ARES-1: Mars Human Exploration Mission

Purdue University

AAE 450 Senior Spacecraft Design – Mars Team 3

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A. Summary

Developed by a team of fifteen undergraduates at Purdue University for AAE 450 Senior Spacecraft Design Spring 2023, ARES-1 is a 7-year Mars human exploration and homesteading mission to understand Mars' potential for life and build an initial framework for a future human colony spanning from 2035 to 2042. ARES-1 is driven by 6 key science goals involving human physiology in zero & partial-gravity, current and ancient Martian climate, and Martian agriculture.

ARES-1 consists of seven sub-teams corresponding to the seven subsystems of the project: Propulsion, Mission Design, Structures & Surface stay, Communications, Cost & Schedule, Space Environment, and Attitude Determination & Control (ADC). Together, these teams developed a full mission point-architecture spanning across these seven subsystems based on six operational requirements by the AAE 450 teaching team seen in Table 1 below:

1	ARES-1 shall support a crew size of four humans for seven years of operation.
2	ARES-1 shall have no more than 2 years' worth of supplies deployed prior to mission timeframe.
3	ARES-1 shall require no more than 5,000 kg of delivery cargo from Earth within a two-year period.
4	ARES-1 shall support a first crewed landing between 2035 and 2040 and a return of the crew between 2040 and 2050.
5	ARES-1 shall support at least 5 opportunities for space science.
6	ARES-1 shall incorporate three novel technologies, methods, architectural features, or capabilities that differ from existing Mars architecture studies.

Table 1: ARES-1 Operational Requirements

Given these requirements, ARES-1 will be the first crewed mission from Earth to Mars composed of eight launches (four cargo Earth-Mars, two crew Earth-Mars, two crew Mars-Earth) spanning from April 17, 2033 to April 9, 2042 with a total of two crew, each composed of four astronauts. To support the crew throughout the mission, there will be four cargo missions. Two pre-arrival cargo missions will occur two years prior to crew launch containing the habitat system, life support systems, MAVs, and two support satellites for telecommunication. Two resupply cargo missions will occur in two-year intervals after the first crew launch, each carrying a 5,000 kg payload consisting of nourishments and consumables.

Each crew will depart from a low Earth parking orbit via a Mars Transit Vehicle (MTV) powered by a Centrifugal Nuclear Thermal Rocket (CNTR). The pre-arrival and crew trajectories will enter Mars into an areostationary orbit to support Earth-Mars communications, with crewed missions departing the MTV from this orbit via the Entry-Descent-Landing (EDL) vehicle towards the selected landing site—Nili Fossae. The resupply trajectories will enter into a Low Mars Orbit (LMO), with the cargo performing the same EDL maneuvers down to the Martian surface. The two crews will live on Mars in an inflatable-regolith-covered habitat for an effective Martian surface occupancy time for 4 astronauts of 7 years, 5 months, and 22 days. During this period, the six aforementioned science objectives will be conducted. Ultimately, each crew will ascend back to the MTV via a Mars Ascent Vehicle (MAV). Finally, the astronauts will depart Mars' areostationary orbit and travel back to Earth on the MTV, arriving into a low Earth parking orbit.

Overall, ARES-1—driven by six key science objectives—will serve as the groundwork for future human occupancy on Mars. Spanning eleven years from start to end, with over an effective seven-year surface stay, ARES-1 will be the next milestone for human spaceflight.

B. Fact Sheet

ARES-1 FACT SHEET

MISSION STATEMENT

ARES-1 is a 7-year Mars human exploration and homesteading mission to understand Mars' potential for life and build an initial framework for a future human colony spanning from 2035 to 2042.

SCIENCE OBJECTIVES

1. Determine the short and long term effects of zero-g & low-gravity and space isolation on humans.
2. Determine daily weather patterns on Mars with a special emphasis on solar wind and radiation effects.
3. Determine possibility of past life on Mars.
4. Determine if Martian soil is suitable for agriculture.
5. Demonstrate success rate of water harvesting ISRU technology.
6. Demonstrate technology for ISRU of Mars regolith.

NEW TECHNOLOGIES

1. **Martian Regolith Bricks** (Radiation Mitigation)
2. **Scaled VEGGIE System** (Food Production)
3. **BOXIE/MAV Propellant Storage** (Life Support/MAV)

PAYLOAD

CARGO
- **PRE-ARRIVAL:** Habitat, Power Systems, Rovers, Communications, Food & Consumables, MAVs
- **RESUPPLY:** 5,000 kg of Food & Consumables

CREW
- Crew of 4
- Food & Consumables
- MTV

PROPULSION

LAUNCH
- **PRE-ARRIVAL:** SLS Block 2
- **CREW:** SLS Block 2
- **CARGO:** Falcon 9 Heavy

TRANSIT
- **ACCELERATION:** Centrifugal Nuclear Thermal Reactor
- **DECELERATION:** Centrifugal Nuclear Thermal Reactor

SPACE ENVIRONMENT

RADIATION
- **MTV SHIELDING:** Carbon Carbon Phenolic Novolac & 10% Tantalum Powder Dope
- **HAB SHIELDING:** Aramid Fiber Wall & Regolith Brick

SURFACE STAY

HABITAT
- **LANDING SITE:** Nili Fossae
- **STRUCTURE:** Inflatable with Regolith Bricks (384 m^2)
- **POWER:** 2 x SAFE-400 100 kW Reactors & LNCAO Batteries

LIFE SUPPORT
- **CONTAMINANT MITIGATION:** Hermetic Containers
- **PRESSURIZED AREAS:** Hab & Rover Fully Pressurized
- **OXYGEN SUPPLY:** Pre-Packaged & Extracted from Mars via BOXIE
- **WATER SUPPLY:** Pre-Packaged & Recycled
- **CO2 RECYCLING:** Captured from Human Presence
- **WASTE MANAGEMENT:** Landfill on Mars

EDL & MAV

EDL
- **PHASE 1:** Hypersonic Aero-Maneuvering
- **PHASE 2:** Supersonic Retro-Propulsive Braking
- **PHASE 3:** Constant Velocity Powered Descent

MAV
- **ENGINE:** 3 x Launcher Engine-2
- **PROP STORAGE:** Multi-Layer Insulation & BOXIE LOX Top Off

TRAJECTORIES (E-M)

PA 1 & 2
- **DEPART:** APR 17/28, 2033
- **ARRIVE:** OCT 15/NOV 8, 2033
- **ΔV** = 6.0/6.4 km/s
- **TOF** = 205/170 days
- **VEHICLE:** SLS Block 2

CREW 1
- **DEPART:** JUL 27, 2035
- **ARRIVE:** NOV 29, 2035
- **ΔV** = 7.50 km/s
- **TOF** = 125 days
- **VEHICLE:** SLS Block 2 / MTV 1

RS 1
- **DEPART:** SEP 05, 2037
- **ARRIVE:** APR 04, 2038
- **ΔV** = 5.9 km/s
- **TOF** = 215 days
- **VEHICLE:** Falcon 9 Heavy

CREW 2
- **DEPART:** SEP 20, 2037
- **ARRIVE:** FEB 12, 2038
- **ΔV** = 8.25 km/s
- **TOF** = 145 days
- **VEHICLE:** SLS Block 2 / MTV 2

RS 2
- **DEPART:** SEP 10, 2039
- **ARRIVE:** JUL 21, 2040
- **ΔV** = 5.69 km/s
- **TOF** = 315 days
- **VEHICLE:** Falcon 9 Heavy

TRAJECTORIES (M-E)

CREW 1
- **DEPART:** SEP 16, 2039
- **ARRIVE:** FEB 28, 2040
- **ΔV** = 8.70 km/s
- **TOF** = 165 days
- **VEHICLE:** MTV 1

CREW 2
- **DEPART:** OCT 16, 2041
- **ARRIVE:** APR 09, 2042
- **ΔV** = 8.98 km/s
- **TOF** = 175 days
- **VEHICLE:** MTV 2

COMMUNICATIONS

ORBITER
- **PRIMARY:** MTV
- **SUPPORT:** 2 x Small Sats
- **ORBIT:** Areostationary

SPECS
- **MTV:** 1 x 9m Antenna
- **SUPPORT SATS:** 2 x 6m Antenna
- **MARS:** 1 x 1m Antenna
- **EARTH:** 1 x 70m DSN Antenna
- **DATA TRANSFER:** 2.3 Mbps
- **VOICE & VIDEO:** 52 Mbps

MISSION COST | $658.02 Billion USD (FY2023)

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D. Science Investigation & Implementation

D.1 Science Objectives

One of the requirements for the mission is to have at least 5 opportunities for space science, so the team decided to explore different options for research on Mars relatively early on. The team used the NASA DRA 5.0 as a source of ideas for possible experiments, as well as experiments both on the ISS and on Earth and previous Mars rover missions. It was decided that the experiments would fall into the following categories: agriculture, astronomy, biology and medicine, in-situ resource utilization (ISRU), and physical sciences. After developing different scientific experiment concepts for each category in a morphological matrix, the following Tier 1 and their corresponding Tier 2 science objectives were determined. These tiered objectives are explored in further detail in the Science Traceability Matrix (STM) in the next section. They will be introduced here.

The first Tier 1 science objective is to determine the short- and long-term effects of partial gravity, zero-g and space isolation on humans. Within this encompassing Tier 1 objective, we have the following Tier 2 objectives: discover the effects of long-term isolation in space on human psychology by studying behavioral and emotional health changes over time, discover the influence of zero-gravity and extended space travel on human vision by studying and documenting changes in eyesight over the duration of the Mars mission, and understand the influence of microgravity on the human body's major systems (including the musculoskeletal, cardiovascular, and immune systems) by studying these changes in human physiology over time. These objectives cover three studies that would take place for biology and medicine studies of human health. The first Tier 2 objective explores the behaviors and emotions of astronauts in isolation. The second Tier 2 objective investigates the impact of partial gravity on human vision for an extended period of time, and the third Tier 2 science objective for this tier is studying the various influences of microgravity on the human body. While conducting research on how human vision deteriorates in zero-gravity, it was determined that it may be worth considering a crew swap to ensure the crew's safety through the long mission duration. This will be explored further in another section.

The next Tier 1 science objective is to determine daily weather patterns on Mars with a special emphasis on solar wind and radiation effects. Within this Tier 1 objective, we have the following Tier 2 objectives: discover the daily weather patterns (temperature, humidity, wind speed) on Mars, and understand the influence of planetary plasmas and magnetic fields and their interaction with the solar wind plasma. These objectives cover studies in astronomy and weather. The first Tier 2 objective explores the changes in the Martian climate, and the second Tier 2 science objective investigates aspects of solar wind on Mars.

The third Tier 1 science objective is to determine the possibility of life on Mars, which studies physical science. This objective is a popular one among Martian rovers, such as Perseverance and Curiosity [SO-10]. Having humans on Mars allows for less dependence on rovers, the ability to conduct analysis right on the planet, and the collection of a greater quantity of samples for storage and possible further analysis on Earth. The Tier 2 objective for this science objective is to discover more about the history of Mars by searching for signs of life in different areas. The astronauts would be collecting samples similar to the Martian rovers.

The next Tier 1 science objective is to determine if Martian soil is suitable for agriculture. The Tier 2 objectives that encompass this Tier 1 objective are as follows: compare Martian soil growth rates to proven low-g plant growth technologies, discover which nutrient additives to Martian soil optimize plant growth, and determine effects of cyanobacteria on plants grown in Martian soil. The first study compares Martian soil plant growth and plant growth in planters from Earth, and the second Tier 2 objective explores different combinations of soil additives to analyze the impact of plant growth. The third Tier 2 objective utilizes cyanobacteria, which uses carbon dioxide to produce organic matter, to measure plant growth. If the plant growth results of the experiments are positive, these different agricultural experiments could also provide another source of food for the astronauts.

The following Tier 1 objective is to demonstrate the success rate of water harvesting ISRU technology. The Tier 2 science objective that is a facet of this objective is to develop and test water discovery and harvesting technology on Mars. This experiment would be similar to the Mars Ice Core Sample Return missions [SO-13] that had been researched in the past. The beneficial aspect of this is similar to the search for life on Mars, where human presence allows for immediate analysis and a greater number of samples collected.

The final Tier 1 science objective that the team chose for the mission is to demonstrate technology for ISRU of Martian regolith. The Tier 2 objective that is included in this science objective is to determine and test if 3D Printing using Mars regolith is possible and if Mars regolith can be used to make protective coating against radiation. This science objective is based on an experiment [SO-1] done on Earth previously, where scientists were experimenting with additive manufacturing to build regolith bricks This is the research basis of one of our novel technologies, where the astronauts would be creating the Mars regolith bricks that had been tested on Earth. This could also help to protect the habitat against harmful Martian radiation, if results of the testing phase prove to be successful. Both aspects will be discussed in detail in later sections.

D.2 Science Traceability Matrix (STM)

The table below is our mission's Science Traceability Matrix (STM), with our Tier 1 and associated Tier 2 science objectives listed. It summarizes the investigation methods, measurements required for investigation, instrumentation required, and any constraint or mission requirement associated with the science objective. A summary of the model instruments, measurements, and mission constraints/requirements for each Tier 1 science objective is included below:

Tier 1 Science Objectives	Tier 2 Science Objectives	Investigation	Measurement	Model Instrument	Mission constraint/ requirements
Determine the short and long-term effects of zero-g and space isolation on humans	Discover the effects of long-term isolation in space on human psychology by studying behavioral and emotional health changes over time.	Analyze behavioral changes, emotional changes, stress levels, and changes in frequent mental health check-ins.	Measure behavioral, emotional, or stress changes through psychological tests, such as the Profile of Mood State Scale or Minicog	Emotion regulation devices, sleep cycle trackers (lack of regular sleep leads to stress), AI therapy programs	**Constraints**: Duration of Mars missions may vary for different crews Astronauts may produce dishonest results if worried about their future missions/future in space HIPAA violations in the mental health field will need to be followed Testing will not further harm astronaut's mental well-being **Requirements**: Personal devices shall be utilized for emotion regulation devices, sleep trackers, and therapy programs.

	Discover the influence of zero-gravity and extended space travel on human vision by studying and documenting changes in eyesight throughout the Mars mission.	Analyze changes in ocular structure and monitor eyesight for signs of disc edema and cerebral spinal fluid pressure buildup	Frequent measurements of astronaut Intracranial Pressure (ICP) and Intraocular Pressure (IOP), imaging of the retina, and early detection of shifting fluid	Optical Coherence Tomography Machine, Ocular Ultrasound, Applanation Tonometer	**Constraints**: Testing and studies will be affected by the fact that it takes an average of 3 months in microgravity before vision-loss symptoms begin to appear/3 years before drastic changes Martian gravity is 38% that of Earth, making vision loss symptoms slower to appear than in microgravity Testing/interventions cannot further harm astronaut vision/internal pressures and will need to work around countermeasures taken **Requirements**: Model instruments and countermeasure instruments shall be able to function in microgravity and Martian gravity Three different model instruments shall be used to test different parts of the body for signs of vision loss.
	Understand the influence of microgravity on the human body's major systems (including the musculoskeletal, cardiovascular, and immune systems) by studying these changes in human physiology over time.	Analyze bone densities, muscle degeneration, fluid shifts, cardiovascular output, and immune response while in microgravity	**Bone densities:** calcium balance **Muscular system:** atrophy of muscles in zero and partial gravity **Cardiovascular:** cardiovascular output **Immune response:** dosimeter measurements, contraction/incubation periods for disease	**Bone densities**: Dual-energy X-ray absorptiometry densitometer (DXA) **Muscular system**: muscle atrophy research and exercise system (MARES) **Cardiovascular:** Electrocardiogram (ECG) **Immune response:** Complete Blood Count (CBC)/Comprehensive Metabolic Panel (CMP)	**Constraints**: No missions of this duration have previously taken place Studies cannot cause further harm to astronaut health **Requirements**: Baseline testing shall be required on Earth for comparison to Martian results.
Determine daily weather patterns on Mars with a special emphasis on solar wind and radiation effects	Discover the daily weather patterns (temperature, humidity, wind speed) on Mars	Analyze the change in temperature, humidity, wind speed data daily	Measurements of temperature, humidity, wind speed on Mars surface	Wind Sensor, Temperature sensor, Relative humidity sensor, Pressure sensor, Thermal Infra-Red Sensor (Referenced Perseverance's MEDA)	**Constraints:** The landing site where the instruments will be placed **Requirements:** Weather measurements shall be taken with the same instrumentation as Perseverance Rover.
	Understand the influence of planetary plasmas and magnetic fields and their interaction with the solar wind plasma	Analyze the solar wind effect on dynamics of the planetary magnetosphere and the evolution of planetary climate	Measurements of solar wind, including IMF	Solar Wind Ion Analyzer and Magnetometers	**Requirements:** Instrumentation shall be identical to MAVEN orbiter hardware to continue Martian atmosphere studies and will be placed on the MTV

Determine the possibility of past life on Mars	Discover more about the history of Mars by searching for signs of life in different areas.	Analyze soil samples, water samples, and clays for microbial life using technology such as PIXL on Perseverance.	Identify signs of microscopic life by using spectrometry and sample collection for analysis of the chemical makeup of samples.	X-Ray spectrometer, x-ray source, X-ray optics, X-ray detectors, high-voltage power supply (HVPS), micro-context camera (MCC), LEDs	**Constraints:** Astronauts will require a vehicle (pressurized rover) to travel if needed to areas further away from habitat. Limitation in types of elements that can be detected in samples. **Requirements:** Sensors shall have a wide range of detected chemical compositions, including Na, Mg, Al, Si, P, S, Cl, K, Ca and more. Sensors shall withstand Mars' atmospheric conditions such as radiation, strong solar winds, and dust storms. Analyzed samples shall come from a wide range of locations on Mars.
Determine if Martian soil is suitable for agriculture	Compare Martian soil growth rates to proven low-g plant growth technologies.	Measure rates of plant growth in Martian soil relative to rates from proven technologies such as VEGGIE.	Record nutrient concentrations and respective plant growth (New leaf rate, root mass, root shoot ratio).	Seeds, Measuring tape, Scale (Augmented to Martian gravity), Martian soil samples, scaled up VEGGIE system. **Soil Testing:** soil texture; electrical conductivity (EC, a measure of soil salinity); soil pH; available phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg); sodium (Na); cation exchange capacity (CEC); and often an analysis of organic matter content.	**Requirements:** System shall utilize two scaled-up VEGGIE systems, one with 12 plants grown in Martian regolith pillows and one with 12 plants grown in ISS used pillows comprised of calcinated clay. The system will receive water periodically based on optimal water needs of species being tested. (Ex. 100 mL of water 2x per week for lettuces). The system shall receive light from red, green, and blue LED lights at intervals optimized for each plant studied. The system shall test growth rates of 7 plant species throughout experiment timeline (one for each year of mission duration).

	Discover which nutrient additives to Martian soil optimize plant growth.	Measure rates of plant growth with various combinations of soil additives to mimic successful food growth on Earth.	Record nutrient concentrations and respective plant growth (new leaf rate, root mass, root shoot ratio).	Seeds, Measuring tape, Scale (Augmented to Martian gravity), nutrients, pipet, Martian soil samples, vertical agriculture system. **Soil Testing:** soil texture; electrical conductivity (EC, a measure of soil salinity); soil pH; available phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg); sodium (Na); cation exchange capacity (CEC); and often an analysis of organic matter content.	**Constraints:** Limited quantities and type of nutrients available. Optimal nutrients dependent on type of plant. **Requirements:** System shall vary concentration of nutrients at levels ranging from 1,1,1% concentrations of Nitrogen, Potassium, and phosphorus to 8,8,8% in Martian Regolith pillows are added every 2 months. System shall utilize a baseline case of no nutrient additives as a baseline. The system will receive water periodically based on optimal water needs of species being tested. (Ex. 100 mL of water 2x per week for lettuces). The system shall receive light from red, green, and blue LED lights at intervals optimized for each plant studied.
	Determine effects of cyanobacteria on plants grown in Martian soil.	Measure rates of plant growth with cyanobacteria added to soil samples (Cyanobacteria produces organic matter from carbon dioxide).	Record nutrient concentrations and respective plant growth (new leaf rate, root mass, root shoot ratio), test for presence of organic matter in soil samples.	Seeds, measuring tape, Scale (augmented to Martian gravity), cyanobacteria, pipet, Martian soil samples vertical agriculture system. **Soil Testing:** soil texture; electrical conductivity (EC, a measure of soil salinity); soil pH; available phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg); sodium (Na); cation exchange capacity (CEC); and often an analysis of organic matter content.	**Constraints:** Planetary protection restrictions, risk of contamination with other samples. **Requirements:** System shall utilize two scaled-up VEGGIE systems, one with 12 plants grown with cyanobacteria present in soil pillows and one with 12 plants grown in ISS used pillows comprised of calcinated clay. System shall utilize a baseline case of no cyanobacteria as a baseline. The system will receive water periodically based on optimal water needs of species being tested. (Ex. 100 mL of water 2x per week for lettuces). The system shall receive light from red, green, and blue LED lights at intervals optimized for each plant studied.

Demonstrate success rate of water harvesting ISRU technology	Develop and test water discovery and harvesting technology on Mars.	Develop technology to discover, excavate, and collect water and ice samples from beneath Mars' surface. Detection tools can be based off technology such as Dynamic Albedo of Neutrons (DAN) instrument on Curiosity and Radar Imager for Mars' subsurface experiment (RIMFAX)on Perseverance.	Use radar to probe and detect geologic features underground. Search for signs of water and ice by measuring subsurface hydrogen concentrations. Use drilling mechanisms to excavate samples after detection.	Neutron spectrometer to detect distribution of hydrogen, ground penetrating radar (GPR) to propagate beneath surface and interpret geology. Drill to dig into surface.	**Constraints:** Astronauts cannot go too far from base, would need to build vehicle to travel if needed. Limitation in depth of detection by sensors and radar. **Requirements:** Neutron spectrometer shall be able to detect hydrogen related neutrons at least 3 ft in depth (like DAN). Neutron spectrometer shall be able to detect water concentrations at a sensitive scale (1%). GPR shall be able to detect geological makeup at least 10 m in depth (like RIMFAX).
Demonstrate technology for ISRU of Mars regolith	Determine and test if 3D Printing using Mars regolith is possible and if Mars Regolith can be used to make protective coating against radiation	Analyze how effective different compositions of Mars regolith (5% - 100% regolith with titanium alloy for example) could be used for manufacturing some rocket parts or any tools that astronauts might require	List of parts to be manufactured should be made and should assess the printed material's texture, appearance, repeatability, protection capabilities from radiation	Dosimeter, 3D printer, Ti64 powder, Martian regolith simulant, 80–2000 grit SiC sandpaper,VibroMet™ 2 vibratory polisher	**Constraints:** Astronauts cannot heavily rely on this technology so when deciding what parts to manufacture on Martian surface should account for this fact. **Requirements:** Technology for regolith brick creation shall be at a TRL of 5 prior to mission. Crew shall obtain 20 hours of training on regolith brick system.

Table 2: Science Traceability Matrix for ARES-1

For the first Tier 1 science objective, some of the model instruments we will use to discover changes in human psychology and emotional health during the course of our mission are emotion regulation devices, sleep cycle trackers, and AI therapy programs. An important constraint to consider is that the duration of the mission will differ for Crew 1 and Crew 2, so our studies must reflect that. Another constraint to consider is that astronauts may be dishonest with some of the results to not affect their future space travel opportunities. In addition, HIPPA guidelines must be followed as our astronaut's mental health is one of our top priorities. Finally, it is required that our astronauts must have their own personal tracking devices. The model instruments for tracking changes in vision over time are an Optical Coherence Tomography Machine, Ocular Ultrasound, and Applanation Tonometer, which will specifically take measurements of astronaut intracranial and intraocular pressures, images of the retina, and early detection of shifting fluid. From previous studies, it was concluded that an average of 3 months in microgravity before vision-loss symptoms begin to appear and 3 years before drastic changes appear [SO-20]. Since Martian gravity is 38% that of Earth, vision loss symptoms will appear slower than this rate, but it is important to consider this information. To prioritize astronaut health, countermeasures will be taken to avoid drastic vision loss. Some examples are potentially using a calibrated proximal thigh tourniquet to regulate fluid imbalances in the body to prevent vision loss and implementing some dietary measures to slow down vision loss. For mission requirements, the model instruments and countermeasure instruments shall be able to function in microgravity and Martian gravity and three different model instruments shall be used to test different parts of the body for signs of vision loss. Finally, for recording changes in human physiology, we will use a dual-energy X-ray Absorptiometry densitometer (DXA) to record bone densities, muscle atrophy research and exercise system (MARES) to record muscle degeneration, an electrocardiogram (EEG/EKG) to monitor cardiovascular output and a complete blood count (CBC) or a comprehensive metabolic panel (CMP) to record immune response. The main constraint for this sub-objective is that we must consider the possibility of instrument decay/replacements and that astronauts must not be exposed to radiation for more than 4 years. A general requirement for this Tier 1 Science Objective is that there will be baseline testing completed on Earth prior to the launch of the crew.

For the second Tier 1 science objective, the weather instruments used in this mission will include a Wind Sensor, Temperature sensor, Relative humidity sensor, Pressure sensor, and Thermal Infrared Sensor, which are the instruments included in the Perseverance Mars Environmental Dynamics Analyzer (MEDA). The main constraint for this sub-objective is the landing site where our instruments will be placed, and the main requirement is that these instruments should be placed in a weather station area where data will be recorded. For understanding the influence of planetary plasmas and magnetic fields and their interaction with the solar wind plasma, we will mainly be using a Solar Wind Ion Analyzer, which will measure the electrons, protons, and heavier particles that make up the solar wind and a Magnetometer that will measure the Interplanetary magnetic field (IMF). These instruments were taken from NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission that had a similar science objective. The main requirement for this sub-objective is that they be placed on the Mars Transit Vehicle (MTV) to collect data in the areostationary orbit.

For the third Tier 1 science objective, the instruments that will be used to record signs of microbial life are X-Ray spectrometer, X-ray source, X-ray optics, X-ray detectors, High-voltage power supply (HVPS), Micro-context camera (MCC), and LEDs. There will be a constraint in the distance traveled by astronauts from the habitat, and for this travel, a pressurized rover or vehicle will be utilized for this travel. The main requirement for this science objective is that our instruments must be capable of measuring chemical compositions including Na, Mg, Al, Si, P, S, Cl, K, and Ca in Martian conditions.

For the fourth Tier 1 Science Objective, the instruments and materials that will be used to assess the suitability of Martian soil for agriculture are the seeds to be cultivated, measuring tape, Martian soil samples, a scaled-up ISS VEGGIE system, and a vertical agriculture system and soil testing equipment that is listed in the STM. We will follow the guidelines for the ISS VEGGIE system with the only exception of using Martian soil. We will have a diverse selection of plant species to test plant growth rates. For our main sub-objectives, we will vary the composition rates of nutrient additives (namely Nitrogen, Phosphorus, and Potassium) and cyanobacteria (limited on Mars and vital for plant growth) to understand their influence on plant growth rate. For understanding how nutrient additives affect plant growth rates we will require the same instruments and material as the first sub-objective in addition to two 2 scaled-up VEGGIE systems. The other main requirements are that the growth rate of 7 plant species will be monitored throughout the mission and LED lights and water supply will be required to support the system. For understanding how cyanobacteria affect plant growth, the same instruments and materials will be used as the first sub-objective. An overarching constraint to consider is that we should follow planetary protection restrictions and prevent contamination within our samples. A baseline case will be included where no additives/ cyanobacteria are added for comparison purposes.

For our fifth Tier 1 science objective, the instruments that will be used to search and collect for signs of water and ice are a neutron spectrometer to detect the distribution of hydrogen and ground penetrating radar (GPR) to propagate beneath surface and interpret geology, and a drill to dig into the surface. A

Neutron spectrometer like the Dynamic Albedo of Neutrons instrument (DAN) on the Curiosity rover will be used and a ground penetrating radar like The Radar Imager for Mars' subsurface experiment (RIMFAX) on the Perseverance rover. A major constraint will be the area limitations for exploration. A pressurized rover/vehicle will be used for travel purposes further away from the habitat. The spectrometer will detect hydrogen-related neutrons at least 3 ft in depth and of 1% concentration. The GPR will detect geology makeup at least 10 m in depth. These requirements were based on the instruments we are using.

For our last Tier 1 science objective, we will require a dosimeter, 3D printer, Ti64 powder, Martian regolith simulant, 80–2000 grit SiC sandpaper,VibroMet™ 2 vibratory polisher to make the 3D printed samples to assess the printed material's texture, appearance, repeatability, protection capabilities from radiation. The main constraint is that astronauts should not rely on this technology to manufacture parts as it is one of our novel technologies. A requirement for this science objective will be that the crew obtain training on the regolith brick system.

D.3 Landing Site Selection

To select a landing site for our mission, we weighed several criteria. In particular, we considered the ease of landing, level of radiation, presence of water resources, proximity to equator or poles, whether the region has been observed by a rover in the past and finally, the ability to carry out science objectives such as physical sciences, agriculture, and In-Situ Resource Utilization (ISRU). Landing in a region that has previously been explored by a rover would allow for smooth landings and could potentially place astronauts in a region with accessible water. The presence of water resources such as water ice and bound water is crucial for life support systems, agriculture as well as the production of rocket propellant to return astronauts to Earth [SO-31]. Due to this indispensability, we examined the viability of eight locations based on this requirement. These were: Columbia Hills, Eberswalde Crater, Holden Crater, Jezero Crater, Mawrth Vallis, Northeast (NE) Syrtis Major, Nili Fossae and Southwest Melas Basin [SO-32]. The location of these regions on the surface of Mars can be seen in figure 1. Each region was formed either by bubbling underground springs or rain-fed rivers. Additionally, we looked at three locations which were the landing sites for rovers in the past. The first such location was the Gale Crater, which has been observed by the Curiosity rover since 2012 [SO-33]. The next location was Ares Vallis, the landing site for the Mars Pathfinder in 1997 [SO-34]. Finally, we looked at Meridiani Planum, which was the landing site for the Opportunity rover in 2004 [SO-35].

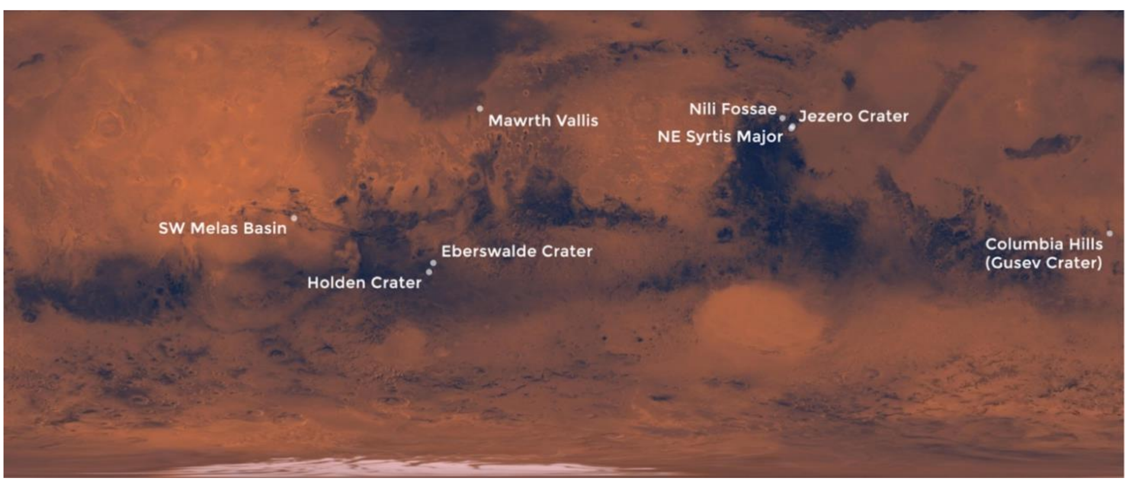


Figure 1: Landing sites based on availability of water resources

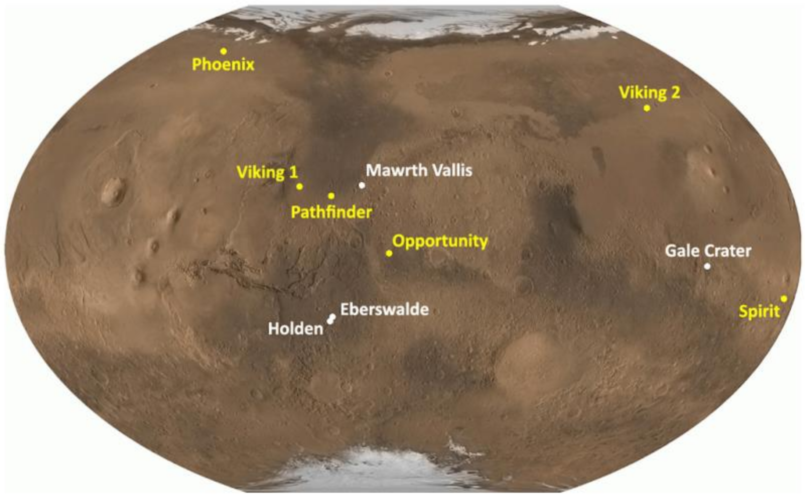


Figure 2: Landing sites based on previous rover landings

To determine the most viable location, we performed a first order analysis based on the mission requirements. Based on the results of this analysis, we chose Nili Fossae as the final landing site for the mission. This location has been mapped by the Perseverance rover, which showed that it has a level terrain for ease of landing. In addition, NASA's Mars Orbiter Laser Altimeter (MOLA) found that this region lies at a low altitude, indicating low levels of radiation as compared to other regions on Mars [SO-36]. The variation of altitudes and corresponding radiation levels can be seen in figure 3. Earth based telescopes detected hints of Methane in this region, which could have potentially been released from living organisms. Finding the source of this methane could provide insight into Mars' ability to support life. The presence of clay, olivine, sulfates, and carbonates makes this region an ideal location to study the history of crust formation on Mars [SO-37]. This location is also in close proximity to the Jezero Crater and NE Syrtis Major, both of which are geologically rich [SO-38]. Therefore, being close to these regions would allow astronauts and rovers to map these areas which could help further the science objectives.

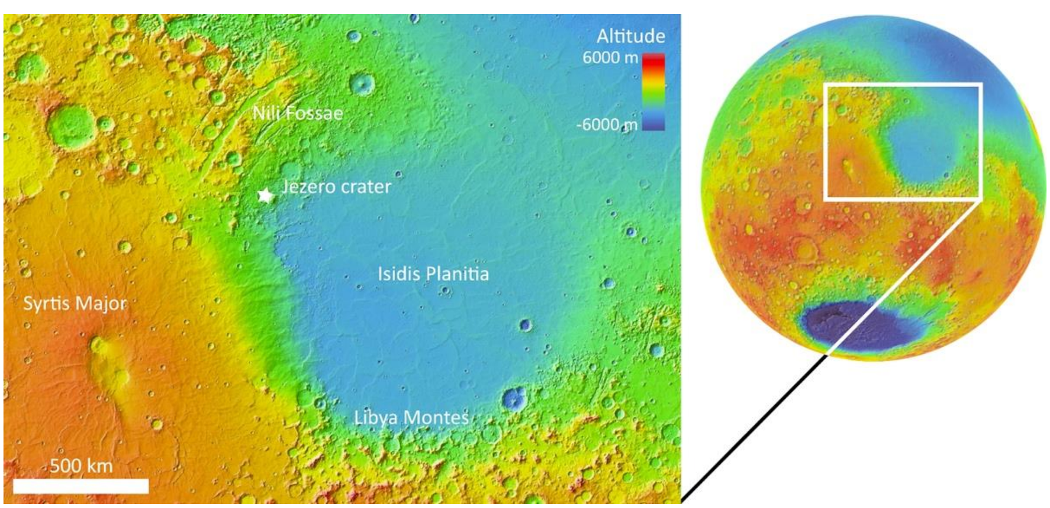


Figure 3: Radiation Level Map

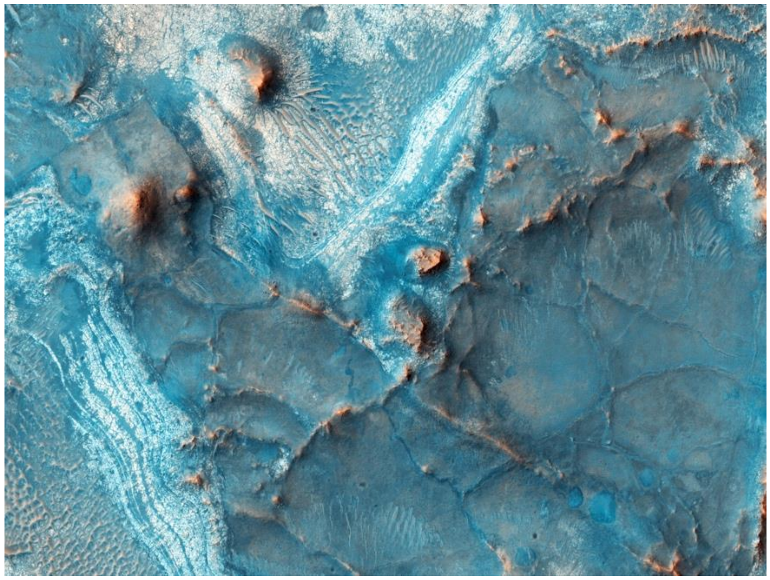


Figure 4: Topography of Nili Fossae

D.4 Novel Technologies

D.4.a BOXIE

The first novel technology chosen to be demonstrated during our mission is a scaled-up version of the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE). MOXIE's technology was successfully demonstrated when it was placed aboard the Perseverance rover in 2020 [SO-39]. Since the Martian atmosphere contains about 96% of carbon dioxide [SO-40], MOXIE uses this abundance to its advantage to produce gaseous oxygen. The process of producing oxygen begins by capturing carbon dioxide, which is then electrochemically split into carbon monoxide and gaseous oxygen [SO-41]. The oxygen is analyzed for purity and the carbon monoxide produced is released into the Martian atmosphere. This oxygen can be used to burn fuel and to provide oxygen supply for breathing in the habitat.

