Aphrodite I

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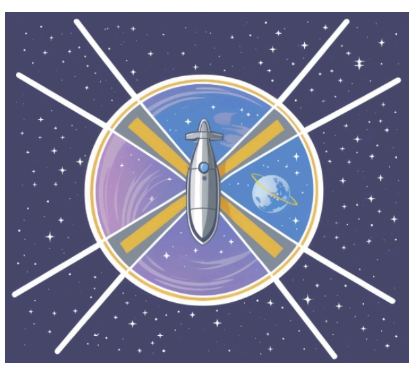
With the unwavering improvement of modern technology, human interplanetary travel and colonization seems to be on the horizon. Despite the rapid improvements in technology, humans have yet to leave Earth's sphere of influence, and many problems caused by spending time in space unanswered. Aphrodite I aims to solve one of the most imposing problems of sustained microgravity - biological degradation. Based on experiments conducted in the ISS and other spacecraft, it is well documented that human bodies begin to rapidly lose function without the constant force of gravity. Astronauts who have lived in the International Space Station for prolonged periods lose significant bone and muscle mass, as well as organ functionality, despite rigorous training regiments. Aphrodite I is a proposed space station that will orbit Earth, rotating on a single axis and housing a crew of four astronauts. The rotation of the station will provide a radial acceleration to everything internal - including the crew - pushing everything towards the outer walls. This is artificial gravity. The constant force of the artificial gravity should mitigate, and even eliminate, the biological degradation that has been previously seen on other spacecraft. Removing this obstacle will allow humans to live in space for prolonged periods of time, making it possible for people to travel interplanetary, or live in orbit, while remaining healthy. Aphrodite I will also be the maiden voyage for many new technologies in space, including inflatable walkways, state of the art radiation shielding, and nuclear power. Additional research will be done by the crew and possibly private organizations to observe the effects of sustained artificial gravity. The best findings from this mission will serve as benchmarks and be directly applied to the spacecraft used in the next Aphrodite mission. Aphrodite I is only the first of many missions within the Aphrodite Project that aims to take humanity to the stars.



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List of ABET Requirement #1

An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.

List of ABET Requirement #2

An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.

List of ABET Requirement #3

An ability to communicate effectively with a range of audiences.

List of ABET Requirement #4

An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.

List of ABET Requirement #5

An ability to function effectively on a team whose members together provide leadership, create a collaborative environment, establish goals, plan tasks, and meet objectives.

List of ABET Requirement #6

An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

List of ABET Requirement #7

An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

Nomenclature

A	Area
a	Semi-major Axis
$\dot{a}$	Rate of Change of Semi-major Axis
B	Ballistic Coefficient
C_D	Drag Coefficient
C_{labor}	Cost of Labor
C_{LV}	Cost of Launch Vehicle
C_{total}	Total Cost
F	Force
I_{sp}	Specific Impulse
m	Mass
M_f	Mass of System
M_P	Mass of Propellant
r	Radius
t	Time
V_{eq}	Equivalent Velocity
ΔV	Velocity Increment
μ	Standard Gravitational Parameter for Earth
ρ	Density
ω	Angular Velocity

List of Abbreviations

Abbreviation	Definition
AAA	Aphrodite Autonomos Arm
ADCS	Attitude Determination and Control System
ATCS	Active Thermal Control System
BEAM	Bigelow Expanded Activity Module
BPA	Brine Processor Assembly
CA	Coverage Analysis
CCM	Crew Command Module
C&DH	Command and Data Handling
CDR	Complete Design Review
CDRA	Carbon Dioxide Removal Assembly
CMG	Control Moment Gyroscopes
CNC	Computer Numerical Control
CTC	Cost and Time Constraints
ECLSS	Environmental Control & Life Support System
ESA	European Space Agency
ERA	European Robotic Arm
FAA	Federal Aviation Administration
GFE	Gravitational Field Effectiveness
GNC	Guidance, Navigation, and Control System
GPS	Global Positioning System
HF&H	Human Factors and Habitability

ISS	International Space Station
I/R	Inspection and Review
LEO	Low Earth Orbit
MMOD	Micro-Meteoroid and Orbital Debris
MOM	Mission Operations and Maintenance
NASA	National Aeronautics and Space Administration
OGA	Oxygen Generator Assembly
OGS	Oxygen Generation System
PDR	Preliminary Design Review
PTCS	Passive Temperature Control System
RCS	Reaction Control System
SF	Structural Feasibility
S/M	Simulation and Modeling
TCS	Temperature Control System
T/D	Test and Demonstration
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking and Command
UPA	Urine Processor Assembly
US	United States
V&V	Verification and Validation
WBS	Work Breakdown Structure
WHC	Waste & Hygiene Compartment
WPA	Water Processing Assembly

I. Overview

A. Introduction

1. *Original Mission/Mission Background*

At its conception, the Aphrodite Mission was planned to be the first manned mission to conduct a flyby around Venus. This mission aimed to gain valuable insight into manned, long-distance space exploration. As the human population continues to explode on Earth, scientists have begun looking to Mars as the next frontier for human habitation. Unfortunately, the closest Mars ever gets to Earth is about 55 million kilometers, while the furthest humans have ever gone from the surface is about 400 thousand kilometers. Not only is the sheer distance to Mars a hurdle humans have never conquered, the time it takes to get there is more than the vast majority of astronauts have spent in space. Currently, there are only three cosmonauts to sustain spaceflights over nine months, and none since 1994. A manned Venus flyby was a logical compromise for humans to gain experience with sustained space travel, while avoiding the complications of landing. Venus comes as close as about 24 million kilometers, just above half the closest Mars will ever come to Earth. The original Aphrodite mission would have served as a stepping stone towards interplanetary and long-term space habitation. If astronauts are sent to another planet, they must be experienced with sustained extraterrestrial living, especially when outside the comfort zone of Earth's orbit.

The original Aphrodite mission would have trained a specialized crew of four astronauts and provided a benchmark for manned interplanetary travel. Unfortunately, as the project developed, the team concluded that more intermediary steps needed to be taken before humans could be sent outside Earth's sphere of influence. Since nothing remotely close to a mission of this scope had been conducted before, there were concerns that many subsystems would not hold up to the challenge. The crew would have needed to survive for months in space without any resupply or safety net, so any failure of any subsystem would have likely deemed the entire mission a failure. Additionally, problems of radiation, communication, and psychological needs had never been tested or considered in this context. Even more problems emerged; Humans create waste, air is not completely recyclable, bones and muscles degenerate if they aren't utilized properly, consumables take up lots of space and expire, the list of issues is massive. The spacecraft needed to execute this mission would have to be incredibly large, robust, and reliable. There were simply too many failure points that needed testing before a mission of this scale could succeed.

This is why Aphrodite I came into existence. Instead of Aphrodite operating as a single mission to fly a crew around Venus, it will be a series of missions, with long-term space travel being the final goal. The Aphrodite missions will serve to flight test both systems and humans to prepare the next generation of astronauts to live among the stars. Aphrodite I is only the beginning.

Biological degradation is the first, and most pressing, issue that needs to be addressed before sustained space travel is possible. Based on the habitation of the International Space

Station, scientists have seen that living in a microgravity environment causes body degeneration, making any long-term stay in space unhealthy and dangerous. If humans are to travel to other planets, they need to be able to do it without their bodies completely failing on the way there.

Extensive research has been conducted on the human biological system and the role gravity plays in maintaining vital bodily functions. Without the presence of gravity, the body undergoes muscle and bone atrophy. [27]. This presents an imposing hurdle when considering the future of space exploration and the long time spans humans will need to spend in zero gravity to reach anywhere outside Earth's sphere of influence.

Despite the copious research done by the ISS and other space stations on human habitability in space, a solution to remove the negative effects of microgravity has not been found. The only thing scientists have currently tested are exercise regimens to attempt to minimize the effects. Astronauts aboard the ISS are required to exercise 6 days a week. They utilize two aerobic and one resistive systems to stimulate the muscles and delay the onset of muscle atrophy [27]. While these methods are useful for muscle and bone, studies also note the negative effect that microgravity has on the kidney, lungs, liver, neurovestibular system, and endocrine organs [26]. The degradation of these organs is not easily preventable, and current research and methods struggle to offer a solution.

2. Updated Mission

The Venus flyby was ultimately deemed cost and time inefficient. Focus shifted to the duration of time in space as well as long term habitation, with an emphasis on great distance from Earth and the destination. These changes in the mission parameters allowed for design changes to the spacecraft and introspection into the ISS and shuttle designs. Aphrodite's updated mission is to establish and maintain a LEO with 4 astronauts for one hundred days to test the viability of several technologies for interplanetary space travel and habitation.

3. Mission Statement

For humans to thrive in space, a solution to the issues caused by microgravity must be found. Aphrodite seeks to thrust humanity into the future of space habitation by producing a space station that employs "artificial gravity". By designing the space station as a ring and rotating it at a precise angular velocity, the astronauts inside will be subjected to centrifugal force, which will mimic the presence of gravity. This should mitigate the effects of microgravity on the astronauts and allow longer habitation in space without negative health effects.

Aphrodite I will serve mainly as a research station in which the effects of artificial gravity will be studied. The health of the astronauts will be closely monitored and compared to data from astronauts who spent time on other space stations. Additionally, robust power, thermal, communication, and life support systems will be tested throughout Aphrodite I's lifespan. State-of-the-art inflatable hallways will also see their maiden voyage, and if successful, they will provide a lightweight alternative for space structures. Lastly, an additional science bay will allow organizations to rent space aboard the station to conduct private experiments in artificial gravity.

Beyond artificial gravity, Aphrodite seeks to set a precedent for uninterrupted human habitation in space. Aphrodite I will have the food, oxygen, and water to sustain the astronauts for at least 100 days without resupply from auxiliary spacecraft. This reduces the cost of maintaining the space station's orbit by reducing the cost of launching resupply missions. Furthermore, it provides a psychological barrier for the astronauts on board, as the isolation will be more akin to that of a deep space mission. Ultimately, the goal of Aphrodite I is to serve as the first step towards future space exploration and colonization. It essentially is a verification assessment for the necessary life support technologies that every human spacecraft will need.

The team anticipates that artificial gravity generated by rotating the station will greatly increase the amount of time a human can remain healthy in space. With this technology and the testing to bolster it, spacecraft of the future may be able to integrate similar systems such that humans can spend months in space without significant loss of function. Aphrodite I will remove this obstacle from space travel and allow humanity to move one step closer towards becoming an interplanetary species.

4. Mission Constraints and Assumptions

The Aphrodite I mission shall receive funding on the order of $11B every year for 10 years. In return, the station shall be assembled and operational in orbit by 2035. It shall continue to be operational for at least 30 years and serve as a core module for future station expansion. Finally, the station shall be assembled within 4 launches from an applicable launch vehicle. In terms of the performance of the station, it must have resources to maintain human life for at least 100 days and shall be capable of generating artificial gravity within the livable space.

Table 1 General Mission Requirements

Req. ID	*Mission Requirement*
MR.1	The space station shall support human life for at least 100 days.
MR.2	The space station shall be orbitally assembled within 4 launches.
MR.3	The space station shall have a means to simulate gravity on at least 1 part of the station.
MR.4	The simulated gravity shall be variable and reach at least 60% of Earth's gravity.

This design report strictly covers the development of the Aphrodite I space station and management once it is in space. Station keeping, crew ferrying, and resupply missions will be handled by a separate spacecraft designed or commissioned by a different organization. Likewise, it is assumed that the necessary equipment, technology, and launch vehicle will be developed and operational by 2035, which is the required launch date.

Table 2 Stakeholders

Primary Customers	NASA, ESA, SpaceX
Secondary Customers	Congress
Operators	Space Station Astronauts, Mission Control Engineers
End Users	Biomedical Researchers, Astrobiologists, Physicists

Aphrodite I will be the successor to the International Space Station, accepting commissions and collaborating mainly with NASA and the ESA. Likewise, SpaceX presents a unique mutually beneficial collaboration. Specifically, SpaceX can provide the means to launch Aphrodite, which will conduct research that benefits their goal of human space exploration. SpaceX is expected to be a primary partner for the entire Aphrodite series. The majority of the funding for the mission will be granted by the United States Congress. Their interest in Aphrodite revolves around its commercial success in the space market as well as maintaining US influence in LEO orbital operations. The station will be monitored and operated by the four astronauts onboard, as well as a series of mission control engineers stationed on the ground. Finally, the end users of the station are biomedical researchers, astrobiologists, and physicists who will utilize the data gathered by the station's unique gravitational conditions.

II. Aphrodite Design

A. Overall System

1. System Requirements

The high level system requirements were determined after considering the mission objectives, assumptions, constraints, and requirements. These requirements are the result of teamwide collaboration and brainstorming. Furthermore, these requirements serve as the basis of the design of the Aphrodite space station and alternate mission systems. Based on the top level system requirements, subsystems stem off and develop their own requirements to aid in the functionality of Aphrodite.

Table 3 System Requirements

Req. ID	*Mission Requirement*	*V&V*
S.1	Shall be capable of supporting four astronauts for at least 150 days without resupply.	
S.2	Shall be capable of simulating the effects of gravity for the astronauts.	

S.3 Shall contain all required scientific instruments and tools for the crews' assignments.

