ARES

To Mars and beyond.

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1.0 Executive Summary

Throughout the 21st century, the initiative to explore and learn more about the celestial bodies in the solar system has increased throughout the world. Missions to planets, moons, and asteroids have proven to be lucrative in providing groundbreaking scientific research and discoveries. The Ares mission seeks to continue this initiative by visiting and landing on the moons of Mars: Phobos and Deimos, for the first time. The primary goal for this mission is to investigate the realm if physical science that would characterize both environments found on the moons of Mars. This mission seeks to study these unchartered moons to deliver information on their origin, establish telecommunication for future endeavors, and distinguish each of their environmental conditions to aid with the viable establishment of potential human bases on Mars.

Seven principal scientific objectives were established in the development of this mission. These include surveying and classifying the composition of Mars's two moons, viewing both bodies across different portions of the electromagnetic spectrum, measure and confirm the lack of a significant magnetosphere surrounding each moon, establish the differences in weathering conditions present, deploy instruments to capture and measure solar energy, determine the internal structure of each moon, and create a radio presence on both moons. Each of these objectives utilize several scientific instruments that will be operated and monitored by two astronauts.

To complete the Ares mission, the team designed an Exploration Excursion Vehicle (EEV), to move in between the moons and land on the surface of each one. The EEV was designed to hold the two crew members, all scientific equipment, and collected samples. It will be launched from Earth in the SpaceX Starship and enter a 5-SOL parking orbit around Mars prior to astronaut arrival. To adhere to this timeline and minimize Δv values of the Earth to Mars transfer, the EEV will launch from Earth on July 20th, 2035, and arrive January 2nd, 2036, using a total Δv of 4.371

km/s. From this point, the EEV will remain in orbit until 2040. The crew members along with scientific equipment will travel from Earth in a Deep Space Transit (DST) vehicle and will dock with the EEV in orbit. From here, the crew and materials will be transferred between the two vehicles and the mission will begin. The DST will stay in orbit until the EEV returns and the mission is complete, where the crew, as well as accumulated samples, can begin the journey back to Earth.

Once the crew and scientific supplies have transferred to the EEV, the vehicle will be launched on January 5th, 2040, from the 5-sol orbit to Phobos, the closer of the two moons to Mars. The EEV will be maneuvered by three Astrius Aestus Engines for its main propulsion system which use dinitrogen tetroxide and monomethyl hydrazine as propellants and require no insulation in the fuel tanks. These engines produce 29 kN of thrust each, providing enough propulsion for the total Δv value of 4.284 km/s and can restart up to six times so that it can complete each stage of the mission. The EEV also uses Marquardt R-6C engines for its Reaction Control System (RCS) to maneuver the EEV. These engines provide 33 N of thrust and a specific impulse (I_{sp}) of 290 s which minimizes its required added fuel. The EEV will also be equipped with an Orbital ATK Megaflex Array solar panel to and Saft Lithium-Ion VL51ES Batteries to provide power to the subsystems within the vehicle.

The thermal control system ensures that instrumentation and crew members remain in habitable conditions during their time on the mission. The electrical systems yield most of the heat with a maximum of 3.04 kW of power produced. The thermal control system dissipates this heat using passive and active thermal control methods. The passive control will consist of covering the external surface in multi-layer insulation (MLI) which is inexpensive and easy to maintain. Active control will maintain the internal temperature using a heat exchanger and cold plates for heat acquisition and a fluid loop and pumps to eliminate heat to the exterior. Radiators will also be used to reject heat within the EEV. Solar radiation will be shielded using Gadolinium Oxide polymer with has a lower density and higher effectivity than other methods commonly used.

For this mission to be successfully carried out, keeping the astronauts comfortable and healthy is of vital importance. The EEV is equipped with life-support systems that ensure the safety of the astronauts remains a top priority. The atmosphere will be maintained using the Bosch carbon Dioxide Reduction System which filters for ammonia, methane, acetone, and methyl alcohol as well as removes 3.6 lbs. of carbon per day. To keep the cabin well oxygenated, Solid Polymer Electrolyte Electrolysis is used. This method produces two lbs. of oxygen per day and released Nitrogen as needed to mimic the atmosphere of Earth. Waste will be disposed of using the Universal Waste Management System which vents human waste into space. In other considerations, the EEV will be equipped with enough food and water for the entire mission as well a significant surplus in case of emergencies. Medical supplies, sleeping arrangements, fitness accommodations and a rehydrator and convection oven will also be provided so that the crew can reside comfortably during the duration of the mission.

For the astronauts within the EEV to communicate with the DST as well as Earth, two telecommunication systems will be utilized. For local communication to the DST, UHF frequencies will be used, and an X/Ka-band system will be used for long range communications to Earth. The EEV will be equipped with a 3-meter High Grain antenna, transceivers, and amplifiers for each communication system.

During transit to each moon, prior to touching down on the surface, the crew will collect solar wind samples and advanced images of the moon. The EEV will deploy a solar sail, solar panel, and pressure sensor while at a point of zero acceleration. The solar sail and panel will determine the amount of solar energy in orbit. The pressure sensor will be used to determine the force that the energy provides to the sail, determining if solar wind can be used as a form of renewable energy for future missions. The EEV is also equipped with a Gamma-Ray and Neutron Spectrometer, Laser Altimeter, and Atmospheric and Surface Composition Spectrometer (IR-UV) to capture close-proximity images during orbit, descent, and ascent. These images help to establish surface conditions and data for future missions. Once the EEV lands on the moons, the crew will begin the surface experimentation.

The lander is equipped with a hydraulic lift where it will store and deploy a rover to maneuver on the surface. The rover is controlled remotely by the crew and will collect a minimum of 50 kg of rock and soil samples using a robotic arm and store them in sealed containers to protect from contamination until the samples are returned to Earth for analysis. Each container will have 3.506×10^{-3} m^3 storing capacity and ten total samples will be collected on each moon. These samples will be collected at various depths and locations around the EEV to get a variety of dust and rocks to test. These samples will help to classify the chemical composition of the surface of the moons and provide insight into their origin. The rock samples as well as a Magnetometer, Energetic Particle and Plasma Spectrometer, and a Charged Particle Spectrometer will help to determine the extent, or lack thereof, of a significant magnetosphere on the moon. The rover will also be equipped with a CCD Image Sensor and an Ultrasonic Transducer that will help to keep the rover from venturing into uneven terrain and allow autonomous control when the crew is performing other tasks.

From inside the EEV, the crew will measure weathering conditions using instruments such as solar panels and thermometers to evaluate solar energy and temperature fluctuations on the surface of each of the moons. This data will be advantageous in determining what equipment and precautions are necessary for long-term human residency. The crew will also measure seismic waves and temperature variations beneath the surface using a Seismometer and Heat Flow probe to establish the internal structure of the moon. The internal structure along with the soil composition analysis will aid in the understanding of whether the moon had Martian origins or was a captured asteroid. The visit to Phobos will also study deep space radio signals using radio receivers and antennae. The Martian environment has significantly lower noise interference than that of Earth and other planets due to its lack of radio traffic and atmosphere. This data will help to observe distant bodies which can provide lucrative data for future space exploration.

Once the EEV initially departs from the DST, it will be in transit for 32 hours and will then land on the surface of Phobos on January 6th, where it will spend 14 hours conducting research and collecting samples. It will land approximately 10^{o} north and 335^{o} west on the surface of the moon. This location yields optimal sun exposure and has a flat terrain for landing. After experimentation is complete, the EEV will depart Phobos, will be in transit for nine hours, and arrive at Deimos on January 7th where it will spend 32 hours on the surface. It will land approximately 20^{o} north 120^{o} west on the surface; where the terrain is flat and has ideal sun exposure. After all experimentation is completed, the EEV will depart back to the DST. The EEV will wait longer on Deimos than on Phobos to optimize the launch window for the return path. The lander will depart Deimos on January 8th where it will travel for 44 hours to arrive back at the DST on January 10th. Once the EEV docks with the DST, the crew, equipment, and samples will be transferred back to the DST which will return to Earth. Once all the samples and data have returned to Earth, analyses comparisons will be made between the two moons to further evaluate and understand each one.

The total cost for this mission cannot exceed $1 Billion USD. All final cost estimates were taken using assessments from 2021 and can be found in Section 6.6. The total cost of the mission is estimated to be $723,591,781, which is 27.64% under the total allocated budget for the mission of $1 billion. The components making up the budget of the mission are as follows: launch costs, scientific experiments, the Exploration Excursion Vehicle, the rover, telecommunication equipment, and crew accommodations.

Component/Subsystem	**Cost Subtotal (USD)**
Launch Vehicle and Refuel	10,000,000
Scientific Objectives and Experimentation	181,200,000
Exploration Excursion Vehicle	348,891,781
Rover	150,000,000
Telecommunications Equipment	10,000,000
Crew Accommodations	23,500,000
Total	**$723,591,781**

Table 1.1 Cost overview of Ares mission broken down into six major categories.

A budget overview can be seen above in Table 1.1, and a detailed, itemized budget for each section can be seen in Tables 6.3 – 6.8. Most of the budget is dedicated to material and assembly cost of the EEV and rover, as well as scientific instruments that are aboard the EEV.

All considerations for this mission were evaluated using trade studies, CAD models, STK simulations, and extensive research to determine the optimal systems and design specifications. While cost was a major consideration for all methods and strategies, minimizing total mass, mission timelines, and determining lucrative scientific research objectives also played an integral part in constructing the Ares mission. Minimizing the mass of the EEV has a significant impact on the propulsion and maneuverability of the vehicle during its transit and landing on the moons. The total mission also could not exceed 30 days, so determining a mission timeline that completed all scientific objectives and utilized optimal launch windows, while staying within this timeframe was of vital importance. The five-day timeline of this mission ensured all of these considerations were met as well as helped to minimize the mass and potential risk factors that could be incurred in a longer mission. All other risk factors from this mission are detailed in section 6.4.

2.0 Mission Overview

This mission seeks to successfully explore the surfaces of the two Martian moons. An exploration excursion vehicle (EEV) will be designed to meet the demands of the mission objectives set forward (Fig. 2.1). A deep space transport vehicle (DST) will launch from Earth and trek a course to an orbit around Mars. Once it arrives, the waiting EEV is to dock with the DST autonomously. Materials and crew members will be transferred from the DST to the EEV via a pressurized tunnel in preparation for a series of scientific experiments. Once the EEV is prepared, it will embark on a journey to both Martian moons: Phobos and Deimos. After conducting experiments while in route to each moon and on each respective surface, the EEV will dock with the DST again. Shortly after, both the EEV and the DST will begin a return to Earth with data and surface samples collected throughout the course of this mission.

Fig. 2.1. A SOLIDWORKS render of the exterior of the EEV [8].

2.1 Needs Analysis

There lies a need to support and arrange deep space exploration programs. NASA, international government agencies, and private sector corporations have notably shown interest in establishing an operational human base on Mars, with the intent to colonize. Taking interest in the moons of Mars is an integral component in seeing the occupancy of Mars come to fruition. A principal goal for this mission is to investigate the realm of physical science that would characterize both environments found on the moons of Mars: Phobos and Deimos. Subjects on the matter include but are not limited to physics, chemistry, and astronomy.

2.2 Mission Objectives

The mission outlined in this document will feature a set of strict constraints and requirements geared towards ensuring success, efficiency, and a proficient study of the two Martian moons. In this section the logistics of the mission are discussed with regards to timelines, weight constraints, general procedures, etc. Furthermore, the scientific objectives used to survey the moons will be summarized.

A. Logistics

This Ares mission will be set to take place in the near future with a strict EEV-DST docking deadline of January 1, 2040. It is assumed that the EEV will already be in a Mars 5-sol orbit once the DST arrives. From there, the EEV has a maximum of 30 days to travel to both Phobos and Deimos, conduct the experiments, and return safely. The EEV must be designed to accommodate two crew members who will carry out the mission procedures. The crew members will remain inside the EEV for the duration of the mission, meaning no extravehicular activities (EVA). The crew will be allowed to bring 200 kg of equipment to be used for experimentation, though it must fit through the pressurized tunnel connecting the DST to the EEV. Also, the EEV must be able to carry 50 kg worth of mass samples from each moon; that is a total of 100 kg at a minimum. Lastly, the whole mission (including launch) must operate with a budget under $1 Billion US Dollars. This study will use estimates from the current fiscal year (2021).

B. Sample Collection

A principal goal for this mission is to survey and classify the composition of the two moons. Current research indicates that both surfaces are comprised of loose C-type rock forming a deep regolith. The sample extractions can help determine the true origin of the moons, whether that be from accretion, orbit capture, or the derivation from a common body like Mars. Also, the material found on Phobos and Deimos can aid in determining further developments on the moons. Mining for natural resources and establishing telecommunication bases are some of the possible aspirations for the future. As previously mentioned, the EEV will be designed to hold 50 kg of samples from each moon.

With any new journey to a celestial body, whether it be the Moon or Mars, collection of samples directly from the body is an important tool in understanding the land. Samples directly from Phobos and Deimos will aid in a more concrete understanding of these bodies' geology and topography, as well as current and past climate. Collecting samples on the moons is of the utmost priority, and as such, special considerations must be taken before doing so.

C. Magnetic Field Measurement

Magnetic fields are vital to humankind and our materials since they provide protection from the sun's harsh radiation. The crew will measure the flux and spectra of energetic particles surrounding each moon. In studying each moon's magnetic field (or lack thereof) this experiment aims to reveal the moons' ability to deflect solar wind. This will provide insight into environmental conditions for materials, manned experiments, and sustaining any kind of recognizable life form.

D. Advanced Imaging

By utilizing a variety of cameras, this mission will be able to view both celestial bodies across different portions of the electromagnetic spectrum. IR, UV, gamma ray, and other spectrometers will be used to capture close-proximity photos of both moons. These images will allow researchers to draw conclusions on the surface conditions present. Any unpredicted or otherwise visually imperceivable conditions can be captured. This will open the discussion for EVA plans in future experiments. This study will also augment the investigations for measuring solar wind, the magnetic field, and weathering conditions since the advanced imaging equipment will further qualify their data.

E. Weathering Variations

While on the surface the crew will seek to mark the impacts of weathering conditions of the past and present. Solar energy, solar wind, and temperature variation are some metrics for measure. Particle density may also be a factor in distinguishing contrasts on each moons' topography. In addition to utilizing the rover for surveying, imaging equipment will also be used for advanced topography mapping.

F. Solar Wind Samples

Solar wind has the capability to induce force on bodies of little acceleration. This energy can be absorbed, recycled, or transmitted. The amount of force exerted on a solar sail may provide a renewable source of mechanical energy on the moons. It is anticipated that there will be a significant amount of force due to the moons' expected lack of atmospheres and low gravity. This may prove to be useful for experiments or procedures in the future.

G. Examining Internal Structure

Ares will seek to learn more about the Martian moons from their internal structure. Using key instruments, the crew will measure seismic waves and detect temperature variations below each surface. From the data, it can be determined if the internal structure is uniform or layered. After the mission, 3-D models can be developed to help visualize the internal structure. The use of these instruments will likely assist in breaking up material for sample collection, especially while in search of larger rocks under the regolith.

H. *Telecommunication*

The same radio antennas and receivers that we are using for comms can also be used to observe distant objects like stars in the radio spectrum. Mars will likely show less environmental interference with these distant signals, as mars has almost no radio traffic, almost no atmosphere, and an expected miniscule magnetosphere. Radios on or around Mars could therefore make better observations than the same radios on earth. Networking multiple receivers together on the EEV, the DST, and any satellites in Mars's orbit can make even more accurate observations.

3.0 Astrodynamics

Some of the most important components for any deep-space mission are the orbital transfers required to get to the desired destination, as well as where any crafts will land when they arrive. This section details the process of determining how the EEV will get to the moons of Mars through a trade study of various launch vehicles, as well as the calculation of the most efficient route from Earth to the moons of Mars. Finally, this section will cover the safest landing sites for our crew on Phobos and Deimos.

3.1 Launch Vehicle Selection

The launch vehicle chosen to deliver the EEV to a 5-sol parking orbit around Mars was the SpaceX Starship. The Starship would be initially launched to low-Earth orbit carrying the EEV and will require an additional launch of a “tanker” Starship loaded with fuel to dock with the Mars-bound Starship in low-Earth orbit. This refueling launch would take place shortly after the initial launch to ensure that Starship reaches Mars with enough fuel to place the EEV in its desired orbit. Starship has the following specifications: \$2 million cost per launch, 9 m diameter and 18 m tall fairing, 150,000 kg maximum payload to Mars orbit, and is aimed to be flight ready by 2024.

Launch Vehicle	Approximate Launch Cost (USD)	Stages	Fairing Height (m)	Fairing Diameter (m)	Max Payload to Mars (kg)
Falcon Heavy	\$170 million	2	13.2	5.2	16,800
Atlas V-401	\$130 million	2	10	4.2	1,025
SLS	\$2 billion	2.5	31	10	20,000
Delta IV Heavy	\$350 million	2	11.2	4.5	8,000
Proton-M	\$65 million	3 or 4 (optional)	11.8	5.1	6,200
Starship	\$2 million	2	18	9	150,000

Table 3.1 Comparison of various launch vehicles capable of bringing large payloads to Mars orbit. Cost was calculated based on an average of launch costs for similar missions.

The SpaceX Starship was selected based on three major criteria: maximum payload to Mars orbit, total launch cost, and fairing size. Other launch vehicle options that were considered were the Falcon Heavy, Atlas V-401, SLS, Delta IV Heavy, and Proton-M. SLS was immediately ruled out because of its hefty \$2 billion price tag per launch, which exceeded the allotted budget for this mission by 100% (Table 3.1). The Atlas V-401 was a strong competitor given its 100% launch success rate with 87 total launches. However, the Atlas V-401’s launch cost of \$130 million, and small fairing size kept it from final consideration. The Delta IV Heavy was another highly dependable launch vehicle with a 97.5% success rate, but the maximum payload able to be carried to Mars orbit was limited to 8,000 kg (Table 3.1). Additionally, the Delta IV Heavy costs \$350 million per launch, and 1/3 of the total budget for launch alone was deemed to be too expensive. The Falcon Heavy was the final competitor for Starship, with a max payload of 16,800 kg to Mars orbit, a large fairing with a 13.2 m height and 5.2 m diameter, and low launch cost of \$170 million (Table 3.1). Starship edged out the Falcon Heavy based on launch cost alone, with Starship costing 85% less per launch than the Falcon Heavy.

Initially, the Starship carrying the EEV will be launched to a low-Earth parking orbit. An additional Starship will be launched from the original launch site and will function as a tanker, carrying the fuel necessary to get to the 5-sol Mars parking orbit. This “tanker” starship will rendezvous with the original Starship in low-Earth orbit, dock, and transfer the necessary fuel. The additional Starship launch will incur a cost of around \$2.5 million, including launch and fuel costs. The total cost of both launch vehicles and the additional fuel is estimated to be \$10 million, with an additional \$5.5 million added if the Starship launch cost increases as the program matures. This is well within the range of the launch vehicle budget and will allow the EEV to successfully be injected into the desired 5-sol parking orbit.

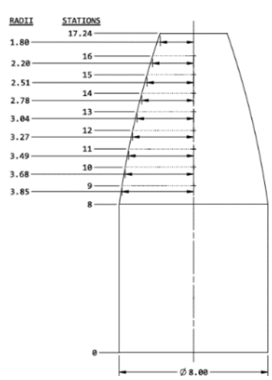

Fig. 3.1. Starship 1.0 fairing diagram, all units in meters. Starship will be offering an extended fairing 22m in height.

