Interplanetary Base Design to Support Mars Exploration and Settlement Via Phobos Expedition

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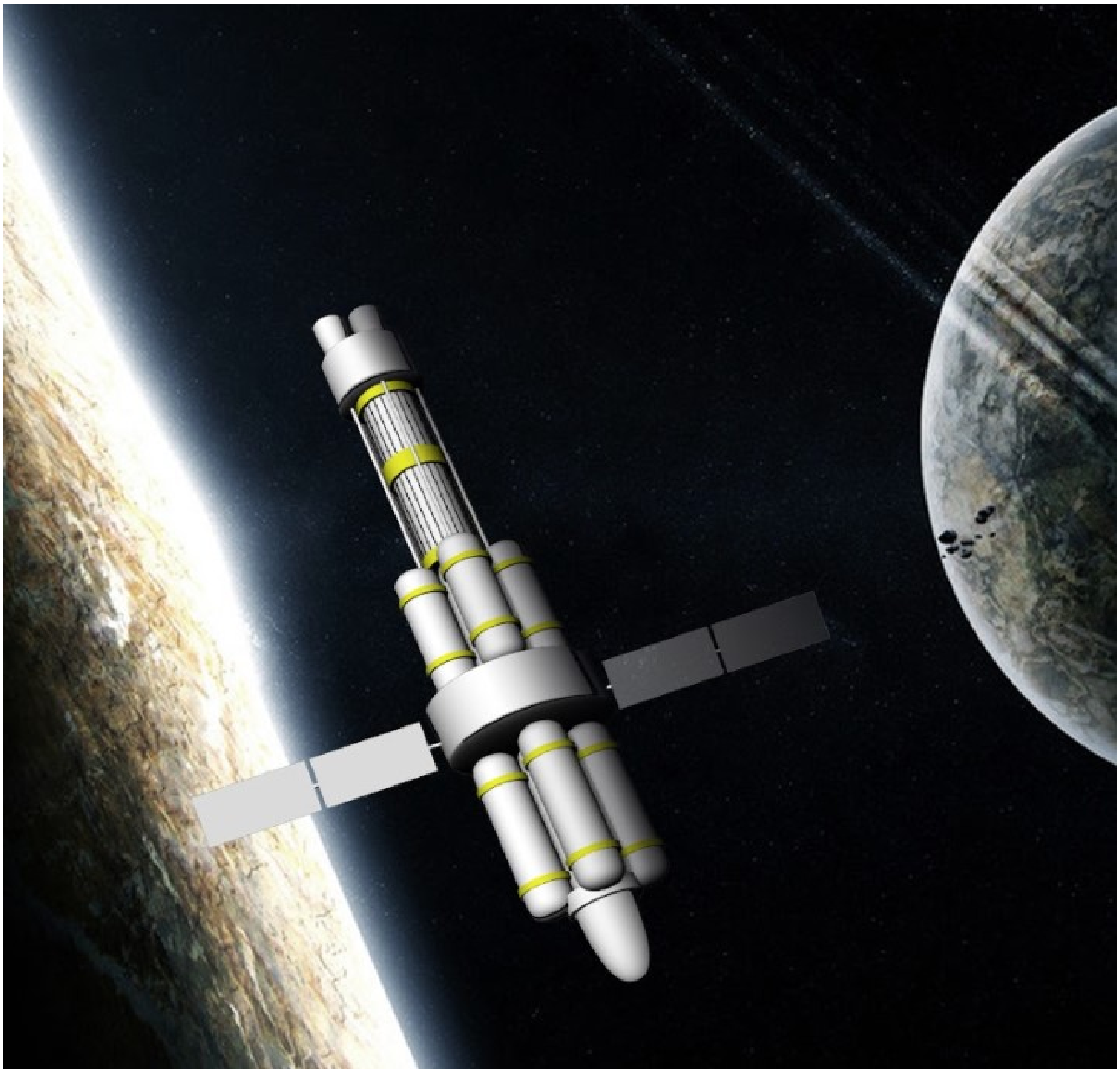

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Abstract

One of the greatest challenges for designing a human mission to Mars and sustaining it from the Earth over many varying synodic cycles is how to deploy and stage the lander descent and ascent modules and overall logistics from Mars orbit. In this paper, we propose the design and operation of an interplanetary vehicle (IPV) whose purpose is to not only transport a specialized team of up to twelve crew members to Phobos proximity, but also to provide a Mars system base of operations at Phobos for the maximum span of 2 synodic cycles (~4.5 years). To achieve this mission, four major concerns are addressed to ensure a high confidence level in the operation of the IPV:

1) The IPV will be constructed within Low-Earth Orbit (LEO) and cycled in cis-lunar trajectories to test and evolve mission critical systems until the IPV is commissioned for operation as early as 2024.
2) Toroidal water shielding technology around crew habitat will be discussed and utilized in the IPV to combat the effects of long-term exposure to Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE), which we believe will allow the IPV to reduce the reliance on extraterrestrial bodies for additional shielding. We are aware of the waning solar maximum over the last few solar cycles and we expect that the increase in GCR fluence in cycle 25 will be compensated by low sunspot and Coronal Mass Ejection (CME) activity.
3) All consumables will be brought onboard the IPV with a large reliance on resource recycling technologies and replenishment potential rather than in-situ resource utilization (ISRU) as ISRU on Phobos or Deimos has not been confirmed as a viable form of survival.
4) Finally, we see no purpose in building a Phobos habitat to support Mars exploration and settlement effort if the overall expedition costs of a Phobos habitat can support the costs of a Mars surface build-up with little extra budget and mission resources. Instead, crewed missions can be conducted via a Phobos co-orbiting IPV with high-end landers to support sampling missions to Phobos, Deimos, and Mars Entry, Descent, and Landing (EDL) as well as real-time analyses from IPV in-orbit. Once a Mars equatorial site has been identified from Phobos orbit for detailed exploration and settlement infrastructure development, we expect to raise the IPV to an areosynchronous orbit above the site so that it becomes possible to conduct continuous line-of-site teleoperation using wideband laser telecom links.

Additionally, the mission becomes an opportunity to perform technology verification and tests for:

1) Landers on Mars, characterization of Mars’ atmosphere, and on-site control of Rovers
2) Landers on Phobos and Deimos to confirm potential of ISRU and research on Phobos and Deimos to demonstrate mining technologies on extraterrestrial bodies in low gravity environments.
3) Finally, to demonstrate long-term deep space and interplanetary radiation shielding without the need for extraterrestrial bodies for shielding

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I. Introduction

Space colonization has been dealt within science fiction for decades, and since the first photos of Mars were taken in the 1960s, the goal to colonize this specific planet has only increased over time. Now, active research and technological advancements are happening to make that goal a reality. The objective of this project is to produce an integrated, multidisciplinary design solution for a base on Phobos to enable the human exploration of the cis-Mars System, including arrival from Earth and return to Earth, plus routine descent to the Mars surface and return to Phobos. The opportunity suggests "the best first step may prove to be establishing an exploration, transportation, and logistical support base on Phobos", but the members of this team disagree. We see no purpose in building a Phobos habitat to support Mars exploration and settlement effort if the overall expedition costs of a Phobos habitat can support the costs of a Mars surface build-up with little extra budget and mission resources. Instead, crewed missions can be conducted via a Phobos co-orbiting Interplanetary Vehicle (IPV) with high-end landers to support sampling missions to Phobos, Deimos, and Mars Entry, Descent, and Landing (EDL) as well as real-time analyses from an IPV in-orbit.

To properly perform Mars exploration and settlement efforts, we propose the design and development of an IPV with a potential capacity of 12 crew members. The IPV carries all consumables needed each synodic cycle and will depend on the upkeep and maintenance of critical life support systems through redundancies and spares, since the IPV will act as both the transport vehicle and the base. In addition, the system will support the crew with an extensive solar storm shelter that is surrounded by a substantial water jacket to ameliorate high energy Galactic Cosmic Rays and Solar Particle Events. We are aware of the waning sunspot activity over the past few solar cycles and feel that this trend may continue for the next few cycles, allowing design for less solar particle fluence. The source of power and propulsion comes from Bimodal Nuclear Thermal Rockets (BNTR) and is intended to be tested and evolved through cislunar trajectories before being commissioned on the IPV. Finally, when an optimistic Mars surface base solution is identified, it could be advantageous to park the IPV in an areosynchronous orbit to allow continuous monitoring and communications with landers and rovers sent to the surface of Mars employing wideband laser links from the IPV.

Rather than building a base to support cis-Mars exploration, the IPV refocuses the purpose of this mission to directly exploring the cis- Mars system; however this shift provides its own set of requirements that are explained below.

II. Requirements Analysis and Interpretation

The assumptions below are taken from the 2017 AIAA Student Design Competition - Human Spaceflight: Phobos Base Request for Proposal and written to provide an overview of how the team's design solution fits within those parameters.

Site Assumptions:

The IPV is not designed for landing on any extraterrestrial body, so the site of the base is any location within the cis-Mars system. Any research requiring physical presence will be performed by Landers to Phobos, Deimos, and Mars. The designed IPV will be capable of attaining and staying within any orbit given there is sufficient propellant to maintain orbital trajectories. However, it is noted that priority will be given to parking orbits within the vicinity of Phobos, Deimos, and Mars to provide Landers the simplest landing trajectories. Additionally, the suggested location for the base is within Phobos Stickney Crater [1]. We believe this is motivated by the Crater's ability to provide natural shielding from Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE); however, the versatile site location means the IPV will be exposed to increased GCR and SPE fluence.

Phobos Base Assumptions:

The crew members must be kept at a reasonably healthy state throughout the expected four year mission; however, while there are numerous hazards in any expedition regarding spaceflight, our team has focused on designing the IPV with four things in mind:

1) Reducing radiation levels within the IPV to near Earth standards (annually 2.4 mSv)
2) Withstand micro-meteoritic puncture
3) Withstand internal pressure and potential loss of pressure
4) Providing a source of internal heating to offset the heat loss in vacuum

Spaceflight Assumptions:

The mission program has the highest potential for success when the IPV is sent at Conjunction class trajectory corresponding with the 25th solar cycle and beyond. Not only will the IPV's travel time be reduced significantly during a Conjunction class trajectory, but the IPV will also take advantage of the consistent decrease of solar maximums in the past few years to allow design for less solar particle fluence. This will increase the viability of the IPV's heavy water jacket shielding and the safety of the crew.

Crew and Crew Protection:

A crew of up to 12 members will be completely sustained within the IPV and will only need to leave the safety of the Mothership to perform mission critical research of Phobos, Deimos, or Mars, or perform mission critical repairs to the exterior of the ship. As a safety precaution, the team has decided not to rely on In-Situ Resource Utilization (ISRU) to replenish consumables as ISRU has not been confirmed as a viable form of survival. Instead, the IPV is designed to carry consumables at a ratio of 1-to-2, so that 6 crew members will be given enough consumables to sustain a crew of 12 over one synodic period. In addition to physical considerations, the team takes into account the mental strain that the crew will experience during the long mission to and from Mars.