S.4 Shall follow all NASA and FAA safety standards and requirements for a crewed mission

S.5 Shall provide a safe and hospitable living environment for the crew for the duration of the mission

S.6 Shall have the structural durability to operate for the duration of the mission in the space environment

S.7 Shall possess power reserves capable of powering the craft for 20 days without power input.

S.8 Shall possess the means to determine and correct attitude in orbit.

S.9 Shall possess the means to make small avoidance maneuvers while in orbit.

S.10 The station's components shall fit within the cargo dimensions of available launch vehicles.

S.11 The station shall support direct-to-ground communication links

S.12 The station shall maintain attitude control within ±1 degree of command orientation.

S.13 Shall support automated and crew-assisted docking.

S.14 Docking ports shall be compatible with international standards.

S.15 Shall regulate internal and external temperature while in space.

S.16 Critical systems shall have appropriate redundancy depending on importance.

S.17 The space station shall be capable of autonomous operation in the event of ground station contact loss.

S.18 Autonomous fault detection and recovery shall be implemented for power, thermal, and life support systems.

As mentioned, the system requirements serve as the foundation for the subsystems featured in Aphrodite. To accomplish all of these, the system is split into 8 subsystems; Propulsion, ADCS/GNC, C&DH, TT&C, Structures, Thermal, Power, and Human systems.

Each of these are essential to the success of Aphrodite I. Team members each chose a subsystem to research and develop based on their design requirements. The following work breakdown structure shows all of the subsystems and their subsequent subparts with the exception of the human systems. Human systems were quickly discovered to be too encompassing and were given their own work breakdown structure, featured later in the report.

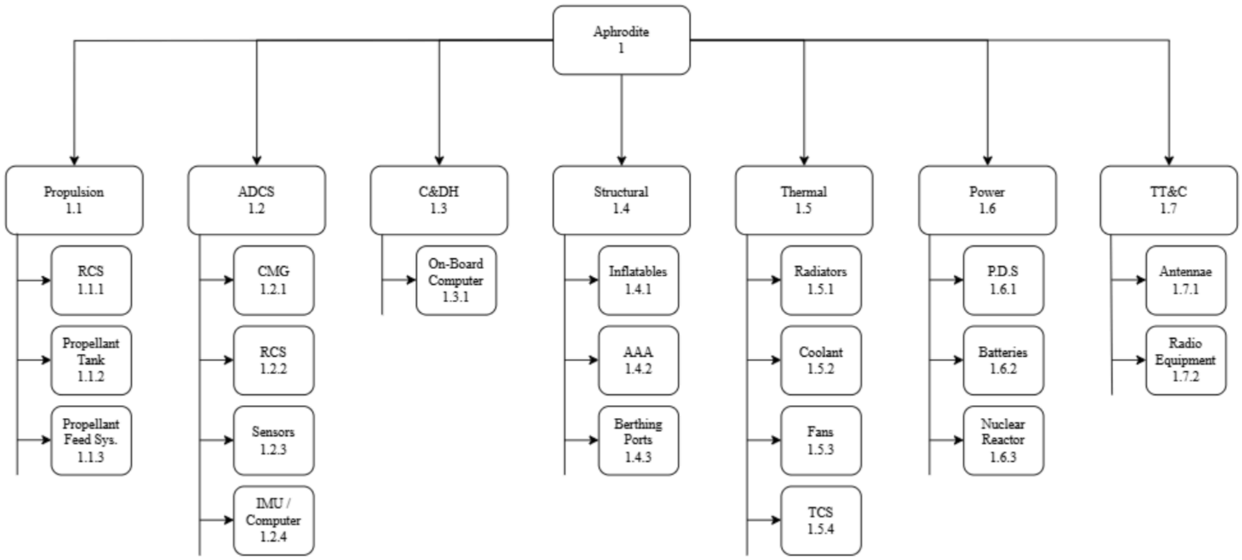


Fig. 1 Aphrodite I Work Breakdown Structure

From this figure, the team constructed a path for developing their respective system requirements thereby allowing for subsequent design and analysis of these subsystems. Some of these subsystems had smaller off-shoots from this work breakdown structure, which will be discussed later.

2. Verification and Validation Methodology

System requirements will undergo verification and validation to ensure mission readiness. An example of these processes is shown below in the Verification and Validation Graphic. The ultimate goal of these processes is implementation of the subsystem into the overall design of our project.

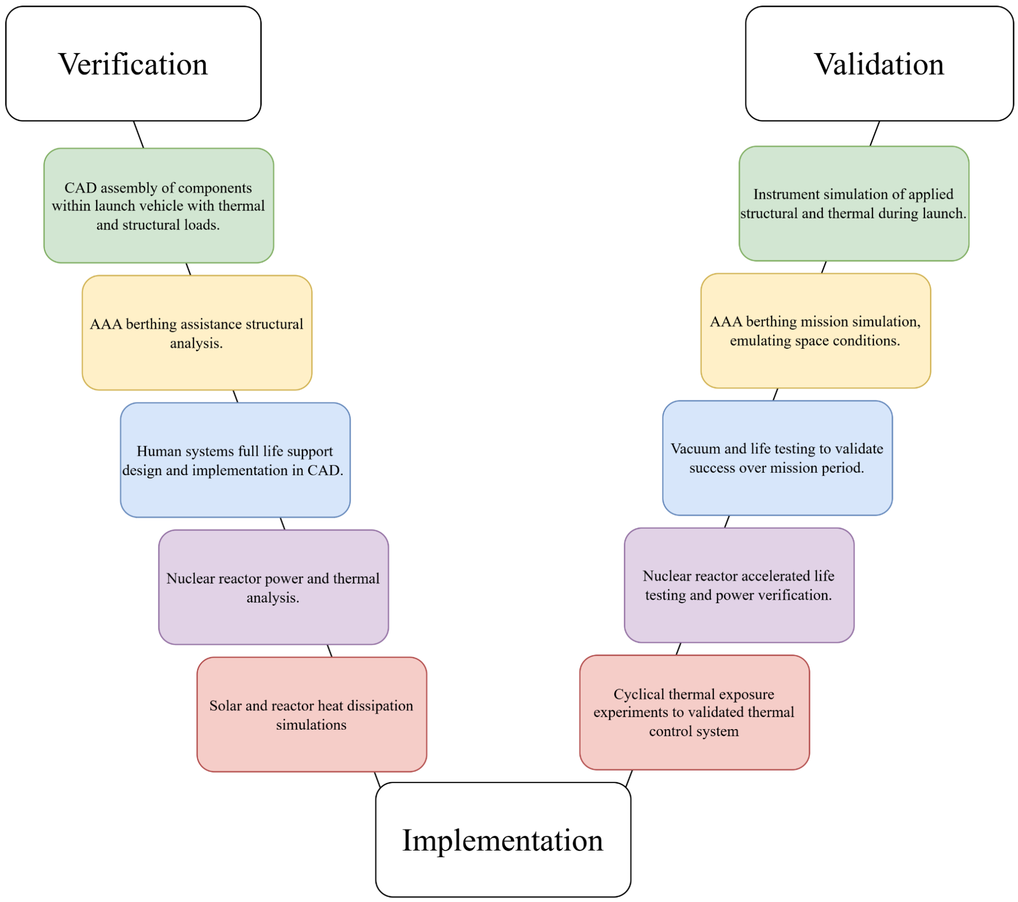


Fig. 2 Verification and Validation Graphic

Verification and validation will occur in one of four methods. These include Coverage Analysis (CA), Inspection and Review (I/R), Simulation and Modeling (S/M), and Test and Demonstration (T/D). The CA method uses verification of subsystems to verify the requirement. For example, using the multiple subsystem requirements pertaining to them being powered on to verify a requirement on the main system that all subsystems are powered on. The I/R method utilizes inspection by a certified engineer to verify the requirement. As we do not have a dedicated certified engineer to inspect our designs at the moment, this method will be rarely utilized in this report.The S/M method uses modeling and simulation to verify requirements for environments not readily accessible and unlikely situations, like failure scenarios. Our team does not currently have access to the necessary testing environments, therefore this will be a recurring method seen in this report. Lastly, the T/D method involves running the equipment or putting the equipment in the environment of final implementation for verification. Many of our subsystems will be unable to utilize the last method prior to launch for vacuum testing related requirements due to its final position being in LEO. Using a variety of these methods, the team will validate and verify our system requirements.

3. Analysis of Alternate Mission Systems

At its core, Aphrodite I serves the role of a space station capable of supporting human life for unprecedented periods of time. However, the design of Aphrodite and its method of construction leave opportunities for an analysis of alternative mission systems. Notable factors within the trade study are gravitational field effectiveness (GFE), structural feasibility (SF), human factors and habitability (HF&H), mission operations and maintenance (MOM), and cost and time constraints (CTC). For most cases, the artificial gravity will be generated through centrifugal force. While physically acceptable, various factors such as the coriolis effect, angular velocity, and radius from the center of rotation will affect the habitability of the system. Thus, the importance of GFE. This is traded with SF and HF&H in order to create a realistically buildable and habitable space station. Likewise, the station must be built in a cost effective, timely manner and must be maintainable. The trade study of these factors along with alternative mission systems is seen below in table 5.

Table 4 Analysis of Alternative Mission Systems

Design Criteria	Norm. Weight	Inflatable Gravity Ring	Tether Split Habitat	Linear Accelerator	Onboard Centrifuge
GFE	0.22	4	4	5	5
SF	0.17	3	4	3	3
HF&H	0.28	5	2	3	1
MOM	0.16	3	2	1	1
CTC	0.17	3	3	1	4
Total	1	3.61	3.167	2.88	3.22

The inflatable gravity ring won out mainly due to the quality of life it is capable of giving the astronauts. Having a ring allows the astronauts to walk around the station as though they were on ground, which is something that the split habitat is unable to provide. Likewise, the inflatable structures allow for the crew modules to be located far from the center of rotation, which results in lower angular velocities for the desired gravitational pull. The onboard centrifuge would be cheap and effective, but it restricts the space in the station where the astronauts could feel the effects of gravity. Likewise, this solution would be difficult to maintain, as the centrifuge would need to spin at high speeds for long periods of time. Finally, the linear accelerator would provide the best quality of gravity, as well as potentially large spaces of habitability. Unfortunately, the spacecraft would need to continually be accelerating using some sort of propulsion, which is extremely expensive and operationally taxing on the engine.

4. Overall System Design

Aphrodite I will tackle the problems with microgravity by spinning along a central axis, inducing artificial gravity along its outer radius through the use of centrifugal force. To capitalize on the centrifugal force, Eq. (1), an outer ring will extend from the center of rotation at a maximum radius of 25m. The long radius works to decrease the coriolis effect.

$$a = F/m = \omega^2 r \tag{1}$$

At this radius, the station will rotate between 4.6 and 6 rev/min in order to achieve between 60% and 100% of earth's gravity at the farthest point. Four crew modules will extend from the center of the space station to the edge of the 25m radius. In order to reduce the profile of these pieces, inflatable structures will be used to allow the crew modules to fit within the constraints of the launch vehicle. Once docked, the inflatables will extend such that four walkways will protrude from the center, and four circular walkways will extend to connect each crew module to each other. At each connecting point, an airlock is featured in the event that one crew module or inflatable structure experiences failure. At the center is the Central Control Module (CCM), which will house all the essential functions and life support systems of Aphrodite. Supplies such as food, oxygen, propellant, and water recycling, as well as computer systems, communication, and power systems will originate here. Eight collapsable radiators, fluid loops, and a passive thermal control system will work to mitigate thermal effects. These effects originate not only from the sun, but also the on-board nuclear reactor which will power Aphrodite I. In order to assist with on-board repairs, berthing, and other miscellaneous tasks, the Aphrodite Autonomous Arm (AAA) was designed. This arm is capable of crawling around the station via grappling points to relocate to a position where it can optimally work. Exterior RCS thrusters are also located along the station at locations which facilitate easy translational or rotational motion. Featured below is a labeled diagram of the architecture, including all of the major visible components on Aphrodite I.

