# Mission Proposal

**April 18th, 2017**

Prepared for:

AE 443 Space Systems Design II

Department of Aerospace Engineering

University of Illinois at Urbana-Champaign

# Aries III


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# List of Acronyms

| | |
|---|---|
| WRS | Water Recovery System |
| ADCS | Attitude Determination and Control System |
| AIAA | American Institute of Aeronautics and Astronautics |
| ARS | Air Revitalization System |
| BOL | Beginning of Life |
| CDRA | Carbon Dioxide Removal Assembly |
| CRA | $CO_2$Reduction Assembly |
| DSN | Deep Space Network |
| ECLSS | Environmental Control and Life Support System |
| EOL | End of Life |
| EPS | Electrical Power System |
| FH | Falcon Heavy |
| GNC | Guidance, Navigation, and Control |
| HGA | High Gain Antenna |
| IMU | Inertial Measurement Unit |
| LEO | Low-Earth Orbit |
| LEOP | Launch and Early Operation Phase |
| LGA | Low Gain Antenna |
| Li-Ion | Lithium Ion |
| MCA | Major Constituent Analyzer |
| MCS | Mission Concept Summary |
| MLI | Multi-Layer Insulation |
| NASA | National Aeronautics and Space Administration |
| Ni-Cd | Nickel-Cadmium |
| NiH2 | Nickel Hydrogen |
| NSBRI | National Space Biomedical Research Institute |
| OGA | Oxygen Generation Assembly |
| OGS | Oxygen Generation System |
| RAM | Radiation Area Monitor |
| RFP | Request for Proposal |
| SLS | Space Launch System |
| TCS | Thermal Control System |
| TEPC | Tissue Equivalent Proportional Counter |
| TT&C | Telemetry, Tracking, and Command |
| TWTA | Traveling Wave Tube Amplifier |
| UPA | Urine Processor Assembly |
| WCS | Waste Collection System |
| WPA | Water Processor Assembly |

## Executive Summary

Crewed spacecraft have not travelled beyond Low-Earth orbit (LEO) since the 1972 Apollo 17 moon mission. The National Aeronautics and Space Administration (NASA) has both new lunar surface missions and Near-Earth Asteroid exploration plans. However, in the Earth-independent regime of deep space, Mars is the destination of most interest. Given the significant robotic exploration, manned Mars missions would be the next logical step. A human spaceflight mission to Mars would lay the foundation for future human exploration of Mars and beyond. The Aries III mission would demonstrate the capabilities of numerous technological developments including launch vehicles, space propulsion systems, and habitable space modules [1].

However, one of the largest concerns regarding deep space travel remains the impact of long-term exposure to the deep space environment on humans. The physical dangers posed from long-term exposure to deep space include muscle atrophy and bone density loss due to absence of gravity, radiation sickness, and spinal cord stretching. Behavioral problems include cognitive maladies, sleep loss, and potential declining interpersonal relationships. These bioastronautic issues pose a substantial threat to astronauts during deep space travel and are a significant uncertainty for journeys of this magnitude [2].

The spacecraft shall house three astronauts as signified by the name "Aries III." Science to be performed on-board include medical monitoring of the physiological and psychological conditions of the astronauts. The mission will therefore address significant knowledge gaps in the field of bioastronautics.

In order to achieve its goals, Aries III will utilize several key technologies that are currently under development such as the Space Launch System (SLS) for the launch vehicle, the Bigelow B330 module for the habitat, the SpaceX Dragon capsule for re-entry, and the Vinci

rocket engine for the spacecraft propulsion. The use of these systems in the Aries III mission will act to validate these technologies for future deep space travel.

The spacecraft will be composed of two primary components, a habitat module and a re-entry capsule. The habitat module will be a Bigelow B330 modified to have an Environmental Control and Life Support System (ECLSS) suitable for long-term human presence; a Guidance, Navigation, and Control system for deep space flight; a communications system for deep space communication; and solar arrays for power generation. In addition to these systems, the B330 will be modified to interface with the SpaceX Dragon re-entry capsule. This capsule serves to protect the astronauts during Earth re-entry.

The proposed crewed mission, launches October 2032 into a free return trajectory, performs a fly-by of Mars and subsequently returns the astronauts safely to Earth. The projected time of rendezvous with Mars is July 2033 with return to Earth May 2034. Upon arriving in the vicinity of Earth, the spacecraft performs highly elliptic Earth orbits, utilizing atmospheric drag to slowly reduce the spacecraft's altitude. Once the altitude reaches 800 km, the habitat is jettisoned and the astronauts return in the re-entry capsule. GNC will reorient the habitat for a less aerodynamic re-entry, guaranteeing its destruction within the atmosphere. This trajectory would result in a mission duration of approximately 650 days, almost twice as long as the previous record for consecutive human space-flight [3].

The design choices and technology selection have been made to minimize cost while balancing risks. The chosen technologies will be flight-proven by the time the mission is commenced. The total mission cost is $3.9 billion. This gives a margin of 21.8% from the $5 billion budget cap. The design fulfills the requirements posed in the RFP.

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# ARIES 3 Fact Sheet

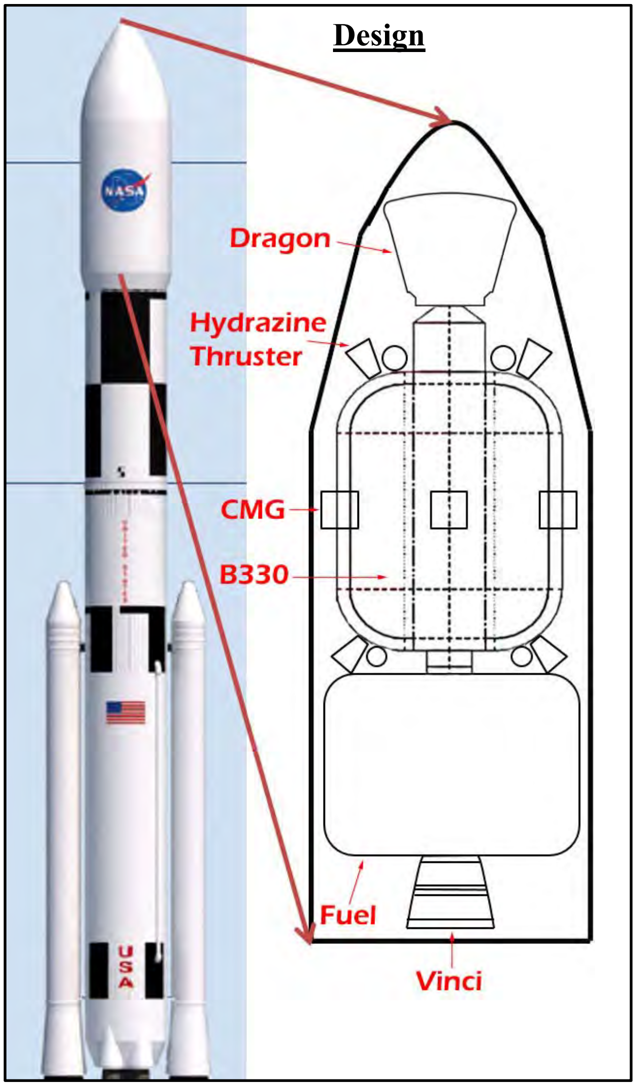
## Mission Statement

The goal of Aries III is to design, launch, and return a spacecraft that will take humans to the orbit of Mars and back to Earth while studying the impact of long term interplanetary space exposure on humans, all for under $5 billion.

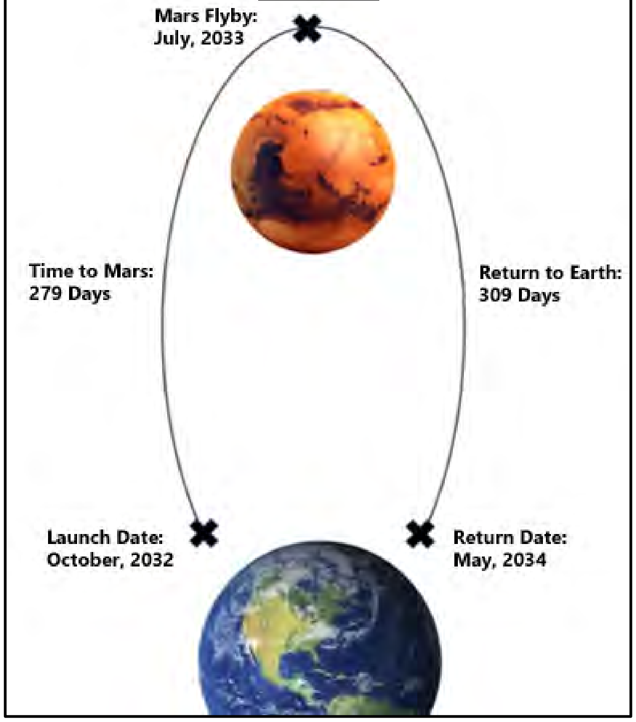
## Scientific Goals

- Monitor the physiological impacts of continuous deep-space exposure on humans
- Observe psychological impacts of space travel to Mars in groups of less than 5 people
- Provide information that will help with future human Mars landing missions and other manned interplanetary missions

## Design




## Timeline




## Key Technologies

**Space Launch System** – NASA is currently developing the SLS for large, deep space missions. Aries III plans on utilizing the SLS's heavy lift capabilities to launch 55,000 kg on a trajectory to Mars.

**B330** – Bigelow is developing an inflatable space habitat. BEAM (a smaller version of the B330) is currently attached to the ISS and being tested.

**Dragon Capsule** – SpaceX is modifying the already successful Dragon to transport humans. The heat shielding is designed to withstand reentry for a Mars mission.

**Vinci Engine** – Under development by the ESA, it is designed for use on the Ariane 6. It will be used as a third stage and all successive burns.

# 2. Mission Goals and Justification

## 2.1. Requirements

**Table 2-1. Program Requirements**

| Program Requirements | | Source |
|---|---|---|
| P1 | Overall cost of the mission shall be no greater than $5 billion. | AIAA RFP |
| P2 | Mission shall transport humans to within the orbit of Mars and back to Earth, without loss of life or severe injury. | AIAA RFP |

The ability to send humans to explore interplanetary space as proposed, will make Mars the ideal first location for exploration. Multiple successful robotic missions to Mars and interplanetary space have gathered sufficient information to launch a successful manned Mars mission [4]. The RFP states that such a manned mission is the next logical step. In addition, a manned orbital Mars mission would be a precursor to landing humans on Mars, much like how Apollo 8 was the precursor to landing humans on the Moon.

A manned mission to Mars' orbit will lay the groundwork for landing humans on Mars by validating current technology and researching potential problems. A manned Mars mission is the final test of technologies like the B330, SLS, Dragon, and Vinci which are being developed and tested right now.

Due to the hostile environment of interplanetary space, cautionary steps must be taken to maintain crew health, both mentally and physically. By providing the necessary radiation protection, food, water, living space, shelter, health equipment, and communication with family and friends on Earth, the crew will have the best chance at surviving the Martian round-trip.

Set by the RFP, a top-level requirement is to keep the mission cost under $5 billion. Unlike the Moon missions which tapped NASA's full financial capacity, the cap makes the mission financially viable.

New technologies such as the B330, SLS, Dragon, and the Vinci engine are a source of increased risk, with the potential to lower costs. This report will go into detailed cost versus risk analyses for major component selection.

The exploratory goal of Aries III is to gather data for use in research and future missions. Crew health, both physical and mental, must be monitored extensively and continuously. Most of the science data will be collected and analyzed, both by the astronauts and the ground crew from launch to landing. Despite steps taken to keep the astronauts healthy while in space, it is expected that health will degrade over time. This is demonstrated by astronauts on the ISS developing many physical problems including bone mass loss and eyesight issues. The design of this mission works to minimize the impact of these problems, while simultaneously studying their effects. The mission's data will inform future deep space missions and pave the way for landing humans on Mars.

## 2.2. Science Goals

**Table 2-2. Science Goals**

| Science Goals | |
|---|---|
| S1 | Monitor physiological impacts of continuous deep-space exposure on humans. |
| S2 | Observe psychological impacts of space travel to Mars in groups of less than 5 people. |
| S3 | Provide information that will help with future human Mars landing missions and other manned interplanetary missions. |

The science is an important aspect of this mission. The following section will go into detail about the specific science goals and what Aries III wants to achieve on its mission.

The first scientific goal, monitoring physiological impacts of deep space on humans, is important because a mission of this length has never been conducted before. From previous missions into space, the effects of microgravity can have quite the toll on the human body;

muscle atrophy and bone loss have been found to be the most significant. Astronauts on six month rotations in space have shown a substantial decrease in bone density and muscle. The mission is just under 600 days, significantly longer than any other manned mission. It will be important to monitor the health of the astronauts and study how well countermeasures prevent such losses. If these countermeasures prove effective, future missions can implement and build upon them.

Not only does microgravity affect the astronauts, but the physiological effects of radiations must be well monitored. Crew on the Aries III will venture further than any other astronaut has before. They will leave the magnetic field of the Earth and be exposed to much more radiation. It will be important to learn how radiation affects the crew given the radiation shielding. The results from the data collected on radiation will help future missions adapt so humans can learn how to travel further into space. The more that can be studied about how the human body reacts to long-duration space missions, the more capability humans will have as a species to continue venturing further into space.