Delivering Payloads:

The only source of transport between Earth and Mars will be through the IPV, so there will be no method of delivering payloads to Phobos or the cis-Mars system. Instead, the IPV will be built within Low Earth Orbit (LEO) in a similar fashion to how the International Space Station (ISS) is currently being constructed: by focusing on creating an inhabitable vehicle and expanding the structure to support subsystems [Refer to Section IV: Base Assembly and Construction Process]. Once the IPV is constructed, preliminary testing will be performed by cycling the IPV within cis-lunar trajectories to confirm and evolve mission critical systems. Finally, the IPV will perform a Conjunction class trajectory with a Mars Insertion orbit. This is further seen in detail in Section III.G: Trajectories.

External Environment:

The IPV needs a minimum of three operational connections to the external environment. Since the IPV will be in sustained orbital trajectory over Mars, there is no need for physical structures outside of the Mothership; however, there needs to be a location for crew members to dock to the IPV. This location is centered at the solar storm shelter and will be used to support the crew's docking ship and two additional landers designed for Extravehicular Activity (EVA). In the event that ISRU is possible, one lander will be dedicated to performing mining procedures for the IPV.

Life Support and Propulsion:

The IPV is designed to utilize the International Space Station's (ISS) Environmental Control and Life Support System (ECLSS) and "Bimodal" Nuclear Thermal Rocket (BNTR) propulsion in conjunction with each other. The BNTR would provide power and propulsion, while the ECLSS uses the stored consumables and BNTR bi-products to supplement the crew member's needs. Many of the values obtained throughout the report will reference the estimated consumable masses and recycling performed by the ISS's ECLSS. The BNTR is kept stable by cycling the water from the shielding jacket and ECLSS as necessary.

III. Key Conceptual Features

A. Architecture

The architecture of the mission describes the relationship the IPV, the Landers, and a few satellites that make up the communication network have with one another and the overall mission. While the IPV acts as the Mothership and home base for the crew, the landers are used to perform on-site research of extraterrestrial bodies. Communications are performed primarily from the IPV using wideband laser communication; however, in instances where large bodies of mass may disrupt line-of-sight communications, an array of satellites is utilized to communicate from virtually any angle and time.

This architectural set-up allows the IPV to adapt to the situation as needed. If more research on Phobos or Deimos is necessary, the IPV can support reconnaissance and research missions closer to the body of interest. If a potential Mars surface base location is identified, the IPV can ascend to an areosynchronous orbit. And if an emergency situation occurs that requires the crew to terminate the mission, the IPV is capable of returning from the cis-Mars system at any time, although transit time will increase.

B. Engineering Systems

The technology of the 21st century has changed drastically since the first manned trip to the moon nearly 50 years ago. These new space systems are often times more accurate, efficient, and are considerably lighter. However, the space industry today tends to design their missions using 20th century technology simply because they have been tested, debugged, and perfected in space throughout the years. There is a certain risk that comes with using technologies that haven't been used before, and this is a risk they are not willing to take. Our manned mission to Mars will include a mixture of both dated and innovative systems in order to take advantage of the improvements while preserving the safety factor.

Communications:

Laser based, or otherwise known as optical communications, is a great example of an innovative technology which will be the new standard in space communications. It offers a massive improvement in data rates from the dated radio frequency (RF) based communications. In 2013, NASA launched the Lunar Atmosphere and Dust Environment Explorer (LADEE). On board LADEE was the Lunar Laser Communication Demonstration (LLCD), which successfully transmitted data at a record breaking download rate of 622 megabits per second along with an error free upload rate of 20 megabits per second [2]. If LADEE would have used S-band communications, it would have taken 639 hours to download an average length HD movie, where the LLCD technology would only take less than 8 minutes [3].

In addition to the improvement in data rates, the size, mass, and energy requirements are also reduced in optical communications. The size of RF antennas has reduced from 7 feet aboard the Apollo spacecraft to 2.5 feet aboard the Lunar Reconnaissance Orbiter (LRO) in 2009 [4]. However, laser terminals used in an optical communication system aboard a spacecraft can be as small as 4 inches, which equates to a 5,625% reduction in area [4].

Calculations for a laser link between Mars and Earth have been made in Laser Space Communications written by David Aviv [5]. David was able to compute the size and power requirements for an optical communication antenna. David states a configuration which uses a 20-cm aperture on Mars would achieve a 10 megabit per second data rate with an average transmitter power of 3 watts and distance of 1AU. David also describes a configuration involving a relay satellite orbiting Mars with a 30-cm aperture capable of achieving a data rate of 70 megabits per second with an average transmitter power of 3 watts. The ability to utilize optical communications will allow our Mothership to send and receive data similar to a common internet connection on Earth, while preserving the reliability of an RF system as a backup.

Life Support:

Our Mothership will also be using a regenerative life support system currently used on the International Space Station (ISS) called the Environmental Control and Life Support System (ECLSS). This system will be the crew's lifeline and main system used during the mission and will be in charge of recycling the reusable materials that the crew uses.

Propulsion and Main Power Source:

The decision process for selecting the main propulsive source of the IPV was based on a few key characteristics: thrust, specific impulse, thrust to weight ratio, ability to maintain sustained engine operation, technology readiness level and reliability. The types of propulsion considered included solid-fuel chemical propulsion, liquid-fuel chemical propulsion, ion propulsion, Bimodal Nuclear Thermal Rocket (BNTR), and solar sails. Each of the power sources was ranked from 1-5 to determine what would be the best propulsion source for the IPV.

	Solid-Fuel	Liquid Fuel	Ion Propulsion	BNTR	Solar Sails
Thrust	4	4	2	5	1
Specific Impulse	1	2	5	3	5
Thrust to Weight Ratio	1	3	5	4	5
Restartability	1	5	5	5	3
TRL	5	5	2	4	1
Reliability	4	4	3	3	1
Overall Rating	16	23	22	24	16

Table III-1: Overall Ratings for Propulsion Sources

For an interplanetary transport vehicle, a solid-fuel propellant engine would not be realistic due to the immense amount of propellant needed for the duration of the mission as well as issues regarding restartability of the engine. A liquid-fuel propellant engine could be achievable but this design does lack the higher specific impulse which a BNTR engine can provide; therefore, leading to shorter duration travel which is critical with a crew onboard. An ion propulsion system does have a high specific impulse and an excellent thrust to weight ratio capability but the amount of power needed to achieve the thrust necessary to propel the IPV would be significant. Additionally, ion propulsion engine has not been tested at the scale necessary for the IPV. Solar sails concept does provide excellent specific impulse and thrust to weight ratio; however, the technology readiness level is not at a level where this can be considered for the IPV. Additionally, this technology is more suitable for interstellar travel during which the thrust can reach a significant level.

The main power source of the IPV was determined to be a Bimodal Nuclear Thermal Rocket (BNTR). This propulsion source can generate high thrust with a specific impulse of 900 seconds or more. This technology has been developed and ground-tested under NASA’s NERVA (Nuclear Engine for Rocket Vehicle Application) program in the 1960’s during which twenty reactor tests and two full-scale engine system tests were performed [6]. Using the improvement in technology regarding materials and efficiency available today, this propulsion source can serve as a reliable propulsion source for the IPV.

By configuring the nuclear thermal rocket for “bimodal” operation, it can provide electrical power for crew life support, high data-rate communications and maintain thermal homeostasis for critical structures and fluids stored within the IPV. The rocket uses a fission reactor core containing enriched Uranium-235 as fuel to generate thermal power required to heat the liquid hydrogen propellant to exhaust temperatures. A representative cross-section of the nuclear reactor is shown in the figure below [6].

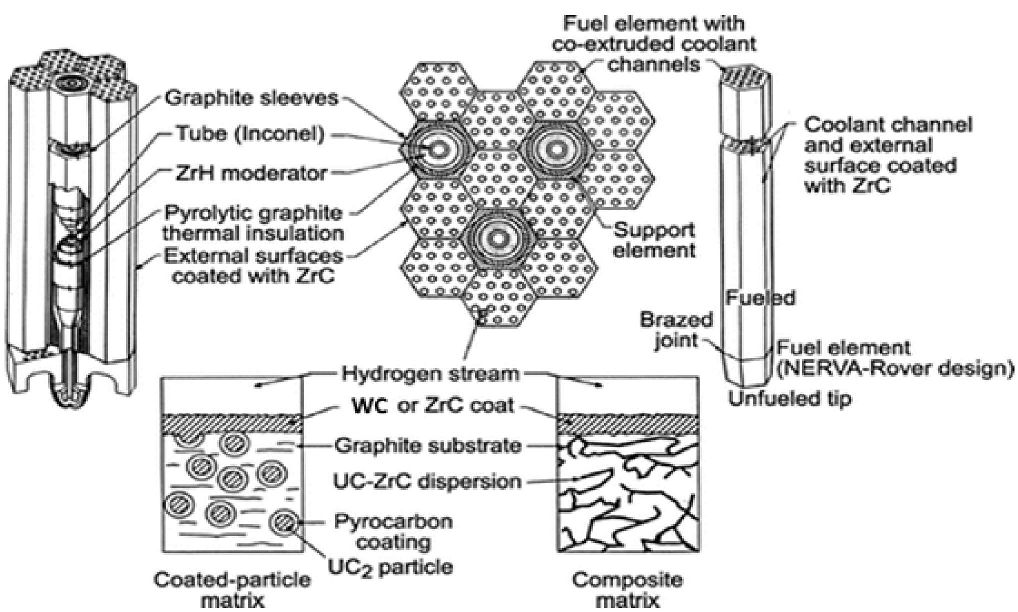


Figure III-1: Representative Cross-Section of the BNTR Nuclear Reactor [6]

The nuclear reactor consists of a tricarbide fuel element consisting of uranium, zirconium, and tungsten carbide (UC-ZrC-WC) reaching a maximum operating chamber temperature near 3200 K [6]. The main combustion chamber will have a maximum expected operating pressure (MEOP) of 1000 psi with a nozzle ratio of 200:1.

The overall propulsion system of the IPV utilizes three BNTR where each is designed such that it can meet a short, high thrust propulsion phase where it can produce ~340 MW of power and ~ 15 klb_f of thrust as well as a long, power generation phase in idle mode where it can produce just ~150 kW of power [7].

