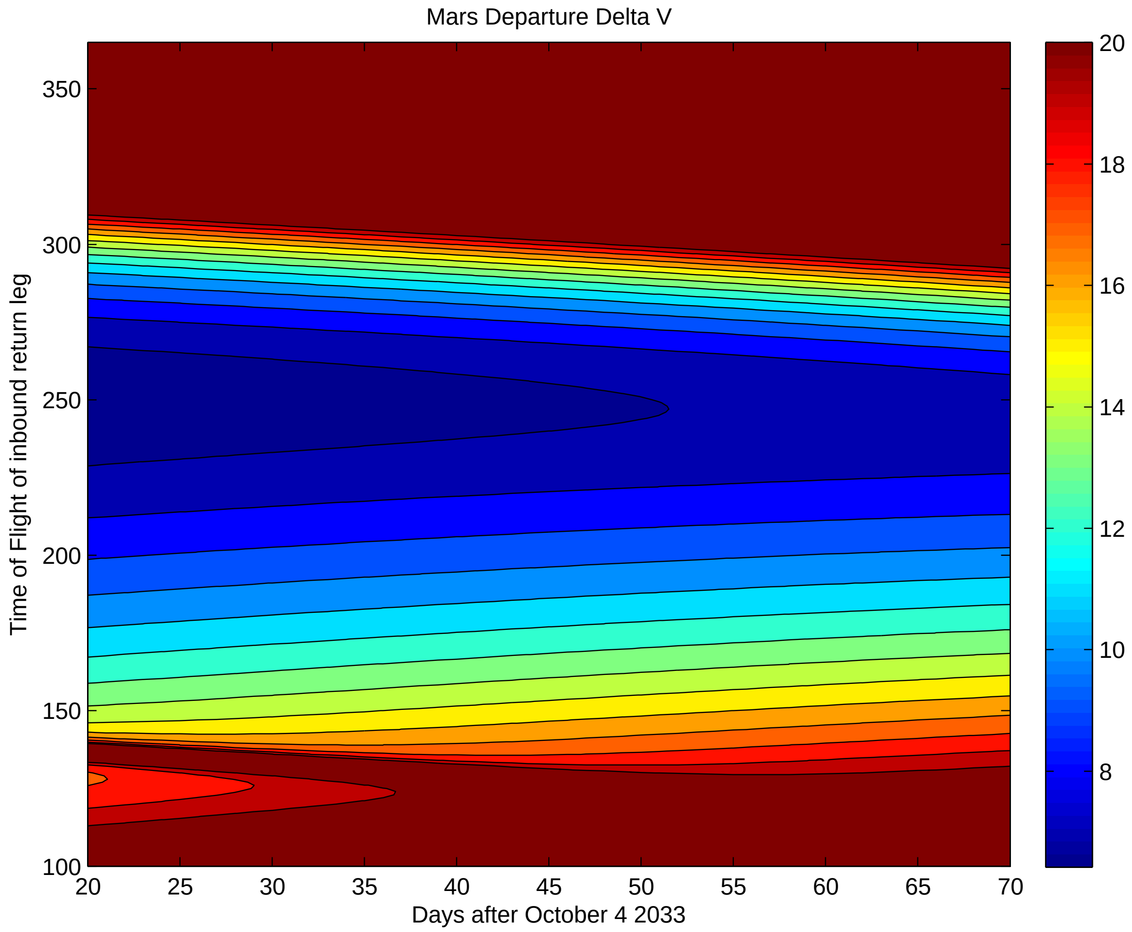


Figure 6.6: Total ΔV (in km/s, depicted in the colorbar) for return Lambert Arc solutions, given a 2033 launch year, for flight times from 100 to 365 days, connecting the states of Mars and Earth.

an inclination of 28.5 degrees with respect to the Earth to a High Mars Orbit that possesses zero inclination with respect to the orbital plane of Phobos [9]. The initial guess obtained from the aforementioned analysis is input into an STK model which integrates the transfer arc using a cislunar propagator until Earth's sphere of influence is reached. Subsequently, a heliocentric propagator is used for the majority of the interplanetary trajectory. In order to connect the desired bounding orbits, a differential corrector is constructed in STK to target a trajectory that is hyperbolic with respect to the Earth, reaching the vicinity of Mars in 180 days. This time of flight constraint is achieved by using the following free variables describing the outgoing asymptote: departure C3, outgoing right ascension, and outgoing declination.

The resulting transfer arc is connected to the LEO portion by employing a three-dimensional impulsive maneuver of approximately 3.7 km/s in magnitude on April 7 2033. This transfer trajectory possesses a departure C3 of 8.4 km^2/s^2, a right ascension of 269 degrees, and a declination of -56 degrees. The resulting outbound

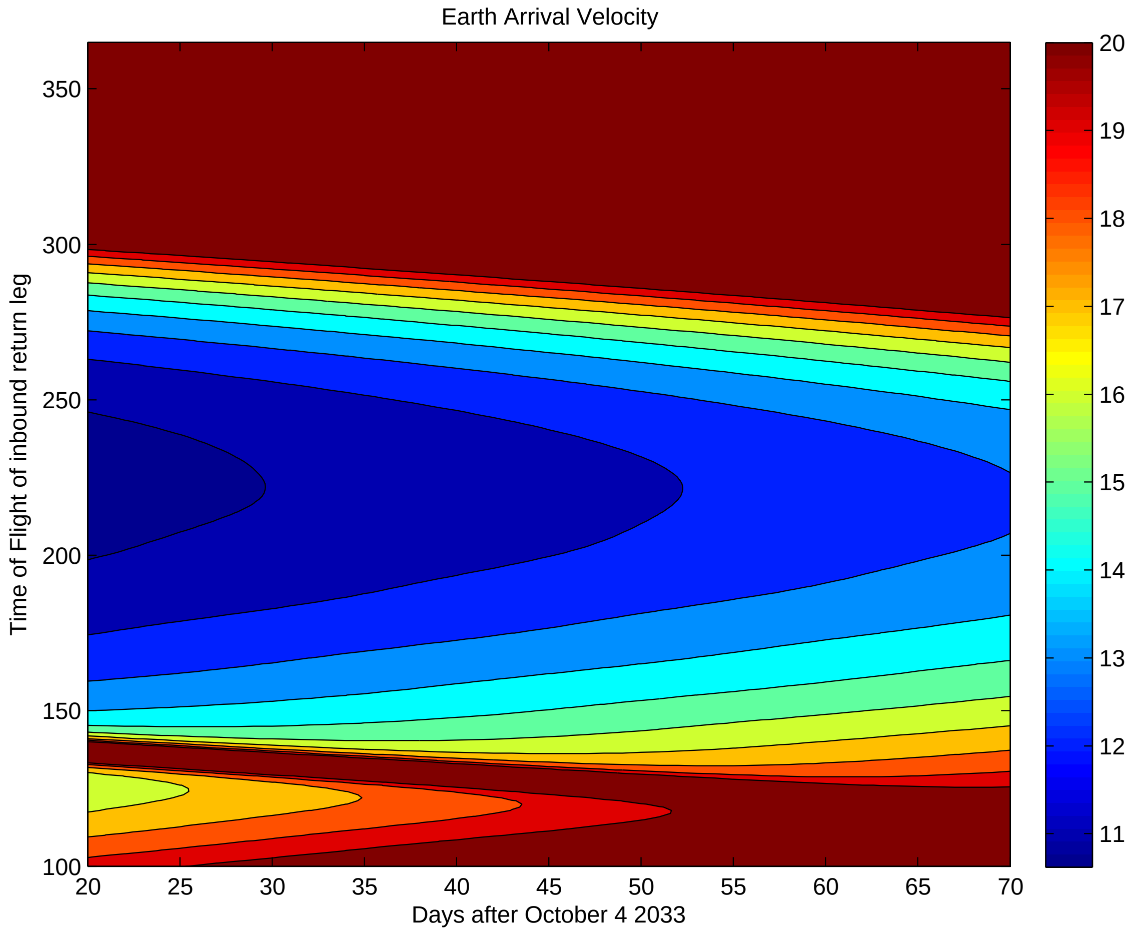


Figure 6.7: Arrival Earth velocity (in km/s, depicted in the colorbar) for return Lambert Arc solutions, given a 2033 launch year, for flight times from 100 to 365 days, connecting the states of Mars and Earth.

interplanetary trajectory is depicted in Figure 6.9. Towards the end of the interplanetary transfer arc, the trajectory is propagated until it crosses the orbital plane of Phobos. This location is chosen for the Mars arrival impulsive maneuver because it intersects the zero inclination High Mars Orbit. In addition, this maneuver serves two purposes: to perform a plane change and to ensure capture about Mars. From this maneuver onwards, a four-body propagator (Mars, Phobos, Deimos, spacecraft) is employed.

6.2.1.2 Mars Intermediate Orbit

The desired Mars intermediate orbit is selected to possess an apoapsis radius of approximately 37000 km, a periapsis radius approximately equal to the radius of Phobos (9736 km), and zero inclination with respect to the orbital plane of Phobos [9]. Note that the apoapsis of the High Mars Orbit lies beyond the orbit of Deimos, allowing opportunistic flybys of Deimos. The desired orbital parameters are achieved using differential corrections to adjust the Mars orbit insertion maneu-

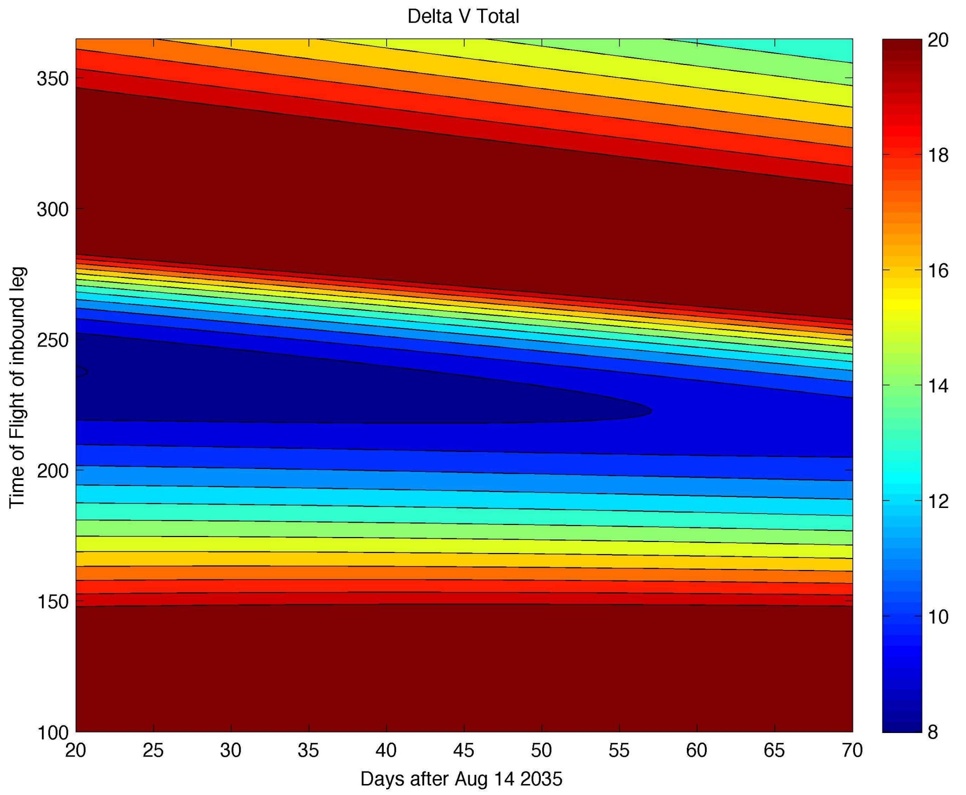


Figure 6.8: Total ΔV for return Lambert Arc solutions in the launch year 2035 for flight times from 100 to 365 days, connecting the states of Mars and Earth.

ver, which connects the interplanetary trajectory to the High Mars orbit. As a result, a maneuver of 2.36 km/s is performed on October 6 2033, acting primarily in the anti-velocity direction. This portion, and the entire Martian system trajectory, is displayed in Figures 6.10 and 6.11, viewed in a Mars-centered inertial frame.

Next, the trajectory is incrementally modified to allow the crew to be captured into a Phobos orbit. On October 7 2033, the periapsis of the High Mars Orbit is raised to the mean radius of Phobos in its near-circular orbit about Mars. This constraint is achieved using a differential corrections scheme which applies a ΔV along the velocity direction at the periapsis of the High Mars Orbit. Placing the maneuver at periapse reduces the ΔV required to satisfy the desired constraints. Using STK, the magnitude of this maneuver is computed as 0.10 km/s. Since the orbital periods of elliptical orbits near Phobos and Deimos are small, an additional maneuver occurs on October 7 2033. This maneuver is used to capture into an orbit about Phobos, by decreasing the apoapsis of the orbit.

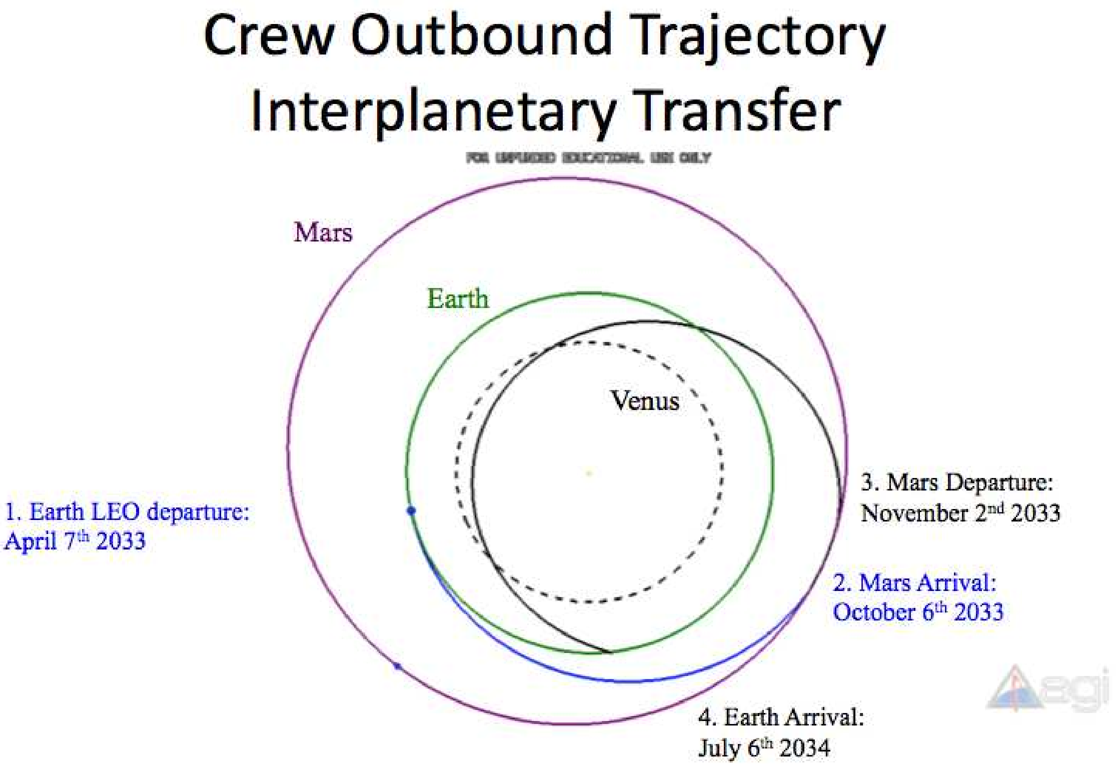


Figure 6.9: Interplanetary transfer arcs between Earth and Mars, as viewed in a Sun-centered inertial frame.

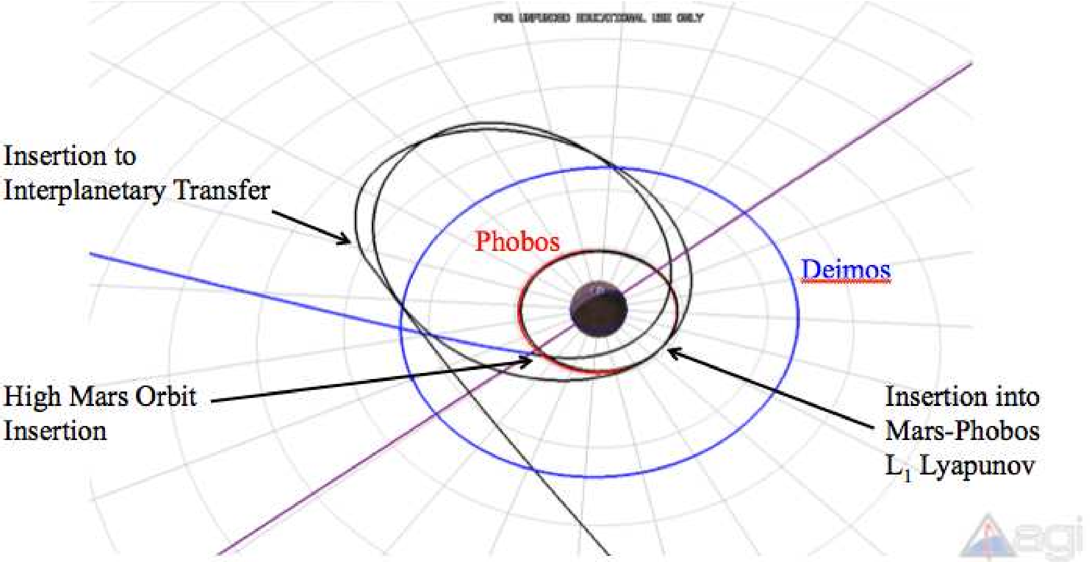


Figure 6.10: Trajectory in the Martian system, viewed in a Mars-centered inertial frame.

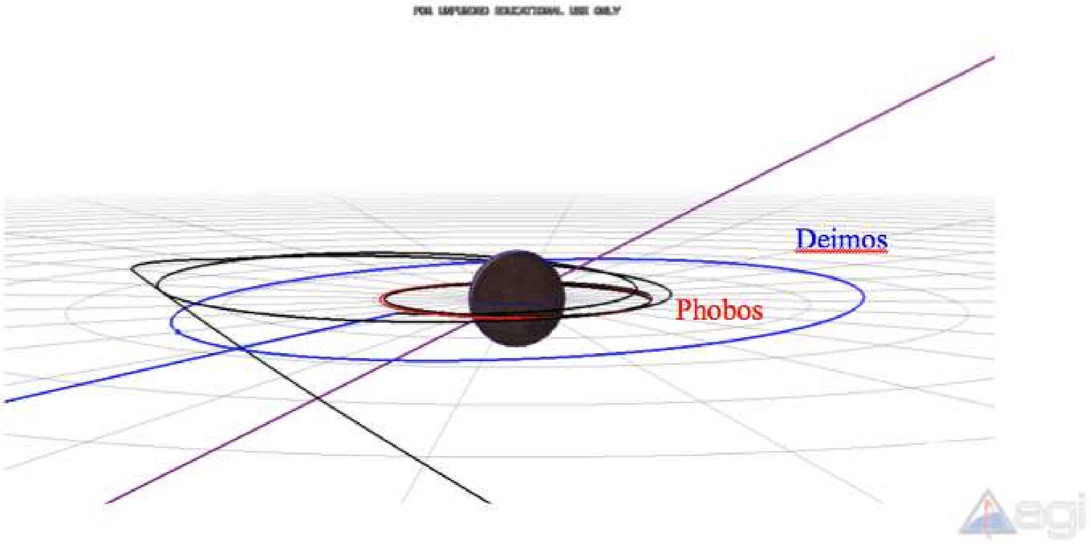


Figure 6.11: Side view of trajectory in the Martian system, viewed in a Mars-centered inertial frame.