When mounting the EEV to the Starship fairing, the center of mass of the Exploration Excursion Vehicle must be considered to reduce any potential wobble or interference with the Starship control systems. The EEV will be mounted 0.5 m off-axis to account for its mass distribution. The moments of inertia of the EEV were found in SOLIDWORKS and can be seen in the table below.

Moments of Inertia [kg*m^2]					
Ixx	49410475	Ixy	6769154	Ixz	10762826
Iyz	6769154	Iyy	40014354	Iyz	20662712
Izx	10762826	Izy	20662712	Izz	18757429

Table 3.2 Moments of inertia of the Exploration Excursion Vehicle found in SOLIDWORKS.

3.2 Trajectory

The Ares Mission has two main trajectory sequences: the launch from Earth's orbit to Mars' and the path between DST, Phobos, and Deimos. Determining an efficient and effective orbital trajectory to transfer the EEV from Earth to Mars was vital to the success of the mission. Low impulses, efficient transfer times, and optimal launch windows were all factors considered when creating this trajectory. For the crew to arrive at Mars on January 1, 2040, the EEV had to park in a 5-sol orbit prior to DST arrival. Launch windows and transfer times were analyzed for the few years prior to 2040 to determine transfer options for this timeline. Using orbital calculations, contour plots, and STK modelling, the most efficient trajectory was established and simulated as a Hohmann transfer.

After the initial transfer, the visiting sequence, and trajectories of the EEV to the Martian moons and DST were established and modeled. For these trajectories, a trade study was created to determine which visiting order would best fit the mission's scientific objectives as well as transfer efficiency. The mission timeline required all objectives and visiting sequences to be completed within 30 days. However, the trade study determined that the optimal mission length – for both transfers and to complete all scientific objectives- would take 5 days.

3.2.1 Orbital Calculations

Assuming circular, coplanar orbits, Hohmann transfers were used for all trajectory calculations. Departure and capture impulses were computed to determine the values required for escaping Earth's orbit and entering that of Mars. From the distances of Mars, R_M, and Earth, R_E, and the gravitational parameter of the sun, μ_s the departure impulse can be calculated from equation (1).

$$\Delta v_1 = \sqrt{\frac{\mu_s}{R_E}}\left(\sqrt{\frac{2R_M}{(R_E + R_M)}} - 1\right) \tag{1}$$

Using the same parameters, the arrival impulse can be calculated using equation (2).

$$\Delta v_2 = \sqrt{\frac{\mu_s}{R_M}}\left(\sqrt{\frac{2R_M}{(R_E + R_M)}} - 1\right) \tag{2}$$

The lower the Δv values, the more optimal the transfer. The travel time, in seconds, of this transfer can be found using the equation (3) and then converted into days.

$$t = \pi\sqrt{\frac{(R_E + R_M)^3}{8\mu_s}} \tag{3}$$

Each of the values from equations (1-3) can be found in Table 3.3.

Δv_1 [km/s]	Δv_2 [km/s]	t [days]
2.493	1.878	196

Table 3.3 Hohmann transfer Δv values.

The Δv values were used to determine specific dates for launch windows from contour plots developed by NASA.

3.2.2 Launch Windows

The dates of the transfer from Earth to Mars were determined using contour plots referred to as porkchop plots (Fig. 3.2, Fig. 3.3)

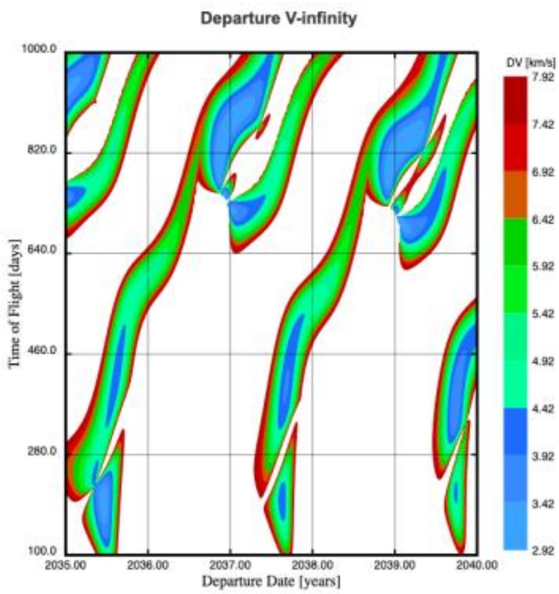

Fig. 3.2. Porkchop Plot Showing launch *Δv* and Travel Time for Departure from Earth [8]

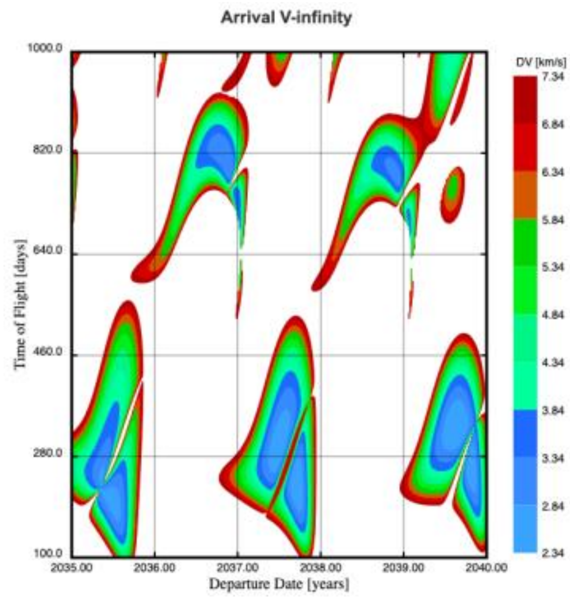

Fig. 3.3 Porkchop Plot Showing capture *Δv* and Travel Time for Arrival to Mars [8]

Porkchop plots are tools used by NASA to display the characteristics of launch and arrival opportunities for interplanetary flights paths. The chart displays the change in velocity (*Δv*) required to transfer from Earth to Mars at any given time. An ideal launch window minimizes the *Δv* required for both the departure and the arrival impulse. The two launch windows with minimum *Δv*, as denoted by light blue areas, are mid-2035 and late 2037.

A trade study was performed to determine which of the two windows was optimal for the transfer from Earth to Mars. Because the porkchop plots are provided for numerical estimation, the trade study was performed using STK to model each transfer from Earth to Mars as a Hohmann transfer, and to further refine the launch time. The results of the trade study are displayed (Table 3.4, Table 3.5).

2035 Departure		
Initial Δv	**Final Δv**	**Total Δv**
2.493	1.878	4.371

Table 3.4 Δv requirement for Earth to Mars transfer in 2035 (units in km/s).

2037 Departure		
Initial Δv	**Final Δv**	**Total Δv**
3.126	1.904	5.030

Table 3.5 Δv requirement for Earth to Mars transfer in 2037 (units in km/s).

From the trade study, it was determined that departure from Earth in 2035, specifically on June 20th, minimized the Δv required to reach Mars. Furthermore, the 2035 schedule provided a larger margin of error in launch time than the 2037 date. Therefore, if the launch had to be delayed, the increase in Δv required would also be minimized. With the launch window set for June 20th, 2035, arrival in the 5-sol parking orbit was calculated to occur on January 2nd, 2036. The complete trajectory is modelled in Fig 3.4.

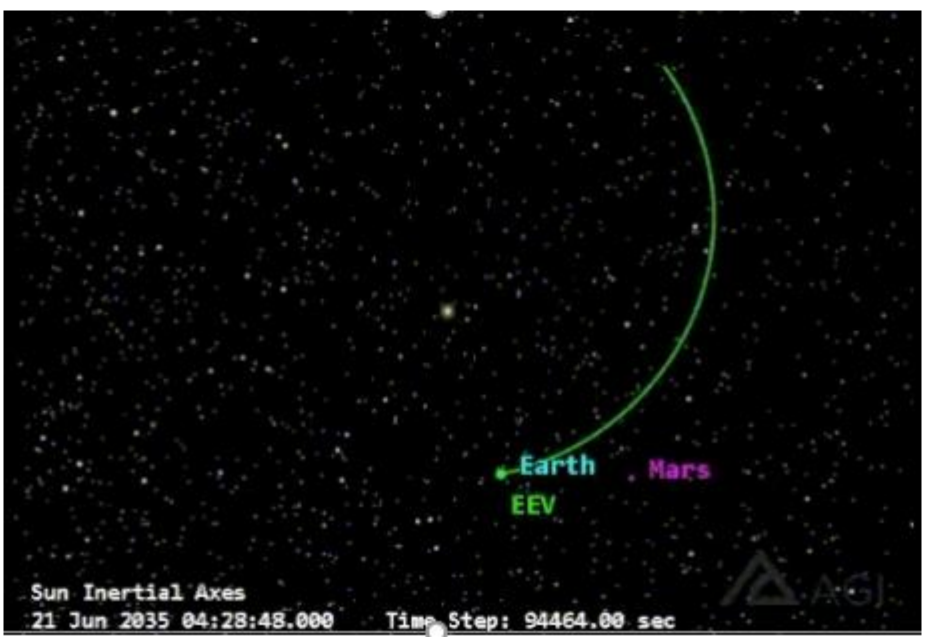

Fig. 3.4 Model of Transfer Orbit from Earth to Mars.

The positions of Earth and Mars in Fig. 3.4 are shown just after launch of the EEV. The green line indicates the total path the EEV will take and the location of Mars when the EEV arrives.

3.2.3 Lunar Trajectories

From this point, the optimal visiting sequence between the moons and the DST to efficiently carry out the mission objectives had to be determined. A trade study was conducted to compare the Δv values of four different potential sequences (Table 3.6).

Table 3.6 Visiting Sequences		
Sequence	**Path**	**Total Δv [km/s]**
1	DST Phobos Deimos DST	4.284
2	DST Deimos Phobos DST	4.746
3	DST Phobos DST Deimos DST	6.510
4	DST Deimos DST Phobos DST	6.363

Table 3.6 Trade study of four different visiting sequences from the DST to the moons of Mars.

From these calculations, it was determined that sequence 1, going from the DST to Phobos to Deimos and back to the DST, was the optimal visiting sequence. The next major trajectory decision revolved around when the EEV should depart from the DST. Mission requirements state that the transfer must begin no earlier than January 1, 2040. Simulations were performed in STK in which the EEV transferred from the DST's circular 5-sol parking orbit to Phobos, and STK's numerical Lambert solver was used to minimize the Δv required for the transfer. By searching for the first departure time that minimized the Δv required to transit to Phobos, it was determined that the EEV should begin its mission on January 5th at 12:00:00 UTCG and would arrive at Phobos on January 6th at 08:00:00 UTCG.

Next, the departure time from Phobos was determined. Due to the short orbital periods of Phobos and Deimos, there were many viable launch windows which minimized the Δv required to reach Deimos. Therefore, the transfer time was governed primarily by the research missions performed on Phobos. It was predicted that the research on Phobos would take approximately 14 hours to complete. Therefore, departure from Phobos was set for January 6th at 20:20 UTCG, with arrival on Deimos on January 7th at 05:00:00 UTCG.

Departure from Deimos was dictated by both the time required for research and the position of Deimos with respect to the DST. Therefore, 32 hours were allocated for time spent on Deimos, and the EEV was scheduled to depart Deimos on January 8th at 13:00:00 UTCG, with arrival at the DST on January 10th, 11:00:00 UTCG. Overall, the mission was designed primarily to minimize Δv requirements, but also to minimize total mission time, thereby reducing costs associated with life support. With departure from the DST on January 5th and return set for January 10th, the total mission time is expected to last approximately 5 days. The breakdown of the impulses for each portion of this sequence is displayed in Table 3.7.

DST to Phobos			**Phobos to Deimos**			**Deimos to DST**		
Initial Δv	Final Δv	Total Δv	Initial Δv	Final Δv	Total Δv	Initial Δv	Final Δv	Total Δv
0.362	2.147	2.509	0.679	0.390	1.069	0.387	0.319	0.706

Table 3.7 Initial and final Δv values for each orbital transfer during the Ares mission.

Each stage of the sequence was modelled in STK to display each of the transfers. First, the transfer from the DST to Phobos was modelled, then the transfer from Phobos to Deimos, and finally the transfer from Deimos back to the DST to complete the mission. The STK models follow the transfer orbit at each phase of the mission from departure to arrival. These models are displayed in Fig 3.5, 3.6, and 3.7.

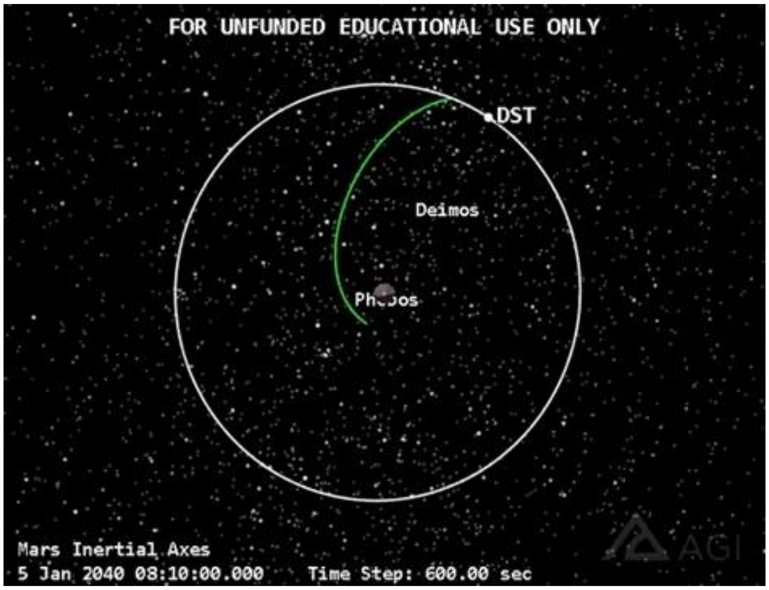

Figure 3.5 EEV Transfer from DST to Phobos

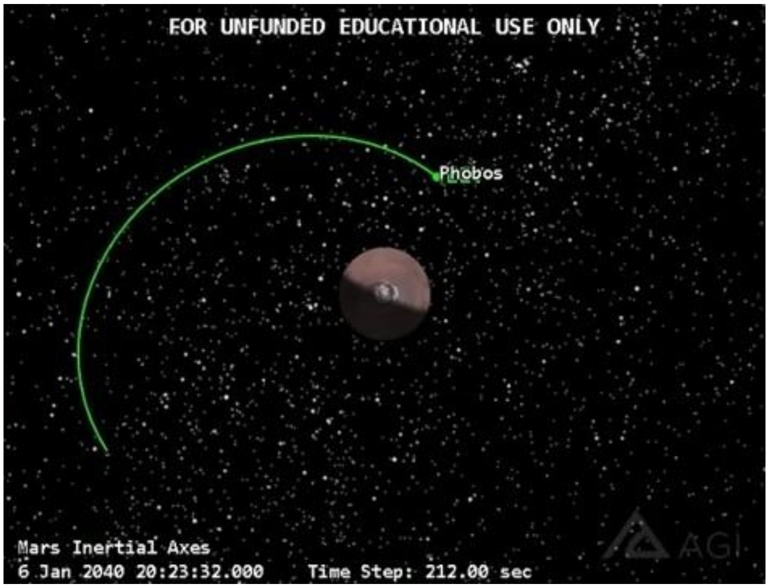

Figure 3.6 EEV Transfer from Phobos to Deimos

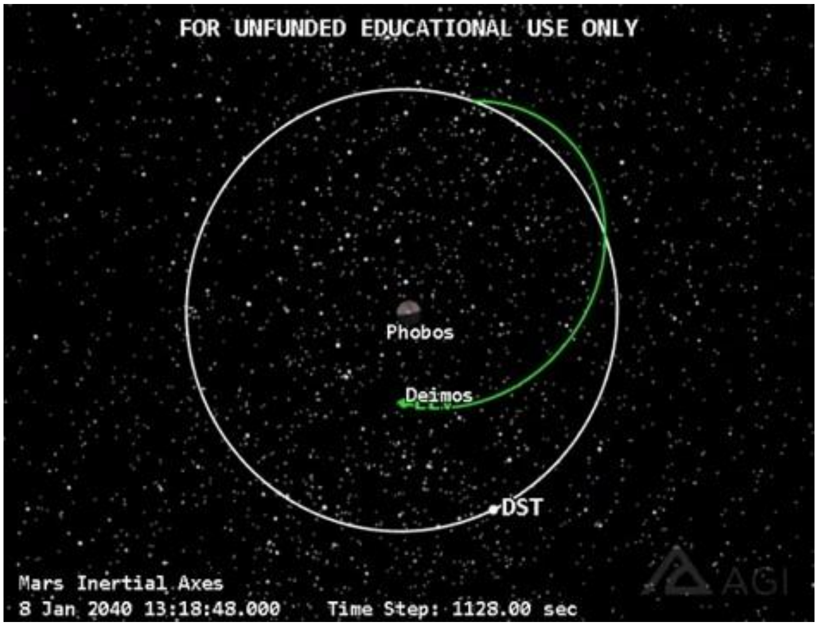

Figure 3.7 EEV Transfer from Deimos to DST

These three transfers make up the total 5-day mission sequence. Each figure indicates the path and departure date and time at each phase.

3.3 Landing Site Selection

Phobos orbits Mars synchronously, both orbiting Mars and rotating about its own axis once every 7 ½ hours. Phobos has no axial tilt and orbits Mars on only a 1-degree inclination, while Mars has an axial tilt of 25 degrees. This means that one "pol9" of Phobos is fully in sunlight while the other is fully in shadow during Martian summer, with the poles switching light and shadow in Martian winter. Our mission will visit Phobos and Deimos in Martian spring. According to source 1, most of Phobos except for the far southern latitudes will receive upwards of 3.5 hours of daylight per orbit. We will thus land in the northern hemisphere of Phobos to maximize our power collection ability. Looking next at a topographical study of Phobos, we selected an area of flat ground for the safest landing possible. Based on data from [44], we choose a site at approximately 10 degrees north and 335 degrees west, illustrated in Fig. 3.8.

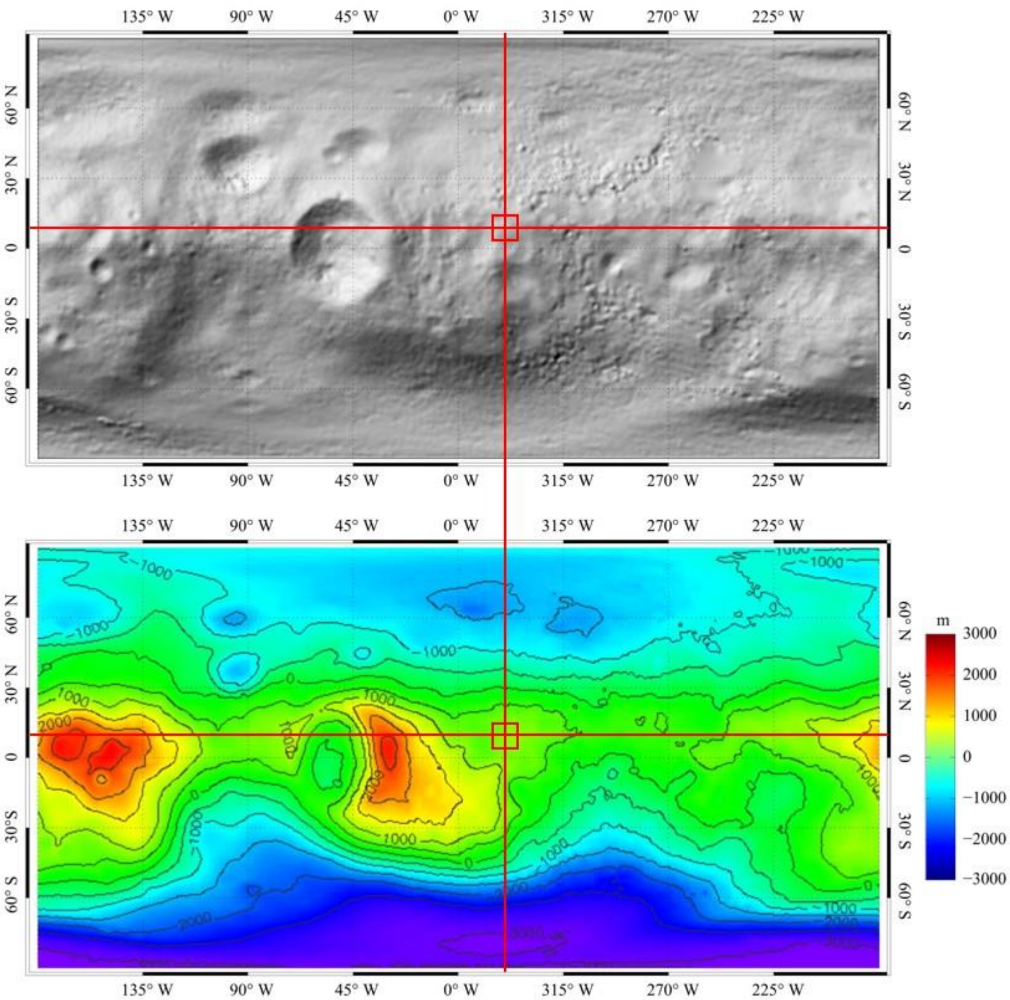

Fig. 3.8 Topographic map of Phobos with the selected landing site displayed.