Supplementary Power:

In addition to the main nuclear power generator, our Mothership will contain an array of solar panels in order to generate power as a backup source. Since the power that solar panels can produce is inversely proportional to the distance from the sun as shown in:

$$\boldsymbol{Solar\ Radiation\ Intensity} \equiv \boldsymbol{G_{sc}} = \sigma \cdot T^4 \cdot \left(\frac{R}{D}\right)^2 \qquad (Eq.\ B-1)$$

We will need a large array in order to generate enough power. From the calculation in Appendix B, Mars has a solar constant of 581 W/m^2 and with current technology, the maximum efficiency for a single solar panel is 26.6 percent [8]. In order to produce 1kW of power, our solar cells would need to be roughly 6.47 m^2 in size [9].

C. Infrastructure

The main communication system will be located at the Mothership; hence, it will be affected by the inherent vibrations of the spacecraft. To stop them from affecting the performance of the system, we decided to include a vibration damper, as the one used in the Mars Reconnaissance Orbiter (MRO). However, if future testing determines that its performance does not meet the standards, the contingency plan will be replacing the previous setup with a "free floating" communications satellite around the IPV.

Given that the Mothership is placed in orbit very close to Phobos, we can infer the communication capabilities of the station by looking at Phobos' motion (circular orbit around Mars' equator, at an altitude of 5980 km). For the duration of the mission, the base will need to be in contact with:

Earth:

As with every manned mission to space, our planet will be the main support for the astronauts as they investigate the Martian system. Laser communications will provide telemetry and scientific data links between the Mothership and Mission Control Centers. However, given the great distance the signal has to cover, Earth communications lag will go from 4 to 21 min.

In addition, direct line of communication with Earth is not always possible from Phobos' orbit for three reasons: Martian eclipse, Phobos' tidal lock and solar conjunction.

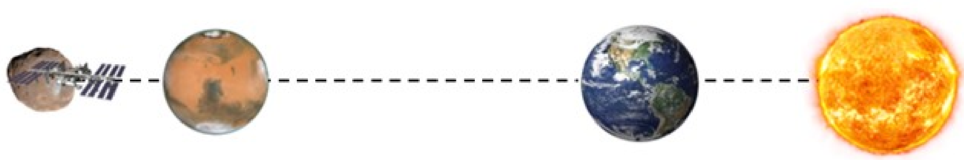


Figure III-2: Martian Eclipse

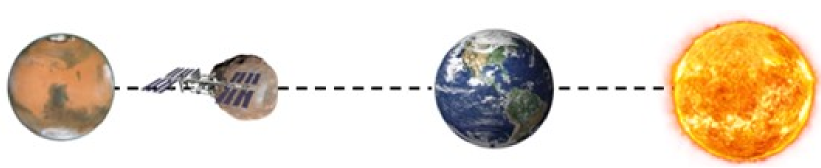


Figure III-3: Phobos' Tidal Lock

The first two will affect our base every orbit, by standing in between the Mothership and Earth. Still, there will be three communication windows per day (once per orbit), 165-170 min each. These are of constant duration throughout the year, and will allow for frequent uplink of science data obtained, as well as status updates and mission commands from NASA.

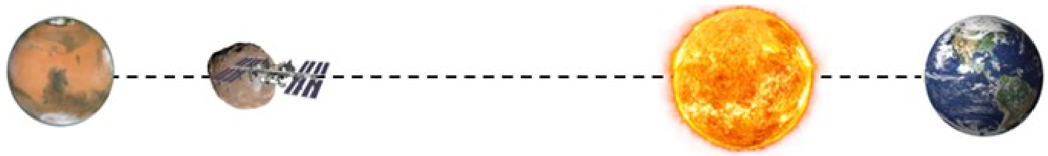


Figure III-4: Solar Conjunction

The only remaining factor in order to guarantee constant yearly communications is the solar conjunction. Fortunately, it is not very frequent (every 26 months; lasts for 3 weeks) and can be overcome by putting up a communications satellite in orbit around the Sun. Our team thought of two alternatives:

1. Placing a satellite in the L4 or L5 Lagrange points.
2. Using the MarsSat setup, by Thomas Gangale [10].

The MarsSat orbits (same period as Mars, but are inclined a few degrees out of the plane) are far superior for this purpose when compared to the L4/L5 option for two reasons. First, L4 and L5 are 228 million kilometers from Mars, about 10 times the distance of a spacecraft in one of the MarsSat orbits. Thus, a relay satellite stationed at L4 or L5 would have to be that much more powerful (and heavy) to receive data at the same rate. Second, a number of Martian Trojan asteroids have been discovered at the Sun–Mars L4 and L5 points, and there are probably countless smaller objects that have collected in these regions that pose a significant threat to any spacecraft. Additionally, the IPV uses laser communications, which are known to have a small beam width. If we consider the time it takes for the laser beam to travel to the L4/L5 points, we could miss the communication satellite completely. Alternatively, the MarsSat setup provides a direct line of sight to Earth even during Solar Conjunction.

Phobos:

The Mothership will be positioned above Stickney Crater, location designated for operations on the surface of Phobos. High-end modules carrying scientific equipment and crew members will land periodically and carry out tests in diverse areas (geology, microgravity, etc.). Radio links will provide support for these tasks, and will also be used during rendezvous and docking procedures and for audio and video communication between crew members.

Given the small altitude above the surface, eclipses will not be an issue. In addition, Phobos is tidally locked to Mars and, as such, constant coverage and direct line of sight can be achieved and maintained from the Mothership without the need for any further considerations.

Mars:

In the beginning, the Mothership will serve as a control center for the operation of rovers on the surface of Mars. These vehicles will explore the Red Planet, looking for the optimal landing site for the crew. It could later provide support to a manned base, which would operate for a short period of time.

Because Phobos moves so quickly, it has short communications passes of 4 hours to sites on Mars every 11.1 hours [11]. Furthermore, assuming that a communications antenna on the Martian surface may have a 5 degree elevation mask due to terrain on the horizon, astronauts on Phobos (or the Mothership) would have line of site communications to a rover up to 64.8 degrees latitude on Mars. This is very important, since the majority of present studies point towards the Martian poles as the most promising landing spots. In order to overcome this issue, the resupply ship can carry a 2-3 communication satellites to be deployed in orbit around Mars. That way, a communication network can be set up, solving the problem as well as serving for future exploration/colonization of the planet.

On the other hand, the two-way speed of light lag from Phobos is 40 ms; this is short enough that hardware latency may be a larger contributor to total communications latency than the distance to Mars. This is the main reason why driving the rovers from the Mothership is so advantageous.

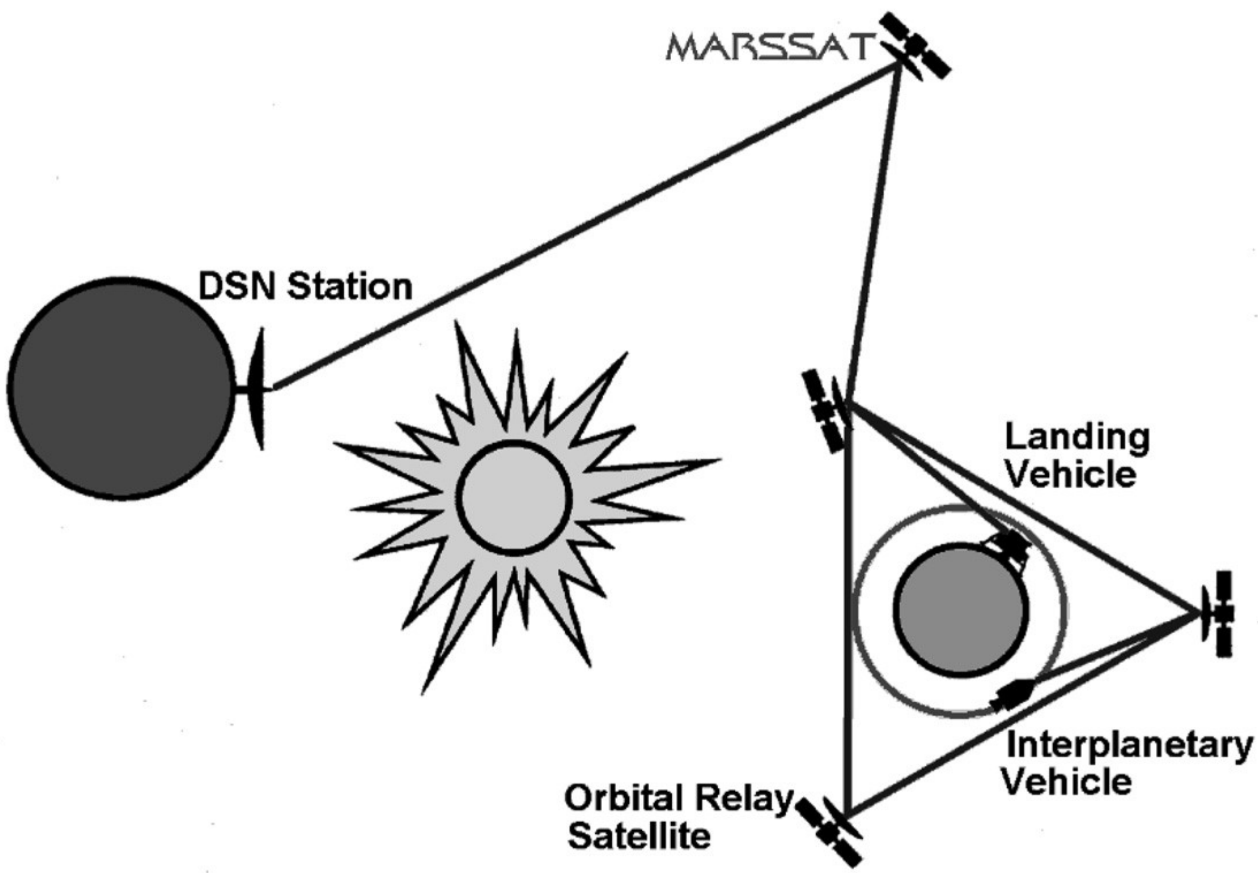


Figure III-5: MarsSat Communications Layout [10]

D. Life Science Provisions

Physical Health Considerations of the Crew:

Interplanetary travel is an extremely risky endeavor for astronauts and must be designed with every precautionary measure in mind. Radiation exposure is a major threat to the safety of the crew and equipment. During their interplanetary transfer outside of the Earth's protective magnetic field, the crews could be exposed to radiation levels similar to receiving a full CT scan every five to six days [12]. An upper estimate for a dose of unshielded astronauts operating outside the Earth's magnetic field, such as a mission to Phobos, is roughly 900 mSv [3]. For reference, the average annual exposure on Earth is roughly 2.4 mSv [13]. This average exposure will quickly approach the 1 to 4 Sv career limits advised by the National Council on Radiation Protection and Measurements for Low Earth orbit activities [13]. An effective shield must be designed in order to protect the most important cargo of the mission, the crew.