6.2.1.3 Phobos Orbit

The landing locations selected to satisfy the science objectives always lie on the Mars-side of Phobos due to tidal-locking. An orbit about Mars-Phobos L_1, therefore, appears to be an appropriate choice of parking orbit for the astronauts that are not landing on the surface of Phobos. In particular, a small L_1 Lyapunov orbit is selected to mitigate the need for an additional plane change, and potentially larger station-keeping maneuvers. Only small amplitude L_1 Lyapunov orbits are considered because they do not intersect the surface of Phobos. To capture into the specified orbit, a maneuver, placed at periapsis, is computed using differential corrections in STK. The required maneuver is equal to 0.57 km/s and is placed at the periapsis of the High Mars Orbit due to the effectiveness of performing a burn along the anti-velocity vector. An approximate ΔV margin of 0.1 km/s is recorded to account for orbital maintenance. Based on the expected periods of Mars-Phobos L_1 Lyapunov orbits, very small corrections maneuvers could occur every few hours at the crossings of the Mars-Phobos line. The crew members that are not assigned to landing on Phobos will remain in this orbit for 24 days until November 1 2033. Given the location of the L_1 Lyapunov orbit, the crew can also communicate with and command a rover or small Cubesats located on any portions of the Martian surface that are within their line of sight.

Line of sight access times from the location of the Mars-Phobos L_1 were computed using STK 10 for the nominal Phobos operations period. A representative diagram of the line of sight gaps is shown in Figure 6.12. Loss of access is due to occultations by Phobos and by Mars. The mean access per Phobos orbital period of 4.64 hours, or 61.2%. This corresponds to two access windows of 2.32 hours on average, separated by a Mars occultation gap of 0.71 hours on average and a Phobos occultation gap of 2.25 hours on average.

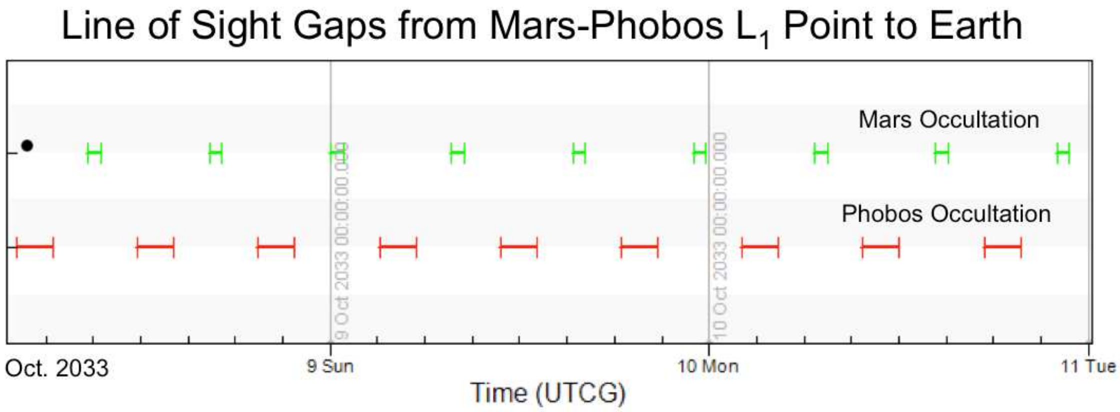


Figure 6.12: Representative diagram of sight access gaps from the location of the Mars-Phobos L_1 to Earth during Phobos vicinity operations. Computed using STK 10.

6.2.2 Inbound Crew Trajectory

6.2.2.1 *Mars Vicinity*

In order to depart the vicinity of Mars and Phobos, the approach trajectory is qualitatively mirrored. First, a maneuver is placed at periapsis to insert into a High Mars Orbit, effectively raising the apoapsis. Using differential corrections in STK to target an apoapsis radius of 37000 km, a ΔV equal to 0.57 km/s is performed on November 1 2033 along the velocity direction. Next, a maneuver is placed at apoapsis to lower the periapsis of the High Mars Orbit in preparation for departure from the Martian system. Occurring on November 2 2033, this maneuver is small, equaling approximately 0.07 km/s tangential to the velocity vector.

6.2.2.2 *Interplanetary Trajectory*

The High Mars Orbit is propagated from apoapsis until a trans-Earth injection maneuver is applied. Given the relative geometry of Mars and the Earth on the selected departure date of November 4 2033, it would be inefficient to depart the Martian system from periapsis, as the interplanetary transfer intersects the High Mars Orbit almost perpendicularly at this orbital location. Instead, the maneuver epoch is targeting using differential corrections in STK such that the maneuver possesses a direction that is closer to tangential to the velocity vector. A ΔV of 6.03 km/s results in the crew traveling on a hyperbolic orbit, with respect to Mars, that possessed a declination of -11 degrees and a right ascension of 211 degrees. The interplanetary trajectory is then propagated using a heliocentric gravitational model, resulting in an inbound transfer time of 246 days. At the direct Earth entry, the arrival v_{inf} of this transfer arc is used to estimate an Earth entry velocity of 11.3 km/s on July 6 2034. Based on existing hardware and expected progression in Earth entry technology, this entry velocity appears acceptable to ensure that the crew return safely. Finally, note that the interplanetary return trajectory passes closer to the Sun than Venus, which impacts certain aspects of the spacecraft design, including radiation and thermal requirements. Although this is a coincidence due to the geometry, the departure epochs and flight times could be modified to leverage a Venus flyby in order to reduce the required ΔV. Further efforts to reduce the propulsion requirements of the mission include optimization of maneuver locations, magnitudes and directions.

6.2.2.3 Abort Scenarios

Given the complex nature of interplanetary space exploration, abort scenarios must be considered. Mechanical or other failures may occur at any time; however, primary abort scenarios can be identified and potential solutions suggested. An error during or following the application of the trans-Mars injection will likely occur at the beginning of the interplanetary transfer [Personal communication, Dan Mazanek]. As a first approximation, an Lambert arc can, therefore, be constructed between the current location and the Earth. Given the orbital geometry, such a maneuver may be expensive and must be compared with the remaining ΔV available to the crew and any restrictions on the time of flight on their return trip.

If a thrusting failure occurs in the Martian system, however, a similar abort scenario may be employed. If the situation permits, the astronauts could orbit in a stable Mars-centered orbit for the remainder of their planned stay and return home on the nominal Mars departure date without landing on the surface of Phobos. To account for these possibilities, an additional ΔV margin is applied to the design and sizing of the propulsion system.

6.3 Re-entry

After returning to Earth vicinity, the Dragon crew module separates from the DSV and performs a direct entry into Earths atmosphere with a entry speed of 11.3 km/s. The DSV is then moved to a graveyard orbit in the Earth-Moons vicinity orbit. Enough ΔV margin was allocated to consider this maneuver.

6.4 Spacecraft

The following sections list and justify the choices of the distinct spacecraft vehicle modules used during the TAPER mission. A general subsystem overview for all spacecraft is provided. Following this, each vehicle is described by means of its principal subsystems. Subsystems which do not drive key mission factors for each vehicle are omitted.

6.4.1 Subsystem Overview

The assembled spacecraft vehicle includes a Deep Space Vehicle (Habitat and Crew Vehicle), a Phobos Surface Explorer vehicle and the propulsion system. The general layout is shown in 6.13.

6.4.2 Introduction

6.4.2.1 AODCS & GNC

For the general scope of the mission, attitude determination sensors and attitude and orbit determination and control system (AODCS) actuators shall be used, Guidance Navigation and Control (GNC) algorithms also need to be included. The spacecraft's trajectory shall then be fully automated.

As it is a requirement to use solar generated power, sun pointing orientation shall be thoroughly considered during the transfer. For some particular phases of the mission (Rendezvous and Landing, respectively for the DSV assembly and PSE vehicle), e.g. Phobos approach, the gravity field and some other properties shall

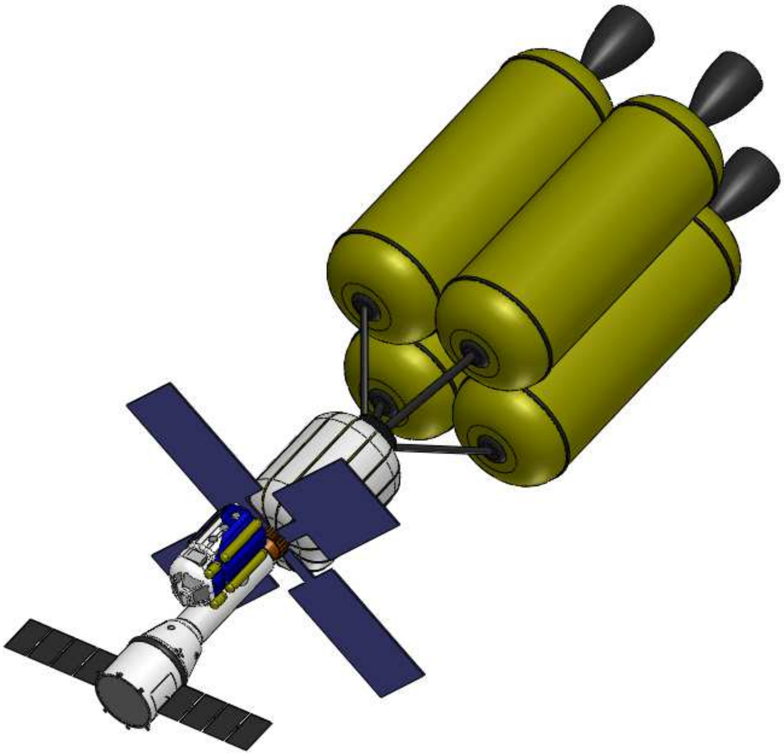


Figure 6.13: CAD model of assembled spacecraft, using SolidWorks.

primarily be understood and modeled in the GNC algorithms. Several types of Reaction Control Systems, as well as Attitude Determination sensors shall be evaluated. At this point in time, it is reasonable to say that these systems have been already thoroughly studied and evaluated, and then represent a smaller asset for the mission compared with other spacecraft subsystems.

The dynamics and the layout of the Spacecraft also needs to be considered and evaluated. Such a particular deep space vehicle, with dimensions and characteristics never before tested in space, shall carefully be dynamically evaluated.

6.4.2.2 Command & Data Handling

Unless otherwise mentioned, the command data and telemetry from the spacecraft are assumed to be relatively minimal in comparison to the science data. The power budget includes appropriations for expected wattages of the communication downlink, but no other data intensive products have been examined within the scope of the project.

6.4.2.3 Communications

The communications subsystems is mission-critical since it allows the sending and receiving of information between Earth and Mars orbit, or Mars and Phobos. An antenna system exists on the three vehicles: Deep Space Vehicle, Crew Vehicle, and the Phobos Surface Explorer. The DSV and PSE will be designed by the TAPER mission to allow Earth-Mars orbit and PSE-DSV communications, respectively. The CV, however, will have its own communications subsystem designed by the CV's manufacturer.

6.4.2.4 ECLSS

Only the Deep Space Habitat Environmental Control and Life Support Systems (ECLSS) is considered in this preliminary analysis. The ECLSS concerning other spacecrafts are not drivers for the mission design and are not detailed in this report.

6.4.2.5 Power

The power system is responsible for supplying electrical power to all vehicle components that require power to operate. The system must budget the vehicle's power usage with the total power generated or stored on each vehicle to ensure the vehicle can function properly. The solar arrays are fairly large since the solar intensity decreases by distance-from-sun squared and the vehicles have high power demands. At Mars, solar intensity is around 575 W/m^2 versus at Earth, where solar intensity is around 1366 W/m^2, so as the spacecraft travels farther away from the sun, the power output will decrease. We assume that throughout the trip, the solar panel degradation is negligible. We also assume the batteries do not have loss in depth of discharge.

Some of the greatest power drawers are the life support systems on both the PSE and DSV. The robots sent to explore Phobos surface will have their own solar arrays to power the on-board scientific instruments. For a detailed mission power budget, refer to Appendix B.

6.4.2.6 Propulsion

The purpose of the propulsion system is to drive the spacecraft to the location indicated in the mission objectives within the required time. The propulsion system must also ensure the safe travel of the crew, in which reliability shall be taken into account during key mission milestones where failure could impact the crew significantly. Key parameters describing propulsive performance are the specific impulse and thrust of the system. Specific impulse is directly related to the exit velocity of the particle and measures efficiency. Thrust describes the force the propulsion device imparts on the spacecraft and is directly related to travel times. The efficiency and force must be balanced to achieve mission objectives and minimize cost. Propulsion systems are selected which demonstrate key technologies for future space exploration missions.

6.4.2.7 Structural Design and Layout

The structural design and layout of each spacecraft is crucial for this mission. The general assembly of the vehicles together with the propellant systems, as well as the interfaces between them, are critical.

The chosen vehicles were considered to be under development having a TRL greater than 5. A structural analysis is beyond the scope of this report, but it does however have the ability to add considerable mass in future missions. These shall be addressed in an advanced phase of the project. Nevertheless, it is believed that given the current vehicles development, the projected availability of each one will be guaranteed, or replaced with a launch vehicle of similar capabilities.

6.4.2.8 Thermal Control

In a crewed mission, the thermal control subsystem shall exist and accomplish the temperature range requirements of both, the crew and the instruments on-board. For the long duration mission as considered here, several sources of thermal radiation exist, solar radiation being the most prevalent for thermal considerations.

In order to control the temperature range inside the different vehicles, both active and passive thermal control system components are desired. Several types of components exist, being the most important ones the insulation components, the isolators, the radiators, the heaters, the louvers and the heat pipes. Assuming a crew vehicle which will at the time of the mission include its own thermal system the thermal control only had to be studied for the Deep Space Habitat vehicle and the Phobos Surface Explorer, shown in Fig. 6.14 [13].

Additionally, the science samples taken at Phobos may require an active cooling system so as to preserve the samples. For this reason, 200 kg of the 500 kg mass allocated for Phobos samples has been given to mass for an active cooling system in the payload holding cell of the PSE. This system stays in the PSEP unit, and returns to the Crew Vehicle once the stay on Phobos is complete.

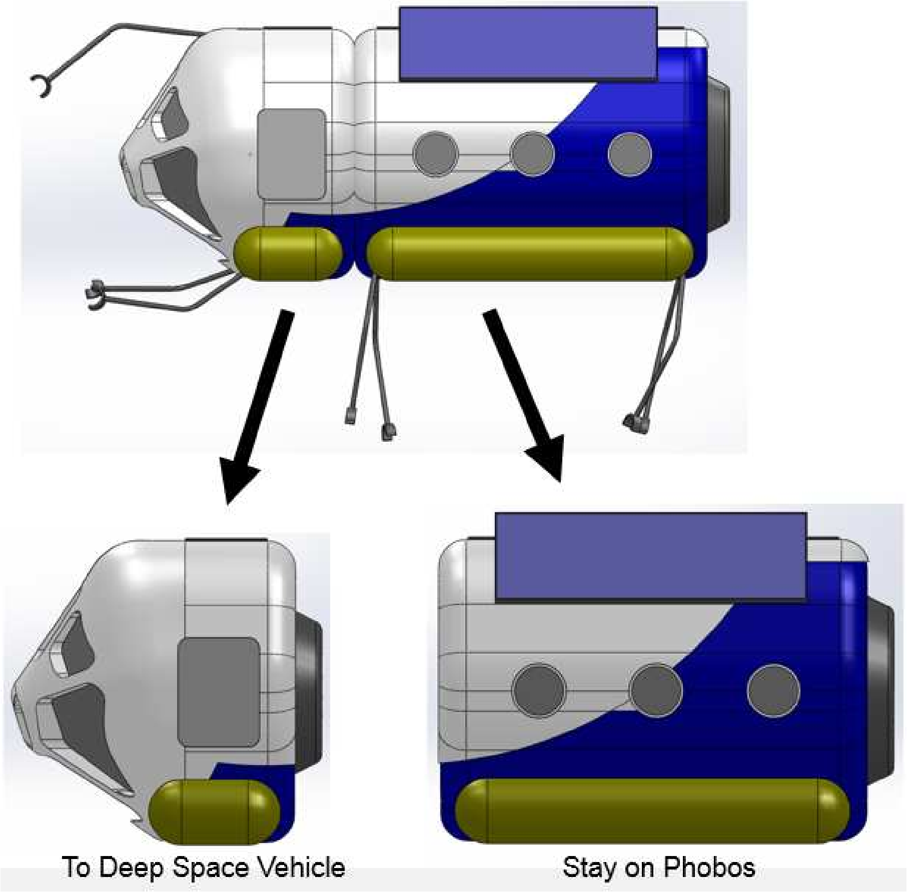


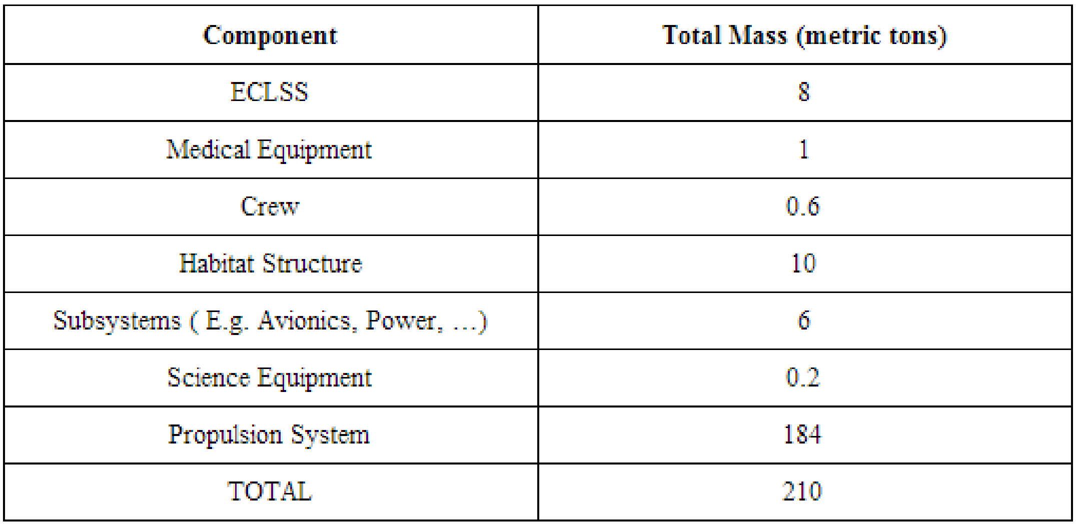
Figure 6.14: PSE Concept.

6.4.3 Deep Space Vehicle

The Deep Space Vehicle (DSV) is an assembly of both the deep space habitat (DSH) and the Crew Vehicle (CV). They are assembled together with the propulsion system and the PSE in LEO and then fly directly to Mars vicinities as mentioned previously. The following subsections present an overview of each of these subsystem as well as the principal key factors that drove each subsystems design.

6.4.3.1 Overview

The DSV is the primary transport mechanism for ferrying the astronauts between Earth and Phobos. It is joined to the Deep Space Habitat (DSH) vehicle which has a total mass weight of approximately 26,000 kg and the crew vehicle which weighs approximately 9,500 kg. It is composed of a Bigelow Inflatable Habitat attached to a Dragon crew vehicle. It is assembled in space with the NTR thrusters, NTR fuel tanks and the PSE. It transits outbound in 180 days and inbound in 233 days. The Mass Breakdown for the DSH is provided in Fig. 6.15.



Component	Total Mass (metric tons)
ECLSS	8
Medical Equipment	1
Crew	0.6
Habitat Structure	10
Subsystems (E.g. Avionics, Power, …)	6
Science Equipment	0.2
Propulsion System	184
TOTAL	210

Figure 6.15: Component Mass Table for the DSH.