The scaled-up version, called Big MOXIE or BOXIE would operate in a similar manner but is also capable of liquifying this gaseous oxygen. Though MOXIE has a production rate of up to 10 g/hour, BOXIE is projected to produce 2000-3000 g/hour. It would also have a projected mass of about 1 ton and would require 50 kW of power for a production rate of 50 kg/day [SO-42]. A prototype of this plant can be seen in figure 5. This scaled-up production plant would also require a monitor and control system to detect and respond to seasonal variations in the Martian atmosphere. In addition to this, adaptative software and extensive self-calibrating sensors of reactant concentrations, pressure and temperature would be necessary.

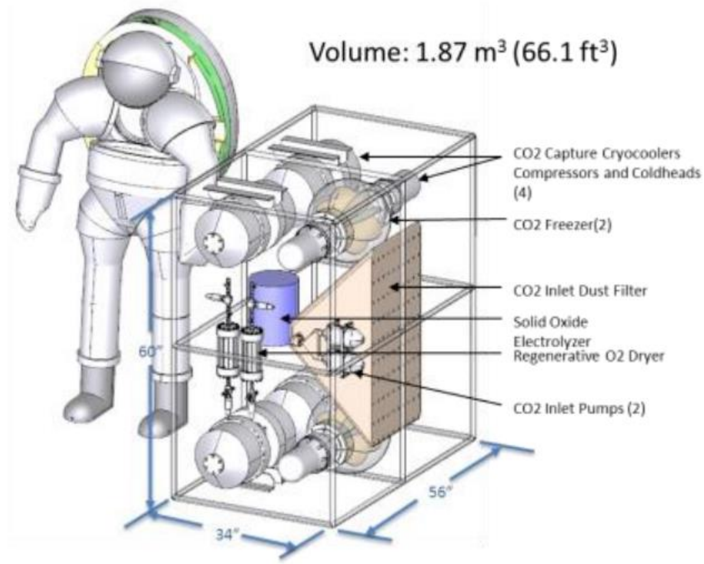


Figure 5: BOXIE Prototype

D.4.b Scaled VEGGIE System for Food Production

The second novel technology selected to be demonstrated during our mission is a scaled version of NASA's VEGGIE system previously flown to the International Space Station to test plant growth in the microgravity environment. The single VEGGIE system launched in 2014 and grew romaine lettuce seeds implanted in the system's 'plant pillows' that contained control release fertilizer. Once installed by astronauts aboard the ISS, VEGGIE is self-sustaining aside from routine maintenance including plant thinning, watering, and photography. The VEGGIE grow cycle lasted for 33 days after which plant samples were sent back to Earth and tested for food safety. After this testing, lettuce samples were deemed safe to consume by flight surgeons. Following its initial success, a second crop of lettuce was grown in 2015 followed by a first crop of Zinnias later that year. With this extensive testing and flight heritage, a singular VEGGIE system is categorized as a TRL of 9. However, a scaled-up system such as will be used in our mission utilizing two VEGGIE systems with doubled growing capacity of six plant pillows to twelve plant pillows lowers the TRL. In addition to a more complex system, this VEGGIE system will have different growing conditions including the use of Martian regolith to compare to the tested plant pillow design. Additionally, Martian regolith will be tested as a growth medium using different nutrient concentrations and cyanobacteria to see their effects on plant growth. While these conditions have been tested on Earth using simulated Martian regolith, this food growth system has not been tested passed the component level in a relevant environment thus it has a TRL of 5, making it one of our novel technology demonstrations.

D.4.c Martian Regolith Bricks

The third novel technology selected to be demonstrated during our mission is the use of the Martian regolith as a primary radiation shield. One of the most significant issues facing any long-duration mission beyond the Earth's magnetosphere is radiation. Traditional shielding–concrete, lead, etc.-- is exceptionally cumbersome, and spacecraft-quality materials are only effective to a certain point. Fortunately, on the surface of Mars, there is a readily available material–regolith. Martian regolith is not an ideal radiation shield, but its abundance makes it the ideal candidate for shielding a long-duration surface habitat.

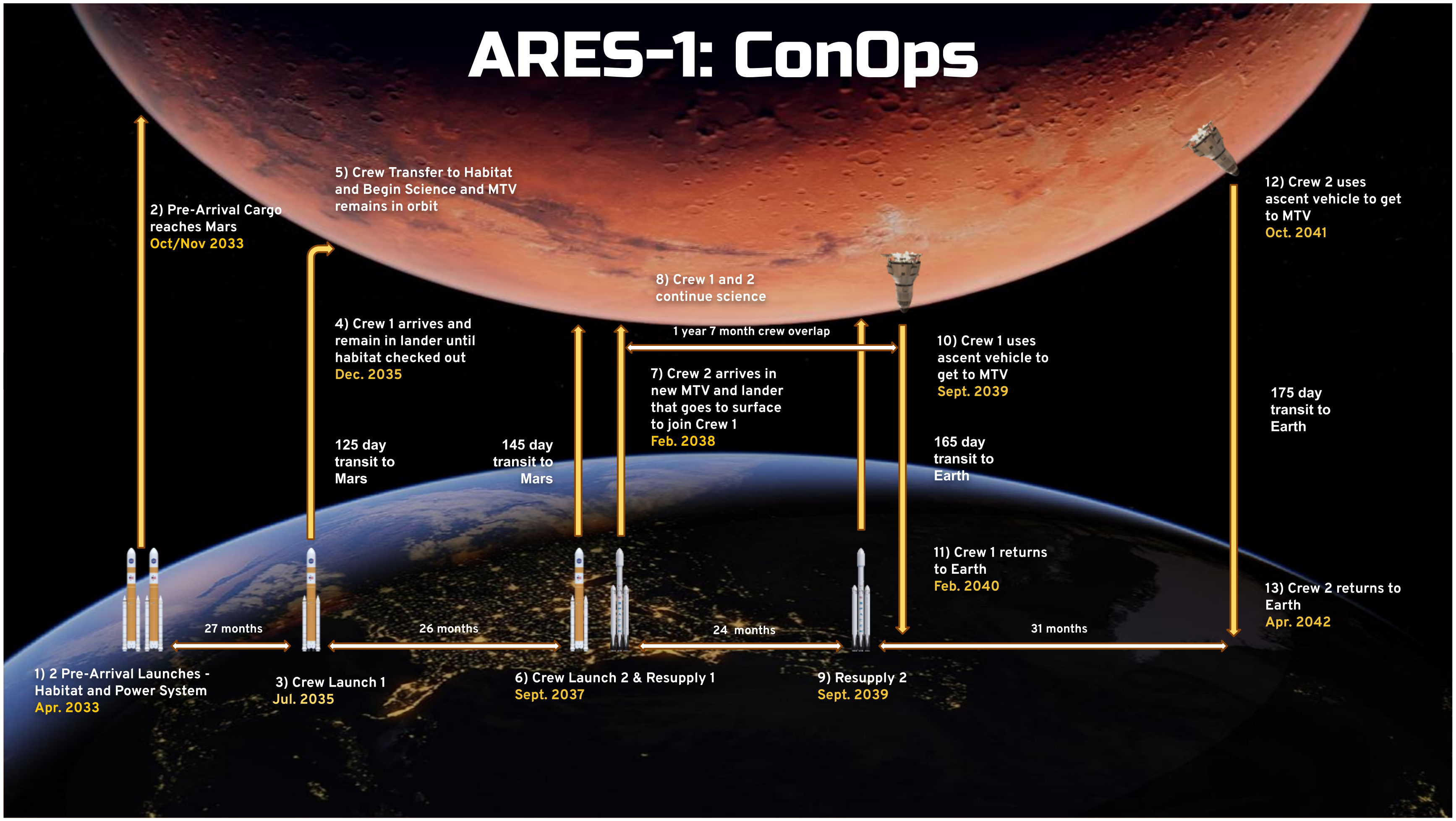
Martian regolith has a relatively high density, roughly 50% greater than that of water, giving it significant ability to attenuate both solar energetic particles and cosmic rays. These bricks, likely manufactured by NASA RASSOR systems prior to crew arrival, will require astronaut assembly onto the habitat as one of the first iterations of the surface habitation mission profile. Once assembled, they will require little to no upkeep. Performance is similarly steadfast, with an attenuation profile increasing as regolith dust accumulates within the cracks and on the surface.

In order to increase the effectiveness of regolith as a shielding material, it can be combined with titanium powder and heated to remove water content. This process is expected to create a durable, brick-like material that can be easily fitted together around the habitat and is more stable than regolith itself.

E. Mission Implementation

E.1 Mission Overview

E.1.a Concept of Operations (ConOps) & Mission Sequence



E.1.b Systems Engineering

E.1.b.i Systems Engineering Process

The systems engineering process began with a team-wide brainstorming session to develop different sub-system options for our mission architecture using a morphological matrix. Following this ideation period, Pareto curves were developed to compare all possible system architectures based on cost and risk compared to the baseline architecture outlined in NASA's DRA 5.0. Through looking at the Pareto frontier, sub-teams selected their primary initial architecture which allowed teams to switch focus to a more detailed sub-system design. To do so, sub-teams conducted literature reviews and developed FOAs to justify their design decisions. In the shift to detailed design, the systems engineering focus shifted to an integration and requirements verification focus, ensuring that each sub-team's decisions integrated into one feasible architecture that met the critical requirements that are described below.

E.1.b.ii Requirements Flow Down

The operational requirements provided at the beginning of the semester for the Mars System Architecture were the fundamental baseline of all our design decisions. These operational requirements (L1 Requirements) were broken down into sub-system level requirements (L2 Requirements) to create the requirements outline shown below:

	Number	Description	Category	Type
L1	**1.1**	The system shall support a crew size of four humans for seven years of operation.	Requirement	Functional
	1.2	The system shall have no more than 2 years' worth of supplies deployed prior to mission timeframe.	Requirement	Functional
	1.3	The system shall require no more than 5,000 kg of delivery cargo from Earth within a two-year period.	Requirement	Functional
	1.4	The system shall support a first crewed landing between 2035 and 2040 and a return of the crew between 2040 and 2050.	Requirement	Functional
	1.5	The system shall support at least 5 opportunities for space science.	Requirement	Functional
	1.6	The system shall incorporate three novel technologies, methods, architectural features, or capabilities that differ from existing Mars architecture studies.	Requirement	Functional
	1.7	The system shall utilize technologies about a TRL of 6.	Requirement	Functional
L2	2.1	Mission Design	Statement	
	2.1.1	Launch times shall minimize delta V for cargo missions.	Requirement	Performance
	2.1.2	Launch times shall minimize flight time for crewed missions.	Requirement	Performance
	2.1.3	Launch times shall align with synodic period of earth and mars of 2.1 years.	Requirement	Functional
	2.2	Propulsion	Statement	
	2.2.1	Resupply Launch vehicle selected shall have a minimum payload of 5,000 kg.	Requirement	Functional
	2.2.2	Transit propulsion system shall be able to propel a 400,000-kg vehicle to 7km/s.	Requirement	Functional
	2.3	Space Environment	Statement	

	2.3.1	Astronauts shall be exposed to a radiation dose made ALARA (as low as reasonably achievable) while on Martian surface.	Requirement	Functional
	2.3.2	Astronauts shall not be exposed to a total mission dose exceeding 4 Sieverts while onboard MTV during expected mission time.	Requirement	Performance
	2.3.3	MTV Personnel thermal system shall be capable of dispersing 50 kilowatts of heat from the crewed modules.	Requirement	Performance
	2.3.4	MTV Reactor thermal control system shall be capable of dispersing 400 kilowatts of heat from the fission reactor.	Requirement	Performance
	2.4	Communications	Statement	
	2.4.1	Telemetry and tracking coverage shall be available for critical events.	Requirement	Functional
	2.4.2	Communication coverage shall extend to maintain communication during all EVA activities.	Requirement	Functional
	2.4.3	Communication data relay between habitat and Earth shall occur daily	Requirement	Functional
	2.4.4	Science objective data relay between Mars and Earth shall occur every 2 weeks.	Requirement	Functional
	2.5	Structures and Surface Stay	Statement	
	2.5.1	Crew life support systems shall provide necessary resources to 8 astronauts.	Requirement	Functional
	2.5.2	Crew personal space shall be 1700 m^3.	Requirement	Functional
	2.5.3	Food supply shall include 3 meals per astronaut per day with 50% margin.	Requirement	Functional
	2.5.4	Pressurized systems shall be equivalent to Earth's pressure of 101.325 kPa.	Requirement	Functional
	2.5.5	Mars ascent vehicle shall fit within SLS Block 2 Ferring.	Requirement	Functional
	2.5.6	Landing site shall have evidence of ground water for scientific objectives.	Requirement	Functional
	2.5.7	Landing site shall have less than 15 rem/yr radiation levels.	Requirement	Functional
	2.5.8	Landing site shall be flat for an area of at least 400 square miles.	Requirement	Functional
	2.6	Cost and Schedule	Statement	
	2.6.1	Cost estimate shall be accurate to 70th percentile.	Requirement	Performance
	2.6.2	Cost estimate shall include a 30 percent margin.	Requirement	Performance
	2.6.3	Astronaut daily schedule shall incorporate 8 sols of science objective work.	Requirement	Functional
	2.6.4	Science schedule shall achieve 7 years of science objective work goal within mission timeframe.	Requirement	Functional
	2.7	Entry, Descent, and Landing	Statement	
	2.7.1	Mars ascent vehicle shall be capable of launch at all times when crew is on Martian surface.	Requirement	Functional
	2.7.2	Propellant shall be capable of storage for a minimum of 8.5 years on Martian surface.	Requirement	Functional
	2.7.3	Mars ascent vehicle shall fit within SLS Block 2 Ferring.	Requirement	Functional
	2.7.4	Mars ascent vehicle shall be capable of reaching Areostationary orbit.	Requirement	Performance

	2.8	Science Objectives	Statement	
	2.8.1	Human Health Science Objectives	Statement	
	2.8.1.1	Personal devices shall be utilized for emotion regulation daily for a duration of 30 minutes.	Requirement	Functional
	2.8.1.2	Personal devices shall be utilized for sleep tracking daily.	Requirement	Functional
	2.8.1.3	Personal devices shall be utilized for AI therapy programs weekly.	Requirement	Functional
	2.8.1.4	Model instruments shall be able to function within Martian gravity.	Requirement	Performance
	2.8.1.5	Three different model instruments shall be used to test different parts of the body for signs of vision loss through bi-monthly testing.	Requirement	Functional
	2.8.1.6	Baseline testing shall be required on earth for comparison to Martian results for same duration.	Requirement	Functional
	2.8.2	Space Weather Objectives	Statement	
	2.8.2.1	Weather measurements shall be taken with same instrumentation as Perseverance rover.	Requirement	Functional
	2.8.2.2	Instrumentation attached to MTV orbiter shall be used with same instrumentation as the MAVEN mission to analyze solar wind.	Requirement	Functional
	2.8.3	Possibility of Past Life Objectives	Statement	
	2.8.3.1	Sensors shall have a wide range of detected chemical compositions including Na, Mg, Al, Si, P, S, Cl, K, and Ca.	Requirement	Functional
	2.8.3.2	Sensors shall withstand Mars' atmospheric conditions including radiation, strong solar winds, and dust storms.	Requirement	Functional
	2.8.4	Agriculture Objectives	Statement	
	2.8.4.1	The system will receive water periodically based on optimal water needs of species being tested. (Ex. 100 mL of water 2x per week for lettuces).	Requirement	Functional
	2.8.4.2	The system shall receive light from red, green, and blue LED lights at intervals optimized for each plant studied.	Requirement	Functional
	2.8.4.3	The system shall test growth rates of 7 plant species throughout experiment timeline (one for each year of mission duration).	Requirement	Functional
	2.8.4.4	System shall vary concentration of nutrients at levels ranging from 1,1,1% concentrations of Nitrogen, Potassium, and phosphorus to 8,8,8% in Martian regolith pillows added every 2 months.	Requirement	Functional
	2.8.4.5	System shall utilize a baseline case of no nutrient additives as a baseline.	Requirement	Functional
	2.8.4.6	System shall utilize a baseline case of no cyanobacteria as a baseline.	Requirement	Functional
	2.8.5	ISRU Objectives	Statement	
	2.8.5.1	Neutron spectrometer shall be able to detect hydrogen related neutrons at least 3 ft in depth (similar to DAN).	Requirement	Functional
	2.8.5.2	Neutron spectrometer shall be able to detect water concentrations at a sensitive scale (1%).	Requirement	Functional
	2.8.5.3	GPR shall be able to detect geological makeup at least 10 m in depth (like RIMFAX).	Requirement	Functional
	2.8.5.4	Technology for regolith brick creation shall be at a TRL of 5 prior to mission.	Requirement	Functional
	2.8.5.5	Crew shall obtain 20 hours of training on regolith brick system.	Requirement	Functional

Table 3: Requirements Flow Down Outline

E.1.b.iii Critical Requirement Change and Justification

Through the development of our system architecture, our team found that a change to the provided operational requirement *"Develop Architecture for a crewed human exploration of Mars that enables a crew of a nominal size of four (at least 4 at all times) to remain on the surface of Mars for seven years (no fewer or more)"* was necessary for mission success. Due to the synodic period of Earth and Mars equating to approximately 2.1 years (26 months), optimal launch opportunities with flight times under 200 days for crew missions do not line up with an exact seven-year mission timeline. The 200-day limitation on crew flight times was implemented due to human physiological limitations with the low-gravity and micro-gravity environments. Thus, our team proposed changing this operational requirement to include conducting seven-years' worth of science on the Martian surface rather than a seven-year total surface stay. Our mission architecture achieves seven-years' worth of science requirement through having a crew-overlap period of 1 year, 7 months and 4 days during which our on-surface science capability doubles as the operational requirement is based on a surface crew of 4 astronauts. This, in addition to Crew 1's surface time being 3 years, 9 months, and 18 days and Crew 2's surface time being 3 years 8 months and 4 days, brings our effective Martian stay time to 7 years, 5 months and 22 days.

While a doubled crew capacity does not equate to a lengthened mission timeline, the ability to perform increased science objectives during the crew overlap helps to justify the shortened mission timeline. This is especially true as astronaut safety is paramount to a slight increase in mission timeline. Further details on the crew swap and surface stay timeline can be found in the following Human Health Considerations section of this report.

E.1.b.iv Block Diagram

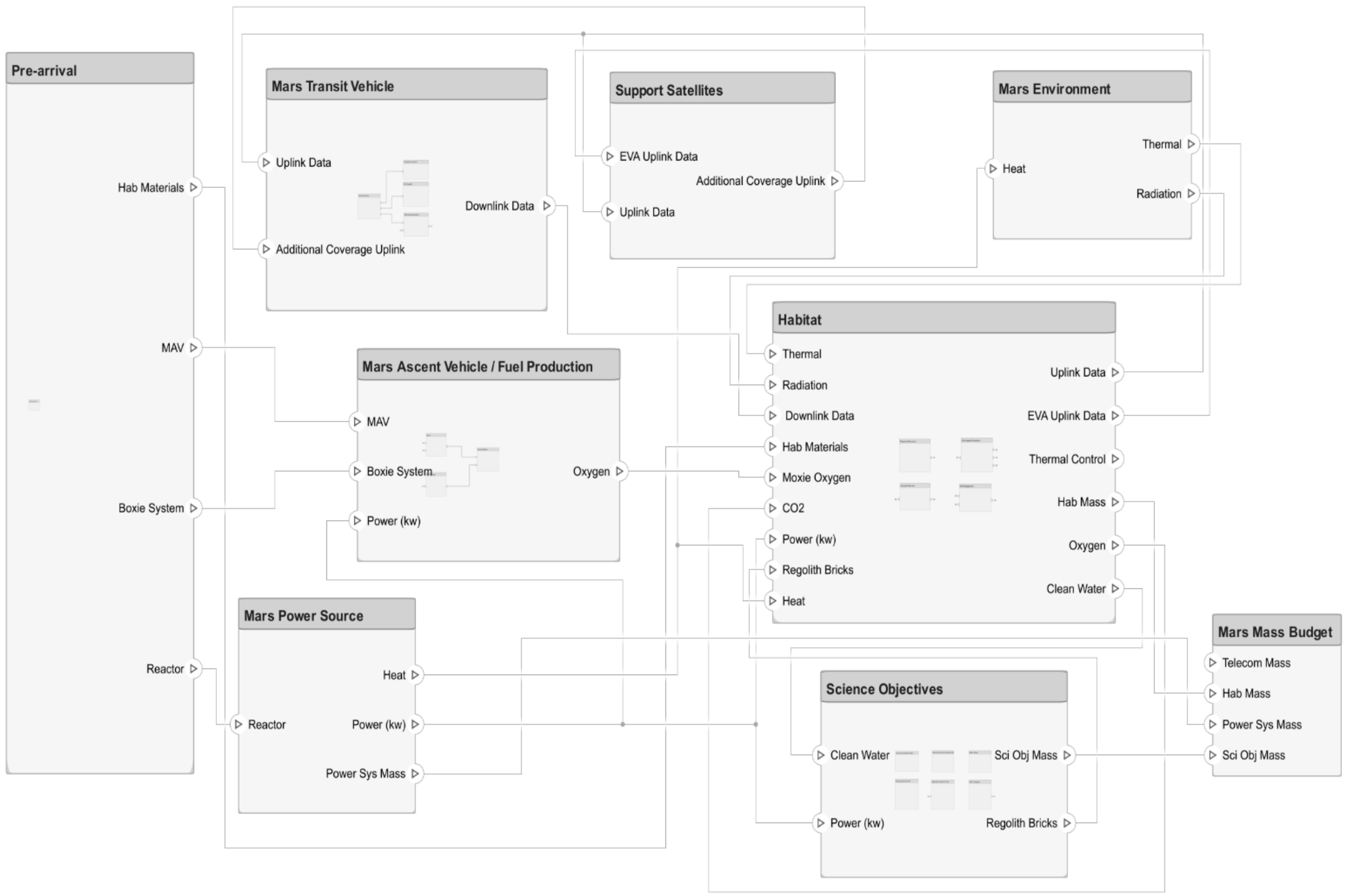


Figure 6: Mars System Architecture MBSE

The above Model Based Systems Diagram depicts a high-level overview of resource flows between sub-system elements of the Mars System Architecture. Elements include Pre-Arrival cargo, the Mars Transit Vehicle which additionally acts as our primary communications satellite, Supporting Satellites, Mars Ascent Vehicle and Fuel Production System, Martian Habitat, Science Objectives. Sources and Sinks of the diagram include the Mars Surface Power Source, and the Martian Environment and the Mass budget respectively. This diagram helped to ensure that all resource flows between sub-systems were accounted for in calculations and analysis and that each sub-team knew how their work affected other elements of the Mission Architecture. Additional sub-system processes were outlined within the model blocks for example, the Mars Ascent Vehicle and Fuel Production sub-system resource flow is depicted below.

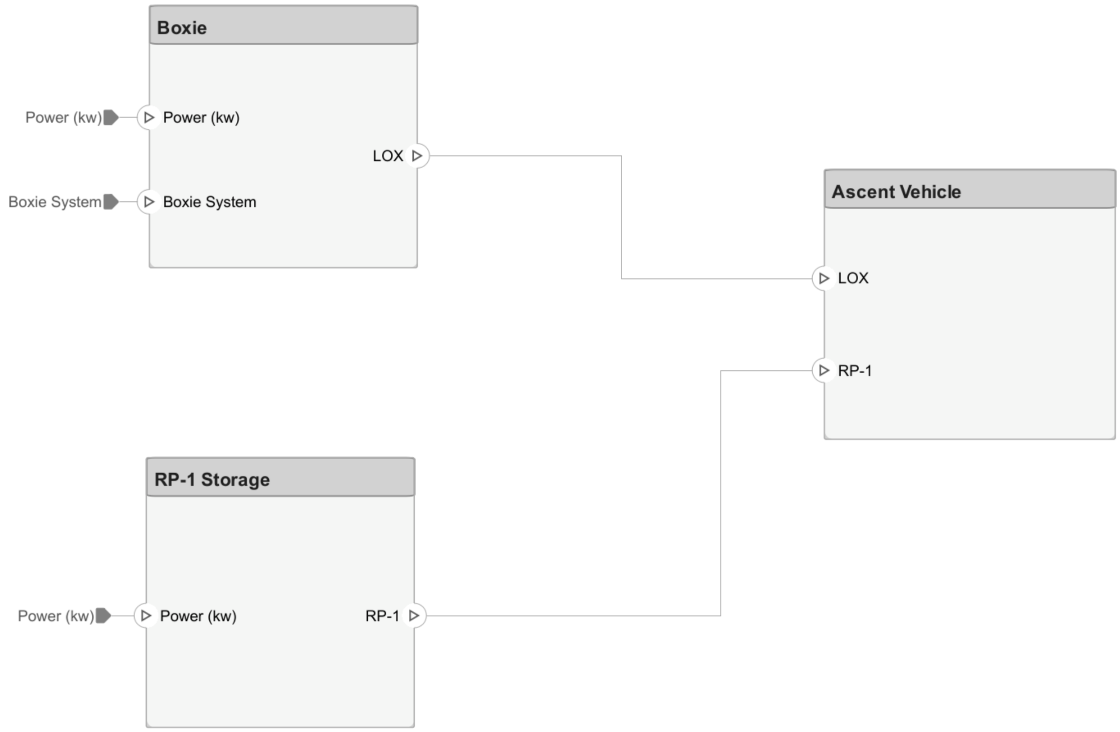


Figure 7: Mars Ascent Vehicle and Fuel Production MBSE.

E.1.c Human Health Considerations

E.1.c.i Selection of Using 2 Crews

The decision to split the time spent on the Martian surface between two crews was made based on human biological limitations in zero and partial gravity, as well as psychological considerations in long-term space isolation.

Martian gravity is about 38 percent that of Earth, causing significant stress on the body's major physiological systems. The most important of these stresses being changes to the cardiovascular and neuro-sensory systems, changes to the musculoskeletal system, and vision loss [HH-5].

Fluid shifts in low gravity can lead to post-flight orthostatic intolerances and cardiovascular deconditioning, which can cause symptoms such as weakness and heart palpitations once on the Martian surface. Partial gravity may also affect the neurovestibular system, in which the otolith organs cause the astronauts to experience extreme motion sickness symptoms. Zero and partial gravity also leads to severe muscle and bone atrophy [HH-3].

However, each of these symptoms and stresses can be at least partially combatted by technology and exercise. These detrimental physiological changes can be monitored using electrocardiograms (ECGs), complete blood counts (CBCs), comprehensive metabolic panels (CMPs), Dual X-ray Absorptiometry (DXA) scans, and using the Muscle Atrophy Research and Exercise System (MARES) [HH-2].

The most detrimental effect that partial gravity has on human physiology is vision loss [HH-1]. It is postulated that increased pressure from cerebrospinal fluid causes extra pressure on the optic nerve, resulting in vision changes during long-term spaceflight. Based on intracranial (ICP) and intraocular (IOP) pressure measurements, it is estimated that these potential vision problems can result in permanent vision loss after a period of about three years in microgravity [HH-5]. As Martian gravity, or partial gravity, is less detrimental to the human body than microgravity, both crews have mission timelines under five years total, with less than one year of microgravity transit time.

As well as being physically demanding, spending a significant amount of time in space can be detrimental to an astronaut's mental health. Confinement to a tight space, with limited personal space and human interaction, can disrupt normal behavioral patterns. There have been instances in the history of much shorter-term space flight where astronauts have reported delusions, and an increase in pressure and paranoia from isolation [HH-4]. Artificial intelligence-based therapy programs, as well as emotion regulation devices are potential solutions for these behavioral and psychological problems. Physiological changes, such as radiation exposure, can have an effect on human psychology as well. This is most prevalent in disruptions to sleep cycles, which can cause discomfort and mood swings, amongst more serious symptoms without the help of sleep cycle trackers and strict daily and nightly schedules [HH-6].

E.1.c.ii Radiation Mitigation Measures

The space environment has two primary types of radiation from which to guard against: Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs).

GCR radiation is the ever-present cosmic background radiation in space, generally within the high frequency range of the electromagnetic spectrum and at energy levels of up to 150MeV [SE-5]. They are blocked by high density materials, but have a tendency to propagate through thick, low-density materials.

SEPs are high-energy atomic nuclei released from the sun during coronal mass ejections, otherwise known as Solar Particle Events. These high-energy particles span from alpha particles to fully ionized uranium atoms traveling at significant fractions of the speed of light, with the corresponding range of energy levels. SEPs are blocked well by both high-density materials as well as large thicknesses of low-density materials, and do not propagate through non-optimal thickness [SE-5].

It is incredibly important to shield against both GCR and SEP type radiation. Both can be ionizing, leading to acute and chronic radiation sickness if not properly mitigated. In the worst cases, this can lead to cancer, central nervous system degradation, and organ related issues. Less serious problems can also occur during extended exposure, such as various skin conditions, vision problems, and a degraded immune system [SE-7]. It is in the program's best interest to maintain the health of the astronauts to the highest degree possible, and as such a maximum allowable radiation dose must be implemented. Current lifetime radiation exposure limits for NASA astronauts are placed at 1 Sievert or equivalent, and due to the high exposure during two phases of this mission (transit to and transit from the Martian surface) this may be an acceptable limit for the ARES-1 mission. Reducing the effective radiation dose on the crew should be considered a significant priority throughout the planning and implementation of the mission.

With the effective dose of the MTV shielding for the mission being 377mSv, our remaining dose from the surface must be minimized to below 623mSv. With this requirement, a lower limit of 1.75m of regolith shielding is required in order to achieve our desired dose cap. If the habitat is able to maintain additional weight, or bricks can be manufactured into an igloo-type interlocking structure to support themselves without adding pressure on the habitat pressure vessel, a nominal shielding thickness of 4m is desired to achieve the lowest "reasonably achievable" radiation dose over the mission duration.

E.2 Mission Design

E.2.a Launch Scheduling and Mission Timeline

E.2.a.i Launch Dates/Windows

The scheduling of our mission is dependent on the synodic period of Earth and Mars. The synodic period characterizes the resonance between the planets, indicating how often launch windows open. Because launching outside of these windows greatly increases the required ΔV for the transfer, we are restricted to launching only within these windows. During the timeline specified by the general requirements, the launch windows available for this mission to Mars occur in the years 2033, 2035, 2037, 2039, 2041, and so on, following the approximately 26-month synodic period. The selection of which launch windows to begin our mission is dependent on the requirement for a first crew landing on Mars between 2035 and 2040. To account for any anomalies or failures in the development of our technologies prior to launching crew, the mission will commence in the earliest possible time window. This allows for the requirements to still be met if the launch schedule must be delayed for any reason. Pre-arrival cargo missions will be sent 2 years prior to the departure of crew in 2033. The first crew, consisting of four astronauts, will launch from Earth in the 2035 launch window, the second crew would fly in the 2037 launch window and resupply missions will fly in 2037 and 2039.

E.2.a.ii Critical Events

While it is important to be able to see and communicate with a spacecraft during an entire mission, there are some points where it is more important for mission success. During a critical event, staffing in mission control will need to be increased and constant to ensure the safety of the mission and a quick response time to any errors that may occur.

Insertion maneuvers are the largest critical event that will need to be carefully considered. Before a large maneuver, verification/validation will need to be performed to ensure that the spacecraft is functioning correctly on all accounts. After the maneuver is performed, tracking will need to be closely monitored to determine the actual trajectory the maneuver resulted in, since some errors or deviations can cause it to be incorrect. Once the resulting trajectory is found, a TCM can be planned to correct for some errors. This TCM will be small in magnitude compared to the primary TOI and MOI maneuvers, around 100 m/s ΔV . Once again, when this TCM is performed, subsystems will need to be checked and actively monitored both before and after.

During MOI, there is a chance that Mars will be in the way, making it impossible to communicate and verify that a maneuver is performed correctly. Before a situation like this occurs, the TCM can also be applied to alter the trajectory such that this ~40 minute outage window is avoided entirely. This is only required for the pre-supply missions, as subsequent missions will have access to the supporting satellites orbiting around Mars to avoid this issue.

Crew departure and arrival at MTV are also critical events requiring heightened staffing and monitoring to ensure the safety of crew. Due to the time delay in communication between Earth and Mars, undocking/docking events should be performed very slowly to allow mission control to verify that all systems are functional.

Mars launching will also require significant monitoring and system checks prior to launch. Once launch has begun, the time delay will not allow for any form of live control from mission control, but it can be regained once the MAV is in orbit and prepared to dock with the MTV. Similarly, Mars landing sequences will need to be automated or controlled by pilot.

E.2.b Transfer Type Considerations

E.2.b.i Cycler, Direct, Semi-Direct, and Stop-Over Trajectories

Various trajectory types offer different levels of flexibility, safety, and reliability. For trajectories between Earth and Mars, the types considered include cycler, direct, semidirect, and stopover.

Cycler trajectories offer continuous encounters with both Earth and Mars. These heliocentric orbits resonate at a precise interval in order to perform routine flybys of both planets. Due to the nature of the orbit, little propellant is needed to maintain this trajectory, making it ideal as a routine transportation method to and from Mars. However, in order to utilize the cycler orbit, a taxi vehicle must rendezvous with the cycling vehicle that performs a flyby of Earth at a high relative velocity. The high relative velocity significantly increases the risk associated with this transfer type. Additionally, the preliminary cost of establishing inbound/outbound cycling vehicles is significantly large. For a preliminary mission to Mars, the establishment of a long-term cycling transit vehicle is not suitable. The costs of designing these vehicles are too high to justify for just two planned crewed missions. The current analysis that had been performed in regard to cycler orbits relies on the assumption of circular and coplanar orbits. However, Earth orbits the sun with an eccentricity of 0.0168, and Mars orbits at a 1.85° inclination and an eccentricity of 0.0934. This relationship creates complications in the repeatability of these orbits, and further research is needed in order to prove the capabilities of cycler trajectories [MD-1]. Additionally, flexibility is lost as the crews would only be able to depart Earth and Mars at very specific intervals when the cycling spacecraft is passing by. The extreme relative flyby speeds and the loss of flexibility create risks that would be mitigated through the use of any other trajectory type.

Direct transfer types involve surface to surface travel from Earth to Mars with no stops in between. While this allows for added simplicity with the removal of intermediate maneuvers into/out of parking orbits, direct transfer can be costly in propellant mass. Additionally, the use of a transit vehicle becomes difficult, as it will need to be expended, or landed and launched from the surface of Mars [MD-2]. Landing and launching large transit vehicles add complication and increases the vehicles' propellant requirement. For this reason, semidirect and stopover trajectory types are more favorable.

Semidirect and stopover types encounter Mars with a parking orbit, rather than a direct surface landing. This allows for a transit vehicle to remain in orbit about Mars, making it available for use on a return mission back to Earth. The difference between the two trajectory types comes from their method of Earth departure. The semidirect departs Earth and immediately places the transit vehicle on a transfer orbit to Mars, while the stopover departs from a parking orbit [MD-2].

For crewed missions to Mars utilizing a transit vehicle, the optimal trajectory type is a stopover, which features parking orbits at Earth and Mars. A parking orbit at Earth allows for an MTV to be constructed in orbit prior to the crew's launch. When crew launches and docks with the MTV, the parking orbit also allows for launch flexibility and exact orbit determination prior to performing a TMI maneuver. When arriving at Mars, having the MTV capture into a parking orbit simplifies the EDL process, by unlocking the ability to perform a surface landing with a smaller vehicle, while keeping the MTV available for the return mission to Earth.

Cargo missions to Mars are classified differently, with there being pre-arrival and resupply missions. Pre-arrival missions carry large masses to Mars prior to crew departure. These payloads contain key elements to mission success like the habitat, power systems and MAV. The massive payloads prevent a launch vehicle from placing the payload directly onto a transfer orbit to Mars. For pre-arrival missions, a stopover trajectory will be used, where the launch vehicle deploys the payload in LEO, and a transfer vehicle maneuvers the payload to Mars where it enters an areostationary orbit for the deployment of communication support satellites. Since no vehicle needs to be kept for cargo return, the transit vehicle can be expended. For resupply missions, with a lighter 5,000 kg payload, launch vehicles can place the payload directly onto a transfer orbit to Mars, allowing for the use of a direct surface to surface trajectory.

E.2.b.ii Flybys

By performing a flyby of celestial body, a spacecraft can gain energy which would reduce the amount of propellant needed to achieve certain orbits. Additionally, through this energy gain transit times can be reduced. However, performing these maneuvers poses new risks and challenges. Flybys of Venus have the potential to greatly reduce both propellant requirements and transit times compared to traditional opposition class trajectories, but they require unique planetary alignments that only repeat every 15 years. For a mission that requires crew and cargo trajectories over a 9-year period, unique opportunities like this will not be available for every launch. With Venus orbiting the Sun at approximately 0.72 AU, thermal loads and solar radiation significantly increase and create an environment that is hazardous for crew [MD-3]. For these reasons, flybys will not be considered for preliminary missions.

E.2.c Trajectory Optimization

E.2.c.i Objective/Problem Definition

The purpose of using optimization in mission design is to provide the best option for interplanetary travel. For this mission, E-M and M-E trajectories are optimized in accordance with the FOA such that the best result is met. To perform the optimization of trajectories, NASA's GMAT software was utilized with its built-in optimization functionality.

To use this optimization, the mission design problem must be split into different sections with control and patch points. A control point is a point along the trajectory that has strictly defined and known conditions, while a patch point is a point along the trajectory that is defined by the intersection of two paths. Following is a visual of the problem breakdown into these points:

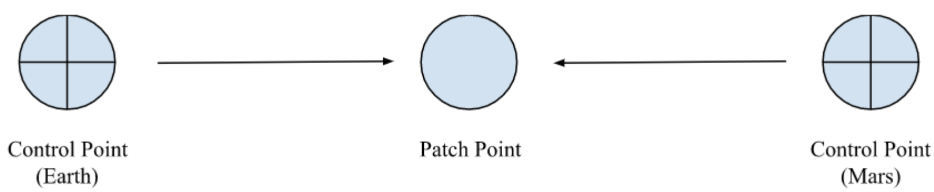


Figure 8: Optimization Problem Visualization

Our mission has a control point at Earth, which is fixed to be the position and velocity of Earth in an inertial heliocentric frame. The Mars control point is fixed to be Mars' position and velocity in the same frame of reference for the E-M missions, the Earth control point is taken at the launch time, and the Mars control point is taken at the arrival time. The inverse is true for the M-E case. The patch point is defined in our problem as the halfway point in TOF.

E.2.c.ii Procedure

With the problem defined in this way, we take advantage of GMAT's capabilities for forward and backward propagation. For an E-M mission, a spacecraft starts at the Earth control point and propagates to the patch point. Then another spacecraft starts at the Mars control point and propagates backward to the patch point. Once both have reached this defined patch point, the constraint is made that their position and velocity must be the same.