Deimos also orbits Mars synchronously at 30.3 hours per orbit and revolution and is less than 1 degree inclined from Mars' equator. From the study of Phobos it can be concluded that the northern hemisphere of Deimos will similarly spend at least 50% of its orbit in sunlight. Using A topographical model of Deimos, we identify flat areas of the moon [6]. We select a relatively flat area in the northern hemisphere at approximately 20 deg north and 120 deg west for our landing site, as illustrated in Fig. 3.9.

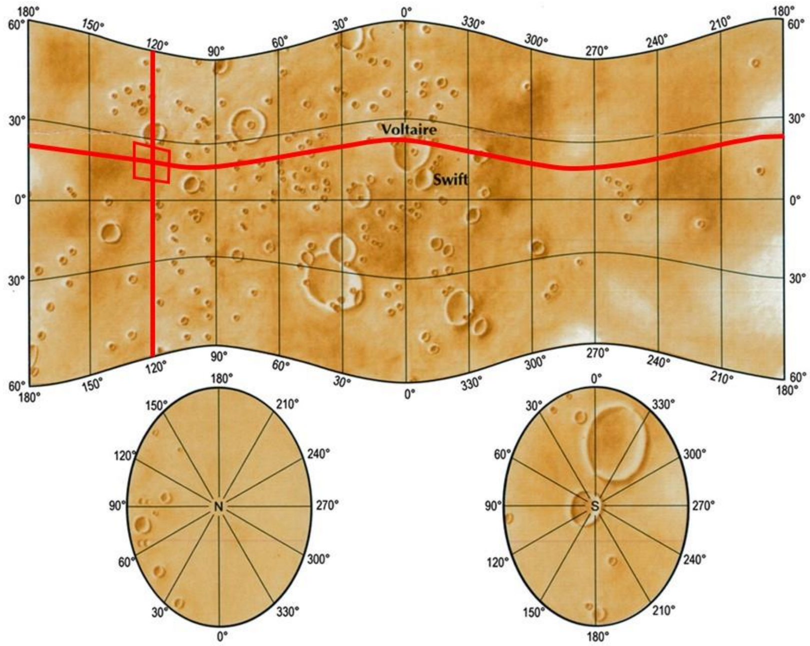

Fig. 3.9 Map of Deimos with the selected landing site displayed.

4.0 Exploration Excursion Vehicle and Subsystems

The Exploration Excursion Vehicle (EEV) transports the crew and equipment between Phobos, Deimos, and the DST. For this vehicle to successfully move through space, complete scientific objectives, and keep astronauts alive and safe, many key factors and considerations went into its design. The EEV consists of a propulsion system, a descent and landing system, thermal control system, structures, radiation shielding, docking, telecommunications, power system, life support systems, and a rover.

4.1 Main Propulsion Subsystem

The decision for the propulsion system on the EEV orbital transfer stages were made with the following requirements:

- A minimum thrust-to-weight ratio of 1.5 sufficient for orbital stages and moon landing and takeoff
- Storability for multiple years on the mission timeline
- The engine must be restartable to allow for each burn throughout the mission
- The propulsion system must provide 4.284 km/s in Δv + 10% contingency

Due to the mission details of using a manned EEV the propulsion system had a focus on reliability and safety for the mission crew. Using this criterion, the engines using electrical power were ruled out due to the current state of this technology being unready for mission use with low thrust and lack of reliability. Nuclear engines were ruled out for similar reasons with the addition of radiation concerns for the mission crew's health and safety. Many types of chemical engines were considered ruling out solid engines for the lack of restartability and throttle control.

With a bi-propellent being chosen as the propulsion propellent, many propellants were considered. Due to the mission timeline of four years in orbit before the mission occurring the bi-propellent must be non-cryogenic as the cost and mass of the insulation to store cryogenic propellants was unrealistic for this mission. A monomethyl hydrazine (MMH) and dinitrogen tetroxide (N_2O_4) bi-propellent was chosen for its long storability and heritage as reliable fuel source. A trade study was then conducted on a choice of many engines of this fuel type.

Engine	Thrust (kN)	Unfueled Mass (kg)	I_{sp} (s)	Burn Time (s)
Aestus	29.0	111	324	1100
Aestus-2	55.4	139	336	600
ATE	20.0	58	347	1200
R-40B	4.0	7.23	293	23000

Table 4.1. Trade study for the EEV's main engine.

The thrust requirements of the EEV cause the R-40B to be insufficient for the mission [10]. The Aestus-2 engine was considered due to its high specific impulse and thrust but ultimately ruled out due to only being restartable 3 times and therefore incapable of completing the mission. The Aestus engine was chosen due to its higher thrust needing only three engines for the entirety of the mission while the ATE engine would require four. The thrust using the three engines will allow for up to 87.0 kN of thrust to be used during burns when the highest thrust is necessary during the landing and takeoff stages for each moon. The engine configuration will also allow for lower thrust to be used during transfer stages to preserve more fuel on longer more efficient burns.

$$m_f = m_0\left(e^{\frac{\Delta v}{g_0 I_{sp}}} - 1\right) \tag{4}$$

The planned path for the mission will require 4.284 km/s in Δv, an additional 10% of the required Δv will be added for contingency. This will result in the fuel required being 3.41 times the dry mass of the craft and payload using the ideal rocket equation (4). The 50kg added at each moon will be added to the total mass before calculation of the fuel mass to ensure a safety contingent of fuel for the mission resulting in a total dry mass of 9945.35 kg and therefore 33913 kg of overall fuel mass. The oxidizer to fuel ratio of the chosen engine is 2.05 resulting in 22790 kg of N_2O_4 and 11123 kg of MMH [10]. A benefit to using these non-cryogenic propellants is a simple titanium spherical fuel tank will hold the propellants for the entire mission. Using the density of these propellants, 1450 kg/m^3 for N_2O_4 and 880 kg/m^3 for MMH, the volume of the required fuel is 15.7 m^3 for N_2O_4 and 12.6 m^3 for MMH. This results in a final diameter of the fuel tanks accounting for a 5 mm thick wall to be 3.11 m for N_2O_4 and 2.90 m for MMH.

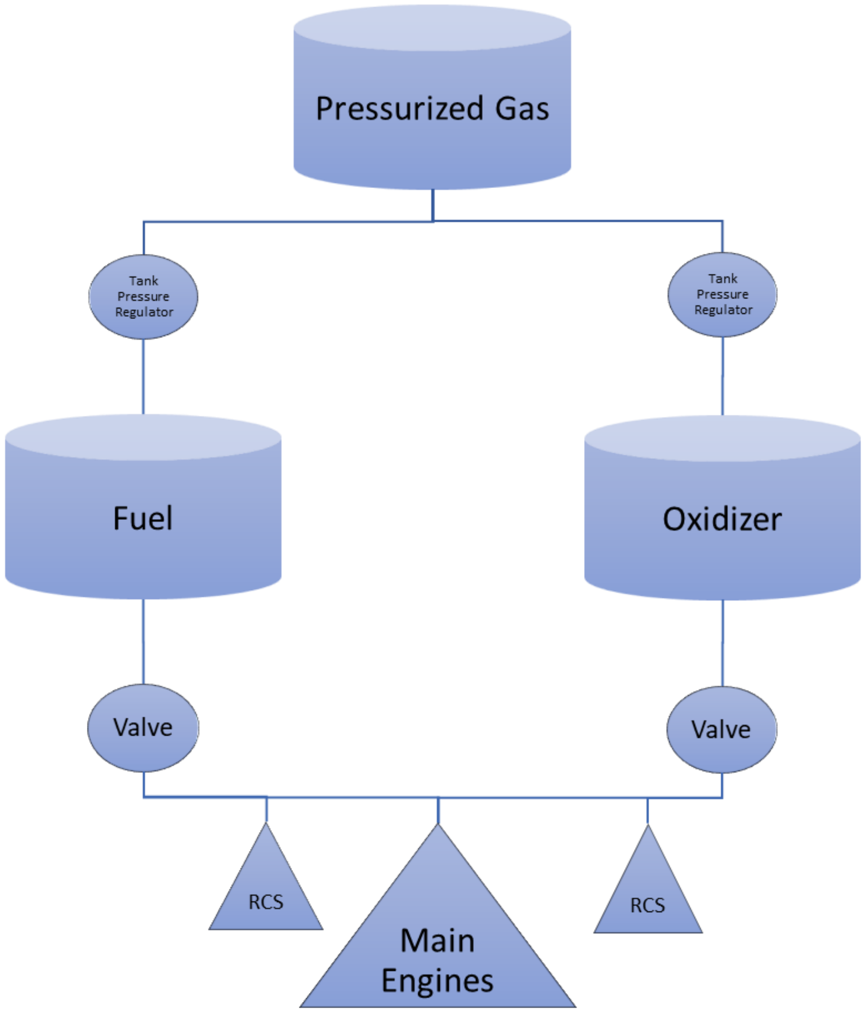

Fig 4.1 Propellant Feed System for the Propulsion System of the EEV

4.1.1 RCS Thrusters

To determine the best RCS thrusters for the mission priority was placed on a few factors including the thrusters producing sufficient thrust to maneuver the EEV, minimizing added fuel by using an engine with a high specific impulse, and being easily integrated into the existing propulsion system. This allowed the scope of the options to be reduced to those using the same fuel and oxidizer combination as the main engines of MMH/N_2O_4. A trade study was then done to determine the best option for the needs of the mission in Table 4.2.

Engine	I_{sp} (s)	Thrust (N)	Dry Mass (kg)
KEW-1	266	29	0.53
R-6C	290	33	0.66
RM-1-2	238	4.41	0.32

Table 4.2 Trade study comparing RCS engines [10].

The Marquardt R-6C was chosen for the mission as the engine satisfies all the mission requirements and will minimize fuel consumption compared to the other options [10]. The RCS thrusters will be added to the propulsion system allowing the system to draw from the two main tanks of MMH and N_2O_4. The added fuel will only amount to a small increase therefore the relatively high contingency of 10% extra fuel mass will safely provide any necessary fuel for the RCS system.

4.2 Descent and Landing

The EEV will require landing legs to protect the fuel tank and rover storage areas during impact with the moons' surfaces. The landing legs will be made to individually extend downward as horizontal disturbances such as wind will not be an issue on these moons. A trade study was done to determine the cheapest and strongest material while prioritizing the minimization of the weight of the material.

Material	Ultimate Tensile Strength (MPa)	Density (kg/m^3)
Stainless Steel	515	8050
7075-T73 Aluminum Alloy	460	2810
Titanium Ti-6Al-4V	855	4420
Cast Iron	400	7200
Nickel-Cromium	720	7768

Table 4.3 Comparison of common structural materials to be used for EEV landing legs.

The trade study concluded that of common materials used in spacecraft, the 7075-T73 aluminum alloy provided the highest strength while reducing the added mass to the EEV [4]. The landing legs then had a structural analysis conducted to calculate the radius and wall thickness of each landing leg for the EEV. Due to the individually extendable nature of the landing legs and for an added safety component for a manned mission, each landing leg will be capable of handling the full stress of the EEV landing. The EEV will experience landing at an acceleration of 0.5 m/s^2 at a maximum weight of just over 43500 kg producing 16.39 kN of compressive force during landing. Using (5) the ratio of the thickness of the wall of the leg with the outer radius of the leg can be found to be 0.01 and using a minimum thickness of 1 mm the outer radius of the landing legs will be 94 mm to withstand the force of landing and takeoff.

$$F_{cr} = 0.6\eta\gamma\frac{Et}{r} \tag{5}$$

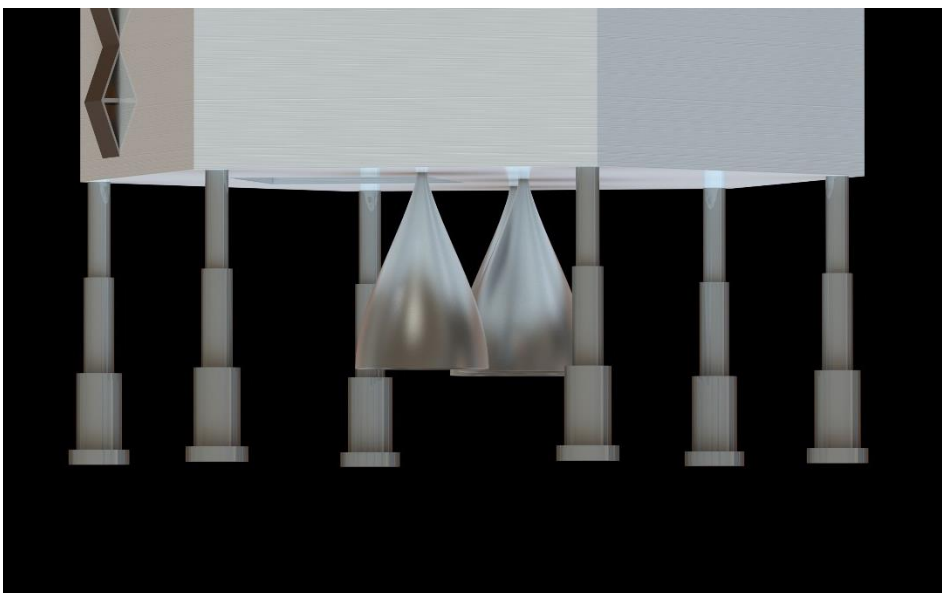

Fig 4.2 Landing gear of the EEV [8]

4.3 Thermal Control Systems

The thermal control systems of the spacecraft are necessary to ensure a proper working temperature for electric systems, as well as to provide a comfortable environment for the crew. The electric systems require a temperature of less than 40°C, while the crew requires a temperature between 18°C and 24°C [9]. The primary source of the EEV's heat will be the power produced by the electrical systems which, at maximum, was calculated as 3.04 kW, disregarding the power used by the thermal control system itself. Therefore, the thermal control system will be designed with the intention of dissipating a minimum 3.04 kW of power. The EEV will have both passive and active thermal control systems. Passive thermal control will consist of multi-layer insulation (MLI). MLI is the preferred method for thermal insulation because it is lighter, cheaper, and easier to maintain than active thermal control. To cover the external surface area of the EEV, 280 m^2 of MLI will be used. The corresponding mass and volume requirements were calculated and are tabulated (Table 4.4).

Additionally, active thermal control systems will be used to maintain the correct internal temperature of the EEV. A heat exchanger and cold plates will be used for heat acquisition, and a fluid loop and pumps will be used to pump heat to the external system. Expendable heat sinks are not viable for missions longer than a few days, so radiators will be used [9]. Radiator calculations were performed assuming an average radiator temperature of 270K. For missions including transit to Mars, an average radiator temperature of 270K results in an approximate heat rejection of 171 W/m^2 [9]. The surface area required for radiators is then given by the following:

$$A = \frac{Q}{HR} \tag{6}$$

In Eq. 6, Q is the heat to be dissipated, and HR is the heat rejection. Therefore, given the maximum power of 3.04 kW and accounting for an extra 10kW in redundancy, 76m^2 of surface area will be allocated for radiators.

The calculations for the mass and volume requirements of the remaining active thermal control components are tabulated (Table 4.4), where Q is the heat to be dissipated (3.04 kW, plus any redundancies), A is the external surface area of the EEV (280 m^2), and TCS is the sum of the masses of the active thermal control system components.

Major Component	Mass Eq.	Mass (kg)	Volume Eq.	Volume (m^3)
Heat Exchangers (1 x 10 kW, redundant)	17 + 0.25Q	20.26	0.016 + 0.0012Q	0.03
Cold plates (5 x 1 kW, redundant)	12Q	96.48	0.028Q	0.23
Pumps (for 14.7 kW, redundant)	4.8Q	85.15	0.017Q	0.30
Fluids	0.05TCS	30.23	-	-
Redundant plumbing, valves, fittings	0.15TCS	90.70	-	-
Radiators	5.3A	402.8	0.02A	1.52
Controls	0.05TCS	30.23	-	-
Multi-layer insulation (280 m^2)	2A	560	0.01A	2.80
TCS Totals		1315.85		4.88

Table 4.4 Overview of the EEV's thermal control systems.

In addition, the power required by the pumps is given by 23Q, which, assuming 10 kW in redundancy, results in the thermal control system requiring 305.9 W. The conceptual diagram for the EEV's thermal control system is shown (Fig. 4.3).

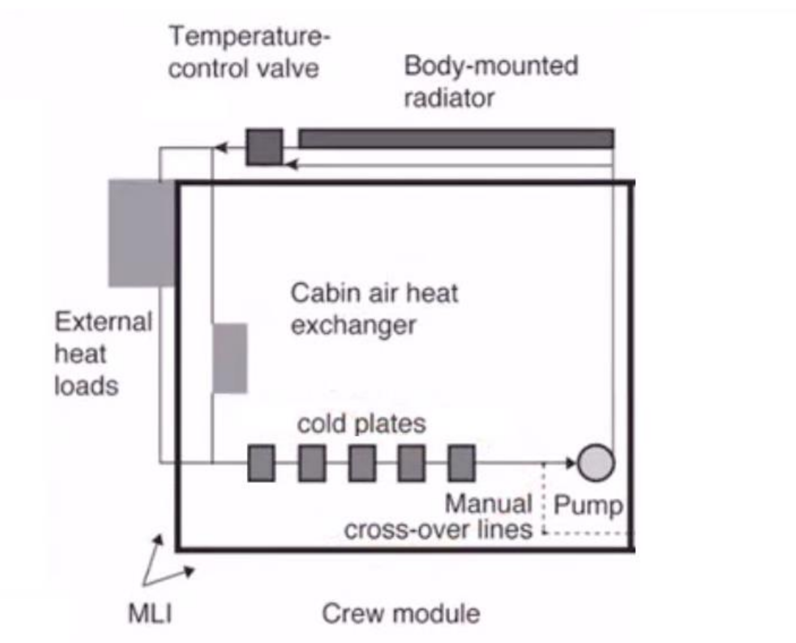

Fig. 4.3 Conceptual design for the EEV's thermal control system [9].