The two most effective methods for protecting against radiation exposure are designing more massive shielding or utilizing the most efficient shielding materials. In a perfect world, the interplanetary vehicle would be heavily protected with a dense layer of shielding such as lead. In reality, mass is directly related to costs. Therefore, in order to minimize costs, we must focus on utilizing the most efficient materials in our interplanetary vehicle design. The hydrogen atom, which consists of a single proton and electron, is a great defense against high energy particles [14]. In fact, this is a main reason why the majority of nuclear power generating plants are built around heavy water. In order to reduce a fuel rod's radioactivity in the event of an emergency, plant operators will flood the reactor with water. Luckily for us, hydrogen is the most abundant element in the universe, making it very cost efficient. The mission will require a large amount of water to be stored aboard the interplanetary vehicle, which allows it to serve a dual purpose. Our design utilizes the water being stored by surrounding the major crew occupancy areas and acting as a shield from the harsh radiation.

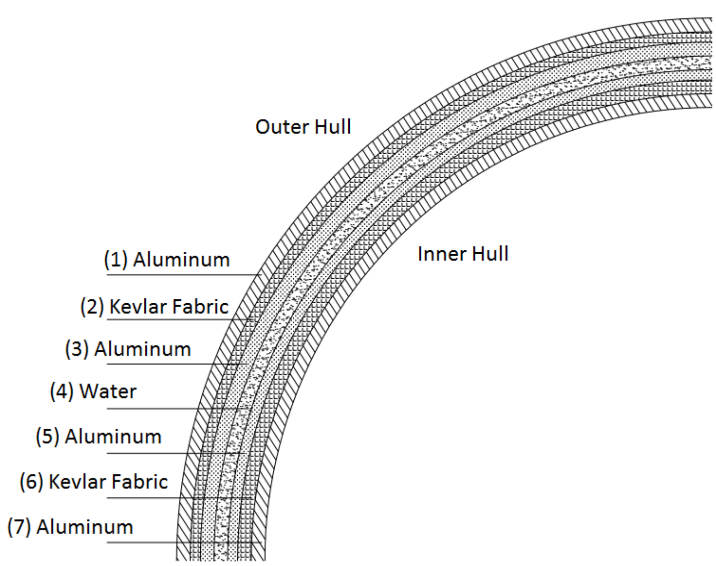


Figure III-6: Layers Composing the Structure of the Hull

Figure 3.6 shows the various layers which make up the structure of the spacecraft's hulls. Layers 1,3,5, and 7 will be composed of a 1/10 inch thick sheet of aluminum. Layers 2 and 6 will consist of a 10cm thick sheet of Kevlar fabric. While layer 4 will act as the toroidal water tank with a thickness of 10cm for the crew's water supply. The outside layers of the spacecraft play multiple roles in ensuring the safety of the crew. They act as a shield against micrometeoroid impacts, reduce the amount of harmful radiation the crew is subject to, and acts as an insulator from the harsh outside temperatures of outer space.

As described in the Reference Guide to the International Space Station, the ISS currently controls the temperatures within the spacecraft by using a Thermal Control System (TCS) [37]. The TCS consists of the Passive Thermal Control System (PTCS) and Active Thermal Control System (ATCS) [37]. The PTCS uses four components: insulation, surface coatings, heaters, and heat pipes and acts as the primary system to control the internal temperatures [37]. "The ATCS kicks in when the heat load exceeds the capabilities of the PTCS and uses mechanically pumped fluids throughout the spacecraft in order to perform three major functions: heat collection, heat transportation, and heat rejection" [37]. Our crew will need to rely on a system similar to the TCS in order to regulate the temperatures within the Mothership and landers. The RECLSS will also help in regulating the internal temperature, however that system would be more focused on controlling the internal humidity.

Mental Health Considerations of the Crew:

It is important to remember the tolls that extended spaceflight can take on a crew. Similar to the ISS, our Mothership will contain recreational items, a system to keep video journal, and possibly an artificial intelligence program which would serve as cognitive behavioral therapy for the crew. These systems may not seem critical, however they play a large role in the psychological aspect of the mission. The crew will require recreational time away from the intense mission to relax, this aid will come in the form of movies, music, games, and time to communicate with friends and family on Earth. As described in the book The Martian written by Andy Weir, the main character, Mark Watney, becomes stranded on the surface of Mars and captures his experiences in a video journal [28]. With nobody to interact with, Mark fills his spare time with old television shows, disco music, and talking to his video camera. Mark became attached to his video journal entries because he felt that he was talking to someone whether it was in the current moment or in the future if someone were to find his journal. The crew in our mission will use the video journal not only to keep a record of their mission, but to send personal videos to Earth. Mission control back on Earth will use these videos to evaluate the psychology of the crew in order to prevent any mental breakdowns. The mission to Phobos will be a long journey, even with these recreational items there will still be times when the crew feels homesick or claustrophobic. During these times, it may help to have an artificial intelligence program on board the ship. In science fiction movies, an artificial intelligence program is shown as a friend to human characters even though it is purely a mechanical device. Currently the technology for an advanced artificial intelligence program has not been perfected. However, when the technology is available it will alleviate the anxiety and claustrophobia that the crew will be subject to.

E. Regenerative Environmental Control and Life Support System (RECLSS)

The Environmental Control and Life Support System (ECLSS) will complete a series of tasks for every manned spacecraft operated in this mission (Mothership, high-end landers, etc.). These tasks include controlling atmospheric pressure, fire detection and suppression and managing nitrogen and oxygen levels. Additionally, the system also will collect, process, and store waste and water used by the crew. Lastly, the ECLSS will produce 50% of the food necessary to feed the crew.

Without landing on the surface of either Phobos or Mars, the physical space and resources in the Mothership are limited. Furthermore, not having a permanent settlement entails that investing in the development of the technology required for a self-sustaining station is not cost-effective for this mission. Thus, a fully regenerative ECLSS (closed loop) is not the most fitting option. Instead, the ECLSS will be designed to support 12 people for at least 2 years in an open loop; supplies will be sent from Earth along with the replacement crew once for every synodic cycle that the base is functioning. The mass estimations for the main consumables are:

Mass (kg) per crew member/day			
	MIN	AVER	MAX
Water	3.71	5.37	7.67
Food	1.3	2.3	3.5
Oxygen		0.835	

TABLE III-2: Amount of Resources Used by the Crew Each Day

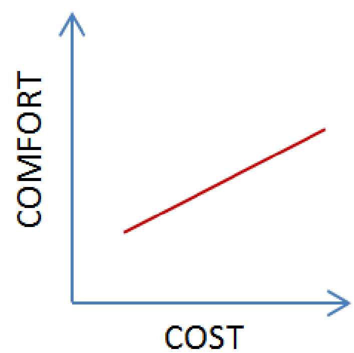


Figure III-7: Comfort vs. Cost

The different approaches (*minimum*, *average* and *maximum*) reflect the relationship between comfort of the crew and the cost. As a general rule, the higher the water content in the food, the better it tastes and the more acceptable it is to the crew, but also means a heavier payload. Planners can envision methods to reduce overall water mass but, even if dehydrated food can save significant mass, its effect on taste and crew acceptance limits its usefulness. The availability of water also affects the hygiene of the crew; since the amount dedicated to drinking cannot be reduced, access to activities such as showering, body wash or oral hygiene could be restricted. Living in these conditions could potentially take a toll on the crew in the long run, but carrying an excessive amount of water would make the spacecraft too heavy and expensive.

For long-duration missions to space stations in LEO, to Mars or other planets, food similar in hydration to International Space Station would provide a comfortable diet [14]. For that reason, the *average approach* was selected for this mission.

Even with intense conservation and recycling efforts, the Station will gradually lose water because of inefficiencies in the life support system. NASA scientists continue to look for ways to improve the RECLSS, reducing water losses and finding ways to reuse other waste products. If the water recycling systems can be improved to an efficiency of greater than about 95 percent, then the water contained in the Mothership's food supply would be enough to replace the lost water [15].

The mission also accounts for the possibility of future In-Situ Resources Utilization (ISRU) at either Phobos or Mars. Although the ECLSS is not dependent on the products of the ISRU, it will make use of these products if they become available.

For instance, one of their first objectives of our crew will be to take samples from Phobos' soil and determine its composition and confirm or refute current theories. Measurements from the Mariner 9 and Viking Orbiter spacecraft led to a commonly held view that Mars' moons are captured asteroids, thought to contain carbon and water ice [3. If that were to be true, it would drastically affect the way the ECLSS works; the mass of resupplies would be greatly reduced, and instead a base on the surface on Phobos would provide for the Mothership.

TOTAL MASS (kg) 12 people, 900 days			
	MIN	AVER	MAX
Water	40068	57996	82836
Food	14040	24840	37800
Oxygen		9018	

Table III-3: Total Amount of Consumables

Finally, we can obtain a rough estimate of the total mass dedicated to consumables that will need to be carried in each resupply. Considering the average approach in all cases, and the 95% efficiency, they add up to about 97 tons.

F. Trajectories

Before the Mothership is actually sent to Phobos, it will be assembled in orbit. Unmanned mission elements are delivered via Space Launch System (SLS) Block 2 to Low Earth Orbit (LEO), where all modules are connected. The ΔV required for this maneuver is around 9.3-10 km/s per launch, depending on the target LEO altitude. It is worth noting that the modeling of the SLS includes an Upper Stage and an Advanced Booster to allow for delivery capabilities on the order of 70-130t, as described in the 2014 SLS Program Mission Planner's Guide [18].

Next, the crew will board the finished Mothership using the Russian spacecraft *Soyuz* and initiate their journey to Mars. Two major types of interplanetary trajectories are proposed:

- Conjunction-class missions are characterized by long stay times on the Martian system (400 to 600 days), short in-space durations (1 year total for the Earth-Mars and Mars-Earth legs), and relatively small propulsive requirements.
- Opposition-class missions have significantly shorter stay times (30 to 90 days), long in space durations (1.5 years total for the Earth-Mars and Mars-Earth legs), and relatively large propulsive requirements.

With sensible increases in propulsive energy, the travel times to and from Mars using the conjunction-class can be reduced by up to 100 days each way [19] (one-way travel times range from 120 to 180 days). This fast transit mission profile minimizes crew exposure to radiation while keeping energy requirements within reason; while the fast transit energy requirements are higher, the physical and mental benefits to the crew are worth the investment. Furthermore, the Mothership has been designed for long stays on the Martian system, which makes the conjunction-class trajectory the most suitable. Not only that, but using the fast transit mission profile would also increase the time on Phobos to 600+ days. After considering the numerous advantages to our mission plan, the first option was selected.