To perform optimization, a few conditions need to be defined as either constraints or initial guesses: maneuvers, TOF, starting date, starting state (position & velocity), and ending state. Early in the optimization process, the primary point of optimization was deciding the launch date that provided the best results in ΔV and TOF. This utilized a simple model only considering the Sun's gravity, with the requirement of starting at Earth's state, ending at Mars' state, and optimization variables being the maneuvers and TOF. While this model is low fidelity, it provides accurate results for optimal planet phasing and specific dates of departure.

One requirement to perform this optimization is to have an initial guess for the maneuvers, which largely impacts the results of the optimizer. Getting this initial guess is non-trivial and is the most important part to ensure that optimization works properly and returns the best result. Multiple methods were tried to apply this. Initially, the values from a single Hohmann transfer assuming circular orbits were used to get an initial condition, which was used as the initial guess for all cases. While this Hohmann transfer provides a decent, non-random guess, it is based on simple dynamics and a single, arbitrary time of departure, thus, the results found from this optimization are not ideal, but will provide a better basis for the guesses in following iterations.

Utilizing various results of the preliminary optimization as the initial guess for various launch dates provides a better understanding of the ideal launch dates. While this method works better than the previous, only one initial guess for each launch date is made for the time of flight. Once again working iteratively, the previous results can be used with an almost ideal launch date and manually varied TOF guesses for each launch date. This results in a few trajectories that are ideal for the simple model that can be used as reference when considering the local gravity effects of Earth and Mars.

Although it would be ideal to have a high-fidelity model that optimizes everything for a trajectory, implementation of that model was unsuccessful, due to the optimizer failing to converge for multiple methods of implementation. However, an alternative solution is applied to gain more accurate values for propulsive requirements when considering local gravity fields through the addition of an impulsive ΔV to the departure maneuver, to account for the impulse requirement to go from the initial orbit to escape velocity, and to the arrival maneuver, to account for capture into the desired orbit.

With a more accurate model applied, optimization is run once again with the previous optimal results to determine accurate, optimal trajectories. All of the results are then tabulated and compared to find the best resultant trajectories for each mission in accordance with the FOA and required spacing between mission launches.

E.2.d Analysis of Electric Propulsion for Mars Orbit Insertion

Efficiency of a propulsion system is an important factor in mission design. The ΔV requirements computed for a specific trajectory affect the propellant sizing, but the use of highly efficient electric thrusters can produce the same effect as a traditional maneuver while using significantly less propellant. To evaluate the true impact that electric propulsion can have on interplanetary transit, trajectories were optimized in GMAT, including the additional impact of an electric thruster. Recent developments show that Hall thrusters can achieve a specific impulse over 5000 seconds with 200 kW of power input [MD-4]. With these capabilities implemented in GMAT, we can recompute the impulsive ΔV required at Earth departure and Mars arrival. Using the outputted data, a direct comparison can be made between the ΔV requirements for the departure and capture maneuvers with and without the addition of a long-duration electric burn.

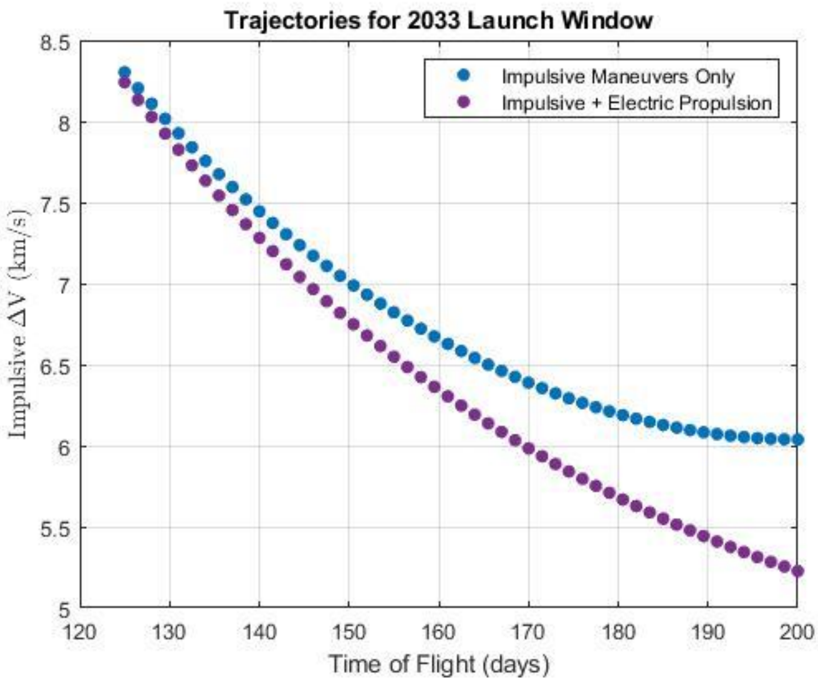


Figure 9: Mission duration vs total impulsive (TMI + MOI) ΔV for a 20,000 kg spacecraft with and without the employment of electric propulsion in the 2033 Earth-Mars launch window

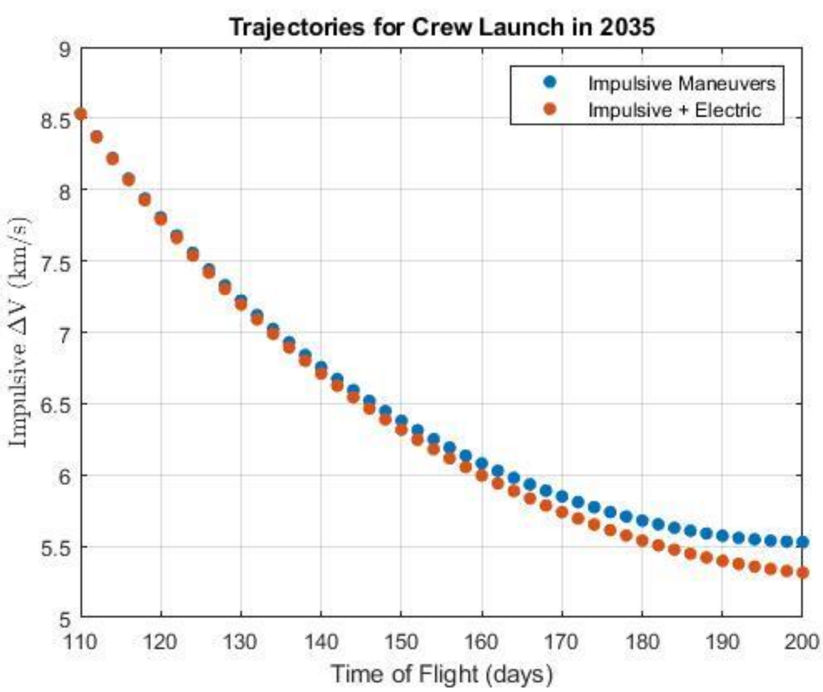


Figure 10: Mission duration vs total impulsive (TMI + MOI) ΔV for a 150,000 kg MTV with and without the employment of electric propulsion in the 2035 Earth-Mars launch window

The figures above show the resulting ΔV requirements for the TMI and MOI maneuvers with and without electric propulsion during the 2033 launch window for pre-arrival cargo, and the 2035 launch window for crew. In both cases, the use of additional electric propulsion decreases the required ΔV. Because of the much larger spacecraft mass for crew missions, the ΔV savings are far less significant than cargo missions. In the 2033 launch window with a cargo payload of 20,000 kg, the ΔV savings for the maneuvers at Earth and at Mars were approximately 0.811 km/s. While significant, this measure does not account for the additional mass of the electric propulsion system including the power system, additional tanks and propellant, and the thruster itself. With the added complexity of incorporating these systems into a cargo transit vehicle, the ΔV savings are not significant enough to justify the decision to move forward with electric propulsion for cargo missions. For the crewed trajectories, the much more massive MTV only begins to see noticeable ΔV savings for longer transit times near 200 days. There is a strong emphasis on crew safety that drives the decision for shorter transit times, but electric thrusters make a more substantial difference when given a longer time to burn. This conflict of interest, along with the insignificant ΔV savings for transit times under 200 days, makes electric propulsion unsuitable for crew missions.

E.2.e Final Trajectory Selections

E.2.e.i Application of FOA

To select the optimal trajectories for each mission, a first-order algorithm was established that generates a score to characterize how well a given trajectory fits the needs of each mission. The algorithm accepts two values: the total ΔV for the transfer, and the total time of flight (TOF). Designated weights are implemented to indicate the relative importance of each variable. The weights ranged from 0 to 1, where a weight of 0 does not consider the impact of the variable, and a weight of 1 indicates that the variable is extremely important. The FOA was of the following form:

$$Score = W_{TOF}\left(\frac{TOF}{TOF_{Hoh}}\right) + W_{\Delta V}\left(\frac{\Delta V}{\Delta V_{Hoh}}\right)$$

In the FOA, W_{TOF} and $W_{\Delta V}$ represent the weights placed on each variable, and TOF_{Hoh} and ΔV_{Hoh} represent the respective values for a Hohmann transfer from Earth to Mars. A lower score represents a better trajectory for our analysis, and a higher score represents a less ideal trajectory. These values for crew and cargo missions are summarized in the table below.

Mission Type	W_{TOF}	$W_{\Delta V}$	TOF_{Hoh}	ΔV_{Hoh}
Crew	1	0.4	258.87 days	6.26 km/s
Cargo	0.1	0.4		

Table 4: Parameters for trajectory selection algorithm (FOA)

To implement this first-order algorithm, a schedule of possible trajectories was generated. By iterating a script in GMAT, it was possible to identify the trajectories that minimized ΔV for a given range of TOFs in a specified launch window. The application of the FOA to the generated schedule determined the optimal tradeoff between ΔV and TOF. Final trajectory selections are tabulated below.

Mission	Departure	Arrival	TOF (days)	Post-Launch ΔV (km/s)
Pre-Arrival 1	04/17/2033	11/08/2033	205	6.050
Pre-Arrival 2	04/28/2033	10/15/2033	170	6.389
Crew 1 (E-M)	07/27/2035	11/29/2035	125	7.498

Resupply 1	09/02/2037	04/05/2038	215	2.084*
Crew 2 (E-M)	09/20/2037	02/12/2038	145	8.255
Resupply 2	09/10/2039	07/21/2040	315	2.037*
Crew 1 (M-E)	09/16/2039	02/28/2040	165	8.706
Crew 2 (M-E)	10/16/2041	04/09/2042	175	8.985
* Launch vehicle deploys transit vehicle directly onto transfer orbit				

Table 5: Final Trajectory Selections

The final trajectories show the "Post-Launch ΔV" required for a mission. This considers any propulsive input by the transit vehicle between separation from the launch vehicle, and the beginning of the entry, descent, and landing phase. The values show considerable variation due to the different trajectory types, and the different relative importance of ΔV and TOF for crew and cargo missions.

E.2.e.ii Final Mission Sequence

Pre-arrival missions follow a stopover trajectory type, with SLS Block 2 deploying the payload and transit vehicle in a low Earth orbit. The TMI maneuver is performed, placing the vehicle on a transfer orbit to Mars. When arriving at Mars, the vehicle performs its MOI maneuver to circularize into an areostationary orbit in order to deploy communication support satellites. From here, the remaining payload descends to the landing site on the surface of Mars. Pre-arrival missions depart on April 17, 2033 and April 28, 2033, allowing 11 days between launches. Mars arrival dates will be November 8, 2033 and October 15, 2033 for these missions, and will require between 6.0-6.4 km/s of ΔV after launch.

Crew missions also follow a stopover trajectory type. Prior to astronauts launching, the MTV is assembled in a low Earth orbit. Once assembled, crew launches via SLS and docks with the MTV in LEO. The TMI maneuver is performed and the MTV transits to Mars. Upon arrival the MOI maneuver is performed to circularize into an areostationary orbit. The MTV remains in the areostationary orbit to provide primary communications during the crewed surface stay. The crew descends to the surface from the areostationary orbit via the attached lander. Crewed missions fly outbound on July 27, 2035, and September 20, 2037. For astronaut health and physiology, the corresponding transit times are 125 and 145 days, requiring between 7.5-8.3 km/s of ΔV.

Resupply missions utilize a semidirect transfer, using a parking orbit only at Mars. The 5,000 kg payload can be placed directly onto a Mars transfer orbit via the Falcon Heavy launch vehicle. No TMI maneuver is considered for these missions, as the ΔV is provided by the launch vehicle. Upon arrival at Mars, the vehicle performs a TMI maneuver to enter a low Mars orbit, prior to descending to the landing site on the surface. Resupply missions depart on September 2, 2037 and September 10, 2039, and require significantly less ΔV due to the lack of a TMI maneuver.

Crew return missions also follow a stopover trajectory. Astronauts will depart the Martian surface using the MAV, and rendezvous with the MTV in areostationary orbit. From there, a TEI maneuver is conducted, setting the MTV's course for a return to Earth. Upon arrival, the MTV captures into a low Earth orbit, followed by crew descent to Earth's surface. Crew return missions depart Mars on September 16, 2039 and October 16, 2041.

The selected trajectories yield a total mission duration of 4 years, 7 months and 1 day for crew 1, which is separated into 3 years, 9 months, 18 days of time of the surface of Mars and 9 months, 16 days of interplanetary transit time. Crew 2 has a slightly shorter mission duration of 4 years, 6 months and 20 days, with 3 years, 8 months, 4 days of time on Mars and 10 months, 15 days of interplanetary transit time. Since Crew 2 arrives at Mars prior to Crew 1's departure from Mars, there is a 1 year, 7 month overlap where both crews occupy the surface. Accounting for this overlap, our effective Martian surface occupancy time for 4 astronauts is 7 years, 5 months and 22 days, exceeding the 7-year requirement.

E.3 Transportation Systems

E.3.a Launch Vehicles

Due to the wide range of requirements facing our mission launch systems, several systems were considered.

SLS: The newly developed SLS, intended for the Artemis series of NASA lunar missions, is a super-heavy lift launch platform first launched on November 16th, 2022. This system far exceeds our mass requirement, with nearly 9 times the required delivery capability to a Mars injection trajectory. Because of this, it is also a relatively heavy and considerably costly system.

SpaceX Falcon 9 Heavy: The Falcon 9 Heavy from SpaceX is the super-heavy lift equivalent of the Falcon 9, as it is essentially three Falcon 9 main stages coupled together to support a single payload. Because of this, the mass delivery to a Mars injection trajectory is significantly improved when compared to the standard Falcon 9 model, while remaining a similarly small and efficient system. The Falcon 9 Heavy is able to support a payload of 16.8 metric tons, allowing for an upper stage and necessary entry, descent, and landing structure to allow for 5 metric tons of cargo to be delivered to the surface [P-2]. An additional consideration for the Falcon and similar systems is the reusability. While a fully expended Falcon 9 Heavy will have a greater Mars injection capability, the ability to land the main stages for reuse has the potential to significantly lower the cost of the system.

SpaceX Starship: The SpaceX Starship promises to be the first next-generation launch vehicle offering significantly reduced launch costs as well as a significantly higher payload capacity, combined with atmospheric descent and ascent capability for both Mars and Earth. This combination of performance features promised is incredibly ambitious and could significantly alter the way space missions are planned in the future. However, the vehicle remains untested in the majority of its promised metrics, including ascent to orbit.

E.3.a.i Pre-Arrival Cargo Launches

For our pre-arrival cargo launches we have chosen to use the SLS Block 2 for our launch vehicle. The volume of the cargo module is 988 m^3 [P-3]. We will have two pre-arrival missions containing the habitat and power systems, resulting in the need for two SLS Block 2 launch vehicles.

E.3.a.ii Crewed Launches

For crewed launches, our team has chosen to use the SLS Block 2 as our launch vehicle. The goal of our crewed mission launch vehicle is to carry four astronauts from the Earth's surface to our MTV which will be orbiting in a 400 km LEO. Our goal is to do this as safely as possible, while also having a large payload capacity for all the resources our astronauts will need to reach and survive on Mars. The relatively high TRL of the SLS Block 2, at around 7, and its exceptionally high reliability, at approximately 99.7%, result in a launch vehicle that we can depend on to safely transport our astronauts to the MTV [P-3]. Additionally, the SLS Block 2's ability to carry a large payload of approximately 130 metric tons into LEO will allow us to sufficiently supply our astronauts with enough resources for their mission on Mars.

E.3.a.iii Cargo Resupply

The requirements outline that the Mars Habitation mission must resupply with no more than 5,000 kg of material no more than every 2 years.

Because of these constraints, only launch vehicles capable of delivering a 5,000 kg payload to a Mars injection orbit are considered. This standard ruled out smaller, LEO class launch vehicles such as the SpaceX Falcon 9, Russian Soyuz, ESA Atlas V, and similar vehicles which are not capable of independently delivering our intended payload. There are three primary launch vehicles currently available that have the ability to complete this task: SLS, Falcon 9 Heavy, and SpaceX Starship. All of these are fully modern devices, being designed and utilized within the last two decades. However, each was developed for a much different purpose. The capabilities of each launch vehicle are compared in Table 5 below.

All of these launch vehicles can be compared against the Falcon 9, the modern standard for launch vehicle capability. However, as the Falcon 9 does not meet the 5,000 kg payload requirement, it is not considered a viable solution.

Launch Vehicle	Mass to LEO (MT)	Mass to Mars (MT)	Cost/Mass ($M/MT)	Human Rated	Reliability	Cost per launch ($M)
Falcon 9 (expended)	22.8	4.02	1.324	Yes	0.992	67
Falcon 9 (reusable)	16.8	4	1.209	Yes	0.992	67
Falcon Heavy (expended)	63.8	16.80	2.4	Yes	0.992	97
Falcon Heavy (reusable)	57	13	1.6	Yes	0.992	97
SLS Block 2	130	46.00	22.80	Yes	0.99	4100
Starship	150	100.00	0.7	Planned	0.588	10

Table 6: Comparison of Launch Vehicle Capability

E.3.b Mars Transit Vehicle (MTV)

E.3.b.i Structural Modules

The MTV is designed with the International Space Station as reference material, since it is currently the only long-term habitable space vehicle. Each module of the ISS was analyzed and considered when designing our MTV.

The first module that will be included on the MTV is the multipurpose laboratory module-upgrade (MLM-U), which is used to conduct experiments as well as storing scientific equipment and serving as a service module. Since this mission is the first long-term manned spaceflight to another planet, many experiments will need to be conducted as this opportunity is both rare and costly. The second module is the cargo block, also known as Zarya. This module will be used to store food, water, equipment, and any other necessities required for the mission. For similar purposes as the MLM-U, the third is the research module, Destiny, as this would provide more room for the needed research equipment. The final sections of the ISS that will be added to the MTV are the expandable airlock modules and the connector nodes. These are required as the MTV will be built in sections in low Earth orbit, much like how the ISS was built. The vehicle that will be landing on the surface of Mars will need to connect to the MTV prior to Mars transit, remain connected during transit, and will act as sleeping quarters during interplanetary travel. For our mission's crewed launches, the MTV will also need to be capable of accepting the small crew capsule that our astronauts arrive in. Thus, all these modules will be serving a role on the mission to Mars.

E.3.b.ii Thermal Systems

The requirements for the thermal system for the Mars Transit Vehicle is to dissipate enough heat to avoid the overheating of the electronic systems or pressurized living areas.

The Mars Transit Vehicle, or MTV, will use a system similar to the Active Thermal Control System on the ISS. The ATCS is a two-loop, low-pressure system for dissipating heat [SE-2]. The first section is the Internal Active Thermal Control System, or IATCS. The IATCS has two independent loops, a Low-Temperature Loop and a Moderate-Temperature Loop, to pull heat from the electronic systems and transfer it to the EATCS, or External Active Thermal Control System. The EATCS uses two ammonia loops that take the heat from the internal water loops and flow through large radiator panels to radiate the heat out into space.

The ATCS on the ISS is capable of radiating 70 kW of energy out into space using 46.8 m^2 of radiators [SE-3]. Following this ratio, the radiators are able to radiate heat at about 1.5 kW per square meter. Using this ratio, the required radiator area can be calculated once the required heat rejection is calculated. The MTV will be powered by the SAFE-400 nuclear reactor, which produces 400 kW of excess heat and will be discussed more in the power systems section. Assuming that the nuclear reactors that are used for the propulsion systems produce negligible heat waste into the MTV and the electronic components produce a maximum of 100 kW of excess heat, the MTV has a total internal waste heat value of 500 kW.

Heat is also radiated into and out of the MTV from the body itself, without the radiators. This must be taken into account to ensure that the vehicle will be able to expel all excess heat including heat from external factors. To solve for the total external heat exchange, some assumptions needed to be made as there is no specified shape, surface area, or color for the MTV as it stands. It was assumed that the MTV was a sphere with the total volume of the pressurized sections to give a surface area and exposure side ratios, and that the vehicle was gray, to give an absorptivity of 0.7 and an emissivity of 0.9. The surface area was assumed to be 202 m^2 using the method described above. Other assumptions that were made were that the internal temperature of the MTV will be kept at 298 K. The average temperature of deep space is 4 K, and the average temperature of earth is 290 K. Using all of these values, an external thermal analysis can be made. The hot case for our vehicle will be in Low Earth Orbit between the Earth and the Sun. The energy radiated from the sun into the vehicle will be 48 kW, and the heat reflected off of the earth and onto the MTV will be 14 kW. Adding these values to the internal energy give a total internal energy of 562 kW. However, some of that energy is radiated out into deep space as well as some back to earth. Using the temperature differences between the vehicle and earth and the vehicle and deep space, the energy radiated out comes to 2 kW to earth and 61kW to deep space. Subtracting this energy from the total internal energy give a net excess heat value of 499 kW in the hottest possible case, as Mars is colder and further from the sun, so the external energy added will not be as high as when orbiting Earth. For the cold case, which is in transit from Earth to Mars, where no planets are close enough to reflect a non-negligible amount of heat back to the MTV. If you disregard all heat interactions with earth, the total excess heat becomes 487 kW, which is very similar to the hot case. Thus, the MTV needs to be able to radiate out 499 kW of heat through the radiators. Using the ratio calculated before, the MTV will need radiators with a total collective surface area of 333 m^2.

E.3.b.iii Propulsion Systems

The Mars Transit Vehicle will have a very large ΔV requirement–approximately 17 km/s. Additionally, the structural mass of the vehicle is higher than previous vehicles–in excess of 150,000 kg. As such, maximizing the I_{sp} of the propulsion system (subsequently minimizing the propellant requirement) will have incredibly large mass and volume savings for the entire vehicle. Traditional chemical bipropellant rocket systems optimized for vacuum use only can achieve I_{sp} values of nearly 450 s as well as incredibly high thrust outputs. Electric propulsion systems can achieve an order of magnitude better specific impulse, on the order of 2,000 s in certain cases, but generally offer thrust values of less than 1N [P-8]. There is, however, an older technology that has begun to re-emerge in the modern age of long-duration spaceflight: Nuclear Thermal Propulsion.

In Space Transit	I_{sp} Range (s)	Fuel Energy Density	Acceleration Capability	System Weight	Reliability
Solar Electric	5,000	5	1	5	0.999
RTG Electric	5,000	5	1	5	0.999
Nuclear Thermal	1,000	4	5	2	0.987
Chemical Bipropellant	350	3	5	3	0.9825
Chemical Monopropellant	200	2	5	3	0.98
Solid Rocket Motor	250	1	5	1	0.99

Table 7: Comparison of Propulsion System Performance Capabilities

Nuclear thermal propulsion systems offer an advantageous middle ground between the capabilities of chemical bipropellant and electric systems. They offer a higher thrust than electric systems, and a significantly improved I_{sp} than chemical. They also offer a few specific advantages–they are monopropellant systems, minimizing the complexity of the fueling and valving systems, and they can utilize multiple fuel types, increasing mission flexibility.

Nuclear thermal propulsion systems also have key disadvantages. They have very low thrust-weight ratios, making them particularly unsuitable for launch vehicle use where peak thrust and inert mass efficiency are critical. For a space-based system, the mass of the propulsion system is a small fraction of the overall mass and thrust/burn time is not quite as significant.

One other key consideration is the TRL of this technology. In the modern area, nuclear thermal propulsion systems are nearly non-existent prior to the year 2020. Many academic papers exist, but very few physical experiments have been documented. Nuclear thermal technology experienced rapid advancement in the

1960s and 1960s, with NASA's NERVA program—even testing full-scale prototypes in simulated environments. Recently, this technology has been revived in Project Draco, a collaboration between DARPA and NASA with the specific intention of developing a nuclear-thermal rocket propulsion system for Lunar and Martian transit missions [P-13].

E.3.b.iv Propellant Requirement

The significant advantage of utilizing nuclear thermal rocket technology is the high I_{sp}. Because of this design feature, our MTV requires significantly less propellant mass to achieve the same vehicle ΔV capability than if it utilized a traditional chemical bipropellant engine. It was decided by our team to utilize this advantage in order to achieve a low structural mass and low propellant requirement, however, it could also be used to allow the MTV to achieve much higher ΔV figures and significantly reduce transit time to and from Martian orbit.

The MTV's propellant requirement was estimated using a numerical approximation method coded into MATLAB. This method took the estimated structural mass from the required MTV pressurized sections, thermal system, power system, scientific equipment, as well as resources such as food, water, and oxygen. The below table includes the sizing estimates for the MTV structure, using the ISS as an analogue system. The necessary MTV structures were compared to their similar system on the ISS, with the mass and internal volume used as references. Accessory systems such as power generation, and consumable items like food mass are also included, but have no contribution to system internal volume.

Module	Mass (kg)	Internal Volume (m^3)
Multipurpose Laboratory	20,357	80.9
Cargo Block	19,323	40.54
Research Module	14,515	104.77
Expandable Airlock Module	1,413	16
Connector Node	11,612	19.63
CNTR Engine	1,500	N/A
Food Mass	32,000	N/A
Water Mass	60,800	N/A
Power System Mass (SAFE-400 100kWe Reactor)	512	N/A
Thermal System Mass	1,750	N/A
Total Estimates	150,420	261.85

Table 8: Mass and Internal Volume of ISS Analog Components of the MTV

Using the ISS as a heavy analog, we determined a structural mass of 150,420 kg was reasonable and utilized that as the necessary payload for the propellant mass calculations.

The numerical method utilized is similar to an Euler Method applied to the rocket impulse equation.

$$m_p = \frac{I}{I_{sp} \cdot g}$$

m_p	Propellant Mass
I_{sp}	Specific Impulse
I	Impulse

g	Gravitational Constant (Earth)

Equation 1: Impulse Burn Propellant Mass

The total mission was divided into a series of four maneuvers, one for leaving Earth, entering Mars orbit, departing Mars, and entering Earth orbit. For each of these maneuvers, the required impulse was divided into a series of timesteps, for which the required propellant mass was calculated and added to the inert mass for the next time step. This is similar method that approximates a finite series of infinitely-small burns. The algorithm exhibited convergence to 1% for cases between 1,000 and 10,000 iterations, suggesting method robustness. Utilizing this method with the maneuver requirements, multiple fuel types, and nuclear thermal rocket system performance, and propellant masses are given in Table 9 below.

I_{sp} (LH2)	1800 s
I_{sp} (Ammonia)	900 s
ΔV	17k m/s
m_{pl}	15420 kg
m_p LH2	249200 kg
m_p Ammonia	678500 kg

Table 9: MTV Propulsion System Specifications

E.3.b.v Power Systems

The MTV will be powered by a single SAFE-400 nuclear reactor. Our MTV is estimated to require 86 kW of electrical energy, with a 15% margin, resulting in a maximum required power output of 98.9 kW. The SAFE-400 reactor outputs approximately 100 kW of electrical power and another 400 kW of thermal power. This power output is larger than that of a small modular reactor, but smaller than a typical nuclear reactor, and lies in an ideal range given our current power needs. Given the amount of research and testing the SAFE-400 reactor has received to this point, we have decided that it sits at approximately a TRL of 5. Some additional benefits of the SAFE-400 reactor is its extraordinarily small mass and volume. This reactor outcompeted all others that we had researched with a mass of only 541 kg and a volume of 10 m^3. Finally, the SAFE-400's cost to manufacture is currently unknown, however basing this cost on the program cost, we estimate a single reactor to be priced at approximately $500 million.

In addition to our nuclear reactor, the MTV will also require a power storage system. For this, our team has decided to use lithium-ion batteries. More specifically, we will be using a set of lithium nickel cobalt aluminum oxide (LNCAO) batteries for standard power storage, and more importantly emergency power storage. These battery systems were commercialized in 1999 and use a graphite anode with a LNCAO cathode. Additionally, these batteries are rechargeable, have a shelf life of longer than 10 years, and operate at low-voltage. What sets this battery apart from all others is its large energy density at 220 Wh/kg. Sizing the battery system to operate at 100 kWe for 12 hours, or in other words 1,200 kWh, we can expect a power storage system with a mass of 10909 kg and a volume of 267.54 m^3. Lastly, comparing our battery system to that of the ISS, we approximated that this battery system will cost $158.4 million.

E.3.b.vi Radiation Shielding

The space environment has two primary types of radiation from which to guard against: Galactic Cosmic Rays (GCRs) and Solar Energetic Particles (SEPs).

GCR radiation is the ever-present cosmic background radiation in space, generally within the high frequency range of the electromagnetic spectrum and at energy levels of up to 150 MeV [SE-5]. They are blocked by high density materials, but have a tendency to propagate through thick, low-density materials.

SEPs are high-energy atomic nuclei released from the sun during coronal mass ejections, otherwise known as Solar Particle Events. These high-energy particles span from alpha particles to fully ionized uranium atoms traveling at significant fractions of the speed of light, with the corresponding range of energy levels. SEPs are blocked well by both high-density materials as well as large thicknesses of low-density materials, and do not propagate through non-optimal thickness [SE-5].

Traditional radiation shielding materials, such as lead and concrete, are incredibly dense. While these two materials are very good shields, this property makes them particularly unsuitable for aerospace applications. In order to choose an aerospace-suitable shielding material, evaluation of individual attenuation coefficients of materials is required [SE-4]. These attenuation coefficients are calculated using Equation 2 below.

$$\sigma_{overall} = \rho \cdot \frac{z^2}{a}$$

σ	Shielding Coefficient
ρ	Density
z	Attenuation Coefficient
a	Atomic Number

Equation 2: Radiation Attenuation Coefficient

Minimizing this value will minimize the areal mass density required to create an effective shield. Materials with high atomic numbers and low densities will be selected, allowing for a material with a high probability of effectively blocking SEPs without creating undue propagating radiation due to GCRs.

The values of density, attenuation constant, and atomic number can all be found in tables from the National Institute of Standards Technology (NIST), and the evaluation of many potential materials can be easily performed.

Radiation Shielding Material	**Z/A**	**Z^2/A**	**Density * (Z/A)**	**Density * (Z^2/A)**
Tungsten	0.4026	29.79	7.75	573.52
Tantalum	0.4034	29.45	6.73	491.55
Lead	0.3957	32.45	4.49	368.00
Gadolinium	0.4069	26.05	3.22	205.78
Aluminum Oxide	0.4904	4.90	1.94	19.37
Diamond	0.5	3.00	1.75	10.50

Aluminum	0.4818	6.26	1.30	16.91
Boron Carbide	0.4705	2.45	1.19	6.17
Sucrose	0.5315	2.15	0.85	3.41
Phenolic Novolac	0.5528	1.74	0.75	2.36
Graphite	0.5	3.00	1.08	6.45
Glycerol	0.5433	1.94	0.68	2.44
Aramid Fiber	0.5211	2.31	0.75	3.32
Lithium Oxide	0.467	2.18	0.94	4.38
PEEK	0.5206	2.30	0.69	3.03
Polycarbonate	1	4.06	1.21	4.91
Water	0.555	1.85	0.56	1.85
HDPE	1	2.67	0.97	2.59
Liquid Hydrogen	1	1.00	0.71	0.71
Lithium Nitride	1	4.00	1.27	5.08

Table 10: Material Attenuation Coefficients

From Table 10 above, we can see that Carbon-Carbon Phenolic Novolac has a minimized attenuation coefficient compared to the majority of the materials evaluated. There are materials with lower shielding coefficients–namely water and liquid hydrogen–but these materials require additional structural mass to make them effective, decreasing their utility when compared to a durable, solid material.

The maximum lifetime dose of astronauts is 1Sv, or 1000 mSv [SE-6]. The duration of the mission on the MTV will be where the most radiation exposure occurs, and subsequently where shielding is the most important.

This material was evaluated using NASA's OLTARIS (On-Line Tool for the Assessment of Radiation In Space) toolbox. In order to evaluate the effectiveness of the shielding material itself, the MTV was approximated to be a sphere with a 5cm aluminum pressure vessel, followed by the phenolic novolac on the exterior with varying thicknesses. The radiation exposure was then split into GCR and SEP scenarios, evaluated over an expected travel interval of 360 days (for transit both two and from) at approximately one half the distance between Earth and Mars. The SEP calculations were evaluated for single events, so the calculated values were then multiplied by the average number of solar particle events within the given time window. The analysis of increasing phenolic thickness is shown in the figure below:

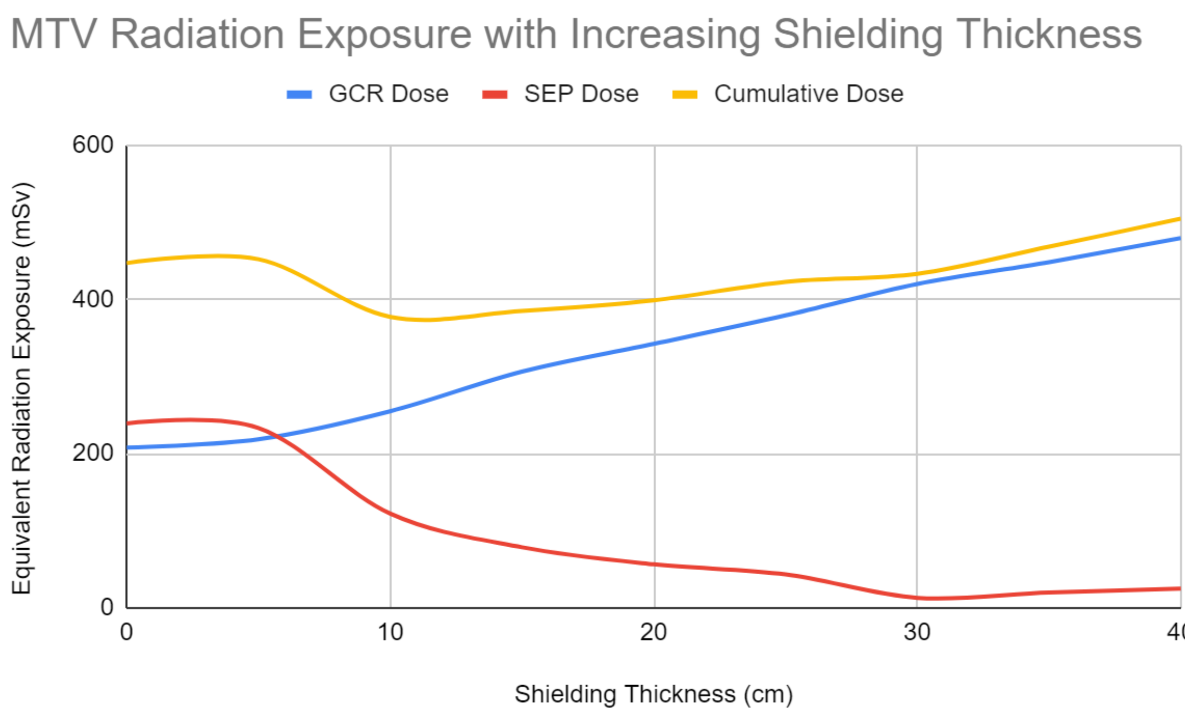


Figure 11: MTV Radiation Shielding Analysis

As shown in the figure, SEP equivalent dose decreases significantly with the first 10 cm of shielding, while significantly more shielding is needed to block the highest energy particles. GCR dose, however, has a local minimum at roughly 10cm of shielding thickness before electromagnetic propagation begins to worsen and overwhelm the shielding effect.

The cumulative dose with 10 cm of shielding across a 360-day mission (representing transit to and from Mars) was estimated at 377 mSv.

E.3.c Entry-Descent-Landing (EDL) Vehicle

E.3.c.i Method Chosen

Entry, descent, and landing to the Mars surface present a number of challenges, including surviving max heating, landing sufficient mass, and accuracy of landing location. To address these challenges, a variety of EDL methods were explored to determine the optimal method. The methods explored were aerobraking, parachutes and supersonic inflatables, retro propulsive, and combinations of methods. Firstly, valid landing methods had to be determined. For example, the inflatable ball style landing used by the Spirit and Opportunity rovers was deemed infeasible for crewed landings, due to excessive landing forces and low accuracy. To ensure an accurate and low velocity landing, only methods that used retro propulsion on final approach were selected, as this method provides sufficient control of landing location and speed. From this determination, four valid EDL architectures were selected for further analysis: using all three methods in tandem, aerobraking and propulsive, parachutes/inflatables and propulsive, and all propulsive. After analysis, the aerobraking and propulsive landing combination was chosen. This method keeps mass at a minimum, while utilizing high design heritage methods to ensure a safe and accurate landing. The parameters for the selected EDL method are summarized in the table below:

Parameter	Value
Cost / Payload Mass	$40,010,422.09
TRL	9
Payload Mass / Gross Mass	36.66%

Table 11: EDL Method Parameters

E.3.c.ii Sequence Diagram

The entry, descent and landing process consists of three phases once separation from the MTV occurs in the areostationary orbit. The first phase is entry hypersonic aero maneuvering, which takes place for about three minutes. The lander enters the Martian atmosphere in a manner similar to that adopted by rover landings in the past. During this phase, it undergoes peak heating and a deceleration of about 6g. Soon after, the vehicle transitions to a zero angle of attack alignment in preparation for the second phase, which is the supersonic retro-propulsion (SRP) phase of the descent. This occurs typically at a Mach of about 3.6 and at an altitude of 3 km above the ground. During this phase, the heatshield is jettisoned to reduce mass and to facilitate the deployment of the landing gear during the third and final phase. The constant velocity powered descent is the final phase of the entry, descent, and landing sequence. This occurs after 43 seconds of burn time for the SRP phase. This phase kicks in at an altitude of 40m and lasts for less than 60 seconds. Thrust is terminated in this phase bringing the final touchdown speed to under 5 m/s. The landing gear would have telescoping tubular legs which would provide large ground clearance by deploying footpads to a distance of 2 m below the bottom of the lander vehicle. To blow any debris away from the lander, the engines are gimbaled out to a large angle. Doing so also provides a clear downward field of view for terminal guidance sensors [ADC-1]. An outline of the entry, descent and landing process can be seen in figure 11.