The second scientific goal of Aries III is to observe psychological impacts of space travel to Mars in groups of less than 5 people. One of the things Aries III will be studying is the isolation the crew will be forced to face. The reason this cannot be studied on Earth is simple; once astronauts arrive at Mars, there is no way to quickly come home. On Earth, no matter where isolation tests are conducted, people know that if things go poorly, they could find their way home. However, that is not the case on a mission to Mars. People cannot escape the test even if they wanted to, and this adds another dimension that can only be studied on this mission. The crew of the Aries III are committing to around 600 days of being isolated and away from home. Not only are these unique conditions ideal to learn more about the psychological effects of isolation, they are also very important to the future of human space travel. When humans eventually explore further than Mars, they will have to be isolated longer. An understanding of how people react in these conditions will allow subsequent missions to prepare and account for it. Aries III will also study the social interactions between the crew during the voyage. A prolonged period between a group of people will be very common in all manned missions. Once again, this interaction can only be measured on this mission because the crew won't be able to return once the mission is launched. Psychological aspects of this mission will provide a foundation for future missions.

The final scientific goal of the Aries III is to provide information that will help with future human Mars landing missions and other manned interplanetary missions. After this mission, the next logical step is to land humans on Mars. A successful mission will provide a basis for that and any upcoming manned missions as well. With a foundation for a manned flight, preparations for a landing mission will become much easier. Along with creating a proven system, this mission can help create public approval. Overall, proving humans can make it safely to Mars will be an important step in human space exploration.

## 2.3. Mission Requirements

**Table 2-3. Mission Requirements**

| Mission Requirements | | Source |
|---|---|---|
| M1 | The spacecraft shall at minimum perform a fly-by of Mars. | S3, P2 |
| M2 | The spacecraft shall be able to carry humans on-board. | S1, S2, P2 |
| M3 | The spacecraft shall keep astronauts alive for the duration of the mission and return them safely to Earth. | S1, S2, P2 |
| M4 | The spacecraft shall return collected science data back to Earth. | S1, S2 |

The mission requirements from Table 2-3 combine the program requirements and science goals to make a unified set of requirements for each subsection to draw from and build upon. The fulfillment of these requirements will be critical to mission success.

# 3. Mission Implementation

## 3.1. Management and Timeline

The timeline for the entire duration of the mission can be seen in Figure 3-1. The exact dates are estimates derived from the structure of the NASA project life cycle [5]. Phases A and B are longer than typical to account for technology development and modification of the B330, Dragon, and Vinci.

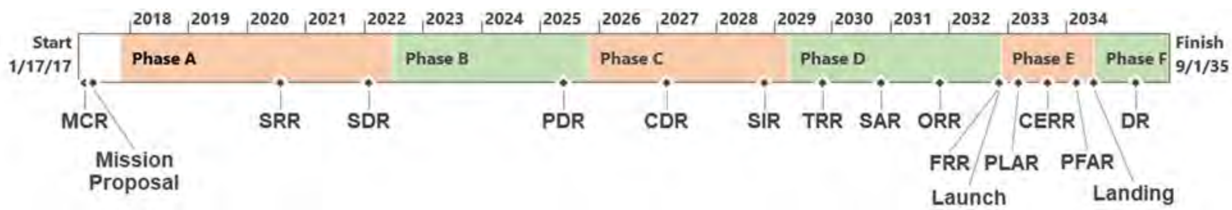



**Figure 3-1. Project Timeline with Key Events.**

The mission will be a NASA managed project. The RFP references NASA and the Apollo 8 mission, as well as listing two NASA employees as the contacts for technical questions. Because it does not explicitly state who the RFP is being prepared for, and with NASA being the only space-flight organization referenced, it is assumed that NASA will manage this project post proposal.

Phases A and B will be minimally staffed. This time will be spent tracking the progress of the developing technologies, finalizing the design, and planning for fabrication and testing. Once in Phase C, the staff for each subsystem will increase, as the individual subsystems begin working on design details. Staff will increase again for Phase D, as the subsystems are integrated, tested, and prepared for launch. Post launch, staff will decrease, as no more designing or building is required. After landing, staff will again decrease, with scientists researching the data brought back and administration formally finalizing the mission.

Figure 3-2 shows an estimate for number of staff members working on Aries 3 per year. Using an average salary of $129,000 [6], the staff cost is estimated to be $600 million for the entire mission lifetime. Staff for the SLS is not factored in, as the cost for SLS already accounts for development, operations, and staff.

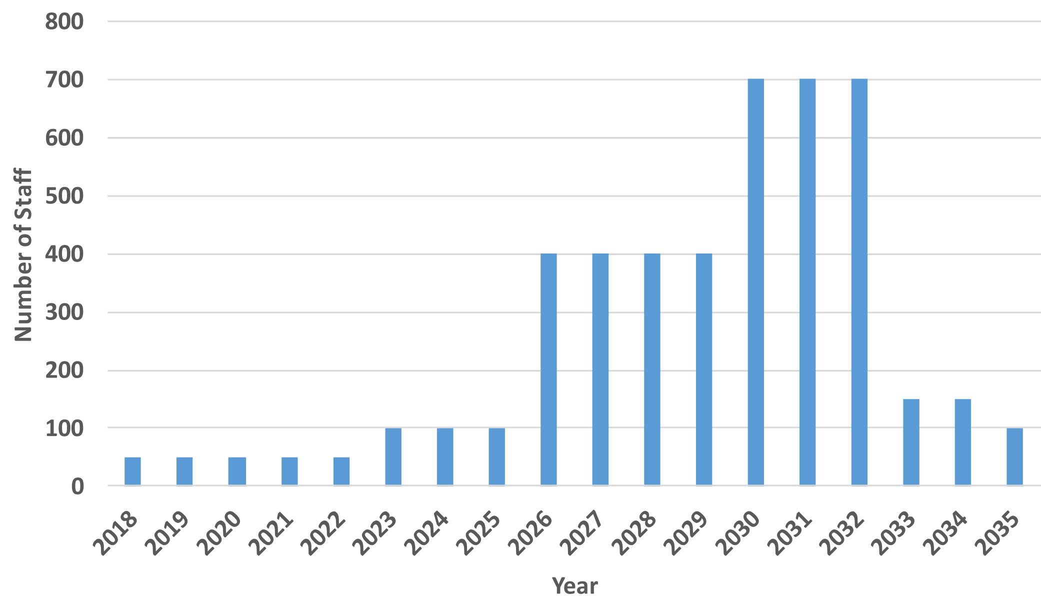



**Figure 3-2. Number of Staff Working on Aries 3 per Year.**

The management staff is important to keep the program on time and within budget. Figure 3-3 shows the hierarchy of management. Those management positions will remain active for the entire mission duration. Technical staff will report to the subsystem level managers. In phases C and D, as more staff is needed, the subsystem managers will also need assistants to manage the large staff. The software used by management will be NASA's Project Management Tool (PMT). This software will be used to handle requirements, deadlines, reports, and budgets [7]. In addition to management, the technical staff will also use this software.

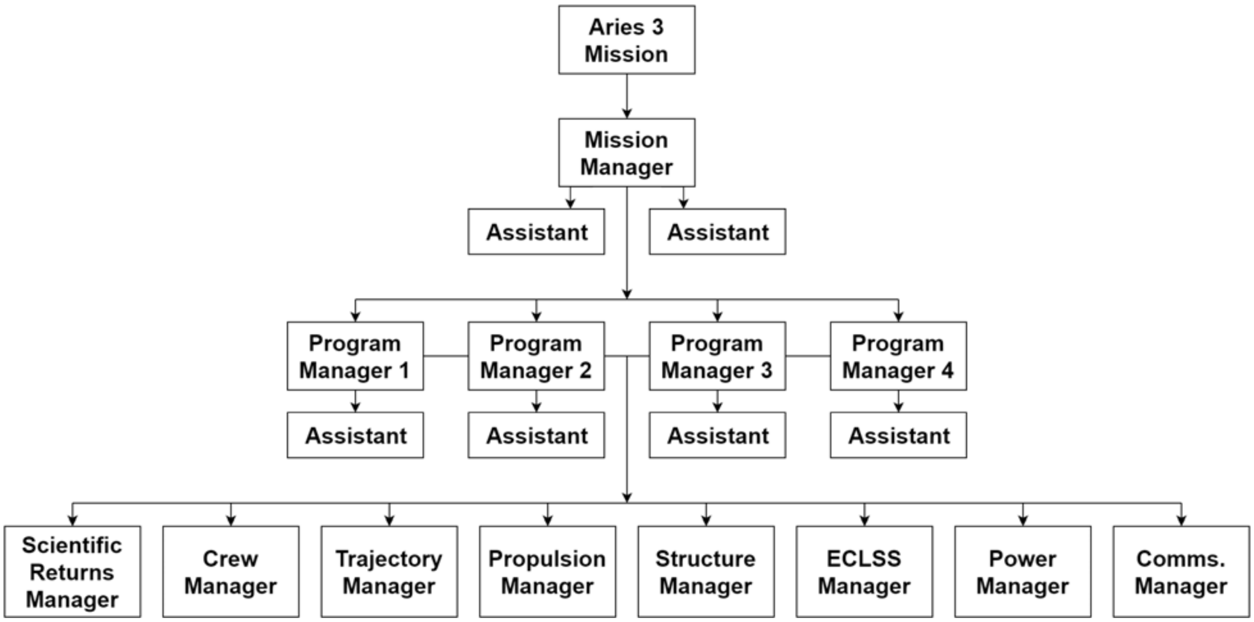



**Figure 3-3. Hierarchy of authority.**

## 3.2. Scientific Returns

**Table 3-1. Scientific Returns Requirements**

| Requirement | | Source |
|---|---|---|
| SM1 | Upon return to Earth, astronaut bone density and muscle atrophy differences shall be examined and compared to pre-flight status | S1 |
| SM2 | Radiation exposure levels of the astronauts shall be studied and monitored | S1 |
| SM3 | The effects of long duration space flight on human health and its immune system shall be monitored | S1 |
| SM4 | The mission shall study the effects of long duration isolation in space on the mental health of the crew | S2 |
| SM5 | The interactions and interpersonal relations between crew members in isolation shall be monitored and studied | S2 |
| SM6 | The mission shall collect data for no less than the duration required to leave the Mars sphere of influence | S1, S2, M1 |

The Aries III Mission will conduct multiple scientific measurements based on the science goals and requirements. As mentioned earlier, the scientific goals of the Aries III are to monitor the physiological impacts of continuous deep-space exposure on humans, observe psychological impacts of space travel to Mars in groups of less than 5 people, and to provide information that will help with future human Mars landing missions and other manned interplanetary missions.

To satisfy the first scientific requirement, as seen in Table 3-1, each crew member's bone density and muscle mass will be measured pre-flight to record base levels for each astronaut. Then, at the end of the mission, the same measurements will be taken and compared to the pre-flight data. The astronauts are expected to lose much of their muscle mass and show a decrease in bone density during the mission. Currently, muscle mass in astronauts is diminished by 20% in two weeks, and on longer missions spanning 3-6 months, a 30% decrease is noted [8]. For bone loss, the typical 6-month mission on the ISS reports around 8%-12% losses. Therefore, a long mission like the one proposed by the Aries III would deteriorate bone to osteoporotic levels and muscle levels dramatically low if no countermeasures are used [8]. Because of these high expected losses, and to satisfy safety requirements, several countermeasures will be implemented. To combat bone loss, the crew on Aries III will be treated with Bisphosphonate. This therapeutic agent has been used to treat osteoporosis patients for more than a decade, with a proven efficacy to increase bone mass and decrease the occurrence of bone fracture [9]. Not only will the astronauts be treated with this agent, but will also have a diet rich in calcium and vitamin D, which will help to reduce bone loss. To combat muscle atrophy, the astronauts on board will be required to work out two and a half hours a day, six days a week. They will work out using a stationary bike, a treadmill, and a machine called the Advanced Resistive Exercise Device [10]. During preflight, astronauts will go through physical conditioning to get their muscles at optimal strength before the mission. By measuring the bone and muscle differences of the astronauts before and after the mission, the success of these countermeasures can be measured. These results will help provide useful measurements that will satisfy Science Goal 1 (S1) and Science Goal 3 (S3).

The second scientific requirement for the mission revolves around radiation exposure. To best meet this requirement, common dosimetry badges will be worn throughout the flight. This data will be transmitted back to Earth and studied on the ground. The radiation data of the craft will be taken using a Tissue Equivalent Proportional Counter (TEPC) and Radiation Area Monitor (RAMs). These two systems have been used on the ISS, and the Aries III will bring a spare TEPC for redundancy [11].

To further monitor the astronaut's physiological conditions during a long-duration mission and to meet the third scientific requirement, the astronauts will monitor their immune systems. By studying the immune system, the effects of long-duration missions on the human body can be measured. There are several ways to measure the immune system of the human body: one could measure blood, saliva, or urine samples.

**Table 3-2. Trade Study on Immune System Measurement Methods**

| | | **Traditional Blood Tests** | **Handheld Blood Testing Device** | **Urine Samples** | **Saliva Samples** |
|---|---|---|---|---|---|
| **Aspect Compared** | **Importance** | **Parameter** | **Parameter** | **Parameter** | **Parameter** |
| Time until analyzed | 40% | 1 | 5 | 3 | 4 |
| Mass | 30% | 3 | 5 | 2 | 5 |
| Volume | 20% | 2 | 4 | 3 | 4 |
| Cost | 10% | 4 | 4 | 4 | 4 |
| **Score** | | **2.1** | **4.7** | **3.1** | **4.3** |

| **Aspect Compared** | **Parameter Explanation** |
|---|---|
| Time until analyzed | (1) Analyzed at end of mission; (5) Analyzed right away |
| Mass | (1) All testing components over 10 kg; (5) under 2 kg |
| Volume | (1) All testing components over 1 $m^3$; (5) All testing components under .2 $m^3$ |
| Cost | (1) over $5000; (5) Under $500 |

As seen in Table 3-2, the handheld blood testing device was valued higher than the other methods, so it will be implemented during the mission. This new device is currently being developed at the California Institute of Technology, among other places, and will be finished and tested before the launch window [12]. To measure crew health, each astronaut will be required to wear biometric sensors. This is implemented through a shirt called Astroskin, which is lightweight and continuously measures the crews' heart and breathing rates, electrical activity of the heart (electrocardiograms), blood pressure, breathing volume, skin temperatures, physical activity levels and blood oxygen levels during the mission [13]. This data is collected via an onboard computer and will then be transmitted back to Earth. This will not only provide real-time information (bar communication delays) regarding the astronauts' health, but can also provide tracking of any slow, developing effects of long-duration space flights.