For this mission, the TAPER team assumes the Dragon crew vehicle will provide an all-in-one point at which all the systems are integrated. For the purposes of this study only the total mass of the vehicle was considered, the mass breakdown is not relevant. The expected allocated payload is at least 1000 kg. This available mass, as well as the available volume is sufficient to retrieve the 500 kg allocated mass to accomplish Scientific requirements - samples will return with the crew to Earth in this vehicle.

It is important to state that all the subsystems masses were increased by a factor of 10%. Margin was added to the system, as well as increasing the overall ΔV requirement for the propulsion system to account for an additional launch window in 2035 in the event the mission misses the 2033 event. A 3D design of both the DSH and the CV is presented in Fig. 6.16.

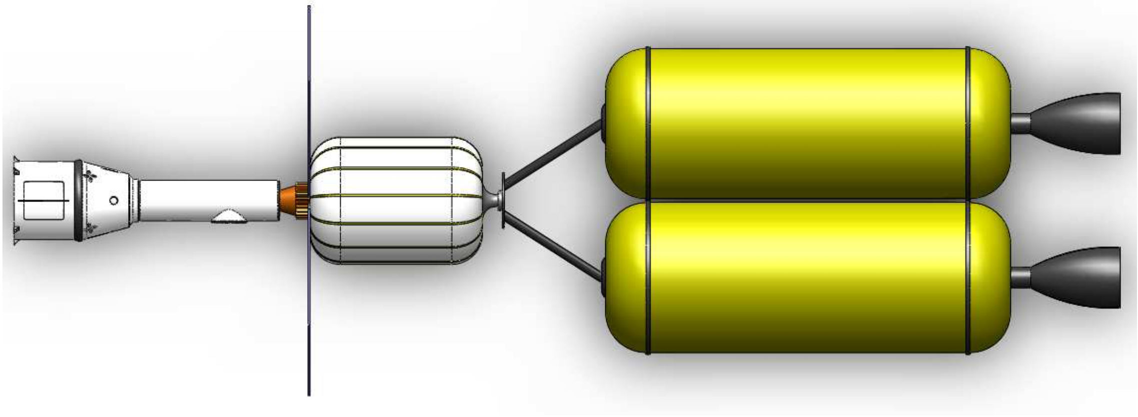


Figure 6.16: DSV layout.

6.4.3.2 AODCS and GNC

The Deep Space Vehicle will have to be assembled together, along with the PSE and the Propulsion System, these rendezvous maneuvers are critical and shall be automated. Being a critical maneuver, it is believed that in the following years, the autonomous rendezvous and docking technology will be developed to a point in which it will be safe and reliable to perform these highly advanced maneuvers. Attitude determination, Close-In rendezvous and docking sensors, Fully autonomous rendezvous and docking algorithms as well as Rendezvous and docking mechanisms still remain to be developed. Nevertheless, current development gives the confident assumption that highly complicated docking maneuvers will be easily performable by the time of the mission [14].

6.4.3.3 Communications

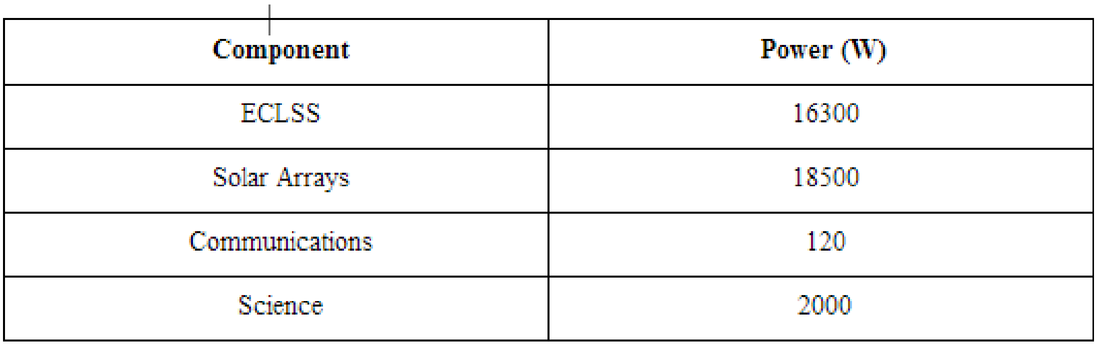
The communications capability will keep the crew in contact with the Earth ground crew and facilitate interplanetary information exchange throughout the missions duration crucial for TAPER’s mission success. The DSV’s transmit antenna is based off of the Mars Reconnaissance Orbiter’s (MRO) link with the Deep Space Network (DSN). The DSV will have a 4 meter diameter transmitter antenna that transmits in the X-band (8.4 GHz) at 60% transmit efficiency, to relay information across the mission’s maximum distance between Mars and Earth 400 million km [15, 16]. It was assumed that the DSV will communicate mostly with the 34-m diameter receiver antenna dishes in the DSN, which is also assumed to have an efficiency of 60% and a low noise amplifier gain of 70 dB. The 50 MHz bandwidth and a minimum data rate of 500 Kbps yields an acceptably low bit error rate of 4.2E-7. Given a max Earth-Mars access time of 4.6 hours during an access period, 1010 megabytes will be transferred between Earth and Mars, with a light delay of around 22 minutes. This example scenario, with a link budget located in the Appendix B, illustrates communication’s worst case scenario. It is also assumed that the transmitter can double as a receiver with no extra changes in characteristics.

6.4.3.4 ECLSS

The four astronauts will spend 456 days in space. Two astronauts will remain in the the Deep Space Habitat (DSH) during the entire mission. During the Phobos exploration stage, the mission specialist and the mission engineer will exit the DSH on the Phobos Surface Explorer (PSE), leaving the commander and flight surgeon on-board the DSV for another 30 days. The DSH ECLSS system has been design to support the four astronauts during the 456 days, taking into account an eventual contingency that prevent the excursion to Phobos.

6.4.3.5 Power

The DSV will require high power generation since the vehicle's ECLSS - the astronauts' life support system - has high power demands, along with maintaining the purity of martian moon samples. The DSV's solar panels must be at least 60 m^2 to satisfy the vehicle's power demands along with any additional losses. We assume the solar arrays do not degrade throughout the mission trip.The power requirements are found in Table 6.17:

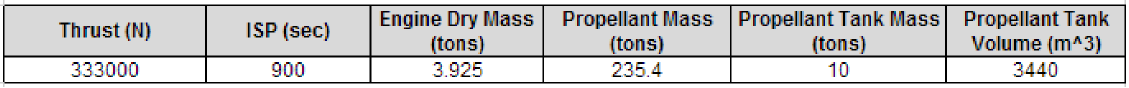


Component	Power (W)
ECLSS	16300
Solar Arrays	18500
Communications	120
Science	2000

Figure 6.17: Power Budget Table.

6.4.3.6 Propulsion

The DSV propulsion system selected for the mission duration was sized as a single stage, three engine Nuclear Thermal Rocket (NTR) which will be launched through a combination of SLS, Falcon 9, and Falcon Heavy launches. A Particle Bed Reactor is chosen over a NERVA variant due to an approximate mass savings of 10 metric tons per rocket. The performance of the NTR chosen is estimated to be 900 seconds with 333 kN of thrust. The NTR system is comprised of a cluster of three Particle Bed Reactors NTRs with four liquid H_2 propellant tanks in addition to the helium pressurant tanks. The performance of the propulsion system is shown in Fig. 6.18.



Thrust (N)	ISP (sec)	Engine Dry Mass (tons)	Propellant Mass (tons)	Propellant Tank Mass (tons)	Propellant Tank Volume (m^3)
333000	900	3.925	235.4	10	3440

Figure 6.18: NTR performance.

These rockets require development beyond the current TRL levels and are an enabling technology for future human space exploration. This mission is a key demonstration of this technology.

6.4.3.7 Structural Design and Layout

The Bigelow Inflatable Habitat is a structure with a habitable area of at least (based on current information) 180 cubic meters (about 240 cubic meters of total pressurized volume). The habitat's external layout is presented in Fig. 6.19.

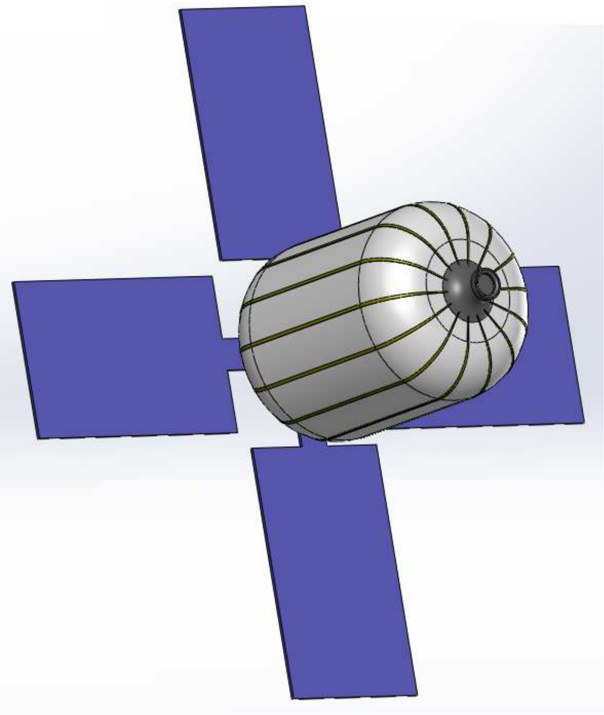


Figure 6.19: Habitat Layout.

The internal layout is divided among the following major sections:

- Avionics, ECLSS and Stowage, for flight electronics, environmental life support control and adjustable storage of food, water, waste and clothing;
- Crew Quarters, for sleep and privacy (one for each crew member;
- Galley Stowage, for eating, communication and quick-access lockers;
- Work stations, for general maintenance tasks, medical operations, telerobotics and daily research activities;
- Hygiene, including a shower and waste facilities;
- Exercise space, including fitness stations and a centrifuge for physiology maintenance.

Below is an internal layout diagram of the Deep Space Habitat (DSH). The total pressurized volume is 240 m^3, with 60 m^3 of that being taken up by avionics, ECLSS, and additional stowage. This gives a habitable volume of 180 m^3 for the four crew. The crew quarters provides a private space for each crew member for sleeping, personal time, family communications, and general relaxation. The Galley and Stowage area encompasses the kitchen and dining area, the group communications and control station, and general storage for supplies that are required to be easily accessible such as the medical emergency kit, daily food, and general maintenance tools. Workstations can be used for several tasks, including: science research, engineering projects, maintenance and repair, and teleoperations workstations. Both hygiene areas includes a latrine and body cleansing area. The last section of the habitable volume is reserved for the exercise area centrifuge, detailed in the countermeasures section of this report. The volumes included below have been derived from NASA heritage listed in the Human Integration Design Handbook [17, 18].

Figures 6.20 and 6.21 show two cross-sectional views of the habitat. Internally, it shall contain enough room to accommodate four astronauts as well as a scientifically significant returned payload quantity which has been estimated. The external view of the expected Dragon vehicle is shown in Fig. 6.22.

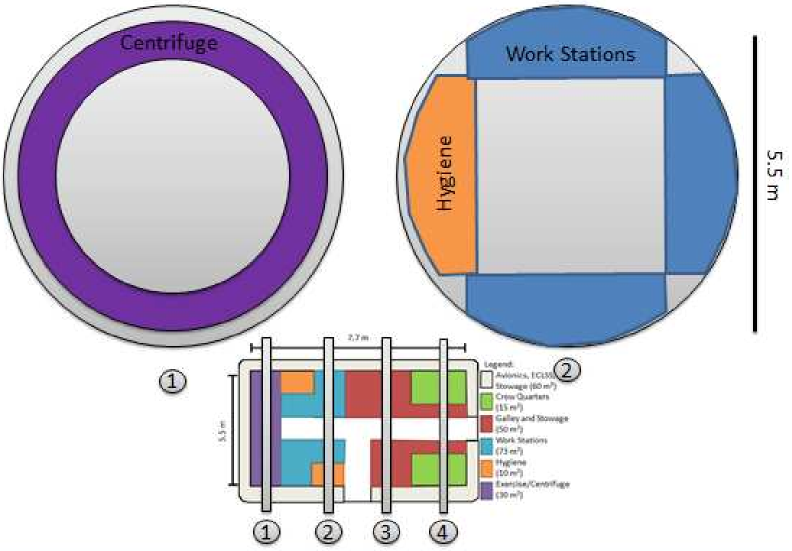


Figure 6.20: Cross sectional view of the habitat 1.

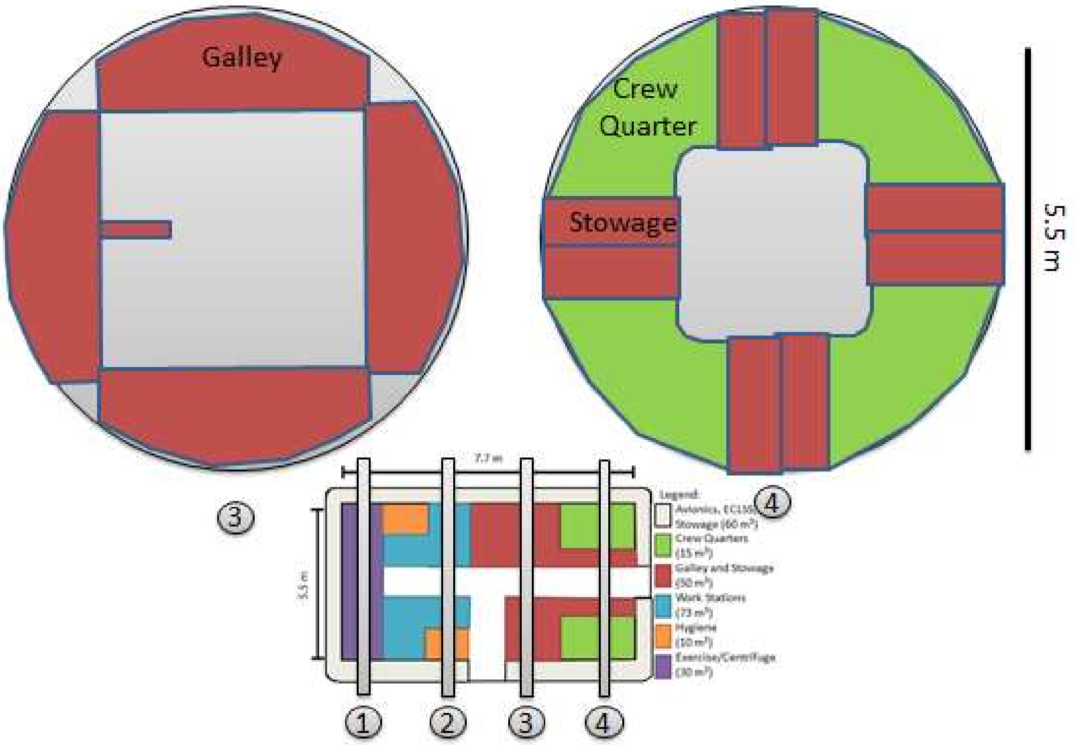


Figure 6.21: Cross sectional view of the habitat 2.

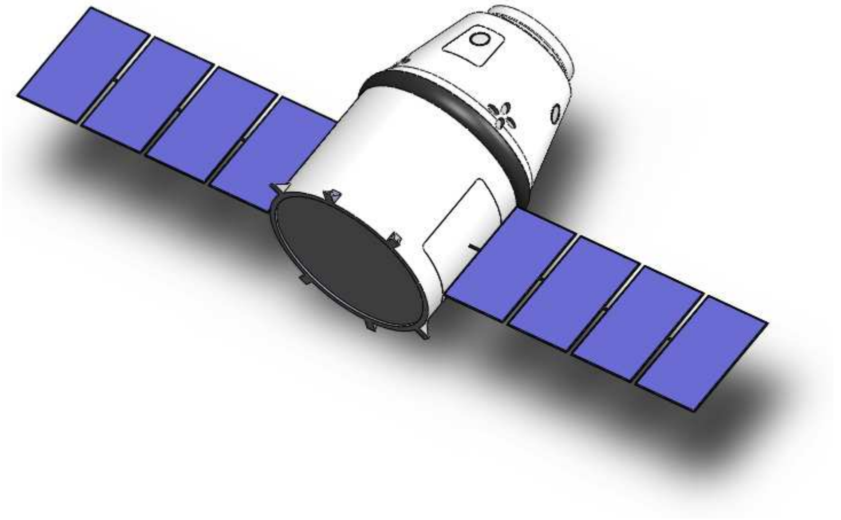


Figure 6.22: Dragon design.

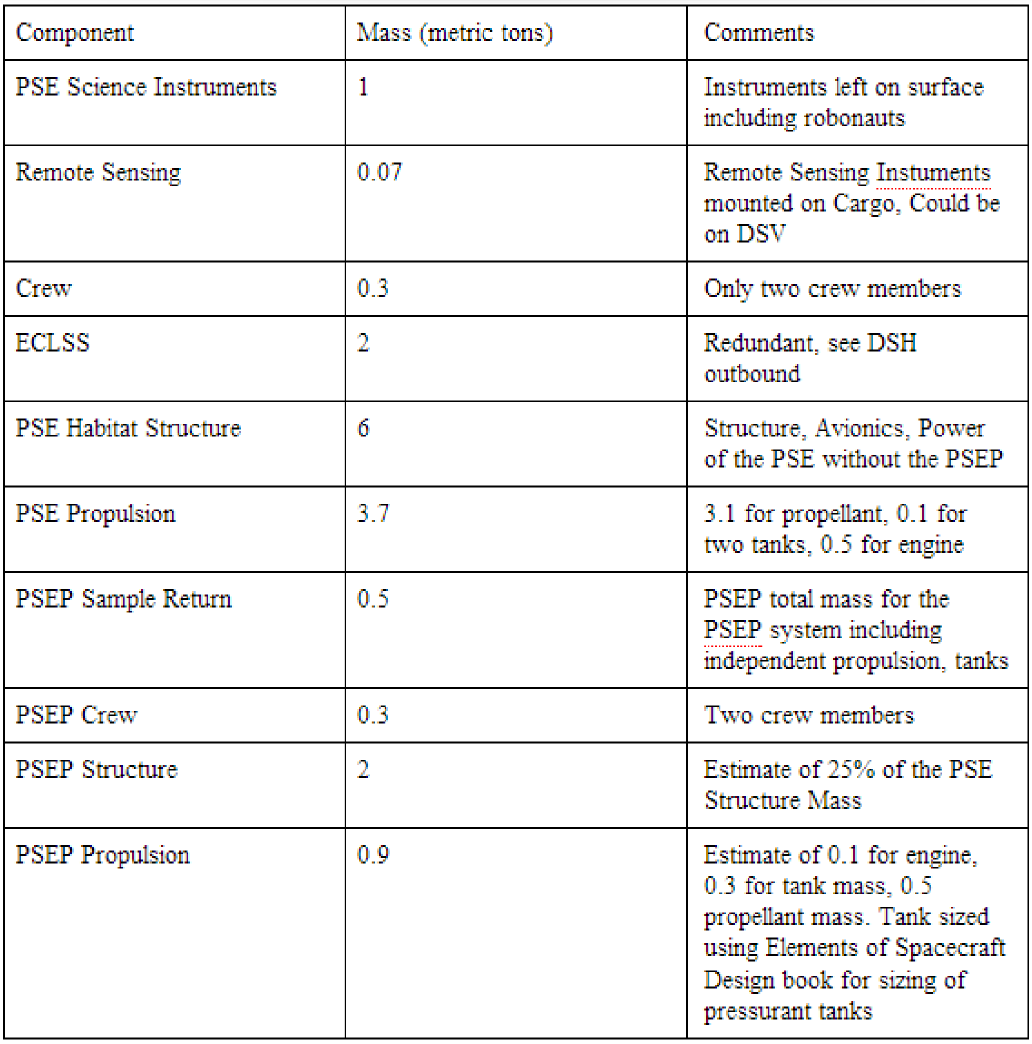
6.4.3.8 Thermal Control

Serving as a first approximation, it can be said that the thermal control hardware mass represents 2%-10% of the habitat dry mass. A mass of 500 kg was found to be a reasonable approximation of the total thermal control mass. This mass was considered part of the wet spacecraft mass budget, which was treated as a whole, giving more margins for mass changes within the different systems.