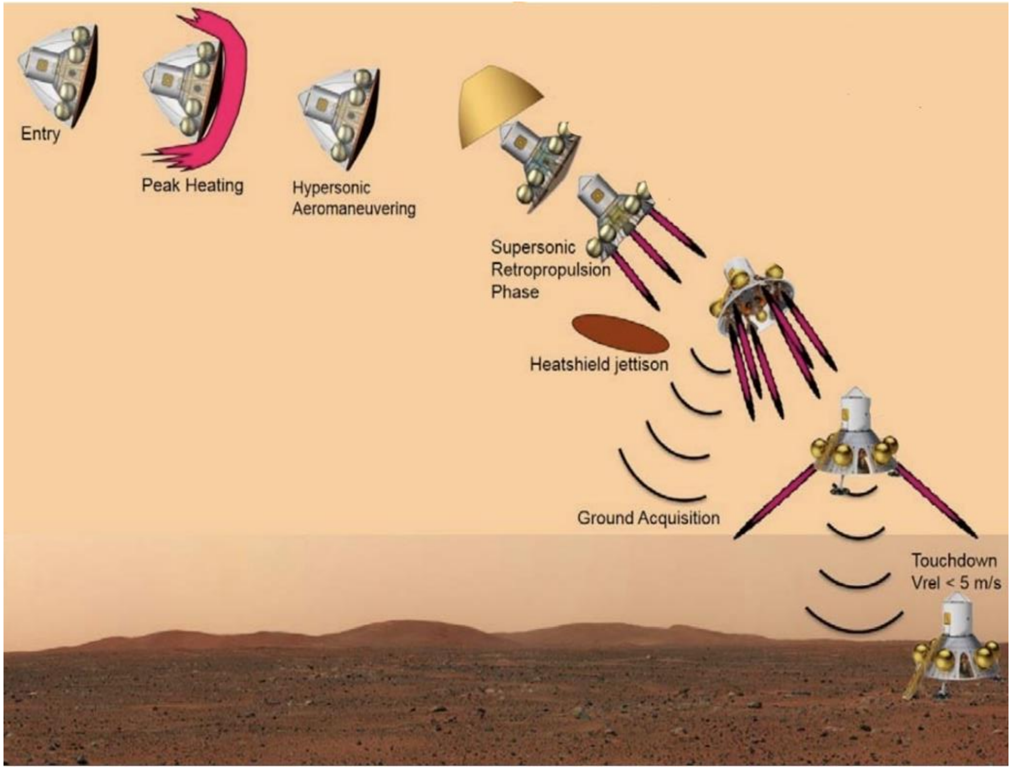


Figure 12: EDL Sequence Diagram

E.3.d Mars Ascent Vehicle (MAV)

E.3.d.i Mars Ascent Sequence

Our mission requirements state that the crew must be able to evacuate at any time during the mission in case of an emergency. This means that by the time the first crew lands the MAV will already be set up and fueled, having arrived with pre-arrival cargo missions occurring two years before crewed landing. Some of the problems associated with keeping a launch vehicle ready throughout the mission are maintenance issues, liquid oxygen boiloff and physical damage to the vehicle. Scheduled checks of the MAV by the crew during the mission should deal with most of these challenges. The issue of oxygen boiloff is discussed in the Propellant Storage section.

E.3.d.ii Final Design

MAV Sizing: Our analysis only involves an initial sizing estimate for the MAV. This is because most existing designs are single stage rockets capable to launch to a Low Mars Orbit only, and since our crew needs to rendezvous with the MTV in the Areostationary orbit we had to perform sizing calculations for a different vehicle to be built in the near future. The MAV sizing was done with the help of a number of optimization simulations done by NASA[ADC-4]. Using the results of these simulations, we performed an FOA to compare the merits of various sizing combinations and came up with the ones that best fit our mission. The main parameters that influenced our decision were vehicle wet mass, propellant mass, cost, TRL and the ability to launch to 1 sol orbit. The oxidizer chosen is liquid oxygen since it can be produced on the Martian surface using ISRU, and the fuel chosen is RP-1. The main advantage of using RP-1 over liquid methane is that RP-1 is stable at room temperature. The estimated masses of the different parts of the MAV are listed in table 12.

Vehicle Gross Mass	26,000 kg
Cabin Mass	3,000 kg
LOX Mass	13,320.93 kg
RP-1 Mass	5,084.32 kg
Total Propellant Mass	18,405.25 kg
Weight on Mars	97,000 N

Table 12: MAV Sizing

Since the oxidizer will be produced on Mars, 2 MAVs and the fuel required for launch will be sent with the pre-arrival mission. This will make up roughly 26 metric tons of mass.

The design of the cabin is very crucial. It should be able to support a crew of 4 astronauts for at least 3 days, in case there is a failed launch, and a rover needs to rescue the crew stranded at some distance from the base. [Insert citation] discusses this in detail and came up with a cabin design of roughly 3,300 kg, which can be cut down to accommodate our sizing estimates.

Engine Selection: The engine we chose for this MAV is the Launcher Engine-2 [ADC-5] produced by Launcher Space. The engine is in an advanced stage in its development and provides a thrust of 98,000 N with a vacuum I_{sp} of 365 s. We decided to use 3 engines in the first stage to allow for increased controllability and redundance, and 1 engine in the second stage. The specifications of the engine are listed in table y.

Launcher Engine-2 Specifications	
Thrust	97,800 N
Propellant	LOX/RP-1
Cycle	Staged combustion
Specific Impulse	365 s (vac)
Mixture Ratio	2.62
First Stage Engines	3
Second Stage Engines	1

Table 13: Engine-2 Specifications

E.3.d.iii ISRU Production

A key mission requirement is that the Mars Ascent Vehicle is always capable of launch when the crew is on the Martian surface. As a consequence of this requirement, all the RP-1 required will be sent as part of the pre-arrival mission along with the 2 MAVs for each of the crews. On the other hand, the oxidizer required for the MAVs will be produced on Mars using ISRU technology to cut down the required payload mass. To produce the liquid oxidizer required for the return missions, a scaled-up version of the MOXIE (Mars Oxygen ISRU Experiment), also known as BOXIE will be used. This system would produce about 2000-3000 g/hour of liquid oxygen, which would be pumped directly into the MAVs propellant tanks [ADC-3]. Since the required production rate for each MAV is about 1000 g/hour, this system fulfills the mission requirements. Two BOXIEs will be sent as part of the pre-arrival mission to aid oxidizer production for each of the MAVs. The production process is expected to start as soon as the autonomous set-up of the system occurs.

E.3.d.iv Propellant Storage

Storing propellants for long periods of time presents numerous challenges, the primary of which is boiloff. RP-1 was selected due to its stability in long term storage, and thus does not require a detailed storage plan. LOX, due to its low storage temperature of -90° C, requires a boiloff mitigation strategy. Both active and passive methods of cooling were explored to reduce the boiloff experienced over the mission lifetime. As LOX is being created on Mars, only storage on the Martian surface was explored.

Active cooling consists of using refrigerants to maintain LOX at the low temperature it needs to be at to avoid boiloff. However, this method requires both significant power and an extensive cooling system. While future methods may enable cooling with less power and equipment mass required, current active cooling was deemed infeasible for use on Mars, due to its power and mass requirements. Should advances be made in the field of active cooling resulting in less massive and energy intensive cooling methods, an active cooling system would provide the most effective method of avoiding boiloff.

Passive cooling does not allow for an avoidance of boiloff altogether, thus a mitigation plan was developed to ensure the MAV is always fueled. Firstly, multi-layer insulation, or MLI, was selected for use on the LOX tanks. MLI reduces the heat exchange with the environment, reducing boil off rate, at the cost of adding mass to the MAV. Using an initial estimate of tank size based on propellant requirements, a modified Lockheed model [ADC-2] was used to determine expected boiloff over a thirty-day period, resulting in an expected loss of 34.66 kg/30 days. This mass of LOX was then used to determine a LOX margin, additional LOX that will be created in addition to the LOX mass required for launch, to ensure that boiloff will not reduce the LOX mass below required levels at any time. A 90-day LOX margin of 102.45 kg, with a refuel every 30 days, was selected. Should any delays occur with LOX top-off, 90 days provides a sufficient safety net to troubleshoot the problem, or decide on a mission abort, while sufficient LOX remains This is especially relevant as an issue with the LOX refueling may not be discovered until the 30-day refuel schedule has passed, resulting in a reduced timeframe to either solve the issue or abort.

E.4 Surface Systems

E.4.a Habitat System

E.4.a.i Habitat Thermal System

The thermal system for the habitat will be slightly different from the thermal system on the Mars Transit Vehicle. Since Mars has an atmosphere as well as the surface which acts as a heat sink, there is more heat loss on the habitat, and more efficient ways to radiate heat out as well as bring heat into the habitat.

The habitat will be covered by regolith bricks to protect from radiation, but the Mars regolith also has a thermal conductivity of roughly 1 W/(m*K), estimated by comparing the surface of Mars to clay. This means that all the surface area of the habitat will be drawing heat out. Using the equation:

$$Q = (K * A * (T2 - T1))/L$$

With K = 1 W/(m*K), the area A = 1042 m^2 calculated from the CAD model of the habitat, T_2 being 298 K for the living area, and T_1 = 192 K which is the temperature of the atmosphere of Mars, and the thickness L = 1 m for the layer of regolith bricks, the calculated heat loss is 241.5 kW of heat [SS-1, SS-2].

The habitat will be using two SAFE-400 reactors to power the habitat, which each generate 400 kW of excess heat. The total heat is 800 kW, and accounting for the heat loss through the walls of the habitat, there is an excess heat value of 558.5 kW of heat. Assuming that the electrical components and astronauts produce a negligible amount of heat, the habitat still needs to expel a large amount of heat. The easiest way to solve this issue is to use reversible heat pumps to transport heat out into the Martian atmosphere or Martian regolith at a much higher rate than the passive heat loss through the surface area.

E.4.a.ii Power Systems Selection

When selecting our power generation system for this mission, our team used a FOA to narrow down and finalize our decision on what system best suited our needs. In our selection process, we considered solar panels, wind turbines, RTGs, microreactors, small modular reactors, and two small nuclear reactors. During our selection process, we found solar panels, wind turbines, RTGs, and microreactors to be infeasible for our mission. With solar panels and wind turbines, the need for maintenance by our astronauts, as well as the large mass and volume of each, resulted in our decision to not use these systems for our mission [SS-3-11]. For RTGs and microreactors, we found the unreasonably large number of each system that would be required to power our structures to be infeasible [SS-12-18]. The remaining systems included small modular reactors, the SP-100 nuclear reactor, and the SAFE-400 nuclear reactor. We decided to not use small modular reactors, similar to our reason for not using the RTGs or microreactors, due to the number of reactors required. While still significantly less in number of systems required, using a large number of these reactors increased risks related to these reactors and led to mass and volume costs that were far larger than the two nuclear reactors [SS-19-22]. Finally, when comparing the SP-100 reactor to the SAFE-400 reactor, the SAFE-400 reactor won out due to its lower mass, volume, and cost requirements in comparison to the SP-100 reactor. Additionally, both of these reactors benefitted from the ability to support 100kW of electrical power with only a single reactor [SS-23-26].

Power Generation	TRL	Mass (Kilograms)	Volume (Cubic Meters)	Cost (Millions USD)	Maintenance (Y/N)	Final Score
Solar Panels	0.18	0.07	0.24	0.00	0.50	-5.32
Wind Turbines	0.10	0.79	0.52	0.00	0.50	-11.57
RTGs	0.18	0.05	0.10	0.92	0.00	-0.67
Microreactors	0.18	0.08	0.00	0.07	0.00	0.27
Small Modular Reactors	0.14	0.02	0.10	0.00	0.00	0.27
SP-100	0.12	0.01	0.03	0.01	0.00	0.45
SAFE-400	0.12	0.00	0.01	0.00	0.00	0.57

Table 14: Power Generation FOA

When selecting our power storage system, we first looked at which battery composition had the greatest energy density. This would minimize the mass of our power storage system and therefore minimize costs. In doing this, we found that lithium-ion batteries best fit our mission needs [SS-27]. Following this, we found which lithium-ion battery could best accomplish our mission goal, resulting in our decision to use lithium nickel cobalt aluminum oxide (LNCAO) batteries [SS-28, SS-29]. Lastly, we chose to base our power storage system sizing on 2,400 kWh of energy, therefore giving our astronauts on Mars a minimum of 24 hours of emergency power [SS-30, SS-31].

E.4.a.iii Habitat Power Systems

The habitat will be powered by two SAFE-400 nuclear reactors. Our habitat is estimated to require 85.046 kW of electrical energy, with a 15% margin, resulting in a maximum required power output of 97.803 kW. The SAFE-400 reactors will output approximately 200 kW of electrical power and another 800 kW of thermal power. This power output is larger than that of a small modular reactor, but smaller than a typical nuclear reactor, and lies in the ideal range given our current power needs. Given the amount of research and testing the SAFE-400 reactor has received to this point, we have decided that it sits at approximately a TRL of 5. Some additional benefits of the SAFE-400 reactor are its extraordinarily small mass and volume. This reactor outcompeted all others that we had researched, requiring a mass of only 1,082 kg and a volume of 20 m^3 for our entire system. Finally, the SAFE-400's cost to manufacture is currently unknown, however basing this cost on the program cost, we estimate the two reactors to be priced at approximately $1 billion.

In addition to our nuclear reactor, the habitat will also require a power storage system. For this, our team has decided to use lithium-ion batteries. More specifically, we will be using a set of lithium nickel cobalt aluminum oxide (LNCAO) batteries for standard power storage, and more importantly emergency power storage. These battery systems were commercialized in 1999 and use a graphite anode with a LNCAO cathode. Additionally, these batteries are rechargeable, have a shelf life of longer than 10 years, and operate at low voltage. Most importantly, LNCAO batteries have 220 Wh/kg of energy density–the largest of any commercialized lithium-ion batteries. Sizing the battery system to operate at 100 kWe for 24 hours (2,400 kWh), we can expect a power storage system with a mass of 21,818 kg and a volume of 535.08 m^3.

Lastly, comparing our battery system to that of the ISS, we approximated that this battery system will cost $316.8 million.

E.4.a.iv Habitat Design Considerations

To conduct a first order analysis of habitat options, figures of merit were created to guide key considerations that the team would make. These considerations are laid out in Table 15 below.

Factors	Rank	Scale	Weight
Radiation Protection	1	1 to 4	8
Payload Mass (kg)	2	1 to 5	7
Volume Ratio (payload volume / Mars volume)	3	0 to 1	6
TRL	4	1 to 9	5
Insulation	5	-5 to 5	4
Total Cost	5	1 to 5	4
Debris Protection	6	0 to 10	3
Cost of Maintenance	7	-5 to 5	2
Disturb Mars	8	1 to 5	1

Table 15: Habitat Figures of Merit

To develop our figures of merit, we began by listing all major factors that could influence our choice of habitat. Following this, we ranked each of these factors based on importance to our mission and created weights for our FOA accordingly. Additionally, we created a scale that we could rate each habitat design on for each factor, therefore allowing for comparison between our options. It is noteworthy that radiation protection and payload mass were among the most important considerations in our design. We placed great importance on radiation protection as this directly relates to the health of our astronauts and therefore the success of our mission. The payload mass of the Martian habitat was viewed as being of similar importance as it is extremely costly to put a large amount of mass on the surface of Mars. The other factors listed and analyzed include the volume ratio (i.e., the volume of the payload on the launch vehicle per the volume it occupies on Mars), TRL, thermal insulation, total cost, protection against debris, cost of maintenance, and the environmental impact of each habitat on the Martian environment.

E.4.a.v Designs Analysis

The team considered a few different types of Mars habitats including subterranean, inflatable modules, a rigid structure, and the lander's crew module. In addition to this, we also analyzed the use of regolith bricks for radiation protection with these habitats and determined whether astronauts or robots would set up our habitat. Beyond this, the group also considered combinations of these options in order to find the most optimal habitat for our mission. Inspiration for our habitat was taken from previous studies and missions, as well as future mission plans.

First, the lava tubes on Mars showed great potential when considering a subterranean design for our habitat. Advantages of a subterranean option include protection from ionizing and ultraviolet radiation, insulation from thermal oscillations, protection from debris, and direct access to potentially important subsurface resources. In the case of storage and investigation, caves without natural openings are preferred due to a better preservation of their contents. For human use, caves must be easily accessible, shallow, and relatively flat. The TRL for required technologies, like inert gas pressurization and oxygen systems, is relatively low for subterranean habitats. For instance, inflatable cave liners with sensing and regulating properties have a TRL of 4 and therefore a subterranean habitat is inherently riskier than some of our other options. Another major challenge with this habitat style is the provision of light for both human and photosynthetic use, such as for life support-related plants. Many of the lighting and heating needs for a cave-based habitat could be provided by recent developments in light-mining and light-piping techniques. Cave airlocks would require shape-conforming to highly irregular openings, easy deployment, insulation, low thermal expansion, ease of use by astronauts in space suits, a leak-tight seal, robust performance under dusty, cold, and ultradry conditions. In addition to this, the habitat would also need to be foamed in place rigid, have a standardized airlock door, and have a frame assembly. The cave sites would also need to be mapped and the conditions inside investigated prior to creating a shelter. Utilizing caves as the habitat also poses a risk of contaminating biological sites [SS-32].

Moving on to utilizing an inflatable habitat, our team investigated the viability of designing a habitat with multiple interconnected modules. In terms of the history of this technology, there were plans to deploy an inflatable module to the ISS that was capable of withstanding complete vacuum and orbital debris associated with low Earth orbit. Therefore, we can be confident that the technology required for inflatable habitats is ready for space applications. One major advantage of inflatable habitats is that they take up far less volume and mass on launch compared to fixed structures. Bigelow Aerospace created a functional inflatable habitat design; however, it was never tested in space [SS-33]. Inflatable habitats can also be much easier and faster to set up than traditional fixed structures as at minimum they only require air to become functional. In the 1960s, Project Echo tested the use of inflatable balloons and the Soviets conducted inflatable airlock tests in their Voskhod 2 project [SS-34, SS-35]. Inflatable airbags have been used on previous Mars landings and show how well these inflatables can hold up under extreme conditions structurally, such as crashing into the Martian surface and rolling for miles [SS-34]. Construction for these inflatables requires highly durable materials, such as Kevlar or mylar around a common air bladder. The pros and cons of this habitat are detailed below.

Clear benefits of using the inflatable habitat include it having potentially higher resistance to debris than aluminum, being lighter than other options, taking up less volume in the payload fairings, having moderate radiation shielding, and a higher TRL of 7. The downside of this technology is the need for more testing and design work as compared to other habitat options.

Opposing inflatables is the utilization of rigid structures on the surface of Mars. Modular structures could be manufactured out of aluminum and have radiation shielding plus an interior air bladder for protection against the Martian atmosphere. These structures could be modified far easier than an inflatable habitat. Rigid structures will likely take up more mass and payload volume on launch but tend to be more reliable than inflatable modules [SS-36]. To solve the mass and volume on launch issue, 3D printing a rigid habitat has been considered as an option. Companies like AI Space Factory are looking into pursuing this option. 3D printing has the benefit of being lighter and taking up less volume than a typical rigid structure but may be the most challenging option to perform due to variations in 3D printing in an adverse environment [SS-37]. What has worked and what has not worked in regard to rigid structures can be extrapolated from the lunar module. In zero g, or ⅓ g on Mars, less space is needed than what is required on Earth due to ease of maneuverability [SS-38].

Using the crew module within our lander as the habitat is another consideration that our team has investigated. One practical example of this is the Artemis missions. For the first few Artemis missions, the landing system will also be where the astronauts lodge, with a fixed habitat in the future of the mission [SS-39]. The fixed habitat will consist of a stationary habitat, a camper van for long trips, and a vehicle for short trips, but for 30 days, half the crew will be staying in the logistics lander [SS-40]. This logistics lander is a European moon lander named EL3 with a mass of 8,500 kg, diameter of 4.5 m, and a height of up to 6 m. It is supposed to allow astronauts to survive a lunar night, which is 14 Earth days [SS-41]. The lander will detach from the orbiter before traveling to the moon's surface [SS-42]. The TRL for using the crew module as the habitat is level 8.

A consideration for the material of the habitat, rather than the structure itself, is using regolith bricks to cover the building, which has a TRL of 5. Radiation shielding material can be produced using Martian regolith and thirteen hydrogen-rich polymers. The combination of these materials can be molded into bricks and built into structural units, which protect humans, electronics, and other materials from the radiation in space. There was an experiment on Earth that created bricks with an individual mass of 20 g composed of either 10% polymer or 20% polymer with the remaining contents consisting of the Mojave Mars Regolith Simulant. To prepare these bricks, four methods were considered. The first is to put these bricks in a vacuum oven and heat press them using a steel mold, which is easy to assemble and can withstand high temperatures. It is better to use a mold made of TEFLON because it requires no glue or posts and shows no signs of mechanical failure. The second method is using the mold in a heated hydraulic press. The third method is to place the mold in a CO2-filled airlock to microwave. The final method is to use a vacuum oven under low CO2 pressure that uses a CO2 pump to breathe to create regolith bricks. Comparing these options, the heated hydraulic press generates the most durable and clean specimens, while the vacuum oven and microwave produces bricks that are sometimes rough around the edges, more likely to crumble, and uneven. The bricks produced by the heated hydraulic press are the strongest. However, due to the weight limitations aboard a spacecraft, the heated press is the least viable option. Both the vacuum oven and microwave are suitable, low-energy mechanisms that form bricks which hold together and perform well during flexural tests [SS-43].

The next thing to be considered is whether astronauts or robots will set up our habitat. There have been design challenges and simulations previously posed that used robots to set up a Martian habitat, meaning that this robot utilization has a TRL of 6. In 2018, there was a design challenge that considered robots going to Mars first to collect Martian materials to make "Martian concrete" for a habitat. 3D printers would use the concrete and other materials to make the habitat [SS-44]. In NASA's Mars simulation, they used a 518.2 m^2 3D printed module that has separate areas for living and working [SS-45, SS-46]. The company that produced this simulation, ICON, has previously 3D printed a neighborhood in Texas [SS-47]. In this simulation habitat, each astronaut gets a room and there are 2 full bathrooms. It gathered inspiration from the ISS, submarines, and Antarctic research stations. The simulation contains an indoor aquaponic vegetable nursery, a gym, a treatment room, workspaces, and lounge space [SS-47]. Meanwhile in the Netherlands, TU Delft has studied robots building underground habitats by utilizing inflatable structures put in holes dug by robots [SS-48]. 3D printing prevents the need for launching heavy building materials, as mentioned before [SS-46].

For the laboratory needs, rovers could provide insight into standard equipment needed for lab setups. The Mars Color Imager (MARCI), Mars Climate Sounder (MCS), High Resolution Imaging Science Experiment (HiRISE), Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), Context Imager (CTX), and Shallow (Subsurface) Radar (SHARAD) are all scientific equipment that need to be considered [SS-49]. It would be beneficial to have a lab that could directly interface with crewed and uncrewed rovers for ease of access. It may also be beneficial to have a lab that can be depressurized to be able to conduct experiments in the Martian atmosphere without being exposed directly to the radiation and debris. Aside from containing instruments for science, the lab also needs to contain instruments for maintenance and repair on the habitat itself [SS-50]. The lab could also include some experimental methods for things like oxygen generation, CO2 scrubbing, and power generation to be used on future human missions. The laboratory module would likely be a "low risk" structure and not something experimental so that necessary functions would not be interrupted [SS-51].

As for the agricultural set up, the NASA Veggie project is a prime example. Veggie utilizes passive wicking to provide water to the plants as they grow. Seeds are glued into plant pillows, which are Teflon-coated black Kevlar with a Nomex bottom, which contains the growth media-controlled release fertilizer and water. Water is injected into the plant pillow, then water is injected into the root mat. The wicks carry the water to the seeds, which are glued in, and the combination of water and light trigger germination. Veggie has successfully grown a variety of plants, including three types of lettuce, Chinese cabbage, mizuna mustard, red Russian kale, and zinnia flowers [SS-52]. The TRL for using passive wicking and plants pillows is 9. Studies suggest that watering plants on Mars could require less water than on Earth because water would flow differently through the Martian soil [SS-53]. Plants could be engineered to use less water, producing greater yields, and having a higher tolerance to cold [SS-54]. The TRL for using less water for plants is 2.

When conducting an analysis on the overall design to be used for the habitat, a first order analysis was used to obtain a rough approximation of what the final design would be. As previously discussed, the team considered subterranean, inflatable modules, a rigid surface structure, crew module, and regolith bricks for habitat options as shown in Table 16.

Habitat	TRL	Volume Ratio (payload V / Mars V)	Estimated Pay Mass (kg)	Debris Protection	Thermal Insulation	Radiation Protection	Cost/ft^2	Disturb Mars	Final Score
Subterranean with inflatable with regolith	4.6	8.9	10.5	4.1	5.3	10.3	5.8	1.2	50.6
Subterranean with rigid with regolith	4.6	7.0	7.7	4.1	5.3	10.3	5.0	1.2	45.2
Subterranean with inflatable	4.6	8.6	7.0	4.1	5.3	8.2	4.3	1.2	43.3
Subterranean with rigid	4.6	5.7	4.2	4.1	5.3	8.2	3.2	1.2	36.5
Inflatable with regolith	5.7	8.6	10.5	1.6	4.2	10.3	7.6	2.3	50.9
Inflatable without regolith	8.0	7.6	10.5	0.8	1.1	4.1	6.5	5.9	44.5
Rigid with regolith	5.7	3.8	6.3	2.5	4.2	10.3	6.5	2.3	41.7

Rigid without regolith	6.9	1.9	2.1	2.5	2.1	4.1	4.3	5.9	29.8
Temp crew module	9.2	1.9	4.2	3.3	3.2	6.2	10.8	5.9	44.6

Table 16: Habitat Options Normalized

The reason the habitat choices were proposed as combinations instead of stand-alone options is due to the fact that multiple design trades could easily be paired with one another while benefiting the overall system. For example, regolith bricks could not be used entirely on their own as a habitat but would rather be paired with any of the other options to amplify the radiation shielding and insulation of another habitat option. It became evident after conducting this first order analysis of our habitat options that an inflatable habitat surrounded by regolith bricks was the ideal choice for this mission.

E.4.a.vi Final Design

The final design for our habitat is a set of Kevlar inflatable modules surrounded by regolith bricks for radiation protection. The rooms were determined to be rectangular rather than round, so that surface area could be optimized for equipment. However, the edges were chosen to be filleted to ensure that the modules inflate properly and fully, while also maintaining structural integrity at these weak points. The thickness of the inflatable material is 0.4572 m (1.5 ft) with 0.06096 m (0.2 ft) fillets on all edges. The ceiling thickness is also 0.4572 m (1.5 ft). The final design has a room surface area of 319.854 m² (3442.88 ft²) and when including the hallways, rover garage, and airlocks the surface area is 383.4926 m² (4127.88 ft²). The bedroom and bathroom area consists of 8 divided bed sections and 4 separate bathrooms. The dimensions were expanded to be 9.144 m x 9.144 m (30 ft x 30 ft) and the ceiling height of 2.8956 m (9.5 ft) remained the same. The bedroom area was expanded for the psychology of the astronauts. The common area dimensions were lowered to be 9.144 m x 9.144 m (30 ft x 30 ft) as well because we wanted to maintain a similar overall surface area to the previous design, and the increase in astronaut personal area was compensated for with a decrease in shared astronaut area. The common area will contain the kitchen, communication systems, exercise equipment, and entertainment. The ceiling will be 2.8956 m (9.5 ft). The other rooms remained the same size and their dimensions are detailed below in Table 17.

Room	**Length (m)**	**Width (m)**	**Height (m)**	**Square Meterage (m^2)**	**Surface Area (m^2)**	**Volume (m^3)**
Common Area	9.144	9.144	2.896	83.613	174.298	242.109
Lab	10.668	6.096	2.896	65.032	147.553	188.307
Greenhouse	6.096	4.572	2.896	27.871	82.370	80.703
Medical	8.534	4.267	4.877	36.418	158.632	177.603
Crew Quarters	9.144	9.144	2.896	83.613	186.874	242.109
Storage	3.414	3.414	2.896	11.654	48.546	33.745

Backup Storage	3.414	3.414	2.896	11.654	51.193	33.745
Garage	6.096	6.096	4.877	37.161	151.444	181.228
Airlocks (x4)	3.048	1.600	2.896	19.510	90.116	56.492
Hallways (x5)	1.524	0.914	2.896	6.968	51.097	20.176
Total	-	-	-	383.493	1142.123	1256.216

Table 17: Habitat Sizing

E.4.a.vii CAD Model

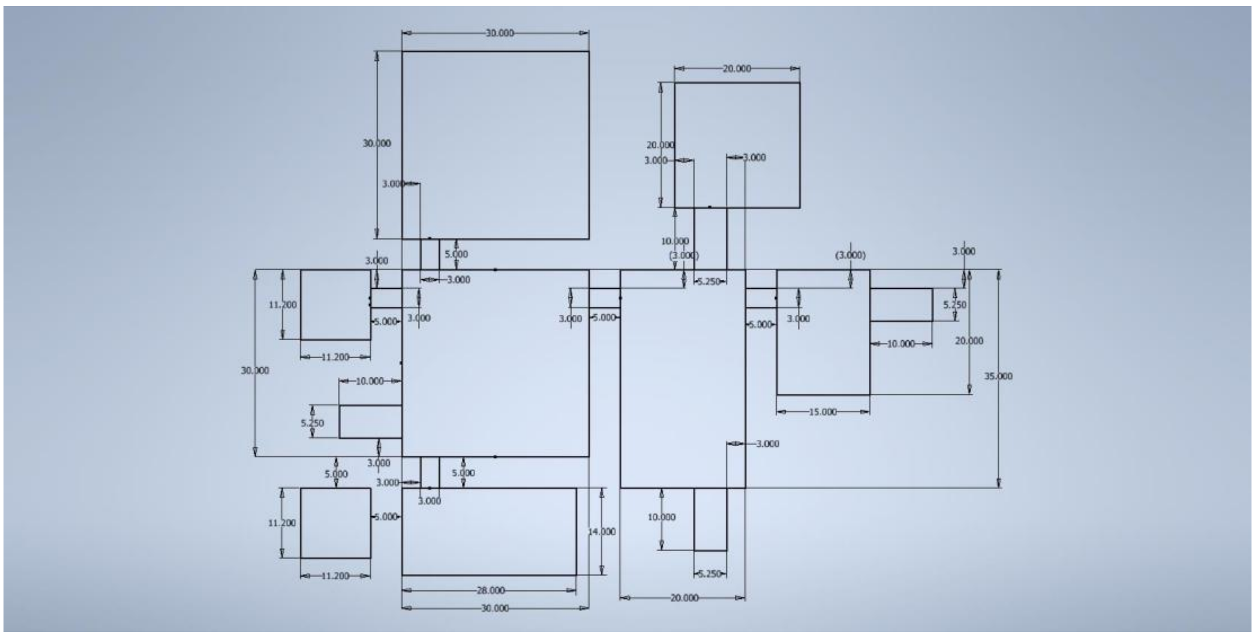


Figure 13: Habitat Top-Down Sketch

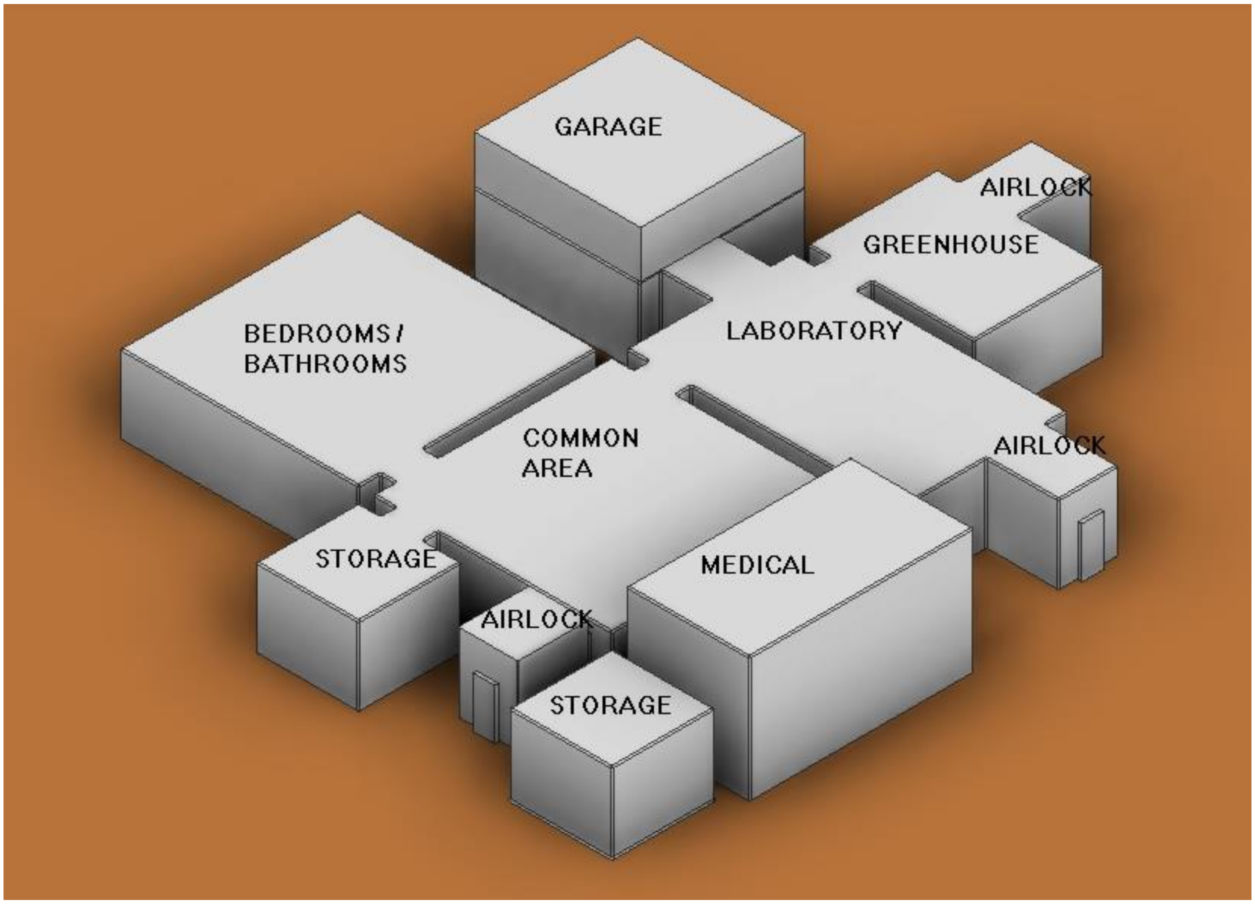


Figure 14: Habitat 3D CAD Model

E.4.b Life Support Systems

E.4.b.i Water Supply

In order to determine the water supply system for the astronauts in the habitat, we considered three courses of action. The first option was to bring all the required water prepackaged from Earth. Though this method has a high reliability, it would add considerable mass to the payload. In addition to this, it would have low longevity since the storage method would most likely contaminate the water over a long duration of time [SS-55]. The next option was to extract the water from the Martian surface and atmosphere. However, since extensive experiments regarding water extraction on Mars have not been conducted, this method would have a low TRL. Combined with the need for more research into detecting locations with substantial amounts of water and a method to process the extracted water, this method is not viable for our mission [SS-56]. And finally, we considered recycling water on Mars in a manner similar to that followed by astronauts in the ISS. This would have the highest longevity since water can continuously be recycled as and when it has been used. In addition to this, it would have a high TRL since the technology has been successfully demonstrated in the past. The one caveat for this method is that the recycling process can begin only when the first crew arrives on Mars so that the associated system can use the wastewater generated in the habitat. Therefore, after performing a first order analysis based on TRL, complexity level, efficiency, longevity and initial mass of payload, we decided to use a combination of prepackaged water and recycling as the water supply system. The prepackaged water will most likely be used first, with some amount being stored as a contingency. Once enough wastewater is generated, the recycling process would begin. Similar to the process followed in the ISS, the water recovery system will begin with the collection of astronaut wastewater in the form of urine, sweat and exhaled breath that condenses on the walls of the habitat [SS-57]. This water would then undergo chemical or biological treatments to filter out the impurities and contaminants. The water obtained as a result of this filtration process can then be used to rehydrate food, bathe, and drink [SS-58].

Water Supply Combinations	TRL	Complexity	Efficiency	Longevity	Initial Mass	Final Score
Prepackaged and Extraction and Recycling	2.9	0.9	3.9	5.6	2.2	15.5
Prepackaged and Extraction	2.5	0.9	3.6	4.5	2.1	13.5
Prepackaged and Recycling	3.7	1.2	4.5	4.9	1.7	16.0

Table 18: Water Supply FOA

E.4.b.ii Contamination Mitigation

For contamination mitigation, our team has chosen to use hermetically-sealed sample containers. These sample containers will allow our astronauts to store scientific research and key items from their mission without risk of damaging or spoiling these specimens prior to them returning to Earth. When selecting these sample containers, we compared them against isolation chambers, clean rooms, and the use of thermal vacuum bakeout. Isolation chambers tended to be a low TRL, high cost, and high mass and volume solution for contamination mitigation making them non-ideal for our mission. Similarly, we found that cleanrooms also had a low TRL with high mass and volume requirements, once again not suiting our needs for contamination mitigation [SS-68 - 79]. Thermal vacuum bakeout was not chosen due to the need for a vacuum which would be very costly on the surface of Mars [SS-80]. As a whole, the sample containers won out due to their high TRL, strong ability to protect our specimens, and the exceptionally low mass, volume, and cost of the containers. Hermetically sealed sample containers have been used for storing research on the ISS, and have been heavily used in many scientific settings on Earth making them a reliable choice for our mission. An additional benefit of these sample containers is their versatility, as they would allow for us to accommodate specimens of various shapes and sizes while the other options are much more fixed. Lastly, hermetically-sealed sample containers are highly transportable, making it much easier for our astronauts to move our specimens without further risk of contamination [SS-59 - 67].