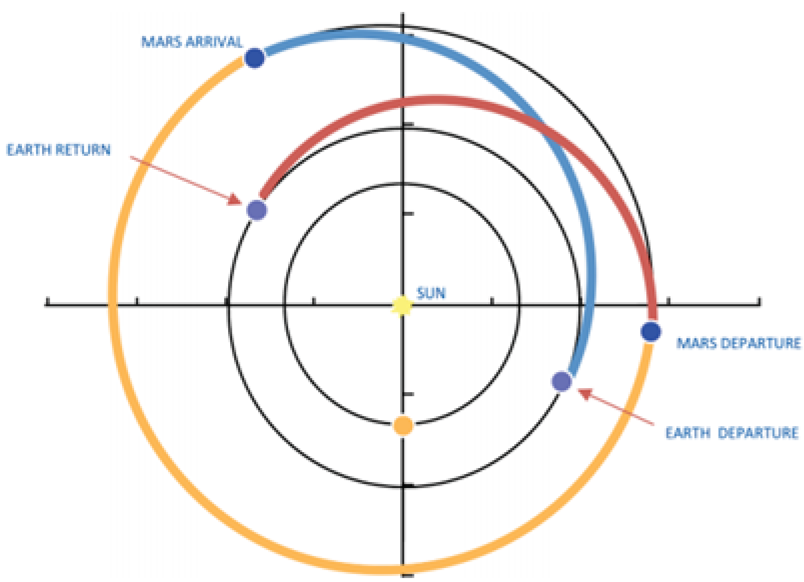


Figure III-8: Representative Conjunction Trajectory Concept [20]

The ΔV needed to enter the transit orbit using a conjunction trajectory has been studied by Paul D. Wooster et al. in the paper *"Trajectory Options for Human Mars Missions"*. Even though the final number is affected by the date of launch and the outward flight time, it can be approximated to 4 km/s, as shown in the figure below.

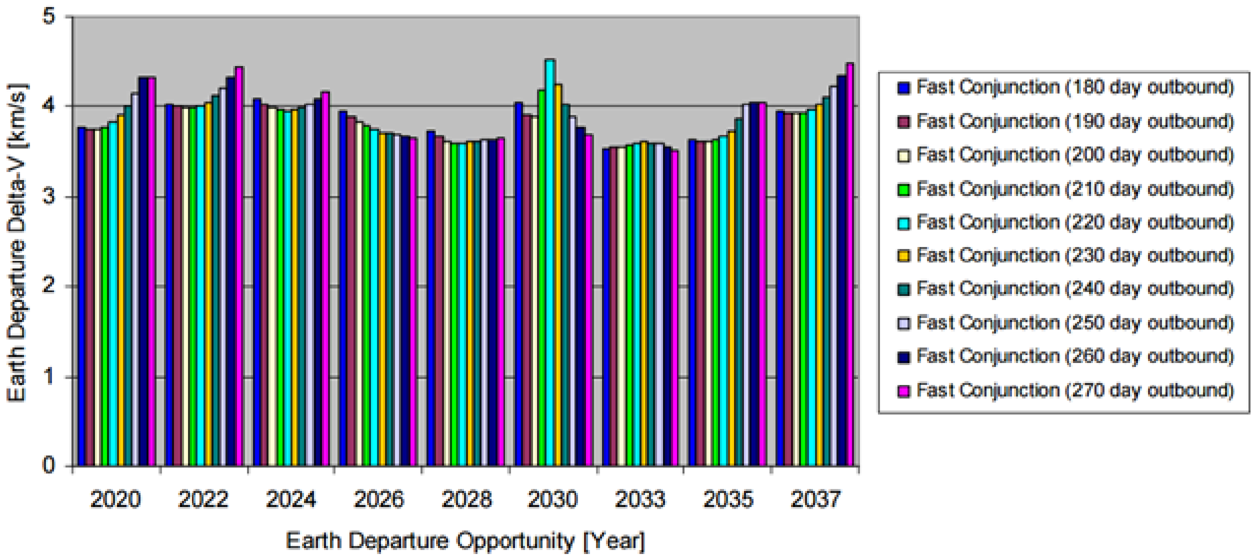


Figure III-9: Conjunction Trajectories, LEO Departure [21]

This result is in accordance with the values shown in Dan Mazanek's presentation in 2013, *"Considerations for Designing a Human Mission to the Martian Moons"*, shown next. Using an analogous technique, the Mothership will be injected into an elliptical orbit after arriving at Mars (1-sol parking orbit, 250 x 33,813 km), which we will be used afterwards to reach our final destination, Phobos.

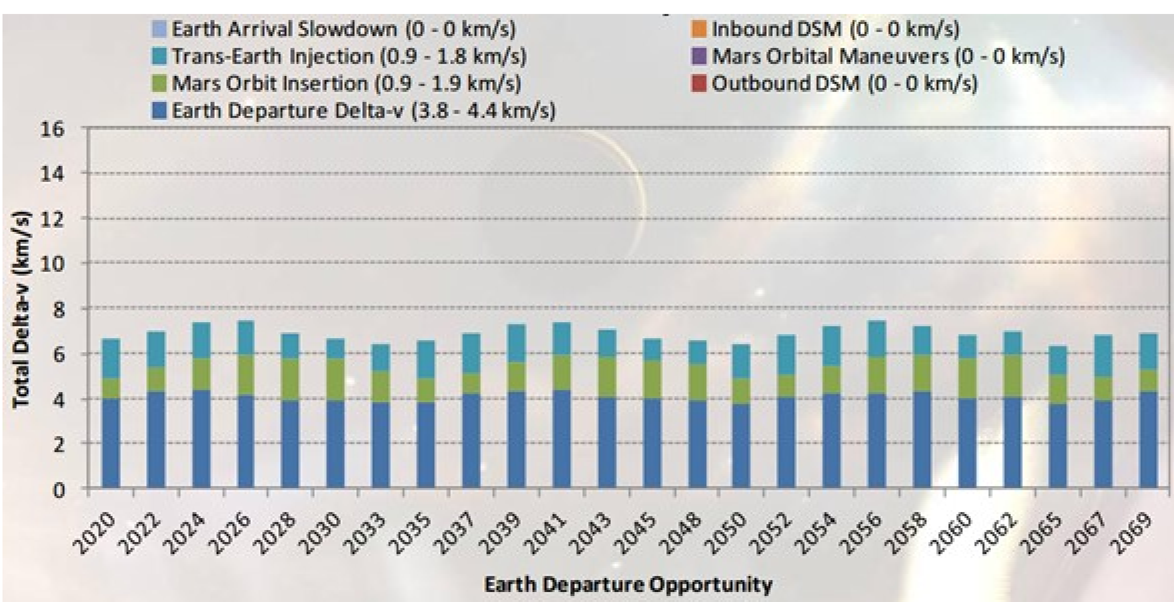


Figure III-10: Conjunction Trajectories, Total ΔV [22]

Phobos is essentially in the equatorial plane of Mars, with nearly circular orbit at 9,378 km. The arrival and departure trajectories will not be in this plane and, thus, additional orbital maneuvers (inclination change and orbit lower/raise) are required once the crew parking orbit is established.

Again, we have two different options: high-thrust transfer and low-thrust transfer. However, we prioritize getting to Phobos as soon as possible, so that its body can be used as radiation protection. In this regard, the second type of transfer (which takes months to be completed), would excessively delay operations on Stickney crater and the mission's timeline. This leaves the high-thrust transfer as the best option.

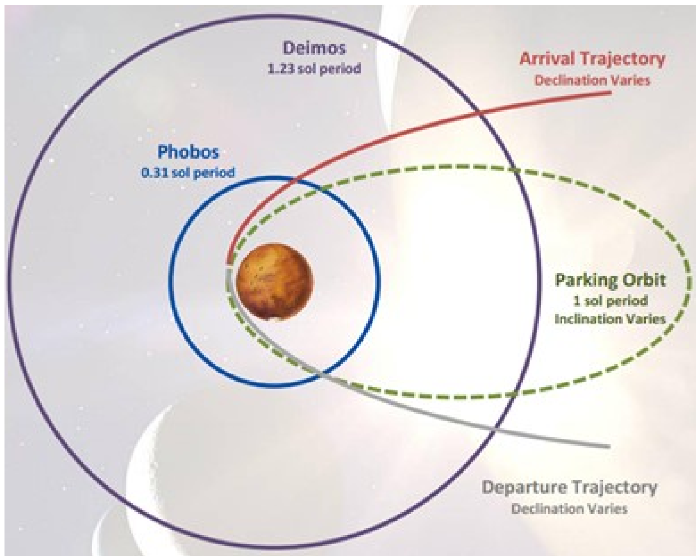


Figure III-11: Maneuvers at Mars [22]

The most efficient to reach Phobos upon arrival at the Mars system is to use a bi-elliptic transfer. At apoapsis of the parking orbit, the spacecraft will perform an additional burn to raise periapsis to the altitude of Phobos, and simultaneously change the orbit inclination to the near-equatorial plane of the moon. A final burn will then circularize the orbit. This can be targeted to match the true anomaly of Phobos by controlling the initial arrival time of the interplanetary trajectory or adjusting the apoapsis of the parking orbit. Using the bi-elliptic technique, the total ΔV required from Mars approach to Phobos is estimated as 2.017 km/s [11]. The return to Earth works in in the same way as the arrival, and the value of ΔV is similar.

Higher apoapsis altitudes can be used to cut the ΔV, but this would increase the time to rendezvous with Phobos. Moreover, using a very high target apoapsis would mean that a slight propulsion underperformance during orbit insertion would leave the spacecraft in a hyperbolic trajectory, which is a safety concern. On the other hand, aerobraking could be used to gradually lower the initial apoapsis altitude without using the engines, potentially reducing the total arrival ΔV, but the Mothership has not been designed to enter the Martian atmosphere.

Finally, adding all of the maneuvers together, the total ΔV (from LEO to Phobos) is determined to range from 8.5 to 10.5 km/s.