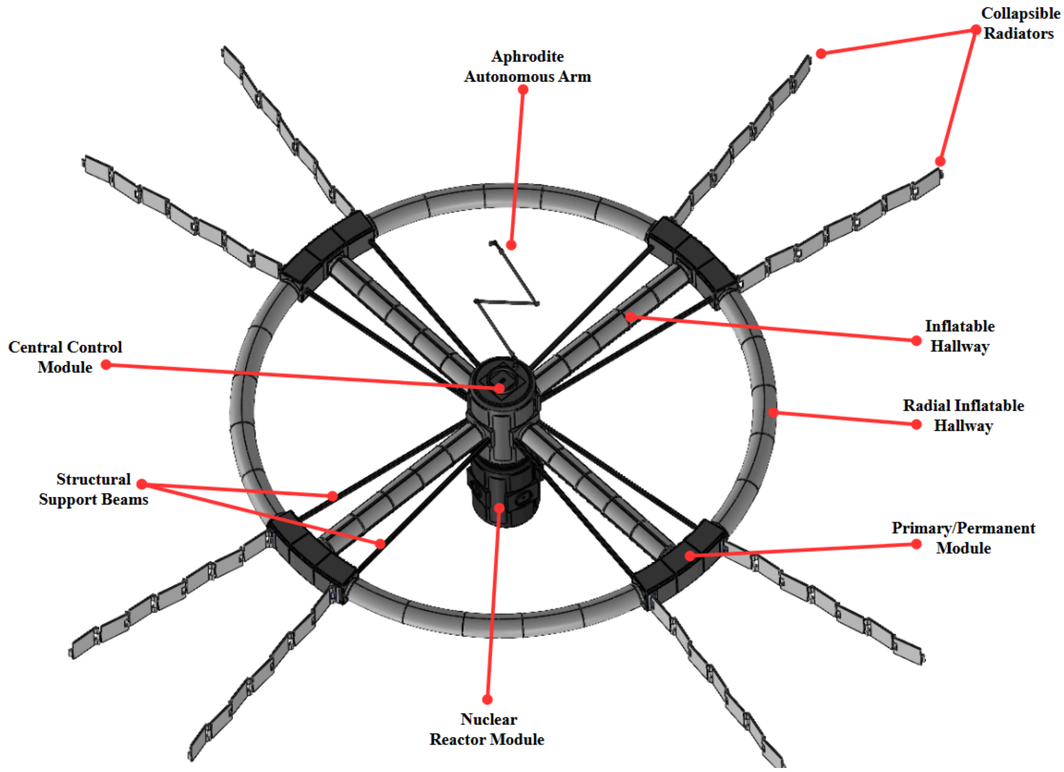


Fig. 3 Aphrodite I (Labeled)

Not featured in fig. 3 are the ADCS/GNC and C&DH/TT&C subsystems. These systems are mainly stored within the CCM to protect the equipment from significant amounts of radiation.

The interaction between each subsystem is represented in the physical architecture chart and N^2 diagram. The physical architecture shows the interactions between each component through fuel lines, power lines, and data lines. All of which is regulated by the Thermal Control system. Likewise, the N^2 shows these interactions through inputs and outputs. Notably, the power system supplies power to each subsystem. The thermal system regulates the temperature of each subsystem. And C&DH is responsible for collecting all telemetry data and relaying instructions to specific subsystems.

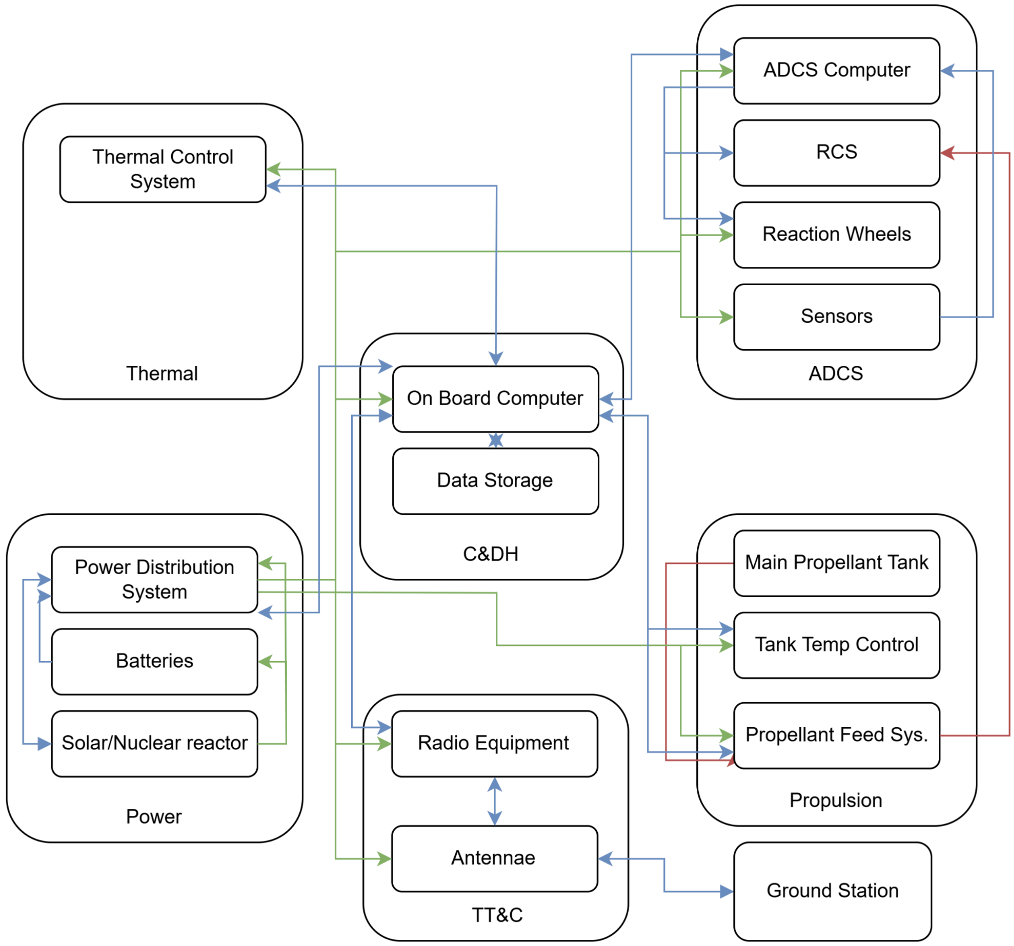


Fig. 4 Aphrodite Physical Architecture detailing fuel (red), data (blue), and power (green) lines.

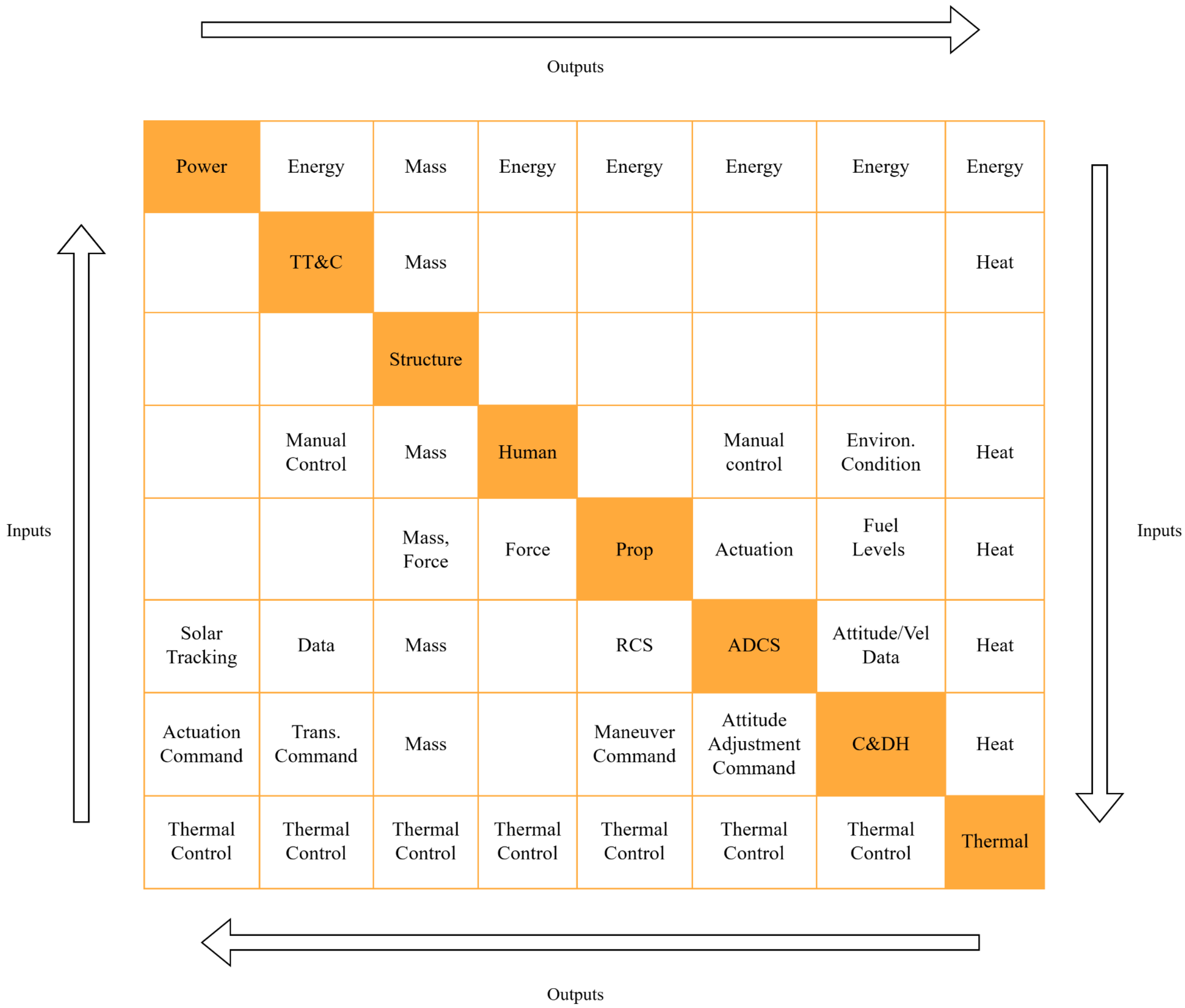


Fig. 5 Aphrodite I N^2 Diagram

5. Concept of Operations

Aphrodite I will be assembled in orbit over the course of 4 launches. It will be assembled at a circular parking orbit at an altitude of 390 km, which is slightly lower than the desired operating altitude of 450 km. This is to allow the launch vehicles to save fuel when reaching the rendezvous. After assembly is complete, an auxiliary spacecraft will be launched with the purpose of performing a hohmann transfer to raise the orbit to a circular orbit at 450 km. After the station has reached operational height and is verified to be safe for human habitation, a final launch will carry the crew and various supplies. Once the crew arrives, they will facilitate the final internal assemblies and final checks. Then, the station will be fully operational and will proceed with its 100 day mission.

The launch process will begin by launching the CCM, AAA, and two interior inflatables. Once in orbit, the AAA activates and assists the inflatables with their connection. After this, the second and third launch will contain two exterior crew modules and two exterior inflatables. The second launch will include two additional interior inflatables, while the third will contain the support beams. Once the launch vehicle rendezvous with the CCM, it will dock momentarily and the AAA will attach and guide each module to its necessary location. Finally, the fourth launch will contain the nuclear reactor and the eight collapsable radiators. Like in the previous launches, the AAA will guide these into their respective locations while the launch vehicle is docked.

Once assembled and verified to be structurally sound, an auxiliary vehicle will be launched and rendezvous with Aphrodite I. This is where the vehicle will assist Aphrodite I in performing a Hohmann transfer to 450 km. It is important that this vehicle has an extremely high I_{sp}, as the burn will require approximately 2.2 km/s of ΔV. Due to the high velocity increment, it is recommended that low thrust engine solutions are employed. Having Aphrodite I reach a higher orbit initially allows for an increase in the time between orbit raising maneuvers, which means that the resupply missions can generally be conducted with a lower performance, lower mass vehicle. This should reduce the carbon footprint that Aphrodite I has on the environment through the reduction in maintenance launches compared to the ISS.

Once the crew is on board and the station is confirmed to be operational, the propulsion system will begin spinning the station to its desired angular velocity. In order to reduce the impulsive inertial loads on the structure, the RCS thrusters will be fired at their lowest possible thrust. Once the station is spinning and the structural integrity of the inflatables is verified, the astronauts may enter the crew modules. Prior to this point, the ferry vehicle shall remain attached to the docking port in case of emergency.