4.3.1 Worst-Case Temperature Study

In general, expendable heat sinks are only used for missions with durations less than a few days. For longer missions, such as transit to Mars, radiators are used [9]. The surface area of radiator required to dissipate the EEV's heat is given by

$$A = \frac{Q}{\sigma\varepsilon\eta(T_r^4 - T_e^4)} \tag{7}$$

Where Q is the heat to be dissipated, σ is the Stefan-Boltzmann constant, ε is the radiator's emissivity, η is the radiator's fin efficiency, and T_r and T_e are the radiator and external temperatures respectively. Given the power systems on the EEV produce 3.04 kW, and assuming a radiator emissivity of 0.9 and a radiator fin efficiency of 0.85, the surface area of radiator can be calculated. According to (7), the worst-case scenario occurs when the external temperature is at its hottest. When exposed to sunlight, the environmental temperature may be as warm as 293K [38]. By substituting these values in to (7), the minimum required radiator surface area is 34m^2. Therefore, with a radiator surface area of 76m^2, the EEV has the capacity to maintain thermal equilibrium with 7 kW in redundancy above maximum expected use in the worst-case scenario, and with factor of safety of approximately 2.2.

4.4 Structural Analysis

Structural analysis is at the heart of the Ares mission's commitment to safety for our crew. Throughout this section, the key components of the EEV and the rover will be put to the test of what they may experience in the vacuum of space, and we will show how our designed systems will keep our crew safe.

4.4.1 EEV Body Structural Analysis

A structural analysis was conducted on the EEV's walls. It is important to be aware of the critical environmental situations and which components will be the most susceptible to each situation. The situations that primary structure of the EEV will be under the most stress is when the EEV is leaving the Earth's orbit in Starship and when the EEV is pressurized in the vacuum of space.

For the launch leaving Earth's orbit, it is estimated that the EEV will experience up to three times the force of Earth's gravity [12]. This force may put the walls of the EEV at risk of buckling. The monocoque cylindrical pressure chamber inside the EEV will provide the majority of the structural support for the EEV and will be used to conduct the structural analysis of its walls. A cylinder under an axial load experiences forces proportional to the thickness and radius (5).

The critical force can be equated to the mass of the EEV multiplied by 3 times the force of Earth's gravity. η can be assumed to have a value of 1 because the stress is being calculated to be below the material's proportional limit. Assuming the force of gravity is 9.81 m/s^2 and knowing that the EEV has a mass of about 43,500kg. Multiplying this value by 3 provides a critical force value of 1,236,060 N. The pressure chamber has a radius of 3.45m and 2219-T6 aluminum has an Elastic Modulus of 72 GPa. γ is assumed to have a value of 0.5 for both compressive and bending loads to determine rough sizing. Plugging these values into the equation and solving for thickness, the minimum thickness to avoid buckling is 0.197 mm or 0.008 in. Accounting for a factor of safety of 1.5 the minimum thickness of wall for the EEV to avoid buckling on launch is 0.296 mm or 0.012 in.

The next and more prominent threat to the integrity of the structure of the EEV is the pressurization of the crew area inside the vacuum of space. The pressurized cylinder that the crew resides in will be pressurized to 1 atmosphere (14.7 psi / 0.10135 MPa). This pressure difference between the inside and the outside of the EEV will subject the cylinder to axial stress and hoop stress; the hoop stress being a higher magnitude than the axial stress. The minimum thickness of the EEV's structure must be calculated based off the maximum hoop stress that will be experienced (8).

$$f_h = \frac{pt}{r} \tag{8}$$

Where *p* is the pressure, *t* is the thickness of the walls of the cylinder, and *r* is the radius of the cylinder. The radius is 3.45 meters and the pressure on the walls pushing outwards is 0.10135 MPa. The yield strength for 2219-T6 Aluminum is 280 MPa. Plugging into Equation 8 and solving for *t*, the resulting minimum thickness is 1.87 mm or 0.074 in to avoid yielding from pressurization. Accounting for a factor of safety of 1.5, the new minimum thickness for the wall of the EEV is 2.8 mm or 0.148 in.

The original plan for the main structure of this EEV was for the EEV to be built out of the same material but in a hexagonal prism shape. The sharp edges and corners of the hexagon created a lot of places for stress concentrations to develop on the walls of the EEV when it was pressurized in space. It performed similarly under buckling. Because of the contrast in performance in combatting hoop stress between a cylinder and a hexagonal prism, it was decided to add the cylindrical pressurized crew area inside of the hexagonal prism. This way the cylinder could effectively combat the hoop stress and the flat walls of the hexagon could deflect and absorb incoming debris. The addition of the cylinder vessel is so much stronger and more efficient than the hexagonal design that the new combined design is about 1,000 kg lighter than the previous hexagonal only design.

To comply with the dimensions required for shielding from radiation and debris, the hexagonal exterior wall thickness will remain at $1/10^{th}$ of an inch (2.54 mm). For the internal cylinder, between the buckling and the pressurization failure, the minimum wall thickness required to prevent a pressurization failure was the thickest at 2.8 mm or 0.148 in. 2219-T6 aluminum was chosen to be used in the manufacturing of the walls of the EEV for its combination of characteristics of relatively low density and high yield stress. For the same weight versus steel, the aluminum will be able to be several times thicker. The thickness of the cylinder plays a large role in both equations. While steel may be about two times stronger than most aluminum alloys, it is also about three times denser. In a situation like this where the volume/thickness of the material plays a role in the failure modes, the aluminum will be about 1.5 times stronger than the steel for the same mass of material used.

The EEV does not have any windows so those do not have to be accounted for in the calculations. The EEV utilizes an exterior camera to deliver a video feed to the crew. For the construction of the walls of the EEV, there is a trade-off between different processes and their costs and benefits. For the outer hexagonal walls of the EEV, it makes the most sense to attach them to each other using mechanical fasteners. This outer sliver of the EEV is not pressurized; thus, there is not a heavy emphasis on using a process like welding or adding seals. The fasteners will prevent the aluminum from reducing in strength from being welded and will help prevent warping. This outer skin will also be easier to replace with the use of fasteners in case it is damaged while still on Earth's surface.

For the construction of the inner cylindrical pressure vessel of the EEV, welding it together would provide the most benefits. This is a pressurized vessel and if it develops a leak while in use, it will pose a major threat to the health and safety of the astronauts deployed on the mission. To ensure the safety of the astronauts it is important to invest in high quality welds to construct the cylindrical inner walls.

4.4.2 Rover Structural Analysis

Although the structural integrity of the rover is not as important as that of the EEV, analysis is run to ensure that the rover can carry out its duties without failure. The chassis is made of aluminum 6061 rectangular channels welded together in a basic square shape when looking down on the rover. Two parallel sides of the chassis each have 3 connection points to the motors powering the wheels. Because of the symmetry the chassis is modeled as a pinned end with a vertical load at the opposite end.

Mechanical Property	Value
Modulus of Elasticity	68.9 GPa
Length	20cm
Thickness	8cm

Table 4.5 Mechanical properties of 6061 aluminum.

This analysis was conducted with a desired 0.5 cm maximum deflection from the chassis. This was estimated from the overall chassis dimensions and the flexibility desired. From this base deflection equation 9 was used to calculate the load needed to obtain this deflection.

$$\delta = \frac{PL^3}{3EI} \tag{9}$$

For the rectangular chassis, the moment of inertia was calculated using (10).

$$I = \frac{1}{12} lt^3 \tag{10}$$

This was solved for the load P which was found to be 1.1×10^6 N for a 0.5 cm deflection. A load of magnitude is completely unrealistic for the rover as no heavy lifting is carried out throughout the journey.

On top of the vertical loading analysis, a simple center of gravity moment analysis was conducted to ensure that even while the rover is grounded, it would not tip over. When fully extended, the rover arms lie 1.5 m in front of the center of gravity of the rover. For this study, both arms are fully extended with a sample container of regolith in hand. This gives a total mass of 10 kg 1.5 meters from the CG. The support rod for the rover is located approximately 0.5 m behind the center of gravity. Equating the moments together, it turns out that the support rod needs only 0.171 N of force in order to ensure no tipping occurs.

4.4.3 Radiation Shielding

Given that this trip will be transporting astronauts beyond the magnetosphere of Earth, the crew members will be exposed to high-energy particles from the Sun and are also faced with the possibility of solar storms or coronal mass ejections. This introduces the need to protect the astronauts from these hazards with some form of radiation shielding. Sadly, there is no current standard for radiation shielding of humans for deep space travel. Even on the Apollo missions, NASA concluded that the mission length of 1-2 weeks did not pose significant risk of radiation exposure, and chose launch periods coinciding with low solar activity, in the hopes that the crew did not get exposed to a coronal mass ejection or other high-radiation events.

There are a few proposed solutions for radiation shielding on a small craft, which include water (ρ=1,000 kg/m^3) and Kevlar (ρ=1,400 kg/m^3). Unfortunately, the necessary amount of each of these materials to adequately shield the crew from radiation drastically increases launch cost due to high weight and can decrease the overall mobility of the spacecraft. Fortunately, researchers at North Carolina State University have developed a proposal for a new, significantly lighter material that absorbs 30% more radiation than traditional methods. The material analyzed by the researchers is a Gadolinium Oxide (Gd_2O_3) polymer, which has a density of nearly half that of Kevlar (ρ=741 kg/m^3). These advancements in both weight reduction and radiation absorption have led our team to select the Gadolinium Oxide polymer as the primary radiation shielding to be utilized for the EEV, which will be employed through a 3 cm thick radiation shield. This thickness was derived from the halving thickness of Kevlar, which is the thickness of a material needed to reduce the amount of a given type of radiation on the other side of the material by 50%.

4.5. Docking System

To transfer supplies and crew members to the EEV when in orbit around Mars, the EEV will have to dock with the DST. During this transaction, the crew members will move any needed supplies and scientific equipment that is required to accomplish the mission over to the EEV. Two requirements that the docking system must meet are reliability and size of the entryway. A proven system that has been consistently used on the ISS is the ISS standard docking system. It functions where each vessel aligns itself into place and makes contact between the two entrances, from which the series of hooks fixed to the edges fixes the two vessels into place. The ISS standard docking system has an entryway diameter of 800 mm [47re]. For this mission, the diameter of the docking entrance has been scaled upwards to 2.5 meters (Fig. 4.4). The larger diameter still holds the base design of the original system so it should be as reliable as the current system used on the ISS, but it will allow for the larger scientific equipment to be moved from the DST to the EEV.

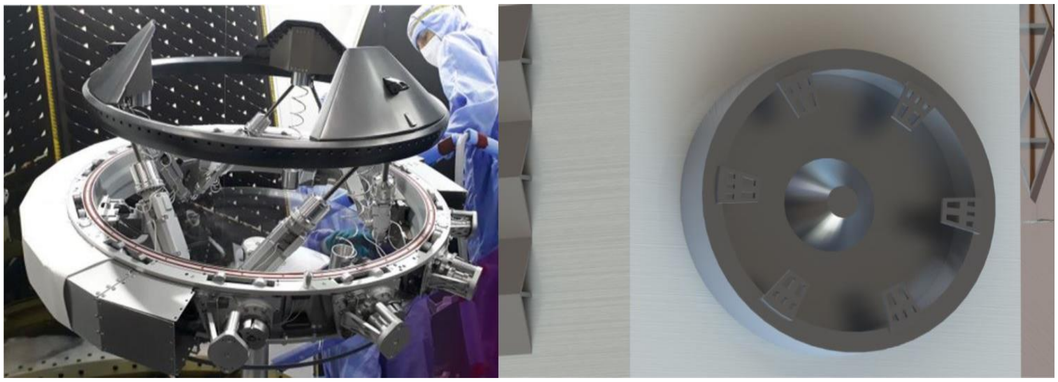

Fig. 4.4 The 2021 ISS docking system (left) [27]. The 2.5 meter diameter EEV docking system (right) [8].

4.6 Telecommunications

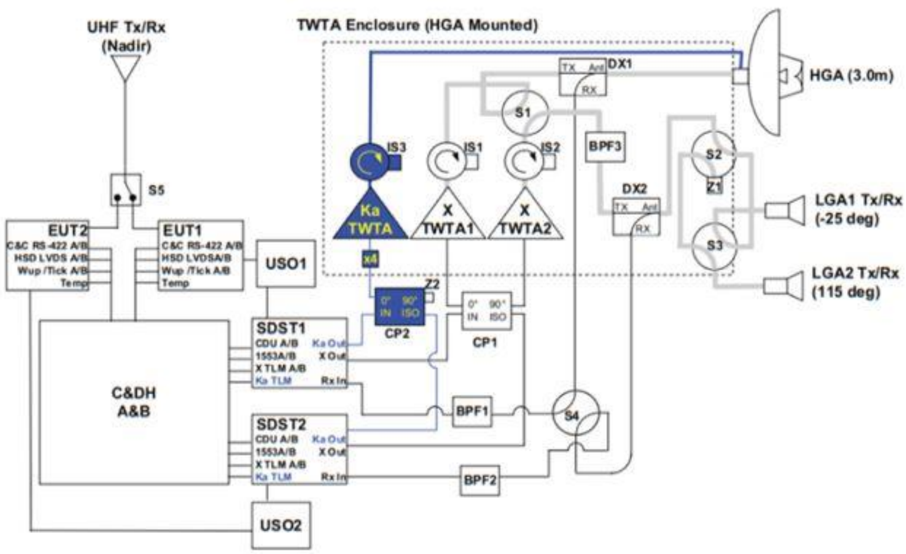

Fig. 4.5 UHF/X/Ka system demonstrated on NASA Mars Reconnaissance Orbiter [18].

Telecommunication systems for deep space missions have evolved over time. The Mariner mission utilized only the S band, the Viking mission added the X band, and in the 1990s, the Ka band was popularized. The active Mars landers and rovers utilize UHF to communicate with orbiters, which then relay the information back to Earth (Fig. 4.5) The active Mars rovers have a lag in communications of between 4 and 24 minutes, depending on the position of Mars relative to Earth. The Mars Perseverance Rover is able to communicate up to 2 Mbps locally, and up to 3 kbps direct to Earth [18]. The Ares mission aims to communicate with speeds up to 1 Gbps locally, with up to 100 kbps direct to Earth.

The EEV will use a dual communication system, utilizing UHF Frequencies for local communication with the DST, and an X/Ka-band system for long range communications directly to Earth. The X/Ka band system will utilize a 3-meter diameter parabolic receiver and draw 100 Watts to transmit. The link budget for EEV-to-Earth downlink will achieve a data rate of 100 Kbps with a link margin of 8.54 dB, illustrated in the table below.

EEV-Earth Downlink	
T_x Antenna	3-meter High Gain
Frequency	31 GHz (Ka Band)
Max Distance	401,000,000 km
R_x Antenna	70-meter DSN
Data Rate	100 Kbps
Bandwidth	100,000 Hz
System Noise Temperature Model	50 K
Modulation	QPSK
BER	1.0E-06
Required E_b/N_o	11 dB

Table 4.6 Details of the EEV-Earth downlink, including data rates, bandwidth, and communication frequencies.

Link Budget		
Value	**Magnitude**	**Unit**
Transmit Power	100	Watts
Efficiency	0.7	
Transmit Power in dBW	18.45	dBW
Transmitter Gain	58.23	dB
EIRP	76.68	dBW
Free Space Losses	-294.34	dB
Misc Losses	-10	dB
Receiver Gain	85.59	dB
Received Power	-142.07	dBW
E_b Received	-192.07	dBW/Hz
N_o	-211.61	dBW/Hz
Received E_b/N_o	19.54	dB
Link Margin	8.54	dB

Table 4.7 Link budget for the telecommunications subsystem.

The Ares telecommunications subsystem will utilize a 3-m diameter high gain antenna with UHF and X/Ka band transceivers. The system will also use X and Ka band Traveling Wave Tube Amplifiers (TWTA) to amplify the signal sent back to Earth for communications with NASA. The telecommunications system has a weight allowance of 80 kg, and a power allowance of 300 W. The telecommunications system will weigh 80 kg and draw 150 Watts of power, which is 50% of the allotted budget. The components will cost $10 million.

4.7 Power Systems

The power system of the EEV is necessary for most of the subsystems and the life support systems as well powering the rover during its expeditions. To determine the best power system for the EEV a power budget for the mission must be created first. The total power requirements at peak expectations for each individual subsystem are listed in Table 4.8.

Sub-System	Power Requirement (W)
Propulsion System	220
Telecommunication System	300
Scientific Objectives	526
Thermal System	306
Life Support System	1773
Power System	120
Rover	100

Table 4.8 Power Requirements for Each Subsystem

The largest source of continuous power during the mission will be produced using a solar panel attached to the body of the EEV. The chosen solar panel for the mission is the Orbital ATK MegaFlex array. This solar panel is the new generation of the highly successful and efficient UltraFlex array that will provide reliable and safe power production [39]. The solar panel will be stored in the outer structure of the EEV and open radially allowing for a large solar panel to occupy little space when compressed. The solar panel on the EEV will need to produce enough power to allow the EEV to function at peak power, therefore the solar panel must produce 3.323 kW of power. Due to the distance from the sun the solar panels on the EEV will only be 30% efficient resulting in a specific power of only 67 W/kg. To produce the power required for the EEV the solar panel will therefore need to be a mass of 50 kg. This will result in a solar panel with a diameter of 6.4 m for the EEV.

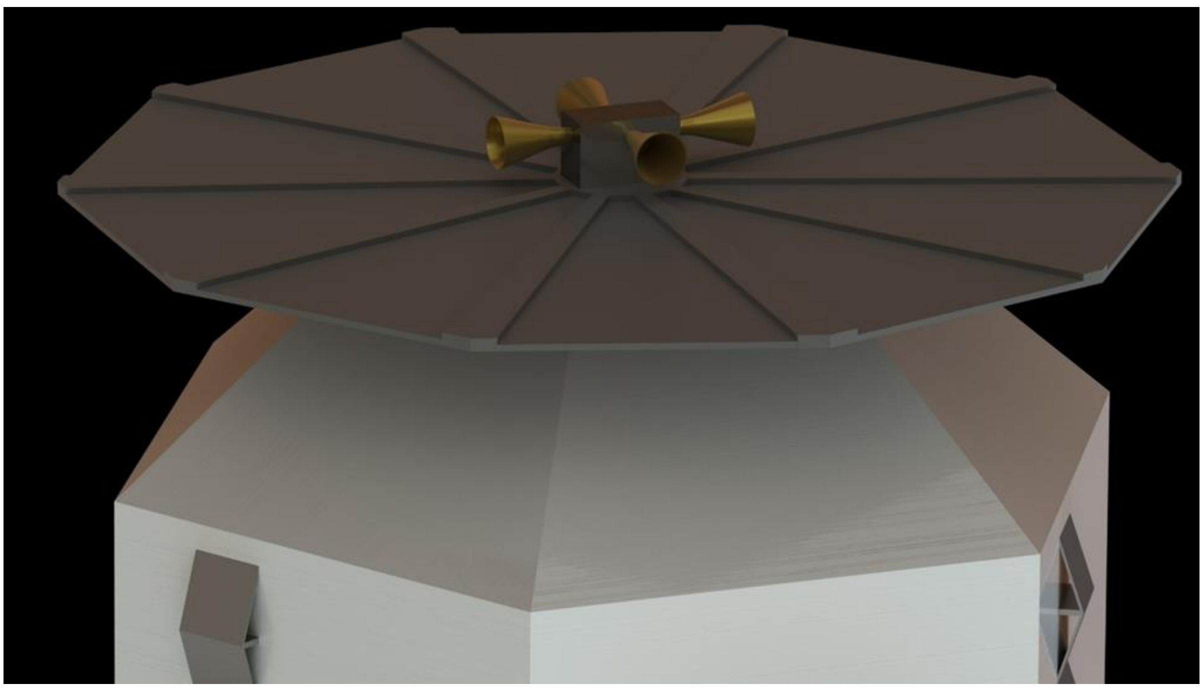

Fig. 4.6. Expanded Solar Panel on the EEV [8]

The rover will rely on solar power for most of its expeditions on the moons, requiring the solar panel to produce 100 W of power. The solar panel working at a similar efficiency as the EEV panel will result in a solar panel 1.5 kg and a diameter of 0.4 m.