In terms of required power, a trade study concluded that the power generators provided by the habitat (Bigelow Sundancer), shall be enough to cover the different systems power needs. However, if mass needs to be added to ensure enough power generation, safety margins for all the masses were given.

6.4.4 Phobos Surface Explorer

The PSE is composed of two separate portions: a PSEP stage which enables crew mobility on the surface of Phobos and returns the astronauts to the DSV; and a habitation segment which provides the life support system for two astronauts throughout 30-day Phobos exploration mission segment. The Mass breakdown for the PSE is shown in Fig. 6.23.



Component	Mass (metric tons)	Comments
PSE Science Instruments	1	Instruments left on surface including robonauts
Remote Sensing	0.07	Remote Sensing Instuments mounted on Cargo, Could be on DSV
Crew	0.3	Only two crew members
ECLSS	2	Redundant, see DSH outbound
PSE Habitat Structure	6	Structure, Avionics, Power of the PSE without the PSEP
PSE Propulsion	3.7	3.1 for propellant, 0.1 for two tanks, 0.5 for engine
PSEP Sample Return	0.5	PSEP total mass for the PSEP system including independent propulsion, tanks
PSEP Crew	0.3	Two crew members
PSEP Structure	2	Estimate of 25% of the PSE Structure Mass
PSEP Propulsion	0.9	Estimate of 0.1 for engine, 0.3 for tank mass, 0.5 propellant mass. Tank sized using Elements of Spacecraft Design book for sizing of pressurant tanks

Figure 6.23: Mass breakdown for the PSE.

6.4.4.1 AODCS and GNC

The PSE will have to perform one of the most critical maneuvers of the entire mission - land on Phobos surface. It is a requirement to land on several places on the moon, to facilitate this the explorer vehicle shall provide autonomous landing. A GNC approach based on the Hayabusa Spacecraft landing [19] will have to be developed and integrated in the vehicle. Sun sensors, Star Trackers, Inertial reference units and other attitude determination sensors would have to be included together with a Reaction Control System. Optical navigation using multiple cameras might also be of great use.

The vehicle shall be able to land in predefined landing sites without any type of manned control. Even though, the possibility of manual control shall be available in the vehicle, the GNC system needs to be robust and feasible enough to perform the required landing maneuvers.

6.4.4.2 Communications

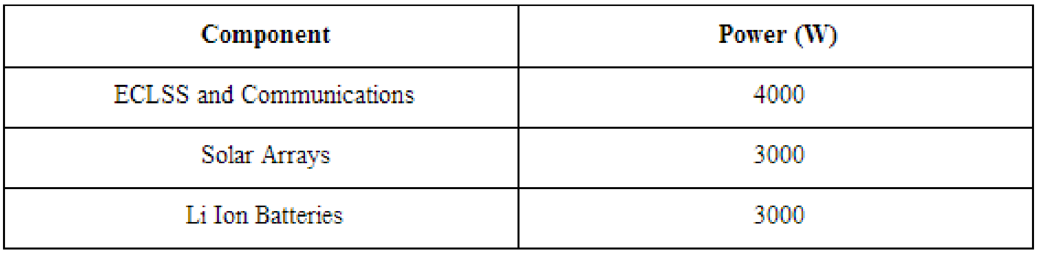
Communication is necessary between the PSE and DSV to maintain contact between the two crew pairs, one pair in the PSE and the other in the DSV during EVA missions. The PSE's communications capability is based off the canceled Mars Telecom Orbiter and the existing Mars Science Laboratory. Since the maximum distance between the PSE and DSV is less than 100,000 km, the losses are minimal. A 0.5 m diameter transmit antenna on the PSE sufficed for communication with the DSV since the bit error rate was calculated to be 4.4×10^{-15} despite a very high assumed 1000 K system noise temperature and 50 dB receiver gain. It was also assumed that the bandwidth was at 50 MHz, the data rate was at 1024 kbps, the DSV does not have a low-noise amplifier, and that the DSV's transmitter antenna can receive data and point accurately [20, 21]. Although many of these parameters may be assumed, the minimal distance between the PSE and DSV allows for a small PSE antenna size. The PSE communicates with the DSV at data rates in the order of 0.5 to 1024 kilobits per second (kbps). The link budget can be found in Appendix B.

6.4.4.3 ECLSS

The ECLSS mass for the PSE has been estimated to be around 2 metric tons.

6.4.4.4 Power

The PSE requires power primarily for the ECLSS and communications systems, which in total demand 4 kW. It was assumed that the ECLSS power value was scaled down from the DSV ECLSS power values by the PSE's required habitable volume. The 15 m^2 solar array and Li-Ion batteries will provide 6 kW, which is enough to power the main power users, with some spare power for miscellaneous operations, like scientific experiments. We assume that any solar panel degradation is negligible throughout the trip. The power budget is presented in Table 6.24.



Component	Power (W)
ECLSS and Communications	4000
Solar Arrays	3000
Li Ion Batteries	3000

Figure 6.24: ECLSS power budget.

6.4.4.5 *Propulsion*

The PSE propulsion system consists of a LOX/Methane engine baselined against the SpaceX Raptor LOX/Methane engine sized comparatively against the Merlin 1D engines currently in production. Specific impulse for the engine has been estimated at 380s with a 24 kN thrust. Propellant tank estimates were calculated using [22] for the low ΔV maneuver the PSE stage would have to complete after undocking with the DSV in Phobos orbit. The PSE propulsion stage for breaking Phobos orbit and safely transporting the crew and landing permanently on the Phobos surface was sized to achieve a ΔV of 0.5 km/s. This is an overestimate using [23] as a reference for similar ΔV maneuvers for landing on Near Earth Asteroids. With the LOX/Methane burn, the PSE propulsion system includes an estimated 200 m/s margin built in for deviations which may be made in the astronauts controlled landing.

6.4.4.6 *Structural Design and Layout*

The PSE vehicle is a 2-stage SEV shown below. The back section (PSE - Hab) is the habitable section that will be left behind on the surface of Phobos as a base, while the front section (PSE - Separator or PSEP). The PSEP has 3 arms for robotic exploration and an exterior compartment to collect samples if this is the method desired, while the PSE-Hab has 4 robotic arms for clamping down permanently onto the surface of Phobos. These arms will most likely require drills in order to get a firm hold of the regolith. The PSEP also has 2 suit ports for EVA within close proximity of the vehicle to retrieve samples (and put them into the airlock compartment), while the P-HAB has a docking ring either on the side for access to the rest of the DSV, and a port for Robonaut, or other robotic tools. All of these features enable the full extent of exploration, and also establishes permanent infrastructure on Phobos.

6.4.4.7 Thermal Control

As happened with the Deep Space Habitat, the same considerations were used to find a first approximation of the thermal control mass. Once again, this mass was diluted in the wet systems mass. Enough margin was provided to allow changes during the critical design phase of this vehicle.

For this vehicle some power will be generated by the solar panels, but most of it will have to be provided by batteries, fuel cells or other means still to be developed. The believe is that, the power required by the thermal control system will be less than 0.5 kW and so, no constraints shall arise given the allocated power budgets and the current state-of-the-art in terms of power generators.

6.5 Robotic Assistance

6.5.1 Goals

Rovers deployed on the surface of Phobos during the mission will fulfill the following roles:

- Scout other sites while the astronauts are at the first site.
- Retrieve of samples from areas inaccessible to the astronauts in the PSE.
- Provide more vision to the astronauts on the ground when accompanying them to sites.
- Allow for testing of new robotic technology which is designed to operate in milli-gravity environments and difficult terrain.

6.5.2 Robot Overview

6.5.2.1 Design

A robotic design proposed in [24] will be adapted for the mission requirements. The original design envisages a mother spacecraft ("Phobos Surveyor") which deploys a number of rovers or "Phobots" to the surface while orbiting Phobos. A graphical depiction of the proposed mission architecture is provided in Fig. 6.25. 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/hour.

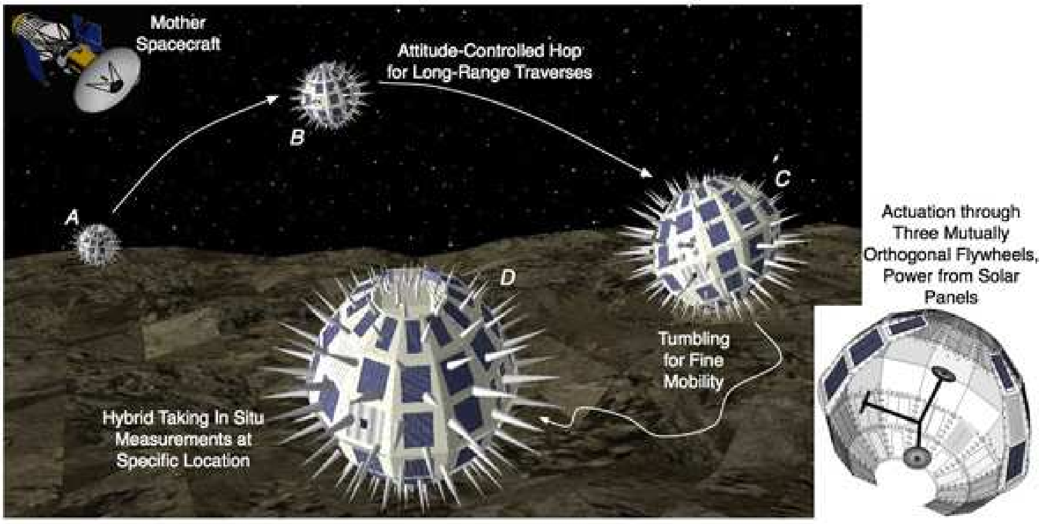


Figure 6.25: The mission architecture of the "hedgehog" robots [24]. A mother spacecraft can deploy several robots, which can then be sent to various sites on the ground.

6.5.2.2 Instruments

On-board instruments will include:

- stereo-vision camera with multispectral filters
- microscope
- Raman/LIBS spectrometer
- neutron spectrometer
- visible/near-infrared spectrometer

To ensure a maximum mass of 10 kg per Phobot, the instruments will be distributed evenly amongst the individual robots.

6.5.2.3 Operation

The robots can act as Mobile Science Platforms (MSP) or scouts, close to or far from the astronauts on the ground. Two operation modes will be used. In the first mode, the robots accompany the astronauts in the PSEP, acting as scouts by providing a better vision of the terrain ahead of the astronauts. They will also provide better maneuverability for samples which 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 key sample collection areas.

6.6 ECLSS

ECLSS maintains a habitable environment within the spacecraft. This system is a closed loop where some of the consumables are recycled to conserve mass. The ELISSA (Environment for Life Support System Simulation and Analysis) software was used to simulate this life support closed loop system in the Deep Space Habitat (DSH) for a 443 day long duration mission to Phobos. The final mission duration is 456 days, but these results can be easily extrapolated the next 13 days. This software was developed at the Institute of Space Systems, University of Stuttgart. Several iterations were performed to obtain and develop the optimal amount of hardware and consumables. Figure 6.26 shows the ECLSS architecture chosen for the Deep Space Habitat (DSH).

The simulation was based on a crew of 4 astronauts living in the DSH for a total mission duration of 443 days in a habitable volume of 180 m^3. This simulation was conservative because for 30 days two astronauts will leave the DSH to explore the surface of Phobos.

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. ELISSA integrated four subsystem including air, water management, food, and waste management. The technologies are reliable and the Technology Readiness Levels (TRL) is provided below [25].

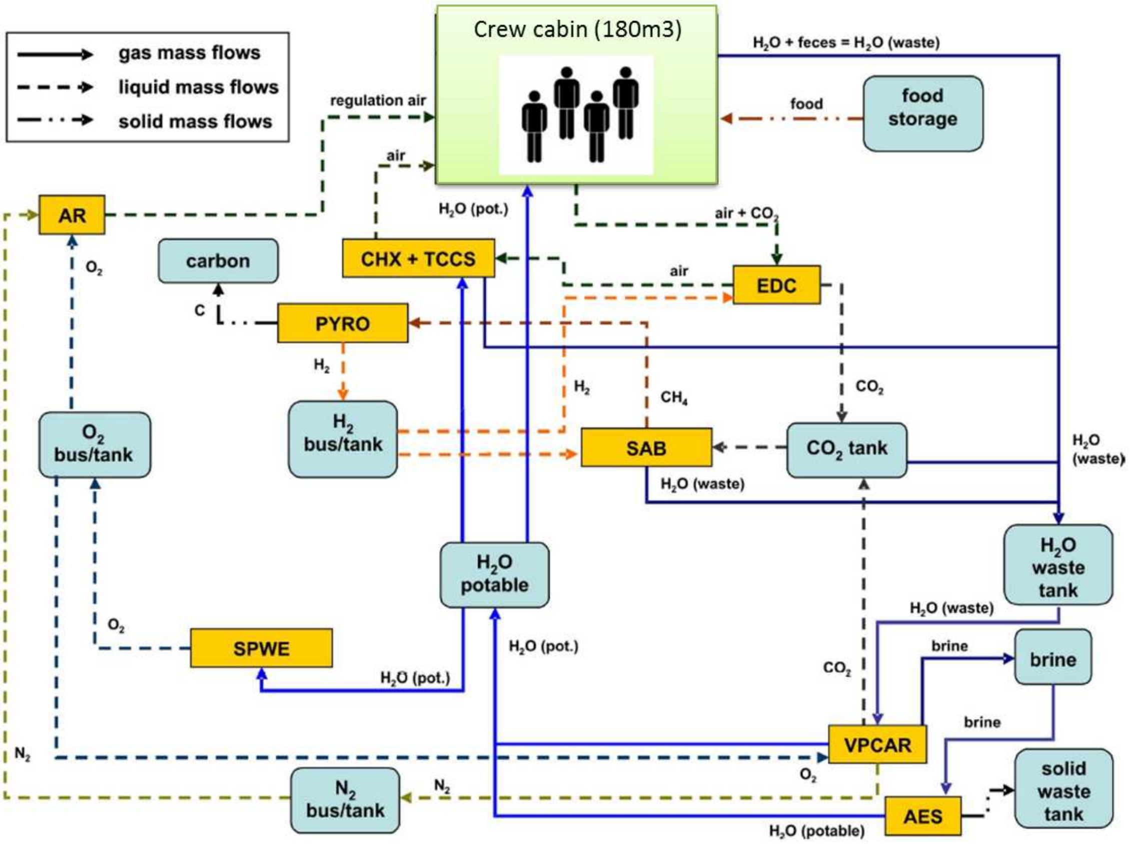


Figure 6.26: ECLSS Architecture.

- Air
  - O_2 generation: 3 Static Feed Water Electrolysis (SFWE)
    - 3 kg/day per unit
    - TRL = 8
  - CO_2 Removal: 2 Electrochemical Depolarized Concentrator (EDC)
    - TRL = 6
  - 2 Trace Contaminant Control (TCC)
    - TRL = 8
  - Heat Exchanger (CHX)
    - TRL = 8
- Water Management
  - Regeneration by 2 VPCAR to produce potable water
    - 250 kg/day per unit
    - TRL = 6

  - Urine treatment: 2 Air Evaporation System (AES)
    - TRL = 3

- Food
  - 1200 kg of dehydrated food
  - Maximum intake per person = 0.56 kg/day

- Waste Management
  - CO_2 Reduction: 2 Sabatier Reactors that convert O2 to CH4 and H2O (CO2 + 4H2 - CH4 + 2H2O)
  - CHF Reduction: 2 Pyrolysis units (it splits CHF into C and H2)
    - TRL = 4

The total mass estimation of the 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. Table 6.2 shows the mass characteristics of the LSS system.

Tanks and Products			**Initial Mass (kg)**
Total empty mass			3419.3
N2			500
O2			400
H2			300
H20			600
Food			1200
Hardware	**Mass (kg) per unit**	**Number of Units**	**Mass (kg)**
EDC	44	3	132
SFWE	100	3	300
TCC	100	1	100
VPCAR	283	2	566
AES	178	1	178
Sabatier	43	2	86
Pyrolysis	154	2	308
		Total Mass	8089.3

Table 6.2: Mass values of the different parts of the LSS.

The graphic below shows the evolution of the major LSS factors during the Phobos mission. These are the O_2, CO_2, H_2O and food masses, amongst others, 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. In addition, the simulation has been done taking into account a adequate astronaut comfort level. These results leave margin to reduce consumption of resources in emergency situation. For example, laundry could be potentially suppressed, reducing in 12 kg/day per astronauts the H_2O consumption.

The evolution of the major LSS factors during the Phobos mission are shown in Fig. 6.27. Figures 6.28 and 6.29 include, for reference, the evolution of other ECLSS parameters during the space mission.

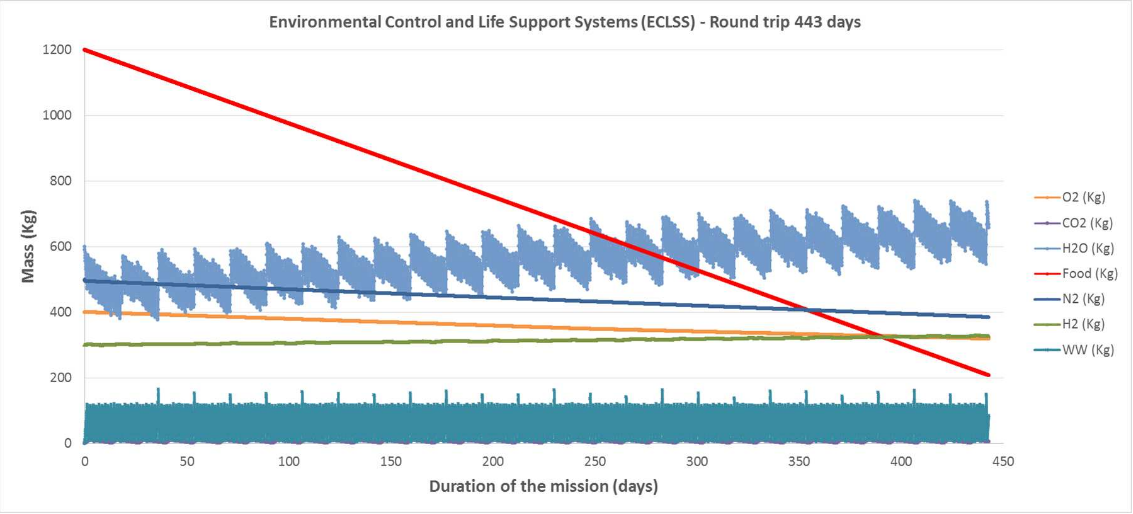


Figure 6.27: Evolution of Deep Space Habitat (DSH) ECLSS parameters during the round trip mission (443 days). This simulation takes into account the conservative approach of 4 astronauts in the DSH during the whole duration.