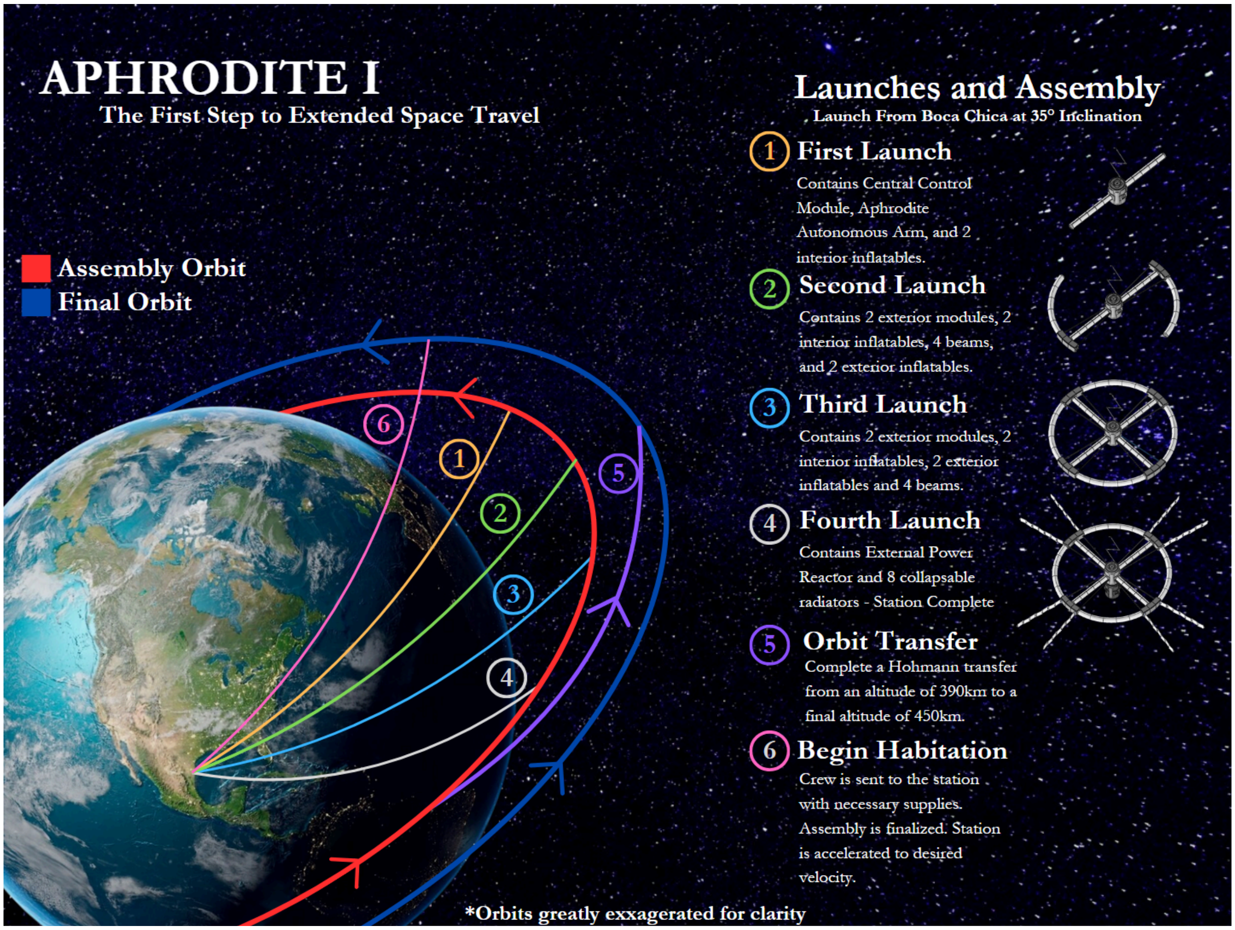


Fig. 6 Concept of Operations Graphic

B. Human Systems

1. System Requirements

The basis for the requirements pertaining to human systems is centered around health, safety, capability, and performance. Human system requirements are based on NASA standards and ISS operating procedures. Accounting for all human requirements was determined to be too extensive for this project. We have highlighted requirements and systems that are crucial to health, safety, capability, and performance. Future development into this program would initiate full compliance with all human requirements for space flight and space living.

Table 5 Human System Requirements

Req. ID	*Mission Requirement*	*V&V*
HS.1	The Aphrodite vehicle shall contain at least one apparatus to maintain, improve, and monitor cardiovascular health.	T/D
HS.2	The station shall sustain a habitable environment.	T/D
HS.3	The food and water rations shall support 4 crew members for 100 days.	T/D
HS.4	The crew shall be trained in medical and subsystem emergency scenarios.	T/D
HS.5	The crew shall have their mental and physical health checked prior to flight.	T/D
HS.6	The station shall provide breathable air to the 4 crew members for 100 days.	T/D

More human system requirements can be found in the Appendix on Tables X-X. With the quantity of requirements for human systems, we did not want to cover the body of the report in tables. The design based on these requirements will be discussed in the following paragraphs.

2. Verification and Validation Methodology

The team primarily used NASA-STD-3001 Volumes 1 and 2 to create a comprehensive list of requirements for human flight. They then modified requirements as necessary to adhere to Aphrodite I specifications. The NASA standard served as a baseline, so any modifications made were because NASA standards needed to be expanded to incorporate longer mission duration and gravity ring requirements.

To verify successful implementation of human systems requirements the team performed case studies on specific systems and components needed to sustain a habitable environment. Additionally the team considered crew training and tasks the crew would need to complete during the mission duration. The team researched modern studies completed on the ISS to develop a list of novel experiments to complete, mostly centered around the implementation of a gravity ring. Lastly, the team considered human-driven tasks and associated risks by creating a risk matrix and evaluating several failure modes.

3. Human Systems Design

Design of the human systems was broken down into 3 major subgroups: Mission Requirements, Health Sustainment, and Training and Records. The mission requirements subgroup involves compatibility and human interface during the mission. Health sustainment covers the needs of maintaining healthy astronauts during the mission. Finally, the training and records subgroup aims to ensure mission readiness and track the overall effects of this mission on the astronauts.

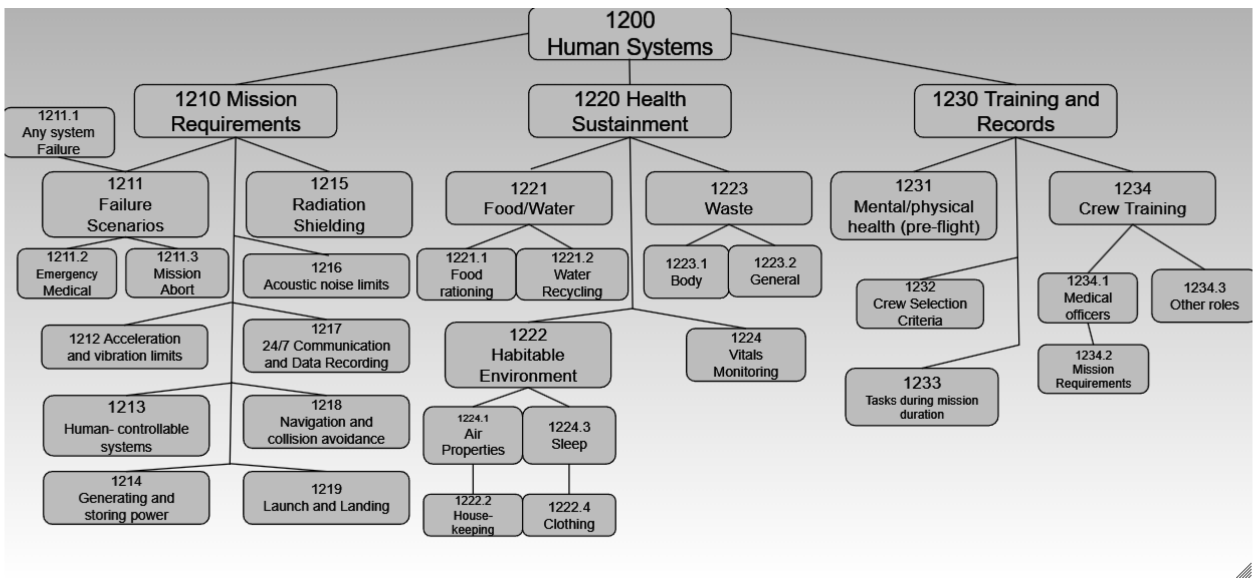


Fig. 7 Human Subsystems Work Breakdown Structure

3.a Flight Mission Requirements

Human flight mission requirements are built into the systems they will be using. Limits will be set on outside variables the astronauts will face during the mission.

3.b Health Sustainment

The primary focus of the human system requirements are to ensure the safety and health of crew members for the entire mission duration. Health sustainment requirements focus on the basic requirements of all humans: food, water, shelter, and air.

The goal is to maximize the self sustainability of the crew and station once in orbit. Prior to that, provisions must be brought up to start the sustainability cycle. Specifically, food, water, and air must be transported into space with the astronauts. Water and air can be recycled, to an extent. With no current plan for a space garden, food is the current most limiting consumable for mission duration. Following the success of the Environmental Control & Life Support System (ECLSS) on the ISS, Artemis I will utilize a similar, yet upgraded ECLSS to manage the recyclable resources (water and air). See Fig.(8) for a subsystem diagram which breaks down the ECLSS.

Environmental Control and Life Support Subsystem Diagram

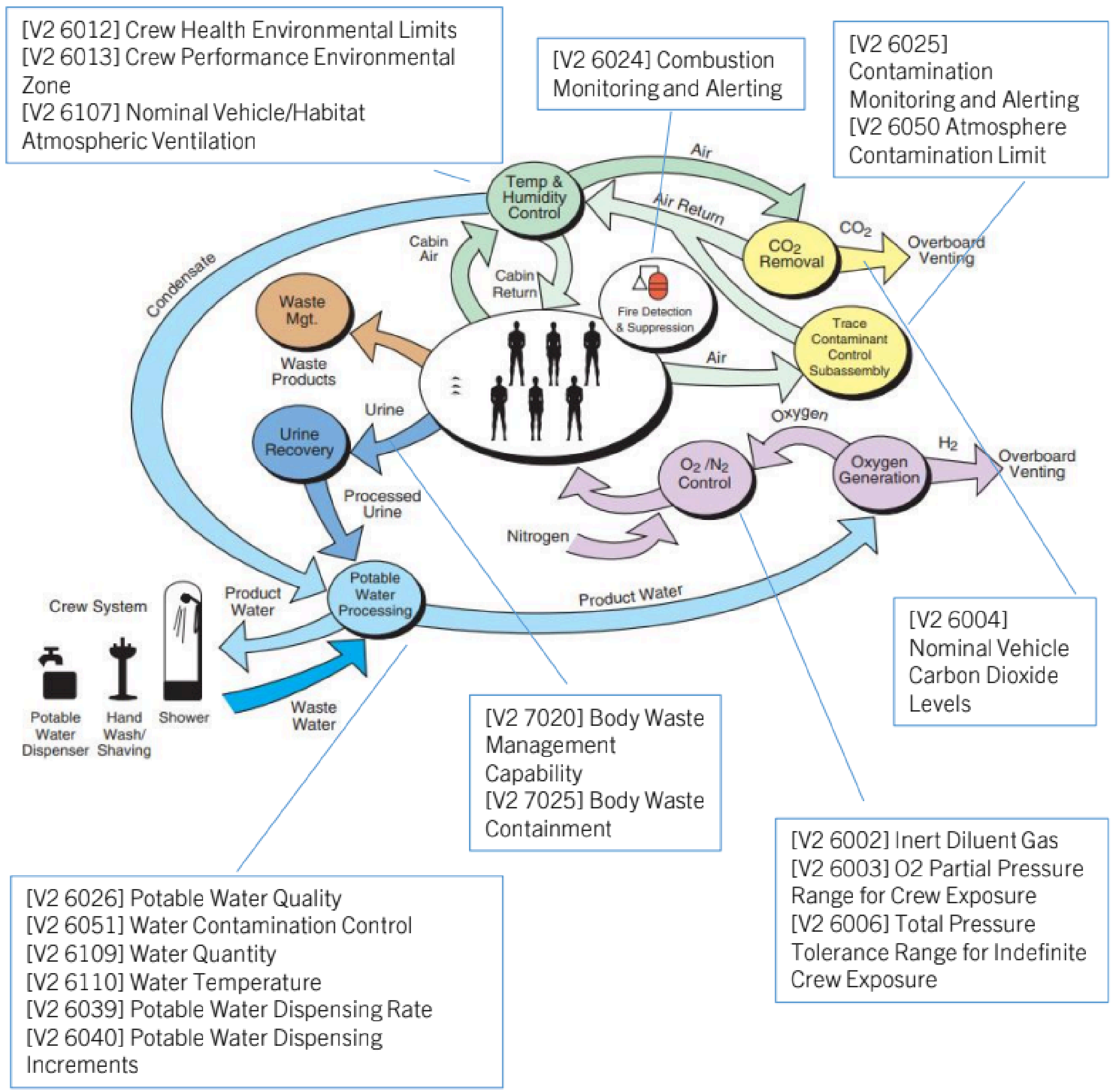


Fig. 8 ECLSS Subsystem Breakdown

3.b.i Food

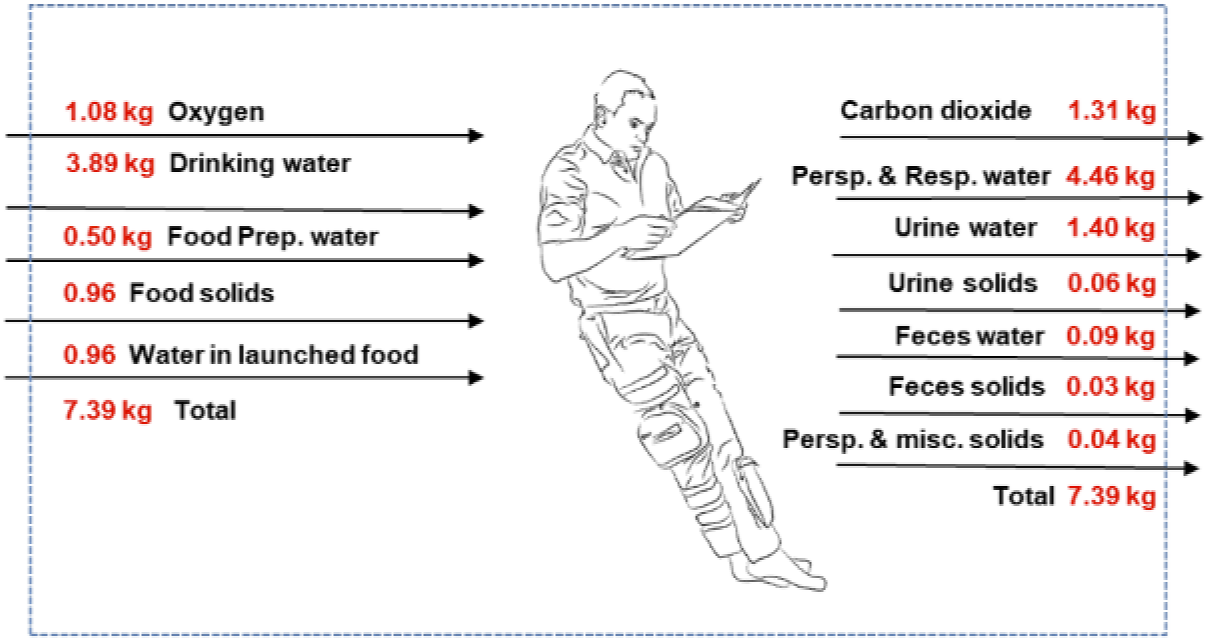


Fig. 9 Astronaut Mass Balance

Based on the graphic from a NASA report on "Astronaut Mass Balance for Long Duration Missions", the food and water requirements were calculated for our hundred day mission. [3] This figure shows an extreme case of a 95th percentile astronaut, meaning they are at the extreme of the consumption spectrum. Using these values allows for a safety-net of food and water reserves in case of an emergency or failure scenario. The values obtained for required food and water, by mass, required for a 100 day mission of 4 astronauts were 956 kgs and 1040 kgs respectively.