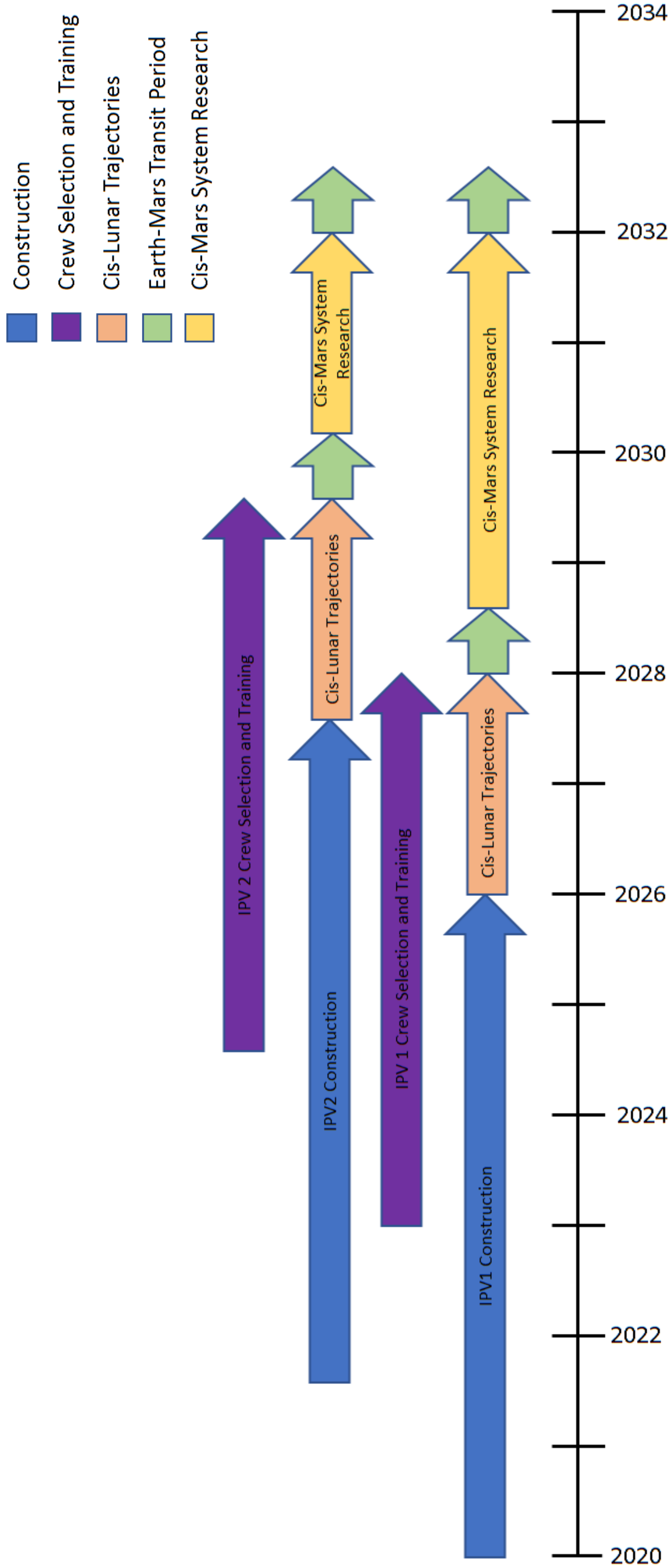
G. Timelines

Once the payloads and trajectories have been determined, as they have been above, the mission timeline can be refined to determine when the IPV begins construction, when crew members are trained and sent to Mars, when mission critical research is performed, and when the return trip is scheduled. It is important to note that recent trends of decreasing solar maximums show that solar cycle 25 and after will have low solar particle fluences and provide a stronger viability for the water jacket shielding the IPV will employ. [39].

Our own rough estimates say solar cycle 24 will end and solar cycle 25 will begin by 2024, so this is when the IPV can begin to consider conjunction class trajectories. Figure 1: Conjunction Trajectories - Total ΔV suggests that conjunction trajectories are possible every two years corresponding to 2024 and later. This provides ample opportunity for departure; however, the team would like to consider the earliest possible start for the mission. It took 18 years to build the International Space Station (ISS); however, the ISS is many times larger than the IPV our design is presenting [40]. With the improved payload delivery capabilities of SLS's launch vehicles, the team believes the IPV structure can be completed within 6 years and then tested and evolved over the course of 2 years within cis-lunar free trajectories. These free-trajectories are approximately 1 month in length and will be used to improve the confidence of the IPV's capabilities and familiarize crew members with IPV controls and mission operations.

SA's Astronaut Candidate Program has a training and selection process of approximately 2 years; however, with the increased danger and length of mission, the candidates should be trained and selected at least 3 years prior to cis-lunar free trajectories and further trained on the preliminarily completed IPV for a total of 5 years. This gives candidates the minimum amount of time to become familiar and mentally prepared for the mission and transit period.

After the IPV has been tested and evolved through cis-lunar trajectories, 6 crew members will be selected for the Phobos mission and start the 4-6 month long conjunction trajectory transit from Earth to Mars that will end with a Mars Insertion orbit at Phobos altitude. Research of Phobos and Deimos will begin immediately after arriving in the cis-Mars system and will focus on creating a regular lander schedule to land on Phobos and Deimos to collect samples. These samples are used to confirm ISRU potential and test low gravity mining techniques. Earth will advise future actions in the event there is a significant breakthrough in any research subject. At the same time, a single rover will be sent to the surface of Mars to begin searching for or confirming potential Mars surface base locations. This research and reconnaissance will be held for the next two years, while Earth is creating a second IPV, named IPV2, for advanced settlement. IPV2 will be modeled and designed exactly the same as the first with an additional 6 crew members, but the subsystems within IPV2 will be focused on getting a manned lander to the surface of Mars, specifically, a manned lander to a Mars surface location that IPV1 has already determined as an ideal surface base. IPV1 and IPV2 will work together with 12 total crew members to begin preliminary settlement actions on Mars. After another two years IPV1 and IPV2 will begin the conjunction trajectory to return home together. Figure III.12 shows a visual representation of the timeline described above if IPV1 is scheduled to be commissioned by 2028.



meline of Expedition to cis-Mars System

IV. Base Assembly and Construction Process

The IPV is composed of 14 critical parts: a Central Solar Storm Shelter, 2 Central Spaces, 8 Side Spaces, a Central Command Center, a Separation Segment, and BNTR Power and Propulsion Module. These components will be built on Earth and launched in SLS's 70-130 metric ton delivery vehicle to Low Earth Orbit (LEO) a minimum of twice a year. The critical parts are launch in the order below:

Solar Storm Shelter:

This is the only section of the IPV that has a power source other than BNTR (solar) and where all other portions of the IPV are built off from. This module is rated to protect crew members from unusually large Galactic Cosmic Rays and Solar Particle Events with a thicker water jacket than the rest of the IPV. Additionally, the Solar Storm Shelter acts as the main docking port for the IPV with two docking locations orthogonal to the solar panels. Thrusters will be necessary to correct trajectory. Launches: 1

2 Central Spaces:

The central spaces are the backbone of the structure and allow access to the main spaces of the IPV. Additional thrusters will be necessary to correct trajectory and combat inertial spin of the system. This section is separated into several to allow: storage, travel between side spaces, and various facilities as needed and protected by a nominal water jacket as mentioned in previous sections. Launches: 2

8 Side Spaces:

Similar to Central Spaces, the side spaces are used as the main storage, research and recreational facilities, living quarters, Medical Bay, and other necessary facilities. These sections are one of two locations with viewing windows and located at orthogonal intervals around the Central Spaces. Launches: Up to 8

Central Command Center:

This is located at the head of the IPV and is used as the central command center for all operations. In the event that this section becomes compromised, the Central Storm Shelter can be used as the next available command center. Communications are mainly overseen in this section and is the only area with a viewing window other than the Side Spaces. The Central Command Center is also capable of detaching from the head of the IPV to perform Vehicular Activity outside the IPV or provide another docking port as necessary. Launches: 1

Separation Segment:

This section is located centrally aligned with Central Spaces, but is slightly thicker to account for the force from the BNTR propulsion and to carry propellant. It connects the BNTR Power and Propulsion Module with the main living spaces, but also separates the two sections to provide an extra layer of safety between the crew members and the BNTR Power and Propulsion Module. All of the section will be dedicated to propellant storage, so any necessary repairs will have to be performed through EVA. Launches: 1

BNTR Power and Propulsion Module:

This section provides the power and propulsion to the IPV as discussed earlier in the proposal. This is also the final section to be installed. The IPV needs to be completed before the BNTR Power and Propulsion Module can be installed to ensure the integrity of the IPV and to make sure the IPV's water jacket shield can flood the BNTR module in the event a meltdown is possible. Launches: 1

With a maximum of 14 launches, the IPV will be preliminarily completed and can move onto IPV testing in cis-lunar trajectories. These trajectories hold two purposes: 1) to test the IPV structure and evolve the systems as problems arise, and 2) to familiarize the selected crew member candidates with the IPV systems and operations. This will be performed for a minimum of two years with as many cycles as possible to acquire sufficient confidence in the IPV structure and mission design.

V. Life Science Countermeasures

A. Microgravity

Living in a microgravity environment for a long period of time can have many negative side effects to the human body. It can cause a decrease in bone mass (also known as disuse osteoporosis), muscle atrophy, motion sickness, and some may temporarily lose their ability to walk when they return to a gravity rich environment. Studies upon the MIR space station have shown that space travelers can lose one to two percent of bone mass on average each month [16]. Although there have been many studies conducted in microgravity, the cause of these side effects remains unknown. It is important for our design to include a variety of systems and precautions to lessen the side effects of prolonged exposure to a microgravity environment.

Our Mothership will utilize technology already present on the ISS, the Advanced Resistive Exercise Device (ARED). This device "uses adjustable resistance piston-driven vacuum cylinders along with a flywheel system to simulate free-weight exercises in normal gravity" [17]. ARED's function is not only to prevent muscle and bone mass, it will also serve as a "resistive exercise which also helps astronauts increase their endurance for physically demanding tasks such as spacewalks" [17]. Once the crew arrives at Phobos and the surface of Mars, they will need to be in the best physical condition in order to carry out their research. The crew will also have the Combined Operational Load Bearing External Resistance Treadmill (COLBERT), which will serve as a cardiovascular exercise. The ARED and COLBERT machines will be the primary means of building muscular strength and endurance in the microgravity environment. Currently, crew upon the ISS are participating in a study called the Integrated Resistance and Aerobic Training Study (SPRINT), which evaluates the use of high intensity, low volume exercise rather than the traditional low intensity, high volume program [25]. The crew upon our Mothership will utilize the training techniques of SPRINT which calls for three days per week of ARED training and alternating days of high intensity interval training with COLBERT [25]. The researchers of SPRINT predict this new training program will better protect against bone and muscle loss as well as improve muscle recovery and endurance compared to traditional programs [25].

Astronauts can quickly become disoriented when they first experience weightlessness, which can cause space sickness. Dr. Victor Schneider, research medical officer for NASA's Biomedical Research and Countermeasures program states, "when people go up into space, many will immediately get space sickness." [23]. The body's vestibular system can feel the pull of gravity when we are on the earth, which allows the brain to identify the body's orientation [23]. Without the pull of gravity, one's view can appear topsy-turvy. Before launching into space, the crew will need to undergo weightless training in order to become familiar with the disorientation. The Mothership will also contain a ready supply of medication to treat the space sickness. Fortunately for the crew, space sickness doesn't tend to last long. Dr. Schnieder states, "space sickness relieves itself after about 3 days" [23]. This is due to the brain's ability to "reprogram" the signals it receives in order to adapt to its new environment.