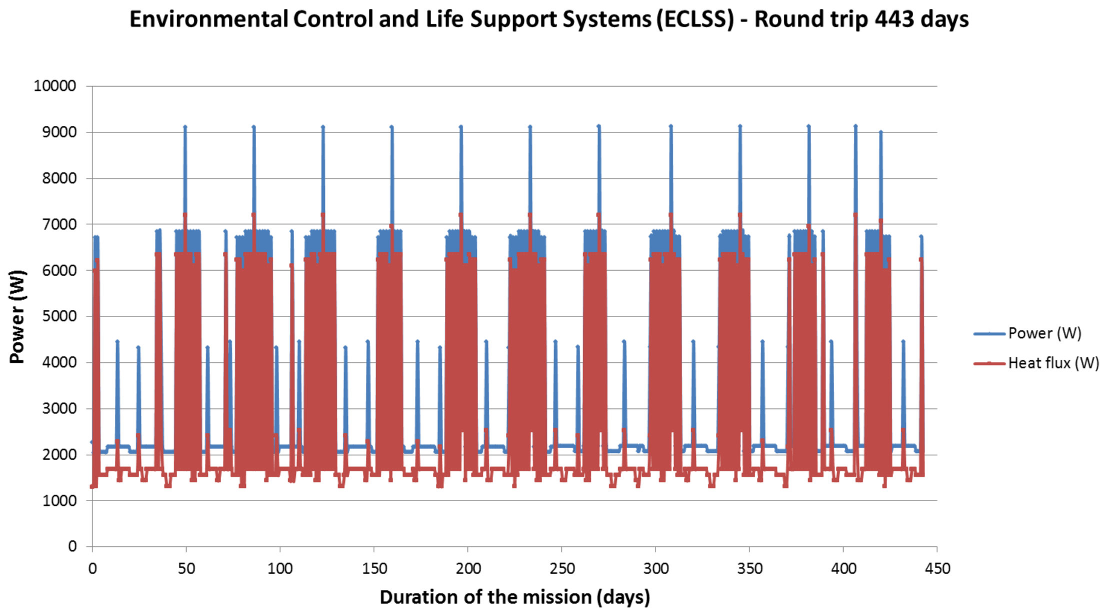


Figure 6.28: Evolution of Deep Space Habitat (DSH) ECLSS power parameters during the round trip mission (443 days).

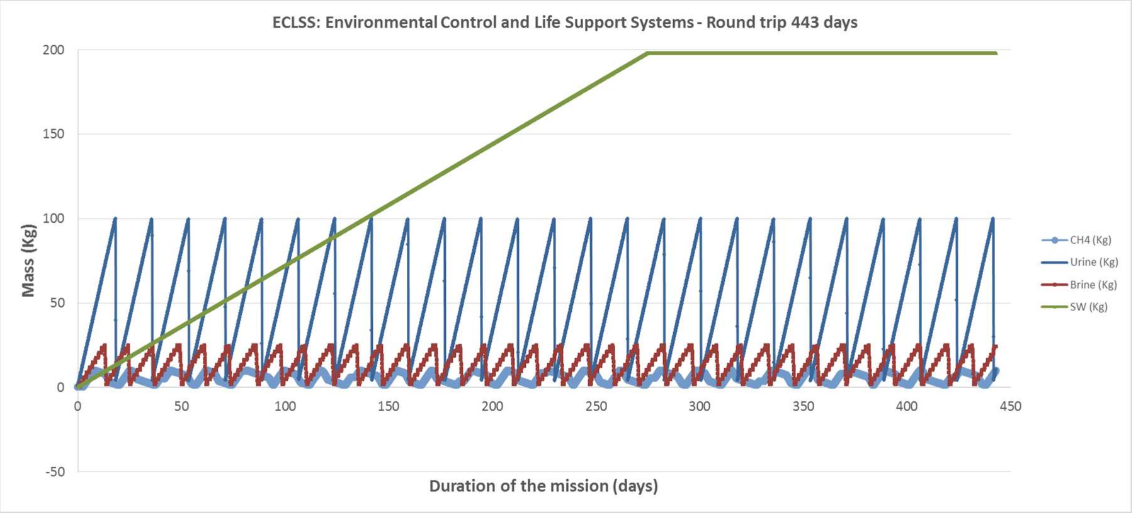


Figure 6.29: Evolution of Deep Space Habitat (DSH) ECLSS waste parameters during the round trip mission (443 days). The solid wasted reached the maximum capacity of the tank (200 kg)

6.7 Risk Analysis and Mitigation

The risk analysis of the TAPER mission lists the possible contingencies that are critical to the success of the mission and the mitigation strategies that will be used to prevent, to the highest extent possible, these risks leading to mission failure (see Table 6.3).

#	Item	Risk and Mitigation Strategy	Impact	Prob.	Risk
1	Risk	Loss of sample containment	3	2	6
	Strategy	System redundancy / multiple samples			
2	Risk	Phobots miss	2	2	4
	Strategy	Ensuring criteria for release			
3	Risk	Rover mobility failure	2	2	4
	Strategy	Robotic exploration capabilities			
4	Risk	Imperfect trajectory maneuvers	4	1	4
	Strategy	Ensuring sufficient margin in course planning			
5	Risk	Radiation and microgravity impacts on crew (chronic)	3	3	9
	Strategy	Shielding and countermeasures			
6	Risk	ECLSS failure	5	1	5
	Strategy	Redundancy			
7	Risk	Decompression sickness / EVA failures	5	2	10
	Strategy	Proper EVA protocol			
8	Risk	Medical emergencies	5	2	10
	Strategy	Crew training, medical supplies, and surgical suite			
9	Risk	Failed in space rendezvous (Earth proximity)	4	2	8
	Strategy	Abort capabilities to earth			
10	Risk	Structural failure of crew habitat	5	2	10
	Strategy	Prior demonstration of technology and testing			

Table 6.3: List of Key Mission Risks and Mitigation

From this list, a risk matrix shown in Fig. 6.30 can be developed to visually represent the severity and likelihood of risks that could impact the success of the mission.

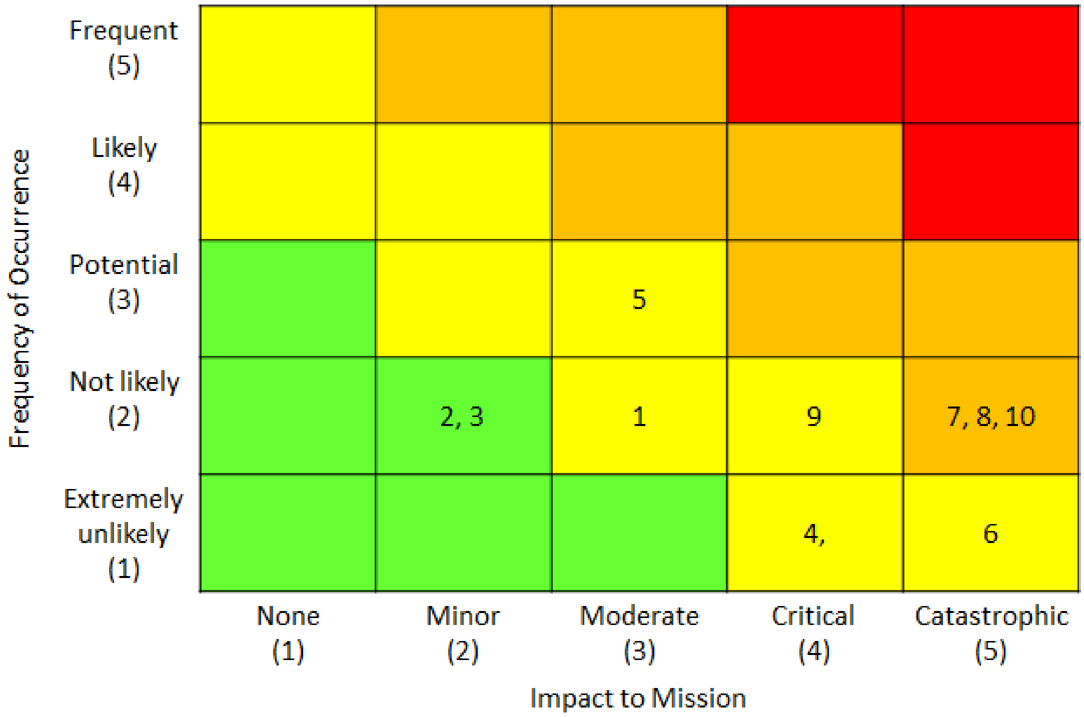


Figure 6.30: Risk Matrix

6.7.1 Design Margins and Safety Factors

The TAPER mission was designed accounting for design uncertainties and possible future changes. Changes in component masses as well as launch windows were considered. Launch vehicle subsystems were over designed with a 10% margin. This consideration allocates comfortable mass change possibilities, a trade-off between subsystems, as well as vehicles can be performed in the critical design phase. The propulsion subsystem was designed to a more restrictive 2035 launch window to enable mission success in the event of missing the preferred 2033 launch. Propulsion margins were also included by designing with an additional 5% on all ΔV requirements which should allow for a maximum of a 2035 launch with an additional 2 week launch margin.

7 Human Factors

During a long duration crewed spaceflight human factors must be considered because seemingly minor issues will be compounded by the mission. The following factors will be considered: radiation protection, crew size and selection, habitat design, psychological and psychological effects of deep spaceflight, and Environmental Control and Life Support Systems (ECLSS).

7.1 Crew Size and Selection

During the design of a crewed spaceflight mission, it is vital to consider the safety, comfort, and operational ability of the personnel involved. For a crewed to the martian system several human factors will have to be considered including: radiation protection, crew size and selection, habitat design, psychological and psychological effects of deep spaceflight, and Environmental Control and Life Support Systems (ECLSS).

The crew size for the Phobos mission will include four astronauts, including two male and two females. Previous studies suggested an odd crew size to avoid decision making problems, an even crew size has been finally selected primarily because of mass constraints. In addition, it has also been suggested that four crew members is desirable over three, in order to minimize psychological issues derived from such a small number of astronauts.

The crew will have a very clear hierarchy structure to avoid decision making issues. The suggested roles for the crew are:

- Chief commander (ideally a pilot)
- Flight surgeon
- Mission specialist (ideally a geologist)
- Mission Engineer

A critical aspect of the mission includes selecting candidates that will be able to handle the high stress, risk, and confined isolation that is inherent with a long duration space mission. Studies have been conducted to screen for the candidates that will successfully meet mission goals. A mixed crew was chosen because Antarctic studies have shown that women can increase the productivity and mood of the environment [26]. Screening will be based on physiological, psychological, and genetic tests.

7.1.1 Physiological Tests

Table 7.1 lists the diagnostic tests that will be conducted to assess the overall health and disorders that may contribute to mission failure.

Physiological Subsystem	**Associated Tests**
Cardiovascular	Electrocardiogram Blood pressure Echocardiogram Aerobic Capacity
Musculoskeletal	Muscle Mass Anthropometric measurements Bone Mineral Density
Reproduction	Pap Smear and Pelvic Exam
Auditory	Audiometry
Visual	Color and depth perceptron Ophthalmological evaluation Visual acuity, refraction and accommodation Tonomer
Dental Assessment	Dental examination Orthopantogram
Diagnostic Imaging Test	Chest X-ray Mammography Abdominal ultrasonography
Renal	Serology Urinalysis Renal stone profile Hemogram
Pre-emptive surgery	Appendectomy Cholecystectomy

Table 7.1: Selection criteria for astronauts [27].

7.1.2 Genetic Tests

The gene Schizosaccharomyces pombe Rad9 (HRAD9) gene was identified as a gene that increases the ionizing radiation (IR) tolerance by initiating a cascade that repairs cellular damage. Additionally, the crewmembers will be screened for future diseases to prevent an episode occurring en route to Phobos.

7.1.3 Psychological Tests

Individuals must be psychologically stable to ensure that they will function optimally under critical situations. The candidates will be screened for the numerous psychological disorders that relate to spaceflight listed in the Psychiatric Diagnostic and Statistical Manual IV [28]. Analog studies have shown that the crewmembers will mostly likely experience anxiety [29]. However, it is imperative that the anxiety will not affect the crewmembers performance. Thus, individuals with anxiety disorders will be screened out. A disorder unique to human spaceflight includes neurasthenia, which is marked by weakness, fatigue, increased irritability, and reduced cognitive function [30]. Candidates will be screened out if tests are conducive with the diagnostic criteria.

Once candidates are screen out, the remaining candidates will be assessed for traits that are common amongst successful astronauts, such as "social compatibility, emotional control, patience, tolerance, self-confidence, flexible, subordination, and a sense of humor" [30]. A committee of experienced astronauts will carefully examine the applications and, after several rounds, 100 candidates will be initially selected. Next, to further reduce the candidate pool, extensive physiological tests will be conducted (Section 7.3). The remaining candidates will be examined under analog situations, such as Antarctica or an underwater habitat. The group dynamics will be assessed and the candidates will be able to rate each other indicating who they would enjoy working with the most. That group dynamics will be examined and the best functioning group with the corresponding skill set will be selected.

7.2 Radiation Protection

Ionizing radiation is the primary concern for humans during long duration space missions [30]. To mitigate the acute and long term effects of radiation the dose shall not exceed the 3% fatal cancer risk [31]. Several considerations were taken to reduce the cumulative galactic cosmic ray (GCR) and solar particle event (SPE) radiation doses. Based on calculations performed by Cucinotta, the maximum number of days a male can stay in space is approximately 526 days and females can stay a maximum of 394 days based on the following assumptions:

- 20 g/cm^3 of aluminum shielding
- Storm shelter for a SPE
- Dosimeters will be placed through the cabin

Several considerations were taken to reduce the cumulative galactic cosmic ray (GCR) and solar particle event (SPE) radiation doses. To minimize the radiation dose, a low-z material called Vectran will be used as the structural material. It is produced by "polycondensation of a 4-hydroxybenzoid acid and 6-hydroxynaphthalene-2-carboxyl acid" [32], and studies have shown that it can shield against MMOD and is UV stable. With a structure designed to have a thickness of at least 20 g/cm^3, the maximum number of days in space can be extended by roughly 10% as extrapolated from comparisons of shielding effects of aluminum versus polyethylene materials [31]. Further, assuming adequate shielding in astronaut habitations on Phobos and noting that shielding from Phobos itself will reduce the radiation exposure angle from roughly 2π to π, one might estimate that radiation will be roughly cut in half while on the moon.

This results in a maximum number of days in space of 579 days for males (if the above assumptions are included) and 433 days for females. Hence, if we assume that females perform EVA activities on the surface of Mars moon, they will be below the 3% excess cancer risk for a total mission duration of 443 days in space [31].

In order to provide countermeasures for radiation damage, the human spacecrafts will have shielding in addition to that built into structural material. Passive shielding materials to be added including water and liquid hydrogen. An integrated ECLSS and structure system could be combined in order to keep the water and liquid hydrogen surrounding the walls of the spacecraft. In addition, active shielding such as the creation of a magnetic field to deflect the radiation could be also implemented. Further research need to be conducted to develop this concept, but it is a promising solution for the proposed mission to Phobos in 2033. Another countermeasure against radiation are antioxidants. They help minimize radiation damage, repairing them chemically. Astronauts will include antioxidants in their diet such as cysteine, glutathione, vitamin C, vitamin E, selenium amongst other [30].

Enroute to Mars several technologies will be tested for future radiation protection. One of which includes the byproducts of the photobioreactor. The photobioreactor for algae cultivation (PBR) produces edible biomass and oxygen by consuming carbon dioxide, water, and nutrients citesynergetic-hybrid-lss. This algae will be used to break down human biological waste products and experiments will be conducted to assess the potential use for radiation protection.

7.3 Physiology

In long duration space missions the human body undergoes many changes due to the microgravity conditions, some of which include bone loss, muscle atrophy, orthostatic intolerance, motion sickness, and neurovestibular effects [30]. Figure 7.1 shows some of the effects of long duration spaceflight on the human body and their evolution during six months of microgravity.

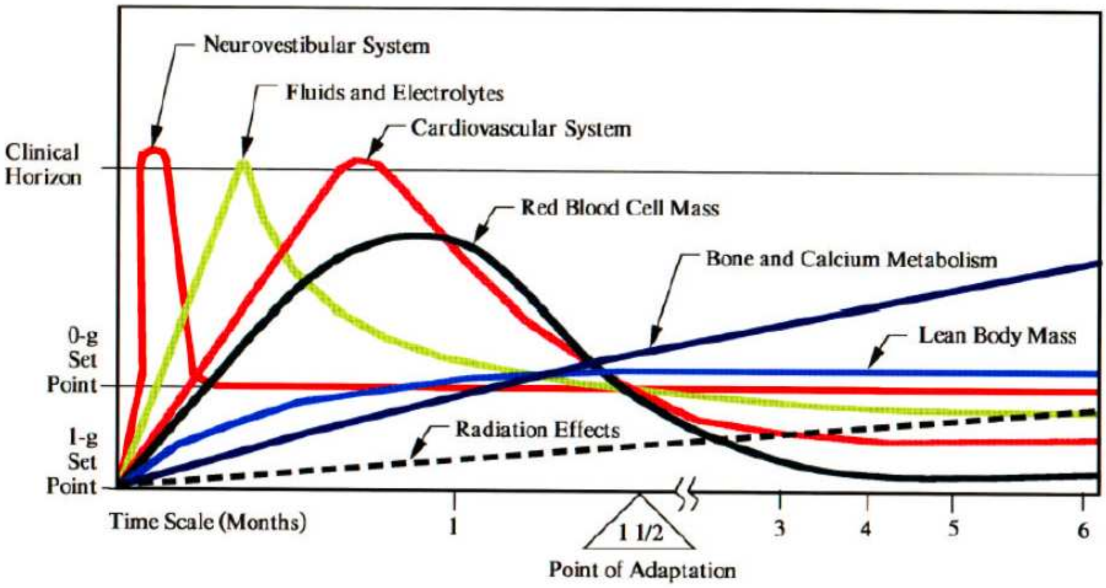


Figure 7.1: Evolution of some of the effects of long duration spaceflight.

Bone loss is perhaps one of the most important physiological deconditioning that occurs during spaceflight. It occurs primarily because of the absence of skeletal loading in microgravity [30, 33, 34]. Bone loss usually begins at the lumbar spine and becomes greater in the lower extremities. These results are explained by the fact that astronauts use their upper limbs to move around the spacecraft, and their lower extremities for stabilization. Other factors that affect the skeleton properties are low light levels, high concentration of CO_2, dietary factors (calcium and vitamin D), and genetic factors. In addition, skeletal unloading conditions led to a significant loss of calcium in the bones and a substantial increase in the risk of kidney stone formation [30, 33]. Figure 7.2 shows an overview of bone loss in space.