3.b.ii Water

With a supply of freshwater in the station, the crew will utilize a system similar to the ECLSS onboard the ISS. The ECLSS is a proven and upgraded subsystem that has ensured a safe and habitable environment for the astronauts on board the ISS. "The ECLSS manages air and water quality, waste, atmospheric parameters, and emergency response systems." In terms of water reuse, the components from the ECLSS chosen for use during Aphrodite I are the Urine Processing Assembly, the Water Processing Assembly, and the Waste and Hygiene Compartment.

The UPA is designed for use by 6-7 crewmembers. It produces purified water using recycled urine and flush water from the WHC. A Brine Processor Assembly was added in 2021 which increased the water recovery to 98% from 85%. This assembly will be implemented on Aphrodite I.

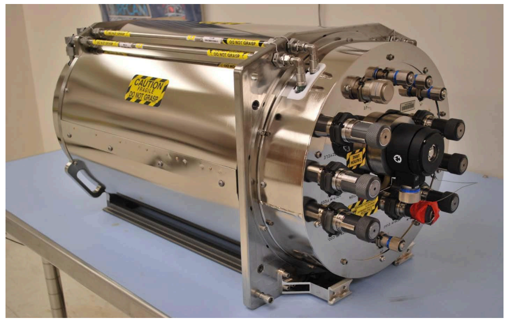


Fig. 10 Urine Processing Assembly

The WPA processes condensate, distillate and system waste water from 6-7 crewmembers. The condensate comes from the Common Cabin Air Assembly in the ISS. This system deals with Oxygen Generation Assembly and CO2 reduction systems which will be expanded upon in the air section when covering the Oxygen Generation System. The product of the WPA is potable water for the crew, iodinated water for the OGS, as well as other systems that require freshwater.

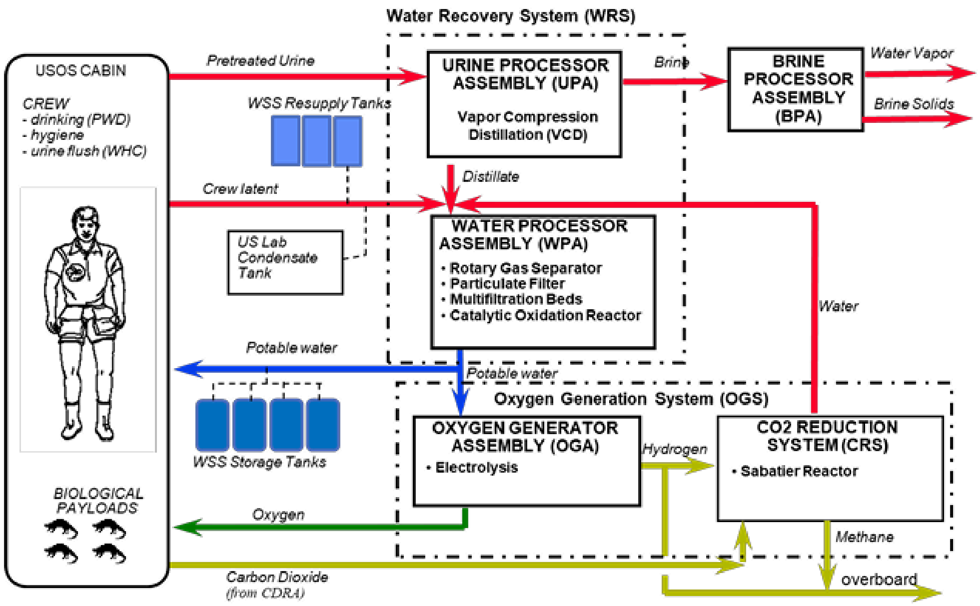


Fig. 11 ISS Water Recovery System Overview

The WHC is where all the liquid and solid human waste is stored. The flush urine is sent to the UPA in a pretreated form for recycling.

Fig. 12 Waste and Hygiene Compartment

3.b.ii Breathable Air

Breathable air will need to fill the prefabricated volumes, as well as the inflatables, during station assembly. The pressure and volume requirements will be based on the overall station volume and inflatable characteristics. Once established in orbit with an assembled station, the crew will utilize recycled and generated air.

Air makeup, monitoring, pressure, temperature, and quality need to be considered in determining the best source of oxygen generation and recycling on the station. The ECLSS was again used as a reference for the air components chosen for our mission. The ECLSS accounts for the characteristics listed above through the following components: oxygen generating units, carbon dioxide removal units, storage tanks, air contamination control units, pressure regulators, fire detection and suppression units, and gas analyzers.

Generation of oxygen on Aphrodite I will be conducted by an electrolyzer, which uses water to produce oxygen and hydrogen through electrolysis. The hydrogen can be stored and combined with CO2 to produce water and methane. The methane or hydrogen would be vented overboard. Storage of the unused gases would present a risk to crew members. The OGA electrolyzer has the ability to support a crew of 11. These larger crew capacity components will be crucial for mission success. The area and capacity they have to cover will be roughly 1 ½ times that of the ISS.

Carbon dioxide removal will be handled by the Carbon Dioxide Removal Assembly (CDRA), which supports a crew of 7. This assembly utilizes absorbents, adsorbents, liquid amine, and permeable membranes to scrubb the station's atmosphere of CO2. Backup and makeup systems, such as lithium hydroxide canisters for CO2 removal and air tanks for makeup usage, are required for emergency scenarios and station maintenance.

3.c Training and Records

Training and verification of the astronauts will be conducted by the hiring agency. In depth medical training is necessary for all crew members in case of any emergency scenario. In depth mission training is essential for the safe and complete operation of the space station. The number of components discussed in this section is small in comparison to the total number components that will be on the station. Many of the components and systems will have connections to outside the station. The crew will need to be, at a minimum, familiar with all of the station's systems and have in-depth knowledge and experience with mission critical systems in order to perform emergency actions if required. As this is a mission in determining the viability of long term human space flight, in depth records of the astronauts will need to be kept. Medical, mental, and physical aspects of the astronauts' lives will be recorded for data review and analysis. All records and necessary procedures will be kept onboard securely.

C. Structural Systems

1. System Requirements

The structural system of Aphrodite 1 is essential to maintaining the safe and normal operations of the mission. Assembled in orbit, the structure of the station is made up of component modules for launch. Due to the unique challenges of the mission there are many considerations to the safety and design of the components and their assembly. The main challenges for the structural systems to overcome are the rotation of the station during operation and the use of inflatable modules in the construction of the station. The mission structural requirements were verified based on the NASA guidelines for spacecraft structural requirements. The inflatable module structural requirements and the station structural requirements are detailed below.

Table 6 Station Structural Requirements

Req. ID	*Mission Requirement (SS Shall)*
SS-1	Station shall survive the thermodynamic, rotational, and vibrational loads during mission lifespan.
SS-2	Must be structurally designed to withstand internal pressurization in vacuum and rotational stresses.
SS-3	Shall be able to handle fluctuations in temperature throughout the course of the mission.
SS-4	Shall withstand the conditions of space in low earth orbit.
SS-5	Shall be modular and able to be assembled in orbit.
SS-6	Each module shall be able to maintain human safety and pressurization individually.
SS-7	Station must maintain structural integrity during orbital maneuvers and rotational acceleration/deceleration.
SS-8	Crew modules must be suitable for human habitation for the duration of the mission.

Table 7 Inflatables Structural Requirements

Req. ID	*Mission Requirement (IS Shall)*
IS-1	Must be structurally designed to withstand internal pressurization in vacuum and rotational stresses.
IS-2	Shall be able to operate under expected thermal expansion.
IS-3	Shall be resistant to bursting due to micro-impacts with orbital debris.
IS-4	Each inflatable module shall be able to maintain human safety and pressurization individually.
IS-5	Shall maintain normal operations under 1.25 times the operating pressure.

2. Verification and Validation Methodology

The structural systems of Aphrodite I will undergo extensive verification through methods of simulation, prototyping, testing and analysis, and inspection. CAD models of the structural components and ANSYS analysis will be used to verify the design of the station modules and assembled configuration. The analysis must account for the static and dynamic stresses on the station during rotational acceleration and deceleration, constant rotation, orbital maneuvers, vibrational modes, and thermal expansion stress. The analysis will confirm the principle design of the station and mission, verifying SS-1, SS-2, SS-3, SS-5, and SS-7. Prototype designs will be tested for the various modules. Due to the rotation of aphrodite, designs will have to be tested through strain cycling and failure analysis under gravitational and tension loads. The bulkhead prototypes will be impact tested and burst tested for failure modes. Due to the cost of testing in orbit the behavior of the modules and station in vacuum at LEO will have to be tested through simulation and modeling. These tests will verify SS-2, SS-4, SS-6, and SS-8.

The design of the inflatable modules will be subject to the most testing of the structural systems. The technology of inflatable habitable space station modules is currently in its infancy. The testing of the Bigelow Expanded Activity Module (BEAM) on the ISS has been very successful but years of development testing and research needs to be done prior to the launch of Aphrodite I. The design of the inflatable modules on the station are based heavily on BEAM, but there are additional challenges with this mission. To develop the technology of BEAM to support the size and structural requirements of Aphrodite I, repeated rounds of simulation, modeling, prototyping, and rigorous testing will be undergone. Burst tests will be conducted on the inflatables to ensure reliability. The inflatables will be under considerable hoop stress during operation, and they will be tested under operating pressures twice the 0.8 atm standard for the mission. Off nominal testing will be done to evaluate the inflatables under increased loads, impacts, high temperatures and radiation, and decoupling during operation. Thermal expansion testing will be performed to ensure there are no failures due to the differing expansion rates of different components. Shear testing will be done on the airlocks and along the length of the inflatables to confirm their operation during station rotational acceleration and deceleration. These methods will verify IS-1-5.

As the mission launches are completed, all modules and structural components will be tested during assembly stages. The proper function of the crew modules and structural attachments will be confirmed during coupling and pressurization. The inflatables will be tested at 1 atm during pressurization to test for bursting. Once assembled, the crew will perform extensive testing of the inflatable function during station acceleration. Each module will be inspected before and after rotation and before and after an orbital maneuver. Crew operations during the start of station operations will validate the station and inflatable requirements during the mission.

3. Structural Systems Design

Due to the station being assembled in orbit and the different structural challenges of the mission, the design of the structural system is split up into the design of the different station modules and the design of the assembled station.

3a. Central Module Design

The central module of the station known as the hub is the foundation of the station. It is the first module launched along with the autonomous arm and support components. It is used by the autonomous arm as a dock to connect the other modules to. The hub is mainly used for docking, transportation and storage. The design is cylindrical to accommodate rotation and is 9 meters in length and 6 meters in diameter. It has two large airlocks on top and bottom of the module for coupling with spacecraft. There are four intermodule airlocks around the circumference for connecting to the radial hallway modules. The intermodule airlocks are designed to maintain the internal pressure of the modules if decoupling occurs. To both sides of each hallway airlock are reinforced platforms for the attachment of structural beams that connect to the crew modules. The walls of the hub are made of various layers of structural steel, thermal piping, electrical components, insulation, and thermal shielding. Unlike other structures in space, the modules of the station will be under constant load due to the rotation. For this reason the hub has a thick layer of aluminum to handle the constant rotational load and instabilities in the rotation of the station.

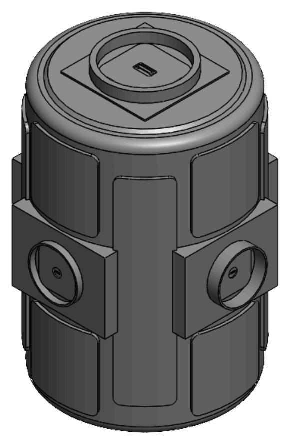


Fig. 13 Central Module Design

3b. Crew Module Design

The crew modules are the main human habitation and work spaces for the mission. There are four crew modules along the circumference of the station's ring. During operation, they maintain artificial gravity for the crew and are connected to each other and the hub by airlocks connected to the inflatable hallways. Each crew module is designed to follow the arc of the station's 25 meter radius outer ring with a rectangular side view. The outer curve of the module is the floor surface for the crew and components. The floor area along the curve is 10 meters by 3 meters. The outer surface of the crew modules are under the largest stress as the edge of the rotating ring experiences the largest forces due to the rotation. The outer surface of the module has a similar layered make-up as the hub but with thicker structural steel. The module uses the same airlock design as the hub which is created to handle the variation in the circumference of the station due to thermal expansion. There are reinforced anchor points on the internal curve of the module for connection to the structural beams.