B. Radiation

As described in section III.D, the Mothership will partially protect the crew from harmful radiation with its toroidal water tank surrounding the critical portions of the IPV. The crew will also need to be protected from the harsh environments when they leave the spacecraft. Their space suits need to protect them from not only the vacuum of space and extreme temperatures, but from radiation as well. During the shuttle program, NASA had two sophisticated space suits called the Advanced Crew Escape Suit (ACES) and Extravehicular Mobility Unit (EMU) [26]. Since these suits were designed for use within the Earth's protective magnetic field in low-Earth orbit, they will not provide the required amount of radiation protection for our mission to Phobos. An Israeli-American company, StemRad, has produced a vest which is made up of non-metallic protective materials [27]. StemRad claims their product has been proven in the laboratory and is scheduled to launch aboard the Orion spacecraft in its unmanned orbit about the moon in 2018 [27]. This vest isn't designed to only be worn outside the Mothership. It is intended to be worn during the entire mission in an effort to protect the crew's vital organs, tissue, and stem cells [27]. In an effort to design a product that is both protective and comfortable, StemRad has designed each vest to be tailor-made for each crew member [27]. This will prevent the crew from shedding the vest due to it hindering their activities or being too bulky.

C. Dust and Contaminants

Dust and contamination can cause major issues for the Mothership and lander systems, not to mention the health and safety of the crew. "For planetary surfaces, such as mars, the airlock itself is a major source of contamination in the form of dust, which is abrasive compared to dust on Earth." [31] In an effort to reduce the amount received, our space suits will be designed with NASA's Suitport technology. Figure X.XX is from a powerpoint presentation by Natalie Mary, an EVA systems engineer, in which she describes the suitport and how the crew would enter the space suit through the back hatch of the suit [32]. The suitport allows the crew to enter their space suits without bringing them into the airlock as performed on the ISS; greatly reducing the amount of contamination received from the outside environment. However, the spaceport system will not be 100 percent efficient, there will still be some contaminants that enter the landers and IPV. In order to filter out these contaminants all the pressurized cabins will contain a Heating, Ventilation and Air Conditioning (HVAC) system with efficient filters.

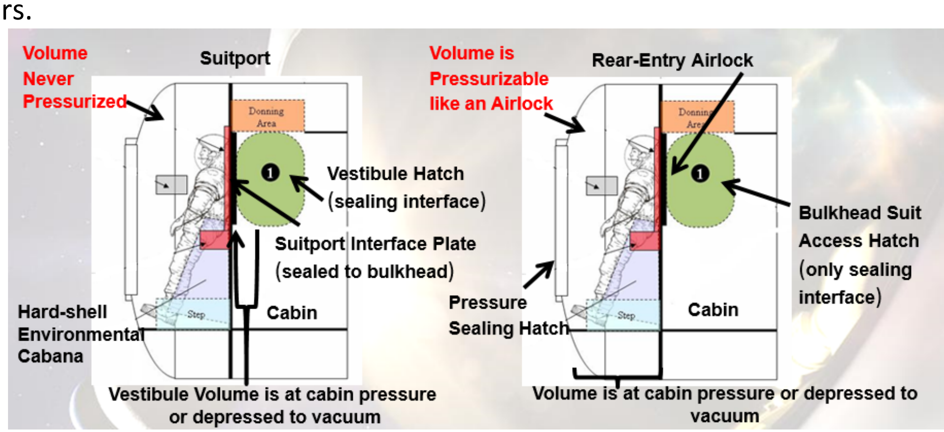


Figure V-1: Profile View of the Suitport Entry [32]

D. Planetary Protection

While protecting our spacecraft and crew from contaminants is vital, we must also recognize that our mission could contaminate possible life that may exist in the form of microbes on Mars or Phobos. NASA has created the Office of Planetary Protection for this very reason. The Office of Planetary Protection has created strict categories for missions as shown below in Figures X.XX and X.XX which restrict some operations and set higher level of cleaning processes for missions which could provide signs of life [36]. Seeing that our mission to Mars and Phobos would be a manned mission, it would fall into a category which hasn't been released by the office yet. However, seeing that humans could easily contaminate the environments on Mars and Phobos, our mission will need to follow the strictest operations and cleaning procedures for the vehicles and research tools. The Office of Planetary Protection is also responsible for the protection of Earth from possibly harmful contaminants when the crew returns from their mission. The Office of Planetary Protection has developed plans to protect the Earth in case any Earth-return missions are carrying harmful extraterrestrial samples [36].

Types of Planetary Bodies	Mission Type[1]	Mission Category[2]
Bodies "not of direct interest for understanding the process of chemical evolution or the origin of life."	Any	I
Bodies of "significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could compromise future investigations."	Any	II & II*
Bodies of significant interest to the process of "chemical evolution and/or the origin of life", and where "scientific opinion provides a significant chance that contamination could compromise future investigations."	Flyby, Orbiter	III
	Lander, Probe	IV[3]
Earth-return missions from bodies "deemed by scientific opinion to have no indigenous life forms."	unrestricted Earth-Return	V (unrestricted)
Earth-return missions from bodies deemed by scientific opinion to be of significant interest to the process of chemical evolution and/or the origin of life.	restricted Earth-Return	V (restricted)
[1]*If gravity assist is utilized during a flyby, constraints for the planetary body with the highest degree of protection may be required.* [2]*For missions that target or encounter multiple planets, more than one PP category may be specified.* [3]*Category IV missions for Mars are subdivided into IVa, IVb, and IVc.*		

Table V-1: Office of Planetary Protection Mission Types and Categories [36]

Types of Mars Missions	Mission Type	Mission Category
Lander systems not carrying instruments for the investigations of extant Mars Life.	Lander, Probe	IVa
Lander systems designed to investigate extant Martian Life.	Lander, Probe	IVb
Missions investigating Martian Special Regions, even if they do not include life detection experiments. Martian Special Regions include those within which terrestrial organisms are likely to replicate and those potentially harboring extant Martian Life.	Lander, Probe	IVc

Table V-2: Office of Planetary Protection Mission Types and Categories for Mars Missions

VI. Arrival on Extraterrestrial Bodies With Landers

A. Crew Transfer from the Interplanetary Vehicle (IPV) to the Extraterrestrial Body

Phobos/Deimos:

Crew members will take a lander, docked at the Solar Storm Shelter, and utilize NASA standard Extravehicular Activity (EVA) protocol to detach from the IPV and perform rendezvous trajectories to the moon. The low gravitational acceleration of 0.0057 m/s^2 and 0.003 m/s^2 for Phobos and Deimos, respectively, allow the landers to use trajectories that virtually neglect gravitational forces between the two bodies, similar to a Soyuz-to-ISS docking procedure. Thrusters on the landers are still available for fine attitude control and to leave the moon.

Mars:

A special lander that takes advantage of the IPV's side space will be used to perform manned or unmanned landings to the moon. This side space will be designed similarly to the Space Shuttle and detached from the IPV to perform atmospheric entry to Mars. The atmosphere of Mars is filled with dust storms and particles with a gravitational acceleration of 3.711 m/s^2. This makes Mars Entry, Descent, and Landing (EDL) incredibly difficult. To save on propellant, the team suggests a hybrid landing procedure of reverse propulsion and aerobraking through dust storms. There has not been extensive research on this subject, so we can only imagine the potential costs of developing a Side Space capable of withstanding heat of entry and compare them to the potential benefits we save from using a hybrid landing procedure.

B. Process by which the Lander provides a temporary base of operations

Phobos/Deimos:

The landers need to designed to be capable of sustaining up to 3 crew members for at least 1 full day on the extraterrestrial body while protecting crew members from galactic cosmic rays. The lander would not be capable of protecting against solar particle events, so careful monitoring of incoming events are necessary for the safety of the crew. This amount of time provides the crew members ample time to collect surface samples, and a location for crew members to recuperate after long EVA periods. Additionally, landers will be equipped with Prototype Exploration Suits (PXS), so landers will keep pressure and environmental control. Rather than bringing more consumables to depressurize and pressurize the Lander cabin, more consumables can be brought along with the lander to support crew members instead.

Mars:

The Mars Lander is transporting a next generation rover to the surface of Mars [41]. However, this rover will not be acting as a base of operations, but rather used to explore the surface of Mars in place of crew members. It will be regularly monitored; however, when a potential Mars surface base is determined, an areosynchronous orbit can be achieved maintain constant teleoperations with the rover. However, when manned Landers are sent to Mars, the Lander will act similarly to the Phobos/Deimos lander and provide a temporary base of operations using PXS space suits and sample collection.

C. Crew return from Research Site

Phobos/Deimos:

Landers will return using the same thrusters used to land and perform trajectory or attitude corrections. Since the gravity on either moon is incredibly small, the thrusters will provide sufficient force to remove the Lander from the moon's surface and perform docking procedures.

Mars:

The crew will return from Mars with the help of a prepared launch vehicle stored within the Side Space sent with the Lander. This method only allows as many Mars EDL and Ascent as there are Side Spaces fitted with landing hulls similar to the Space Shuttle. IPV2 will control the number of landing vehicles and will have a minimum of two Landers designed for Mars entry.

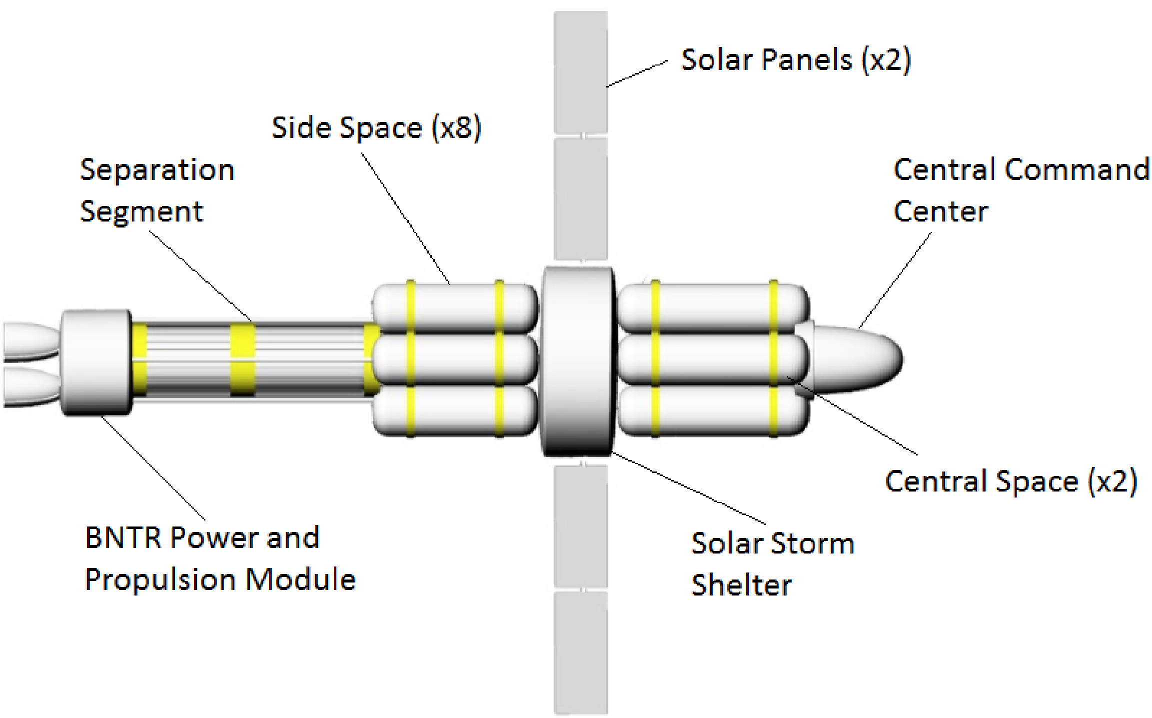


Figure VI-1: Layout of the IPV

VII. Concept of Operations for Completed Phobos Base

All Crew Members on IPV:

After an initial team review of mission plans, crew members, that are assigned, can begin preparations for Lander EVA or continue research that has been brought along for deep-space exploration. At least one crew member will be assigned to the Central Command Center to monitor communications and have line-of-sight visual of any potential threats to the IPV. The assignment will be worked in shifts throughout the day and at least one member of the team will be awake. Additionally, all crew members will have a regular physical and psychiatric review to maintain crew health. This information along with any research performed during the day will be sent back to Earth during the next communication window.