Along with taking the physiological measurements, Aries III will also take multiple psychological measurements to meet the science requirements. To best meet this requirement, and study the mental health of the crew, each astronaut will be required to take a therapy session every two weeks. Because of the long delays of communications once at Mars, Aries III will implement a therapy computer program being developed by National Space Biomedical Research Institute (NSBRI). This program will put the crew through "problem-solving treatment" and will supplement this with other behavior programs [14]. These tests will monitor the mental health of the crew throughout the mission, and any differences in them will be compared to the risks and situations faced during the flight, as well as pre- and post-mission tests. Along with the therapy sessions, the astronauts will also undergo basic cognition tests, vision tests, and motor skill tests. These tests will be taken bi-monthly as well, but staggered from the therapy sessions. This is to provide separation in the astronaut's schedule. These tests will show if there is degradation in any of the astronauts' skills which would be important to know if longer duration missions were planned. Also, like the computer program, these tests will be compared to situations faced during the flight as well as pre- and post-mission tests. These tests and therapy sessions will adequately fulfill this first requirement.

Aries III will also study interpersonal relations between the crew in isolation on a long-duration mission. When discussing how to study the social interactions between the crew, the number of astronauts aboard Aries III had to be decided. Two or fewer crew member were initially decided against as this limited the amount of social interactions. To further decide, mass, volume, and ECLSS requirements were considered.

**Table 3-3. Mass and Volume Estimates of Food per Astronaut**

| # Astronauts | Mass | Subtotal Mass (kg) | Volume | Subtotal Volume ($m^3$) |
|---|---|---|---|---|
| 1 | 2.3 kg/person/day | 1610 | .008 $m^3$/person/day | 5.6 |
| 2 | | 3220 | | 11.2 |
| 3 | | 4830 | | 16.8 |
| 4 | | 6440 | | 22.4 |
| 5 | | 8050 | | 28 |

The most pressing constraint concerning crew size was mass. As seen in Table 3-3, the mass of food alone is sizably higher as crew members increase. Along with food, around 1000 kg of other supplies are considered in the ECLSS subsystem. When mass and total mass margins from all systems were considered, three astronauts were selected for the mission. To monitor the interactions between the crew, cameras will be placed in shared living spaces. The cameras currently used internally on the International Space Station, the Nikon D4, will also be implemented inside the Aries III [15]. No cameras will be placed in personal quarters, to ensure privacy for the astronauts. The footage from the cameras will be sent to psychologists and scientists who can look for differences in crew behavior as the flight progresses. In order to satisfy both requirements regarding psychological measurements, the astronauts will keep both video and written logs. The written logs are to be performed daily and will be collected after the mission, while the video logs must be taken once a week and will be reviewed by a psychologist on Earth.

It is important to note that all scientific measurements must collect data for no less than the duration required to leave the Mars sphere of influence. At that point in the trajectory, the crew would be the farthest from Earth. If anything were to happen to stop collecting data after this point, Aries III would have gathered enough information to help future missions. However, Aries III has been designed to collect and transmit data for the entire mission duration.

### 3.3. Crew Selection

The crew will be required to go through an application process designed and enforced by NASA. They will be thoroughly vetted and rigorously trained. However, there are certain requirements that need to be fulfilled pertaining to the specific needs of the current mission. These may overlap with the general criteria laid out by NASA for similar missions.

To be considered as an applicant, a person needs to meet certain standards in terms of physiological and mental health, and educational qualifications. The applicant needs to have correctable 20/20 vision, no history of chronic conditions or any other illness that might make launch or re-entry difficult to sustain [16]. Apart from the testing before selection, basic tests will be conducted even during the training process to keep a track of their growth or any changes that may occur. During the training, emphasis will be placed on maintaining the physical fitness of the crew and acclimatizing them to the conditions they are likely to come up against.

Mental health and psychological readiness is as crucial to the mission as physical health. Extensive studies will be held to gauge if the applicants are equipped to survive such an intense mission. The training will also be directed at preparing them for what lies ahead and for any extreme situations that they might have to encounter. It would be advisable to have a panel of doctors conduct the psychological exams and selection must be unanimous. Apart from induvial exams, the potential crew will be trained and tested as a group. Not only do they need to have the mental capacity to survive but they also need the maturity to be able to survive with others.

Another key aspect for vetting is the profession of the applicant. Since it is a manned mission, it is prudent to have a doctor onboard. Not only will this help with the medical tests that need to be performed during the mission, it will also ensure that there is someone onboard to help with any emergencies. It would be worthwhile to have an engineer on the crew, who is most likely to understand the workings of the spacecraft. While it is advisable to have all three crew members with experience in space travel, it is necessary to have a team lead/commander with it.

## 3.4. Trajectory

**Table 3-4. Trajectory Requirements**

| Requirement | | Source |
|---|---|---|
| T1 | The trajectory shall include a flyby of Mars. | P2 |
| T2 | The trajectory shall not take longer than 700 days to complete. | P1 |
| T3 | The spacecraft velocity shall remain under 14.2 km/s on its approach to Earth. | P2 |

This trajectory will take the astronauts to Mars and back in approximately 588 days. It will involve a gravity assist to swing around Mars and back towards Earth. The orbital injection will occur in 2032, with the return to Earth occurring in 2034.

The key design decisions that were made up to this point are as follows. The trajectory must be a free return trajectory. This is a design decision based on two requirements: the mission requirement to keep the astronauts alive until back on Earth and the program requirement to keep the mission under $5B. The trajectory will use the gravity assist of Mars to swing back towards Earth without having to burn more fuel. It would also take the craft to the orbit of Venus before returning to Earth. This trajectory type minimizes time spent in the harsh environment. This also only requires two major burns, an inclination change and an injection burn. There would also be correction burns and alignment maneuvers for the gravity assist around Mars and during the approach to the re-entry of the Earth's atmosphere, but these would be minor compared to the injection. This means a lower fuel requirement, thus keeping the number of launches to one.

A Hohmann transfer orbit was one of the preliminary choices for trajectories. This mission type would likely leave the astronauts in space for a little over 2.6 years [17]. To shorten the mission time, a free return trajectory was chosen, and to shorten it by another 166 days, the craft will use the orbit of Venus. In total this free return flyby would only last 588 days at minimum. This creates a great deal of risk, as the levels of radiation will be much higher than at LEO [18]. However, these risks can be greatly mitigated through the personalized medical care that the astronauts will be receiving, both from the doctor onboard and from doctors on the ground. It was also found that the levels or radiation experienced during this mission would be lower than a similar mission that did not go to the orbit of Venus [19].

A Vinci engine should be used for the orbital injection. This is a design decision that was based on the free return trajectory decision, which was based on the budget and the astronaut's health requirements. The Vinci engine has the highest $I_{sp}$ which reduces the amount of fuel. This can be seen in the trade study of potential engines in Table 3-5. The ΔV's for the two major burns came to 4.8 km/s. As a back up to the Vinci engine [20], the Japanese made LE-5A [21] could be used. The Vinci engine has its first planned flight test in 2017. If all goes to plan, then the Vinci engine would be a viable engine when the launch occurs. The reason that the Vinci engine would be preferable is that it has the same specific impulse of 465s, as the comparable RL10, from Pratt and Whitney, but with 63% greater thrust and a lower weight, which both reduces the cost. Analysis has shown that the LE-5A, which is a heritage system, is capable of the orbital injections.

**Table 3-5. Trade Study of Potential Upper Stage Engines**

| Engine | $I_{sp}$ in Vacuum (s) | Thrust (kN) | Dry Weight without Nozzle (kg) | Restarts | Total |
|---|---|---|---|---|---|
| Weighting | 5 | 3 | 2 | 1 | |
| Vinci | 465 | 180 | 160 | Up to 8 | 43 |
| HM7B | 446 | 64.8 | 165 | None | 15 |
| RL-10 | 450-465.5 | 110 | 277 | None | 24 |
| LE-5A | 452 | 121.5 | 248 | Up to 16 | 27 |

The total value is calculated by multiplying the attributes weighting by its ranking out of the 4 engines. With $1^{st}$ equaling 4 points, $2^{nd}$ equaling 3 points and so on. This mission requires a high $I_{sp}$, a high thrust, a low weight and a high number of restarts.

The trajectory must include an inclination change to align with the Martian orbital plane. This is a design choice that was influenced by the mission requirements of preforming a Mars fly-by and returning the crew safely back to Earth. From LEO, final system checks and pre-injection procedures can be carried out from mission control. It also allows an easy abort if a critical failure is detected in a subsystem. Aborting after the orbital injection would only be beneficial up to 40 days, and the fuel requirements would be too large, which can be shown in Figure 3-4.

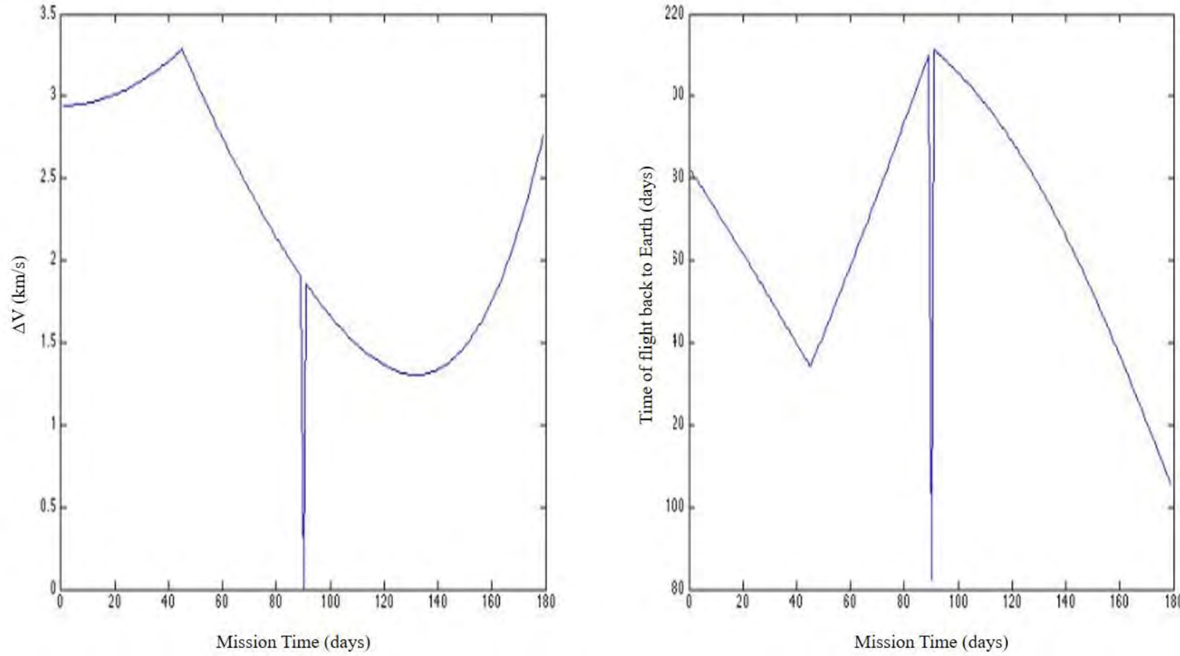



**Figure 3-4. Abort Trajectory Analysis.**

Mars injection must take place within a month of 10/10/2032. This design decision is also based on the free return trajectory decision, and hence the budget and crew health requirements as well. The synodic cycle of Earth and Mars, as well as the precession of their nodes, means that this trajectory would only be possible every 15 years. For this trajectory, the launch window would therefore be a month long. Any later or earlier than that and the ΔV required would be too large [22], meaning that the fuel requirements would be huge and therefore costly.

In the interplanetary legs, the craft will need to do trajectory correction maneuvers (TCM). This is due to the need to clear up any errors due to the initial injection, from variation in the solar radiation pressure or from the non-sphericity of the Martian body. These errors are likely to be very small but could result in mission failure if they build up. The thrusters selected have a max thrust of 254.9 N. This is relatively small, but as the time between these maneuvers is relatively long and the error is so small, the size of these thrusters is appropriate.