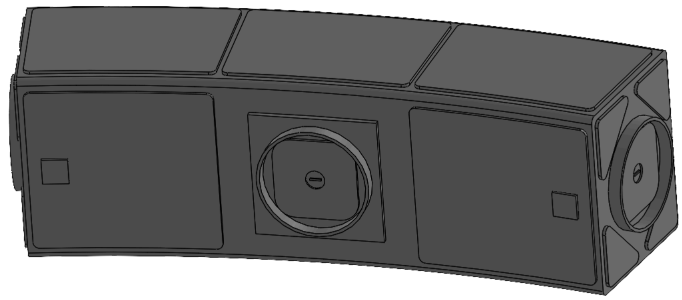


Fig. 14 Crew Module Design

3c. Inflatable Hallway Module Design

One of the most critical components of Aphrodite I is the inflatable hallway modules. Due to the size of the outer ring, long hallway modules are required to connect the central hub to the crew modules and the crew modules to each other. To ensure crew safety, every crew module is connected to two other crew modules and the hub so there are multiple paths of exit should an emergency happen. These large hallways are designed to be inflatable, growing 33% in length when pressurized. This design allows the modules to take up less space in the assembly launches where launch space is critical.

The design of the inflatables is based on the Bigelow Expanded Activity Module (BEAM). BEAM is an experimental module launched in April 2016 that is currently in testing attached to the ISS. BEAM is made of many layers of soft goods. There is a pressure maintaining air bladder layer, a structural restraint layer, and debris protection layers. The design allows the module to expand into roughly a sphere as it inflates and maintains a safe environment for astronauts. The Aphrodite I inflatables will work on the same principle as BEAM, but will require far more structural support to stand up to the rotation of the station. In addition to the inflatable layers seen in BEAM, interlocking aluminum structural layers will be added that expand when the module is inflated. This will cause the module to expand in a similar way to a collapsible straw. Once attached and inflated, ladders and walkways will be installed in the hallways for crew access. These components are fitted so they can shift along the length of the hallways and space is left between them and the airlocks, this allows for thermal expansion and contraction without causing stress to the components.

Fig. 15 BEAM Attached to ISS

There are two types of inflatable modules on Aphrodite I, the central hallways and the outer hallways. The central hallways are straight cylindrical modules attached to the central hub and the crew modules. There are four, one attached to each crew module. They are 2.2 meters in diameter and 19.3 meters in length when inflated. The airlocks connecting it to the modules are designed to expand to allow for different thermal expansion between components.

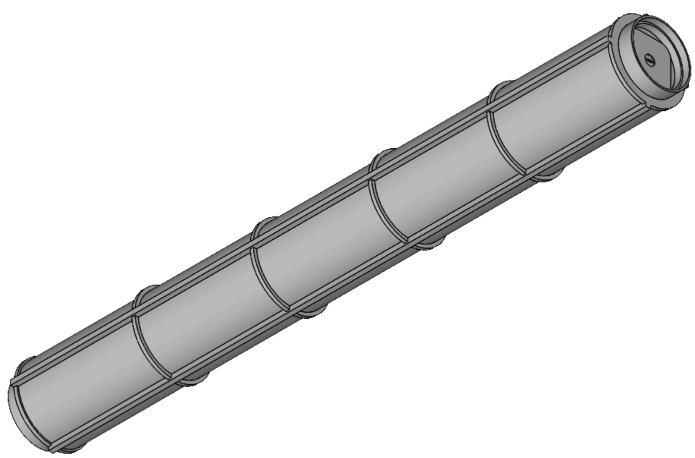


Fig. 16 Inflated Central Hallway Module Design

The outer hallway modules connect crew modules together and complete the outer ring of the station. They have a similar design to the central hallways but curve to follow the circumference of the outer ring. These are the longest modules on the station, extending to a length of 29.3 meters when inflated. To support the structure cables are connected at intervals along the hallway to anchors on the central hub.

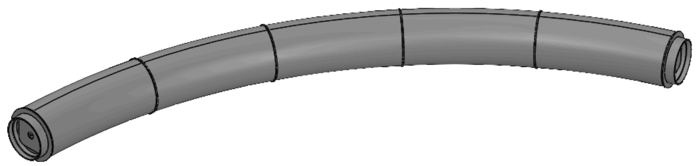


Fig. 17 Inflated Outer Hallway Module Design

3d. Assembled Station Design

In total on Aphrodite I, there are four crew compartments, eight inflatable hallways, a central hub module, and multiple structural components. The design of the station is broken down into separate modules so that they can be transported on separate launches and assembled in space. There are four assembly stages until Aphrodite is completed, corresponding to the four mission launches. The first phase of assembly includes the central hub, autonomous arm, and two central hallway modules. Once the two hallways are docked to the hub and inflates, the second stage attaches two crew modules and two outer hallway modules to the central hallways. The third stage attaches the final four hallways to the station. The final assembly stage attaches the external power reactor and eight collapsible radiators to the crew modules.

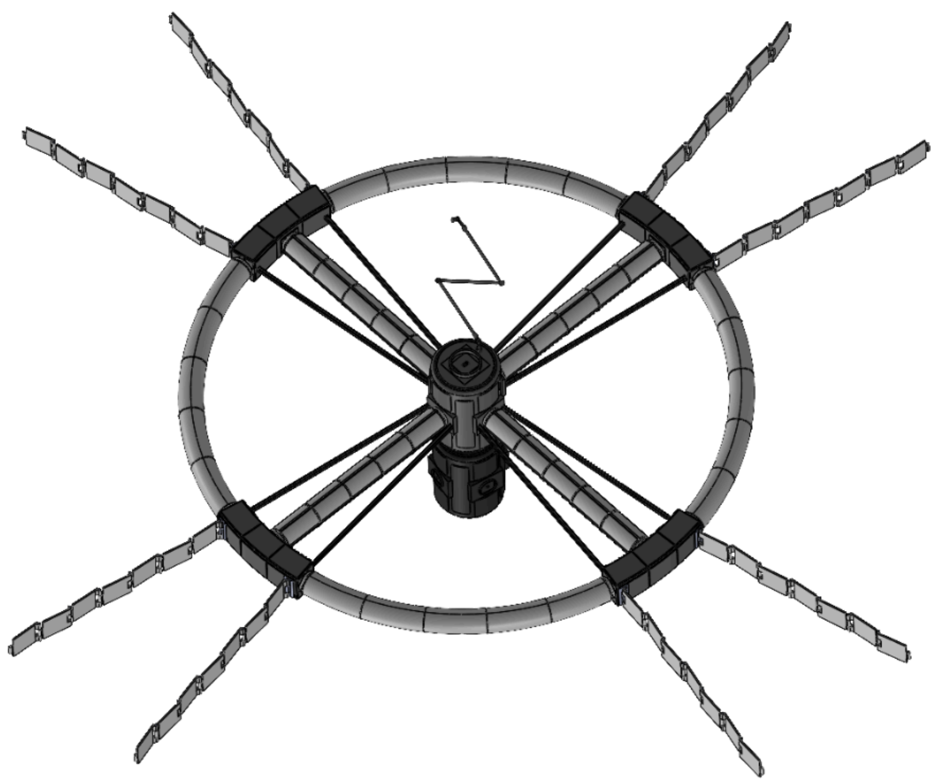


Fig. 18 Final Assembled Station Design

D. Power Systems

1. System Requirements

Table 8 Power System Requirements

Req. ID	*Mission Requirement*	*V&V*
PS.1	The system shall provide continuous power ≥ 100 kW to support station operations (artificial gravity, life support, thermal, etc.).	
PS.2	The power system shall operate independent of solar proximity (functional in LEO, deep space, or eclipses)	
PS.3	The reactor core shall be ≤ 3 m^3 in volume and ≤ 5,000 kg mass to fit launch vehicle constraints.	
PS.4	Shielding shall limit crew radiation exposure to < 50 mSv/year (NASA astronaut limit).	
PS.5	The system shall use passive cooling (heat pipes) to minimize moving parts.	
PS.6	Fuel (HALEU) shall sustain operation for ≥ 10 years without refueling.	
PS.7	Redundant power pathways shall ensure > 99% uptime during critical operations.	
PS.8	The reactor shall incorporate automatic shutdown in case of malfunction.	
PS.9	Power output shall be scalable (100 kW–1 MW) to support future station expansion	
PS.10	The system shall interface with thermal control to dissipate excess heat via radiators.	

2. Verification and Validation Methodology

The power system requirements will be verified through a combination of testing, simulation, inspection, and analysis to ensure compliance with mission objectives. For PS.1 (continuous ≥100 kW output), ground testing of a reactor prototype under simulated mission loads—including vacuum and thermal cycling—will validate performance, drawing on methodologies from NASA's Kilopower KRUSTY experiment, which demonstrated a 1–10 kW reactor's viability for space applications. PS.2 (sun-independence) will be verified via orbital simulations modeling power demand in LEO and deep-space environments, leveraging data from the International Space Station's solar degradation studies. PS.3 (size/mass constraints) will undergo CAD and physical inspection against SpaceX Starship payload specifications, while PS.4 (radiation shielding) will be validated using Monte Carlo neutron transport codes (e.g., MCNP) and benchmarked against shielding designs from NASA's Project Prometheus. Passive cooling (PS.5) will be tested in vacuum chambers to replicate heat pipe performance, informed by the Advanced Stirling Radioisotope Generator's thermal management system. Fuel longevity (PS.6) will be analyzed via burnup simulations and compared to HALEU fuel behavior in terrestrial reactors. Redundancy (PS.7) will be stress-tested using fault-tree analysis and live power grid switchovers, mirroring ISS electrical system protocols. Autonomous shutdown (PS.8) will be demonstrated through overpower/overheat failure injections, building on DARPA's Project Pele safety protocols. Scalability (PS.9) will be modeled using modular reactor arrays, referencing NASA's Fission Surface Power studies. Finally, thermal interfacing (PS.10) will combine CFD analysis with radiator deployment tests in thermal vacuum chambers, following ISS Active Thermal Control System validation methods.

For system-level validation, a three-phase approach will be implemented. Phase 1 includes component testing: the nuclear core will undergo criticality and decay heat removal tests at facilities like NASA's Diamond Peak, while shielding will be irradiated at the Space Radiation Laboratory. Phase 2 integrates the reactor with power conversion and thermal systems in vacuum chambers, followed by an orbital demo of a scaled reactor (50 kW) to replicate KRUSTY's success. Phase 3 validates operational readiness through crewed safety drills and a 1-year simulated mission, incorporating lessons from Russia's TOPAZ-II space reactor program . Compliance with IAEA SSG-34 and NASA-STD-4005 ensures adherence to nuclear safety standards, while risk mitigation strategies—such as post-launch fuel loading—draw from Cassini's RTG launch protocols. This methodology ensures Aphrodite's power system meets reliability targets while mitigating risks identified in prior space nuclear projects.

3. Power Systems Design

3a. Nuclear System

At the center of the Aphrodite space station's operational capabilities lies its nuclear power system, a carefully engineered solution designed to meet the station's substantial energy demands while overcoming the challenges of deep-space operation. This system represents an integration of advanced nuclear technology, thermal management, and fail-safe engineering principles, all working in concert to provide uninterrupted power for the station's critical functions. The power system begins with its core component - a compact fission reactor utilizing High-Assay Low-Enriched Uranium (HALEU) fuel, enriched to between 5% and 20% uranium-235. This fuel choice represents a deliberate balance between energy density, operational longevity, and proliferation concerns. The reactor core itself, with dimensions comparable to a large refrigerator (approximately 1.5 meters in diameter and 2 meters tall), contains precisely arranged fuel elements surrounded by neutron moderators and reflectors that optimize the fission chain reaction while minimizing fuel consumption.

When operational, the controlled nuclear fission process within the core generates thermal energy, with temperatures reaching several hundred degrees Celsius. This heat becomes the primary energy of the system, carefully managed and converted through multiple stages to ultimately produce the station's electrical power. The thermal-to-electric conversion process employs either advanced Stirling engines or solid-state thermoelectric generators, both technologies selected for their reliability in the space environment. Stirling engines, with their moving pistons driven by the reactor's heat, offer higher conversion efficiency (approaching 30-35%), while thermoelectric systems, with no moving parts, provide exceptional reliability despite slightly lower efficiency (around 10-15%).

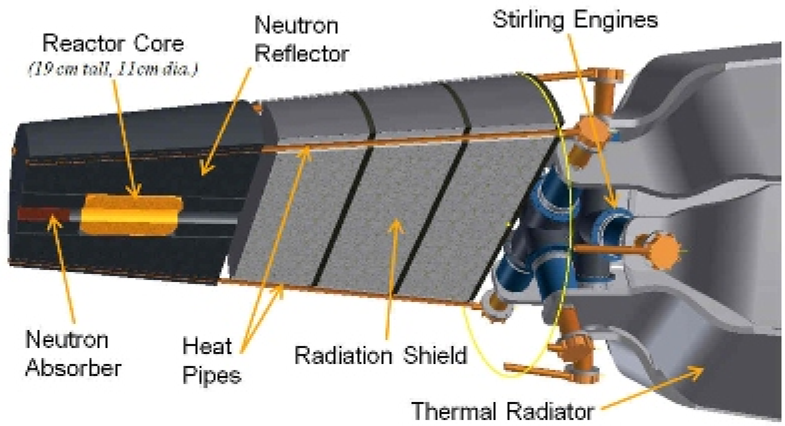


Fig. 19- Stirling Engine

The heat management system is one of the most important aspects of the power plant's design. A network of sodium or potassium heat pipes, embedded throughout the reactor structure, passively transports thermal energy away from the core. These heat pipes operate through capillary action, requiring no pumps or moving parts, making them reliable for long-duration missions. The transported heat serves dual purposes, primarily driving the power conversion systems, and secondarily providing thermal energy for station heating requirements. Excess heat is ultimately dissipated through large, deployable radiators positioned away from the main habitat modules, their surfaces carefully engineered to maximize infrared radiation into space while minimizing solar absorption.