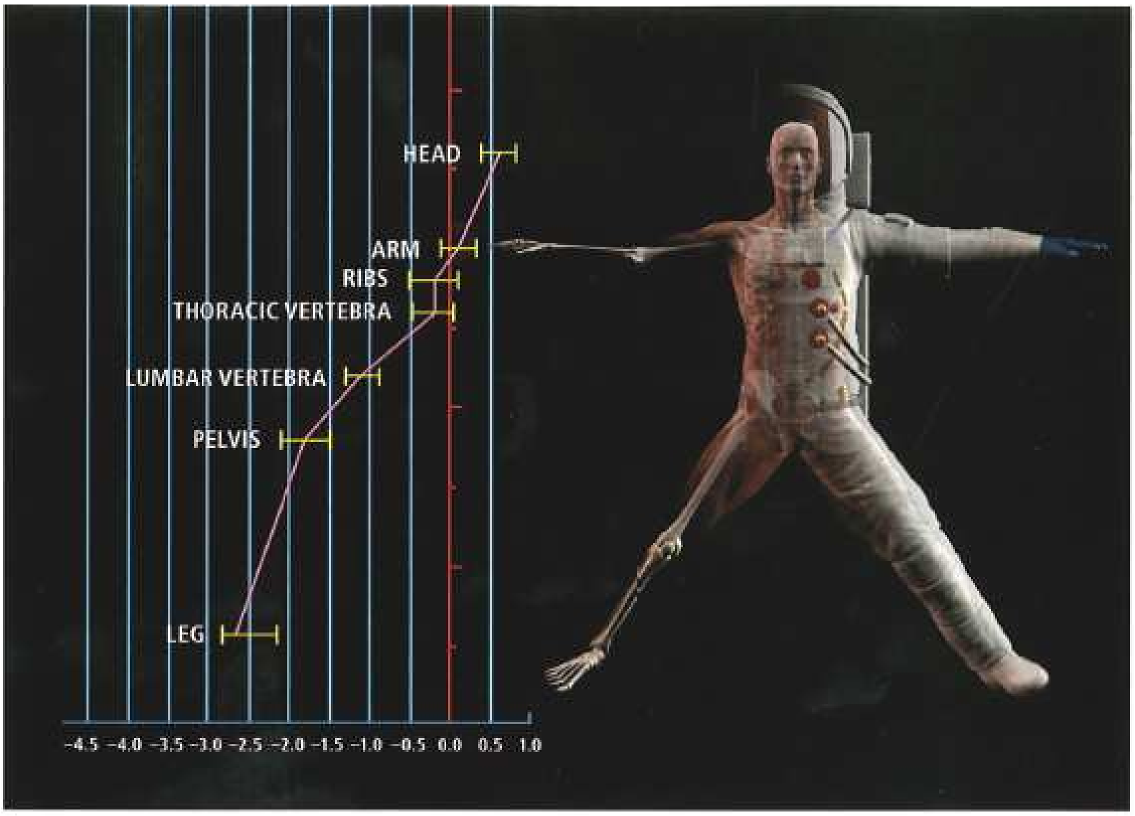


Figure 7.2: T-scores obtained from dual energy x-ray absorptiometry scans. A score above -1 is considered normal. A score below -2.5 is defined as osteoporosis.

Muscles are also highly affected by microgravity, in particular the antigravity muscles. These are the muscles 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 and -19.6% for the soleus [30]. Muscles also lose mass and strength. Muscle atrophy is caused by two major factors : the lack of activity that decrease the protein synthesis, and inadequate caloric intake. Other factors include oxidative stress (balance between oxidants and antioxidants) and hormonal influences. The effects of muscle have been studied extensively on Earth using bed rest studies. However, muscle loses seen in space are much greater than expected based on bed rest studies [30].

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 cause by conflicting cues provided by the vestibular system and other sensory senses [30].

7.3.1 Countermeasures

Bone remodeling is highly dependent on the mechanical loading applied on the skeleton [35, 36]. Two types of mechanical loading can be distinguished: static loading and dynamic loading. A clear example of static loading is the gravity force. People on Earth are continuously subjected to the gravity force, and this gravitational acceleration has an important role in skeleton remodeling. On the other hand, dynamic loading may include short periods of high-impact peak loads (such as ground reaction forces while running or jumping) or frequent low-level loading (such as low frequency vibration). Lastly, muscle contraction also plays an important role in skeleton loading [33, 34, 35, 36]. The muscle forces developed to move the limbs in 1G contribute to bone remodeling. In weightlessness conditions, skeleton mechanical loading is highly reduced because of the absence of gravity and ground reaction forces, and also the significant reduction of muscle forces generated to move in space, especially in the lower limbs [30, 33].

The Deep Space Habitat will 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, an cyclometer could be included in the centrifuge to improve the aerobic capacity and cardiovascular effects of astronauts (see Fig. 7.3). This design presents some engineering challenges (TRL 2/3) such as shock and vibration absorption on board, but this problem will likely be resolved within the next 20 years.

The Deep Space Habitat will also include a treadmill and a resistance device similar to the Advanced Resistive Exercise Device (ARED) exercise machine currently used in the International Space Station. 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 include Intravehicular Activity (IVA) concepts providing continuous loading or resistance on the human body. Exoskeletons can provide continuous resistance to the wearer in order to improve muscle atrophy. The Grav-

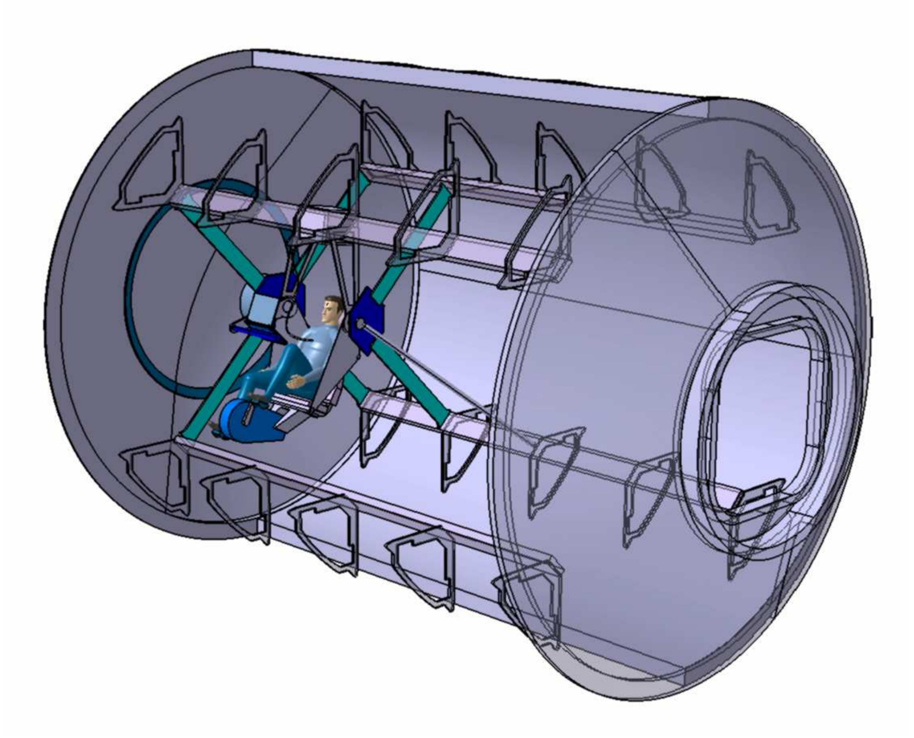


Figure 7.3: Short radius centrifuge concept combined with exercise in the Deep Space Habitat.

ity 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 (see Fig. 7.4). In addition, the GLCS will be combined with current exercise countermeasures devices to improve the dynamic loading generated while exercising. The GLCS gradually increase the loading in the z axis, from the upper torso to the feet. It provides a low circumferential tension to avoid suit slippage. The GLCS contains bands to produce several vertical stages. Each of these stages produces a slightly different vertical loading that increases from the torso to the feet. These concepts are in TRL 2/3 and will likely be ready within the next 20 years.

Finally, astronauts will 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 will be carefully monitored in order to personalize and adjust the countermeasure program for each one of the astronauts. Monitored parameters will include weight, anthropometric measurements (leg volume, calf circumference), urinary calcium excretion and serum levels, and cardiac activity [30].

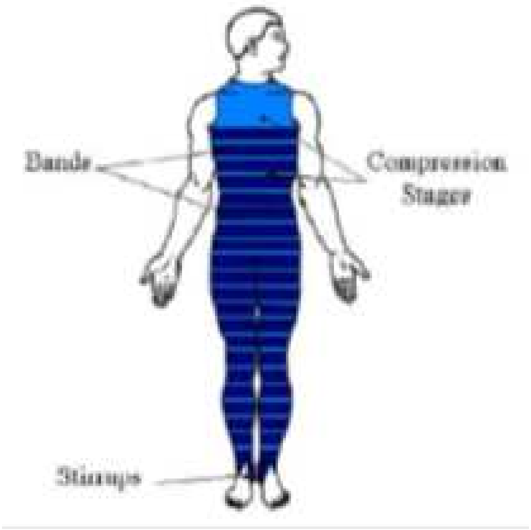


Figure 7.4: Conceptual design of the GLCS [33]

7.4 Clinical Medicine

Medical care and contingency procedures must be established to maintain crew health during a long duration space mission. Currently the International Space Station has a Crew Health Care System (CHECS) which contains a non-emergency medicine, non-emergency hardware, and emergency medication and hardware as depicted in Fig. 7.5.

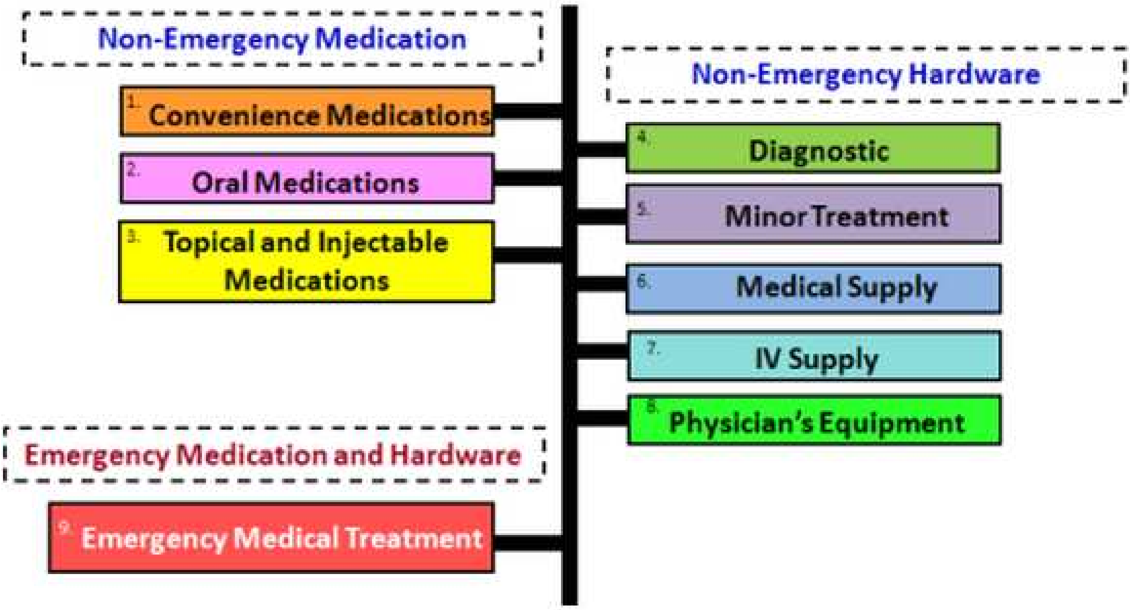


Figure 7.5: CHECS system currently on the ISS.

For a long duration mission inherent risk is assumed and, due to mass, volume, and power restrictions,only a limited amount of supplies can be taken. In order to optimize the medical system, the estimated risk and probability of mission abort was estimated based on previous studies.

A study conducted by the Advanced Research in Space Medicine I and II [37] calculated the estimated space incidence per man-year physiological contingencies during transfer and Mars surface exploration. The highest risk and incidence disorders are listed in Table 7.2.

Physiological Disorder	**Incidence (%)**	**Mission Abor.**	**Countermeasure**
Infectious Diseases	0.01	0.005	Antibiotics
Mental Disorders	0.07	0.003	See Section XX
Eye Related Disorders	0.04	0.003	Tonometer and virtual eye chart
Cardiovascular Disease	0.01	0.002	Emergency Pack, 3D printer, and surgical suite
Acute respiratory infections	0.01	0.004	Decongestants and antibiotics
Dental diseases	0.01	0.005	3D printer and surgical suite
Cystitis	0.9	0.005	Urine tests (Diagnostic Pack)
Fractures	0.02	0.005	
Open Wounds	0.01	0.002	First Aid Pack
Space Motion Sickness	4	0.001	First Aid Pack

Table 7.2: Highest risk and incidence disorders.

A basic first aid kit will contain bandages, wraps, topicals, decongestants, antibiotics, and diagnostic hardware. The diagnostic hardware will be comparable to instruments found in a doctors office. It will be used to assess the health of the crewmember throughout the length of the mission. Data will be recorded and analyzed by the astronauts during transit. The emergency medical pack derived items comparable to those used by paramedics in an emergency scenario. Items will include emergency shears, epipen, AMBU bag, and alcohol wipes.

To extend the shelf-life of medications the enclosing medical pack will be covered with a lightweight low-z material such as polyethylene [38].

7.4.1 Telemedicine

The clinical medicine aboard this mission will account for the most common incidents and highest severity contingencies. The diseases that fall between those spectrums will be analyzed and treated via telemedicine. The goal is to have the crew able to diagnose themselves, analyze the symptoms, and use the necessary materials to regain optimal health. A touch screen tablet will be able to wirelessly communicate with sensors that provide biological data preloaded with a program that compares it against symptoms. After a proper diagnosis is confirmed, the device will provide step by step directions that show the crewmember how to carefully execute the necessary protocol.

7.4.2 3D Metal Printing

Over the past decade this technology has rapidly progressed to the point that aluminum can be printed in 3D [39]. Traditional 3D printers use spray welding, a powdered dispenser, and torch that melts the powder into the specified configuration. To use this technology with metals the torch was replaced with a laser and it is currently in market.

Instead of bringing all the surgical hardware or extra hardware tools, a 3D metal printer will be flown. Leftover aluminum wrappers from the food will be ground to a fine powder and be fed into the 3D printer. Tools will then be constructed as needed.

7.4.3 Surgical Suite

To maintain a sterile surgical environment while reducing the mass and radiofrequency interferences, a large inflatable environment will be provided. The hands, feet, and wrist of the “surgeon” will be restrained and the hands will be inserted through sterile ports. A magnetic tray will be contained within the inflatable surgical station and will be used to retain the instruments in microgravity [40]. Laminar flow will be emitted throughout the station to carry away escaping fluids and surgical debris. Figure 7.6 shows an inflatable surgical suite, which provides a sterile environment and has a magnetic tray to restrain instruments and provides laminar flow to drive away impurities [40].

Figure 7.6: Inflatable surgical suite that provides a sterile environment and has a magnetic tray to restrain instruments and provides laminar flow to drive away impurities [40].

7.4.4 Psychology

Astronauts show a low incidence of debilitating illnesses because they are highly trained and are screened for disorders. However, analog studies show that spending a long duration of time in a confined area may lead to interpersonal conflicts, sleep disturbances, boredom, performance decrement, and decline in group compatibility [41] (see Table 7.3).

Reported Problems	**Documented**	**Shuttle**	**Submarines**	**Polar Expeditions**
Interpersonal Conflicts	Documented	Documented	Documented	Documented
Sleep Disturbances	Documented	Documented	Documented	Documented
Boredom, Restless	Anecdotal		Documented	Documented
Performance Decrement	Anecdotal		Documented	Documented
Decline in Group Compatibility	Anecdotal	Anecdotal	Anecdotal	Documented
Substance Abuse	Anecdotal			Documented

Table 7.3: Psychological issues associated with spending long durations in confined locations [41].

To prevent interpersonal conflicts the crew will be trained on how to approach conflict. The approach includes becoming aware of their emotional triggers and avoiding the emotional triggers of their crewmates. Conflicts should also be resolved in a manner where each party gains something. Tablets will be used as an aid for conflict resolution by providing the crewmember with suggestions on conflict resolution.

It is imperative that the crewmembers obtain sufficient sleep, otherwise it will contribute to psychological problems. Drugs, such as ambien and benadryl, can be used as a temporary solution but should be used seldomly otherwise it will result in drug dependency.

To combat against boredom several innovative technologies will be provided to the crewmembers. Tablets will be used to provide recreational reading, video games, and skill training. Skill training includes having each crewmember develop a new skill via virtual technology, which includes earning a new language, virtual piano, or engineering projects. Virtual reality will also be provided to the crewmembers. The Family Support Office at JSC will be used to develop interpersonal dynamics between the crewmember and their family. Digital picture albums will be provided and the family will be briefed on the status of the crewmember. Additional tasks performed by the crewmember will include a virtual journal, outreach activities, and science experiments (refer to appropriate section).

Lastly, to maintain group dynamics a common dining area will be provided for the crew and a personal space will be designed in the habitat. Crewmembers will be able to post pictures of their family or personal memorability in their personal space.

To help the crew maintain an Earth based connection when they are out of sight from the Earth virtual reality will be incorporated. The Johnson Space Center (JSC) a Virtual Reality Lab is dedicated to developing real-time graphics and motion simulators that permit the individual to experience mass and inertia. This technology will be incorporated in the DSH and the crewmember will be allowed to choose from a variety of Earth-based scenarios. These virtual reality scenarios will provide a Earth-based connection that reminds the crewmember of the importance of the mission.

8 Programmatic Considerations

8.1 Costing

Costing human exploration missions to Mars is not a trivial undertaking. Estimates in literature range from the low tens of billions up to $500 billion or even $1 trillion for very conservative studies. This is due to the large number of uncertainties in the development of a key number of enabling technologies. Therefore it not possible to provide an accurate total cost estimate within the scope of this study, however key cost drivers can be identified.

Development of the Pebble Bed Reactor type Nuclear Thermal Rocket poses a significant expense, with estimates of $4 billion for development of the Nuclear Cryogenic Propulsion Stage (NCPS) which encompasses development of the simple solid core reactor type. Therefore it can be assumed that development of Pebble Bed Reactor type will be at least equivalent, likely more. Another key cost driver is that of the development of composite cryogenic, zero-boil off fuel tanks. Estimate for this do not exist currently, but it will be significant.

Finally, the utilisation of the Space Launch System poses significant expense, with cost estimates of $2.5 billion per launch [4], and subsequently total cost of upwards of $10 billion for the mission.

8.2 Risk

The size and scope of the TAPER mission is by no means minimal. In a mission of this magnitude there is programmatic risk from budgetary constraints and contractual contributions by the key partners. The mission has been designed to fit within a larger vision for space exploration, as laid out by the Global Exploration Roadmap, in an effort to prevent against the loss of international contributions. The participation of international partners serves as a mitigation strategy for funding cuts by any one nation as it is more difficult for a nation to pull out of an international obligation. Through these efforts the TAPER mission will prevent against, to the programs fullest capability, the descoping or possible cancellation of the mission.

8.2.1 Descope Options

If, for whatever reason, the TAPER mission is found to be infeasible, possible descope options include:

- Use of mission knowledge and hardware for a mission to a NEA;
- The use of precursor science data for future missions to the martian system;
- Benefit of technology development for future missions and industry partners;
- Lessons learned from design and development of mission.

8.3 Political Sustainability

The long schedule cycle for this mission that encompasses many political cycles, and it is important to address the aspect of political sustainability, and how it can be insulated from policy fluctuations. Pragmatic, flexible approaches are required when it comes to budgeting and schedule to ensure that changes in funding levels are accompanied.

The introduction of international cooperation to share the cost of the endeavour also creates obligations between the partners that make it harder for a program or mission to be cancelled. This has had a positive effect on the political sustainability of the International Space Station program, and would likewise do so for the the TAPER mission.

8.4 Planetary Protection

Planetary protection considerations are an important factor in this mission primarily due to the proximity of Phobos to Mars. Phobos itself is not classified as a body suitable of sustaining life, however as outlined earlier in this proposal there is the possibility of ejected material from Mars impacting or accreting onto the surface of Phobos leads to a Category 5 classification for Phobos.

Therefore, with regards to forward contamination, Phobos has the classification of Category 2, requiring only basic cleanliness on exterior of spacecraft elements, However the prospect of EVAs adds complexity to the planetary protection considerations. Suitports will be required to eliminate the possibility of contact between the astronauts and the exterior of the spacesuits, and subsequently indirect with Phobos. One further consideration with regards to forward contamination is the requirement to ensure that any spacecraft hardware does not enter the martian atmosphere (>99% certainty within 20 years, >95% certainty within 50 years). Due to the high altitude orbits of this mission around Mars (>9000 km) this does not cause a problem.