Contamination Mitigation	TRL	Cost	Mass	Required Space/Volume	Contaminant Protection	Final Score
Isolation Chambers	0.21	0.1	0.1	0.1	0.3	2.71
Clean Room	0.28	0.3	0.2	0.2	0.4	4.25
Hermetically sealed sample containers	0.31	0.4	0.4	0.4	0.2	4.82
Thermal vacuum bakeout	0.21	0.2	0.3	0.3	0.1	3.21

Table 19: Contamination Mitigation FOA

E.4.b.iii Pressurized Areas

For pressurized areas, the aspects of a whole habitat fully pressurized, tunnels that are less pressurized and separate sections, separate habitats, fully pressurized transportation, and non-pressurized transportation were considered. NASA has proposed the use of a 'Minimum Functional Tunnel' that is a pressurized tunnel used to get astronauts to the MAV from a pressurized rover without going outside into the Martian environment. If the astronauts are in IVA suits, the tunnel does not need to be pressurized, but there are benefits if it is. These benefits include positive pressure reduces risk of Martian dust leakage, ease of suit translation, and opens up the design space. Ways to pressurize these tunnels include a self-contained system, pressurize from the MAV, pressurize from the rover, or a combination of the previous options. However, if the tunnel is repurposed for rover-to-Habitat operation, it must be able to meet the higher differential pressure requirements of the surface habitat, which currently operates at pressures almost double that of current nominal operation pressures of rovers and MAVs. If multiple modules were used, tunnels would be needed, and this goes back to the issue of maintaining the habitat's higher pressure in the tunnel which would likely result in more stringent reliability requirements. Options other than tunnels include an EVA hatch, airlock, suitport, and suitport-airlock [SS-81]. As for rovers, there are many available concepts available for the lunar surface. Unpressurized rovers can be easily packaged with other flights elements, but pressurized rovers have an extended range, shirt sleeve environment, and improved radiation protection [SS-82]. Once concept for a Mars mission is that the crew lives in a pressurized rover, but also has an unpressurized rover to utilize [SS-83].

Pressurized System	TRL	Human Maneuverability	Leakage	Packageability	Pressure level need	Final Score
Whole habitat fully pressurized	1.6	1.5	1.7	0.3	1.4	22.2
Less pressurized tunnels	0.4	0.3	0.3	1.5	1.4	9.4
Separate habitats	0.4	0.9	1.0	0.9	1.4	12.6
Fully pressurized transportation	1.1	1.5	1.7	0.9	0.8	18.2
Non-pressurized transportation	1.6	0.9	0.3	1.5	0.0	12.6

Table 20: Pressurization FOA

For the habitat, it was determined that having a fully pressurized habitat entirely was the best option, as well as having fully pressurized transportation.

E.4.b.iv Oxygen Supply

The team began by exploring different concepts for oxygen supply via a morphological matrix. The possible sources of oxygen were as follows: pre-packaged, extracted from the Martian atmosphere, and a combination of both. Having pre-packaged oxygen would be like the ISS [SS-84]. Therefore, it is a reliable option since it had been used to sustain astronauts before. The concept of extracting oxygen from the Martian atmosphere comes from technology currently being tested on the Perseverance rover, called MOXIE. MOXIE is a novel technology, built into Perseverance to use electrolysis to create oxygen from the carbon dioxide in Mars' atmosphere [SS-85]. As mentioned in the section that highlights novel technologies of the mission, if chosen the MOXIE would have to be scaled up to support the whole crew, since it currently is able to produce up to 10 grams per hour of oxygen [SS-85]. Finally, the last option that was considered for analysis was having pre-packaged oxygen and extraction from the atmosphere. A combination was considered because it would reduce the risk of either running out of oxygen or if the MOXIE system is unable to produce enough oxygen.

With all these options in mind, the team created an FOA and weighed each of the options and assigned scores based on certain aspects and functions the system would need to accomplish and achieve. The FOA can be seen below:

Oxygen Supply	**TRL**	**Reliability**	**Heritage**	**Longevity**	**Initial Mass**	**Final Score**
Pre-packaged	2.45	4.17	5.45	2.25	0.56	14.90
Extracted from Mars	1.36	3.13	4.36	6.00	1.31	16.17
Combination	2.18	4.70	2.18	6.75	1.13	16.93

Table 21: Oxygen Supply FOA

The factors that were considered in the FOA were TRL, reliability, precedence, longevity, and initial mass. TRL is self-explanatory, since it measures how technologically ready the system would be. Reliability is a measure of the system's ability to function without breaking down too often or needing too much maintenance. Precedence is like TRL, but it is more of a measure as to whether the system had been used before as an oxygen source. Longevity is a measure of how effectively the method would last the duration of the mission, and initial mass accounts for how much weight it would add to carry the oxygen system to Mars during the supply missions. The team chose to rank longevity as the most important and highest weighted factor, with initial mass being the lowest since pre-supply missions and other supply missions could reduce the total amount of mass that is being sent for the oxygen system.

After assigning scores, adding them up, and normalizing them, it was found that the combination oxygen system had the highest score as shown in Table 21. This aligns with the research done before using the FOA to quantify the decision. Having a combination of the pre-packaged oxygen tanks and the oxygen extraction system would ensure the safety of our astronauts and reduce the risk of not having enough oxygen for them to survive.

The specifications of a scaled-up MOXIE were highlighted in the Novel Technologies section (D.4.a). It will produce a greater amount of oxygen than the MOXIE and be the main source of oxygen for the crew in the habitat. The compressed pre-packaged oxygen tanks could be used while the BOXIE system is being set up and tested. The choice of oxygen system impacts various factors of the mission, such as the payload mass of the supply missions and the initial crewed mission to Mars. It would also take up space in the habitat, which would need to be accounted for when sizing each section of the habitat.

E.4.b.v CO2 Recycling

Similar to the previous sections, the team began by using a morphological matrix to explore different options for CO2 recycling. The options included high consumption plants, capturing from human presence, and CO2 removal systems. The idea for high consumption plants stems from a test conducted by Russia called BIOS-3 in the 1960s and 1970s, where chlorella algae was used to absorb CO2 for a 1-to-3-man crew [SS-86]. Another option was to capture CO2 from human presence, similar to the zeolite on the US Skylab, or the CDRA from the ISS. These systems use beds of material such as zeolite to extract the CO2 exuded from humans and vent the extracted material overboard [SS-87]. The last option the team came up with, the CO2 removal systems, were inspired by the NASA CDep. This system captures CO2 and deposits CO2 devoid air to a possible oxygen supply system [SS-88].

With all of these options in mind, the team developed an FOA and weighed the options, assigning scores and ranking the factors of importance. The FOA is shown below:

CO2 Recycling	TRL	Reliability	Precedence	Longevity	Initial Mass	Final Score
High-consumption plants	3.15	2.67	2.14	2.14	1.26	11.37
Captured from human presence	4.05	4.67	4.29	6.43	0.95	20.38
CO2 Removal Systems	1.80	4.67	2.57	6.43	0.79	16.26

Table 22: CO2 Recycling FOA

The factors that were considered for the CO2 recycling option were the same as the oxygen system: TRL, reliability, precedence, longevity, and initial mass. TRL measures how technologically ready the system would be. Reliability is a measure of the system's ability to function without breaking down too often or needing too much maintenance. Precedence is like TRL, but it is more of a measure as to whether the system had been used before as a CO2 removal system. Longevity is a measure of how effectively the method would last the duration of the mission, and initial mass accounts for how much weight it would add to carry the system to Mars during the supply missions. The team chose to rank longevity as the most important and highest weighted factor, with initial mass being the lowest since pre-supply missions and other supply missions could reduce the total amount of mass that is being sent for the system.

After scoring the options and adding them up to form a normalized score, it was found that the method of capturing CO2 from human presence was the highest-ranking option, and therefore the option that was chosen. This score can be seen in Table 22 above. The team agreed with these results as well, since CO2 capturing is a process done on the ISS and has a high precedence rating and longevity. The system in the mission would be similar to what has been done previously, by using zeolite molecular sieves to remove CO2 from the air in the habitat and vent it outside. From research, it was found that these sieves can build up with zeolite dust [SS-89]. This will cause the astronauts to have to address possible dust buildup on the sieves and clean it up during allocated maintenance hours in their schedule.

E.4.b.vi Waste Management

For waste management, our team has chosen to use a landfill on the surface of Mars. This landfill will likely be built nearby our habitat for ease of access and disposal of any unneeded resources. At minimum, this landfill will likely be fenced off and built in a specific location to prevent any waste from escaping the landfill due to wind on Mars. The landfill could also be fully enclosed; however, this would require a greater number of resources and time to build. When selecting our waste management technique, we compared the landfill option against biodegradable storage, incineration, and storage for future removal. While biodegradable waste management is useful, the fact that it is incapable of storing non-organic waste makes it a non-viable option for our mission [SS-102 - 108]. Incineration of our waste, while able to produce some useful energy and minimize our waste volume, was ultimately found to be too costly for waste management [SS-109 - 119]. Storing our waste for future removal was seen as a non-viable option due to the great expense it would take to remove this waste from the surface of Mars [SS-120]. The primary reasons we decided to use a landfill for our mission was the simplicity and low cost, in terms of both money and mass, that this option provides. Landfills, as would be expected, are extremely reliable and low maintenance, making this option ideal for our mission in which we would like to remain focused on our science objectives above all else. One added benefit of landfills is their ability to produce methane due to the biodegradation of organic materials [SS-90-101]. While small in quantity, this methane could help supplement any methane needs, such as those with propulsion, were we to decide to use a methane-based engine on our MAV. The leading problem that we could face with using a landfill is if we wanted to protect the environment on Mars around our landing site. This is currently not a concern for our group, however our choice for waste management could be reconsidered for one of our other options if need be in the future.

Waste Management	TRL	Volume	Non-Organic Waste	Energy Recovery	Methane	Cost	Required Materials Mass	Final Score
Biodegradable	0.19	0.13	0.00	0.50	1.00	0.30	0.14	5.40
Incineration	0.23	0.38	0.33	0.50	0.00	0.20	0.14	7.67
Stored for future removal	0.35	0.25	0.33	0.00	0.00	0.10	0.29	6.82
Landfill on Mars	0.23	0.25	0.33	0.00	0.00	0.40	0.43	8.11

Table 23: Waste Management FOA

E.4.c Radiation Shielding

The crew's duration on the surface of Mars will be significantly longer than the duration on the MTV, with 7 years (2500 days) split between two crews. The Martian atmosphere is of nearly negligible thickness compared to Earth's, and combined with the lack of a magnetic field, indicates that the Martian surface will experience a similar radiation environment as space. The key difference is that the Martian surface has a significant amount of available regolith, which can be utilized for additional shielding.

Utilizing regolith in conjunction with our habitat pressure vessel minimizes the mass requirement for descent, improves the insulation capability of the habitat, and creates an effective shield against debris/puncture. It also allows for increases in shielding thickness with locally available materials as needed.

The estimated radiation exposure for a surface mission was evaluated using the NASA OLTARIS tool, following a similar process to the evaluation performed for the transit vehicle, and described in the MTV section. For the purposes of the simulation, the habitat was described a layered slab with an 18 cm aramid fiber wall as our habitat pressure vessel, with increasing thicknesses of Regolith added onto the surface. This slab was exposed to a 1-D radiation simulation across a 2500 day mission timeline.

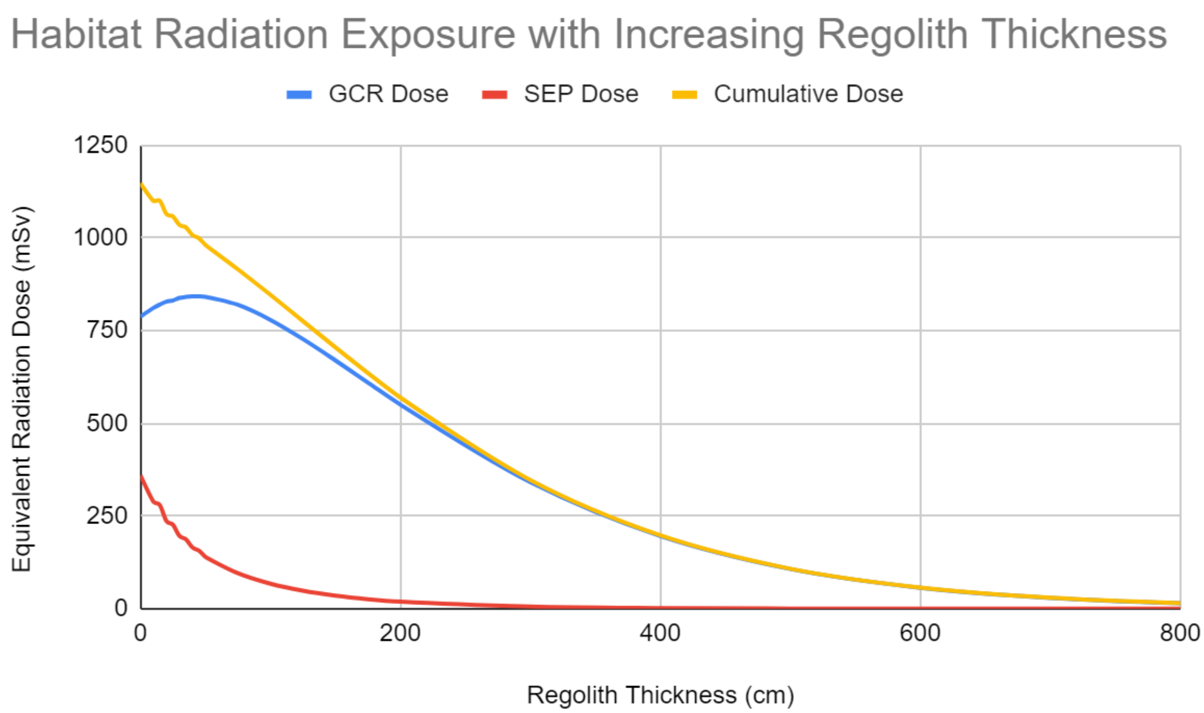


Figure 15: Regolith Shielding Analysis

With the effective dose of the MTV shielding for the mission being 377 mSv, our remaining dose from the surface must be minimized to below 623 mSv. With this requirement, a lower limit of 1.75 m of regolith shielding is required in order to achieve our desired dose cap. If the habitat is able to maintain additional weight, or bricks can be manufactured into an igloo-type interlocking structure to support themselves without adding pressure on the habitat pressure vessel, a nominal shielding thickness of 4m is desired to achieve the lowest “reasonably achievable” radiation dose over the mission duration.

E.5 Communications Systems

E.5.a Key Considerations

E.5.a.i Communication Requirements

Key considerations for the communications architecture included following NASA’s Gold Rules related to mission communication requirements. The first consideration included retaining telemetry and tracking coverage for all critical mission events. For our mission this includes transit from Earth to Mars, landing on the Martian surface for both crewed missions, astronauts entering the habitat for the first time, EVA missions, launch in MAV to MTV for Earth-bound mission, and transit between Mars and Earth for both crews. Further requirements for the communications system architecture included having data relay between the Mars habitat and Earth occur daily and scientific data relay occur every two weeks. Additionally, Ka band is required as the baseline for scientific data return. Based on these design considerations, we were able to develop the architecture determined below.

E.5.a.ii Key Challenges

A key outstanding challenge to the Mars communication architecture is solar conjunction within the mission timeline. This occurs when the sun is between Mars and Earth, impeding direct communication from Earth to Mars and vice versa. During our mission timeline solar conjunction will occur three times: September 17, 2036 to October 1, 2036; October 29, 2038 to November 5, 2038; and December 9, 2040 to December 23, 2040. During these periods, to reduce unnecessary risk crews will not leave the habitat. The second solar conjunction period occurs during the crew-overlap period where long-range searching for signs of life via the pressurized rover is scheduled, however, during the solar conjunction period this research will be postponed.

Possible options to mitigate the solar conjunction effects include placing a communications satellite at a Lagrange point between Earth and Mars or placing a communications satellite in a cycler orbit between Earth and Mars. Both options provide continued communications capabilities between Earth and Mars during solar conjunction. However, both options would require launches in addition to the pre-arrival, crew, and resupply cargo missions scheduled for our mission architecture. Without scientific backing as to the need for either a Lagrange or cycler satellite, we determined that the high cost of both mitigation efforts was not justified for our mission architecture. Further consideration needs to be given to mitigating solar conjunction communications blackout beyond the scope of this project including the scientific potential of both Lagrange point and Ears-Mars cycler orbits.

E.5.b Physical Assets

To meet telecommunication requirements for this mission, a 3-satellite constellation is proposed in areostationary orbits, the Martian equivalent of a geostationary orbit. Areostationary orbit was selected to ensure the MTV remains in line-of-sight of the surface habitat, and to reduce pointing error between the surface habitat and the satellite constellation. Although an areostationary orbit occurs at a 0 degrees inclination and the habitat will be at 22 degrees latitude, an areostationary orbit provides +/- 70^{o} latitude line-of-sight [CM-7]. A 3-satellite constellation was selected to ensure that line-of-sight contact is not lost with the Earth when the surface habitat is on the opposite side of Mars. Additionally, selecting three satellites provides redundancy in the satellite constellation, as the loss of any individual satellite can be compensated for by the remaining two. The MTV will act as the primary communication satellite between Mars ground and Earth while crew is on the surface, with supporting satellites deployed in the same orbit with 10.2 degrees of separation. The figure below shows the layout of the constellation, including all communication links.

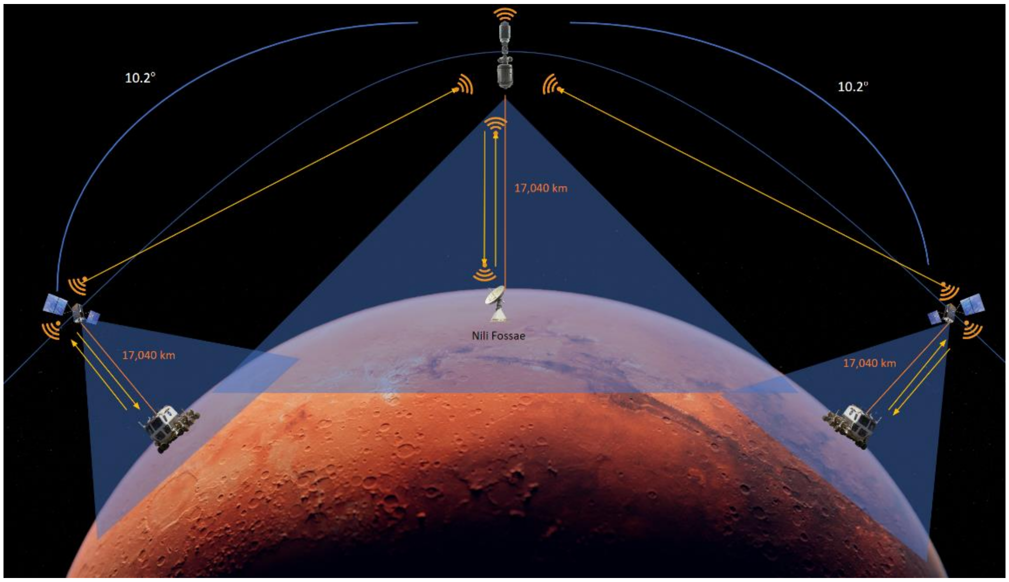


Figure 16: Satellite Constellation Layout

As the primary satellite, the MTV will handle be used for data transmission and the bulk of voice and video communication. Due to its large size, readily available power source, and requirement for communications during Mars transit, the MTV can support a robust communications array well suited to this purpose. The support satellites are included to provide additional transmission capabilities, should they be required, and provide redundancy and Earth line-of-sight capabilities. The support satellites will additionally support both crewed and robotic exploration away from the surface habitat, serving as a relay between the exploratory teams and the habitat.

Antenna sizing and power budgets for each satellite and the surface habitat were selected from link budget requirements, discussed in the Link Budget section below. The surface habitat will make use of 1-meter antennas, operating at 1 watt of power. If higher data rates are desired, a higher power may be used, however this serves as a baseline enabling sufficient data transmission both between ground stations, and between the surface and the satellite constellation. The MTV will use a 9-meter antenna operating at 180 watts of power, and the support satellites will have 6-meter antennas operating at 20 watts of power. As the support satellites are not designed for robust data transmission, they do not require the same transmission ability as the MTV, and thus can make use of cheaper hardware. Given the magnitude of a seven-year crewed Mars stay, and the importance and uniqueness of the data collected, it is assumed that a 70-meter Deep Space Network antenna will be always available for use for data transmission and other critical events.

An important point to consider for this constellation is the cost and deployment of these satellites. Through cost analysis, it was found that utilizing the MTV as the primary satellite provided the cheapest option when compared to a dedicated satellite [CM-1] due to the MTV already having power and equipment for communications since it is used for the manned transfer missions. Further considerations on the placement of the MTV into this orbit and the supporting satellites into their required orbit are detailed further in the Mission Design sequence.

E.5.c Link Budget

The first step in the creation of link budgets for Earth to Mars communication is to determine the required signal to noise ratio, or Ebno, for each transmission type. This analysis considered two types of transmissions: data, and voice and video communication. Requirements for data transmission are stricter than for voice and video communications, and thus require special consideration. The required Ebnos are calculated from desired bit error rate, or BER, signal modulation type, and a selected margin. For data transmission, standard BER's are on the order of magnitude of 10^{-11}, while for voice and video transmission, BER's on the order of 10^{-6} are acceptable [CM-6]. The figure below shows relations between BER and signal to noise ratio for various signal modulation methods.

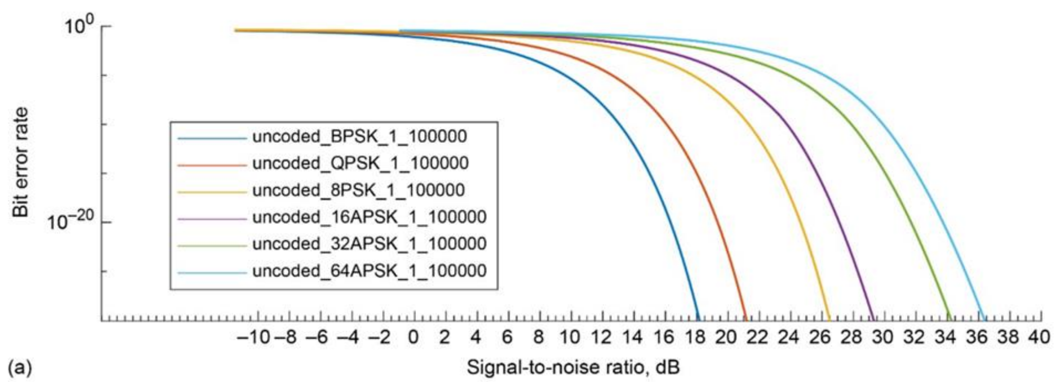


Figure 17: Bit Error Rate vs. Signal to Noise Ratio for Uncoded Modulations [CM-4]

The standard for signal modulation is quadrature phase shift keying, or QPSK, as it provides increased data rates to other types of signal modulation, while maintaining the same BER. Values were then selected from the above plot for both data transmission and voice and video communications Ebnos. Then, a margin factor was applied to determine a final required Ebno for both communications methodologies. The results are summarized in the table below.

	Data Transmission	**Voice and Video**
BER	10^{-11}	10^{-6}
Modulation Type	QPSK	QPSK
Ebno	18 dB	10 dB
Ebno Margin	1.5	1.5
Required Ebno	27 dB	15 dB

Table 24: Required Ebno Parameters

For Mars to Earth communications utilizing a satellite relay, there are four link budgets that must be calculated: Mars surface to satellite, satellite to Earth, Earth to satellite, and satellite to Mars surface. For simplicity, these will be referred to as Mars or Earth uplink or down, depending on the planet involved in the transmission leg. Initial analysis was conducted using 32 Ghz Ka-band, and other parameters used in the link budget calculations are available in Appendix I.6, while losses were calculated using the following methods.

E.5.c.i Free-Space Path Loss

The free-space path loss is the loss in our communication network due to distances between transmitter and receiver, and it can be expressed as:

$$L_{FS} = \left(\frac{4\pi d}{\lambda}\right)^2 \quad \text{[CM-3]}$$

where d is the distance between points and λ is the wavelength of the signal.

As the distance between points of communication increases, the loss increases. For the Earth-Mars communication link, this becomes the largest loss and a key factor in the sizing of the communication network.

Since the free-space path loss is directly dependent on the frequency, a range of frequencies was used to influence the overall design. Figure 18 shows the relationship between the loss and the frequency used, with a maximum and minimum loss determined by the distances between Earth and Mars.

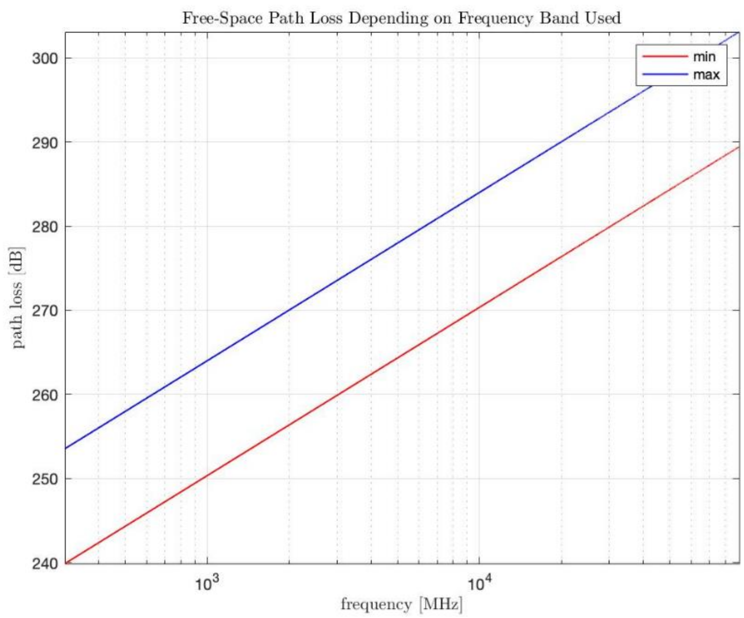


Figure 18: Frequency Effect on Free-Space Path Loss

E.5.c.ii Pointing Loss

The pointing loss is the loss due to inaccuracy in pointing the transmitting antenna at the receiver. This error can be caused by perturbations in the attitude of a spacecraft, small inaccuracies in spacecraft state estimation, physical limitations in fine tuning position, etc. While it is practical to calculate this error given values and margins about a spacecraft, without the spacecraft, it can only be roughly estimated. The following equation can be used to get an estimate on the pointing loss to expect:

$$L_p = 12\left(\frac{\theta}{\theta_{0.5}}\right)^2 \text{ [CM-3]}$$

where θ is the antenna pointing error and $\theta_{0.5}$is the beamwidth.

This equation takes into consideration an estimated pointing error angle, and beamwidth. Once again, there is an issue with knowing the pointing error angle, so the ratio of pointing error angle and beamwidth, called the pointing error, is the variable to be adjusted based on previous missions and data. For this mission, a pointing error of 20% is assumed [CM-6].

E.5.c.iii Earth Atmospheric Loss

Earth's atmosphere can cause a lot of difficulty with telecommunications systems, split between Ionospheric effects and Tropospheric effects. A few of the Ionospheric effects are polarization rotation, absorption, propagation delay, and dispersion. These effects are typically negligible for frequencies above 10 GHz, so they will be neglected for this system. The Tropospheric effects are much more impactful and consider rain attenuation, gas absorption, polarization, and more. These effects vary greatly in different weather conditions and in different locations around the world and is still a large area of research. Due to the complexity of models for the Earth atmospheric loss, a value of 3.35 dB is used when determining the link budget based on upper limits of atmospheric loss. More detailed information on Earth atmospheric loss can be found in [CM-5].

E.5.c.iv Martian Atmospheric Loss

Similar to Earth's atmospheric loss, the loss due to Mars' Ionosphere can be neglected due to the high frequency used in the system. In Mars' Troposphere, losses occur due to clouds/fog, dust, and gases, with the highest losses occurring due to a Martian dust storm. Considering this worst-case scenario, the total loss due to the Martian atmosphere is around 3.4 dB [CM-3].

The final consideration for Ebno calculation is the data rate required for each leg of the transmission. The analysis assumes that all transmission legs will transmit at the same data rate, to reduce data transmission backups. Data generation estimates were taken from Mars short duration mission estimates, resulting in an assumed data generation of 2-8 Mbps [CM-7]. An additional concern is data transmission during emergency situations. Medical emergencies requiring Earthside assistance can result in data transmission needs of up to 66 GB per day, or 0.763889 Mbps over the course of the day [CM-2]. This serves as the baseline for data transmission needs, with increasing data rates included in the link budget analysis. This analysis selected a data transmission rate of 2.3 Mbps for scientific data. For voice and video communications, the selected hardware enables a data transmission rate of 52 Mbps.

Ebnos for each leg of the communications relay were calculated using a MATLAB script to iterate through various parameters of interest, including power, antenna size, and data rate. The link budget calculations are available for reference in Appendix I.6. The link budgets are summarized in the tables below.

	Data Transmission	**Voice and Video**
Mars Uplink	63.29 dB	49.74 dB
Mars Downlink	89.82 dB	76.28 dB
Earth Uplink	29.95 dB	16.41 dB
Earth Downlink	28.56 dB	15.02 dB

Table 25: Ebno for Each Relay Leg

Given the ability of 32 GHz Ka-band to meet the required mission Ebnos, other transmission bandwidths were not explored, and Ka was selected for use. Using this MATLAB script, hardware and data rate could be selected based on performance across multiple parameters. Antenna size identified as the primary parameter to minimize, due to volume and mass constraints. Due to the use of the MTV as a primary data relay satellite, and the power generation abilities of both Earth and the Mars surface base, power was not considered a limiting factor, although a maximum of 200 watts was selected for initial iteration of the script. The performance curves for various antenna diameters are shown below. The curves are generated for Earth Downlink only, as this is the “limiting” leg of the relay, meaning that the Ebno for Earth Downlink is the lower than any other leg.

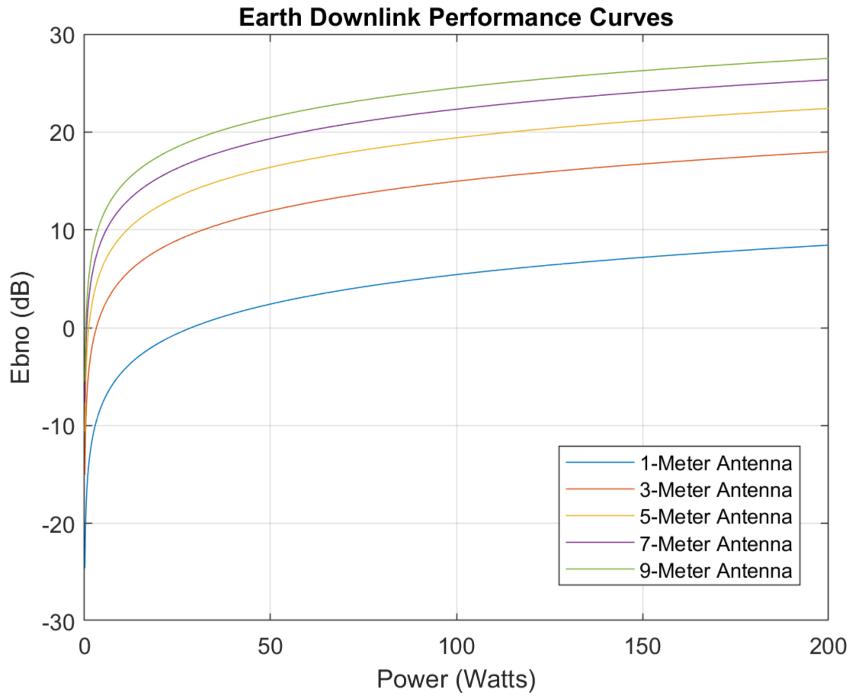


Figure 19: Performance Curves

As can be seen from Figure 19, with a required Ebno of 27 dB for data transmission, only the 9-meter antenna can achieve the desired performance within the selected power range.

F. Cost & Schedule

F.1 Life Cycle Cost

To determine our mission life cycle cost, we first determined the work breakdown structure (WBS) components for our mission. We came up with 11 overarching components, which include Propulsion, Science Objectives, MTV, Surface Stay, EDL/MAV, Communications, Space Environment, Program Level, Flight Support Operations and Services, Aerospace Ground and Space Equipment, and Launch Operations. Below is our WBS figure for our mission:

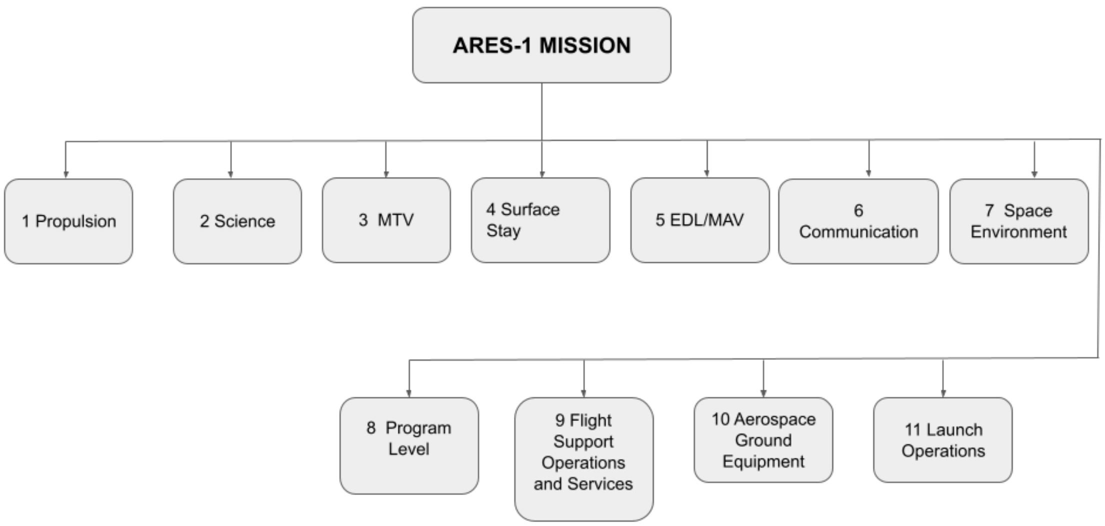


Figure 20: Work Breakdown Structure for ARES-1

The breakdown within each WBS component and their cost calculations are included in the lifecycle cost spreadsheet posted in Appendix I.9. To estimate the costs for WBS components 8-11, our team utilized the Cost Estimation Relationships (CERs) directly from the SMAD to determine the costs. However, for components 1-7, we couldn't rely on the SMAD because the CERs listed for these components are for unmanned missions and therefore are not applicable to our mission. The method our team used to work around this challenge was that we used the cost-by-analogy method to determine the costs excluding the Design, Development, Test, and Evaluation (DDT&E) and Production costs. To determine those costs, we used the Advanced Mission Cost Model (AMCM FY$1999) [CS-6] which estimates the cost in millions of dollars in 1999. This CER was developed by the Exploration Programs Office at Johnson Space Center and its database includes eight manned spacecraft developed by NASA: Mercury, Gemini, Apollo command module, Apollo lunar module, Skylab, Shuttle orbiter, etc.

The total cost breakdown for the WBS cost components can be summarized in the table and pie chart below. As seen in the pie chart, flight support, and operations and the EDL/MAV costs make up the majority of our mission costs while communications, program level, aerospace ground, and support equipment were some of the lowest costs reported. It must be noted that some of the lower costs were too small to be included in the pie chart, therefore they didn't appear in the pie chart or were reported as very close to 0.

Cost WBS Component	Total Cost (Billion $USD FY2023)
1.0 Propulsion	80.02
2.0 Science Objectives	0.35
3.0 MTV	146.75
4.0 Surface Stay	15.03
5.0 EDL/MAV	162.02
6.0 Communications	0.38
7.0 Space Environment	1.55
8.0 Program Level	0.01
9.0 Flight Support Operations and Services	251.77
10.0 Aerospace Ground and Support Equipment	0.09
11.0 Launch Operations	0.06
Total Cost of Deployment	**658.02**

Table 26: Total Life Cycle Cost for ARES-1

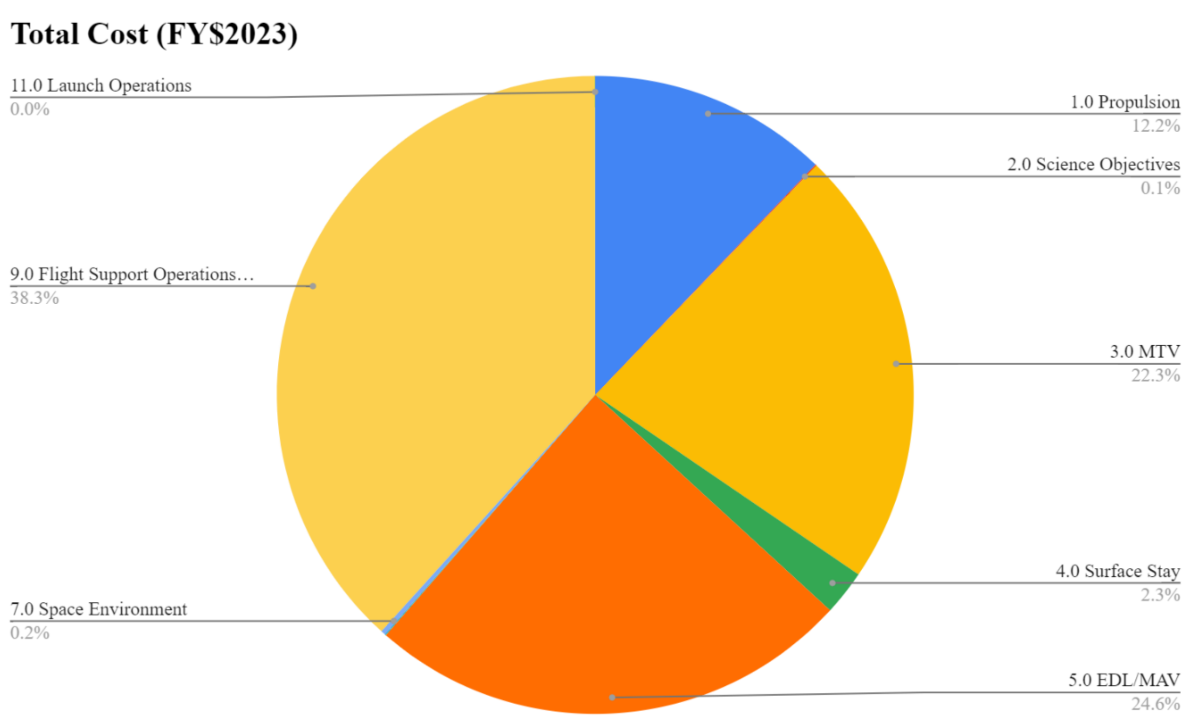


Figure 21: Pie Chart of Total Cost Breakdown

For creating our probability cost model specifically to develop a cumulative distribution function, we used the AW Stochastic Capital Budget Worksheet [CS-13] and put in inputs for low, most-likely, high costs for all our cost components. In addition, since most of our CERs determined costs within a 30% margin, we estimated this for all our cost components. We were able to obtain the s-curve seen below, and the associated table with percentile data. From our s-curve, we can conclude that the expected value (EV) for our total mission cost is $658 billion dollars.