The re-entry must utilize a skip entry to slow the vehicle before it re-enters the atmosphere. This was derived from the top-level requirement that the crew must survive the entire trip. The crew are more likely to survive a re-entry at lower velocities. Also, this allows the splashdown location to be accurately executed. The planned technique to perform this is an aero-braking initial phase followed by a retrograde burn to slow the craft down. The aero-braking phase would consist of the craft effectively skipping out of the atmosphere multiple times, in between which retrograde burns will also be performed, before reaching a suitable velocity, and final location for landing. The spacecraft is expected to reach about 155 km at perigee from Earth and will be expected to be travelling at 9.5 km/s after the first skip. After which, if a suitable splashdown location can be achieved, the final re-entry will begin; if not then, another skip will be made to reduce the velocity even further, with initial calculations estimating that the capsule will be travelling around 3.9 km/s. Through calculations, it can be shown that the maximum number of skips would be 2. If the incoming velocity was at the upper limit of 14.2 km/s to achieve a re-entry speed that will not harm the astronauts, however there may be cause for 3$^{rd}$ and 4$^{th}$ skips if a suitable landing location is not achievable. These calculations will be done on approach to Earth, so that if the 3$^{rd}$ and 4$^{th}$ skips are needed a shallower entry angle will be selected as to not slow the craft down as much. This technique must be carefully monitored as if the re-entry is too steep on any of the skips, it could cause the temperature to increase to a point that would cause the craft to burn up or it could cause the g-load on the astronauts to be too great. Retrograde burns will also be performed using a thruster fitted to the nose of the craft. This thruster, along with several others positioned across the structure, will also be responsible TCM. After the vehicle has entered the Earth's atmosphere, 3 drogue parachutes will deploy to slow the vehicle down to a controllable velocity of about 201 km/hour, this number has been collected from historical data. After the drogue parachutes are jettisoned, three main parachutes will deploy to slow the vehicle to under 15 km/hour, for splashdown. An extra crumple zone will be added to further protect the skeletons of the astronauts. Even though the Dragon capsule is being developed to land on a barge with re-usability in mind, a water landing was chosen for its heritage and safety.

For the correction burns on approach to Mars and Earth, the large MR-107 thruster will be used. The thruster is currently in use on NASA's OSIRIS-REx mission. The thruster produces a thrust in the range of 51.2 - 257.9 N, the burns from this engine will be accompanied by a smaller 4 N Hydrazine thruster for error correction. To reduce boiloff, the fuel tank used will be based off a NASA design in which they achieved zero boiloff. The design consists of an active cryocooling system in addition to a traditional passive thermal insulation. This tank would need careful monitoring as drops in pressure will increase boiloff, and will also need thermal shielding from other systems onboard, as any extra energy will speed up boiloff.

The costing of the upper stage system was found through research into other missions. It includes the cost of 3 Vinci engines. 1 engine will be used in the mission and the other 2 will be used for launch condition testing.

## 3.5. Propulsion

### 3.5.1. Launch Vehicle Selection

**Table 3-6. Launch Vehicle Requirements**

| Requirement | | Source |
|---|---|---|
| L1 | Vehicle shall have the capabilities to inject payload into proper trajectory. | M1 |
| L2 | Vehicle shall be capable of housing the spacecraft within its payload fairing dimensions. | M1 |
| L3 | Vehicle shall stay within 4 G-forces for ten seconds and 8 G-forces for four seconds immediately after launch. | M3 |

Launch vehicle selection is dominated by the structure and trajectory requirements. There are three leading requirements derived from those two subsystems that are summarized in Table 3-6. The primary source for these requirements is transporting humans within the orbit of Mars (M1). Failure to meet these requirements will be detrimental to the astronauts' health and results in mission failure.

These three overarching requirements provide the baseline for launcher selection, but give little in direction for which launcher to select. To analyze a launcher's capabilities from the mission design parameters, mass and trajectory of the payload are the driving factors. A quick analysis of current technology shows that modern launchers are severely inadequate for this type of mission. Given the requirements on the spacecraft, the estimated dry mass of the mission comes close to 55,000 kg. Taking the most capable, the Delta IV Heavy, at least two launches would be needed to get the payload into space, and another five would be needed to get the fuel to leave on a trajectory to Mars. Present launch capabilities are summarized in Table 3-7.

**Table 3-7. Summary of Launch Vehicle Attributes**

| | **Ariane 5** | **Delta IV Heavy** | **Long March 5** | **Proton-M** | **Falcon 9** |
|---|---|---|---|---|---|
| Mass (kg) | 777,000 | 733000 | 879,000 | 705,000 | 549,054 |
| Cost ($ million) | 160-220 | 375 | N/A | 105 | 62 |
| Mass to LEO (kg) | 16,000 | 28,790 | 25,000 | 21,600 | 22,800 |
| Fairing Diameter (m) | 6.9 | 5 | 4.8 | 6 | 5.2 |

Two future launchers were considered in prior analysis, the Falcon Heavy (FH) and the Space Launch System (SLS). While the FH has the cost advantage, the SLS was able to complete the mission with a single launch. The FH would need at least four launches, and similar to the reason for not selecting current launches, there is a significant risk of failure. The current Falcon 9 launches approximately once every month and half; assuming a longer window of three months for FH launch frequency, station keeping for an entire year deems too complex. Lastly, add in the difficulties with combining four launch modules together, and the FH is inadequate and unsafe. Therefore, the SLS is the launcher the mission will use going forward.

Current design parameters estimate the dry mass of the mission to be 55,000 kg with the 10% mass margin, and the payload height of about 15 m. The change in velocity ($\Delta V$) needed to leave Earth and align with Mars was calculated to be 11.56 km/s; with an added 2 km/s $\Delta V$ added for losses due to gravity and atmospheric drag, the final $\Delta V$ needed was 13.56 km/s. The SLS can provide a 7.56 km/s $\Delta V$ with its two stages, but will need a third stage for the remaining $\Delta V$. The engine selected for the third stage is the Vinci engine, designed to model the Delta IV rocket. After a trade study on the capabilities of the SLS with the 3rd stage, it was found that the launcher is capable of providing the required $\Delta V$ for up to about 65000 kg of dry mass. If a 7.5% unused fuel margin is used, the SLS can provide enough $\Delta V$ for up to the 54,850 kg. A comparison of different levels of fuel is summarized in Table 3-8. Overall, this would need about 158,500 kg of 3rd stage LOX/LH fuel. If a 5% unused fuel margin is used, the SLS can provide enough $\Delta V$ for up to 57,370 kg. For comparison sake, the similar fuel levels are compared in Table 3-9. With both a 5% and 7.5% unused fuel margin, this 3rd stage would fulfill the requirement to inject the payload into the proper trajectory.

**Table 3-8. Summary of 3rd Stage Effects on the 1st and 2nd Stages of the SLS with a 7.5% Fuel Margin**

| Initial Fuel (kg) | 1st Stage $\Delta V$ (km/s) | 2nd Stage $\Delta V$ (km/s) | 3rd Stage $\Delta V$ (km/s) | Tank Height (m) | Total Height (m) | Max Mass Allowed (kg) |
|---|---|---|---|---|---|---|
| 0 | 6.77 | 3.58 | 0 | 0 | 0 | 0 |
| 100,000 | 6.16 | 2.1 | 5.3 | 8.65 | 10.95 | 46,700 |
| 140,500 | 5.95 | 1.81 | 5.80 | 11.43 | 13.73 | 52,430 |
| 158,500 | 5.86 | 1.70 | 6.0 | 12.67 | 14.94 | 54,850 |
| 165,000 | 5.83 | 1.67 | 6.07 | 13.13 | 15.43 | 55,680 |

**Table 3-9. Summary of 3rd Stage Effects on the 1st and 2nd Stages of the SLS with a 5% Fuel Margin**

| Initial Fuel (kg) | 1st Stage ΔV (km/s) | 2nd Stage ΔV (km/s) | 3rd Stage ΔV (km/s) | Tank Height (m) | Total Height (m) | Max Mass Allowed (kg) |
|---|---|---|---|---|---|---|
| 0 | 6.96 | 3.73 | 0 | 0 | 0 | 0 |
| 100,000 | 6.32 | 2.18 | 5.07 | 8.45 | 10.75 | 49,200 |
| 140,500 | 6.10 | 1.87 | 5.59 | 11.22 | 13.52 | 55,000 |
| 158,500 | 6.00 | 1.76 | 5.80 | 12.47 | 14.77 | 57,370 |
| 165,000 | 5.97 | 1.72 | 5.87 | 12.93 | 15.23 | 58,200 |

Considering the full fairing dimensions, the mission has about 31.1 m of fairing height to use. According to calculations done in the sizing section, there is 15 m of extra fairing height available. The Vinci engine has an expanded height of 4.2 m and an unexpanded height of about 2.3 m. This gives a total height for tanks to be about 12.7 m. Taking into account the mixing ratio of the Vinci engine at 5.8, the density of LOX/LH, and the Vinci height, the 3rd stage will require 14.973 m of height. Given the oblong shape of the B330, there is extra space between the proposed third stage fuel tank that would be utilized for fuel, pressure chambers, and pumps. This fulfills the requirement that it shall fit the payload within the payload fairing dimensions.

Given the number of unknowns surrounding the performance metrics of the SLS, creating a G-force curve for the SLS would be highly inaccurate. However, the size of the SLS is comparable to Saturn V. According to Figure 3-5, the G-force curve of Saturn V, the design does not exceed the threshold of 4 G-forces for 10 seconds and 8 G-forces for 4 seconds, fulfilling the final launcher requirement.


**Figure 3-5. G-Force Curve of the Saturn V Launch.**

### 3.5.2. Guidance Navigation and Control

**Table 3-10. Guidance, Navigation, and Control Requirements**

| Requirement | | Source |
|---|---|---|
| G1 | GNC shall maintain correct trajectory for mission duration. | M1 |
| G2 | GNC shall provide real-time trajectory information for mission duration. | M1 |
| G3 | GNC shall properly orient spacecraft upon trajectory insertion and re-entry to Earth. | M1, M3 |

Guidance, navigation, and control (GNC) functions to properly orient and guide the spacecraft for the duration of the mission. Three main requirements listed in Table 3-10 lead the overall design parameters for the GNC system. The primary source for these requirements is transporting humans within the orbit of Mars (P2). Meeting these three requirements will mean the success of the system, and ultimately, lead to the satisfying of getting humans to Mars.

Maintaining the correct trajectory implies that the system must be able to correct itself, whether the system uses active or passive methods. Two passive methods were considered, gravity gradient and spin stabilization. Since the mission is out of Earth's sphere of influence, utilizing a gravity gradient proves unfeasible. Spin stabilization passively orients the spacecraft as long as the spin axis's moment of inertia is significantly larger than the other axis' moments of inertia. The design of Aries III fits this criterion, meaning spin stabilization could be selected as an option of stability. While it would be useful for maintaining the proper axis for travel, the constant rotation of the spacecraft would limit the amount of time the antennas have with Earth's line of sight. Therefore, spin stabilization was not chosen as a method of control.

For active methods, three options were considered: reaction wheels, thrusters, and control moment gyroscopes (CMG). Reaction wheels were the main selection initially, but given the mass of the spacecraft, they were deemed ineffective for mission of this size and duration. Looking at thrusters, they allow both translational and rotational movement for the orientation of the spacecraft. They will need to counter any drift of the spacecraft's spin from solar pressure and any external rotations from antennas. With the size of the craft at about 55,000 kg, rotating the spacecraft will require an immense amount of thrust. With 3 axes to consider and assuming the craft is a cylinder seen in Figure 3-6, it was found that 42 500N thrusters would be the minimum to rotate the craft 180 degrees along any axis in a reasonable time. Six of those thrusters would be used for translational movement.

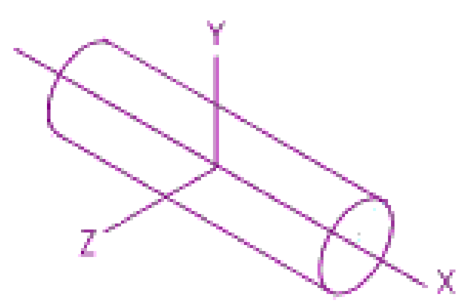



**Figure 3-6. Cylindrical Craft Approximation.**

The thrusters complete the rotation within five minutes with burn times of 10 seconds for the X axis and 68 s for the Y and Z axis of the craft. The summary of the rotation burns is in Table 3-11.

**Table 3-11. Summary of a 180° Axis Burn Using Three 500 N Thrusters**

| Axis | Burn Time (s) | Fuel Burn Rate (kg/s) | Fuel Consumption (kg) |
|---|---|---|---|
| X | 10 | .4648 | 4.65 |
| Y | 68 | | 31.61 |
| Z | 68 | | 31.61 |

Considering control moment gyroscopes (CMG), the design borrows from the International Space Station (ISS). This analysis considers similar CMGs similar to the one ISS [23].

This analysis uses CMGs with about 19% of the ISS size. Their primary function will be used during trajectory injection and atmospheric reentry, with their secondary role to maintain proper orientation during transit to and from Mars. Three CMGs would be mounted on the exterior of the B330, leaving close to 1 m of extra space between them and the payload fairing. All three CMGs would be active at a time, which would allow full rotation around the 3 axes. Rotation around the X axis is the easiest, and it was calculated to take about 45 minutes to do a 180° rotation with the CMGs. On the contrary, to rotate around the Y and Z axes, the CMGs would take a little over four hours. Considerations were given to stronger CMGs as can be seen in Table 3-12

**Table 3-12. Various Strength CMGs and their Capabilities**

, but they were deemed not advantageous. Weaker CMGs would take too long to rotate around the Y and Z axes upon re-entry.

**Table 3-12. Various Strength CMGs and their Capabilities**

| Axis | 700 N-m-s Time (hrs) | 900 N-m-s Time (hrs) | 1100 N-m-s Time (hrs) | 1300 N-m-s Time (hrs) |
|---|---|---|---|---|
| X | 0.82 | 0.63 | 0.52 | 0.43 |
| Y | 6.5 | 4.15 | 3.5 | 3.0 |
| Z | 6.5 | 4.15 | 3.5 | 3.0 |

To compliment the CMGs, four clusters of four thrusters would be placed at the back of the B330 that allows thrust in the three directions and allows the CMGs to unload some momentum after a rotation. Additionally, strong thrusters (200 N or more) would be placed at the front of the B330 to counter translational thrust from the rear thrusters. Overall, this design would allow full rotational control of the spacecraft, allow momentum dumping for the CMGs, and allow for minor trajectory corrections for the mission duration.