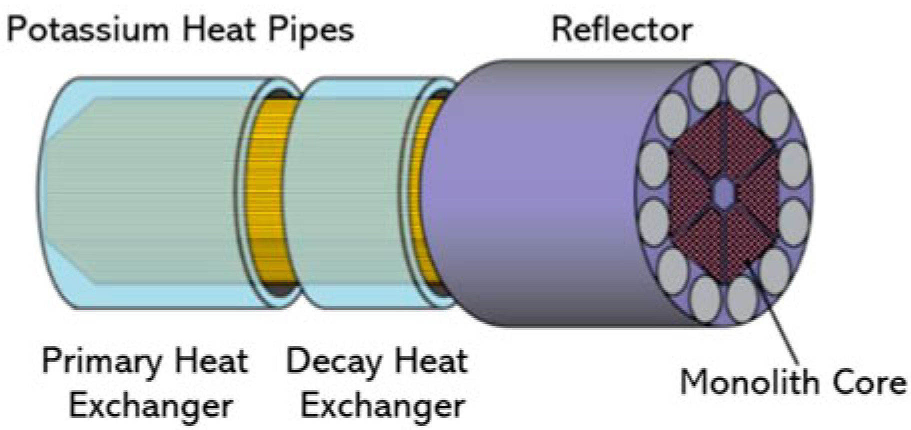


Fig. 20 - Potassium Heat Pipes

Radiation shielding forms a multilayered defensive system around the reactor to protect human astronauts from the negative impact of radiation. The innermost layer consists of boron carbide, effectively absorbing neutron radiation from the fission process. Surrounding this, thick tungsten or lead shielding blocks harmful gamma radiation, with the entire assembly carefully positioned to minimize exposure to crew areas. Innovative design approaches incorporate the station's water storage tanks and other dense materials as supplemental shielding, creating a cost-effective defense-in-depth strategy against radiation exposure. Issues may arise from the fact that this system's weight increases dramatically as the required size of the reactor scales. Power distribution throughout the station utilizes a redundant, fault-tolerant electrical grid designed to maintain operation even with multiple component failures. High-voltage direct current (HVDC) transmission minimizes power loss across the station's extensive structure, with automated switchgear capable of isolating damaged sections while rerouting power through alternative pathways. The system includes substantial energy storage capacity, utilizing advanced lithium-ion or solid-state batteries to handle peak demand periods and provide emergency backup power if needed. Since nuclear power is inconsistent in forms of energy output, batteries have been included into the systems to store energy during times of high energy usage and to pull on energy in times of lower production.

Safety systems employ multiple redundant protection mechanisms. Passive safety features include temperature-reactive control rods that automatically insert into the reactor core if temperatures exceed safe limits, while active systems feature computerized monitoring that can initiate a full reactor scram within milliseconds of detecting any anomaly. The entire power plant is designed with fail-safe principles, ensuring that any malfunction results in a safe shutdown rather than a hazardous condition. Operational management of the nuclear system combines automated control algorithms with crew oversight. While the reactor can operate autonomously for extended periods, crew members regularly monitor system parameters and perform maintenance during resupply missions. The control interface provides intuitive visualization of the reactor's status while maintaining multiple layers of protection against unauthorized or accidental changes to critical settings.

The nuclear power system's integration with the station's other subsystems demonstrates careful planning. The substantial thermal output supplements the station's environmental control systems, reducing the load on dedicated heating elements. Similarly, the electrical output synchronizes with the station's rotation mechanism, providing steady power to maintain the precise angular velocity required for artificial gravity without fluctuations that could affect crew comfort. Long-term sustainability considerations have influenced every aspect of the design. The reactor core is engineered for a minimum operational lifespan of ten years before requiring refueling, with potential for extended operation through careful fuel management. Modular design elements allow for future upgrades or replacement of components as more advanced technologies become available, ensuring the power system can evolve alongside the station's growing needs.

This comprehensive nuclear power solution enables the Aphrodite station to operate independently of solar proximity, providing reliable, continuous power for all systems regardless of the station's orbital position or orientation. The design's emphasis on safety, redundancy, and efficiency makes it not just a power source, but a foundational element enabling the station's ambitious scientific and exploration missions.

3b. Backup Solar System

Should the nuclear power system prove unfeasible due to technical or regulatory constraints, the Aphrodite station could instead rely on a solar power architecture modeled after the International Space Station (ISS), but scaled and optimized for its unique requirements. The station would deploy massive photovoltaic arrays, arranged in multiple symmetrical wings to ensure consistent power generation regardless of orientation. Each array would consist of high-efficiency, radiation-hardened solar cells—likely advanced multi-junction gallium arsenide (GaAs) panels—capable of converting sunlight into electricity at efficiencies exceeding 30%, a significant improvement over the ISS's older silicon-based technology. These arrays would be mounted on rotating gimbals, allowing them to track the Sun continuously and maximize energy capture, even as the station rotates to maintain artificial gravity.

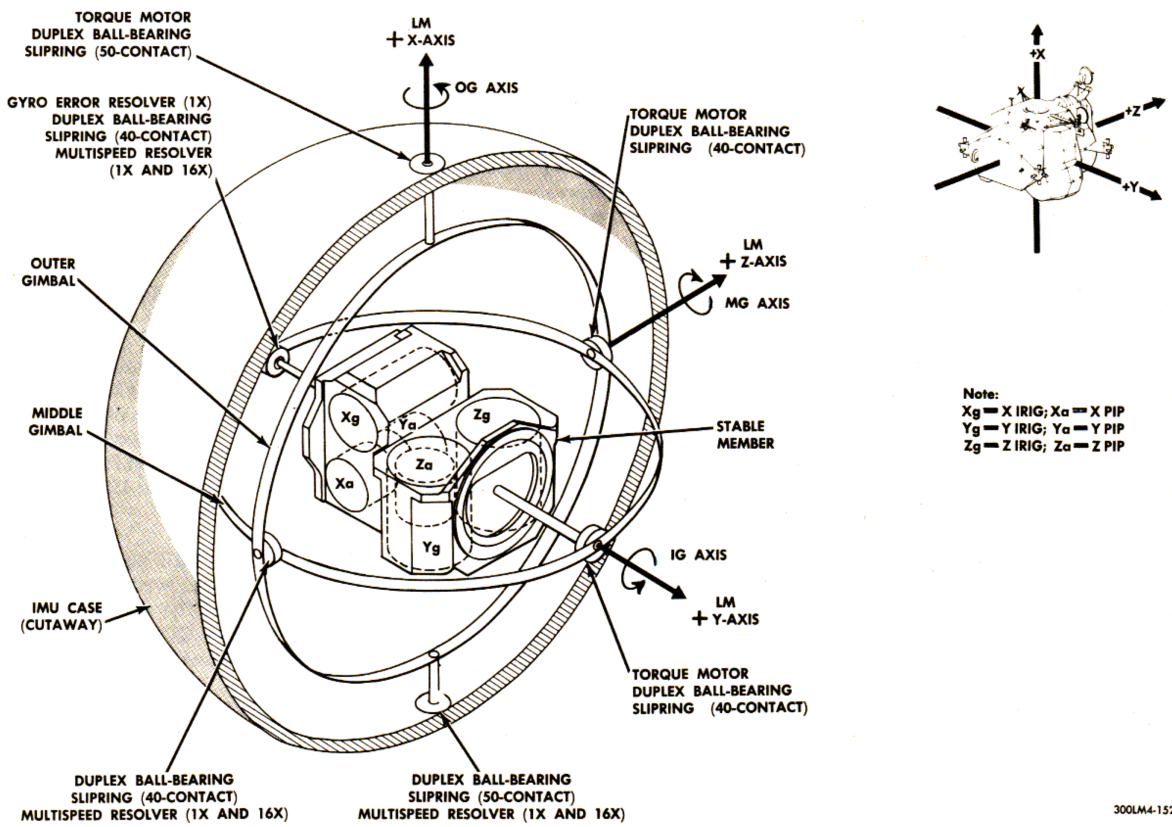


Fig. 21 - Rotating Gimbal System

Power distribution would follow a modular design, with each solar wing feeding into a decentralized network of lithium-ion battery banks that store excess energy during sunlit periods and discharge during orbital eclipses. Unlike the ISS, which experiences 45-minute night cycles in low Earth orbit, Aphrodite's higher orbit or deep-space location might necessitate larger battery reserves or alternative storage solutions, such as flywheels or regenerative fuel cells, to handle longer periods without sunlight. The electrical system would employ a high-voltage bus (likely 120V DC, similar to the ISS but potentially higher for efficiency) to minimize transmission losses across the station's sprawling structure. Thermal management would be critical, as the solar arrays and power electronics generate significant waste heat. To mitigate this, the station would use an active cooling system with ammonia-based fluid loops—like those on the ISS—to transport heat from the arrays and electronics to dedicated radiator panels. These radiators would be strategically positioned to avoid shadowing from the solar wings and would employ variable-emissivity coatings to optimize heat rejection in changing thermal environments. This is further described in the thermal systems section.

While this solar-based system could theoretically meet Aphrodite's power needs, it would come with major compromises. The station's artificial gravity mechanism, life-support systems, and scientific payloads would demand far more energy than the

ISS's requirements, necessitating enormous solar arrays—potentially spanning thousands of square meters—to compensate. This would introduce substantial mass penalties, increased vulnerability to micrometeoroid impacts, and greater complexity in station-keeping maneuvers. Moreover, in deep-space missions beyond Mars, where sunlight is drastically weaker, solar power would become impractical, forcing reliance on nuclear systems regardless. Thus, while an ISS-derived solar architecture could serve as a backup for near-Earth operations, it would ultimately fall short of enabling Aphrodite's most ambitious deep-space exploration goals.

E. Thermal Systems

The thermal system of Aphrodite I will exist to limit the internal temperature of the space station to a range of comfortable living degrees while making sure all mechanical components stay within their operating temperature limits. This will be accomplished using several passive and active elements detailed below.

1. System Requirements

Table 9 Passive Thermal System Requirements

Req. ID	*Mission Requirement (PTCS Shall)*
PTCS-1	Reduce internal heat fluctuation in permanent modules to ∓ 5℃ for one orbit with no assistance from the ATCS.
PTCS-2	Reduce internal heat fluctuation in inflatable sections to ∓ 10℃ for one orbit with no assistance from the ATCS.
PTCS-3	Be heavily resistant to micro-impacts with orbital debris.
PTCS-4	Have low emissivity and low solar absorption.
PTCS-5	Be easily repairable, should orbital debris damage anything.

Table 10 Active Thermal System Requirements

Req. ID	*Mission Requirement (ATCS Shall)*
ATCS-1	Be able to extend and collapse radiators on demand.
ATCS-2	Allow full control of permanent module internal temperature between 15℃ and 28℃, ∓ 2℃.
ATCS-3	Allow full control of inflatable module internal temperature between 10℃ and 32℃, ∓ 5℃.
ATCS-4	Interface and regulate all other subsystems within safe operating temperatures.
ATCS-5	Circulate air within modules such that air stagnation pockets are avoided (in tandem with air recycling units).
ATCS-6	Be modular such that the modules can be regulated independently.
ATCS-7	Contain all systems necessary to radiate excess heat into deep space.
ATCS-8	Be manually and remotely operated from a ground station.

2. Verification and Validation Methodology

The thermal control system that has been designed for Aphrodite I was created based on designs used in the ISS, with some modifications to make the system suitable for rotation and the new architecture. The NASA passive control engineering guidebook [13] was referenced heavily to learn more about coatings, coverings, insulation, reflectance, albedo, emissivity, and impact resistance. Reference [18] and many others cited were used to implement the radiator design. Although it uses a similar concept of operations, the thermal control system in Aphrodite I will be much safer and much more reliable than the system used in the ISS. With much more efficient technology now available, efficiency will be greatly improved. As discussed in the *Thermal Systems Design* section, many choices were made to adapt the large radiator panels to the rotating station.

Once Aphrodite I is constructed, the success of the thermal control system will be validated by making sure that the primary requirements, ATCS-2 and ACTS-3 are met. Once those objectives have been confirmed, the rest of the requirements must be systematically tested and monitored to determine that all systems are functioning as intended. In addition, the crew will have access to NASA's thermal control requirements, which will provide general limits that the system must operate within.