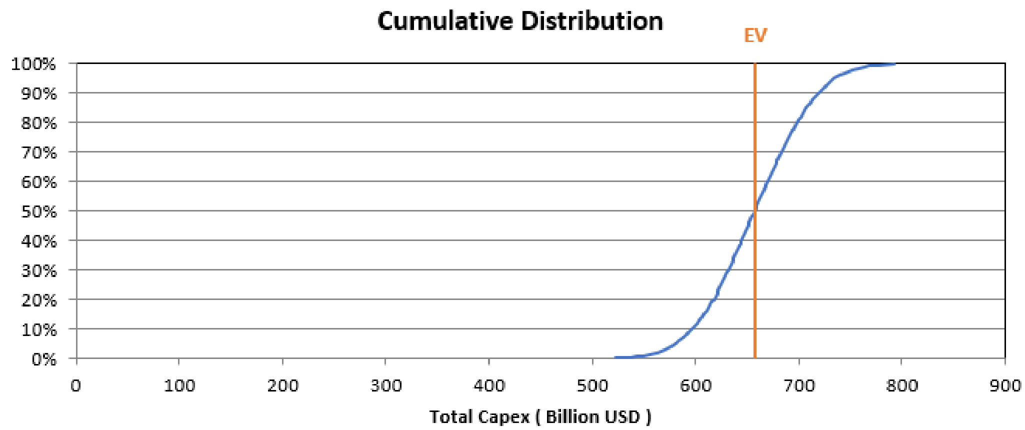


Figure 22: S-Curve for Cumulative Distribution of Total Mission Cost

	EV	P10	P50	P90
Total Mission Cost (Billion $USD FY2023)	658	597.02	657.21	719.12

Table 27: Percentile Total Mission Costs from S-Curve

F.2 Schedule

F.2.a Astronaut Schedule

While on the Martian surface, the Ares-1 astronauts will work on a schedule based off of the ISS and previous simulated Mars missions on the Earth. A daily schedule will consist of, at most, seven main parts. These include sleep, mealtime, hygiene, research and science, routine maintenance, exercise, and human experience or personal time. To keep the Ares-1 astronauts on a consistent schedule, the astronauts will work on the Martian Solar Day, or Martian Sol, which is 24 hours, 39 minutes, and 35 seconds, making a solar hour about 1 hour, 1 minute, and 39 seconds. This is based off of the ISS astronauts working on Greenwich Mean Time.

Research and science exploration will make up about 7 to 8 hours of the daily schedule, similar to a regular 8-hour workday. Within research and science, time will be allotted for routine medical testing, as human biological considerations are a main science objective of the Ares-1 mission. Other biological schedule considerations include exercise and meals. It is necessary to exercise for a minimum of 2 hours per day in order to prevent muscle and bone atrophy and keep up cardiovascular health. Food and water consumption should both precede and follow exercise, so 3 hours per day will be allotted for mealtimes. Sleep is the most important part of a daily schedule, as it is imperative that astronauts follow a sleep schedule that matches their natural circadian rhythms. The Ares-1 astronauts will follow the allotted 8 hours of sleep for astronauts on the ISS. Finally, hygiene and routine maintenance take about 3 hours total, leaving about 1 hour a day minimum for human experience time.

On the ISS, the astronauts work on two different schedules, an "on" day schedule with each of these seven main parts, and an "off" day schedule, which includes little to no research and science and only necessary maintenance, with an extra focus on personal time. Additionally, there will be a Shift A and a Shift B, to ensure that at least one astronaut is always awake for safety reasons.

Figure 23 below gives a sample graphic for an Ares-1 astronaut "on" day, and Figure 24 below gives the same for an "off" day, with Shift A shown in red and Shift B in green.

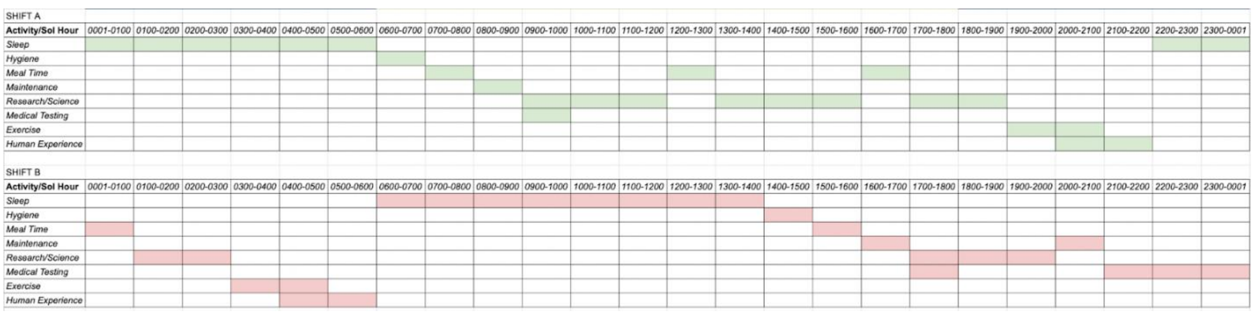


Figure 23: On-Schedule

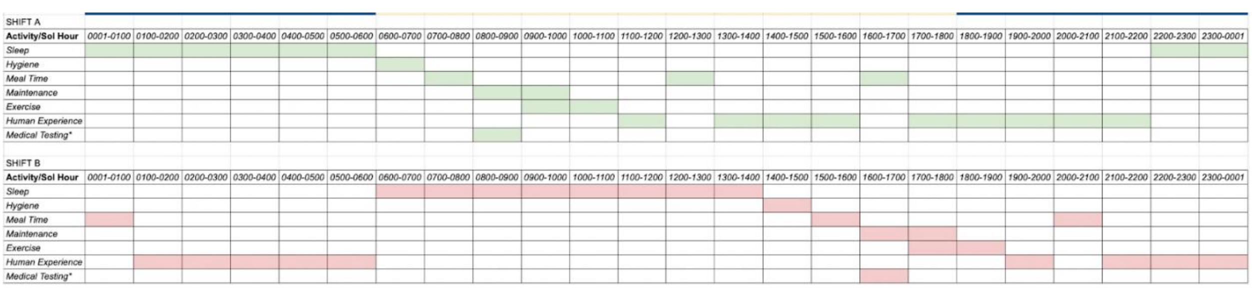


Figure 24: Off-Schedule

F.2.b Science Schedule

We have divided our science schedule on the Martian surface into three phases and created a Science Schedule Gantt chart that can be viewed in Appendix I.4.b. The first phase, where only Crew 1 will be present, will be from December 2035-February 2038, the second phase, where both Crew 1 and 2 will be present, will be from March 2038-September 2039, and the third and final phase, where only Crew 2 will be present will be from September 2039 - October 2041. All the phases will further be divided into 3-month test windows. Below is a summary of what each science objective will look like throughout the phases. Unless specified otherwise, the sample window section in each table below will be repeated in every phase.

For the first Tier 1 science objective, it is important to reiterate that there will be baseline testing done on human health for conducting comparisons to when the astronauts are on Mars. Then throughout the phases, the tests for each sub-objective along with the frequency of it throughout the phases are listed below in the sample window section of Table 28. The analysis will be summarized at the end of phases and any necessary intervention will take place.

Science Objective 1	**1.1 Discover the effects of long-term isolation in space on human psychology by studying behavioral and emotional health changes over time.**	**1.2 Discover the influence of zero-gravity and extended space travel on human vision by studying and documenting changes in eyesight over the duration of the Mars mission.**	**1.3 Understand the influence of microgravity on the human body's major systems (including the musculoskeletal, cardiovascular, and immune systems) by studying these changes in human physiology over time.**
Initial System Setup (Phase 1)	Analyze Earth testing; complete baseline testing	Analyze Earth testing; complete baseline testing	Analyze Earth testing; complete baseline testing
Sample Test Window	Conduct nightly sleep pattern tracking (8 hours at a time) Track emotion regulation device feedback (from 30 min./day sessions) Track AI therapy feedback (from 1x/week, 1hr sessions)	Conduct Optical Coherence Tomography Scans (bimonthly) Conduct Ocular Ultrasound Scans (bimonthly) Conduct applanation tonometry tests (biweekly) Analyze test results	Conduct DXA scans (monthly) Obtain EEG/EKG results (48 hr. test intervals, every 2 months) Obtain CBC/CMP counts (monthly) Analyze test results
Phase Closeout Period	Analyze phase data Implement necessary sleep pattern/schedule adjustments to improve psychological aspects of Mars mission	Analyze phase data Implement necessary vision interventions	Analyze phase data Implement necessary health interventions

Table 28: Summary of schedule for first Tier-1 Science Objective

For the second Tier 1 Science objective, for the first sub-objective, which is to discover daily weather patterns on Mars, the weather instruments will be set up during the first month of phase 1 and then throughout the phases, weather data will be collected for 5 min every 30 min. Weekly maintenance checks will also be conducted throughout the phases. For the second sub-objective, the instruments used to understand the influence of planetary plasmas and magnetic fields and their interaction with the solar wind plasma will be placed on the MTV and once it reaches orbit the instruments will be turned on and will collect data throughout the phases. The phase closeout period is listed as N/A since the instruments will continue to collect even after the mission finishes as the weather instruments will remain on the surface of Mars and the instruments will remain in MTV. In Table 29, a summary of what the second Tier 1 science objective will look like through the phases.

Science Objective 2	**2.1 Discover the daily weather patterns (temperature, humidity, wind speed) on Mars.**	**2.2 Understand the influence of planetary plasmas and magnetic fields and their interaction with solar wind plasma.**
Initial System Setup (Phase 1)	Setup the weather instruments on Mars surface and begin collecting weather data for 5 min every 30 min (this is how often the Perseverance rover's instruments collect weather data)	Instruments will be placed on the MTV and will be turned on When it reaches orbit, it will begin collecting data
Sample Test Window	Conduct weekly maintenance checks Then the daily weather report is created, where data is collected for 5 min every 30 min	Instruments continue to collect data
Phase Closeout Period	N/A	N/A

Table 29: Summary of schedule for second Tier-1 Science Objective

For the third Tier 1 science objective, the first couple of months will be used to set up the lab material for searching for signs of past life on Mars. In phases 1 and 3, solid samples will be collected near the habitat and then the necessary analysis work will be done. However, during phase 2 when both crews are present on Mars's surface because of the overlap period, soil samples will be collected from further away from the habitat with the assistance of a pressurized rover/ vehicle. In Table 30, a summary of what the third Tier 1 science objective will look like through the phases.

Science Objective 3	3.1 Discover more about the history of Mars by searching for signs of life in different areas.
Initial System Setup (Phase 1)	Set up lab materials
Sample Test Window	Phase 1: • Collect multiple soil samples from locations near the habitat. • Analyze nearby samples for microbes. Phase 2: • With a small group of astronauts, travel to areas away from habitat • Upon return with soil and clay samples, analyze for microbes. Phase 3: • Collect multiple soil samples from locations near the habitat. • Analyze nearby samples for microbes
Phase Closeout Period	Phase 1: End analysis of samples throughout different Mars climates, compare and analyze samples around habitat region. Phase 2: Analyze samples from different areas across different Mars climates, compare the samples and microbes possibly found. Send samples to Earth from Phase 1 and 2 on Crew 1 Return mission. Phase 3: End analysis of samples throughout different Mars climates, compare and analyze samples around regions. Compile collection of samples for Crew 2 return.

Table 30: Summary of schedule for third Tier-1 Science Objective

For the fourth Tier 1 Science objective, each phase will be focused on one of the sub-objectives. The first part of each phase will be focused on system setup, which will then be proceeded with planting the seeds and quantifying the growth, harvest, and then lastly test for food safety rating. The first phase will focus on comparing Martian soil growth rates alone to proven low-g plant growth technologies, the second phase will focus on how different compositions of nutrient additives to Martian soil affect plant growth rate and lastly, the third phase will focus on determining how different cyanobacteria composition affect plant growth rate. In Table 31, a summary of what the fourth Tier 1 science objective will look like through the phases.

Science Objective 4	**4.1 Compare Martian soil growth rates to proven low-g plant growth technologies**	**4.2 Discover which nutrient additives to Martian soil optimize plant growth**	**4.3 Determine effects of cyanobacteria on plants grown in Martian soil**
Initial System Setup	System setup	System setup	System setup
Sample Test Window	Phase 1: Plant seeds (3 mo. grow period) Quantify growth measures, Harvest, Test for food safety rating in Martian soil	Phase 2: Plant seeds (3 mo. grow period) 1,1,1% to 8,8,8% nutrient measures Quantify growth measures, Harvest, Test for food safety rating	Phase 3: Plant seeds (3 mo. grow period) Vary concentration of cyanobacteria Quantify growth measures, Harvest, Test for food safety rating
Phase Closeout Period	Phase 1: Transition to nutrient composition experiment	Phase 2: Transition to cyanobacteria experiment	Phase 3: System closeout

Table 31: Summary of schedule for fourth Tier-1 Science Objective

For the fifth Tier 1 science objective that focuses on water harvesting and ice core sample collection, the first 19-20 months (which extends for the entirety of Phase 1) will focus on setup and development. Water and ice core samples will only be collected in the winter months because during the warmer months, water on the surface readily evaporates and therefore sample collection is not possible. Therefore, analysis work will be conducted primarily in the warmer months. In Table 32, a summary of what the fifth Tier 1 science objective will look like through the phases.

Science Objective 5	5.1 Develop and test water discovery and harvesting technology on Mars.
Initial System Setup	19-20 months of system setup and development
Sample Test Window	Phase 1: • Winter begins in July, use excavation tools and technology to dig for water samples below surface. • Analyze and store samples as they are collected for further analysis during summer/spring/autumn months. Phase 2: • System Development and Improvement. Analysis of samples collected during winter. Phase 3: • Winter begins in April, use improved excavation tools and technology to dig for water samples below surface (easier to dig for water in the winter) • Analyze and store samples as they are collected for further analysis during summer/spring/autumn months
Phase Closeout Period	Phase 1: Winter ends in December. Store and analyze samples that have been collected during the winter. Evaluate the effectiveness of the technology developed and determine if changes and updates must be made for next winter. Phase 2: Winter begins in June, so prepare for more excavation of water possibly on the same travel missions as soil sample collection. Send samples to Earth from Phase 1 (and 2, if possible) on Crew 1 Return mission.

	Phase 3: End analysis of samples, compare and analyze samples around different regions. Analyze effectiveness of system. Compile collection of samples for Crew 2 return.

Table 32: Summary of schedule for fifth Tier-1 Science Objective

For the final Tier 1 Science objective, which is to assess the 3D printing capabilities and protection capabilities against radiation of Martian regolith, a series of 3 steps will be repeated throughout the phases. The first step will be the system setup including obtaining the Martian regolith. The second step will include preparing the samples using different compositions of Mars regolith (5% - 100%) and titanium alloy and the very last step will include testing the 3D printing abilities and radiation protection capabilities. At the end of the phase, analysis reports will be created to summarize the report's findings. In Table 33, a summary of what the sixth Tier 1 science objective will look like through the phases.

Science Objective 6	**6.1 Determine and test if 3D Printing using Mars regolith is possible and if Mars Regolith can be used to make protective coating against radiation.**
Initial System Setup	System setup and obtain Mars Regolith
Sample Test Window	Prepare samples using 5%, 10%, 15% Mars regolith and titanium alloy (these percentages increase with each phase/test window) Test 3D printing abilities and radiation protection capabilities
Phase Closeout Period	Preparing analysis reports and report findings

Table 33: Summary of schedule for sixth Tier-1 Science Objective

Furthermore, we also had to account for any communication blackouts during our mission. This happens when Mars is on the opposite side of the Sun from Earth, resulting in a communication blackout. The following were the blackout dates provided by the Mission Design team:

Sep. 17, 2036 - Oct. 1, 2036
Oct. 29, 2038 - Nov. 5, 2038 (during crew overlap period)
Dec. 9, 2040 - Dec. 23, 2040

The blackouts occur during Phase 2, Test Window 3 of our science schedule. During this time, none of our crew members will leave the habitat to collect soil samples for our third Tier 1 Science objective for safety reasons.

G. Risks

G.1 Risks

G.1.a Risk Identification and Ranking Process

Our team followed NASA's Guidelines for Risk Management Handbook to identify key mission risks for all subsystems. Beginning with the informal process of brainstorming to identify the most pressing risk for each subsystem element. This brainstorming process was completed both at the subsystem and mission architecture level to ensure that risk related to integration of subsystems were not overlooked. Risk documentation included aggregating the brainstormed risks and formally writing them to match NASA Risk Statement Standards. Additionally, context statements were created for risks including key circumstances surrounding the risk, contributing factors, uncertainties, the range of possible consequences, and related information such as what, where, when, how, and why. The next step was to analyze the risks using quantifiable measures for likelihood and consequence which are outlined in the following section: *Risk Rating Criteria*. The last step in the process was the plan for each identified risk to develop mitigation and contingency plans for each risk.

G.1.b Risk Rating Criteria

Likelihood		
Score	**Likelihood of Occurrence**	
5	Very Likely	>1E-01
4	High	1E-02 < x < E-01
3	Moderate	1E-03 < x < 1E-02
2	Low	1E-06 < x < 1E-03
1	Very Low	< 1E-06

Table 34: Risk Likelihood Rating Criteria

Consequence	
Scale	**Mission Impact**
5	Mission Catastrophic: Loss of mission, mission cancelation, failure to achieve any mission objectives.
4	Major Impact: Loss of instrument, loss of critical mission data set, failure to meet full minimum mission success criteria.
3	Moderate Impact: Loss of science objective, failure to meet full mission success criteria.
2	Minor Impact: Loss of non-critical data, delay in critical events.
1	Minimal Impact: Example: minor delay in obtaining non-critical data.

Table 35: Risk Consequence Rating Criteria

G.1.c Risk Matrices

Transit Vehicle Risk Matrix						
Likelihood	5					
	4	[13]				
	3		[14]	[7]	[8]	
	2		[5][12]	[16]	[2]	[6][17]
	1		[1][3]	[11][15]		[4][9][10]
		1	2	3	4	5
		Consequence				

Table 36: Transit Vehicle Risk Matrix

Risk Identifier	Risk Owner	Risk
1	Structures and Surface / Space Environment	Radiation Shielding Failure/Insufficient
2	Structures and Surface / Space Environment	Thermal Control System Failure
3	Structures and Surface / Space Environment	Small Debris Impact
4	Structures and Surface / Space Environment	Large Debris Impact
5	Propulsion	Cargo Ascent Vehicle Failure
6	Propulsion / Mission Design	Crew Ascent Vehicle Failure
7	Propulsion / Mission Design	Mars Route Transit Engine Non-Start
8	Propulsion / Mission Design	Earth Route Transit Engine Non-Start
9	Propulsion / Mission Design	Propellant Tank Rupture
10	Communications	Primary Communication System Failure
11	Communications	Support Satellite Deployment Failure
12	Communications	Damage to Mars Ground Equipment
13	Communications	Data Corruption During Transmission
14	ADC	EDL Misses Landing Site
15	ADC	MAV Ascends to Wrong Orbit
16	ADC	MAV suffers damage during Mars Stay
17	Propulsion	CNTR Development Delays

Table 37: Transit Vehicle Risk Descriptions

Surface Stay Risk Matrix						
Likelihood	5					
	4		[10]			
	3		[5]		[1]	
	2		[2]		[4][7][8]	
	1	[3]	[7]	[6]		[9][11]
		1	2	3	4	5
		Consequence				

Table 38: Surface Stay Risk Matrix

Risk Identifier	Risk Owner	Risk
1	Structures and Surface	Space Suit Depressurization from Breach
2	Structures and Surface	Seismic Activity
3	Structures and Surface	Minimized Personal Space
4	Structures and Surface	Power System Failure
5	Structures and Surface	Astronaut Psychological Stress
6	Structures and Surface	Radiation Shielding Failure
7	Structures and Surface	Thermal Control System Failure
8	Structures and Surface	Habitat Depressurization from Breach
9	Structures and Surface	Fire
10	Structures and Surface	Habitat Setup Incomplete for Crew Arrival
11	Structures and Surface	Lack of Essential Life-Support Elements

Table 39: Surface Stay Risk Descriptions

G.2 Mitigation

G.2.a Transit Vehicle Risk Mitigation

Risk Identifier	Risk	Risk Mitigation
1	Radiation Shielding Failure/Insufficient	Phenolic Material Selection
2	Thermal Control System Failure	Redundant Thermal Control System
3	Small Debris Impact	Double Hull Structural Design
4	Large Debris Impact	Trajectory Correction
5	Cargo Ascent Vehicle Failure	Re-launch cargo vehicle / Thorough Pre-Launch Inspections
6	Crew Ascent Vehicle Failure	Thorough Pre-Launch Inspections
7	Mars Route Transit Engine Non-Start	Descend Crew from MTV to Earth.
8	Earth Route Transit Engine Non-Start	Free Return Trajectory / Cycler Trajectory
9	Propellant Tank Rupture	Free Return Trajectory / Cycler Trajectory
10	Primary Communication System Failure	Support Satellites Adjust to Provide Primary Communications
11	Support Satellite Deployment Failure	Dual Support Satellites for Redundancy
12	Damage to Mars Ground Equipment	Daily checks, Routine Maintenance
13	Data Corruption During Transmission	On-site Storage of Data
14	EDL Misses Landing Site	Propellant Margin for Trajectory Correction Maneuver / Remote Control of Pressurized Rover
15	MAV Ascends to Wrong Orbit	Propellant Margin for Trajectory Correction Maneuver
16	MAV suffers damage during Mars Stay	Redundant MAVs on Martian Surface / Routine Maintenance
17	CNTR Development Delays	Increased Development Funding / Rigorous Testing Schedule

Table 40: Transit Vehicle Risk Mitigations

Phenolic Material Selection: A material such as Carbon-Carbon Phenolic Novolac mitigates the risk of radiation shielding failure during the long duration mission timeline due to its high durability.

Redundant Thermal Control System: Redundancy in thermal system design components will help mitigate the risk of thermal system failure throughout the mission timeline. Redundancy helps to eliminate the risk of single-point failures within the thermal system design. Thus, if one component of the thermal system fails a backup system can be utilized.

Double Hull Structural Design: A double hull design adds durability to the MTV's structure. This allows the MTV to withstand small debris impacts similar to the design of the ISS.

Trajectory Correction: Regarding large debris impacts, performing a trajectory correction maneuver to avoid large debris if necessary will prevent large-scale or mission catastrophic damage to the MTV.

Re-launch of Cargo Vehicle / Thorough Pre-launch Inspections: In the event of a cargo launch failure, having a reserve launch vehicle and supplies to resend crucial resources to Mars will prevent the astronauts from running out of mission critical supplies. Thorough pre-launch protocol including vehicle inspection and a pre-launch sequence that checks all launch systems will help prevent cargo ascent vehicle launch failure.

Thorough Pre-launch Inspections: Thorough pre-launch protocol including vehicle inspection and a pre-launch sequence that checks all launch systems will help prevent crew ascent vehicle launch failure.

Free Return Trajectory / Cycler Trajectory: Utilizing a free return trajectory to perform a Martian flyby that provides the proper gravity assist to place the MTV on a trajectory that will rendezvous with Earth. In the event of a failed engine relight, or a ruptured propellant tank, a free return trajectory can return the MTV to Earth with no additional propulsive input. Further research into free return and cycler trajectory maneuvers is required to determine feasibility.

Support Satellite Adjustment: In the event of Primary Communications System Failure, the support satellites utilized for additional coverage for the Mars habitat and EVA activities can take over the primary communications activities at a reduced rate to ensure crucial information transfers between Earth and Mars.

Dual Support Satellite for Redundancy: Utilizing two support satellites provides redundancy in case of a support satellite deployment failure as a single support satellite can provide the support coverage necessary for a successful mission.

Daily Checks / Routine Maintenance: Daily checks and routine maintenance can mitigate the risk of damage to Mars ground equipment through repairs of any damage as it arises.

On-site Data Storage: On-site data storage prevents the risk of loss of scientific data or data corruption during transmission as data can be re-sent when erroneous data is downlinked.

Propellant Margin / Remote Controlled Rover: In the event of an off-nominal EDL trajectory to the Martian surface, propellant margin for the landing vehicle allows for a trajectory correction maneuver to move the lander back to the targeted landing site. In the event of the lander missing the landing site, if the pressurized rover that will be used for EVA activities can be remotely controlled, it can traverse to the site of the lander to bring the crew to the habitat's location.

Propellant Margin for Trajectory Correction Maneuver: In the event of an off-nominal MAV trajectory to the MTV, propellant margin for the MAV allows for a trajectory correction maneuver to ensure that the MAV can dock with the MTV.

Redundant MAV / Routine Maintenance: Redundancy in both MAVs being on the surface prior to crew arrival to the Martian surface provides a backup system in the event of damage to the MAV during the long Martian stay timeline. In the event that one MAV is unusable, an additional redundant system may need to be sent with a subsequent resupply mission. Routine maintenance of the MAV systems prevents damage that would otherwise occur from remaining on the Martian surface for the extended mission timeline.

Increased Development Funding / Rigorous Testing Schedule: Providing the CNTR engine development project with increased funding and implementing a rigorous testing procedure that follows the product development cycle can mitigate the risk of delayed development for this mission critical technology.

G.2.b Surface Stay Risk Mitigation

Risk Identifier	Risk	Risk Mitigation
1	Space Suit Depressurization from Breach	Maintain Proximity to Pressurized Areas
2	Seismic Activity	Secure Habitat to Surface
3	Minimized Personal Space	Maintain Ability to Utilize Lander Long-term
4	Power System Failure	Multiple, Redundant Power Sources
5	Astronaut Psychological Stress	Astronaut Mental Health Initiatives
6	Radiation Shielding Failure	Install Additional Shielding
7	Thermal Control System Failure	Backup Thermal Control System
8	Habitat Depressurization from Breach	Separate, Airtight Doors
9	Fire	Fire Suppression and Fire-Resistant Materials
10	Habitat Setup Incomplete for Crew Arrival	Continue Living in Lander
11	Lack of Essential Life-Support Elements	Additional Supply Missions

Table 41: Surface Stay Risk Mitigations

Maintain Proximity to Pressurized Areas: While a breach in the space suit is a significant consequence, the risk can be mitigated by staying within a proximity to the habitat and/or rover in addition to equipping astronauts with backup suit repair equipment.

Secure Habitat to Surface: Prior to the crew moving into the habitat long-terms and the start of critical science inside, the habitat is to be properly fixed to the surface to mitigate the risk of seismic activity. This cannot be done during the automated setup period as it would require too much complexity to be automated prior to astronaut arrival.

Maintain Ability to Utilize Lander Long-term: Although the amount of space each astronaut requires has been carefully thought through, in the event astronauts require more space the lander can be utilized for a longer period for one or multiple of the astronauts to live in.

Multiple, Redundant Power Systems: Multiple nuclear fission surface reactors (SAFE-400) will be used in the case that one of the reactors goes down. Minimal solar capability will also be available for vital operations.

Astronaut Mental Health Initiatives: Scheduling recurring astronaut therapy sessions and maintaining the ability for astronauts to take breaks and spread out would mitigate the risk of psychological stress during the mission.

Install Additional Shielding: Installing additional layers of bricks to the outside of the habitat would increase the amount of shielding available. This could only be implemented in more critical areas of the habitat such as crew living quarters or other places where the crew would spend most of their time.

Backup Thermal Control Systems: The heat pump used for heating the habitat is reversible to cool this habitat. This allows for multiple heat pump units to be used for both heating and cooling, which created redundancy for the thermal control system.

Separate Airtight Doors: Separate, airtight doors would be installed between each module in the habitat. These would remain open during normal operations and living in the habitat but could be quickly closed and sealed should there be a breach and depressurization of any area in the habitat.

Fire Suppression and Fire-Resistant Materials: Maintain the functionality of fire-retardant materials and fire suppression systems in the habitat. Separate airtight doors would also be closed and locked around the module with a fire risk in the event the fire becomes uncontrollable. Should living quarters be deemed unsafe to live in, astronauts can temporarily live in the lander until issues and damage are fixed.

Continue Living in Lander: In the event the habitat is not ready on schedule, the astronauts would continue living in the lander. This requires minimal action as astronauts would already be living in the lander while the habitat is being set up after they arrive and until completion.

Additional Supply Missions: Additional items that are lacking would be scheduled to be shipped in future supply missions or the second crew arrival mission for their rotation. In the event this is not possible, astronauts could work to repurpose an item into an essential one that is limited in quantity.

H. Final Thoughts

H.1 Mission Architecture Summary

The full mission architecture for ARES-1 can be seen in the table below:

Science Objectives	
Objective	**Description**
1	Determine the short and long-term effects of zero-g and space isolation on humans.
2	Determine daily weather patterns on Mars with a special emphasis on solar wind and radiation effects.
3	Determine the possibility of past life on Mars.
4	Determine if Martian soil is suitable for agriculture.
5	Demonstrate success rate of water harvesting ISRU technology.
6	Demonstrate technology for ISRU of Mars regolith.

Mission Design				
Mission	**Departure**	**Arrival**	**TOF (days)**	**Post-Launch ΔV (km/s)**
Pre-Arrival 1	04/17/2033	11/08/2033	205	6.050
Pre-Arrival 2	04/28/2033	10/15/2033	170	6.389
Crew 1 (E-M)	07/27/2035	11/29/2035	125	7.498
Resupply 1	09/02/2037	04/05/2038	215	2.084*
Crew 2 (E-M)	09/20/2037	02/12/2038	145	8.255
Resupply 2	09/10/2039	07/21/2040	315	2.037*
Crew 1 (M-E)	09/16/2039	02/28/2040	165	8.706
Crew 2 (M-E)	10/16/2041	04/09/2042	175	8.985
** Launch vehicle deploys transit vehicle directly onto transfer orbit*				

Transportation Systems			
Mission	**Vehicle**	**Propulsion**	**Payload Mass**
Pre-Arrival 1	SLS Block 2 (Cargo)	LH2/LOX	46 MT
Pre-Arrival 2	SLS Block 2 (Cargo)	LH2/LOX	46 MT
Crew 1 (E-LEO)	SLS Block 2 (Crew)	LH2/LOX	43 MT
Crew 1 (LEO-M)	MTV	Centrifugal Nuclear Thermal Reactor (CNTR)	1078 MT
Resupply 1	SpaceX Falcon Heavy	LCH4/LOX	5 MT
Crew 2 (E-LEO)	SLS Block 2 (Crew)	LH2/LOX	43 MT
Crew 2 (LEO-M)	MTV	Centrifugal Nuclear Thermal Reactor (CNTR)	1078 MT
Resupply 2	SpaceX Falcon Heavy	LCH4/LOX	5 MT
Crew 1 (M-E)	MTV	Centrifugal Nuclear Thermal Reactor (CNTR)	407 MT
Crew 2 (M-E)	MTV	Centrifugal Nuclear Thermal Reactor (CNTR)	407 MT

Habitat Systems	
Power Generation System	4 x SAFE-400 100kW Nuclear Reactor
Power Storage System	2 x 1200 kWh Lithium Nickel Cobalt Aluminum Oxide (LNCAO) Battery System
Heating System	Heat Pump
Cooling System	Reversible Heat Pump
Structure	Inflatable (0.46 m thickness)
Room Surface Area	320 m^2
Total Surface Area	384 m^2
Total Volume	1256 m^3
Life Support Systems	
Water Supply	Prepackaged & Recycled
Contaminant Mitigation	Hermetically Sealed Sample Containers
Pressurized Areas	Pressurized Habitat & Pressurized Rovers
Oxygen Supply	Prepackaged & Extracted from Mars via BOXIE
CO2 Recycling	Captured from Human Presence
Waste Management	Landfill on Mars
Radiation Shielding	
MTV	10 cm Carbon-Carbon Phenolic Novolac with a 10% Tantalum Powder Dope
Habitat System	18 cm Aramid Fiber Wall & 400 cm Regolith Brick
Communications Systems	
Orbit	Areostationary
Orbiter Configuration	3-Satellite Constellation with 10.2° Orbital Separation
Primary Satellite	MTV (9 m antenna)
Support Satellites	2 x Small Satellite (6 m antenna)
Earth Ground Station	Deep Space Network (70 m antenna)
Mars Ground Station	Habitat System (1 m antenna)
Bandwidth	32 GHz Ka-Band
Data Transmission Rate	2.3 Mbps
Voice & Video Rate	52 Mbps
Entry-Descent-Landing (EDL)	
Payload Mass / Gross Mass	36.66%
Phase 1	Hypersonic Aero-Maneuvering
Phase 2	Supersonic Retro-Propulsive Braking
Phase 3	Constant Velocity Powered Descent
Mars Ascent Vehicle (MAV)	
Gross Mass	26,000 kg
Weight on Mars	97,000 N
Propellant	RP-1/LOX
Engine	3 x Launch Engine-2 (97.8 kN/Engine, 293 kN Total Thrust)
Propellant Storage	Multi-Layer Insulation (RP-1/LOX) & 30-Day Top Off (LOX) via BOXIE

Novel Technologies	
Purpose	**Technology**
Radiation Mitigation	Martian Regolith Bricks
Food Production	Scaled VEGGIE System
Life Support/MAV	BOXIE/MAV Propellant Storage
Mission Life Cycle Cost	
$658.02 Billion USD (FY2023)	

Table 42: ARES-1 Mission Architecture

H.2 Challenges

H.2.a Technical Challenges

Over the course of the Spring 2023 semester, the development of ARES-1 posed some technical challenges across all subsystem teams.

For the cost & schedule team, the cost estimation of novel technologies and architectures posed a challenge, as many unique novel ideas had little to no public documentation in terms of cost, and estimates were performed using the cost by analogy method and based on a technology's estimated TRL. Moreover, since ARES-1, being a crewed mission to Mars, is one of a kind, CERs for this type of mission were nonexistent, and CERs for crewed missions were hard to come by, thus posing another difficulty when determining the mission's development costs.

When it came to calculations, the space environment team faced the challenge of determining an accurate and robust method of determining the amount of radiation astronauts were exposed to on the MTV. Similarly, the structures & surface systems team was tasked with developing a preliminary design for the habitat system, and given little to no heritage of such a system, the team had to develop a sizing model from scratch. This habitat system sizing model was iterated multiple times based on internal and external feedback, and the development of further requirements.

During the development of the Mars Ascent Vehicle (MAV), the ADC team initially planned on utilizing a LCH4/LOX propellant. However, LCH4, being a cryogenic substance, imposed a major challenge in its ability to be stored for a long duration. Thus, the ADC team switched to an RP-1/LOX propellant and developed a safe and reliable storage method for both the fuel and oxidizer using multi-layer insulation and a scaled version of MOXIE to maintain a 3-month supply of propellant on hand at all times.

A key challenge faced by the mission design team included the steep learning curve required to use NASA's GMAT software for optimizing trajectories to and from Mars. Initially, the mission design team performed literature reviews and utilized NASA's trajectory browser to determine viable trajectories for ARES-1. However, due to the unique mission profile and the limited public data on Mars-Earth trajectories post-2040, GMAT was introduced.

Given the iterative methodology used to optimize the trajectories for ARES-1, small changes to each mission's ΔV were being made. Simultaneously, other subsystem teams were developing sizing estimates for their architectures, leading to small deviations in mass. Both seemingly small variations posed a challenge to the propulsion team, as they resulted in larger changes to propellant and thrust requirements for the MTV. Additionally, since the MTV was powered and propelled using nuclear technology, the propulsion team faced challenges in accessing public information about this technology due to its export-controlled nature.

Finally, the communications team faced a challenge in validating the link budgets that were developed due to the novel-factor of the mission, as well as the little public information readily available. Thus, ensuring the accuracy of parameters such as system noise temperature, environmental losses, etc. was not a straightforward task. Moreover, iterating on the link budget was again difficult to validate due to the varying constraints of antenna types, communications platforms, and options available for consideration. Due to this, methods to narrow down which factors to alter needed to be developed, alongside in-depth analyses of each parameter.

H.2.b Program Challenges

Aside from technical challenges, ARES-1 also faced, and anticipates, program and management-level challenges impacting the overall mission.

First, a major program challenge would be the unpredictable and unknown development timeline for existing and future technologies. For example, the CNTR engine used on the MTV is a TRL 6 technology, and this lower TRL could lead to extending or delaying the timeline of ARES-1. Similarly, the MAV contains a TRL 5 technology in the form of storing the RP-1/LOX for a long duration of time on the Martian surface. The development of such a technology may delay the scheduling of ARES-1. Existing technologies such as SpaceX's Falcon Heavy and SLS may also face development challenges. Although these technologies are flight-proven, other impacts to timeline can exist. For Falcon Heavy, the ability to assemble, integrate, and launch multiple vehicles during the assembly of the MTV in LEO may prove difficult, and is currently unknown. For SLS, potential challenges regarding the ability to assemble, launch, and integrate two rockets with a short turn-around time for both pre-arrival launches scheduled for April 17, 2033, and April 28, 2033 exist. Moreover, the availability and infrastructure of the launch pads to support two high-cadence SLS launches are yet to be known.

The next challenge faced with the development timeline of ARES-1 is that of a global nature. Being a milestone for human spaceflight, ARES-1 will require collaboration from nations worldwide. Thus, in the future, those in charge of ARES-1 will be tasked with managing the engineering and development of systems, technologies, and architectures to be flown to Mars on a global scale.