With those two solutions considered, the second option was selected for the mission. The largest disturbance to the spacecraft comes from the sun's solar pressure; while the pressure is small, it's relatively constant for entire journey. If a pure thruster design was selected, more than 2000 kg of propellant would need to be brought along given the length of the mission. Utilizing CMGs reduces the complexity of a thruster based system, reduces the amount of propellant needed, and allows full control of the spacecraft's orientation. Prior to reentry, the CMGs would be able to orient the spacecraft as needed.

During reentry, the B330 will separate from the Dragon capsule. Accomplishing this task will require thrusters to slow down the B330 module. Slowing down the B330 rather than accelerating the Dragon capsule allows a safer reentry speed for the capsule. Four 500 N thrusters placed near the front will be able to slow the module down by 6.33 m/s burning 100 kg of fuel. The fuel for the forward thrusters would be stored in the gap between the Dragon capsule and the B330. Excess fuel from the aft thrusters would utilized for any additional slowing of the B330. Finally, the CMGs will orient the B330 into a less aerodynamic reentry configuration, increasing atmospheric drag to slow it down further.

### 3.5.3. Development and Design of the CMGs

For the mission, the CMGs will need to be designed and tested. Three fully functional CMGs will be on the spacecraft at launch. To design and implement, the first design will be the most costly. While this technology needs to be developed, the concept is not new. It is estimated that it would take a minimum 20,000 man hours to create the first function unit. After that, it is assumed half the amount of man power would be need to create future iterations of the device. Overall, 12 units will be created with the first nine being test devices and the remaining three to be used on Aries III. The CMGs on the spacecraft will be smaller than those used on the ISS by about 80%. This decreases their overall ability to rotate the spacecraft quickly, but still allows full control of the system.

### 3.5.4. Attitude Determination

Determining position requires a bit of redundancy. The Apollo missions had an IMU isolating three single-degree-of-freedom gyros and three single-axis accelerometers [24]. Modelling that, a similar IMU and accelerometers on the command module would allow for orientation determination with high accuracy. To counteract gimbal lock, a series of commands should be programmed to avoid orienting the spacecraft into that position. For the longest stretch of the journey, the spacecraft will be in direct line of sight with the sun. A sun sensor would be adequate for positioning, while keeping the IMU from drifting measurements. Although a little more expensive, a star tracker should be utilized to provide another accurate position determination. For the approach to Mars and Earth, two different horizon sensors would provide relevant data on the departure and approach. This suite of sensors would provide real -ime trajectory information, thus satisfying that requirement.

### 3.5.5. GNC Data

The position and orientation of the spacecraft will constantly be updated, but will transmit back to Earth once a day for the main course to Mars. Additionally, angular rates and angular accelerations will be stored every hour. Orientation and saturation of the CMGs will be transmitted back to Earth once every hour. Finally, the fuel levels will be stored after every burn. This data will be transmitted back to Earth once a day as well, which will adequately update Earth on the spacecraft's position, attitude, and system's health.

## 3.6. Structure

**Table 3-13. Structure and Habitat Requirements**

| | Requirement | Source |
|---|---|---|
| H1 | The structure shall be at least 275 cubic meters to support crew and equipment. | M2 |
| H2 | The habitat shall provide radiation shielding to keep the crew within the NASA allowable radiation standard. | NASA |
| H3 | The structure total dry mass shall be less than the propulsion mass capability of 54,850 kg. | L1 |
| H4 | The structure shall be able to withstand 5G loads during launch. | L3 |
| H5 | The structure shall be able to return crew safely back on Earth by maintaining structural integrity. | M3 |

### 3.6.1. Habitat and Sizing

Each crew member needs 20 cubic meters of space for a mission of this duration [25], therefore a crew of 3 would need 60 cubic meters of space. In addition, volume must be allocated for equipment from other subsystems. Table 3-14 shows the volume needed by major subsystems and components. The total Volume required is 275 $m^3$.

**Table 3-14. Major Volume Contributors**

| System | Volume ($m^3$) |
|---|---|
| Crew | 60 |
| Science Equipment | 15 |
| ECLSS | 50 |
| Storage | 60 |
| Batteries | 5 |
| Computer | 10 |
| Fitness Equipment | 25 |
| Common area | 50 |
| **Total** | **275** |

A trade study was run on potential habitats by assigning performance parameters to comparable aspects of each habitat. The parameters, on a scale of 1 to 5 with 5 being the best and 1 being the worst, were multiplied by an importance factor and summed to get a final score, the greater the better.

**Table 3-15. Habitat Trade Study**

| | | **Bigelow B330** [26] | **MIR Base Block** [27] | **Orbital Workshop** [28] |
|---|---|---|---|---|
| **Aspect Compared** | **Importance** | **Parameter** | **Parameter** | **Parameter** |
| Volume/Mass | 25% | 5 | 1 | 2 |
| Modules Needed | 10% | 5 | 2 | 5 |
| Mass | 25% | 5 | 3 | 2 |
| Reliability | 20% | 3 | 5 | 5 |
| Radiation Protection | 10% | 3 | 3 | 3 |
| Ballistic Protection | 10% | 3 | 3 | 3 |
| **Score** | | **4.2** | **2.8** | **3.1** |

| **Aspect Compared** | **Parameter Explanation** |
|---|---|
| Volume/Mass | (1) under .005 $m^3$/kg; (5) over .015 $m^3$/kg |
| Modules Needed | (1) 5 modules needed; (5) 1 module needed |
| Mass | (1) over 100,000 kg; (5) under 25,000 kg |
| Reliability | (1) no testing; (3) some testing; (5) long term space use |
| Radiation Protection | (1) no radiation protection; (3) LEO radiation protection; (5) interplanetary space radiation protection |
| Ballistic Protection | (1) no ballistic protection; (3) LEO ballistic protection; (5) deep space ballistic protection |

Table 3-15 shows the results followed by the parameter scale for each aspect compared. The B330, an inflatable with 330 $m^3$ of internal volume, was the chosen habitat. It is large enough to meet the volume requirement with only a single unit and has the highest volume to mass ratio. In addition, it comes equipped with radiation and ballistic protection greater than or equal to the ISS [26]. A smaller version of the B330, named BEAM, is currently being tested on the ISS [29].

Figure 3-7 shows an example layout of the B330. The cylindrical core surrounded by the water tiles is the sleeping quarters and can double as an emergency room in case of large solar events.

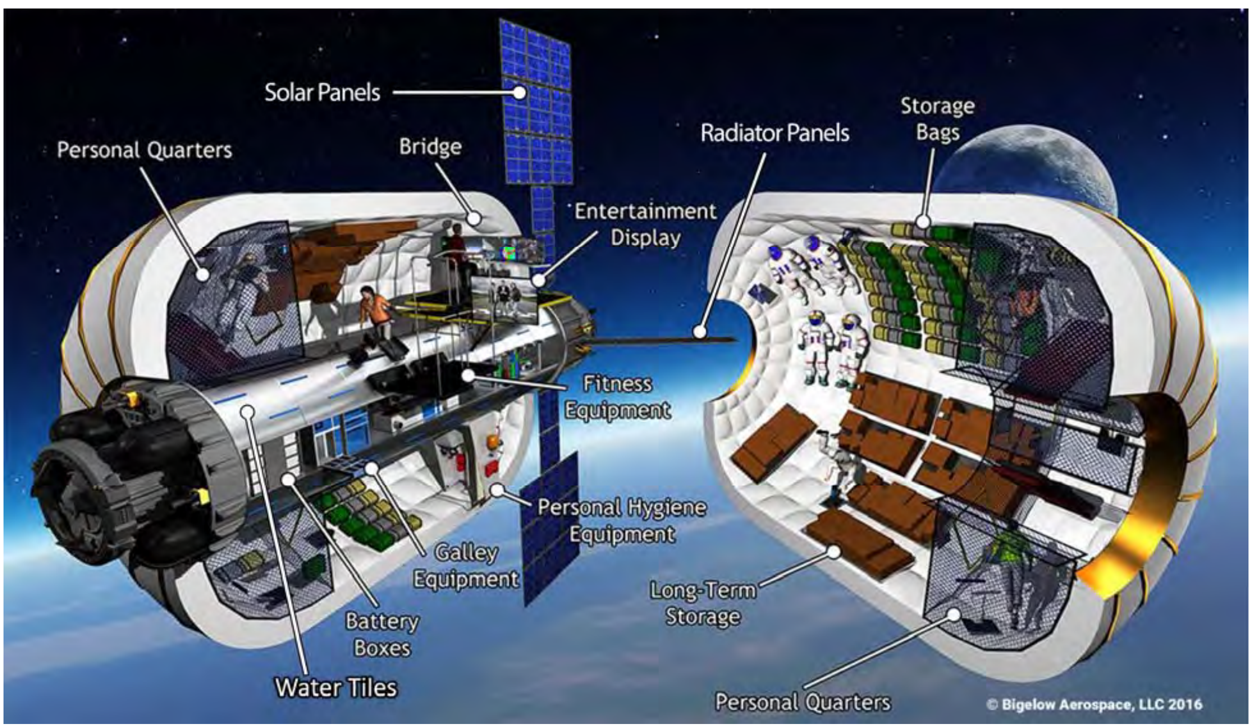



**Figure 3-7. Cutaway Diagram of the B330** [26]**.**

### 3.6.2. Radiation Protection

The NASA maximum allowable human radiation exposure is set at 1000 mSv [30]. In interplanetary space, crew in the B330 will reach this radiation cap in about 550 days [30]. Because the duration for this mission is greater than that, extra radiation shielding is needed.

The B330 already has some radiation shielding in the form of water tiles surrounding the center cylindrical sleeping chambers. Similar water tiles will be used to surround the entire habitat. The thickness of these water tiles depends on how long the mission will take, as seen in Figure 3-8. For a mission duration of 700 days, 2.5 cm thick water tiles are needed to keep the radiation below 1000 mSv.

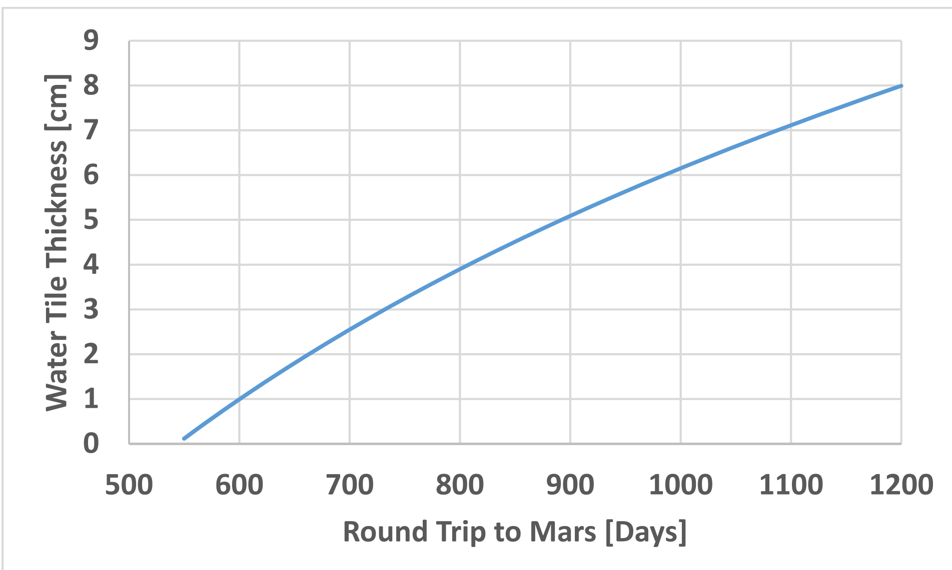



**Figure 3-8. Water Tile Thickness Needed for Round Trip Time to Mars.**

### 3.6.3. Ballistic Protection

While the B330 already has ballistic protection greater than the ISS [26], additional protection is required for interplanetary travel. In order to protect the structure from micrometeoroid impact, a Whipple shield needs to be added to the top of the habitat. The shield will be comprised of 2 mm of aluminum, followed by 6 Nextel layers and 6 Kevlar layers, followed by a final layer of 4.8 mm thick aluminum plate. The distance between the first layer and final layer is 11.4 cm [31]. The design is a modification of the Stuffed Whipple shield used on the NASDA JEM Cylinder on the ISS [32]. Figure 3-9 shows a diagram of the layers and a graph relating impact velocity to maximum micrometeoroid diameter that will not cause harm to the habitat.