The mission will take place as the EEV orbits Mars, Deimos, and Phobos, causing eclipse time during the mission rendering solar power useless. To remain in power during these periods a system of batteries will be used to power the EEV and the rover. The EEV will experience a maximum of 15% of the orbital period in an eclipse period. The maximum orbit will be a 5-sol orbit therefore requiring 18 hours of battery power to be provided during the mission as the batteries will recharge during periods of solar power production. This results in a peak consumption of 59.6 kWh of battery power necessary for the EEV.

To select a type of rechargeable chemical battery, a trade study was done on common rechargeable batteries commonly used in space exploration in Table 4.9.

Battery	Power-Weight Ratio (W/kg)	Safety
Ni-Cad	30	High
Li-Ion	130	Med
Ni-H_2	60	Med

Table 4.9 Trade study comparing common batteries to be used in the EEV.

The trade study gives lithium-ion batteries a large advantage in power capacity for its weight and the technology readiness and reliability of the type of batteries allows it to be the best choice for the battery power of this mission. The lithium-ion batteries used will be the VL51ES lithium-ion battery by Saft Technologies. This battery has a very high power-weight ratio of 130 W/kg with each battery weighing 69.6 kg and storing 9.1 kWh [44]. This high power to weight ratio and the batteries' ability to configure into a connected system allows for precision tuning of necessary power to minimize excess weight and power storage. The required power during periods which solar power is unavailable is 59.6 kWh requiring a total of 7 VL51ES batteries to power necessary systems.

The rover will use Lithium-ion batteries as a source of reserve power. However due to the lower power requirements the VL51ES battery is an unnecessarily large source of power storage therefore a smaller and slightly less efficient battery, the VES16, will be used on the rover to obtain the required power storage more accurately for the rover. The rover requires only to be powered during the moon landing periods therefore only requiring a maximum of 2.4 hours of battery power resulting in only 240 Wh of power storage being necessary. This power requirement results in the use of 4 VES16 batteries [1].

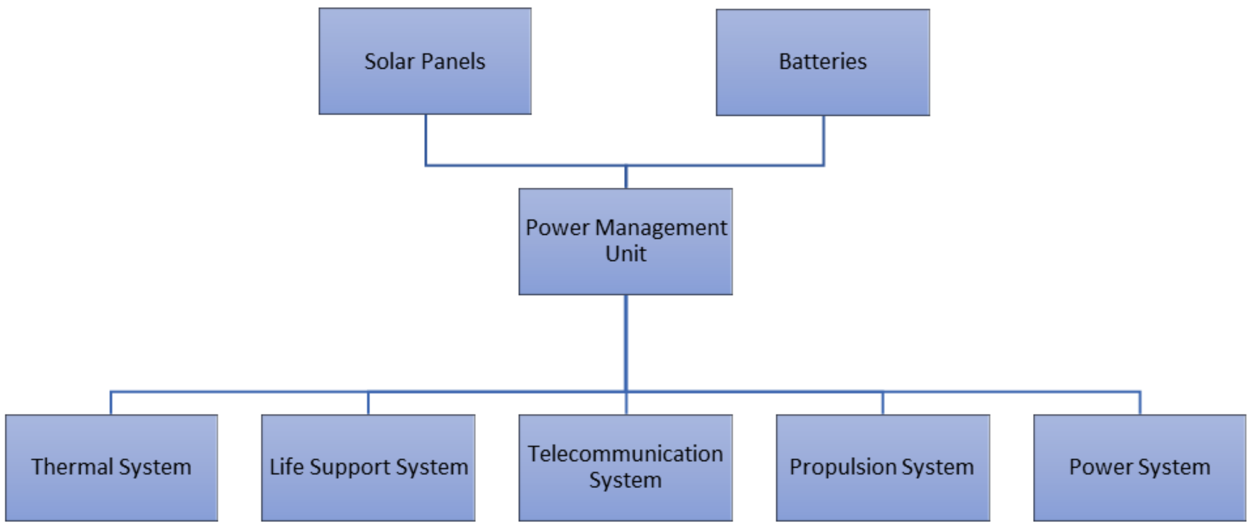

Fig 4.7 Power Distribution System for the EEV

4.8 Environmental Control and Life Support Systems

Ultimately, human physiology is the driving factor when determining the parameters of the environmental control and life support systems. Factors including daily water, oxygen, and food requirements, waste generation and disposal, and the activity levels of the crew will all be considered when defining the baseline characteristics of the life support systems on the EEV. Specifications from the Apollo Command Module and Lunar Exploration Module will be used as a reference for the generation of the EEV life support system since the missions are similar in scope and in length.

Starting from the simplest level, humans need to breathe oxygen rich air to survive in the vacuum of space. Air on Earth is composed of about 78% nitrogen, 21% oxygen, 0.9% argon, and 0.1% of other trace gases. The air composition on the EEV will aim to learn from the lessons of a pure oxygen environment seen on Apollo 1 and use nitrogen as a significant portion of the atmosphere within the EEV. On average, an adult human inhales and exhales about 0.008 m^3 of air per minute, adding up to approximately 11 m^3 of air per 24-hour period [21]. Since there are 2 astronauts on board of the EEV, it is necessary to have at least 22 m^3 of oxygen-rich air aboard the EEV to be recirculated for the duration of the mission. Additionally, a human generates 1.04 kg of carbon dioxide throughout an average day. This number depends heavily on the amount of activity that takes place throughout the day, which leads to a rough figure of about 2.5 kg of carbon dioxide generated by the EEV crew in one 24-hour period. This carbon dioxide will need to be scrubbed from the recirculating atmosphere by some type of filter, since air with >2500 ppm of carbon dioxide can impair humans and even be fatal.

Food and water are also two main staples that need to be accounted for on the mission. One human needs about 3 liters of water per day on average, so the mission will need to account for a total of 6 liters of water per day for the crew. Additionally, more water must be provided for sanitary purposes, like bathing and brushing teeth. Additional water should be provided for these purposes during the mission. Finally, food rations must be brought on board for the crew to sustain themselves. On an average day, humans are recommended to eat about 2,000-2,500 calories per day, which breaks down to 400-600 calories for breakfast, and 700-900 calories for lunch and dinner. Each of the crew members will need to have at least 3 square meals a day for every day of the mission, with some to spare. Finally, humans generate waste in the form of urine and feces, which need to be disposed of properly. Average urine generation varies between 1.5 and 2 liters per person per day, and average feces mass is around 250 g per person per day [24]. These all need to be properly disposed of to maintain a sanitary environment within the EEV.

4.8.1 Atmospheric Regulation Technology

As for removing heat if the appliances are producing too much, heat can be removed using heat exchangers and cold plates with a circulating water system. This water exchanges heat with another loop of ammonia. Ammonia has a freezing temperature of -107 degrees Fahrenheit and is cycled through the outside of the EEV and exposed to space in radiators. The radiators exchange the heat outside the system and cool the ammonia before it takes another trip inside the EEV [25].

The air in the EEV will need to be constantly processed in order to maintain a livable environment for the astronauts. Just from existing in space, byproducts of breathing and digestion need to be removed from the air supply. Some of the gases produced by humans that can become problematic in a closed system are carbon dioxide, ammonia, methane, acetone, and methyl alcohol. Activated charcoal filters will be used to remove the ammonia, methane, acetone, and methyl alcohol from the air.

The EEV's air filter system will be stationed against the wall on the top floor and connect directly via air vents to both floors of the EEV. This will help promote air flow and prevent the build-up of dangerous gas accumulation and stagnation around the astronauts.

The most important gas of all, oxygen, can be maintained in healthy amounts on the EEV through several processes. Some of the processes that could provide oxygen to the astronauts are:

- A garden on the spacecraft to convert carbon dioxide into oxygen and water through the process of photosynthesis. The problem with this is that the garden is unreliable due to plants being able to die. The garden also is not space or mass effective.
- An electrolysis system: The chemical decomposition of water produces oxygen and hydrogen. This decomposition is initiated by running an electric current through water and producing hydrogen and oxygen. Water can be carried safely on board without any

explosive risk. The hydrogen produced can be vented into space. This is the same process that the oxygen generation system on the ISS uses to produce oxygen for the astronauts.

- Pressurized oxygen tanks: while this solution is very reliable in that the exact amount of needed oxygen could be calculated and carried, it is not very space or mass effective. In addition, the compressed oxygen is flammable and could pose an explosion risk to the astronauts.
- Perchlorate Candles: Lithium Perchlorate is the same chemical that is used on board commercial aircraft when the cabin experiences rapid depressurization and the oxygen masks drop from the ceiling. The chemical reaction cannot be stopped once it is started, a byproduct of this chemical reaction is oxygen [7]. It would take up a lot of space and weigh a lot to carry enough perchlorate to produce enough oxygen for the entire journey. Another challenge that perchlorate candles pose is that they burn at high temperatures. If they were being continuously burned on board the spacecraft it would add a large load to the thermal control system to have to deal with. Perchlorate candles are available that produce enough oxygen for one person for one day.

The most viable solution is relying on an electrolysis system to produce the bulk of the oxygen for the astronauts and have a combination system of perchlorate candles and pressurized oxygen tanks to serve as an emergency backup. The average adult man consumes 2 pounds of oxygen per day [25]. The main system that will be used to produce the bulk of the oxygen is the solid polymer electrolyte (SPE) system. This system produces more than enough oxygen through the process of electrolysis, and it can produce enough oxygen for 6 average adult men. As a secondary byproduct it produces 1.56 pounds of hydrogen per day, which will be vented into space. This system functions and keeps the cabin total pressure at a value of 14.7 psia or 1 atm. The cabin size is roughly 200 cubic meters before any supplies or equipment is added to the chamber. In case of emergency, several perchlorate candles will be carried on board, ready for use, and should buy the astronauts precious time to either fix the problem or rendezvous with the DST.

The main waste gas that will be produced by the astronauts is carbon dioxide. There is no way of reducing the amount that is produced; the average adult man produces 2.2 pounds of carbon dioxide per day. The system in the EEV to tackle this problem is the Bosch CO2 Reduction System. The system heats gases in a regenerative heat exchanger and then passes the gases through catalysts and filters, trapping any solid waste products like carbon [25]. Lastly the air passes through a condenser where water is produced. This water that is produced by the system can then be fed into the electrolysis system; thus, reducing the amount of water that needs to be brought into space from Earth. The carbon dioxide reduction system is also more than capable for the mission requirements, in that it can reduce the carbon dioxide produced by 3 adult men. This system also functions at 1 atm. The system produces 10.8 pounds of water per day and 3.6 pounds of carbon [25].

In addition to oxygen, another gas that is desired to remain in the atmosphere is nitrogen. Humans breathe back out just about as much nitrogen as they breathe in, so there does not need to be a continuous system in place to produce more oxygen gas. Some nitrogen can be brought on board in pressure vessels and released as needed to keep the nitrogen levels around 78%. Having the nitrogen mixed in the atmosphere helps reduce the fire risks that come along with an oxygen rich environment.

Humidity in the EEV also needs to be maintained to proper levels below 70% humidity. If left unchecked, the longer the astronauts are in the DST, the more humid it would become until the air became completely saturated with moisture. This poses a problem as condensation will form on surfaces and ruin electrical equipment. To combat the humid conditions, the air will be run through filters containing silica gel. The silica gel absorbs the water out of the air and lowers the humidity of the cabin. Another bonus is that the activated charcoal filter works more effectively at lower humidity levels.

4.9 Crew Accommodations

While the primary goal of the Ares mission is to obtain samples from Phobos and Deimos, as well as to carry out valuable scientific experiments along the way, we must make sure that the crew is happy, healthy, and safe throughout the duration of the mission. Crew accommodations include anything that crew members may use within the EEV on a day-to-day basis, including meals, waste management, recreational activities, and hygiene (Fig. 4.8 and 4.9).

Fig. 4.8 Render of the proposed layout of the top of floor of the inside of the EEV [8]

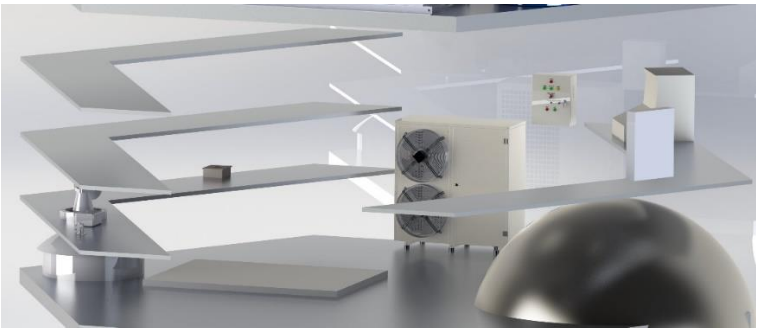

Fig. 4.9 Render of the proposed layout of the bottom floor of the inside of the EEV [8]

4.9.1 Food and Water Allocation

Making sure that the crew have enough food, water, and nutrients to complete the mission is of the utmost importance. On an average day, humans are recommended to eat about 2,000-2,500 calories per day, which breaks down to 400-600 calories for breakfast, and 700-900 calories for lunch and dinner. Each of the crew members will need to have at least 3 square meals a day for every day of the mission, with some to spare. To meet this need, a similar approach to the Apollo missions will be taken. Packages of dehydrated meals will be provided for the crew within the EEV, and hot water will be added to the package from the 60-gallon storage tank to make it easily consumable in a microgravity environment.

The breakfast menu will be composed of items like sausage patties, bacon squAres, dehydrated fruit, and accompanying beverages. The lunch and dinner menu will be made up of meals like beef and potatoes, salmon, spaghetti and meat sauce, and other calorie-dense options. 3 square meal containers per day come out to an average mass of 1.8 kg per person per day, assuming a mass of about 0.6 kg for an average meal. Meals will be supplied for the duration of the 5-day mission, with surplus in the event of mission extension. An additional 10 days of food will be supplied to meet these needs, bringing the total mass of food on board to 54 kg.

4.9.2 Waste Disposal Methods

Waste management will be one of the most important means of maintaining a clean environment for the crew of the Ares mission. Humans generate waste in the form of urine and feces, which need to be disposed of properly. Average urine generation varies between 1.5 and 2 liters per person per day, and average feces mass is around 250 g per person per day [24]. Disposal of both substances can quickly become burdensome in a microgravity environment. Power and space are both a premium on the EEV, so any choice of waste disposal mechanism must be both compact and use as little energy as possible while in use.

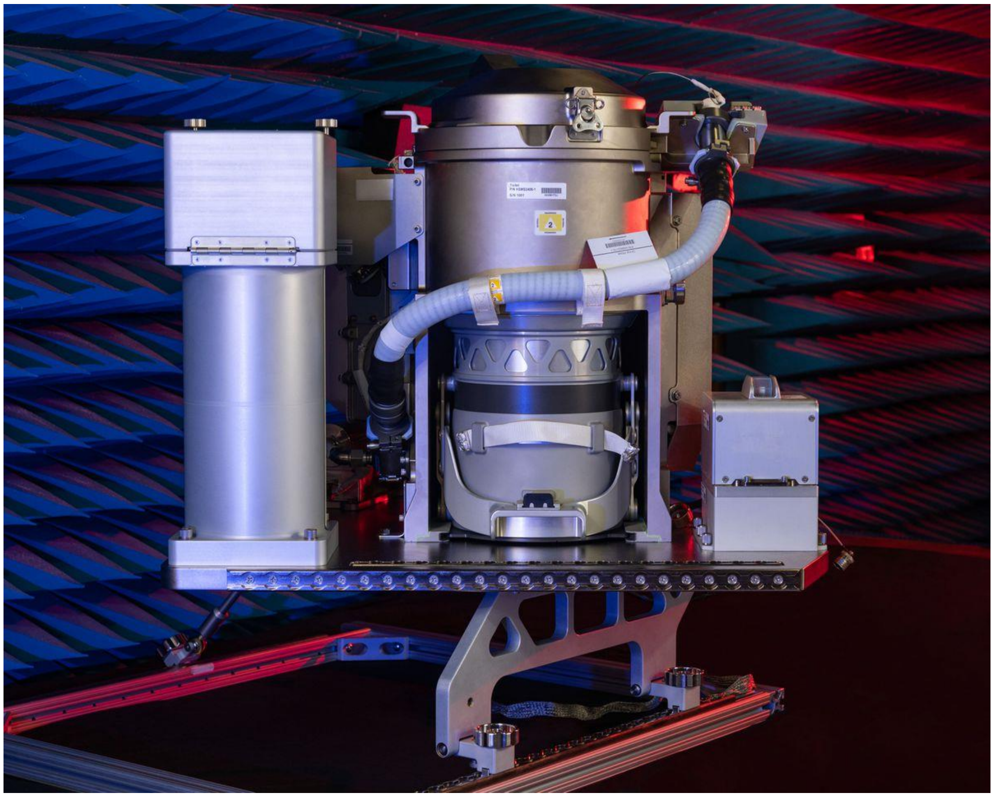

Fig. 4.10 Newly developed Universal Waste Management System (UWMS), which will be used for the Ares mission onboard the EEV [32].

On their 2-week missions, Apollo astronauts did not have any distinct method of disposing of waste. Astronauts urinated and defecated into plastic bags, which were stored on-board until arrival back to Earth, where the samples were then thrown away. This is not the method of choice but could be used as a failsafe if traditional waste disposal mechanisms fail. In the case of the International Space Station, astronauts will soon use the Universal Waste Management System (UWMS), which will be the primary method of waste disposal on the Ares mission [32]. The UWMS is a more compact and efficient version of toilets currently in use on the International Space Station and will help to conserve space on the EEV.

The UWMS is equipped with both urine and fecal collection and storage systems. Urine is collected using a series of hoses and suction, adapted for both male and female crew members. The urine could either be vented into space during the mission or stored on-board. NASA trade studies show that the complexity and weight of urine venting systems (storage tank, valves, and heated vent orifices) outweigh the added weight of storing urine on-board, which will be the method of choice for the EEV. Over a period of 5 days with 2 crew members, it is estimated that only about 20 liters of urine will be generated, with a mass of around 20 kg.

Similar considerations have been made for fecal storage. A single, hydrophobic bag is placed under the seat of the UWMS, and a manual fecal compactor is used to compress the feces for storage. Around 200 N of force is supplied through the mechanical advantage of the compactor, allowing the volume of the feces to be minimized for future storage [32]. Over the course of the Ares mission, it is estimated that 2.5 kg of feces will be generated, which is not consequential enough to develop a method of disposing of the feces into space during the mission. To combat the smell and bacteria generated by the feces, an advanced odor/bacteria filter using activated charcoal is used to surround the commode and limit possible smells.

The UWMS weighs less than 50 kg, and costs around $23 million USD. When in idle use, the UWMS pulls 274 W, and at peak consumption, the UWMS pulls 380 W (for 6 seconds or less) [32]. The UWMS is relatively compact as well, occupying around 0.05 m^3 of space. All these considerations have led the ECLSS team to determine that the UWMS is the ideal choice of waste management for the Ares mission. In case the UWMS fails, the crew will be provided with 75 fecal collection bags and 75 urine collection bags, which can be vacuum sealed manually and stored following collection.