Since ARES-1 would be the first human exploration mission on Mars, the selection of the 8 astronauts which will comprise the two crews will not be an easy task. A program-level challenge will be the selection of these eight humans from a global pool of hundreds and thousands of exceptional and worthy candidates to represent and explore the Martian frontier on behalf of humanity. Furthermore, although space agencies across the globe have previously sent unmanned missions to the surface of Mars, we are yet to know how living on Mars truly is. Preparing astronauts for an extended stay on Mars will pose a challenge in crew training, and simulating the physiological, psychological, and environmental effects of ARES-1.

Finally, and most importantly, will be the challenge of unifying the global public to support a Mars human exploration mission politically, financially, and socially. This will include potentially bringing taxpayers from around the world to elect officials, vote on policies, and join the workforce to make ARES-1 a reality. Additionally, given the emergence of renewable energy sources and the recent importance of environmental health on a global scale, there will be a need for the public to adopt and support the use of nuclear power technology. This will be vital in aiding the development and usage of key architectures such as CNTRs, SAFE-400, etc. vital to ARES-1. Together, nations will be required to join hands in bringing humanity interplanetary.

H.3 Moving Forward

Although outstanding work has been this semester by the fifteen undergraduates on Mars Team 3 part of the AAE 450 Spring 2023 class at Purdue University, ARES-1 has only been developed to roughly a Pre-Phase A level and has great potential to be brought to life.

Future public and private organizations may take the groundwork of ARES-1 and mature it throughout the development life cycle. During the next phase, detailed design of the MTV, EDL vehicle, habitat and life support systems, and MAV would be done. Phase A would also include the creation of an MTV orbital assembly plan, preliminary verification & validation plans, and human rating & evaluation plans. Finally, Phase A would also include mission software development and mission risk assessments, including further analysis of free-return trajectories to mitigate the risk of MTV engine non-start.

Looking ahead beyond Phase A would be the remainder of the mission life cycle: Phase B (Design & Technology Completion), Phase C (Final Design and Fabrication), Phase D (System Assembly, Integration and Test, Launch), Phase E (Operations and Sustainment), and Phase F (Closeout). These steps would enable ARES-1 to propel humanity one step further into the cosmos.

I. Appendices

I.1 Table of Proposal Participants

Name	Role
Shashwat Punjani	Project Manager, Mission Design
Laney Ciaccio	Systems Engineer, Cost & Schedule, Communications
Caden Dosier	Propulsion Lead, Space Environment Lead
Calvin Carta	Communications Lead, ADC
Sheetal Jayasaal	Cost & Schedule Lead
Keely Cunnane	Structures & Surface Stay Lead, Propulsion
Kevin Spiegelman	Mission Design Lead
Keertana Yendru	ADC Lead, Structures & Surface Stay
Maya McDonald	Mission Design, Cost & Schedule
Mahira Ahmad	Cost & Schedule, Structures & Surface Stay
Jacob Wargon	Structures & Surface Stay, Space Environnent
Nicholas Allegro	Propulsion, Space Environment
Walter Brownlee	Propulsion, Structures & Surface Stay
Davis Bradstreet	Mission Design, Communications
Keshav Agarwal	ADC, Structures & Surface Stay

I.2 Authors

Section	Author(s)
A. Summary	Shashwat Punjani
B. Fact Sheet	Shashwat Punjani
C. Table of Contents	Shashwat Punjani
D.1 Science Objectives	Mahira Ahmad
D.2 Science Traceability Matrix	Sheetal Jayasaal
D.3 Landing Site Selection	Keertana Yendru
D.4.a Novel Technologies, BOXIE	Keertana Yendru
D.4.b Novel Technologies, Scaled Veggie System for Food Production	Laney Ciaccio
D.4.c Novel Technologies, Martian Regolith Bricks	Caden Dosier
E.1.a Concept of Operations (ConOps) & Mission Sequence	Shashwat Punjani
E.1.b Systems Engineering	Laney Ciaccio
E.1.c Human Health Considerations	Maya McDonald Caden Dosier
E.2.a Launch Scheduling and Mission Timeline	Kevin Spiegelman Davis Bradstreet
E.2.b Transfer Type Considerations	Kevin Spiegelman
E.2.c Trajectory Optimization	Davis Bradstreet
E.2.d Analysis of Electric Propulsions for Mars Orbit Insertion	Kevin Spiegelman
E.2.e Final Trajectory Selections	Kevin Spiegelman

E.3.a.i Launch Vehicles, Pre-Arrival Cargo	Keely Cunnane
E.3.a.ii Launch Vehicles, Crewed	Walter Brownlee
E.3.a.iii Launch Vehicles, Cargo Resupply	Caden Dosier
E.3.b.i Mars Transit Vehicle (MTV), Structural Modules	Nicholas Allegro
E.3.b.ii Mars Transit Vehicle (MTV), Thermal Systems	Nicholas Allegro
E.3.b.iii Mars Transit Vehicle (MTV), Propulsion Systems	Caden Dosier
E.3.b.iv Mars Transit Vehicle (MTV), Propellant Requirements	Caden Dosier
E.3.b.v Mars Transit Vehicle (MTV), Power Systems	Walter Brownlee
E.3.b.vi Mars Transit Vehicle (MTV), Radiation Shielding	Caden Dosier
E.3.c.i Entry-Descent-Landing (EDL) Vehicle, Method Chosen	Calvin Carta
E.3.c.ii Entry-Descent-Landing (EDL) Vehicle, Sequence Diagram	Keertana Yendru
E.3.d.i Mars Ascent Vehicle (MAV), Mars Ascent Sequence	Calvin Carta
E.3.d.ii Mars Ascent Vehicle (MAV), Final Design	Keshav Agarwal
E.3.d.iii Mars Ascent Vehicle (MAV), ISRU Production	Keertana Yendru Keshav Agarwal
E.3.d.iv Mars Ascent Vehicle (MAV), Propellant Storage	Calvin Carta
E.4.a.i Surface Systems, Habitat System, Key Considerations	Jacob Wargon
E.4.a.ii Surface Systems, Habitat System, Design Analysis	Jacob Wargon Keely Cunnane
E.4.a.iii Surface Systems, Habitat System, Final Design	Keely Cunnane
E.4.a.iv Surface Systems, Habitat System, CAD Model	Walter Brownlee Keely Cunnane
E.4.a.v Surface Systems, Habitat System, Thermal Systems	Nicholas Allegro
E.4.b.i Surface Systems, Life Support Systems, Water Supply	Keertana Yendru
E.4.b.ii Surface Systems, Life Support Systems, Contaminant Mitigation	Walter Brownlee
E.4.b.iii Surface Systems, Life Support Systems, Pressurized Areas	Keely Cunnane
E.4.b.iv Surface Systems, Life Support Systems, Oxygen Supply	Mahira Ahmad
E.4.b.v Surface Systems, Life Support Systems, CO2 Recycling	Mahira Ahmad
E.4.b.vi Surface Systems, Life Support Systems, Waste Management	Walter Brownlee
E.4.c Surface Systems, Radiation Shielding	Caden Dosier
E.5.a Communications Systems, Key Considerations	Laney Ciaccio
E.5.b Communications Systems, Physical Assets	Calvin Carta Davis Bradstreet
E.5.c Communications Systems, Link Budget	Calvin Carta Davis Bradstreet
F.1 Life Cycle Cost	Sheetal Jayasaal
F.2 Schedule	Maya McDonald Sheetal Jayasaal
G.1 Risks	Laney Ciaccio Jacob Wargon
G.2 Mitigation	Laney Ciaccio Jacob Wargon
H. Final Thoughts	Shashwat Punjani

I.1 Table of Proposal Participants	Shashwat Punjani
I.2 Authors	Shashwat Punjani
I.3 Satisfaction of ABET Requirements	Shashwat Punjani Jacob Wargon
I.4 Schedules	Maya McDonald Mahira Ahmad
I.5 Habitat System Power Budget	Keely Cunnane
I.6 Link Budget & Satellite Constellations	Calvin Carta
I.7.a Sizing, MTV	Caden Dosier
I.7.b Sizing, EDL Vehicle	Keertana Yendru
I.7.c Sizing, Habitat System	Keely Cunnane
I.7.d Sizing, MAV	Keertana Yendru
I.8 First Order Algorithms (FOAs)	Keely Cunnane Jacob Wargon
I.9 Mission Life Cycle Cost	Sheetal Jayasaal
I.10 Master Equipment List	Laney Ciaccio
I.11 Heritage	Shashwat Punjani Laney Ciaccio
I.12 List of Abbreviations and Acronyms	Shashwat Punjani
I.13.a References, Science Objectives	Sheetal Jayasaal
I.13.b References, Mission Design	Kevin Spiegelman
I.13.c References, Propulsion	Caden Dosier
I.13.d References, Space Environment	Caden Dosier
I.13.e References, Communications	Calvin Carta
I.13.f References, ADC	Keertana Yendru
I.13.g References, Cost & Schedule	Sheetal Jayasaal
I.13.h References, Structures & Surface Stay	Keely Cunnane Jacob Wargon

I.3 Satisfaction of ABET Requirements

<table>
<tr><th>ABET Requirement</th><th>Satisfaction</th></tr>
<tr><td>a. Provide a general description of the system to be delivered by this design project.</td><td>This requirement was satisfied in the following sections of this document:
A. Summary
B. Fact Sheet</td></tr>
<tr><td>b. What is the purpose of this system? For whom is it intended?</td><td>This requirement was satisfied in the following section of this document:
A. Summary</td></tr>
<tr><td>c. Describe how you used the engineering design process to create your product. Include how you were able to develop and conduct appropriate experiments, analyze and interpret data, and use engineering judgment to draw conclusions related to the development of your system.</td><td>The team used a variety of design techniques such as a Pareto analysis, first order algorithms, and iterations on point designs to move through phases of the engineering design process as highlighted in I.5 through I.10. During biweekly design reviews, feedback was utilized to alter designs and make changes along the way to proceed with a more robust design. Data from literature reviews and trade studies further aided in drawing conclusions related to system development.</td></tr>
<tr><td>d. Describe the design constraints, and resulting specifications, incorporated into your system (list a minimum of 3).</td><td>This requirement was satisfied in the following sections of this document:
A. Summary
E.1.b Systems Engineering</td></tr>
<tr><td>e. Describe why and how each of the following factors did or did not influence your design specifications and constraints:
Public health, safety, and welfare
Global factors
Cultural factors
Social factors
Environmental factors
Economic Factors</td><td>This requirement was satisfied in the following sections of this document:
D. Science Investigation & Implementation
F. Cost & Schedule
H.2 Challenges
H.3 Moving Forward</td></tr>
<tr><td>f. Describe any appropriate engineering standards incorporated into the creation of your product (e.g., FAR, ***).</td><td>This requirement was satisfied in the following section of this document:
E.1.b Systems Engineering</td></tr>
<tr><td>g. Describe the final status of your product.</td><td>This requirement was satisfied in the following sections of this document:
A. Summary
B. Fact Sheet
H.1 Mission Architecture Summary</td></tr>
</table>

h. Describe the makeup of your project team and how you were organized to establish goals, plan tasks, and meet the objectives of this project.	• I.1 Table of Proposal Participants
i. Did your project require the production of any written documentation other than this document (i.e., manuals, educational materials, etc.)? If so, describe the types, composition, and nature of the audiences for whom these materials were intended.	Conceptual Design Review (ConDR) and Preliminary Design Review (PDR) presentations were created by the team to receive feedback on our system architecture and answer any questions put forth by our peers, instructors, and reviewers. The intended audience for these materials was students and faculty within Purdue's AAE department and any industry reviewers in attendance.
j. Describe the types, composition, and nature of the audiences in attendance for the final oral design review. Discuss how you prepared for this audience.	The final oral design review was attended by peers from the senior design course, the teaching team for this course, graduate students from Purdue AAE, and industry professionals invited to attend the review session. Our team prepared for this audience by ensuring that our presentation matched the background knowledge of our audience, giving a high-level overview to our architecture and ensuring the information presented would provide the information necessary for an industry-standard Pre-Phase A proposal.

I.4 Schedules

I.4.a Astronaut Schedule

SHIFT A																								
Activity/Sol Hour	0001-0100	0100-0200	0200-0300	0300-0400	0400-0500	0500-0600	0600-0700	0700-0800	0800-0900	0900-1000	1000-1100	1100-1200	1200-1300	1300-1400	1400-1500	1500-1600	1600-1700	1700-1800	1800-1900	1900-2000	2000-2100	2100-2200	2200-2300	2300-0001
Sleep																								
Hygiene																								
Meal Time																								
Maintenance																								
Research/Science																								
Medical Testing																								
Exercise																								
Human Experience																								
SHIFT B																								
Activity/Sol Hour	0001-0100	0100-0200	0200-0300	0300-0400	0400-0500	0500-0600	0600-0700	0700-0800	0800-0900	0900-1000	1000-1100	1100-1200	1200-1300	1300-1400	1400-1500	1500-1600	1600-1700	1700-1800	1800-1900	1900-2000	2000-2100	2100-2200	2200-2300	2300-0001
Sleep																								
Hygiene																								
Meal Time																								
Maintenance																								
Research/Science																								
Medical Testing																								
Exercise																								
Human Experience																								

I.4.b Science Schedule

I.4.b.i Phase One Schedule

PHASE ONE - Crew 1 Science													
					December 2035 -February 2038								
TIER 1 SCIENCE OBJECTIVE	**TASK TITLE**	**START DATE**	**DUE DATE**	**DURATION**	**Dec 2035 - Feb 2036**	**Mar 2036 - May 2036**	**June 2036 - Aug 2036**	**Sept 2036 - Nov 2036**	**Dec 2036 - Feb 2037**	**Mar 2037 - May 2037**	**June 2037 - Aug 2037**	**Sept 2037 - Nov 2037**	**Dec 2037 - Feb 2038**
1	**Determine the short- and long-term effects of zero-g and space isolation on humans**	Dec. 2034 (baseline testing completed prior to mission start date)	Aug. 2043 (follow up testing to be completed after mission end date)	Entire Mars Mission									
1.1	Discover the effects of long-term isolation in space on human psychology by studying behavioral and emotional health changes over time.			**Phase 1: 27 months** Phase 2 Phase 3	Initial System Setup: analyze Earth testing; complete baseline testing	Test Window 1: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Test Window 2: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Test Window 3: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Test Window 4: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Test Window 5: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Test Window 6: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Test Window 7: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Phase 1 closeout: analyze phase 1 data Implement necessary sleep pattern/schedule adjustments to improve psychological aspects of Mars mission
1.2	Discover the influence of zero-gravity and extended space travel on human vision by studying and documenting changes in eyesight over the duration of the Mars mission.			**Phase 1: 27 months** Phase 2 Phase 3	Initial System Setup: analyze Earth testing; complete baseline testing	Test Window 1: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Test Window 2: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Test Window 3: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Test Window 4: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Test Window 5: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Test Window 6: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Test Window 7: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Phase 1 closeout: analyze phase 1 data Implement necessary vision interventions
1.3	Understand the influence of microgravity on the human body's major systems (including the musculoskeletal, cardiovascular, and immune systems) by studying these changes in human physiology over time.			**Phase 1: 27 months** Phase 2 Phase 3	Initial System Setup: analyze Earth testing; complete baseline testing	Test Window 1: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Test Window 2: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Test Window 3: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Test Window 4: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Test Window 5: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Test Window 6: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Test Window 7: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Phase 1 closeout: analyze phase 1 data Implement necessary health interventions
2	**Determine daily weather patterns on Mars with a special emphasis on solar wind and radiation effects**	Dec 2035 (The weather instruments will be launched with Crew 1 and the other instruments will be placed on the MTV)	Aug 2043	Entire Mars Mission									
2.1	Discover the daily weather patterns (temperature, humidity, wind speed) on Mars			**Phase 1: 27 months** Phase 2 Phase 3	Setup the weather instruments on Mars surface and begin collecting weather data for 5 min every 30 min (this is how often the Perseverance rover's instruments collect weather data)	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min
2.2	Understand the influence of planetary plasmas and magnetic fields and their interaction with the solar wind plasma			**Phase 1: 27 months** Phase 2 Phase 3	Instruments will be placed on the MTV and will be turned on when it reaches orbit. It will begin collecting data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data
3	**Determine possibility of past life on Mars**	Dec. 2035	Aug. 2042	Entire Mars Mission									
3.1	Discover more about the history of Mars by searching for signs of life in different areas.			Phase 1 of experiment: 27 months	Initial System Setup: set up lab materials	Test Window 1: - Collect multiple soil samples from locations near the habitat - Analyze nearby samples for microbes	Test Window 2: - Collect multiple soil samples from locations near the habitat - Analyze nearby samples for microbes	Test Window 3: - Collect multiple soil samples from locations near the habitat - Analyze nearby samples for microbes	Test Window 4: - Collect multiple soil samples from locations near the habitat - Analyze nearby samples for microbes	Test Window 5: - Collect multiple soil samples from locations near the habitat - Analyze nearby samples for microbes	Test Window 6: - Collect multiple soil samples from locations near the habitat - Analyze nearby samples for microbes	Test Window 7: - Collect multiple soil samples from locations near the habitat - Analyze nearby samples for microbes	End of Phase 1: End analysis of samples throughout different Mars climates, compare and analyze samples around habitat region
4	**Determine if Martian soil is suitable for agriculture**	Dec. 2035	Aug. 2042	Entire Mars Mission									
4.1	Compare Martian soil growth rates to proven low-g plant growth technologies.	Dec. 2035	Feb. 2038	**Phase 1: 27 months**	Initial system setup	Initial system setup	Trial 1 - Plant seeds (3 mo. grow period) - Quantify growth measures - Harvest - Test for food safety rating in Martian soil	Trial 2 - Plant seeds (3 mo. grow period) - Quantify growth measures - Harvest - Test for food safety rating in Martian soil	Trial 3 - Plant seeds (3 mo. grow period) - Quantify growth measures - Harvest - Test for food safety rating in Martian soil	Trial 4 - Plant seeds (3 mo. grow period) - Quantify growth measures - Harvest - Test for food safety rating in Martian soil	Trial 5 - Plant seeds (3 mo. grow period) - Quantify growth measures - Harvest - Test for food safety rating in Martian soil	System Closeout Transition to nutrient composition experiment	Setup nutrient composition experiment
4.2	Discover which nutrient additives to Martian soil optimize plant growth.	N/A	N/A	**Phase 2**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4.3	Determine effects of cyanobacteria on plants grown in Martian soil.	N/A	N/A	**Phase 3**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5	**Demonstrate success rate of water harvesting ISRU technology**	Dec. 2034 (for initial development of technology)	Aug. 2042	Entire Mars Mission									
5.1	Develop and test water discovery and harvesting technology on Mars.			Duration of development: 19-20 months. Tests towards the end of Phase 1: 6-7 months	Initial System Setup	System Setup and Development	System Setup and Development	System Setup and Development	System Setup and Development	System Setup and Development	Test Window 1: - Winter begins in July, use excavation tools and technology to dig for water samples below surface (easier to dig for water in the winter) - Analyze and store samples as they are collected for further analysis during summer/spring/autumn months	Test Window 2: - Winter continues, use excavation tools and technology to dig for water samples below surface (easier to dig for water in the winter) - Analyze and store samples as they are collected for further analysis during summer/spring/autumn months	End of Phase 1: Winter ends in December. Store and analyze samples that have been collected during the winter. Evaluate the effectiveness of the technology developed and determine if changes and updates must be made for next winter.
6	**Demonstrate technology for ISRU of Mars regolith**	Dec. 2035	Aug. 2043	Entire Mars Mission									
6.1	Determine and test if 3D Printing using Mars regolith is possible and if Mars Regolith can be used to make protective coating against rust and radiation			**Phase 1: 27 months** Phase 2 Phase 3	Initial System Setup and obtain the Mars regolith	Initial System Setup and obtain the Mars regolith	Prepare samples using 5%, 10%, 15% Mars regolith and titanium alloy	Test 3D printing abilities and radiation protection capabilities	Preparing analysis reports and report findings	System setup preparation for second testing and obtain Mars regolith for second batch	Prepare samples using 5%, 10%, 15% Mars regolith and titanium alloy	Test 3D printing abilities and radiation protection capabilities	Preparing analysis reports and report findings

I.4.b.ii Phase Two Schedule

PHASE TWO - Crew 1 and 2 Science										
					March 2038 - Sept 2039					
TIER 1 SCIENCE OBJECTIVE	**TASK TITLE**	**START DATE**	**DUE DATE**	**DURATION**	**March 2038 - May 2038**	**Jun 2038 - Aug 2038**	**Sept 2038 - Nov 2038**	**Dec 2038 - Feb 2039**	**Mar 2039 - May 2039**	**Jun 2039 - Sept 2039**
1	**Determine the short- and long-term effects of zero-g and space isolation on humans**	Dec. 2034 (baseline testing completed prior to mission start date)	Aug. 2043 (follow up testing to be completed after mission end date)	Entire Mars Mission						
1.1	Discover the effects of long-term isolation in space on human psychology by studying behavioral and emotional health changes over time.			Phase 1 **Phase 2: 19 months** Phase 3	Test Window 1: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Test Window 2: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Test Window 3: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Test Window 4: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Test Window 5: - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Phase 2 closeout: analyze phase 2 data Implement necessary sleep pattern/schedule adjustments to improve psychological aspects of Mars mission
1.2	Discover the influence of zero-gravity and extended space travel on human vision by studying and documenting changes in eyesight over the duration of the Mars mission.			Phase 1 **Phase 2: 19 months** Phase 3	Test Window 1: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Test Window 2: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Test Window 3: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Test Window 4: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Test Window 5: - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Phase 2 closeout: analyze phase 2 data Implement necessary vision interventions
1.3	Discover the influence of zero-gravity and extended space travel on human vision by studying and documenting changes in eyesight over the duration of the Mars mission.			Phase 1 **Phase 2: 19 months** Phase 3	Test Window 1: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Test Window 2: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Test Window 3: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Test Window 4: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Test Window 5: - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Phase 2 closeout: analyze phase 2 data Implement necessary health interventions
2	**Determine daily weather patterns on Mars with a special emphasis on solar wind and radiation effects**	Dec 2035 (The weather instruments will be launched with Crew 1)	Aug 2043	Entire Mars Mission						
2.1	Discover the daily weather patterns (temperature, humidity, wind speed) on Mars			Phase 1 **Phase 2: 19 months** Phase 3	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min *NOTE: In case of any permanent damage to instruments, spare instruments will be brought with the crew 2 and setup will first be done*	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min
2.2	Understand the influence of planetary plasmas and magnetic fields and their interaction with the solar wind plasma			Phase 1 **Phase 2: 19 months** Phase 3	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data
3	**Determine possibility of past life on Mars**	Dec. 2035	Aug. 2042	Entire Mars Mission						
3.1	Discover more about the history of Mars by searching for signs of life in different areas.			Phase 2 of experiment: 19 months	Test Window 1: - With a small group of astronauts, travel to areas away from habitat (it would be best to do this during the overlap so that the habitat isn't left with very few people to maintain it) - Upon return with soil and clay samples, analyze for microbes	Test Window 2: - With a small group of astronauts, travel to areas away from habitat (it would be best to do this during the overlap so that the habitat isn't left with very few people to maintain it) - Upon return with soil and clay samples, analyze for microbes	Test Window 3 (Communications Blackout): - Collect multiple soil samples from locations near the habitat - Analyze nearby samples for microbes	Test Window 4: - With a small group of astronauts, travel to areas away from habitat (it would be best to do this during the overlap so that the habitat isn't left with very few people to maintain it) - Upon return with soil and clay samples, analyze for microbes	Test Window 5: - With a small group of astronauts, travel to areas away from habitat (it would be best to do this during the overlap so that the habitat isn't left with very few people to maintain it) - Upon return with soil and clay samples, analyze for microbes	End of phase 2: Analyze samples from different areas across different Mars climates, compare the samples and microbes possibly found. Send samples to Earth from Phase 1 and 2 on Crew 1 Return mission.
4	**Determine if Martian soil is suitable for agriculture**									
4.1	Compare Martian soil growth rates to proven low-g plant growth technologies.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4.2	Discover which nutrient additives to Martian soil optimize plant growth.	March 2038	August 2039	Phase 2: 19 months	Trial 1 - Plant seeds (3 mo. grow period) - 1,1,1% to 8,8,8% nutrient measures - Quantify growth measures - Harvest - Test for food safety rating	Trial 2 - Plant seeds (3 mo. grow period) - 1,1,1% to 8,8,8% nutrient measures - Quantify growth measures - Harvest - Test for food safety rating	Trial 3 - Plant seeds (3 mo. grow period) - 1,1,1% to 8,8,8% nutrient measures - Quantify growth measures - Harvest - Test for food safety rating	Trial 4 - Plant seeds (3 mo. grow period) - 1,1,1% to 8,8,8% nutrient measures - Quantify growth measures - Harvest - Test for food safety rating	Trial 5 - Plant seeds (3 mo. grow period) - 1,1,1% to 8,8,8% nutrient measures - Quantify growth measures - Harvest - Test for food safety rating	System Closeout
4.3	Determine effects of cyanobacteria on plants grown in Martian soil.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
5	**Demonstrate success rate of water harvesting ISRU technology**	Dec. 2034 (for initial development of technology)	Aug. 2042	Entire Mars Mission						
5.1	Develop and test water discovery and harvesting technology on Mars.			Development/improvement/analysis: 15 months. Tests: 3 months	System Development and Improvement. Analysis of samples collected during winter.	System Development and Improvement. Analysis of samples collected during winter.	System Development and Improvement. Analysis of samples collected during winter.	System Development and Improvement. Analysis of samples collected during winter.	System Development and Improvement. Analysis of samples collected during winter.	End of phase 2: Winter begins in June, so prepare for more excavation of water possibly on the same travel missions as soil sample collection. Send samples to Earth from Phase 1 (and 2, if possible) on Crew 1 Return mission.
6	**Demonstrate technology for ISRU of Mars regolith**	Dec. 2035	Aug. 2043	Entire Mars Mission						
6.1	Determine and test if 3D Printing using Mars regolith is possible and if Mars Regolith can be used to make protective coating against rust and radiation			Phase 1 **Phase 2: 19 months** Phase 3	Initial System Setup and obtain the Mars regolith for third testing	Prepare samples using 20%, 30%, 4% Mars regolith and titanium alloy	Test 3D printing abilities and radiation protection capabilities	Preparing analysis reports and report findings	Initial System Setup and obtain the Mars regolith for fourth testing	Prepare samples using 50%, 60%, 70% Mars regolith and titanium alloy

I.4.b.iii <u>Phase Three Schedule</u>

PHASE THREE - Crew 2 Science																
					September 2039 - October 2041											
TIER 1 SCIENCE OBJECTIVE	**TASK TITLE**	**START DATE**	**DUE DATE**	**DURATION**	**Sept 2039 - Nov 2039**	**Dec 2039 - Feb 2040**	**Mar 2040 - May 2040**	**Jun 2040 - Aug 2040**	**Sept 2040 - Nov 2040**	**Dec 2040 - Feb 2041**	**Mar 2041 - May 2041**	**Jun 2041 - Aug 2041**	**Sept 2041 - Nov 2041**	**Dec 2041 - Feb 2042**	**Mar 2042 - May 2042**	**Jun 2042 - Aug 2042**
1	**Determine the short- and long-term effects of zero-g and space isolation on humans**	Dec. 2034 (baseline testing completed prior to mission start date)	Aug. 2043 (follow up testing to be completed after mission end date)	Entire Mars Mission												
1.1	Discover the effects of long-term isolation in space on human psychology by studying behavioral and emotional health changes over time.			Phase 1 Phase 2 **Phase 3: 26 months**	<u>Test Window 1:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	<u>Test Window 2:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	<u>Test Window 3:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	<u>Test Window 4:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	<u>Test Window 5:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	<u>Test Window 6:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	<u>Test Window 7:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	<u>Test Window 8:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	<u>Test Window 9:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	<u>Test Window 10:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	<u>Test Window 11:</u> - Conduct nightly sleep pattern tracking (for 8 hours at a time) - Track emotion regulation device feedback (from 30 min./day sessions) - Track AI therapy feedback (from 1x/week, 1hr sessions)	Phase 3 closeout: analyze phase 3 data
1.2	Discover the influence of zero-gravity and extended space travel on human vision by studying and documenting changes in eyesight over the duration of the Mars mission.			Phase 1 Phase 2 **Phase 3: 26 months**	<u>Test Window 1:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	<u>Test Window 2:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	<u>Test Window 3:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	<u>Test Window 4:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	<u>Test Window 5:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	<u>Test Window 6:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	<u>Test Window 7:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	<u>Test Window 8:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	<u>Test Window 9:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	<u>Test Window 10:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	<u>Test Window 11:</u> - Conduct Optical Coherence Tomography Scans (bimonthly) - Conduct Ocular Ultrasound Scans (bimonthly) - Conduct applanation tonometry tests (biweekly) Analyze test results	Phase 3 closeout: analyze phase 3 data
1.3	Discover the influence of zero-gravity and extended space travel on human vision by studying and documenting changes in eyesight over the duration of the Mars mission.			Phase 1 Phase 2 **Phase 3: 26 months**	<u>Test Window 1:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	<u>Test Window 2:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	<u>Test Window 3:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	<u>Test Window 4:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	<u>Test Window 5:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	<u>Test Window 6:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	<u>Test Window 7:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	<u>Test Window 8:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	<u>Test Window 9:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	<u>Test Window 10:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	<u>Test Window 11:</u> - Conduct DXA scans (monthly) - Obtain EEG/EKG results (48 hr. test intervals, every 2 months) - Obtain CBC/CMP counts (monthly) Analyze test results	Phase 3 closeout: analyze phase 3 data
2	**Determine daily weather patterns on Mars with a special emphasis on solar wind and radiation effects**	Dec 2035 (The weather instruments will be launched with Crew 1)	Aug 2043	Entire Mars Mission												
2.1	Discover the daily weather patterns (temperature, humidiity, wind speed) on Mars			Phase 1 Phase 2 **Phase 3: 26+ months**	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min *NOTE: In case of any permanent damage to instruments, spare instruments will be brought with the crew 2 and setup will first be done*	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min	Conduct weekly maintenance checks and then the daily weather report created where data is collected for 5 min every 30 min. Instruments will be left on Mars surface for future Mars mission
2.2	Understand the influence of planetary plasmas and magnetic fields and their interaction with the solar wind plasma			Phase 1 Phase 2 **Phase 3: 26 months**	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data	Instruments continue to collect data until time of departure. Instruments will be turned off at the end of Phase 3
3	**Determine possibility of past life on Mars**	Dec. 2035	Aug. 2042	Entire Mars Mission												
3.1	Discover more about the history of Mars by searching for signs of life in different areas.			Phase 3 of experiment: 26 months	<u>Test Window 1:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	<u>Test Window 2:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	<u>Test Window 3:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	<u>Test Window 4:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	<u>Test Window 5:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	<u>Test Window 6:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	<u>Test Window 7:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	<u>Test Window 8:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	<u>Test Window 9:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	<u>Test Window 10:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	<u>Test Window 11:</u> - Collect multiple soil samples from locations near the habitat/travel if possible - Analyze samples for microbes	End of Phase 3: End analysis of samples throughout different Mars climates, compare and analyze samples around regions. Compile collection of samples for Crew 2 return.
4	**Determine if Martian soil is suitable for agriculture**															
4.1	Compare Martian soil growth rates to proven low-g plant growth technologies.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		N/A	N/A	N/A	N/A	N/A	N/A
4.2	Discover which nutrient additives to Martian soil optimize plant growth.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A		N/A	N/A	N/A	N/A	N/A	N/A
4.3	Determine effects of cyanobacteria on plants grown in Martian soil.	Sept 2039	August 2042	Phase 3: 26 months	System Setup	Trial 1 - Plant seeds (3 mo. grow period) - Vary concentration of	Trial 2 - Plant seeds (3 mo. grow period) - Vary concentration of	Trial 3 - Plant seeds (3 mo. grow period) - Vary concentration of	Trial 4 - Plant seeds (3 mo. grow period) - Vary concentration of	Trial 5 - Plant seeds (3 mo. grow period) - Vary concentration of	System Closeout Transition to combination experiments	Trial 1 - Plant seeds (3 mo. grow period) - Introduce soil/nutrient/bacteria to test based	Trial 2 - Plant seeds (3 mo. grow period) - Introduce soil/nutrient/bacteria to test based	Trial 3 - Plant seeds (3 mo. grow period) - Introduce soil/nutrient/bacteria to test based	System Closeout	System Closeout

						cyanobacteria - Quantify growth measures - Harvest - Test for food safety rating	cyanobacteria - Quantify growth measures - Harvest - Test for food safety rating	cyanobacteria - Quantify growth measures - Harvest - Test for food safety rating	cyanobacteria - Quantify growth measures - Harvest - Test for food safety rating	cyanobacteria - Quantify growth measures - Harvest - Test for food safety rating		on previous results - Quantify growth measures - Harvest - Test for food safety rating	on previous results - Quantify growth measures - Harvest - Test for food safety rating	on previous results - Quantify growth measures - Harvest - Test for food safety rating		
5	**Demonstrate success rate of water harvesting ISRU technology**	Dec. 2034 (for initial development of technology)	Aug. 2042	Entire Mars Mission												
5.1	Develop and test water discovery and harvesting technology on Mars.			Tests: 10 months Development/improvement/analysis: 26 months	Test Window 1: - Winter continues and ends in November, use improved excavation tools and technology to dig for water samples below surface (easier to dig for water in the winter) - Analyze and store samples as they are collected for further analysis during summer/spring/autumn months	System Development and Improvement. Analysis of samples collected during winter.	System Development and Improvement. Analysis of samples collected during winter.	System Development and Improvement. Analysis of samples collected during winter.	System Development and Improvement. Analysis of samples collected during winter.	System Development and Improvement. Analysis of samples collected during winter.	Test Window 2: - Winter begins in April, use improved excavation tools and technology to dig for water samples below surface (easier to dig for water in the winter) - Analyze and store samples as they are collected for further analysis during summer/spring/autumn months	Test Window 3: - Winter continues, use improved excavation tools and technology to dig for water samples below surface (easier to dig for water in the winter) - Analyze and store samples as they are collected for further analysis during summer/spring/autumn months	Test Window 3: - Winter ends in the end of September, use improved excavation tools and technology to dig for water samples below surface (easier to dig for water in the winter) - Analyze and store samples as they are collected for further analysis during summer/spring/autumn months	System Development and Improvement. Analysis of samples collected during winter.	System Development and Improvement. Analysis of samples collected during winter.	End of Phase 3: End analysis of samples, compare and analyze samples around different regions. Analyze effectiveness of system. Compile collection of samples for Crew 2 return.
6	**Demonstrate technology for ISRU of Mars regolith**	Dec. 2035	Aug. 2043	Entire Mars Mission												
6.1	Determine and test if 3D Printing using Mars regolith is possible and if Mars Regolith can be used to make protective coating against rust and radiation			Phase 1 Phase 2 **Phase 3: 26 months**	Test 3D printing abilities and radiation protection capabilities	Preparing analysis reports and report findings	Initial System Setup and obtain the Mars regolith for fifth testing	Prepare samples using 80%, 90%, 100% Mars regolith and titanium alloy	Test 3D printing abilities and radiation protection capabilities	Test 3D printing abilities and radiation protection capabilities	Preparing analysis reports and report findings	Preparing analysis reports and report findings	Preparing analysis reports and report findings	Preparing analysis reports and report findings	Preparing analysis reports and report findings	Preparing analysis reports and report findings

I.5 Habitat System Power Budget

Habitat Power Budget	
Subsystems	**Power Estimates (kW)**
Expected Power Generation (2 SAFE-400 Reactors)	200
Water System	0.343
Oxygen and Pressure System	3.573
Waste Management	0.380
Medical and Food Storage	3.500
Servicing / Maintenance	4.400
Research	30.000
Lighting	0.500
Heating	2.350
Power Generation Input	10.000
ISRU	30.000
Expected Power Usage	85.046
Factor of Safety	(+/-) 15%
Power Margin	72.2891 – 97.8029

I.6 Link Budget

Mars Uplink – Data Transmission		
Line Loss	2	dB
Transmit Power	1	W
Transmit Efficiency	55	%
Transmit Diameter	1	m
Transmit Gain	47.9132	dBi
EIRP	75.9132	dBW
Receive Diameter	9	m
Receive Efficiency	55	%
Receive Gain	66.9981	dBi
System Noise Temperature	25	K
Data Rate	2.3	Mbps
Point Loss	2	dB
Path Loss	207.1593	dB
Atmospheric Loss	2	dB
Ebno	63.2869	dB

Mars Downlink – Data Transmission		
Line Loss	2	dB
Transmit Power	180	W
Transmit Efficiency	5	%
Transmit Diameter	9	m
Transmit Gain	66.9981	dBi
EIRP	117.5508	dBW
Receive Diameter	1	m
Receive Efficiency	55	%
Receive Gain	47.9132	dBi
System Noise Temperature	10	K
Data Rate	2.3	Mbps
Point Loss	2	dB
Path Loss	207.1593	dB
Atmospheric Loss	2	dB
Ebno	89.8191	dB

Earth Uplink – Data Transmission		
Line Loss	2	dB
Transmit Power	200	W
Transmit Efficiency	55	%
Transmit Diameter	70	m
Transmit Gain	78.5	dBi
EIRP	129.5103	dBW
Receive Diameter	9	m
Receive Efficiency	55	%
Receive Gain	66.9981	dBi
System Noise Temperature	25	K
Data Rate	2.3	Mbps
Point Loss	2	dB
Path Loss	294.0914	dB
Atmospheric Loss	2	dB
Ebno	29.9524	dB

Earth Downlink – Data Transmission		
Line Loss	2	dB
Transmit Power	180	W
Transmit Efficiency	55	%
Transmit Diameter	9	m
Transmit Gain	66.9981	dBi
EIRP	117.5508	dBW
Receive Diameter	70	m
Receive Efficiency	55	%
Receive Gain	78.5	dBi
System Noise Temperature	31	K
Data Rate	2.3	Mbps
Point Loss	2	dB
Path Loss	294.0914	dB
Atmospheric Loss	2	dB
Ebno	28.5606	dB