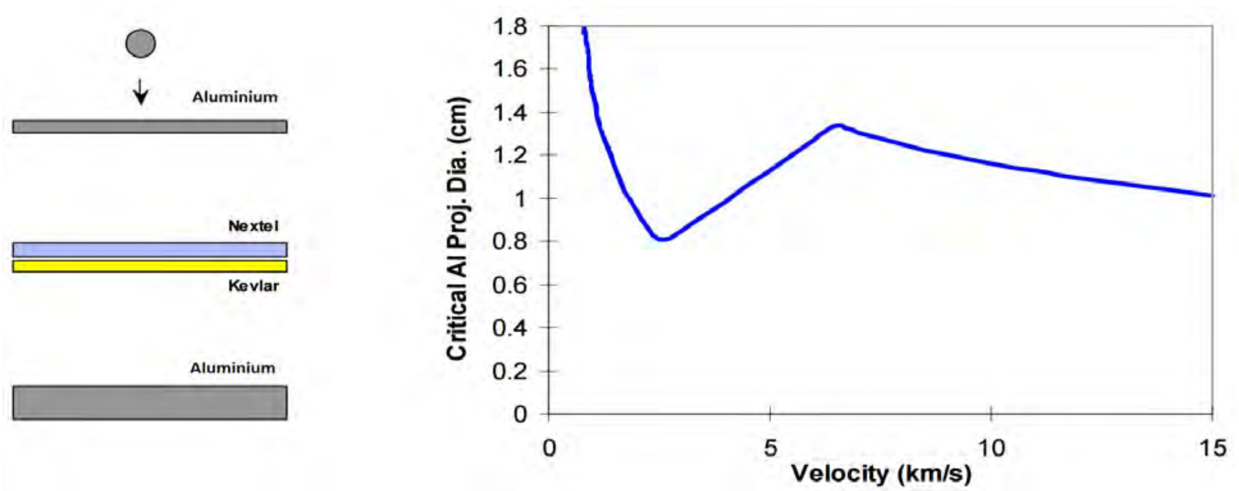



**Figure 3-9. Stuffed Whipple Shield Design and Micrometeoroid Stopping Capabilities** [31]**.**

### 3.6.4. Earth Return Capsule

Because the B330 is not capable to withstanding re-entry to earth, a separate re-entry vehicle is needed to safely return the crew to earth. A trade study was run on common re-entry vehicles by assigning performance parameters to comparable aspects of each re-entry vehicle. The parameters, on a scale of 1 to 5 with 5 being the best and 1 being the worst, were multiplied by an importance factor and summed to get a final score, the greater the better. The results can be seen in Table 3-16 along with an explanation of the parameters.

**Table 3-16. Re-entry Vehicle Trade Study**

| | | **SpaceX Dragon** [33] | **Orion** [34] | **CST-100 Starliner** [35] |
|---|---|---|---|---|
| **Aspect Compared** | **Importance** | **Parameter** | **Parameter** | **Parameter** |
| Volume | 10% | 3 | 2 | 4 |
| Cost | 30% | 4 | 1 | 4 |
| Mass | 30% | 4 | 2 | 1 |
| Reliability | 20% | 4 | 2 | 2 |
| Heat Shielding | 10% | 4 | 4 | 3 |
| **Score** | | **3.9** | **1.9** | **2.6** |
| | | | | |
| **Aspect Compared** | **Parameter Explanation** | | | |
| Volume | (1) under 9 $m^3$; (5) over 13 $m^3$ | | | |
| Cost | (1) over $1,000,000,000; (5) under $300,000,000 | | | |
| Mass | (1) over 12,000 kg; (5) under 6,000 kg | | | |
| Reliability | (1) no testing; (3) some testing; (5) long term space use | | | |
| Heat Shielding | (1) no Earth re-entry; (5) high velocity Earth re-entry | | | |

Based on the trade study in Table 3-16, the Dragon capsule was chosen as the re-entry vehicle for this mission; it had both low cost and mass. All three re-entry vehicles are still in development. Only the Dragon and Orion are designed for a Mars mission.

The PICA-X heat shield material used on the Dragon has already been used on the Stardust spacecraft, which re-entered Earth's atmosphere at 12.9 km/s, setting the record for the fastest reentry speed and proving its reliability [36]. So far, the Dragon capsule has flown multiple unmanned resupply mission to the ISS [37]. The first manned flight using the Dragon capsule is planned for 2018 [38].

### 3.6.5. Structure Overview

The habitat and structure is designed to launch a crew from Earth, fly to Mars, and return them to Earth safely. The layout of the B330 and Dragon inside the SLS payload fairing can be seen on the fact sheet. The B330 has enough internal volume to accommodate a crew of 3, as well as the equipment needed by the ECLSS, scientific returns, power, and communications subsystems. The Dragon will be able to safely withstand re-entry to Earth with the crew on board, however the B330 cannot withstand an Earth atmosphere reentry. Because the B330 acts as the habitat and service module, it must remain attached to the Dragon capsule until reentry. At this time, the two will separate, with the crew and all important equipment inside the Dragon. The control thrusters attached to the B330 will be used to separate its trajectory from the Dragon's trajectory, with the B330 burning up over an ocean as the Dragon safely lands.

The mass and cost of the structure can be seen in Table 3-17. Overall, the weight is 36,000 kg and cost is $472 million. The cost estimation comes from the actual cost to buy the B330 and Dragon as there is no closely comparable missions to base the cost on. The cost for water tiles and Whipple shield are estimates for manufacturing, testing, and implementation.

**Table 3-17. Mass and Cost for the Structure**

| **Part** | **Cost (USD)** | **Mass (kg)** |
|---|---|---|
| B330 | 150,000,000 | 20,000 |
| Dragon | 320,000,000 | 6,000 |
| Water Tiles | 1,000,000 | 9,000 |
| Whipple Shield | 1,000,000 | 1,000 |
| **Total** | **472,000,000** | **36,000** |

## 3.7. Environmental Control and Life Support System

**Table 3-18. ECLSS Requirements**

| **Requirement** | | **Source** |
|---|---|---|
| E1 | The habitat shall provide an environment like Earth at sea-level, as seen in Table 3-19, for the survival of the crew | M3 |
| E2 | The habitat shall provide food, water, and waste management for the entire duration of the mission. | M3 |

ECLSS has one main purpose – keeping the crew alive. To attain this goal, a system was created using the International Space Station (ISS) as the model. The ISS utilizes robust and heritage technology to satisfy all needs of the human body and hence qualifies as a reliable prototype. Based on the requirements stated in Table 3-18, the system can be divided into four main sections - atmosphere control, water, food, and waste management. Atmosphere covers controlling the temperature, pressure, and humidity of the habitat along with monitoring the composition of the air and fire safety; water management satisfies drinking and sanitation needs, processes waste water and monitors the quality; food management entails the preparing, storing and availability of nourishment; waste management involves collecting, storing and processing of human waste and trash onboard [39]. The system being utilized is a semi-closed loop system, depicted by Figure 3-10, where certain portions are recycled but others are not. More details regarding this become evident as each subsystem is studied in greater detail.

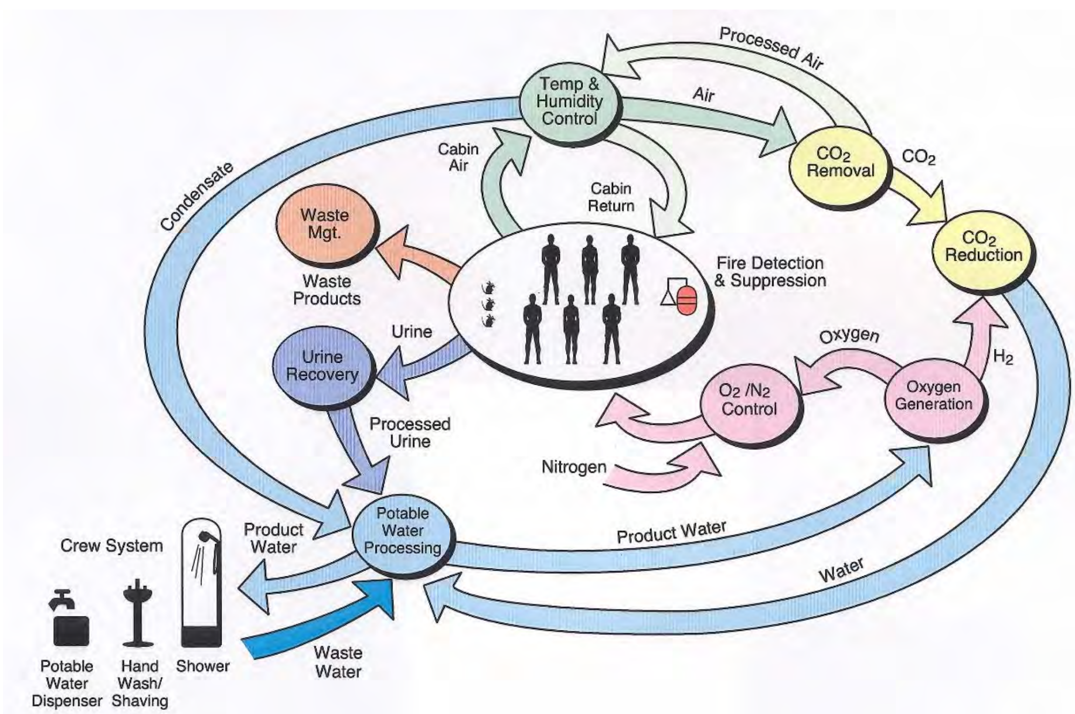



**Figure 3-10. Regenerative ECLSS on ISS** [40]**.**

### 3.7.1. Atmosphere Control

**Table 3-19. Nominal Values for Atmospheric Conditions** [39]

| Atmosphere Requirements | Nominal Values (based on ISS) |
|---|---|
| Total Pressure | 99.9 kPa – 102.7 kPa |
| Oxygen, partial pressure | 19.5 kPa – 23.1 kPa |
| Nitrogen, partial pressure | 79 kPa |
| Carbon dioxide, partial pressure | 0.4 kPa |
| Temperature | 291.5 K – 297 K |
| Relative Humidity | 30% - 70% |
| Ventilation | 0.08 m/s – 0.2 m/s |

The atmosphere is ideally required to replicate Earth at sea-level with its nominal values listed in Table 3-19. There are different systems in place that take care of these requirements separately. These parameters are constantly monitored and kept within the nominal range at always.

The first aspect of atmosphere control is maintaining the pressure and the composition of the air. This goal is achieved using the Major Constituent Analyzer (MCA). It is a mass-spectrometer system which records and analyses levels of various gases, including but not limited to nitrogen, oxygen, and carbon dioxide [41].

Oxygen Generation System (OGS) produces the oxygen that is required for survival of the crew. It has two subsystems – Oxygen Generation Assembly (OGA) and a Power Supply Module. OGA consists of a cell stack that breaks down the water into oxygen and hydrogen using the method of electrolysis [42]. OGS produces 9 kg of oxygen per day in the operational mode and 5.4 kg of oxygen per day in the cyclic mode [42].

Carbon dioxide is handled with a two-fold system. Carbon Dioxide Removal Assembly (CDRA) focuses on removing $CO_2$ from the atmosphere, and the $CO_2$ Reduction Assembly (CRA) uses this $CO_2$ to form water. CRA uses the hydrogen produced by OGS to form water first and eventually converts it into oxygen. It uses a device called Sabatier $CO_2$ reactor [43]. This process currently recovers 42% oxygen from the carbon dioxide [44].

Temperature and Humidity Control (THC) focuses on monitoring and maintaining the air temperature and regulating the level of moisture in the air supply. The Common Cabin Air Assembly (CCAA) will be utilized to preserve the cabin temperature and humidity levels and generate ventilation air flow [45].

Multiple fire detectors will be used for redundancy, which detect the presence of charged particles and sound an alarm to alert the crew of any potential threat. To quench a fire that may have arisen, a carbon dioxide based extinguisher will be used. This leads to increase in levels of carbon dioxide in the habitat but they can easily be controlled using the methods mentioned previously. Also for precaution, the crew will be required to wear oxygen masks during such an event till the carbon dioxide levels are stabilized [44].

### 3.7.2. Water

**Table 3-20. Water Requirements by Mass for ECLSS** [39]

| Activity | Requirement (kg/person/day) |
|---|---|
| Human water needs | 2.5 |
| Hygiene | 7.5 |
| Housekeeping | 10.5 |

Table 3-20 shows the amount of water needed by humans daily. It covers water needed for drinking, preparing food, showering and other activities. It is not practical for volume and mass considerations to store the entire amount of water required onboard. Moreover, it is difficult to maintain the quality of standing water for a long-duration mission and to detect leaks in the absence of gravity [39]. Water is recovered from urine, humidity and waste water collected after other activities, and processed to satisfy the requirement.

Water Recovery System (WRS) has two parts – Urine Processor Assembly (UPA) and Water Processor Assembly (WPA). It is estimated that each crew member would produce about 1.5 kg/day of urine [39]. The UPA uses the method of vapor compression distillation to recover 80% of the water from urine [44]. There is waste water coming in from condensation in the atmosphere, hygiene and housekeeping related activities which is estimated to be around 21.5 kg/person/day [39]. This water unites with the output of UPA and is sent to WPA where it undergoes filtration, adsorption, ion exchange, catalytic oxidation, and a series of other processes to recover almost 100% of the water [44]. Purity of water is checked and tested before use [42]. The WRS satisfies the basic needs of the crew but water is stored onboard for emergencies.

### 3.7.3. Food

**Table 3-21. Mass and volume requirements for food** [39]

| Item | Mass | Volume |
|---|---|---|
| Food (with water) | 2.3 kg/person/day | 0.008 $m^3$/person/day |
| Freezers | 50 kg | 2 $m^3$ |
| Oven | 50 kg | 0.25 $m^3$ |
| Cleaning Supplies | 0.25 kg/day | 0.0018 $m^3$/day |
| Cooking Supplies | 5 kg/person | 0.0014 $m^3$/person |

The mass of food mentioned in Table 3-21 also accounts for the mass of water in the food and the amount of water needed to prepare the food. The food that is carried to space is dehydrated before packaging and the water needed to prepare the food was accounted for in the previous section. So, the actual mass of food comes down to 0.6 kg/person/day. Considering a crew of three people and a mission of 750 days for margin, the total mass of the food itself comes to be around 1350 kg. To store this food, nine freezers will be needed onboard which brings their total mass to 450 kg. It can be concluded based on Table 3-12 and the details mentioned after that the total mass for food would be 2100 kg and total volume would be 20 $m^3$.