4.9.3 Housekeeping Accommodations and Miscellaneous Supplies

The crew aboard the EEV will need clean clothes, a place to sleep, ways to stay clean, and a place to store their personal items. To accomplish this, the EEV will be stocked with 5 clean jumpsuits for each crew member. Though one jumpsuit may not be used each day, this allows for the crew to continue to have clean clothes in the event of mission extension. Additionally, each of the crew members will be provided with two sleeping bags and one set of restraints to keep the sleeping bag secure in the microgravity environment. Finally, for the maintenance of hygiene, each crew member will be provided with the following: 2 toothbrushes, 2 tubes of toothpaste, 2 containers of dry shampoo, 15 cleaning rags to be used for showering, 2 towels, 5 razors, and a package of single-use wet wipes. To store their personal items, each crew member will be provided with 2 one-gallon canvas zipper bags. Crew members will also be supplied with an extensive first-aid kit including painkiller medication, gauze, basic surgical supplies, and other essentials in case of emergency.

Extracurricular activities for the crew members must also be considered in the final design of the EEV. Long-term spaceflight has proven to be damaging to existing bone and muscle structure, so active measures must be taken to ensure that the crew is able to stay in peak physical condition during the mission. Since space on the EEV is limited, each crew member will be supplied with a set of resistance bands to carry out a 30-minute workout each day during the mission. Crew members of the EEV will also be tasked with documenting the mission through photographs, so each member will be supplied with a Canon 5D MKIV, a 100-400mm telephoto lens, a 24-70mm wide angle lens, 5 batteries, 2 chargers, and 10 SD cards for safe digital storage.

4.9.4 Crew Accommodations Mass Budget

Crew accommodations include elements of mission hardware and procedures that directly serve the needs of the crew members. The mass of each of the crew accommodations was derived from a text titled "Space Mission Analysis and Design," or were pulled from official NASA sources. The largest masses in this case include those of waste disposal and food/water accommodations.

Crew Accommodation	Mass Subtotal (kg)
Waste Collection	50
Generated Feces and Urine	22.5
Personal Hygiene	17.5
Housekeeping	7
First-Aid	3
Food and Water	280
Photography	10
Total	**390**

Table 4.10 Mass budget for EEV crew accommodations.

4.10 Rover and Subsystems

The rover is a major system in the Ares mission, being a robot capable of carrying out multiple experiments at once. The rover is designed to collect samples of regolith from both moons and survey the landscape for chemical composition. The rover was created to determine variability in the sample results based on region. When compared to a traditional mission, the EEV would land and collect the samples around the landing site. This means that if there once were bacteria or sources of water even a few dozen meters away, the EEV is only collecting regolith found straight underneath. The Ares rover aims to avoid this method by collecting samples far away and at numerous depths to add variability in findings.

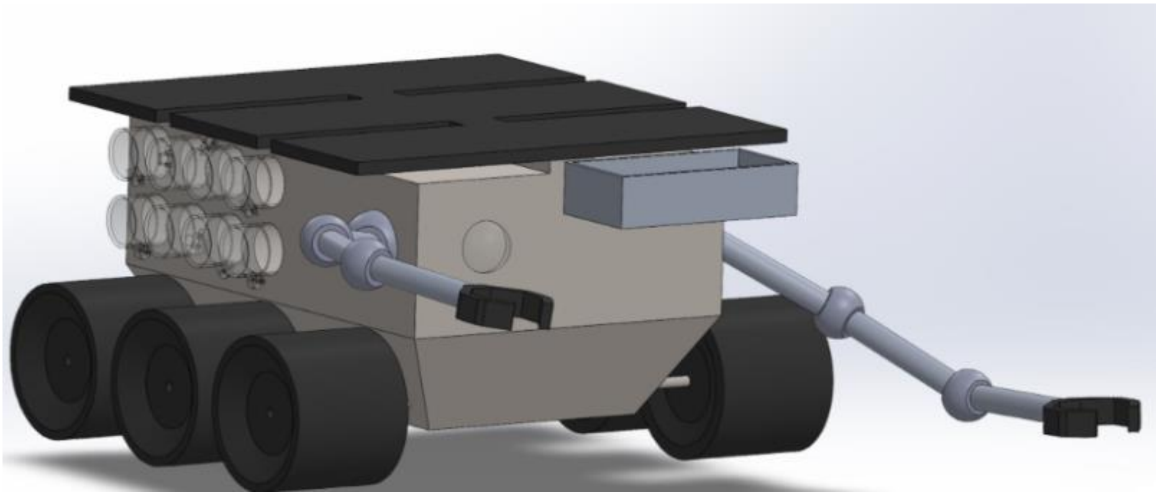

Fig. 4.11 SOLIDWORKS render of the proposed design of rover

The rover is designed to collect and store key soil and rock samples on the surface of each of the moons. It will be dropped from the EEV using a hydraulic lift and will be equipped with two robotic arms that can collect samples from the surface and store them in cylindrical containers each with 3.506×10^{-3} m^3 storing capacity. With an averaged density of $1.471 g/cm^3$ for the regolith on Phobos and Deimos, if the storage containers were filled completely this gives a mass of 5.157kg per container. Since a 50kg minimum is needed per moon, 10 samples will be collected on each moon giving a total sample collection of 51.57kg. The goal is to run the rover in a circle with the EEV in the center. The rover will start the trip by going to the outer radius of the circle and performing its first collection. The rover then makes its way around the circle repeating the collection 2 more times along the circumference. Finally, the rover returns to the EEV, collects its final samples, and then boards back onto the EEV. In the event that communication is lost or the crew is busy with the EEV, the rover is equipped with both imaging and ultrasonic transducers to allow for autonomous control.

The rover can also collect regolith from multiple depths on each moon. Both a surface level sample and a sample at 0.25 m in depth will be collected at each location. The rover will carry out two sample collections at 0.5 m below ground bringing a total of 10 samples altogether. To get to the lower depths, the rover is equipped with a modified version of the Rock Abrasion Tool (RAT) found on the Mars Exploration Rovers. The RAT for these missions is designed to drill a hole in dense rocks up to 2 inches in diameter. Instead of a sharp drill bit used to drill a hole, the Ares RAT utilizes a fan type blade with a much larger surface area to move larger amounts of regolith in a short time. The arms each have 3 joints which allow for a large range of motion. The first joint allows for 300-degree rotation which allows the arms to be lowered to the ground and then store the containers in the back of the rover. The second joint allows for z-axis and x-axis rotation. The final joint as the hand has full range of motion using a gimbal joint which allows for precise movements of the arm. The sample storage on the rover is separated from the inside of the rover so no temperatures are compromised.

With extremely low gravity values of about 0.0057 m/s^2, support is needed to assure that the rover stays grounded at all times. Because of the lack of atmosphere on both moons, wind is not a concern, so only the uneven terrain will cause a problem. To account for this, the rover is equipped with specifically designed wheels for greater traction and a support rod that drills into the surface of the moons. The support rod is located in the back of the rover between where the samples are stored. The rod acts as a large worm screw which is lowered and lifted using a motor and work gear set.

The Ares rover chassis is manufactured with rectangular AI-6061 aluminum channels. Six 76 RPM brushed planetary gear motors are connected to the chassis and power each of the six wheels. The body of the rover is made of a carbon composite material which provides high strength and stiffness as well as easier manufacturing of curves with molds [43]. The body is coated with aerogel which provides insulation to keep the temperatures inside the rover optimal. From the

NASA Perseverance rover, the temperatures will be kept between –20C and 40C to ensure all electronics are working properly [35].

Rover Major Components	Function	Location
AI 6061	Chassis	Bottom or rover
76 RPM Planetary Gear Motors	Power the wheels	Inside rover lateral with wheels
CCD Image Sensor	View rover surroundings	Front of rover
Ultrasonic Transducer	Autonomous Control	Front of rover
Intel NUC Processor	Register the sensors	Inside body
Solar Panel	Supply secondary power	Top of rover
Batteries/Battery Box	Primary power	Front of rover body
Robotic Arms	Collects samples	Front of rover
RAT	Get to lower layers of regolith	On end joints of rover arms
Support Rod	Adds stability	Back of rover body in a separate section

Table 4.11 Major components of the rover and their function.

The rover will be moved from its compartment on the EEV to the surface of the moons using the rover lift (Fig 4.12). The rover lift is composed of four hydraulic pistons attached to a flat platform. When lowered to the floor, the rover will drive off the platform and onto the surface of the moon. A potential issue that was not addressed in the initial design was the potential for the lift to be lowered over ground that was not completely flat, having a rock below it for example. To solve this, the bottom of each of the pistons will be attached to the platform using pins so that each corner can be lowered to different heights and allow the platform to angle itself to be flush with the ground.

Fig. 4.12 SOLIDWORKS render of the proposed design for the rover lift [8]

4.11 EEV Dry Mass Budget

Category	Percentage of Total Mass [%]	Mass [kg]
Propulsion	13.4	1333.5
Thermal Control	13.2	1315.85
Structures and Radiation Shielding	50.3	5000
Power and Electronics	5.5	545
Scientific and Telecommunications Equipment	2.5	247
ECLSS	3.2	314
Crew Accommodations	3.9	390
Rover	8.0	800
Total	**100**	**9945.35**

Table 4.12 Total dry mass budget of the EEV for each subsystem category.

Calculation of the EEV dry mass is essential for determining how much fuel is necessary for the mission for Phobos and Deimos. Of the subsystem categories, structures and radiation shielding make up most of the dry mass budget, accounting for 50.3% of the EEV's dry mass (Table 4.12). Other subsystems that account for a significant portion of the EEV's dry mass are the propulsion and thermal control subsystems, making up 13.4% and 13.2% of the dry mass, respectively (Table 4.12).

5.0 Scientific Equipment and Procedures

At the heart of the Ares mission lies the scientific experiments to learn more about Mars, as well as its moons Phobos and Deimos. A large portion of the mission concept of operations is the carrying out of various scientific objectives to assist in the next generation of crewed missions to Mars and other planets in the solar system.

5.1 Sample Collection

The mechanical procedures behind sample collection depend upon the surface of the moons. Both Phobos and Deimos have a very thick layer of regolith covering the surface of the Moons and is estimated to be around 100 meters deep. This makes the technology used in the Ares mission different from that used in the Moon and Mars missions. The Earths' moon had a regolith layer of around 10 meters, much smaller than Mars' moons. This made drilling down under the regolith layer a viable option for collection of larger rock samples. In the Ares mission, this is made obsolete.

The sample collection will be carried out by an independent rover detached from the EEV. The rover is a self-sufficient robot much like the Perseverance rover found on Mars. The samples are obtained through a robotic arm on the rover. The arm has a set of grippers used to grab the empty test tube and scoop up the regolith from the ground. The test tubes are adopted from the Perseverance mission. These test tubes are made from titanium for strength with a coating on the outside to protect the samples from the Sun and other contaminants. Each sample tube is 31 cm long with a diameter of 12 cm. Once the material is collected, the arm sets the sample tube in a specially made storage unit within the chassis of the rover. The arm is also equipped with a small scoop that uncovers deeper layers of regolith. 10 samples are obtained with 2 samples at surface level and ¼ meter depth at each location as well as 2 samples at ½ meter depth. This design is implemented to allow the study of differences in composition much like the soil on Earth. In the event that larger rocks are found, a rock abrasion tool (RAT) will be used to break up material. This allows the rover to easily scoop up regolith material.

5.2 Advanced Imaging

During the mission transit, and specifically when in close proximity to each moon, the EEV will utilize a series of imagers to map the elements environment found on the surfaces and surrounding them. Ares will employ specialty telescopes capturing nearly the whole range of the electromagnetic spectrum. First, a gamma-ray/neutron spectrometer (GRS) will be used to determine the elements found in the areas of interest. Adapted from the Mars Odyssey mission, the GRS can determine what elements are present on a celestial body by determining how gamma rays from deep space interact with the surface materials. Additionally, the GRS can detect changes as neutrons are released from the sandy surface which will be an indication of liquid or frozen water if present. In the past the GRS has been able to show the presence of hydrogen, silicon, iron, potassium, thorium, and chlorine [45], providing insight on how an environment changes over time. The GRS will take up roughly 1 m^3 of space and will be mounted on the exterior of the EEV, where other science equipment will be assembled.

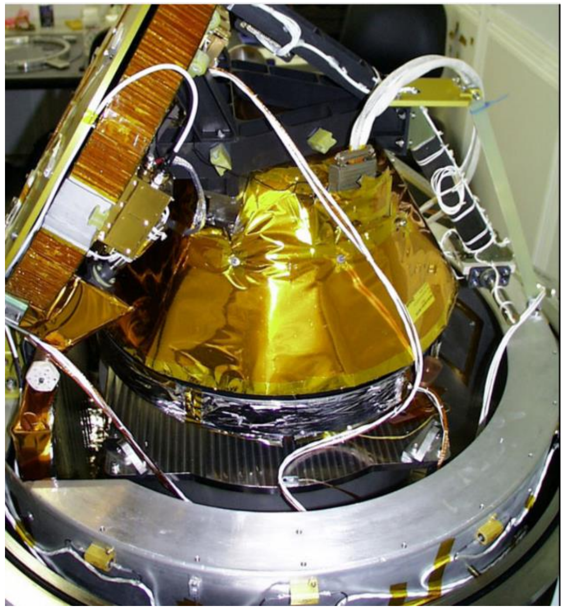

Fig. 5.1 Gamma-ray/neutron spectrometer used on Mars Odyssey Mission. The GRS can characterize the reactions of surface material as they are struck by cosmic rays. These reactions act as signatures for particular elements found on the surface. Also, by analyzing the presence of hydrogen in a given region, the GRS can help detect if water is present within the surface [45].

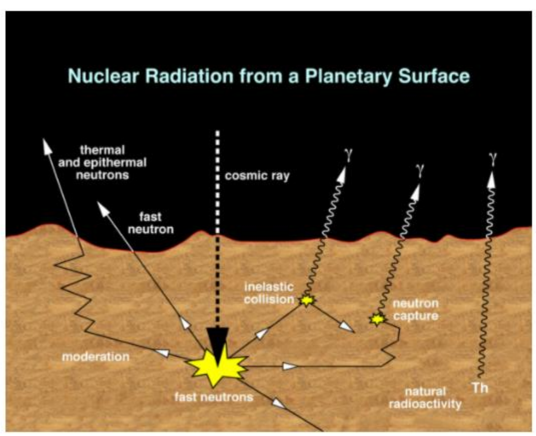

Fig. 5.2 Neutron scattering when struck by cosmic rays**.** The neutron spectrometer is able to detect neutrons in three energy bands: thermal, epithermal, and fast [45].

The second imaging instrument used will be a laser altimeter. This tool can collect altimetry data revealing the height of surface features on Phobos and Deimos. The laser altimeter uses infrared laser pulses leaving the EEV and measures the time it takes to reflect off the surface. From this data the altimeter can illustrate the topography of each moon. Not only will this provide scientists with a map of the land, but it can also allow them to draw inferences about the interior structure and the evolution of the landscape [23]. The altimeter will be very similar to the Mars Orbiter Laser Altimeter (MOLA) used on the Mars Global Surveyor (MGS). Taking up only 0.15 m^3 of space the laser altimeter will also be mounted on the exterior of the EEV. This instrument can capture a 5,000-kilometer profile in only 20 minutes and will be used while in orbit around each moon to reveal the full topography profiles.

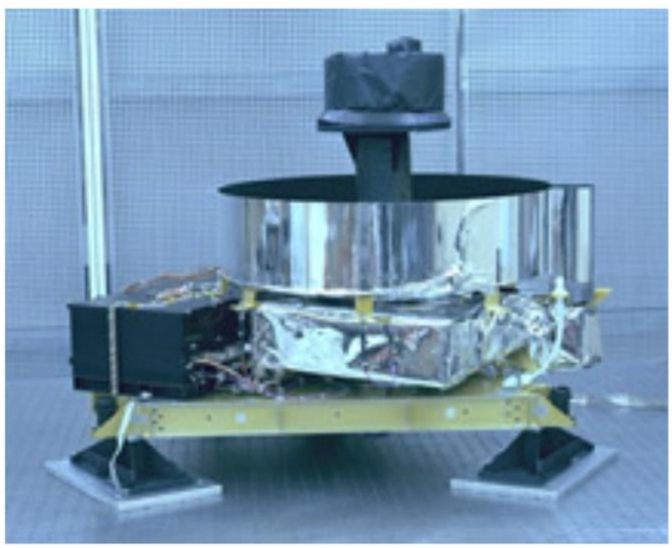

Fig. 5.3 Mars Orbiter Laser Alitmeter (MOLA). This infrared laser altimeter performs the same topographic investigations that Ares will carry out for Phobos and Deimos [23].

Lastly, the Ares mission will use an atmospheric and surface composition spectrometer (ASCS) to help characterize surface materials present, but more importantly to measure the elements present surrounding the moons where an atmosphere would be present. Due to the weak gravitational forces, it is likely that there is no atmosphere present, which the Ares crew intends to confirm with the data from the ASCS. The ASCS consists of an ultraviolet-visible spectrometer (UVVS) and a visible-infrared spectrograph (VIRS) which examines sunlight reflected off of the surface, much like the human eye [28]. By examining light reflection by the surface materials, the ASCS will further qualify the data collected by the GRS, by examining different portions of the electromagnetic spectrum. This will allow scientists to identify more possible elements on Phobos and Deimos. Possible elements to detect will be hydrogen, oxygen, sodium, potassium, calcium, sulfur, silicon, aluminum, magnesium, iron, and the compound [29]. These types of spectrometers have been used largely throughout history to characterize surface and atmospheric compositions of Mercury (Messenger), Jupiter (Galileo), Mars (Mariner), and even on earth and near-earth asteroids (NEAR). Like the other imaging instruments, the ASCS will be mounted on the exterior of the EEV.

5.3 Magnetic Field Measurements

The outline of the Martian moons' physical environments will continue with an investigation into the possible magnetospheres, ionospheres, and interactions with solar wind. To do so, the Ares mission will make use of a magnetometer. The magnetometer is used to measure the vector magnetic field surrounding planets. It is hypothesized that both moons will have no magnetic field since it is unlikely that they harbor a metallic core, which would generate alternate poles. In that sense, the magnetometer will be used to confirm the lack of a magnetic field. This would imply that many materials and life forms found on earth would be subject to harmful radiation if left exposed on the surface of the moons. The magnetometer used for this mission will mirror the one used in the Mars Atmosphere and Volatile Evolution Mission (MAVEN). It consists of two small sensors outboard of a solar array and is equipped with the ability to measure ions, electrons, energetic particles and waves including solar wind [14]. This device has a core of only 1 centimeter in size and will be mounted on the together with the imaging equipment.

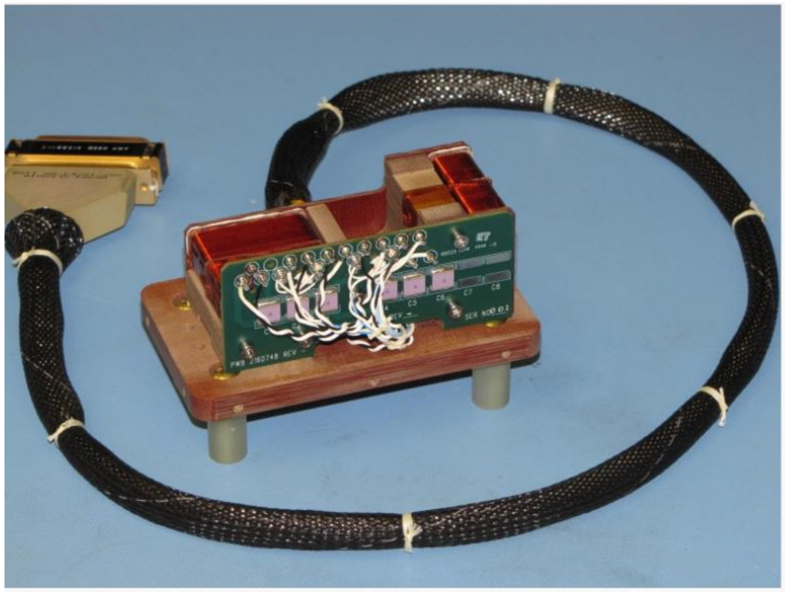

Fig. 5.4 Magnetometer with Particles and Fields package. This is the magnetometer used on MAVEN which characterized the energetic ions surrounding Mars [14].