Backwards contamination mitigation poses a much larger problem in the context of this mission. No surface that has been exposed to Phobos material can be exposed to either the Astronauts or the Earth environment. This poses very strict requirements on EVA and sample collection processes. Requiring the use of suitports and associated EVA suits and specialist double layer sample containers.

8.5 Public Relations and Outreach

As the TAPER mission is at an international scale, a plan to reach and engage the public is vital to the missions success. It is expected that the key players in the TAPER mission will already be participating in strong outreach in accordance with what is typical for space programs and aerospace companies today. Below are specific outreach concepts that take advantage of the unique opportunities the TAPER mission provides.

8.5.1 International CubeSat Design Competition

Five 3U CubeSats are required for the Deimos flyby aspect of the mission. As university-development of flight-ready CubeSats is growing exponentially, an international competition is proposed to challenge schools and universities to develop the CubeSats required for the mission. This challenge would be similar in scope to other competitive CubeSat development challenges, such as QB50, which have proven educational merit.

The competition would challenge students to meet the design requirements of both the CubeSat standard as well as the propulsion and instrument requirements specific to this mission. The winning CubeSats would be launched as part of the TAPER 1 mission (subject to extensive design review and verification).

8.5.2 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 mission plans to explore. In an effort to inspire future scientists and engineers about the effects of deep space flight, a competition to design an external biology experiment will be ran prior to launch. Much like the YouTube SpaceLab competition in 2012, the External Biology Experiment Challenge will invite students to consider the scientific though process, as well as develop critical thinking skills, while having a chance to have their hardware fly in space.

8.5.3 Astronaut Interfacing

Currently, astronauts onboard the ISS participate in teleconferences with students across the world to talk about their experiences and excite children about space exploration. It is expected that as technology increases, the ability to expand teleconferencing capabilities will increase as well. This opens up the possibility for an entirely new realm of interfacing with the astronauts. Preliminary ideas include having the public compete with astronauts while on orbit. For example, having the opportunity to challenge an astronaut in a computer game one-on-one as a reward for winning a competition in the sciences would both increase the astronauts connection to home and provide incentive for students to challenge themselves and enter competitions.

8.5.4 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 both TAPER 0 and TAPER 1 could be named as part of an international competition.

8.5.5 Online Education

Leading up the the mission, each space agency involved would present one or more scientists to teach online courses related to the subjects involved in the mission. For instance, the lead scientists, or possibly the Principal Investigator, could give short online courses on services like edX or Coursera. The online education format provides the students with intimate access key mission figure; this would be a major motivational boost for the students to pursue STEM education.

9 Conclusion

As has been mentioned, the vision is for TAPER to act as a critical stage in the ascension of humankind to the Martian system. TAPER addresses the key technological and knowledge gaps mentioned by the Global Exploration Roadmap, as shown in section 1.3.3. TAPER's scientific knowledge gains, addressed in the science traceability matrix shown in section 4.2, not only answer the GER's stated knowledge gaps but explore deeper questions about the Phobos and martian systems. To support both TAPER's science objectives and the GERs stated technology gaps, TAPER's engineering framework requires significant innovation in both minor and major technologies, such as those shown in section 2.1.1.

While pushing the envelope in such a manner may seem to be a foregone conclusion, one must be reminded of the effort and involvement required by the project contributors as well as the public at large. Although involvement of the general public was addressed in section 8.5, 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 20-year 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.

The manned exploration of Mars is seen by many to be a foregone conclusion. The question considered by the scientific and engineering community is not why; the questions are how and when. This viewpoint is not considered to be shared globally, as many people outside of science and engineering still need to know why. It is not a simple task to answer why a government would spend billions of dollars on a space program when so many other issues face us at home. However, we feel Neil De Grasse Tyson provides an inspirational answer [42]:

"Ever since there have been people, there have been explorers, looking in places where other hadn't been before. Not everyone does it, but we are part of a species where some members of the species doto the benefit of us all."

Just as TAPER passes the torch of knowledge to future Mars explorers, it will also light a fire for all of humankind.

A Answers to the Five Challenge Questions

1. What are the science and technology objectives for a mission to a Martian Moon?

   (a)
   - **Question:** What are the objectives of the proposed project and how will one know if the project has succeeded?
   - **Short Answer:** The project objectives are to: 1] Demonstrate the ability to safely transport humans to and return from the martian system; 2] Develop key technologies and operations vital to human Mars exploration; 3] Learn more about the solar system to better understand the past, present, and future of our planet Earth, and humanitys role in the universe; 4] Foster international collaboration in preparation for eventual missions to Mars. Success will be achieved when the project objectives are met.
   - **Respondant Group:** All

   (b)
   - **Question:** What are the requirements needed to meet the project objectives?
   - **Short Answer:** Each project objective is broken down into high level mission and system requirements. This was used as a feed forward in the design of the TAPER mission profile. This is defined further in section 3.4 and the appendix.
   - **Respondant Group:** All

   (c)
   - **Question:** What specification flow down from these requirements?
   - **Short Answer:** Specifications pertaining to the engineering, scientific and operational design of the TAPER mission have been developed. This has been defined in each section of the report, where a coherent margin approach has been implemented throughout.
   - **Respondant Group:** All

   (d)
   - **Question:** What specific science objectives for primitive bodies would be addressed by such a mission, e.g., minearology, chemical composition, structure, size, shape, mass, bulk density, porosity, rotation characteristics?
   - **Short Answer:** Determining the origin of the moons is a mission objective, and this will be achieved through measurements of the composition and interior. Soil cores brought back to Earth for analysis will allow for improved knowledge of space weathering processes that affect small bodies. Specific measurements we will make include: minearology, chemical composition, structure, bulk density, and porosity.

- **Respondant Group:** All

(e)
- **Question:** What are the strategic knowledge gaps that need to be addressed (through research or precursor missions) and what (new) technologies would need to be tested before more challenging Human exploration missions are attempted?
- **Short Answer:** Eng: Precursor missions will address the strategic knowledge gaps in landing techniques and demonstration and surface characterization. Specific technologies addressing the development of advanced subsystem and material selection will also be examined. This includes electric and nuclear-thermal engines, power generation, communications, gravity models for trajectory design. Experiments will also advance the state-of-the-art in human factors.

  Science: Strategic Knowledge Gaps in the surface and subsurface composition, topography, gravitation, radiation, thermal and the regolith/dust environment of Phobos will be addressed through remote and in-situ precursor missions. New technologies will be developed through LEO demonstration missions. This includes the human factors of extended operations in microgravity and the independent prediction and mitigation strategies of solar particles and galactic cosmic ray events. Specific spacecraft development includes electrical and nuclear propulsion, solar cells and advanced structures.
- **Respondant Group:** All

(f)
- **Question:** What are the advantages of sending Humans to Mars moon vs. other targets on the flexible path? For example, what is the advantage of sending Humans to Mars moons instead of on an aerostationary orbit or to Mars itself?
- **Short Answer:** Landing on Mars' moons vs. other flexible path is advantageous because it allows demonstration of technology to enter/exit the Martian system, scientific investigations of targets directly in the Martian system, an investigation for in situ resources that could be used for future Mars missions, and ability to establish intial architecture and operation experience for future manned missions to Mars.
- **Respondant Group:** All

2. Why should the proposed work be undertaken?

(a)
- **Question:** For science, what measurements would provide constraints on Mars system formation and evolution?
- **Short Answer:** Measurements designed to constrain the origin of the Martian moons will provide insight into the evolution of the Martian system.

These measurements include detailed composition analysis (do the moons look like carbonaceous chondrites? = implies asteroid capture hypothesis, space weathered differentiated Mars? = implies impact formation hypothesis, undifferentiated bulk Mars? = coaccretion formation). Characterization of the Phobos' interior through a seismic network could also reveal whether the moon is a unconsolidated rubble pile or possibly potentially differentiated, and presence of subsurface water ice detected by neutron spectrometer or orbiting radar would imply the moon likely formed in the outer solar system and migrated inwards. Finally, investigation of the regolith will provide of record of the space environment around Mars throughout (likely) several billion years.

- **Respondant Group:** Science

(b)
- **Question:** What measurements may provide key information on Mars itself?
- **Short Answer:** If Phobos is found to be formed through impact or co-accretion, measurements of Phobos materials will be an investiation of Martian materials, which would provide key information about early Mars' material. A secondary science goal is also to search for an collect and possible Martian meteorites on Phobos' surface, and if found, this material would also provide insight about Mars itself.
- **Respondant Group:** Science

(c)
- **Question:** What information would we learn at Phobos and Deimos that could be leveraged to better understand small bodies in general and near Earth asteroids (NEAS) in particular?
- **Short Answer:** If Phobos is found to be a primitive body, an investigation of Phobos would be the first investigation of a dark primitive small body. Additional, analyses performed Phobos' regolith will provide a better understanding of the kinds of the space weathering processes that operate across the solar system, and this knowledge would be extendable to remote observations of other small bodies. (Currently the best understood space weathering processes are for our own moon based on returned lunar samples).
- **Respondant Group:** Engineering and Science

(d)
- **Question:** Could Phobos and Deimos be sources for future resources in the Martian system, e.g., metals, minerals, water?
- **Short Answer:** This is indeed a possibility, and answering this question is one of our main mission objectives.
- **Respondant Group:** Engineering and Science

(e)
- **Question:** Why/how would they serve such a role in an effective manner?

- **Short Answer:** Our mission intends to investigate this question. If in situ resources are found to be present, knowledge about their locations and amount could be used to develop efficient extraction technology. Resources may also not be found and/or found in such low abundances that in utilizing them costs would outweigh benefits.
- **Respondant Group:** Engineering and Science

(f)
- **Question:**Would there be interest in performing tele-operations from one of the moons to Mars? What would be the benefits of such an activity?
- **Short Answer:** We decided against tele-operations of rovers on Mars for our mission because (a) we wanted to maximize the science return for Phobos and found 30 days would not be sufficient to do this and tele-operate rovers and (b) we didn't want a major science goal to depend on a program than may or may not be in place by the time our mission launches.
- **Respondant Group:** Engineering, Operations and Science

(g)
- **Question:** What knowledge is needed before Humans explore the Martian moons?
- **Short Answer:** See answer to question about strategic knowledge gaps (question 1).
- **Respondant Group:** All

(h)
- **Question:** Do we need robotic precursor missions?
- **Short Answer:** Remote sensing and in-situ robotic precursor missions will be used to address the current SKGs. This is addressed further in question 1.5.
- **Respondant Group:** Engineering, Policy and Science

(i)
- **Question:** If so, how does one maximize the synergies between robotic and human missions?
- **Short Answer:** Synergies will be developed as a feed forward for the future robotic exploration of the Mars-Moon system. Lessons learnt from the robotic precursor missions have been included as additional payload margin for future scientific and engineering analysis. Synergies also includes the astronaut-surface-control of in-situ mobility systems. This will be used assess a greater diversity of samples and to maximize the EVA activity time of the astronauts.
- **Respondant Group:** Engineering, Operations

(j)
- **Question:** What are the advantages/disadvantages of robotic flybys, rendezvous, and sample return?

- **Short Answer:** Robotic flybys would be the cheapest mission, but would yield the least amount of information. A sample return would be most expensive, but return the maximum science. Based on the SKGs it was determined that an Orbiter and in-situ sampling would be the appropriate technique for achieving the necessary scientific and engineering objectives a minimal expense.
- **Respondant Group:** Science

(k)
- **Question:** Considering answers the questions/sub-questions above, what would be the ideal suite of science instruments to use and technologies to test on precursor to human exploration missions?
- **Short Answer:** Primary surface science instruments include human sample collection (robonauts, sample boxes, bags, tongs, rakes, hammer, cameras etc), mobile science platforms (spectrometers, imaging systems, communication), seismic network stations and space weather stations (plasma wave, micrometeorite, dust particle detector and communication system). Additional science can also be performed on the DSV, during transmit and through lessons learnt gained from the precursor missions. This will be used for fundamental science, technology demonstration and understanding human factors of extended operations in space.
- **Respondant Group:** Science

(l)
- **Question:** Which moon would be most attractive for a human mission?
- **Short Answer:** Both Phobos and Deimos can be used for a human mission. Phobos was considered to be the more geologically attractive mission and was therefore selected for the TAPER mission. It also provides a reliable trajectory.
- **Respondant Group:** All

(m)
- **Question:** Do the two moons offer the same potential from a science standpoint? From an exploration standpoint?
- **Short Answer:**From a science AND exploration standpoint following our mission objectives, we felt Phobos was the more desirable moon based on its hypothesized greater likelihood to contain subsurface volatiles, spectral homogenity and geologic features of interest (large Stickney crater, groove system).
- **Respondant Group:** Engineering and Operations

(n)
- **Question:** Which of the two moons is more easily accessible for possible first robotic and human exploration missions?

- **Short Answer:** Phobos is the most desirable moon based on science and exploration standpoint. Its position closer to the moon may make the trajectory more expensive, but the ΔV will finally depend on the specific trajectory
- **Respondant Group:** Science

(o)
- **Question:** Are there potential planetary protection/contamination issues?
- **Short Answer:** Forward Planetary Protection Issues include ensuring no contaminated hardware enters the atmosphere of Mars (Phobos is not a major concern for forward contamination). Backwards contamination poses larger issues, especially when returning samples. Any surface that comes into contact with Phobos material cannot come into contact with any Astronaut or the Earth environment. Therefore any samples have to break the chain of contact.
- **Respondant Group:** Operations and Science

3. How will the proposed work be accomplished?

(a)
- **Question:** How would a human mission to a Martian moon be undertaken?
- **Short Answer:** The TAPER mission proposed a feasible way to get humans to the moon and get the back safely. Details are given on the report.
- **Respondant Group:** All

(b)
- **Question:** What are the mission drivers in terms of risks and costs?
- **Short Answer:** The largest risk of this mission is the potential loss of crew members. Crewed missions, while enabling greater capacity for exploration and data collection, are inherently risky because of the added complexity of life support systems and human factors. This is the major mission cost driver due to the mass requirements levied on engineering subsystems to incorporate life support.
- **Respondant Group:** Operations

(c)
- **Question:** What are the launch and spacecraft capability requirements, e.g., numbers of launches, staging in orbit, transit to Martian moon, operations in orbit, landing, length of stay, sample collection, departure, Earth return?
- **Short Answer:** Although a variety of launch combinations and qualitative trajectory characteristics could be analyzed, this design considers one single solution. In the proposed solution, 6 launches are employed: first, four launches for the fuel tanks, the next for the Deep Space Habitat and PSE, and the final for the crew. All components are launched into LEO and must rendezvous prior to departing LEO, on the nominal Earth departure date. The five prior launches must be staged based on launch locations and minimum

launch intervals. A Lambert arc is employed to transfer from LEO to a High Mars Orbit in the orbital plane of Phobos. Successive maneuvers are applied in order for the crew to enter an L1 Lyapunov in the Mars-Phobos system. This plan is reversed for departure from the Martian system, and a Lambert arc is used to transfer to Earth. When the crew returns to Earth, direct Earth entry is employed. The total time of flight is 456 days and the total delta v is 13.5 km/s. Based on launch and spacecraft requirements, this mission concept appears feasible.

- **Respondant Group:** All

(d)
- **Question:** What should be the components of an orbiting spacecraft and a proximity or landing unit be and why, e.g., cameras, propulsion, communications, attitude control, science instruments, sample-collection devices, habitat, etc.?
- **Short Answer:** An orbiting spacecraft should include remote sensing capability, which our mission has been designed to. RCS thrusters on the spacecraft are vital to maintain stationkeeping ability, and with the ADCS propulsion system, the main propulsion should be something reliable in the event the spacecraft is to avoid risk. Our landing unit attempts to demonstrate technology that hasn’t been done before, however it also incorporates a reliable hypergol system. For communications, the satellite shall maintain line of sight for at least 50% of the time which will effect the orbit. The landing system should include provisions for the crews stay, including sample collection devices that mitigate the risk of contamination. For transportation of the samples, a cryogenic system should also be incorporated to keep the samples from getting contaminated.
- **Respondant Group:** All

(e)
- **Question:** Do the necessary components exist, or must they be developed? If they must be developed, what is the level of maturity, e.g., technology readiness level (TRL), of the various components that must be successfully integrated for success?
- **Short Answer:** The mission concept is mainly based on available technologies or technologies already in development. However, the mission includes some revolutionary concepts that will need a further research investigation. Each one of the technologies are explained in the appropriate chapter.
- **Respondant Group:** Engineering and Operations

(f)
- **Question:** What is the budget, schedule, and risk of the proposed undertaking? What budget and schedule reserves need to be planned and how can the project be descoped, if in the course of its development it is proven that the

technical and other risks were underestimated, i.e., if the original goals cannot be met within the allocated budget and schedule? Are there enough margins in its goals so the project can be descoped and still meet its main/primary objectives?

- **Short Answer:** The budget for the project is required to remain below $100 Billion to maintain feasibility by comparing the program cost with the ISS. The schedule is somewhat flexible with launch, as the margin has been allocated to the latest launch window of 2035, and also includes a +/- one week launch window so that it can still achieve mission success. In the event the project must be descoped, the science requirements of conducting science on the way to Phobos can be descoped. To be successful, the mission must still be able to land on Phobos, as this mission element can not be changed. If technologies extrapolations for the PBR technologies are not achieved in the near future, the reactor can be redesigned for a NERVA type system, however with a mass penalty of an extra 10,000 in reactor mass.
- **Respondant Group:** Operations

(g)
- **Question:** What are the spacecraft ΔV requirements, mission phases, and mission timeline?
- **Short Answer:** The total ΔV for the TAPER mission is estimated at approximately 13.5 with an additional margin factor of 5% to account for maneuvered the astronauts may need to correct for in flight. The mission goes through three phases. LEO to Martian transit, PSE landing on Phobos, and the return trip of the Crew vehicle. The second phase of the mission is critical for the crew's return.
- **Respondant Group:** Engineering

(h)
- **Question:** Is chemical propulsion, advanced propulsion techniques, or some combination of the two indicated? Why?
- **Short Answer:** Advanced propulsion is necessary to achieve an orbit to the Mars region in a reasonable amount of time. Without using non-chemical methods, the PMF of the propellant approaches 100% making the mission impossible.
- **Respondant Group:** Engineering

(i)
- **Question:** What are the specific communications issues for the proposed project? How would they be met?
- **Short Answer:** If an emergency occurs on orbit and the crew is not able to communicate with ground operations then tablet teleoperations will be used to mitigate the issues. The crew will be trained on how to use these devices. An example is provided in the telemedicine section.

- **Respondant Group:** Engineering

(j)
- **Question:** What additional requirements are there for Human exploration of the Martian moons?
- **Short Answer:** The requirements are defined in the appropriate section in the report.
- **Respondant Group:** Engineering

(k)
- **Question:** What are the needs for in-space repairs, spares, dissimilar redundancies (“multiple string”), and contingencies? How does the proposed project balance system complexity and cost with risk?
- **Short Answer:** The 3D metal prototyping machine will be used to make spare parts from powder aluminum. The aluminum will be used from the consumable wrappers as well as a small supply that was launched. Single point failures will have a back-up to prevent mission failure.
- **Respondant Group:** Engineering

(l)
- **Question:** What is the optimal crew size for the proposed mission and why?
- **Short Answer:** The crew size will be 4 astronauts, including 2 male and 2 female. This number is primarily driven by mass constraints. Even if initially an odd number has been suggested, four crew members have been chosen over three to maximize the mission objectives and minimize psychological issues derived of a really small crew number.
- **Respondant Group:** Engineering

(m)
- **Question:** How do we best mitigate radiation-tissue damage and extended periods of weightlessness?
- **Short Answer:** Techniques to perform these can be included in the SC, but shall be provided by Science/HSF HF: Habitat structure will be made of a low-z material (Velctran) with a 20 [g/cm2] thick shell. In addition, magnetic field active shielding will deflect the radiation.
- **Respondant Group:** Engineering

(n)
- **Question:** How do we mitigate the psychological effects of long flight times, out of sight from Earth, and in habitats of minimal sizes?
- **Short Answer:** Will account for interpersonal conflicts, sleep disturbances, boredom, performance decrement, and decline in group compatibility.
- **Respondant Group:** Engineering

(o)
- **Question:** Why is the proposed approach best-suited to achieve the objectives?