Determining the quality of the food is just as essential as quantity. Space travel causes changes in human body and may lead to long term side-effects. These can be minimized to some extent by supplying vitamins and minerals to the crew either through the food or by supplements. Vitamin D and K, which are essential for bone health, needs to be provide via diet to astronauts [46]. Minerals such as Calcium and Iron are also very important for bones and blood. Making sure of the presence of these nutrients is not enough. For long-term travel, it needs to be made sure that the vitamins remain stable and will still be in the food for the duration of the mission [46]. Despite strict regulations being placed on the health benefits of the food, today's technology offers the crew a wide selection. The crew can work with nutritionists to form individualized menus based on their palette and dietary requirements [47].

### 3.7.4. Waste Management

Waste Collection system (WCS) is a multi-faceted structure that collects, processes and stores the wastes obtained from all crew-related activities. WCS accumulates and dries the fecal matter for storing, has the UPA as a part of it, provides ventilation to throw trash container gases overboard, and transfers Air Revitalization System (ARS) wastewater into WPA [48]. It consists of a commode, urinal, fan separators, odor and bacteria filter, and waste collection system controls [48]. The commode has two modes of operation – when in use, it pressurizes to collect the waste and when not in use, it depressurizes to dry and compress the waste collected. The urinal is a pipeline to send the liquid waste for processing to the UPA. The fan separator creates flow separation of liquid wastes and air. It sends the liquids on their way and sets the air back into the atmosphere after using odor and bacterial filters on it. The mode of operation varies with the status of the spacecraft; they have different protocols for launch or re-entry or on-orbit operations. For all other kinds of waste, soft trash bags maybe used to store them. Used since the time of Apollo, these bags are called the jettison bags. They are quite spacious (101x70 cm) and very light weight (380 g) [49].

### 3.7.5. ECLSS Overview

The system is designed to keep three people alive for a duration of 750 days. Since the mission is estimated to be 588 days long, this provides reserves which reduce the risk significantly. It provides constant monitoring, margins and redundancies for all subsystems involved. Including the food, potable water, waste storage and all the equipment required, the mass of the system is estimated to be about 4,700 kilograms. The costing of the system is done based on similar missions and is estimated to be $100 million. This does not include the cost required to integrate these systems on to the Bigelow habitat. The cost of modification and testing is included in the cost of the staff required for the whole mission. Margins are added to the mass of the third stage and cost for the overall mission.

## 3.8. Communications

**Table 3-22. Communication System Requirements**

| Requirement | | Source |
|---|---|---|
| C1 | The spacecraft shall be able to send and receive radio frequency transmissions to and from Earth | P2 |
| C2 | The communications system shall have the capability to transmit all collected science data to Earth. | P2, T2, M2 |

The main function of the communication system is to provide the Aries III with Telemetry, Tracking, and Command (TT&C). TT&C will allow the spacecraft to communicate with Earth through the transmission of electromagnetic signals at radio frequencies. This communication will encompass downlinking engineering data about the spacecraft, scientific data about the astronauts' health and psyche, the astronauts' voice or text messages, and radiometric links that will allow the spacecraft's position, speed, and orientation to be determined. In addition to downlinking, the communication will also include uplinking command data and voice or text messages to the astronauts.

### 3.8.1. Subsystem Component Selection

To achieve reliable communications and keep with the design philosophy of using heritage technology, Aries III will communicate with NASA's deep space network (DSN). The DSN has three facilities that are spaced by 120° longitude, allowing for continuous communication with any spacecraft in space. The largest distance that the spacecraft would travel from the Earth was considered to be 375 million km, based on the largest possible distance between the Earth and Mars. To provide margin, the size and gain of the antenna were designed for losses encountered at this distance.

The two radio frequency bands that were chosen are the X-band (8.4 GHz downlink and 7.145 GHz) and the Ka-band (32 GHz downlink). The Ka-band has a very high frequency and can, therefore, achieve high data rates even in deep space but is subject to very high atmospheric losses during overcast condition. The X-band also provides high data rates, although not as high as the Ka-band, but is not subject to similarly severe atmospheric losses. The use of both bands allows for reliable transmission to and from Earth regardless of weather patterns on Earth.

The minimum data rates were then chosen for worst case conditions and largest distance between Aries III and Earth. For uplink, the minimum data rate was chosen to be 500 kilo-bits per second (kbps) during normal operation mode and 8 bps during emergency mode. For downlink, the minimum data rate was chosen to be also 500 kbps during normal operation mode and 5 bps during emergency mode. To improve data quality and reliability, forward error correction coding was implemented into data transmission, specifically, rate-1/6 Turbo coding.

To meet antenna coverage requirements, a high gain antenna (HGA) and two low gain antennas (LGA) were chosen to be installed on Aries III for communication. The HGA will serve as the main source of communication during the majority of Aries' III mission and will provide a narrow beam of coverage with a strong signal allowing for high data rates to be sent to or received from Earth. The LGAs will serve as the main source of communication during the spacecraft's Launch and Early Operation Phase (LEOP) and emergency mode. They will provide a wide beam of coverage but with a weak signal as a tradeoff allowing for weak communication in the line of sight of the antennas, therefore the two LGAs will be placed on the spacecraft pointing in opposite directions to provide omni-directional communication. This omni-directional coverage will allow the ground stations on Earth to transmit signals to and receive signals from Aries III during LEOP and 30 emergency mode when the orientation of the spacecraft is not fully known but communication is necessary. To design a complete communication system, additional components need to be added. The subsystem typically consists of five basic hardware elements: transponder, power amplifier, diplexer, RF switching/combining network, and antennas. Thus, a transponder, a 100 W Traveling Wave Tube Amplifier, a diplexer, and an RF switching/combining network have been added. There are two choices for a power amplifier, the first one being a solid-state power amplifier (SSPA) and the second being a traveling wave tube amplifier (TWTA). The TWTA was chosen because a high RF power level amplifier is necessary for designing a successful deep space communication system and TWTAs are more applicable for high RF power levels. A TWTA with an RF power level of 100 W was chosen and this choice will become apparent in the calculations shown later. Certain hardware was chosen to have redundant components for improved reliability and the final weight of the communications system was calculated to be about 120 kg after including a margin of 20%.

### 3.8.2. Link Analysis

**Table 3-23. System Link Analysis**

| Parameter | Unit | High Gain Antenna | | | Low Gain Antenna | |
|---|---|---|---|---|---|---|
| | | X-band downlink | X-band uplink | Ka-band downlink | X-band downlink | X-band uplink |
| RF Frequency | GHz | 8.4 | 7.145 | 32 | 8.4 | 7.145 |
| Distance to ground station | AU | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| Information bit rate | bps | 500,000 | 500,000 | 2,100,000 | 5 | 8 |
| HPBW | deg | 0.83 | 0.09 | 0.22 | 90 | 90 |
| Transmit power | dBm | 50 | 73.01 | 50 | 50 | 73.01 |
| Transmit passive loss | dB | -2 | -2 | -2 | -2 | -2 |
| Transmit antenna gain | dBic | 45.83 | 66.80 | 57.45 | 3 | 66.80 |
| Transmit antenna efficiency | % | 55 | 74 | 55 | 55 | 74 |
| EIRP | dBm | 93.83 | 137.81 | 105.45 | 51 | 137.81 |
| Path loss | dB | -282.39 | -280.99 | -294.01 | -282.39 | -280.99 |
| Atmospheric loss | dB | -0.3 | -0.3 | -1 | -0.3 | -0.3 |
| Receive antenna gain | dBic | 68.21 | 44.42 | 79.82 | 68.21 | 3 |
| Receive antenna efficiency | % | 74 | 55 | 74 | 74 | 55 |
| Total power received | dBm | -120.66 | -99.05 | -109.74 | -163.49 | -140.48 |
| Data-to-total power | dB | -0.61 | -0.61 | -0.61 | -0.61 | -0.61 |
| System noise density | dBm/Hz | -183.83 | -183.83 | -179.57 | -183.83 | -183.83 |
| Received Eb/No | dB | 5.57 | 27.17 | 5.99 | 12.74 | 33.71 |
| Required Eb/No | dB | 1 | 1 | 1 | 1 | 1 |
| Receiver system loss | dB | -1 | -1 | -1 | -1 | -1 |
| Link Margin | dB | 3.57 | 25.17 | 3.99 | 10.74 | 31.71 |

The communication system was sized based on the required RF transmitter power and downlink antenna size. The RF transmitter power was determined to be 100 W and the HGA was sized to be 3 m in diameter. To have a robust communications system, the link margin was set to be 3 dB for downlink and 20 dB for uplink. Table 3-23 shows the system link analysis.

### 3.8.3. Data Budget

Table 3-24 shows the data generated by the various subsystems that needs to be transmitted back to Earth. It can be observed that the communications system can meet the requirements of these subsystem by transferring data back to Earth once per day. The transfers are performed with transmission times of 150 seconds for Ka-band and 500 seconds for X-band downlink. These transfers yield a data margin of 34% for Ka-band transmission and a margin of 6.5% for X-band transmission.

**Table 3-24. Data Budget**

| System | Data Generated (per day) |
|---|---|
| Habitat | 0.58 Mb |
| ECLSS | 1.35 Mb |
| GNC | 1.35 Mb |
| Science | 230 Mb |
| Total | 235 Mb |
| Data Transmitted (Ka-Band) | 315 Mb |
| Margin | 80 Mb |
| Data Transmitted (X-band) | 250 Mb |
| Margin | 15 Mb |

## 3.9. Power

**Table 3-25. Power System Requirements**

| Requirement | | Source |
|---|---|---|
| PW1 | The power system shall generate enough power for full spacecraft functionality for the duration of the mission lifetime | P2 |
| PW2 | The power system shall store sufficient power for use during periods of zero power generation | P2, T2, M2 |
| PW3 | The power system shall be able to maintain functionality for duration of the mission lifetime | P2, M2 |
| PW4 | The power system shall be able to dissipate excess power that cannot be stored | P2, M3 |

The primary function of the power system is to provide, store, and distribute electrical power to the Aries III spacecraft. Table 3-26 shows the power required by all of the sub-systems of the spacecraft.

**Table 3-26. Aries III Power Requirements**

| Subsystem | Peak Power (kW) |
|---|---|
| Habitat | 3 |
| ECLSS | 20 |
| Communications | 0.4 |
| GNC | 0.5 |
| Science | 0.05 |
| Other | 0.05 |
| **Total** | **24** |

The subsystem labeled "Other" refers to various other spacecraft components that also require some amounts of power. The total power required comes out to be 24 kW. These power requirements are the peak power requirements for each subsystem and both the power storage and power generation components were sized using the peak power.

### 3.9.1. Subsystem Component Selection

The most common spacecraft power generators/sources are the solar photovoltaic (solar cell), solar thermal dynamic, radioisotope thermoelectric generator, nuclear reactor, and fuel cell. Solar photovoltaics were chosen as the power source because it is the cheapest and safest technology. Silicon cells, Gallium-Arsenide (GaAs) Single Junction (SJ) Cells, GaAs Multijunction (MJ) cells, GaAs improved MJ cells, and GaAs ultra MJ cells were considered for the use on the solar arrays. Table 3-27 shows the parameters of the different cells considered.

**Table 3-27. Sollar Cell Parameters**

| Technology | Beginning of Life (BOL) efficiency (%) | Performance Degradation (% per year) | BOL weight ($kg/m^2$) | BOL Cost ($/W) |
|---|---|---|---|---|
| Silicon | 14 | 3.75 | 2.3 | 378 |
| GaAs SJ | 18.5 | 2.75 | 2.7 | 852 |
| GaAs MJ | 22.6 | 0.5 | 2.8 | 695 |
| GaAs improved MJ | 26 | 0.5 | 2.8 | 617 |
| GaAs ultra MJ | 28 | 0.5 | 2.8 | 617 |

**Table 3-28. Solar Cell Trade Study**

| Performance Parameter | Weight | Score (1-5) | | | | |
|---|---|---|---|---|---|---|
| | | Silicon | GaAs SJ | GaAs MJ | GaAs improved MJ | GaAs ultra MJ |
| Beginning of Life Efficiency (%) | 0.7 | 1 | 2 | 3 | 4 | 5 |
| Performance Degradation (% per year) | 1.0 | 1 | 3 | 5 | 5 | 5 |
| BOL weight (kg/$m^2$) | 0.4 | 5 | 4 | 3 | 3 | 3 |
| BOL Cost ($/W) | 0.6 | 5 | 1 | 3 | 4 | 4 |
| TRL | 1.0 | 5 | 5 | 5 | 1 | 1 |
| **Final Score** | - | 11.7 | 11.6 | **15.1** | 12.4 | 13.1 |

Table 3-28 shows the trade study used to determine the cells for use of solar array panel construction. The solar cells chosen were the GaAs MJ cells. These cells will be used in solar panels that will be combined into arrays that are mounted on gimbals for rotation.

The spacecraft shall make use of rechargeable batteries for storage of excess power. Some of the most common rechargeable battery chemistries used in space are Nickel-Cadmium (Ni-Cd), Nickel Hydrogen (NiH2), and Lithium Ion (Li-Ion). Table 3-29 shows the performance characteristics for those chemistries.

**Table 3-29. Properties of Ni-Cd, Ni-$H_2$, and Li-Ion Batteries**

| Performance Characteristics for Rechargeable Batteries | Ni-Cd | Ni-$H_2$ | Li-Ion |
|---|---|---|---|
| Energy Density (W-hr/kg) | 30 | 60 | 125 |
| Energy Efficiency (%) | 72 | 70 | 98 |
| Thermal Power (scale 1-10) | 8 | 10 | 1 |
| Self-discharge (% per day) | 1 | 10 | 0.3 |
| Operational Temperature Range (°C) | 0 to 40 | -20 to 30 | 10 to 25 |
| Memory Effect | Yes | Yes | No |
| Energy Gauge | No | Pressure | Voltage |
| Trickle Charge | Yes | Yes | No |
| Modularity | No | No | Yes |
| Heritage | Yes | Yes | Yes |

Table 3-30 shows the trade study used to determine the batteries to be used on-board the spacecraft. The primary concerns for battery selection were energy density and efficiency. In accordance with this, Li-Ion batteries were the choice for the batteries.