Some Crew Members on IPV:

At least 3 crew members must be on the IPV at all times in order to have enough individuals present for emergency situations. If one crew member becomes incapacitated, there will be still be one for communications and another for IPV control. This is the same for all Landers.

Extravehicular Activity:

There will be a minimum of two crew members performing EVA to monitor one another for anomalous behavior or health; however, emergency situations can override this statement. Ideally, even if 3 crew members are performing a Lander mission, there will still be two members for EVA, while another crew member monitors from the Central Command Center.

Communications:

During operations, the crew will need to contact Earth for diverse reasons (mission commands, scientific data, video and audio messages to family, etc.). As previously indicated, there are three communication windows per day (165-170 min each), which means daily contact is possible (and desired). The first comm window of the day will give the astronauts the programmed schedule and directives from the Mission Command Center.

Since the amount of data that needs to be sent back is usually much larger than the uplink data rate, the second comm window should be used to upload the most important information obtained by the crew. In the end, part of the data will not be transmitted during operations, but it will instead be brought back in the second Mothership with the replaced crew (every 2 years).

Finally, the third comm window will generally be unused, left to possible emergencies or unexpected events; that way, the crew will have some free time after each shift. In relation to this, this spare window could also serve an additional purpose once a week, i.e. personal vlogs, chat with family, download of new leisure items such as music or books, etc.

VIII. Critical Technologies and Their Current Technology Readiness Level (TRL)

Figure IX-1: TRL Levels Breakdown [29]

Laser Communications:

Laser communications will be a critical technology which allows the crew to send and receive data at a high rate compared to current RF communications. This system was completed and flight proven on board the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission in 2013. This mission broke the record for data transmission with a download rate of 622 megabits per second and an upload rate of 20 megabits per second. Therefore the current TRL for this system would be TRL 9.

Bimodal Nuclear Thermal Rocket Propulsion (BNTR):

Bimodal Nuclear Thermal Rocket (BNTR) propulsion is one of the key technologies enabling transportation of the crew and supplies to the Martian system in a timely and cost-effective manner. This technology currently is at TRL 6 since it has been ground-tested during the NERVA program by NASA in the 1960's [33]. However, in order for this technology to be "flight qualified" several tests will need to be performed in the years leading up to the deployment of the BNTR to LEO for assembly.

Environmental Control and Life Support Systems (ECLSS):

ECLSS technology has been successfully implemented for over a decade in the International Space Station (ISS), proving that astronauts can live safely in space. However, this mission will require a much more developed system, given its long duration and the far greater distance from Earth's support. For instance, ISRU technology has not been tested and we will not know how it performs in the different environments of both Mars and Phobos until we actually get there. In addition, packaging and preserving of food that lasts up to 2 years in reduced gravity is an issue. The growth of food in microgravity has not been developed enough to fulfill the requirements (50% of the total food) either. If we were to look at the separate subsystems, we would find that most items have a current TRL 2-5 [38] but, according to NASA estimates, the ECLSS technology will be ready in 4-6 years; soon enough to make this mission possible.

High-End Landers:

High-End Landers capable of sustaining up to 3 crew members for a full day have not been developed or tested; however, technology within the Landers are both tested and in testing: such as an ECLSS system within a Lander sized module and a PXS spacesuit, respectively. This technology would range from TRL 2-5 since some components have been tested in relevant environments, while other components are still being prototyped; however, the overall Lander should be rated at TRL 2 since the Lander has not been engineered as a single system.

IX. Conclusion

After studying the value proposition of a Phobos mission we concluded that, if the final goal is to colonize Mars, a mission to establish an operational base on Phobos is a waste of resources. With a similar budget size, an operational base on Mars' surface is just as feasible and can still provide an opportunity to explore Phobos and Deimos. Setting up a base on either of these moons, however, is not necessary. Additionally, ISRU potential is significantly higher on the surface of Mars and, still, a completely viable surface base has not been established. This is what our design solution seeks to resolve.

For Mars exploration and settlement expedition mission, we propose an Interplanetary Vehicle (IPV) with a capacity of up to 12 crew members that will orbit in the vicinity of Phobos, used for radiation protection. Since no midflight abort strategies have been considered, the IPV depends on critical life support system redundancies and spares. Therefore, it will also carry all consumables for each synodic cycle of opportunity (resupplies are sent in a secondary spacecraft), and includes landers and rovers for extraterrestrial body exploration. That way, we suggest a more cost-effective and short-term method of researching the cis-Mars's space until a permanent settlement can be built on the Martian surface.

Operations are proposed to be conducted during the solar maximum period to minimize GCR flux, but measures against radiation have been taken regardless, given the great effect they could have on the crew. The IPV has a substantial solar storm shelter that is surrounded by a water jacket to ameliorate effects of up to X class CMEs. This water jacket also has the capacity to produce enough fuel for all propulsion needs, performed with a BNTR that will be evolved and tested in the cislunar regime before being implemented on the IPV. A suitable base location on the Martian surface might be identified well in advance, or confirmed during the initial phases of IPV operations. Then, it may be advantageous to park in the denominated "areosynchronous orbit" instead, directly above the surface site of operations. This would allow continuous monitoring of Mars and would serve as a wideband teleoperations and communications relay for exploration and settlement establishment activities. Further development of Mars Colonization using the IPV Mothership as the main form of transport may be also pursued after the mission has concluded.

In the upcoming future, structures could be 3D printed in microgravity using powdered metals, very much accelerating and simplifying the construction of an independent base. Mining in microgravity is another technology that will be researched and further developed with the help of our mission, enabling in-situ collection of resources from extraterrestrial bodies not large enough to have significant gravitational forces. In the decades to come, humanity will most likely continue to expand throughout the Solar System, towards Jupiter, Saturn and Jovian satellites that seem to hold more promise for life sustaining materials. The development of long-term human spaceflight systems using the technology proven on the IPV will serve as the foundation of this exciting adventure. However, one thing is clear: space mission designers should consider how confidence can be built from the definition of necessary steps to achieve a mission design goal, rather than just engaging in detailed engineering studies and tools without arriving at a sound program.

X. References

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APPENDIX

A. ECLSS Mass Budget Expanded Table

CONSUMABLES	Mass	Subtotal
Air (Oxygen)	0.835	9018
Water	5.37	57996
Food	2.3	24840
Human accommodations		11477.6
GALLEY AND FOOD SYSTEM		
Freezers	400	400
Conventional Oven	50	50
Microwave ovens (2)	70	70
Kitchen cleaning supplies	0.25	225
Sink, spigot	15	15
Dishwasher	40	40
Cooking/eating supplies	5	60
WASTE COLLECTION SYSTEM		
Toilets (2)	90	90
WCS Supplies	0.05	540
Contingency collection bags	0.23	2484
PERSONAL HYGIENE		
Shower	75	0
Handwash faucet	8	8
Personal hygiene kit	1.8	21.6
Hygiene supplies	0.075	810
CLOTHING		
Clothing	99	1188
Washing machine	100	100
Clothes dryer	60	60

TABLE A-1: ECLSS Components Part 1

RECREATIONAL EQUIPMENT		
Personal stowage/closet space	50	600
HOUSEKEEPING		
Vacuum	13	13
Disposable wipes	0.3	0
Trash compactor	150	150
Trash bags	0.05	540
OPERATIONAL		
Operational supplies	20	240
Restraints and mobility aids	100	100
MAINTENANCE		
Hand tools	300	300
Spare parts/consumables	--	--
Test equipment	500	500
Fixtures, large machine tools, etc.	1000	1000
PHOTOGRAPHY		
Equipment	120	120
Film	0	0
SLEEP ACCOMMODATIONS		
Sleep provisions	9	108
CREW HEALTH CARE		
Exercise equipment	145	145
Medical suite	1000	1000
Medical consumables	500	500

TABLE A-2: ECLSS Components Part 2

B. Solar Panel Calculations

$$\boldsymbol{Solar\ Radiation\ Intensity} \equiv \boldsymbol{G_{sc}} = \sigma \cdot T^4 \cdot \left(\frac{R}{D}\right)^2 \qquad (Eq.\ B-1)$$

- **Where:**

$$\boldsymbol{\sigma} \equiv \boldsymbol{Boltzmann\ Constant} = 5.67 \cdot 10 - 8 \cdot \frac{W}{\mathrm{m}^2 K^4}$$

$$\boldsymbol{Radius\ of\ the\ Sun} \equiv \boldsymbol{R} = 6.96 \cdot 10^6\ m$$

$$\boldsymbol{Temperature\ of\ the\ Sun} \equiv \boldsymbol{T} = 5785\ K$$

$$\boldsymbol{Distance\ from\ the\ Sun\ to\ Mars} \equiv \boldsymbol{D} = 228 \cdot 10^9\ m$$

- **Then:**

$$G_{sc} = 5.567 \cdot 10^{-8} \frac{W}{\mathrm{m}^2 K^4} \cdot (5785\ K)^4 \cdot \left(\frac{696 \cdot 10^6\ \mathrm{m}}{228 \cdot 10^9\ \mathrm{m}}\right)^2 = \mathbf{581}\ \boldsymbol{\frac{W}{m^2}}$$

- **Calculation For 1000W of Generating Power:**

$$\boldsymbol{Solar\ Panel\ Area} \equiv \boldsymbol{A} = \frac{Power\ Generated}{(Solar\ Radiation\ Intensity)(Efficiency)} \qquad (Eq.\ B-2)$$

$$A = \frac{1000\ W}{581\ \frac{W}{\mathrm{m}^2} \cdot 0.266} = \mathbf{6.47}\ \boldsymbol{m^2}$$