The Energetic Particle and Plasma Spectrometer EPS operates very similarly to the previously used spectrometers. “The EPS determines the distributions of the higher-energy magnetospheric ions and electrons,” by investigating the species of an element based off its signal reflection [31]. With only a 60 mm diameter, the EPS will easily fit on the exterior of the EEV grouped along with other imaging equipment. The results from the ESP will be a great source of redundancy to qualify the magnetometer data.

5.4 Weather Sampling

To investigate the conditions that may be present on Phobos and Deimos, the Ares crew will first use cameras operating in the visible region. By making use of a wide angle and narrow angle imagers, the appropriately named Dual Imaging System (DIS) [30], will provide detailed photography of the moons. By also operating near the infrared range, the DIS will be able to highlight thermal properties of different regions and their compositions. Understanding the chemical makeup of the sediment found on each moon will allow scientists to recognize the geological processes that have taken place over time. The DIS will be attached to the imaging equipment assembly. The imaging and spectrometry trials will be conducted simultaneously.

Another step towards understanding the environmental conditions would be to study the amount of iron found within the regolith. Iron is a major component of Mars's chemical make-up. The presence of iron may reveal the possible origin of the moons being from a once larger Mars. To measure iron deposits the team designed rover will host a Mössbauer Spectrometer (MB). The MB is small enough to be held in your hand and can provide exceptionally accurate results for composition and magnetic properties [11]. These metrics will reveal any past magnetic fields and how they may have vanished. The MB will be mounted on one of the arms of the rover.

5.5 Solar Readings

To advance the pursuit of renewable energy, the Ares mission will collect solar wind readings. To do so, the EEV will utilize a solar sail during points of zero acceleration during flight. The sail will be made with advanced composites giving it a very light weight. Like the current Deep Space Exploration sail NASA has built in 2021 [20], the solar sail will deploy from an initial "cross beam" into a full 9 m by 9 m surface (Fig. 5.5- 5.6).

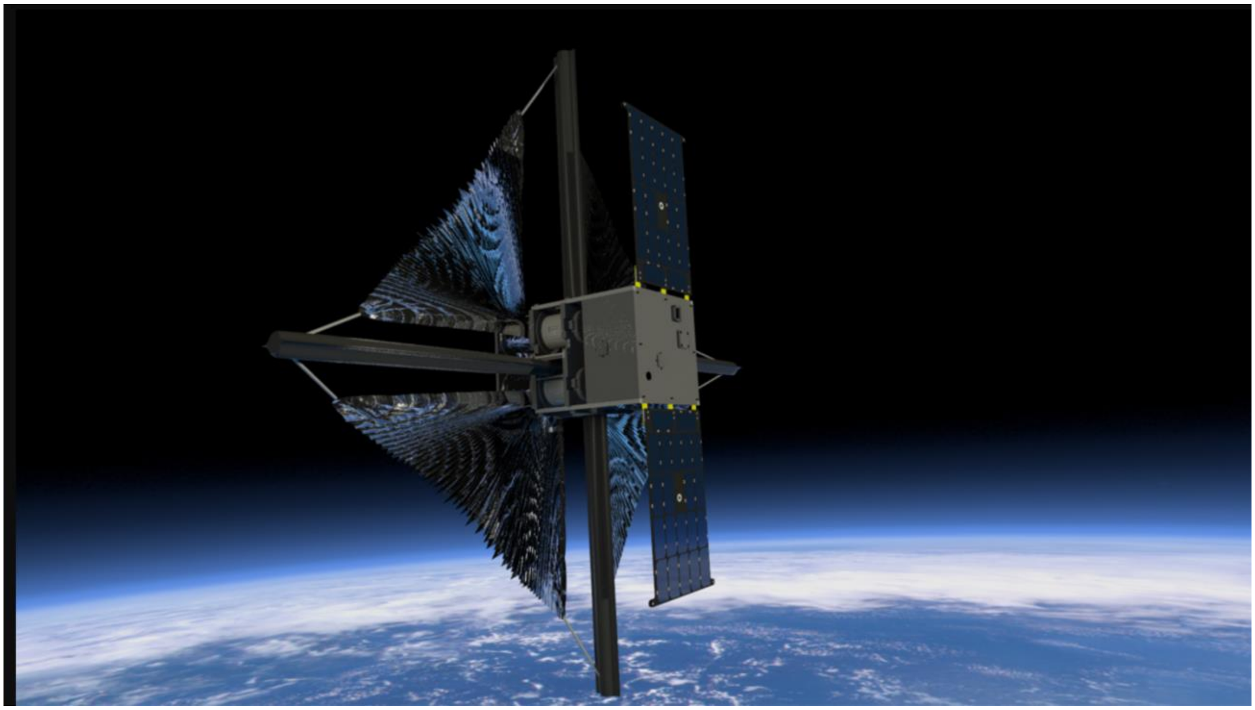

Fig. 5.5 NASA’s Advanced Composite Solar Sail System during retraction [20]**.**

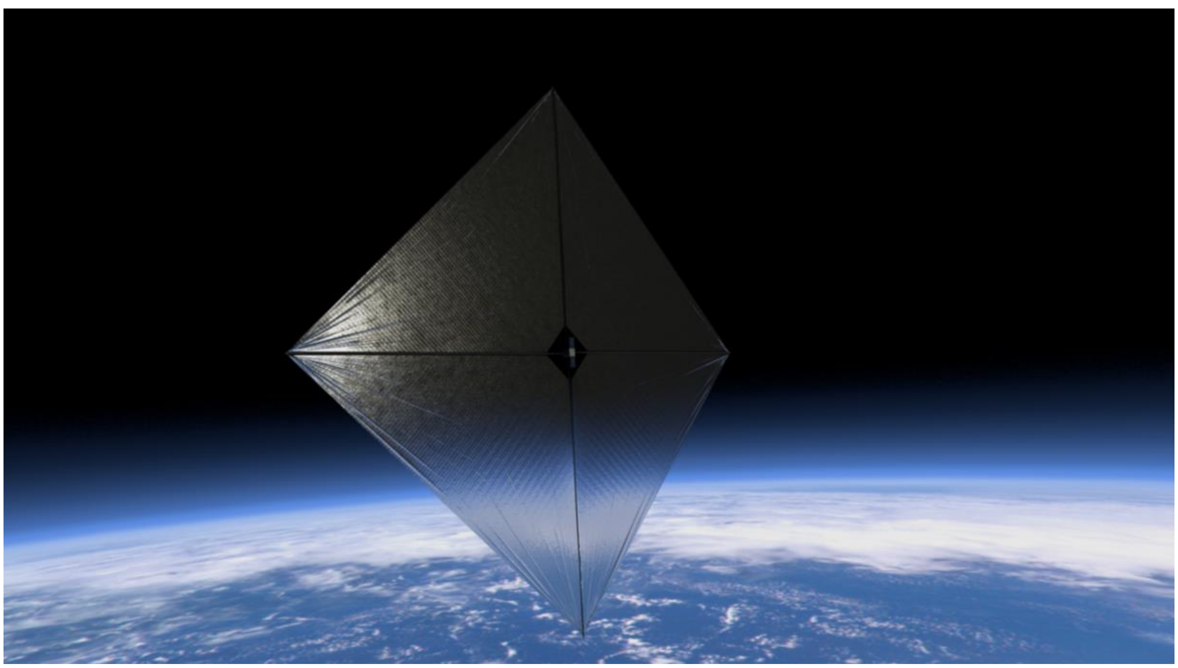

Fig. 5.6 NASA’s Advanced Composite Solar Sail System fully retracted [20].

The solar sail will have 100 industrial-grade micro-sized force sensors distributed throughout the surface area of the sail. Outsourced from ABQ Industrial, the sensors used on the sail will have the capability to read up to 2.5 N with an accuracy of ±0.2% [26]. The readings will be compared to the amount of solar energy absorbed by the MegaFlex Solar Panel Array. Note both instruments will be constantly oriented towards maximizing energy capture. The data is even further qualified by the magnetometer readings. The results of the data will indicate if the solar wind energy is significant enough to be applied to practical applications (controlled flight, applied motion, etc.). This procedure will take place while the EEV is in a zero-acceleration orbit around each moon.

5.6 Internal Structures Mapping

The survey of each moon's internal structure will require highly advanced instruments. Drawing inspiration from the Mars InSight Mission, the Ares mission will design and employ a seismometer used to measure the pulse (if any) of the moons by studying waves created beneath the surface [39]. The reduced version of NASA's InSight seismometer will be roughly 2 liters in volume. It will be designed to be able to fit into the docking interlock and will be the only piece of equipment coming from the DST. After descent and landing, the crew will deploy it from EEV, by using the rover. Using its arms, the rover will carry and place the seismometer onto the surface and back onto the EEV. Another NASA-inspired instrument used will be the RIMFAX. The Radar Imager for Mars' Subsurface Experiment uses radar waves to measure the layers directly underneath the surface of Phobos and Deimos [37]. It can measure up to 10 meters below the surface and weighs only 3 kg which makes it acceptable to place it onto the rover. That way data can be collected for a large area.

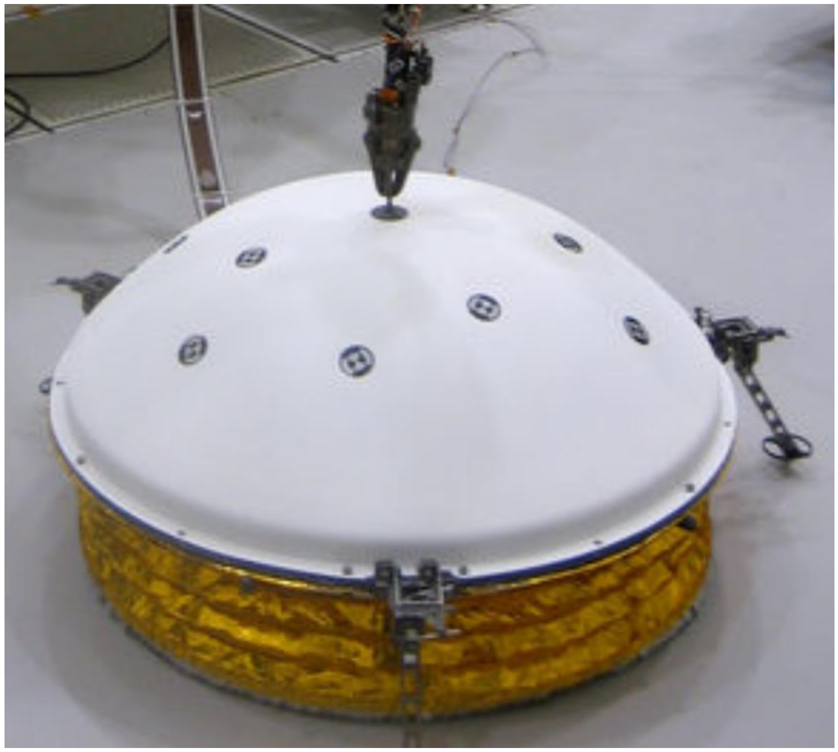

Fig. 5.7 NASA’s Seismometer used on InSight [41].

Fig. 5.8 Radar Imager for Mars’ Subsurface Experiment (RIMFAX) [37].

6.0 Program Schedule

An essential component of the Ares mission is ensuring that all the objectives are completed within the time constraints presented by the mission prompt. This section details the exact timescale on which the Ares mission will be completed. The Earth to Mars launch window is valid without altering the Δv for roughly 42 days. The current schedule outlines the mission and predicts completion in 5 days. While in the Mars 5-sol orbit and during the mission, launch windows frequently present themselves if they are missed. The orbital period of Phobos and Deimos are 8 and 30 hours, respectively. At most, the crew will be delayed by 68 hours. That allows the crew to complete the mission within the 30-day period even if launch windows are missed.

6.1.1 Launch Windows

The program schedule's largest limitation is undeniably the launch windows used to depart Earth's orbit. As previously described, the best time to transport the EEV to Mars within a Starship spacecraft is June 20th, 2035, at 12:00:00 UTCG (see 3.8 Trajectory). To organize an on-time departure from Earth's orbit, two Starship vehicles must launch from the ground three hours prior. Though it only takes roughly 8.5 minutes to reach Earth's orbit [22], the remaining time will be allocated towards running diagnostics, refueling, and optimizing the departure location. Afterward, the Starship vessel will initiate the Hohmann transfer with a total $\Delta v = 4.371\ m/s$. This would bring the space vessel bearing the EEV to a Mars 5-sol orbit by January 2nd, 2036, where it will await the DST transporting the crew members. The total Earth to Mars transfer time is 196 days (~6.5 months). The launch of the DST will be conducted with a similar procedure and will arrive to the Mars 5-sol orbit on January 1st, 2040, at 12:00:00 UTCG.

6.1.2 Docking

Once the DST arrives on January 1, 2040, it will dock with the EEV via the enlarged version of the ISS standard docking system. The 2.5 m diameter allows for the two crew members to transfer into the EEV with room to spare, enabling them to transport large science equipment with ease. At this stage the crew has 4 days to dock, transfer materials, run diagnostics, and rest before undocking and leaving for Phobos in the EEV.

6.1.3 Transit to Phobos

After undocking, the EEV will power up the Aestus engines initiate its Hohmann transfer to Phobos. The total Δv for this maneuver will be 2.509 km/s. The EEV will depart to Phobos on January 5, 2040 12:00:00 UTCG and will arrive 20 hours later on the morning of January 6th. The EEV will start an orbit around the moon and will cycle around five times, at an altitude of 30 km. At this point, the crew will carry out the scientific objectives set for advanced imaging, magnetic field measurements, examining weather conditions, solar wind sample collection, and telecom testing. After sufficient data is collected, the solar panel is retracted, and the instruments are secured for a descent, the crew will initiate a landing on the surface of Phobos. Excluding the solar wind samples, data collection will continue while in flight.

6.1.4 Phobos Landing and Surface Exploration

The EEV will descend with a downward acceleration of 0.5 m/s^2. The six landing legs will experience 3 MPa during touchdown. The crew will travel through Phobos's northern hemisphere and travel to the landing site previously selected as 10°N, 335°W (see 3.3 Landing Sites). The crew will visually assess the terrain and perform a landing in a smooth area. The landing site is to minimize the risk for the EEV and hydraulic lift deployment. The crew will shut down the engines.

For the remaining time during this stage of the mission, the crew will carry out the remaining science objectives that are to take place on the surface of Phobos. First, the rover and seismometer will be positioned into the hydraulic lift and dispatched. The rover will lift the seismometer with its arms and travel out of the EEV. It will move the seismometer out to a position into the regolith where it can start to measure seismic waves below the surface. After, the rover will autonomously venture out to collect surface samples. Traveling at 0.9 m/s, the rover will cover an area of as much area as possible in roughly 8 hours. Once the estimated 51.57 kg of sample material is collected, the rover will return to the EEV and collect the seismometer. While the rover collects samples, the crew will continue to monitor the data collection for advance imaging, magnetic field measurements, mapping weathering conditions, and the telecom testing.

The crew will have 4-6 hours in downtime during this period where they may rest and rejuvenate. The crew will then prepare for takeoff from the surface of Phobos. Once the rover returns, the samples are to be quarantined immediately. The EEV will power up the engines and ascend to an orbit around Phobos, arriving there before 20:20:00 UTCG. The data collection for Phobos will cease and the scientific instruments will be secured. The EEV will then start a transit course out to Deimos at the prescribed time.

6.1.5 Transit to Deimos

The transit to Deimos will be performed by another Hohmann transfer with a total Δv of 1.069 km/s. It will take the EEV a total of 8 hours and 40 minutes to be placed into orbit. The crew will rest during transit. On January 7th 05:00:00 UTCG once the EEV arrives, the crew will repeat the sequence for the science objectives. The EEV will orbit Deimos at an altitude of 30 km and will complete five trips around the moon. The advance imaging, magnetic field, weathering conditions, solar wind, and telecom trials will be initiated. After sufficient data is collected at altitude, the solar sail will retract, and the EEV will begin its descent. Once again, the EEV will approach the surface at 0.5 m/s^2.

6.1.6 Deimos Landing and Surface Exploration

The EEV will land on the surface of Deimos early on January 7th. The crew will traverse the northern hemisphere to 20°N, 120°W and select a clear landing spot. After engine shutdown, the crew will lower the hydraulic lift and dispatch the rover with the seismometer. The rover will have much more time on Deimos and will cover a larger area for sample collection. Meanwhile, the crew will continue to monitor results for the data being collected. The crew will have nearly 30 hours in downtime. For this stage, they will be able to rest, rejuvenate, and entertain themselves while continuing to monitor the data collection. On January 8th at 12:00:00 the crew will prepare for the ascent back to orbit around Deimos. After the seismometer and rover are returned to the EEV, the engines will be powered back up. Also, the surface samples will be quarantined. Once all instruments are secured, the EEV will take off. Once in orbit, the data collection for all science experiments will conclude. At 13:00:00 the crew will begin their course back to the DST.

6.1.7 Return to the DST

The EEV will embark on its longest leg of the trip back towards the DST. The two impulse Hohmann transfer will get put the crew back in contact with the DST after 22 hours. At 11:00:00 UTCG on January 10th, the EEV will approach the DST to dock once again. After successfully docked, the crew will transfer the sample collection bins and the science equipment from the EEV to the DST. Once all equipment is secured in the DST, the crew will undock the Starship vessel from the EEV and start its course back towards Earth.

6.2 Risk Analysis and Mitigation Strategies

A failure mode and risk analysis were conducted in order to assess the potential risks involved with the Ares mission. A visual diagram was developed to highlight the failures most likely to occur throughout the course of the mission and to aid the team in making the proper design decisions to mitigate these risks.

6.2.1 Risk Analysis

Each failure mode was assigned a weight based on likelihood and consequence, with the overall health and well-being of the astronauts being the most important consideration throughout the analysis. From this analysis, it was deemed that the launch vehicle failing to meet the desired requirements posed the largest threat to the overall success of the mission due to the launch vehicle thus becoming unusable and any alternatives would come at the expense of large amounts of time and funding. Despite this large risk, its severity can be easily mitigated by pre-selecting an alternative launch vehicle to confirm launch capabilities. This risk, as well as several others, can be observed in the table below alongside their consequences and likelihood.

Number	Risk	Consequence	Likelihood Score	Consequence Score
1	Rover fails to deploy or be recovered due to deployment mechanism mechanical failure.	Failure of primary mission objective; potential risk to astronauts.	2	2
2	Landing/Launching maneuvers cause damage to the EEV from debris or terrain.	Potential risk to astronauts and mission completion.	3	4
3	Solar panels fail to deploy.	EEV is unable to charge batteries; potential total mission failure.	2	5
4	DST fails to capture EEV.	Astronauts unable to enter EEV. Total mission failure.	2	5
5	EEV is struck and damaged by orbital debris.	Potential risk to astronauts and mission completion	1	3
6	Selected launch vehicle does not meet requirements.	Selected launch vehicle becomes unusable; alternative may be required with delays and increased costs.	4	4
7	EEV delivery delayed.	Potential to miss launch window and miss rendezvous with DST.	3	3
8	On-orbit EEV systems failures (non-payload).	Potential risk to astronauts and mission completion.	2	4
9	On-orbit EEV systems failures (science payload).	Potential risk to mission completion.	3	4
10	Rover fails to function or retrieve samples	Failure of primary mission objective.	3	2
11	EEV Flight/thrust is imperfect.	EEV may require more delta-v and fuel than modeled.	4	3

Table 6.1 Potential risks faced by the Ares mission as well as likelihood and consequence scores.