**Table 3-30. Battery Trade Study**

| Performance Characteristics for Rechargeable Batteries | Weight | Score (1-5) | | |
|---|---|---|---|---|
| | | **Ni-Cd** | **Ni-$H_2$** | **Li-Ion** |
| Energy Density (W-hr/kg) | 1.0 | 2 | 3 | 5 |
| Energy Efficiency (%) | 1.0 | 3 | 3 | 5 |
| Thermal Power (scale 1-10) | 0.7 | 4 | 5 | 1 |
| Self-discharge | 0.7 | 3 | 1 | 5 |
| Operational Temperature Range | 0.4 | 3 | 4 | 1 |
| Modularity | 0.5 | 1 | 1 | 5 |
| **Final Score** | - | 11.6 | 12.3 | **17.1** |

### 3.9.2. Subsystem Design Analysis

The size of the solar arrays was determined by calculating the solar array area that would provide the peak power requirements of the spacecraft. In the analysis, the efficiency of the path the power travels from the arrays to the batteries or loads was assumed to be 85%. Throughout the mission, Aries III will travel as far from the sun as Mars is and as close to the sun as Venus is, therefore, the solar flux will largely vary. In order to meet the power requirements at all points in the mission, the solar flux at Mars was used as the solar flux for the sizing analysis. Additionally, in order to ensure that the spacecraft can function as required for the duration of the mission, the end of life (EOL) production capability was used to size the solar arrays.

**Table 3-31. Solar Array Parameters**

| Parameter | Value |
|---|---|
| Peak power tracking efficiency (%) | 85 |
| Power production required (W) | 28500 |
| Mars Solar energy flux (W/m$^2$) | 592.11 |
| EOL power production (W/m$^2$) | 130.46 |
| Area of Solar panel required (m$^2$) | 220 |
| Solar panel mass density (kg/m$^2$) | 2.8 |
| Solar panel total mass (kg) | 620 |

The designed solar arrays generate 27.5 kW of power. Accounting for peak power tracking efficiency yields a power available of 24.5 kW, which is sufficient to meet the power requirements laid out by the systems. While this approach to solar array sizing ensures the power requirements are met for all stages of the mission, it does mean that there will be surplus of power during the early stages of the mission, particularly during the early parts of the mission where the spacecraft is close to Venus. Table 3-32 shows the maximum power generation during the mission lifetime.

**Table 3-32. Maximum Power Generated**

| Parameter | Value |
|---|---|
| Peak power tracking efficiency (%) | 80 |
| Solar Panel Area (m$^2$) | 120 |
| Venus Solar Energy Flux (W/m$^2$) | 2643 |
| EOL power production (W/m$^2$) | 580 |
| Power Generated (W) | 92800 |

This power is significantly more than the spacecraft requires and thereby will see the vast majority of it dissipated. However, this peak generation only occurs for a short duration and thereby does not pose much of an issue to the mission design.

The spacecraft will also have a Li-Ion battery on-board. These batteries were sized to be able to provide 1.75 kW-hr for the spacecraft to use during periods of eclipse, yielding a battery of 350 kg. While this number is very small in comparison to the spacecraft power requirements, these batteries are not required to be used for long durations. There are two times during the mission where eclipse occurs, once when performing the fly-by of Mars and again during re-entry. The eclipse portion of the fly-by is a very short duration on the order of minutes, so the battery will be able to provide the power necessary to continue operation of the spacecraft.

### 3.9.3. Power Budget

Table 3-33 shows the overall power budget of the spacecraft at the time when the spacecraft is at Mars. The power requirements of the spacecraft are met with a margin of 0.5 kW when the spacecraft is furthest from the Sun and a margin of 68.8 kW when the spacecraft is closest to the Sun. These are margins of 2% and 280% respectively.

**Table 3-33. Power Budget**

| **Subsystem** | **Peak Power (kW)** |
|---|---|
| Habitat | 3 |
| ECLSS | 20 |
| Communications | 0.4 |
| GNC | 0.5 |
| Science | 0.05 |
| Other | 0.05 |
| Total | 24 |
| Power Generated at Mars | 24.5 |
| Margin | 0.5 |
| Power Generated at Venus | 92.8 |
| Margin | 68.8 |

## 3.10. Thermal Control System

**Table 3-34. Thermal Control System Requirements**

| **Requirement** | | **Source** |
|---|---|---|
| TC1 | The Thermal Control System shall be able to maintain component temperatures within operational range | M3 |

Space has varying temperature based on location and proximity to sun. Most components have a range of temperature they need to be in to be operational. As mentioned in Table 3-34, TCS must maintain these temperatures for the smooth and efficient working of all components on board [39].

**Table 3-35. Typical Temperature Requirements** [50]**.**

| Equipment | Operational(°C) | Survival(°C) |
|---|---|---|
| Batteries | 10 to 30 | 0 to 40 |
| Hydrazine Fuel | 15 to 40 | 5 to 50 |
| Solar Arrays | -150 to 110 | -200 to 130 |
| Antennas | -100 to 100 | -120 to 120 |
| Reaction Wheels | -10 to 40 | -20 to 50 |
| Crew | 18.3 to 26.7 | 18.3 to 26.7 |
| Surface Temperature (places crew touches with bare skin) | 12.8 to 40 | 4 to 45 |

Table 3-35 shows ranges for some basic components needed in most spacecraft. The temperature of the habitat which consists of all the crew belongings, exercise, and science equipment along with the computing and communication devices will be maintained by THC of ECLSS. The solar arrays, antennas and control moment gyroscopes lie outside this space and need protection. The batteries need an outlet to dissipate the excess power produced.

The CMGs and antennas can be protected from the environment with the use of multilayer insulation (MLI). MLI blankets will be used both to prevent excessive heat loss from the component and excessive heating from environmental fluxes or rocket plumes [50]. The batteries are present within the habitat and are protected from the external environment. But we need to employ heat pipes on them to release the excess heat that maybe let out by excess power generation. Heat pipes use a closed two-phase fluid-flow cycle to transport large quantities of heat from one location to another without using any electrical power [50]. Solar arrays are operational within a wide temperature range so the major concern is dissipation of excess heat which is taken care of with the help of radiators which would be about fifty-five cubic meters in size and will be placed at the same location that radiation panels can currently be seen in the Bigelow module. The batteries and solar arrays combined are estimated to release a maximum of 65kW of power.

### 3.11. Anticipated Risks and Mitigation Strategies

**Table 3-36. Mission Risks and Mitigation Strategies**

| Risk | Description | Impact | Likelihood | Mitigation Strategy |
|---|---|---|---|---|
| MR1 | Crew health negatively affected due exposure to space environment | 4 | 2 | Radiation shielding, Sanitization, ECLSS |
| MR2 | Launch vehicle failure | 5 | 1 | Checks and testing |
| MR3 | Trajectory perturbed from planned path | 4 | 1 | Carry extra fuel on-board |
| MR4 | Solar array damage | 4 | 1 | Redundant solar panels, margins on sizing |
| MR5 | Failure to meet launch window | 4 | 1 | Scheduling |

**Table 3-37. Implementation Risks and Mitigation Strategies**

| Risk | Description | Impact | Likelihood | Mitigation Strategy |
|---|---|---|---|---|
| IR1 | SLS cost higher than expected | 5 | 2 | Planning, follow timeline |
| IR2 | SLS development delays | 4 | 1 | Delay launch, design alternative |
| IR3 | B330 development delays | 4 | 1 | Delay launch, design alternative |
| IR4 | Dragon development delays | 3 | 2 | Use alternative |
| IR5 | Vinci development delays | 3 | 1 | Use alternative |
| IR6 | Schedule overrun | 4 | 1 | Scheduling, management |
| IR7 | Mass overrun | 5 | 1 | Mass margin |
| IR8 | Integration overrun | 4 | 1 | Scheduling, engineering staff |

The risks in Table 3-36 and Table 3-37 are the major overall risks for the mission with likelihood numbers corresponding to post mitigation strategy. The impact and likelihood scales are from 1 to 5, with 5 being the worst. Figure 3-11 shows a stoplight chart with labeled risks. There are only 4 medium level risks and no risks with a likelihood above 2.

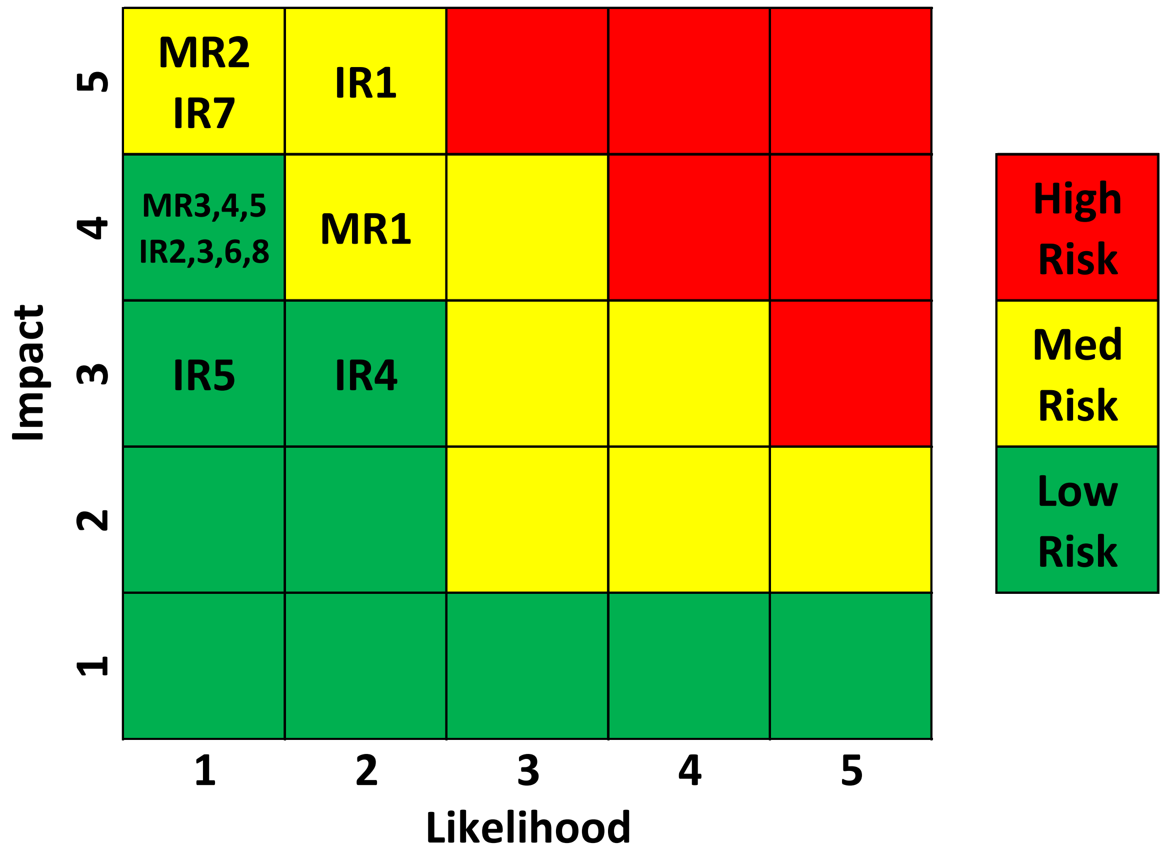



**Figure 3-11. Stoplight Chart.**

## 3.12. System Mass

**Table 3-38. Mass Contributors**

| System | Mass (kg) |
|---|---|
| Scientific Returns | 2200 |
| ECLSS | 4700 |
| B330 | 20000 |
| Dragon | 6000 |
| Water Tiles | 9000 |
| Whipple Shield | 1000 |
| Solar Panels | 340 |
| Batteries | 320 |
| Vinci | 1000 |
| GNC | 700 |
| Crew | 200 |
| **Total** | **45460** |

The total mass for the craft comes out to be 45,460 kg. This gives a margin of 17% for the total allowable mass of 55,000 kg.

## 3.13. Cost and Cost Estimating Methodology

**Table 3-39. Subsystem and Total Cost**

| Subsystem | Cost ($) | Determination |
|---|---|---|
| Launch | 1,500,000,000 | Current estimates from NASA interviews. Includes launching and operations cost. |
| GNC | 6,500,000 | Estimated cost based on price of major components. |
| Propulsion | 432,000,000 | Estimated cost based on price of major components. |
| Structure | 472,000,000 | Estimated cost based on price of major components. |
| Power | 50,000,000 | Estimated cost based on price of major components |
| Communications and Operations | 100,000,000 | Estimated based on cost of communication satellites. Includes operations of DSN based on NASA estimate |
| ECLSS | 100,000,000 | Estimation based on studies of similar missions |
| Scientific Payload and Operations | 650,000,000 | Estimation based on similar missions and price of scientific components |
| Staff | 599,850,000 | Assuming 4,650 staff-years at an average salary of $129,000 |
| **Total** | **3,910,350,000** | |

Table 3-39 shows the cost for each subsystem and the total estimated cost. The subsystem costs have been presented without margins. Each subsystem cost estimate can be seen in more detail in the corresponding section. The total estimated cost is $3,910,350,000 which gives a margin on cost of 21.8%. The estimated budget is under the cap of $5 billion. The highest cost comes from the launch subsystem, specifically the SLS. The $1.5 billion estimated cost include the SLS, and all the personnel, locations, and equipment required to launch and monitor its progress. However, the cost of SLS is one of the highest risks for this mission.

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