- **Short Answer:** A crewed mission to Phobos is the best design to fulfill the challenge objectives because of the capabilities it offers to collect the proposed science data and begin to prepare for a martian surface landing.
- **Respondant Group:** Operations

(p)
- **Question:** Should there be international partners? If so, should they be part of the critical path?
- **Short Answer:** International partners will be incorporated into the mission to dilute cost and increase knowledge base. The mission will be managed by one entity, much like the ISS, but will have contributions from all partner nations.
- **Respondant Group:** All

(q)
- **Question:** If not, would that be a unilateral US choice?
- **Short Answer:** N/A
- **Respondant Group:** Operations

(r)
- **Question:** Outreach: how would you engage the public and convince taxpayers that such a mission is worth the cost?
- **Short Answer:** Public will be engaged though opportunities to interface with astronauts and design non-critical flight hardware. Please refer to report main body for more detail.
- **Respondant Group:** Operations

(s)
- **Question:** How will you organize your mission campaign to promote political sustainability? What milestones (hardware delivery and testing, determination of unknown parameters, etc.) will you define to help sustain progress towards your ultimate mission goal? How will the program and project be managed?
- **Short Answer:** The mission will be incorporated in a global exploration roadmap as defined by partner nations. Milestones include technology development detailed in report and precursor missions. Please refer to report main body for more detail.
- **Respondant Group:** Operations

4. What will be learned and what will the benefit(s) be if the project is successful?

(a)
- **Question:** What results and conclusions can be expected that will advance the state of our understanding and the state of the art? What would their benefits be?

- **Short Answer:** TAPER results in the filling of key technology and science gaps leading to Mars crewed exploration. Benefit is characterized similar to the Apollo program - the advancement of humankind, both in technological development at home and in space, as well as understanding of the universe.
- **Respondant Group:** All

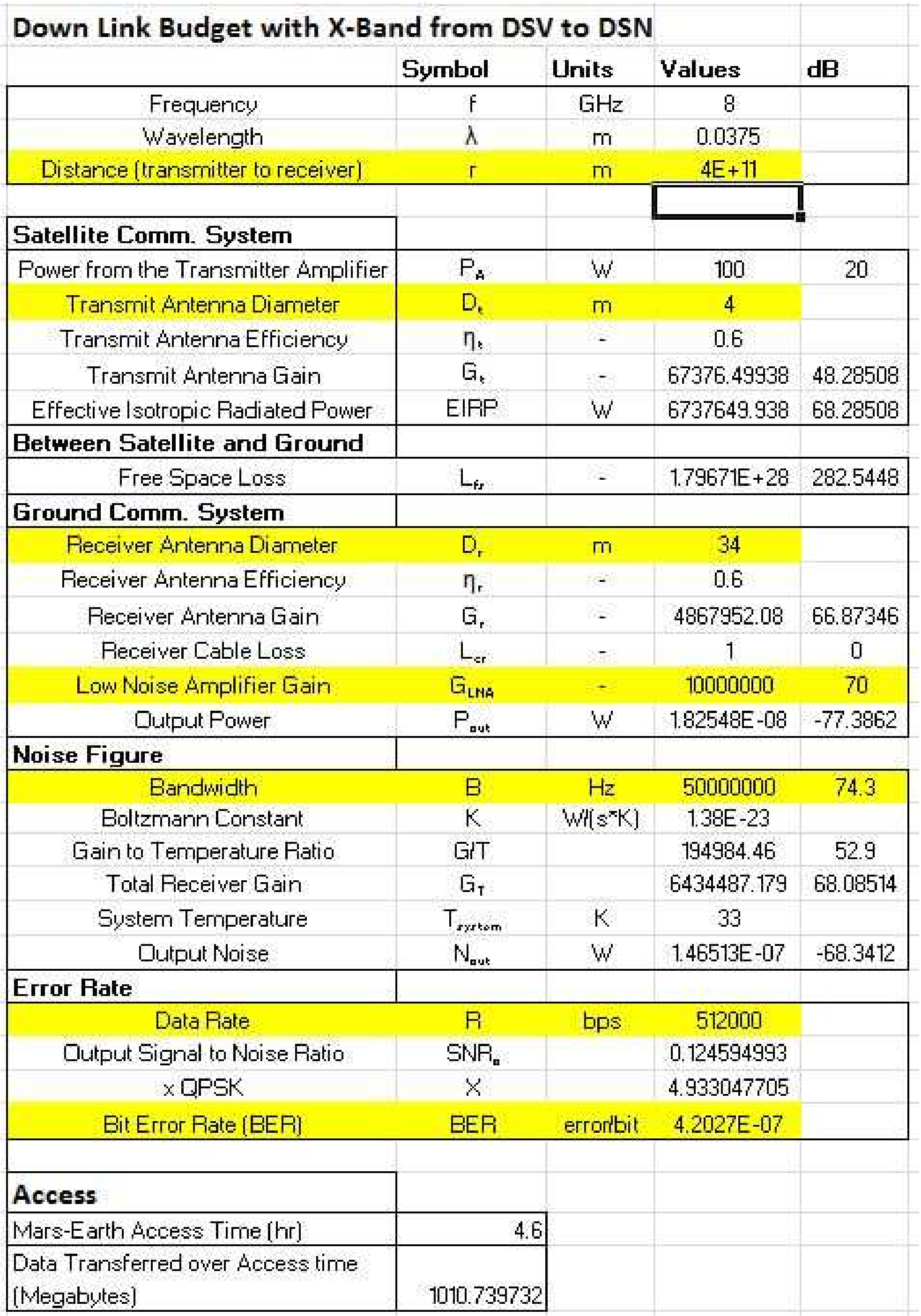
5. How will the results change the future?

    (a)
    - **Question:** It may appear to be a tall order that the results of the proposed project should be expected to change the future. However, if the results will have no influence on the future, i.e., if the project will make no difference, and benefits commensurate with its cost and risk cannot be identified then one could argue that such a mission should not be undertaken at all.
    - **Short Answer:** Humankind's landed exploration of Mars is a near inevitability, and the benefits are legion. The larger challenge is to ensure the benefits of such a venture are properly communicated to the public, especially when pressing concerns at home arise and overshadow the long-term goals of the space program.
    - **Respondant Group:** All

B Mission Power and Link Budgets

Vehicle	Component	Power (W)	Power Source
Cargo Vehicle	Solar Arrays	300000	Solar Power
	Communications	200	
	Science	100	
Deep Space Habitat	ECLSS	16300	Solar Power
	Solar Arrays	18500	
	Communications	120	
	Science	2000	
Phobos Surface Explorer	ECLSS + Comms	4000	Solar Power + Li Ion Batteries
	Solar Arrays	3000	
	Li Ion Batteries	3000	
PSEP	Robotic Arm Control + Comms	2500	Li Ion Batteries
	Li Ion Batteries	3000	
Crew Vehicle	Sample Storage	400	Solar Power
	Solar Arrays	2000	
Science Instruments in Robots	Solar Array (self-powered)	20	Solar Power
	On-board scientific instruments	20	

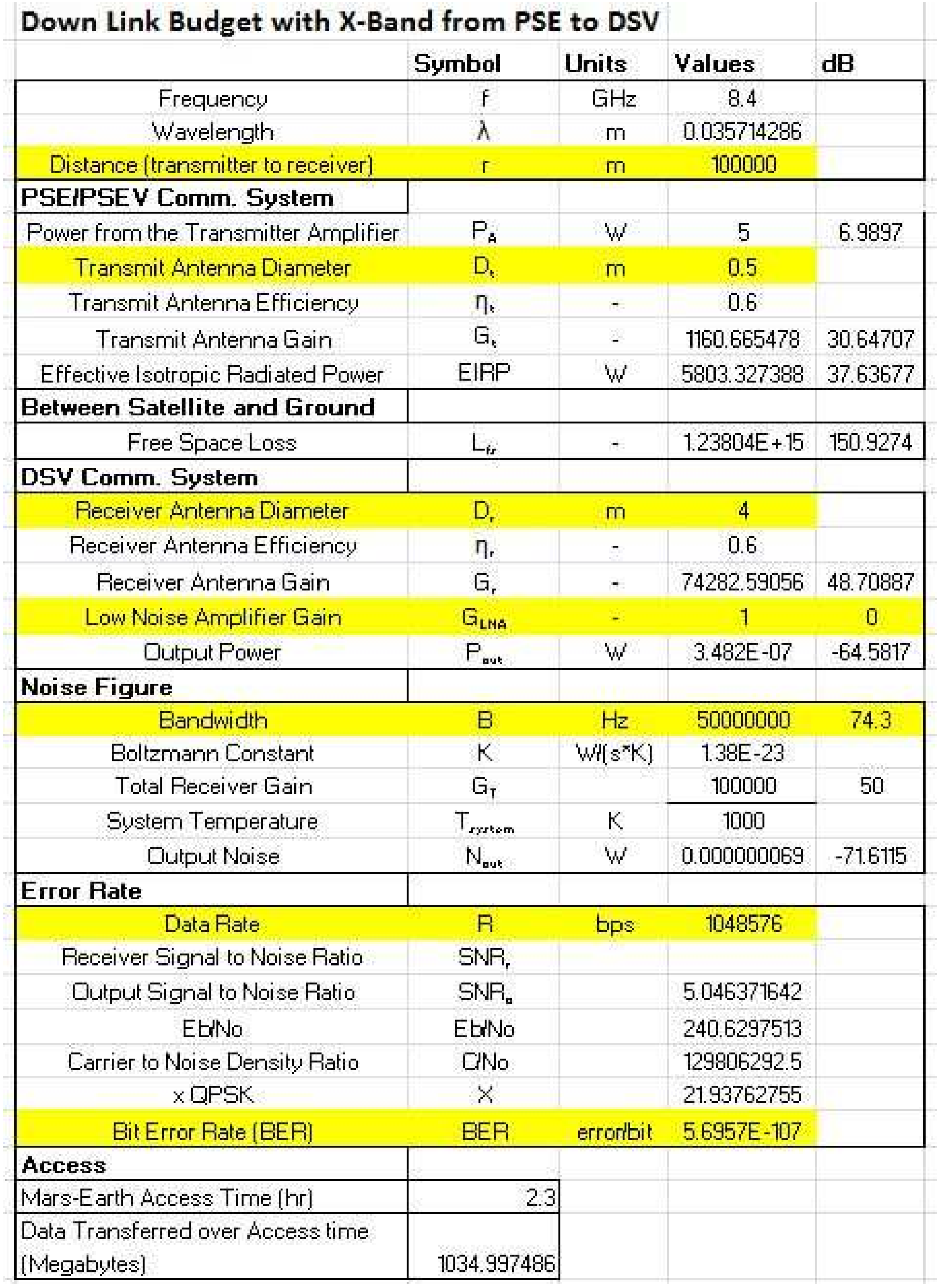
Figure B.1: Mission power budget.



Down Link Budget with X-Band from DSV to DSN

	Symbol	Units	Values	dB
Frequency	f	GHz	8	
Wavelength	λ	m	0.0375	
Distance (transmitter to receiver)	r	m	4E+11	
Satellite Comm. System				
Power from the Transmitter Amplifier	P_A	W	100	20
Transmit Antenna Diameter	D_t	m	4	
Transmit Antenna Efficiency	η_t	-	0.6	
Transmit Antenna Gain	G_t	-	67376.49938	48.28508
Effective Isotropic Radiated Power	EIRP	W	6737649.938	68.28508
Between Satellite and Ground				
Free Space Loss	L_{fs}	-	1.79671E+28	282.5448
Ground Comm. System				
Receiver Antenna Diameter	D_r	m	34	
Receiver Antenna Efficiency	η_r	-	0.6	
Receiver Antenna Gain	G_r	-	4867952.08	66.87346
Receiver Cable Loss	L_{cr}	-	1	0
Low Noise Amplifier Gain	G_{LNA}	-	10000000	70
Output Power	P_{out}	W	1.82548E-08	-77.3862
Noise Figure				
Bandwidth	B	Hz	50000000	74.3
Boltzmann Constant	K	W/(s*K)	1.38E-23	
Gain to Temperature Ratio	G/T		194984.46	52.9
Total Receiver Gain	G_T		6434487.179	68.08514
System Temperature	T_{system}	K	33	
Output Noise	N_{out}	W	1.46513E-07	-68.3412
Error Rate				
Data Rate	R	bps	512000	
Output Signal to Noise Ratio	SNR_o		0.124594993	
x QPSK	X		4.933047705	
Bit Error Rate (BER)	BER	error/bit	4.2027E-07	
Access				
Mars-Earth Access Time (hr)	4.6			
Data Transferred over Access time (Megabytes)	1010.739732			

Figure B.2: DSV to DSN communications budget.



Down Link Budget with X-Band from PSE to DSV

	Symbol	Units	Values	dB
Frequency	f	GHz	8.4	
Wavelength	λ	m	0.035714286	
Distance (transmitter to receiver)	r	m	100000	
PSE/PSEV Comm. System				
Power from the Transmitter Amplifier	P_A	W	5	6.9897
Transmit Antenna Diameter	D_t	m	0.5	
Transmit Antenna Efficiency	η_t	-	0.6	
Transmit Antenna Gain	G_t	-	1160.665478	30.64707
Effective Isotropic Radiated Power	EIRP	W	5803.327388	37.63677
Between Satellite and Ground				
Free Space Loss	L_{fs}	-	1.23804E+15	150.9274
DSV Comm. System				
Receiver Antenna Diameter	D_r	m	4	
Receiver Antenna Efficiency	η_r	-	0.6	
Receiver Antenna Gain	G_r	-	74282.59056	48.70887
Low Noise Amplifier Gain	G_{LNA}	-	1	0
Output Power	P_{out}	W	3.482E-07	-64.5817
Noise Figure				
Bandwidth	B	Hz	50000000	74.3
Boltzmann Constant	K	W/(s*K)	1.38E-23	
Total Receiver Gain	G_T		100000	50
System Temperature	T_{system}	K	1000	
Output Noise	N_{out}	W	0.000000069	-71.6115
Error Rate				
Data Rate	R	bps	1048576	
Receiver Signal to Noise Ratio	SNR_i			
Output Signal to Noise Ratio	SNR_o		5.046371642	
Eb/No	Eb/No		240.6297513	
Carrier to Noise Density Ratio	C/No		129806292.5	
x QPSK	X		21.93762755	
Bit Error Rate (BER)	BER	error/bit	5.6957E-107	
Access				
Mars-Earth Access Time (hr)	2.3			
Data Transferred over Access time (Megabytes)	1034.997486			

Figure B.3: PSE to DSV communications budget.

C Mission Requirements

1. Demonstrate the ability to send humans to the martian system and return them safely with samples of the environment.

    (a) The human crew shall travel to Phobos and return.

        i. The vehicle(s) shall provide transportation to and from the martian System with acceptable risk.

            A. A Crew Vehicle shall provide for Launch and Entry into Earth's atmosphere.

            B. A Deep Space habitat shall provide for the comfortable habitation of the crew during the Earth-martian system travel.

            C. A Phobos Surface Explorer (PSE) shall enable the crew to descend to the surface of Phobos and move around on the surface.

            D. Adequate propulsion capability must be provided to perform all manoeuvres throughout the mission profile, with an appropriate margin.

        ii. A Deep Space habitat shall provide for the comfortable habitation of the crew during the Earth-martian system travel.

        iii. A Phobos Surface Explorer (PSE) shall enable the crew to descend to the surface of Phobos and move around on the surface.

        iv. Adequate propulsion capability must be provided to perform all manoeuvres throughout the mission profile, with an appropriate margin.

            - Including operating in Phobos' eclipse seasons.

        v. The crew shall be capable of performing an Extra Vehicular Activity.

    (b) The human crew shall remain safe for the mission duration.

        i. An ECLSS System shall support the crew in acceptable environment for the duration of the mission.

        ii. The crew shall not be exposed to unacceptable levels of radiation.

            A. The radiation dose shall not exceed the 3% excess cancer mortality risk.

            B. There shall be an adequate "safe haven" to completely mitigate SPE during a solar storm.

            C. The sleeping quarters shall include adequate shielding.

            D. There shall be a minimum 20 kg/cm^2 of shielding throughout spacecraft.

            E. The level exposure should be measured for verification.

        iii. Appropriate countermeasures for the effects of microgravity shall be provisioned.
            - The astronauts shall be capable of perform EVAs on the moon upon arrival.
        iv. Consumables for crew sustenance shall be provided for the duration of the mission.
        v. The crew shall maintain reasonable psychological health throughout the mission.
            A. The habitat shall be of sufficient volume to be comfortable.
                - 1.62 kg/day/Astronaut Drinking.
                - 0.75 kg/day/Astronaut Food Preparation.
                - 1.15 kg/day/Astronaut Food Content
                - 1 kg/day/Astronaut Hygiene
            B. There shall be adequate rest periods scheduled.
            C. The crew work schedule should be reasonable.
            D. The crews shall be carefully selected to be capable of performing in the environment.
        vi. Clinical Care provisions shall be included.
            A. Provide a first Aid Kit.
            B. Provide a Dental Kit.
            C. Provide Minor Surgical Equipment.
            D. Telemedicine principals shall be included.
    (c) The mission shall comply with all planetary protection guidelines.
        i. No part of the mission hardware shall have a high probability of entering the martian atmosphere (Forward contamination).
            A. $<$99% in 20 Years.
            B. $<$95% in 50 Years.
            C. Suitable End of Life provisions should be planned and implemented for all mission elements.
        ii. No part of the hardware exposed to potentially martian material shall return to earth without being thoroughly sealed ($< 1 \times 10^{-6}$ chance of exposure to Earth's atmosphere outside a containment field.)
    (d) There should be contingency of launch opportunities in the case of mission delay.
    (e) Key Technologies relevant to future missions to the surface of Mars shall be demonstrated.

   (f) Demonstrate the ability to mitigate psychological and physiological effects of deep space flight to and from the martian system.

2. Assess the feasibility of Phobos and/or Deimos as resources for future missions to the martian surface.

   (a) Determine is the volatile content of the moon's surface and subsurface

      - Measure regolith water content in situ, drill into areas identified by precursor as potential having subsurface water

   (b) Detect and quantify any mineable material including magnesium, methane, ammonia, clays, REE

3. Investigate the origin and evolution of the moons to better understand the martian system.

   (a) 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)

   (b) Determine 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)

   (c) Constrain internal structure of Phobos.

      - Seismic measurements from 3 (nominal) or 5 (preferred) separate locations.

   (d) Characterize Phobos regolith and processes that may have modified it over time.

      - High resolution imaging of regolith in situ to characterize grain size/distribution/roundness; investigation of returned core samples.

4. Understand the current environment of Phobos in the context of the martian system to support architecture for future manned Mars missions.

   (a) Characterize effects of space weathering on the Phobos' regolith.

      - Collect core samples from at least three locations on each of two sites.

   (b) Understand how radiation is attenuated and blocked on the surface over time.

      - Measure fluxes and energies of particles received at Phobos surface.

   (c) Quantify amount of dust fall and frequency of micrometeorite impacts on Phobos.

      - Measure dust fall on Phobos

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