6.2.2 Risk Mitigation

In the event of any risks from the analysis coming to fruition, a risk mitigation strategy was developed to minimize their impacts on the Ares mission. The following table outlines the mitigation strategy for each corresponding risk from the risk analysis alongside their likelihood and consequences, and the following post-mitigation risk matrix visually depicts their likelihood and severity.

Number	Mitigation Strategy	New Likelihood Score	New Consequence Score
1	Robust testing of deployment mechanisms; designed failure modes to mitigate debris risk.	1	1
2	Impact-resistant outer layer of EEV. Careful selection of landing sites.	1	3
3	Robust testing. Use of flight-proven hardware. Astronauts may perform EVA to manually fix arrays.	1	3
4	Robust testing and modeling. Use of standardized, flight-proven hardware.	1	5
5	Hardening of exterior surfaces where practicable.	1	2
6	Pre-select alternative launch vehicle to confirm launch capability	4	2
7	Front-load delivery timeline to allow for slippage. Use flight-proven suppliers.	2	1
8	Robust testing. Use flight-proven systems where practicable.	1	3
9	Robust testing. Use flight-proven systems where practicable.	1	3
10	Robust testing. Use flight-proven systems where practicable	2	2
11	Incorporate extra fuel for additional maneuvering.	4	1

Table 6.2 Mitigation strategies to address risks posed to Ares mission presented in Table 6.1.

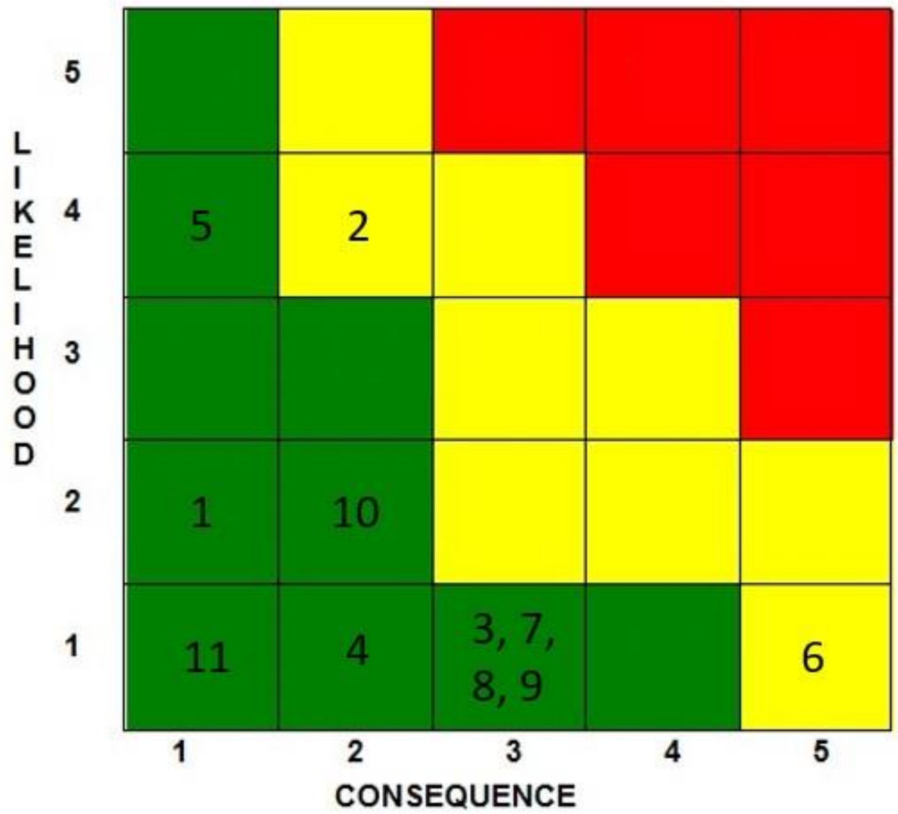

Fig. 6.1 Mitigated risk matrix displaying likelihood and consequence scores.

6.3 Cost Analysis

The cost analysis was conducted to ensure that the mission would not surpass the maximum budget of $1 Billion US FY 2021. The budget was categorized into 6 sections: launch costs, scientific experiments, EEV, rover, telecommunication equipment, and crew accommodations. Tables 6.3-6.8 show itemized lists for each section, and Table 6.9 shows the overall budget by section. The total incurred cost for this mission is $723,591,781. The Ares team feels that the near $300 million in reserve will be sufficient to address any unforeseen circumstances. If obstructions do become apparent, the team will strive towards ensuring mission completion under the prescribed budget.

Launch Vehicle Costs	**Cost (USD)**
Starship Spacecraft (DST)	2,000,000
Starship Spacecraft (Refueling Vehicle)	2,000,000
Expected changes in selling price from Space-X	6,000,000
Total	**$10,000,000**

Table 6.3 Costs for launch.

Experimentation	**Cost (USD)**
Mission Designed Rover	*Included in Production*
Rock Abrasion Tool (RAT)	100,000
Gamma-ray/Neutron Spectrometer	4,000,000
Laser Altimeter	4,000,000
Atmospheric and Composition Spectrometer	4,000,000
Magnetometer (MAVEN)	25,000,000
Energetic Particle and Plasma Spectrometer	25,000,000
Dual Imaging System	10,000,000
Mossbauer Spectrometer	100,000
Solar Panel	*Included in Production*
Solar Sail (9x9m)	3,000,000
Pressure Sensor	1,000,000
Seismometer	100,000,000
RIMFAX: geological structure of subsurface	5,000,000
Telecommunication Equipment	*Included in Production*
Total	**$181,200,000**

Table 6.4 Costs for Scientific Experiments.

EEV	Cost (USD)
Body (Material and Production)	263,000,000
Aestus Engines	18,000,000
Solar Panel	30,000,000
Lithium Ion Batteries	700,000
Fuel	1,856,996
Fuel Tanks	2,000,000
Hydraulic Lift	20,000
Environmental Systems	8,309,085
Medical Supplies	1,900
Thermal Control Systems	2,000,000
Fitness Accommodations	100
Rehydrator	2,000
Conduction Oven	1,200
60 Gallon water tank	500
Total	**$348,891,781**

Table 6.5 Costs for producing the EEV.

Rover	Cost (USD)
Body (Material and Production)	54,000,000
Test tubes	5,000,000
Motors, Sensors, Etc.	20,000,000
Wheels and Chassis	30,000,000
Robotic Arms	40,000,000
Batteries + Battery Box	500,000
Solar Panel	500,000
Total	**$150,000,000**

Table 6.6 Costs for producing the rover.

Telecommunication	Cost (USD)
Radio Telescopes	7,000,000
Networks	3,000,000
Total	**$10,000,000**

Table 6.7 Costs for the telecommunication equipment.

Crew Accommodations	Cost (USD)
Toilet	23,000,000
Housekeeping and Miscellaneous	500,000
Total	**$23,500,000**

Table 6.8 Costs for the crew accommodations.

Component/Subsystem	**Cost Subtotal (USD)**
Launch Vehicle and Refuel	10,000,000
Scientific Objectives and Experimentation	181,200,000
Exploration Excursion Vehicle	348,891,781
Rover	150,000,000
Telecommunications Equipment	10,000,000
Crew Accommodations	23,500,000
Total	**$723,591,781**

Table 6.9 Cost overview of Ares mission broken down into six major categories.

7.0 Conclusion

Ares will be the next leap in scientific understanding and exploration of the origins of Mars. The mission will use current technology to ensure the manned expedition is safe and reliable and will use future technologies to decrease the total cost of the mission. The manned element of the mission demanded a large portion of the focus of the life support systems to ensure the safety of the astronauts. The life support systems include all the basic everyday needs such as food, water, and breathable air storages as well as exercise options, waste disposal and cleaning supplies. The majority of the mission budget will go towards the scientific objectives of the mission in order to research many characteristics of the Martian moons. The research conducted during this mission will aid in the discovery of the origin and historical events surrounding Mars and its relationship to the two moons.

7.1 Compliance Matrix

A compliance matrix is provided below as an easy reference to verify that all design constraints are met by the Ares team.

Requirement	Comply	Page Numbers
Mission Overview and CONOPS	Yes	7, 68-71
Trajectory Design, Mission Design and Δv requirements	Yes	14-21
Landing Site Selection	Yes	21-23
Docking System	Yes	37, 38
Descent and Landing System	Yes	27, 28
Crew Accommodations and Life Support	Yes	43-53
Surface Rover	Yes	53-56
Scientific Experiments	Yes	58-68
Propulsion Subsystem	Yes	24-28
Power Subsystem	Yes	41-44
Thermal Control Subsystem	Yes	28-31
Telecommunication Subsystem	Yes	38-40
Structural Analysis	Yes	31-36
Launch Vehicle Selection	Yes	12-14
EEV CAD Model	Yes	7
Total Cost under $1 Billion budget	Yes	76-78

Table 7.1 Ares Mission Compliance Matrix.

References

[1] “4S1P VES16 Battery,” *Saft Batteries,* 08-Jun-2021. [Online]. Available: https://www.saftbatteries.com/products-solutions/products/4s1p-ves16-battery?text=&tech=&market=324&brand=&sort=newest&submit=Search. [Accessed: 13-Dec-2021].

[2] A. Akbas, “Air handling unit,” *GrabCAD*, 08-Jul-2021. [Online]. Available: https://grabcad.com/library/air-handling-unit-3. [Accessed: 13-Dec-2021].

[3] A. Akbas, “Cooling cabinet split unit,” *GrabCAD*, 16-Jan-2020. [Online]. Available: https://grabcad.com/library/cooling_cabinet_splitunit-1. [Accessed: 13-Dec-2021].

[4] “Aluminum 7075-T73; 7075-T735x,” *Matweb*. [Online]. Available: http://www.matweb.com/search/datasheet_print.aspx?matguid=6653b72914864cc0a0ff7adf5b720167. [Accessed: 13-Dec-2021].

[5] B. Nidhal, “Tool Cabinet,” *GrabCAD*, 25-May-2021. [Online]. Available: https://grabcad.com/library/tool-cabinet-13. [Accessed: 13-Dec-2021].

[6] C. Ernst, “Updated shape models of Phobos and Deimos from stereophotoclinometry,” *Universities Space Research Association*. [Online]. Available: https://www.hou.usra.edu/meetings/lpsc2015/pdf/2753.pdf. [Accessed: 13-Dec-2021].

[7] “Chlorate Candle Technical Data Sheet ,” *OC Lugo Company*. [Online]. Available: https://oclugo.com/wp-content/uploads/2019/06/Chlorate-Candle-Technical-Data-Sheet-Revision-3.pdf. [Accessed: 13-Dec-2021].

[8] D. Carter, “SOLIDWORKS EEV model render,” [Personal]. [Accessed: 12-Dec-2021].

[8] “Easy Porkchop,” *Space Dynamics Group*. [Online]. Available: http://sdg.aero.upm.es/index.php/online-apps/porkchop-plot. [Accessed: 12-Dec-2021].

[9] *EGM3520 - Thermal Control*. University of Florida, 2021.

[10] “Encyclopedia Astronautica - Engine Specifications,” *Encyclopedia Astronautica*. [Online]. Available: http://www.astronautix.com/. [Accessed: 13-Dec-2021].

[11] G. Klingelhöfer, “Mössbauer Spectrometer (MB),” *NASA*. [Online]. Available: https://mars.nasa.gov/mer/mission/instruments/mb/. [Accessed: 13-Dec-2021].

[12] H. Lane, “Astronaut health and performance - NASA,” *NASA*. [Online]. Available: https://www.nasa.gov/centers/johnson/pdf/584739main_Wings-ch5d-pgs370-407.pdf. [Accessed: 13-Dec-2021].

[13] I. Delgado, “Sport car seat,” *GrabCAD*, 04-Nov-2021. [Online]. Available: https://grabcad.com/library/sport-car-seat-3. [Accessed: 13-Dec-2021].

[14] J. Connerney, “Magnetometer (MAG),” *MAVEN*, 29-Sep-2017. [Online]. Available: https://lasp.colorado.edu/home/maven/science/instrument-package/mag/. [Accessed: 12-Dec-2021].

[15] J. Farfan, “First-aid box,” *GrabCAD*, 01-Feb-2018. [Online]. Available: https://grabcad.com/library/first-aids-box-primeros-auxilios-1. [Accessed: 13-Dec-2021].

[16] J. Mrnavek, “Counter freezer,” *GrabCAD*, 03-Sep-2019. [Online]. Available: https://grabcad.com/library/counter-freezer-1. [Accessed: 13-Dec-2021].

[17] J. Ryan, “Thetford 12V electric cassette toilet/motorhome toilet,” *GrabCAD*, 20-Oct-2021. [Online]. Available: https://grabcad.com/library/thetford-12v-electric-cassette-toilet-motorhome-toilet-1. [Accessed: 13-Dec-2021].

[18] J. Taylor, D. K. Lee, and S. Shambayati, “Mars Reconnaissance Orbiter,” *Deep Space Communications*, pp. 193–250, 2016.

[19] L. B. Du, “Electrical cabinet Mitsubishi,” *GrabCAD*, 09-Jul-2021. [Online]. Available: https://grabcad.com/library/electrical-cabinet-mitsubishi-1. [Accessed: 13-Dec-2021].

[20] L. Hall, “Advanced composite solar sail system,” *NASA*, 23-Jun-2021. [Online]. Available: https://www.nasa.gov/directorates/spacetech/small_spacecraft/ACS3. [Accessed: 13-Dec-2021].

[21] “Lung volumes and vital capacity,” *BBC News*. [Online]. Available: https://www.bbc.co.uk/bitesize/guides/z3xq6fr/revision/2. [Accessed: 13-Dec-2021].

[22] M. Leinbach, “Ask the mission team - question and answer session,” *NASA*. [Online]. Available: https://www.nasa.gov/mission_pages/shuttle/shuttlemissions/sts121/launch/qa-leinbach.html. [Accessed: 13-Dec-2021].

[23] M. Torrence, “About MOLA,” *NASA*, 19-Jan-2007. [Online]. Available: https://attic.gsfc.nasa.gov/mola/about.html. [Accessed: 12-Dec-2021].

[24] M. Weisberger, “How much do you poop in your lifetime?,” *LiveScience*, 21-Mar-2018. [Online]. Available: https://www.livescience.com/61966-how-much-you-poop-in-lifetime.html. [Accessed: 13-Dec-2021].

[25] M. Yakut, “Cost analysis of oxygen recovery systems - NASA technical reports server (NTRS),” *NASA*, 01-Jun-1973. [Online]. Available: https://ntrs.nasa.gov/citations/19730018348. [Accessed: 13-Dec-2021].

[26] “Mark-10 plug and testtm force sensors series R04 - Data Sheet.” [Online]. Available: https://www.abqindustrial.net/store/images/products/pdf/force-and-torque-measurement/r04-miniature-s-beamforce-sensor-data-sheet.pdf. [Accessed: 13-Dec-2021].

[27] *Maxon Docking System*. https://www.designworldonline.com/wp-content/uploads/maxon-docking-system.jpg.

[28] “Mercury Atmospheric and Surface Composition Spectrometer (MASCS),” *Mercury Atmosheric and Surface Composition Spectrometer*. [Online]. Available: https://www.messenger-education.org/instruments/mascs.html. [Accessed: 12-Dec-2021].

[29] “Mercury Atmospheric and Surface Composition Spectrometer,” *PDS/PPI home page*. [Online]. Available: https://pds-ppi.igpp.ucla.edu/mission/MESSENGER/MESS/MASCS. [Accessed: 12-Dec-2021].

[30] “Mercury Dual Imaging System (MDIS),” *Mercury Dual Imaging System*. [Online]. Available: https://www.messenger-education.org/instruments/mdis.html. [Accessed: 13-Dec-2021].

[31] “MESSENGER,” *PDS/PPI home page*. [Online]. Available: https://pds-ppi.igpp.ucla.edu/mission/MESSENGER. [Accessed: 12-Dec-2021].

[32] “NASA TechPort,” *NASA*. [Online]. Available: https://techport.nasa.gov/view/93128. [Accessed: 13-Dec-2021].

[33] R. Marwan, “Electric gallon pump,” *GrabCAD*, 15-Dec-2020. [Online]. Available: https://grabcad.com/library/electric-gallon-pump-pompa-air-galon-cas-led-elektrik-dispenser-air-galon-charge-1/details?folder_id=9491246. [Accessed: 13-Dec-2021].

[34] R. Pansari, “Water tank 400 L,” *GrabCAD*, 24-Nov-2020. [Online]. Available: https://grabcad.com/library/water-tank-400-ltr-1. [Accessed: 13-Dec-2021].

[35] “The Rover's temperature controls,” *NASA*. [Online]. Available: https://mars.nasa.gov/mer/mission/rover/temperature/#aerogel. [Accessed: 13-Dec-2021].

[36] S. Hidayat, “PRV 0.5 inch with lever,” *GrabCAD*, 22-Jul-2019. [Online]. Available: https://grabcad.com/library/prv-0-5inch-with-lever-1. [Accessed: 13-Dec-2021].

[37] S.-E. Hamran, “Radar Imager for mars' subsurface exploration (RIMFAX),” *NASA*. [Online]. Available: https://mars.nasa.gov/mars2020/spacecraft/instruments/rimfax/. [Accessed: 13-Dec-2021].

[38] S. Lovello, “SOLIDWORKS rover model render,” [Personal]. [Accessed: 12-Dec-2021].

[39] “Spacecraft Components,” *Northrop Grumman*, 24-May-2021. [Online]. Available: https://www.northropgrumman.com/space/spacecraft-components/. [Accessed: 13-Dec-2021].

[40] T. Sharp, “What is the temperature on Mars?,” *Space.com*, 30-Nov-2017. [Online]. Available: https://www.space.com/16907-what-is-the-temperature-of-mars.html. [Accessed: 12-Dec-2021].

[41] T. Spohn, “Mars InSight Heat Probe,” *NASA*, 09-Nov-2021. [Online]. Available: https://mars.nasa.gov/insight/spacecraft/instruments/hp3/. [Accessed: 13-Dec-2021].

[42] “Urine Quantity,” *Medipee*, 18-Aug-2021. [Online]. Available: https://www.medipee.com/en/urinalysis/micturition/urine-quantity. [Accessed: 13-Dec-2021].

[43] V. Kucherenko, A. Bogatchev, and M. van Winnendael, “Chassis concepts for the ExoMars Rover,” *European Space Agency*, 02-Nov-2004. [Online]. Available: http://robotics.estec.esa.int/ASTRA/Astra2004/Papers/astra2004_D-05.pdf. [Accessed: 13-Dec-2021].

[44] “VL51ES Battery,” *Saft Batteries* , 02-Nov-2020. [Online]. Available: https://www.saftbatteries.com/products-solutions/products/vl51es-battery?text=&tech=&market=324&brand=&sort=newest&submit=Search. [Accessed: 13-Dec-2021].

[45] W. Boynton, “GRS,” *NASA*. [Online]. Available: https://mars.nasa.gov/odyssey/mission/instruments/grs/. [Accessed: 12-Dec-2021].

[46] Z. Q. Li, G. de Carufel, E. Z. Crues, and P. Bielski, “Lighting condition analysis for Mars' moon phobos,” *IEEE Xplore*, 2016. [Online]. Available: https://ieeexplore.ieee.org/document/7500772. [Accessed: 13-Dec-2021].

[47] “_IDSS_IDD,” *NASA*. [Online]. Available: https://www.nasa.gov/pdf/490477main_idss_idd_rev101810%200924.pdf. [Accessed: 12-Dec-2021]