I.7 Sizing

I.7.a MTV

Module	Mass (kg)	Volume (m^3)
Multipurpose Laboratory	20,357	80.9
Cargo Block	19,323	40.54350983
Research Module	14,515	104.77
Expandable Airlock Module	1,413	16
Connector Node	11,612	19.63330475
CNTR Engine	1,500	
Food Mass	32,000	
Water Mass	60,800	
Power System Mass (SAFE400 100kWe Reactor)	512	
Thermal System Mass	1,750	7.8
Total Estimates	150,420	269.6468146

I.7.b EDL Vehicle

Module	Mass (kg)
EDL Vehicle	53,000

I.7.c Habitat

Room	Length (m)	Width (m)	Square Meterage (m^2)	Height (m)	Volume (m^3)	Surface Area w/o Openings (m^2)	Surface Area w/ Openings (m^2)
Common Area	9.144	9.144	83.613	2.896	242.109	189.522	174.298
Lab	10.668	6.096	65.032	2.896	188.307	162.116	147.553
Greenhouse	6.096	4.572	27.871	2.896	80.703	89.651	82.370
Medical	8.534	4.267	36.418	4.877	177.603	161.280	158.632
Crew Quarters	9.144	9.144	83.613	2.896	242.109	189.522	186.874
Storage	3.414	3.414	11.654	2.896	33.745	51.193	48.546
Backup Storage	3.414	3.414	11.654	2.896	33.745	51.193	51.193
Garage	6.096	6.096	37.161	4.877	181.228	156.077	151.444
Airlocks (x4)	3.048	1.600	19.510	2.896	56.492	90.116	90.116
Hallways (x5)	1.524	0.914	6.968	2.896	20.176	51.097	51.097
Total	-	-	383.493	-	1256.216	1191.768	1142.123
			319.854			Note: Airlocks and Hallways did not have openings included	

I.7.d MAV

Module	Mass (kg)
MAV	26,000
MOXIE	1,000

I.8 First-Order Algorithms (FOAs)

I.8.a Habitat System – Structure

Habitat	TRL	Volume Ratio (payload V / Mars V)	Estimated Pay Mass (kg)	Debris Protection	Thermal Insulation	Radiation Protection	Cost per square foot	Disturb Mars
Subterranean	4	5	5	5	5	4	1	1
Inflatable modules	7	4	5	1	1	2	3	5
Rigid surface structure	6	1	1	3	2	2	2	5
Crew module	8	1	2	4	3	3	5	5
Regolith bricks	5	5	5	2	4	5	4	2
Robots set up	6	3	3	-	-	-	-	-
Average	6	3.167	3.5	3	3	3.2	3	3.6

Table 43: Habitat - Single Options

Habitat	TRL	Volume Ratio (payload V / Mars V)	Estimated Pay Mass (kg)	Debris Protection	Thermal Insulation	Radiation Protection	Cost per square foot	Disturb Mars	Final Score
Subterranean	3.3	9.5	10.0	5.0	6.7	10.0	1.3	0.3	46.1
Inflatable modules	5.8	7.6	10.0	1.0	1.3	5.0	4.0	1.4	36.1
Rigid surface structure	5.0	1.9	2.0	3.0	2.7	5.0	2.7	1.4	23.6
Crew module	6.7	1.9	4.0	4.0	4.0	7.5	6.7	1.4	36.1
Regolith bricks	4.2	9.5	10.0	2.0	5.3	12.5	5.3	0.6	49.4
Robots set up	5.0	5.7	6.0	-	-	-	-	-	16.7

Table 44: Habitat - Single Options Normalized

Factors	Rank	Scale	Weight
Radiation Protection	1	1 to 4	8
Pay Mass (kg)	2	1 to 5	7
Volume Ratio (payload V / Mars V)	3	0 to 1	6
TRL	4	1 to 9	5
Insulation	5	-5 to 5	4
Total Cost	5	1 to 5	4
Debris Protection	6	0 to 10	3
Cost of Maintenance	7	-5 to 5	2
Disturb Mars	8	1 to 5	1

Table 45: Habitat - Single Options Figures of Merit

Habitat	TRL	Volume Ratio (payload V / Mars V)	Estimated Pay Mass (kg)	Debris Protection	Thermal Insulation	Radiation Protection	Cost per square foot	Disturb Mars
Subterranean with inflatable with regolith	4	4.7	5.0	5.0	5.0	5.0	2.7	1.0
Subterranean with rigid with regolith	4	3.7	3.7	5.0	5.0	5.0	2.3	1.0
Subterranean with inflatable	4	4.5	3.3	5.0	5.0	4.0	2.0	1.0
Subterranean with rigid	4	3.0	2.0	5.0	5.0	4.0	1.5	1.0
Inflatable with regolith	5	4.5	5.0	2.0	4.0	5.0	3.5	2.0
Inflatable without regolith	7	4.0	5.0	1.0	1.0	2.0	3.0	5.0
Rigid with regolith	5	2.0	3.0	3.0	4.0	5.0	3.0	2.0
Rigid without regolith	6	1.0	1.0	3.0	2.0	2.0	2.0	5.0
Temp crew module	8	1.0	2.0	4.0	3.0	3.0	5.0	5.0
Average	5.2	3.1	3.3	3.7	3.8	3.9	2.8	2.6

Table 46: Habitat - Combinations

Habitat	TRL	Volume Ratio (payload V / Mars V)	Estimated Pay Mass (kg)	Debris Protection	Thermal Insulation	Radiation Protection	Cost per square foot	Disturb Mars	Final Score
Subterranean with inflatable with regolith	4.6	8.9	10.5	4.1	5.3	10.3	5.8	1.2	50.6
Subterranean with rigid with regolith	4.6	7.0	7.7	4.1	5.3	10.3	5.0	1.2	45.2
Subterranean with inflatable	4.6	8.6	7.0	4.1	5.3	8.2	4.3	1.2	43.3
Subterranean with rigid	4.6	5.7	4.2	4.1	5.3	8.2	3.2	1.2	36.5
Inflatable with regolith	5.7	8.6	10.5	1.6	4.2	10.3	7.6	2.3	50.9
Inflatable without regolith	8.0	7.6	10.5	0.8	1.1	4.1	6.5	5.9	44.5
Rigid with regolith	5.7	3.8	6.3	2.5	4.2	10.3	6.5	2.3	41.7
Rigid without regolith	6.9	1.9	2.1	2.5	2.1	4.1	4.3	5.9	29.8
Temp crew module	9.2	1.9	4.2	3.3	3.2	6.2	10.8	5.9	44.6

Table 47: Habitat - Combinations Normalized

I.8.b Habitat System – Thermal System

Heating systems	TRL	Cost	Reliability	Thermal Efficiency	Weight
Heat pumps	9	1	3	3	1
RTG Waste Heat	7	1	4	1	5
Electrical Resistive Heaters	9	1	5	5	5

Averages	8.333333333	1	4	3	3.666666667

Table 4848: Habitat Heating Systems Options

Factors	Rank	Scale	Weight
TRL	1	1 to 9	5
Cost	5	1 to 10	1
Reliability	2	1 to 5	4
Efficiency	3	1 to 5	3
Weight	4	1 to 5	2

Table 4949: Habitat Thermal Systems - Figures of Merit

Heating systems	TRL	Cost	Reliability	Thermal Efficiency	Weight	Total
Heat pumps	1.00	0.20	0.60	0.60	0.20	9.80
RTG Waste Heat	0.78	0.20	0.80	0.20	1.00	9.89
Electrical Resistive Heaters	1.00	0.20	1.00	1.00	1.00	14.20

Table 5050: Habitat Heating Systems - Normalized

Cooling systems for habitat	TRL	Cost	Reliability	Thermal Efficiency	Weight	Total
Reversible heat pump	1	1.25	1.2	1.2	0.6666666667	15.98333333
Radiators	1	0.75	0.8	0.8	1.333333333	14.01666667

Table 5151: Habitat Cooling Systems Normalized

I.8.c Habitat System – Power System

Power Generation	TRL	Mass (Kilograms)	Volume (Cubic Meters)	Cost (Millions USD)	Maintenance (Y/N)
Solar Panels	9	58380	465.16	0.2776	1
Wind Turbines	5	680118	1000	3.028206	1
RTGs	9	40909	193	99091	0
Microreactors	9	66923	0.48	7338	0
Small Modular Reactors	7	15000	190	200	0
SP-100	6	4518	57.3	1000	0

SAFE-400	6	241	10	500	0
Total	51.0	866089.0	1915.9	108132.3	2.0

Table 5252: Habitat Power Systems Options

Factors	Rank	Scale	Weight
TRL	2	1-9	4
Cost	5	1-10	1
Power / Mass	1	1-10	5
Ease of Maintenance	3	1-10	3
Volume	4	1-10	2

Table 5353: Habitat Power Systems - Figures of Merit

Power Generation	TRL	Mass (Kilograms)	Volume (Cubic Meters)	Cost (Millions USD)	Maintenance (Y/N)	Final Score
Solar Panels	0.18	0.07	0.24	0.00	0.50	-5.32
Wind Turbines	0.10	0.79	0.52	0.00	0.50	-11.57
RTGs	0.18	0.05	0.10	0.92	0.00	-0.67
Microreactors	0.18	0.08	0.00	0.07	0.00	0.27
Small Modular Reactors	0.14	0.02	0.10	0.00	0.00	0.27
SP-100	0.12	0.01	0.03	0.01	0.00	0.45
SAFE-400	0.12	0.00	0.01	0.00	0.00	0.57

Table 5454: Habitat Power Systems - Normalized

I.8.d Life Support Systems – Water Supply

Water Supply Options	TRL	Complexity	Efficiency	Longevity	Initial Mass
Prepackaged	9	10	10	2	2
Extraction (surface and atmosphere)	3	3	6	7	8
Recycling	9	8	10	8	6
Average	7.0	7.0	8.7	5.7	5.3

Table 55: 55Water Supply Options

Factors	Rank	Scale	Weight
TRL	3	1-9	3
Complexity	5	1-10	1
Efficiency	2	1-10	4
Longevity	1	1-10	5
Initial Mass	4	1-10	2

Table 5656: Water Supply - Figures of Merit

Water Supply Options	TRL	Complexity	Efficiency	Longevity	Initial Mass	Final Score
Prepackaged	3.9	1.4	4.6	1.8	0.8	12.4
Extraction (surface and atmosphere)	1.3	0.4	2.8	6.2	3.0	13.7
Recycling	3.9	1.1	4.6	7.1	2.3	18.9

Table 5757: Water Supply - Normalized

Water Supply Combinations	TRL	Complexity	Efficiency	Longevity	Initial Mass
Prepackaged and Extraction and Recycling	7.0	7.0	8.7	5.7	5.3
Prepackaged and Extraction	6.0	6.5	8.0	4.5	5.0
Prepackaged and Recycling	9.0	9.0	10.0	5.0	4.0
Average	7.3	7.5	8.9	5.1	4.8

Table 5858: Water Supply - Combinations

Water Supply Combinations	TRL	Complexity	Efficiency	Longevity	Initial Mass	Final Score
Prepackaged and Extraction and Recycling	2.9	0.9	3.9	5.6	2.2	15.5
Prepackaged and Extraction	2.5	0.9	3.6	4.5	2.1	13.5
Prepackaged and Recycling	3.7	1.2	4.5	4.9	1.7	16.0

Table 5959: Water Supply - Combinations Normalized

I.8.e Life Support Systems – Contamination Mitigation

Contamination Mitigation	TRL	Cost	Mass	Required Space/Volume	Contaminant Protection
Isolation Chambers	6	1	1	1	3
Clean Room	8	3	2	2	4
Hermetically sealed sample containers	9	4	4	4	2
Thermal vacuum bakeout	6	2	3	3	1
Average	7.25	2.5	2.5	2.5	2.5

Table 6060: Contamination Mitigation Options

Factors	Rank	Scale	Weight
TRL	4	1(Worst) - 9(Best)	2
Cost	5	1(Worst) - 4(Best)	1
Mass	3	1(Worst) - 4(Best)	3
Required Space/Volume	2	1(Worst) - 4(Best)	4
Contaminant Protection	1	1(Worst) - 4(Best)	5

Table 6161: Contamination Mitigation - Figures of Merit

Contamination Mitigation	TRL	Cost	Mass	Required Space/Volume	Contaminant Protection	Final Score
Isolation Chambers	0.21	0.1	0.1	0.1	0.3	2.71
Clean Room	0.28	0.3	0.2	0.2	0.4	4.25
Hermetically sealed sample containers	0.31	0.4	0.4	0.4	0.2	4.82
Thermal vacuum bakeout	0.21	0.2	0.3	0.3	0.1	3.21

Table 6262: Contamination Mitigation - Normalized

I.8.f Life Support Systems – Pressurized Areas

Pressurized System	TRL	Human Maneuverability	Leakage	Packageability	Pressure level need
Whole habitat fully pressurized	9	5	5	1	101

Less pressurized tunnels	2	1	1	5	101
Separate habitats	2	3	3	3	101
Fully pressurized transportation	6	5	5	3	56.5
Non-pressurized transportation	9	3	1	5	0
Average	5.6	3.4	3	3.4	71.9

Table 6363: Pressurized Areas Options

Factors	Rank	Scale	Weight
TRL	1	1-9	5
Human Maneuverability	4	1-5	2
Leakage	2	1-5	4
Packageability	5	1-5	1
Pressure level need	3	0-101	3

Table 6464: Pressurized Areas - Figures of Merit

Pressurized System	TRL	Human Maneuverability	Leakage	Packageability	Pressure level need	Final Score
Whole habitat fully pressurized	1.6	1.5	1.7	0.3	1.4	22.2
Less pressurized tunnels	0.4	0.3	0.3	1.5	1.4	9.4
Separate habitats	0.4	0.9	1.0	0.9	1.4	12.6
Fully pressurized transportation	1.1	1.5	1.7	0.9	0.8	18.2
Non-pressurized transportation	1.6	0.9	0.3	1.5	0.0	12.6

Table 6565: Pressurized Areas - Normalized

I.8.g Life Support Systems – Oxygen Supply

Oxygen Supply	TRL	Reliability	Precedence	Longevity	Initial Mass
Pre-packaged	9	8	10	3	3

Extracted from Mars	5	6	8	8	7
Combination	8	9	4	9	6
Average	7.3333	7.6667	7.3333	6.6667	5.3333

Table 6666: Oxygen Supply Options

Factors	Rank	Scale	Weight
TRL	4	1-9	2
Reliability	2	1-10	4
Precedence	3	1-10	4
Longevity	1	1-10	5
Initial Mass	5	1-10	1

Table 6767: Oxygen Supply - Figures of Merit

Oxygen Supply	TRL	Reliability	Precedence	Longevity	Initial Mass	Final Score
Pre-packaged	2.45	4.17	5.45	2.25	0.56	14.90
Extracted from Mars	1.36	3.13	4.36	6.00	1.31	16.17
Combination	2.18	4.70	2.18	6.75	1.13	16.93

Table 6868: Oxygen Supply - Normalized

I.8.h Life Support Systems – CO2 Recycling

CO2 Recycling	TRL	Reliability	Precedence	Longevity	Initial Mass
High-consumption plants	7	4	5	3	8
Captured from human presence	9	7	10	9	6
CO2 Removal Systems	4	7	6	9	5
Average	6.667	6.000	7.000	7.000	6.333

Table 6969: CO2 Recycling Options

Factors	Rank	Scale	Weight
TRL	3	1-9	3
Reliability	2	1-10	4
Precedence	4	1-10	3

Longevity	1	1-10	5
Initial Mass	5	1-10	1

Table 7070: CO2 Recycling - Figures of Merit

CO2 Recycling	TRL	Reliability	Precedence	Longevity	Initial Mass	Final Score
High-consumption plants	3.15	2.67	2.14	2.14	1.26	11.37
Captured from human presence	4.05	4.67	4.29	6.43	0.95	20.38
CO2 Removal Systems	1.80	4.67	2.57	6.43	0.79	16.26

Table 7171: CO2 Recycling - Normalized

I.8.i Life Support Systems – Waste Management

Waste Management	TRL	Volume	Non-Organic Waste	Energy Recovery	Methane	Cost	Required Materials Mass
Biodegradable	5	1	0	1	1	3	1
Incineration	6	3	1	1	0	2	1
Stored for future removal	9	2	1	0	0	1	2
Landfill on Mars	6	2	1	0	0	4	3
Average	6.5	2	0.75	0.5	0.25	2.5	1.75

Table 7272: Waste Management Options

Factors	Rank (1 = Most Important)	Scale	Weight
TRL	4	1(Worst) - 9(Best)	4
Volume	1	1(Worst) - 3(Best)	7
Non-Organic Waste	3	0(No) / 1(Yes)	5
Energy Recovery	6	0(No) / 1(Yes)	2
Methane Production	7	0(No) / 1(Yes)	1
Cost	5	1(Worst) - 4(Best)	3

Required Materials Mass	2	1(Worst) - 3(Best)	6

Table 7373: Waste Management - Figures of Merit

Waste Management	TRL	Volume	Non-Organic Waste	Energy Recovery	Methane	Cost	Required Materials Mass	Final Score
Biodegradable	0.19	0.13	0.00	0.50	1.00	0.30	0.14	5.40
Incineration	0.23	0.38	0.33	0.50	0.00	0.20	0.14	7.67
Stored for future removal	0.35	0.25	0.33	0.00	0.00	0.10	0.29	6.82
Landfill on Mars	0.23	0.25	0.33	0.00	0.00	0.40	0.43	8.11

Table 7474: Waste Management - Normalized

I.8.j Landing Site

Location Options	Latitude (deg)	Elevation (m)	Rover	Clay	Signs of water	Radiation (rem/yr)	Olivine	Sulfates	Carbonates	Terrain (Flat, Rough, etc.)
Columbia Hills	-15.2	-1000.0	1.0	1.0	1.0	15.0	1.0	1.0	1.0	0.0
Eberswalde Crater	-24.0	-1400.0	0.0	1.0	1.0	19.0	0.0	0.0	0.0	0.0
Holden Crater	-19.2	-2000.0	0.0	1.0	1.0	19.0	0.0	0.0	0.0	0.0
Jezero Crater	18.4	-2700.0	1.0	1.0	1.0	15.0	1.0	1.0	1.0	0.0
Mawrth Vallis	22.0	-2000.0	0.0	1.0	1.0	16.0	0.0	0.0	0.0	0.0
NE Syrtis	18.0	-2000.0	0.0	1.0	1.0	15.0	1.0	1.0	1.0	0.0
Nili Fossae	22.0	-600.0	1.0	1.0	1.0	16.0	1.0	1.0	1.0	1.0
SW Melas Basin	-11.0	-2000.0	0.0	0.0	1.0	18.0	0.0	0.0	0.0	1.0
Gale Crater	-5.4	-4400.0	1.0	1.0	1.0	20.0	0.0	1.0	0.0	0.0
Ares Vallis	10.4	-3000.0	1.0	0.0	1.0	19.0	0.0	0.0	0.0	1.0

Meridiani Planum	-2.0	-2500.0	1.0	0.0	1.0	16.0	1.0	1.0	0.0	1.0
AVERAGE	15.2	-2145.5	0.5	0.7	1.0	17.1	0.5	0.5	0.4	0.4

Table 75: Landing Site Options

Figures of Merit	Weight	Metric
Latitude	10	degrees
Elevation	9	meters
Rover	7	0/1
Clay	5	0/1
Signs of Water	5	0/1
Radiation	8	rem/year
Olivine	3	0/1
Sulfates	3	0/1
Carbonates	3	0/1
Terrain	11	0/1

Table 76: Landing Site - Figures of Merit

Location Options	Latitude (deg)	Elevation (m)	Rover	Clay	Signs of water	Radiation (rem/yr)	Olivine	Sulfates	Carbonates	Terrain (Flat, Rough, etc.)	Final Score
Columbia Hills	10.0	4.2	12.8	6.9	5.0	-7.0	6.6	5.5	8.3	0	52.2
Eberswalde Crater	15.8	5.9	0.0	6.9	5.0	-8.9	0.0	0.0	0.0	0	24.6
Holden Crater	12.6	8.4	0.0	6.9	5.0	-8.9	0.0	0.0	0.0	0	24.0
Jezero Crater	12.1	11.3	12.8	6.9	5.0	-7.0	6.6	5.5	8.3	0	61.4
Mawrth Vallis	14.4	8.4	0.0	6.9	5.0	-7.5	0.0	0.0	0.0	0	27.2

NE Syrtis	11.8	8.4	0.0	6.9	5.0	-7.0	6.6	5.5	8.3	0	45.4
Nili Fossae	14.4	2.5	12.8	6.9	5.0	-7.5	6.6	5.5	8.3	30.25	84.8
SW Melas Basin	7.2	8.4	0.0	0.0	5.0	-8.4	0.0	0.0	0.0	30.25	42.4
Gale Crater	3.5	18.5	12.8	6.9	5.0	-9.4	0.0	5.5	0.0	0	42.8
Ares Vallis	6.8	12.6	12.8	0.0	5.0	-8.9	0.0	0.0	0.0	30.25	58.6
Meridiani Planum	1.3	10.5	12.8	0.0	5.0	-7.5	6.6	5.5	0.0	30.25	64.5

Table 77: Landing Sites – Normalized

I.8.k Communications Systems

Parameter	Weight (1-10)	Satellite	Satellite + Support Sats	MTV	MTV + Support Sats	Cargo Cruise Stage	Cargo Cruise Stage + Support Sats	Support Sats x2
Cost ($US)	2	$600,000,000	$742,784,160	$321,099.60	$143,105,259.91	$599,982,149	$742,766,309	$142,784,160
Power (W)	5	20000	21500	210	1710	20000	21500	1500
Mass (kg)	8	1,300	1,700	305	705	1,300	1,700	400
Ground Coverage (1-5)	10	3	1	4	2	3	1	N/A

Table 78: Communications Satellite Constellation Architecture Parameters

Parameter	Weight (1-10)	Satellite	Satellite + Support Sats	MTV	MTV + Support Sats	Cargo Cruise Stage	Cargo Cruise Stage + Support Sats
Cost	2	0.81	1.00	0.00	0.19	0.81	1.00
Power (W)	5	0.93	1.00	0.01	0.08	0.93	1.00
Mass (kg)	8	0.76	1.00	0.18	0.41	0.76	1.00
Ground Coverage	10	0.75	0.25	1.00	0.50	0.75	0.25
Total		19.88	17.5	11.49	9.10	19.88	17.50

Table 79: Normalized Communications Satellite Constellation Weighted Decision Matrix

I.9 Mission Life Cycle Cost

Cost WBS Component	Cost Estimate from Research (FY$2023)	Q (constant)	M (lbs)	S (constant)	B (constant)	IOC (year)	D	AMCM (FY$1999)	Total Cost (FY$2023)
1.0 Propulsion									**80,018,759,223.09**
1.1 CNTR	1,000,000,000.00	1.00	8,599.50	2.46	2.00	1,960.00	-2.50	341,413,311.51	1,617,958,093.84
1.2 Hall Thruster	400,000.00	1.00	507.15	2.46	2.00	1,960.00	-2.50	52,713,054.34	95,810,628.35
1.3 LH2 Propellant	638,048.00	1.00	384,397.65	2.46	2.00	1,950.00	-1.50	4,334,970,545.32	7,846,934,735.02
1.4 Storable Propellant	71,891.00	1.00	179,129.79	2.46	2.00	1,960.00	0.00	7,822,904,482.40	14,159,529,004.14
1.5 Electric Propellant	89,307,000.00	1.00	65,640.65	2.46	2.00	1,964.00	0.00	4,595,130,813.05	8,406,493,771.62
1.6 Launch Vehicles (4 SLS and 2 F9H)	16,594,000,000.00	1.00	388,080.00	2.46	2.00	2,011.00	-1.50	17,291,730,933.77	47,892,032,990.13
2.0 Science Objectives									**348,064,616.60**
2.1 Tier 1 Science Objective 1	177,020.00	1.00	689.34	2.13	2.00	2,000.00	-2.50	34,962,132.92	63,282,149.94
2.2 Tier 1 Science Objective 2	40,000.00	1.00	37.00	2.13	2.00	2,020.00	-2.50	6,250,906.51	11,354,140.78
2.3 Tier 1 Science Objective 3	173,000.00	1.00	15.24	2.13	2.00	2,000.00	-2.50	2,825,497.01	5,287,149.59
2.4 Tier 1 Science Objective 4	85,350.00	1.00	83.78	2.13	2.00	2,014.00	-2.50	10,146,582.09	18,450,663.58
2.5 Tier 1 Science Objective 5	35,000.00	1.00	16.93	2.13	2.00	2,020.00	-2.50	3,731,374.61	6,788,788.05
2.6 Tier 1 Science Objective 6	37,300.00	1.00	401.24	2.13	1.00	2,035.00	0.00	134,179,240.14	242,901,724.66
3.0 MTV									**146,745,440,560.42**
3.1 Multipurpose Laboratory (Nauka)	15,000,000,000.00	2.00	44,887.19	2.13	2.00	2,000.00	-2.50	828,399,578.21	16,499,403,236.55
3.2 Cargo Block (Zarya)	15,000,000,000.00	2.00	42,607.22	2.13	2.00	2,000.00	-2.50	800,383,232.85	16,448,693,651.47
3.3 Research Module (Destiny)	15,000,000,000.00	2.00	32,005.58	2.13	2.00	2,000.00	-2.50	662,655,829.71	16,199,407,051.77
3.4 Expandable Airlock Module (Bigelow Expandable Activity Module)	15,000,000,000.00	2.00	3,115.67	2.13	2.00	2,000.00	-2.50	142,423,811.27	15,257,787,098.40
3.5 Connector Node (Unity)	15,000,000,000.00	2.00	25,604.46	2.13	2.00	2,000.00	-2.50	571,909,636.63	16,035,156,442.31
3.6 CNTR Engine	15,000,000,000.00	2.00	3,307.50	2.13	2.00	2,000.00	-2.50	148,152,507.88	15,268,156,039.27

3.7 Food Mass	15,000,000,000.00	2.00	70,560.00	2.13	2.00	2,000.00	-2.50	1,116,574,646.20	17,021,000,109.62
3.8 Water Mass	15,000,000,000.00	2.00	134,064.00	2.13	2.00	2,000.00	-2.50	1,705,552,682.65	18,087,050,355.60
3.9 Power System Mass (SAFE400 100kWe Reactor)	15,000,000,000.00	2.00	1,128.96	2.13	2.00	2,000.00	-2.50	72,879,762.85	15,131,912,370.75
3.10 Thermal System Mass	500,000,000.00	2.00	3,858.75	2.13	2.00	2,000.00	-2.50	164,018,897.62	796,874,204.69
4.0 Surface Stay									**15,031,489,808.44**
4.1 Water System	97,197,273.18	1.00	8,202.60	2.13	2.00	2,000.00	-2.50	179,241,850.69	421,625,022.92
4.2 Water Storage	2,821,920.00	1.00	283,298.40	2.13	2.00	2,000.00	-2.50	1,856,575,125.72	3,363,222,897.56
4.3 Contamination Mitigation	25,000.00	1.00	441.00	2.13	2.00	2,000.00	-2.50	26,035,197.48	47,148,707.44
4.4 Pressure System	4,153,292.40	1.00		2.13	2.00	2,000.00	-2.50	0.00	4,153,292.40
4.5 Oxygen System	28,155,434.82	1.00	4,524.66	2.13	2.00	2,021.00	0.00	464,636,789.55	869,148,023.91
4.6 Oxygen Storage	28,155,434.82	1.00	25,754.40	2.13	2.00	2,000.00	-2.50	381,411,124.04	718,509,569.33
4.7 CO2 Recycler	135,493,682.80	1.00		2.13	2.00	2,000.00	-2.50	0.00	135,493,682.80
4.8 Waste Management	23,000,000.00	1.00	110.25	2.13	2.00	2,000.00	-2.50	10,428,006.23	41,874,691.28
4.9 Medical Supplies	100,000,000.00	1.00	4,410.00	2.13	2.00	2,000.00	-2.50	119,003,812.83	315,396,901.22
4.10 Food Storage	1,000,000.00	1.00	73,400.04	2.13	2.00	2,000.00	-2.50	761,361,589.37	1,379,064,476.75
4.11 Regolith Production	10,000.00	1.00	1,102.50	2.13	1.00	2,035.00	2.50	807,526,593.09	1,461,633,133.49
4.12 Servicing / Maintenance	3,500,000,000.00	1.00	44,805.60	2.13	2.00	2,000.00	-2.50	549,680,997.26	4,494,922,605.04
4.13 Research	350,000,000.00	1.00	32,005.58	2.13	2.00	2,000.00	-2.50	440,230,700.28	1,146,817,567.51
4.14 Lighting	42,000.00	1.00	2,399.04	2.13	2.00	2,000.00	-2.50	79,626,229.27	144,165,474.97
4.15 Heating	100,000,000.00	1.00	7,308.21	2.13	2.00	2,000.00	-2.50	166,091,190.04	400,625,053.98
4.16 Power Generation Input	53,660.00	1.00	1,128.96	2.13	2.00	2,000.00	-2.50	48,417,153.51	87,688,707.86
4.18 Inflatable	17,800,000.00	1.00	5,000.00	2.13	2.00	2,016.00	-2.50	153,678,248.86	193,634,593.56

5.0 EDL/MAV										**162,018,163,291.02**
5.1 EDL	7,139,000,000.00	2.00	116,865.00	2.46	1.00	2,035.00	0.00	36,375,404,756.98	72,978,482,610.14
5.2 MAV	194,000,000.00	2.00	57,330.00	2.46	1.00	2,035.00	1.50	44,721,632,538.44	81,140,154,894.58
5.3 RP-1	17,737.05	2.00	8,623.80	2.46	2.00	1,950.00	-1.50	532,352,862.23	963,576,417.68
5.4 Moxie	50,000,000.00	2.00	1,999.94	2.46	2.00	2,035.00	1.50	3,804,391,916.36	6,935,949,368.62
6.0 Communications									**378,258,309.00**
6.1 MTV Comms System	143,105,259.91	1.00	1,554.53	2.13	2.00	2,035.00	-1.50	129,918,811.65	378,258,309.00
7.0 Space Environment									**1,546,570,276.86**
7.1 Radiation Shielding	20,000.00	1.00	882.00	2.13	2.00	2,035.00	-1.50	89,377,214.73	161,792,758.65
7.2 Thermal System (ATCS)	100,000,000.00	1.00	7,307.37	2.13	2.00	2,035.00	0.00	709,821,833.26	1,384,777,518.21
8.0 Program Level	10-20% (15% average) of operations cost								**9,178,843.96**
9.0 Flight Support Operations and Services									**251,770,142,256.13**
9.1 Contractor PM, SE, PA, I&T, Manufacturing MTV	150,000,000,000.00							150,000,000,000.00	150,000,000,000.00
9.2 Launch	408,776,000.00							408,776,000.00	564,110,880.00
9.3 Software Development	3,337,500,000.00							3,337,500,000.00	4,605,750,000.00
9.4 Ground Facilities	29,982.70							29,982.70	41,376.13
9.5 Mission Ops Trainers	240,000.00							240,000.00	240,000.00
9.6 Labor	70,000,000,000.00							70,000,000,000.00	96,600,000,000.00
10.0 Aerospace Ground and Support Equipment									**92,807,147.72**
10.1 Aerospace Ground Equipment (MTV, 2 Additional)	48,382,854.63								66,768,339.39
10.2 Ground Support Equipment (MTV, 2 Additional)	18,868,701.69								26,038,808.34

11.0 Launch Operations									**61,192,293.07**
11.1 Program Management and System Engineering	5,783,770.61								
11.2 Space Segment	18,750.00								
11.3 Ground Segment									
11.3.1 Mission Operations	13,000,000.00								
11.3.2 Ground Segment Software Maintenance	21,276,595.74								
11.3.3 Ground Hardware Maintenance	13,125.00								
11.3.4 Facilities	4,250,000.00								
Total Cost of Deployment (FY$2023)									**658,020,066,626.32**

AMCM (FY$1999) [CS-6]	$5.65x10^{-4} \times Q^{.59} \times M^{.66} \times 80.6^{S}\left[(3.81 \times 10^{-55})^{\frac{1}{IOC-1990}}\right] \times B^{-.36} \times 1.57^{D}$
Q	The total quantity of development and production units/system *(Note: Q = 1 for Launch Vehicles but this actually means 1 system of 4 SLS and 2 Falcon 9 Heavy)*
M	The system dry mass in pounds of system
S	Specifies the type of mission (2.13 for human habitat, 2.46 for crewed planetary lander)
IOC	IOC (Initial Operation Capability) is the first year of system operations
B	The hardware block or generation (1 for new design, 2 for second generation)
D	The estimated difficulty (0 for average, 2.5 for extremely difficult, and -2.5 for extremely easy). (Guerra and Shishko 2000, pp. 946-7) - convert TRL ratings to these ratings as shown below: • 1, 2, 3: 2.5 • 4, 5, 6: 0 • 7, 8, 9: -2.5

Table 80: AMCM Model Variables

I.10 Master Equipment List (MEL)

I.10.a Transportation Systems

Item	Quantity	Mass (kg)	Cost ($USD FY2023)
SpaceX Falcon 9 Heavy	10	16,800 (To Mars)	150,000,000
Space Launch System Block 2	12	46,000 (To Mars)	2,000,000,000
Multi-purpose Laboratory	2	20,357	15,000,000,000
Cargo Block	2	19,323	15,000,000,000
Research Module	2	14,515	15,000,000,000
Expandable Airlock Module	2	1,413	15,000,000,000
Connector Node	2	11,612	15,000,000,000
SAFE 400 Reactor	1	512	53,660
Thermal System	1	1,750	500,000,000
Radiation Shielding	1	400	20,000
Communication System	1	705	143,105,259.91
CNTR	3	3,900	1,000,000,000
LH2 Propellant	N/A	2,610,457.37	9,554,274
Ammonia (Storable Propellant)	N/A	240,408.08	109,866

I.10.b Surface Systems

Item	Quantity	Mass	Cost ($USD FY2023)
Inflatable Structure	1	5,000	17,800,000
Water System	1	3,720	97,197,273.18
Water Storage	1	128,480	28,21,920
Contaminant Mitigation	Unknown	2 per container	250 per container
Pressure System	1	684	4,153,292.4
Oxygen System	1	684	28,155,434.82
Oxygen Storage	1	11,680	28,155,434.82
CO2 Recycler	1	684	135,493,682.8
Waste Management System	1	50	23,000,000
Medical Supplies	1	2,000	100,000,000
Food Storage	2	33,288	1,000,000
Regolith Production	1	500	10,000
Servicing and Maintenance	1	20,320	3,500,000,000
Lighting System	1	1,088	42,000
Heating System	1	3,314.38	100,000,000
SAFE 400 Reactor	3	512	53,660
MAV	2	26,000	194,000,000
RP-1	N/A	3,911	8868.52
BOXIE	2	907	50,000,000
LOX	N/A	10,247	Included in BOXIE
Scientific Objective Equipment	N/A	3,140.595	4,160,000,000

I.11 Heritage

Subsystem	Mission
Launch Vehicle: Space Launch System (SLS)	NASA Artemis
Launch Vehicle: SpaceX Falcon 9 Heavy	Various
MTV: Centrifugal Nuclear Thermal Rocket (CNTR)	NASA DRACO
MTV: Multipurpose Laboratory (Nauka)	NASA ISS
MTV: Cargo Block (Zarya)	NASA ISS
MTV: Research Module (Destiny)	NASA ISS
MTV: Expandable Airlock Module (Bigelow Expandable Activity Module)	NASA ISS
MTV: Connector Node (Unity)	NASA ISS
Habitat System: Inflatable	Bigelow, Project Echo, Voskhod 2
Habitat System: Lander as a temporary habitat	NASA Artemis
Life Support Systems: Heat Pump	NASA ISS
Life Support Systems: Oxygen System	NASA ISS
Life Support Systems: Pressurization System	NASA ISS
Life Support Systems: CO2 Recycling System	NASA ISS
Life Support Systems: Water Recycling System	NASA ISS
Life Support Systems: Food Packaging	NASA ISS
Life Support Systems: Medical Kit	NASA ISS
Life Support Systems: MOXIE	NASA Perseverance
Life Support Systems: Scaled VEGGIE Food Production	NASA VEGGIE
Science Objectives: Solar Wind Sensor	NASA MAVEN
MAV: Propellant Production via MOXIE	NASA Perseverance

I.12 List of Abbreviations and Acronyms

Acronym	Definition
AAE	Aeronautical and Astronautical Engineering
ADC	Attitude Determination and Control
BOXIE	Big Mars Oxygen ISRU Experiment
CBC	Complete Blood Count
CEC	Cation exchange capacity
CER	Cost Estimating Relationship
CMP	Comprehensive Metabolic Panel
CNTR	Centrifugal Nuclear Thermal Rocket
ConDR	Conceptual Design Review
ConOps	Concept of Operations
DAN	Dynamic Albedo of Neutrons
DXA	Dual X-ray Absorptiometry
E	Earth
ECG	Electrocardiogram

EDL	Entry, Descent, and Landing
E-M	Earth to Mars
EOI	Earth Orbit Injection
FOA	First Order Algorithm
GCR	Galactic Cosmic Rays
GMAT	General Mission Analysis Tool
GPR	Ground Penetrating Radar
HIPPA	Health Insurance Portability and Accountability Act
HVPS	High-voltage power supply
ICP	Intracranial Pressure
IOP	Intraocular Pressure
ISRU	In-Situ Resource Utilization
LED	Light-Emitting Diode
LEO	Low Earth Orbit
LMO	Low Mars Orbit
LNCAO	Lithium Nickel Cobalt Aluminum Oxide
M	Mars
MARES	Muscle Atrophy Research and Exercise System
MAV	Mars Ascent Vehicle
MAVEN	Mars Atmosphere and Volatile Evolution
MCC	Micro-Context Camera
M-E	Mars to Earth
MOI	Mars Orbit Injection
MOLA	Mars Orbiter Laser Altimeter
MOXIE	Mars Oxygen ISRU Experiment
MTV	Mars Transit Vehicle
NE	Northeast
PDR	Preliminary Design Review
RIMFAX	Radar Imager for Mars' subsurface experiment
RTG	Radioisotope Thermoelectric Generator
SEP	Solar Energetic Particle
SRP	Supersonic Retro-Propulsion
STM	Science Traceability Matrix
TEI	Trans-Earth Injection
TMI	Trans-Mars Injection
TOF	Time of Flight
TRL	Test Readiness Level
WBS	Work Breakdown Structure

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