3. Thermal Systems Design

The thermal system is broken down into two main categories: active and passive regulation. The passive thermal control system is composed of the outer coatings and the general structure of the space station, which are designed with thermal fluctuation in mind. The exterior of the structure will be made to absorb as little energy as possible (in the form of heat) from the Sun and the reflection of Earth. The active control system combines large collapsible radiators, heat exchangers, and fluid loops to transfer the internal heat of the station out to deep space.

3a. Passive Control System

The entire station will be covered in materials that prevent radiation from drastically fluctuating internal temperatures of the station, while also providing high impact resistance. The solid modules of the station will integrate a Whipple shield that will function to both insulate and protect the main structures against debris. Additionally, this Whipple shield will be made with Micro-Meteoroid and Orbital Debris (MMOD) protection made of a material that has low solar absorption, such as reflective, white, Kevlar, Mylar, or Dacron. The Whipple shield is composed of many layers, and there will be an additional layer of insulation between the shield and the primary module wall. Despite great external temperature fluctuation, the passive thermal structures will regulate internal temperature fluctuation to a minimum stated in the requirements. The inflatable modules will be made completely out of MMOD protective material. The walls will have multiple layers of material, with space in between them, similar to a Whipple shield. These inflatables will be repairable from the inside and the outside by using patch kits that will go up with the station. Featured below is an image of a Whipple Shield after being hit by debris.

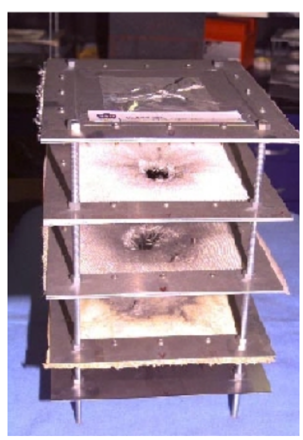


Fig. 22 Whipple Shield

3b. Collapsible External Radiators

The only way to transfer heat in space is through radiation, and to take advantage of this fact, large collapsible radiators will be mounted radially to the primary modules of the station. These radiators will remain collapsed while the station is accelerating, such that they experience minimal uneven loading. Once the station is accelerated to speed, the radiators will extend radially outward, with their panels facing into deep space. Internal fluid loops will transfer the heat from the inside of the station to external fluid loops running through the radiator panels. The heat from the fluid will conduct into the radiators, where it will then radiate outwards. The radiators will be made of extremely lightweight metal alloys and will be coated in a material that reflects radiation but allows for heat to leave the fluid loops. The figures below show preliminary models of what the radiators will look like in their collapsed and extended forms.

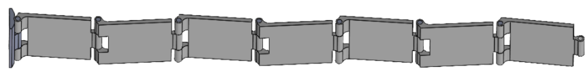


Fig. 23 Extended Radiators

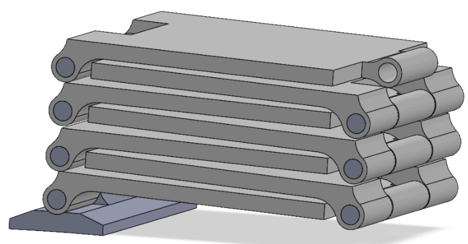


Fig. 24 Collapsed Radiators

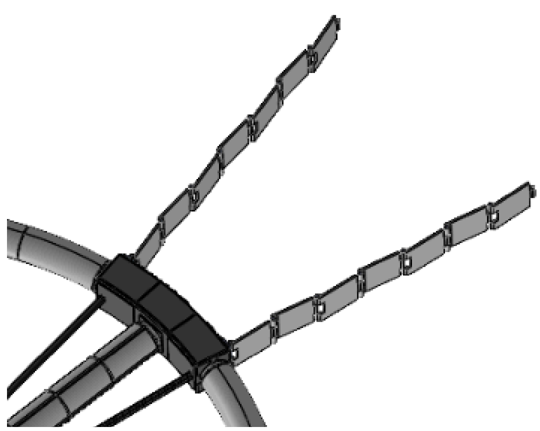


Fig 25- Radiators Attached to Module

3c. Fluid Loops/Heat Exchangers

Each permanent module will have over 30 meters of rigid internal water piping and over 60 meters of flexible external ammonia piping. The water will be pumped around the module, interacting with the heat exchangers and air filtration systems to remove excess heat from the air. The water will also be pumped across critical components such as computers to cool them down. The heat from the water will be transferred to the external ammonia loop via another heat exchanger. The ammonia will then flow through the radiators, where the radiators will absorb the majority of the energy from the ammonia. Water and ammonia have been selected because water is non-volatile and non-toxic to the astronauts aboard, and ammonia has a low freezing point and will not obstruct the external loops. A similar system has already been tested on the ISS, but this system will feature an external heat exchanger for the water and ammonia loops. Since ammonia is dangerous, a breach of the loop into the module would be catastrophic for astronauts and would likely end the mission. Thus, the heat exchanger will be able to be fully sealed off from the system if need be. As an additional countermeasure, each primary module will have its own fluid loops, heat exchangers, and radiators such that they can operate independently.

3d. Inflatable Modules

The ATCS of each primary module will be able to pump excess air into the inflatable modules, maintaining a constant circulation of air. Although due to complications with the inflatable module airlocks, the thermal regulation of the modules will not be nearly as accurate as in the primary modules.

F. Aphrodite Autonomos Arm (AAA)

The Aphrodite Autonomous Arm will be a critical component for constructing and maintaining the space station. It will be over 21 meters in length, and 8 axis movement. The several attachment points across the station on each permanent module will allow the arm to "walk" around by attaching one end and detaching the other. The AAA will be launched with the command module in the first launch.

1. System Requirements

Table 11 AAA Requirements

Req. ID	*Mission Requirement (AAA Shall)*
AAA-1	Able to attach and detach to multiple anchor points across the station at will.
AAA-2	Secured to the station by at least one end effector at all times.
AAA-3	Able to rotate in 8 axes.
AAA-4	Manipulate objects up to 30,000Kg with under 10mm accuracy.
AAA-5	Circulate air within modules such that air stagnation pockets are avoided (in tandem with air recycling units).
AAA-6	Able to move around the station by securing both end effectors, releasing one of them, and placing the free effector on the desired anchor.
AAA-7	Stored on the central module of the station when not in active use.
ATCS-8	Freely move attached crewmembers to assist during spacewalks.

2. Verification and Validation Methodology

The design of the AAA was heavily inspired by the European Robotic Arm [16] currently installed on the International Space Station. In-depth research was conducted to learn more about the design choices made on the ERA so that the AAA could be more suited for Aphrodite I. The AAA features three primary length segments, with two elbows, where the ERA only has two length segments and one elbow. The addition of an extra elbow and an extra segment will provide the AAA with much more flexibility and length than the ERA. The ERA is only about 11.3 meters when fully extended, so the AAA is just about 10 meters longer.

Other research on autonomous arms used for CNC and assembly machines were studied as well to learn more about joints and rotation degrees of freedom [4] [12]. Some of these machines are extremely robust; they feature joints with up to five degrees of freedom and immaculate precision. However, instead of using a single joint that allows for three or more axis rotation, the AAA only features joints that have one axis of rotation each. This is because separating the axes into various joints allows for more even load distribution across the joints, which will lead to more longevity in the long run. Additionally, since each joint is rigid in all but one axis, the arm can reliably carry much more weight without torquing any of the joints out of place. Lastly, if the AAA were to fail, it would only lose one axis of rotation at a time, instead of three, and the joints could be replaced. So, despite more complex joints existing on smaller scale machines, it makes more sense to design the AAA with simplicity first.

Once the AAA is constructed, it will be validated by manual operation first. After the first launch, only the central hub, the AAA, and two inflatables will be in orbit, so the ground operators will be able to test the arm with minimal worry of damaging any of the more fragile structures. This will allow the most critical requirements AAA-1, AAA-2, and AAA-3 to be validated.

3. AAA Design

The joints of the AAA allow for 8 axes of rotation, as shown in the figure below. The end effectors will use an internal clamping design that allows them to grasp objects without risking puncture or damage on the station. As labeled in the figure, the total stretched length is just above 21 meters, enabling the arm to easily reach the furthest points of the station. The arm will function extremely slowly, a few centimeters every minute, so that it can move objects over 22,000Kg in mass.

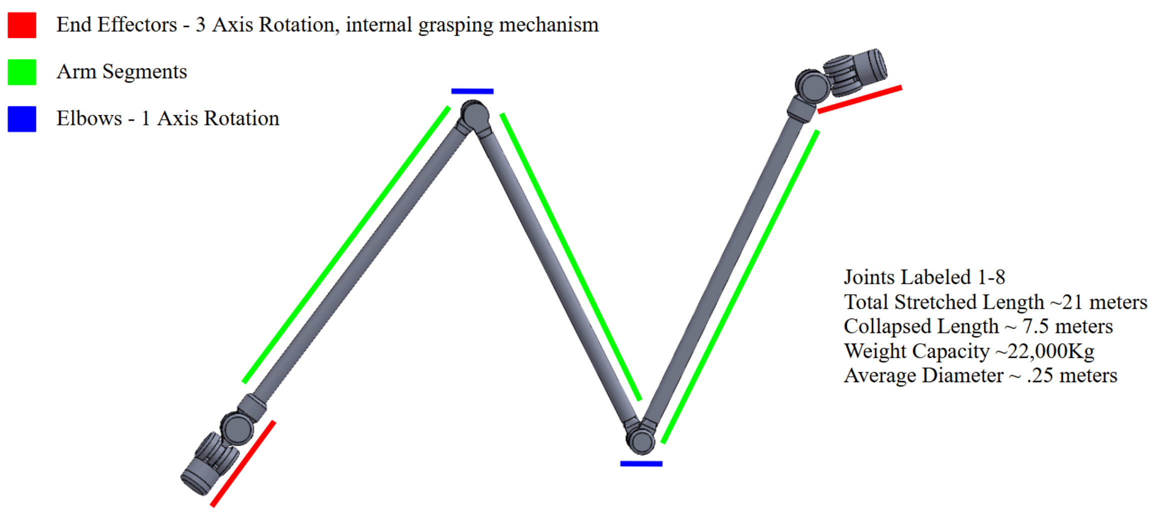


Fig. 26 AAA Architecture

G. C&DH / TT&C

1. System Requirements

Command and Data Handling (C&DH) and Telemetry, Tracking and Command (TT&C) are both crucial systems for ensuring the safety of the crew members and the transfer of essential data from aboard the spacecraft. These communication systems requirements are established for the current mission of Aphrodite. For future missions, and potential long distance missions, these requirements must be altered accordingly.

Table 12 C&DH/TTC System Requirements

Req. ID	*Mission Requirement*
TTCS.1	Communication between the spacecraft and ground network shall be constant, negating celestial interference.
TTCS.2	The communication delay between the spacecraft and ground control shall be within 5 minutes
TTCS.3	Shall maintain acceptable download and upload rates
TTCS.4	Shall have variable available bandwidth
TTCS.5	Shall be able to operate autonomously
TTCS.6	Shall operate while being energy efficient
TTCS.7	Shall keep transmission secure

2. Verification and Validation Methodology

There are several ways that this system will have to be validated before and after launch. Because of the initial missions' similarity with the International Space Station, proper compliance with standards will be kept. These standards will come from the ITU, which will regulate and involve spectrum, orbit, and security management. While the CCSDS standards are not mandatory, it would be in Aphrodite's best interest to implement most, if not all of their standards. This will allow ease of use in the future, especially as Aphrodite looks towards interplanetary travel.

The hardware will have to be tested and designed such that it can withstand the harsh conditions of space. For the first phase of the Aphrodite mission, the temperatures and radiation will cause some considerations to be made. Performing environment testing will ensure that the system is safe for human usage in Earth orbit and later for deep space exploration. At an individual level, each part of the system should be tested and benchmarked to find noise figures and bit error rates. Simulations can be used to find end-to-end communication with ground stations. The crew members should be familiar with the systems themselves so testing and training with the interactable modules is necessary. This training includes emergency fail-safe procedures as well as ease of access and emergency usage. Finally, once the satellite is initially assembled in orbit, the system should be tested to ensure that constant communication with ground stations are established and secure.

3. C&DH/TTC System Design

Having constant access to ground stations and other systems aboard the spacecraft is necessary to the success of the mission. Additionally, having adequate upload and download speeds are necessary for keeping the crew, ground station, and other systems well informed. Because of this, for data transmission and reception, the spacecraft and ground stations will be using the K_a-band. This band selection allows for higher data rates as opposed to the traditional X-band. However, one aspect that needs to be addressed is the weather attenuation. Because of the natural frequency of water vapor, the K_a-band needs to travel through a relatively dry medium. This creates a problem when considering where to select ground stations. In order to preserve the signal, the ground station will be kept to three strategic locations: Yuma, Arizona, Spanish Canary Islands, and Ahmedabad, India. These three locations were selected for three reasons: weather conditions, inclination, and United States relationship. It is clear why each of these factors are crucial for the success of the project.

Yet another down-side of the K_a-band frequency is its inability to perform well in deep space. Lower frequencies are better suited for this purpose. Despite this, the data rate makes up for this reason. Because this spacecraft is in earth orbit, this is not a problem, however for later stages of Aphrodite, this may be a concern. To combat this, cubesats could be implemented to ensure the distance between transmission and reception is still viable for K_a-band usage.

The figure below shows a visual representation of the step-by-step process for the TTC system. Each block represents a stage that is either performed by hardware or software aboard the spacecraft or ground station.

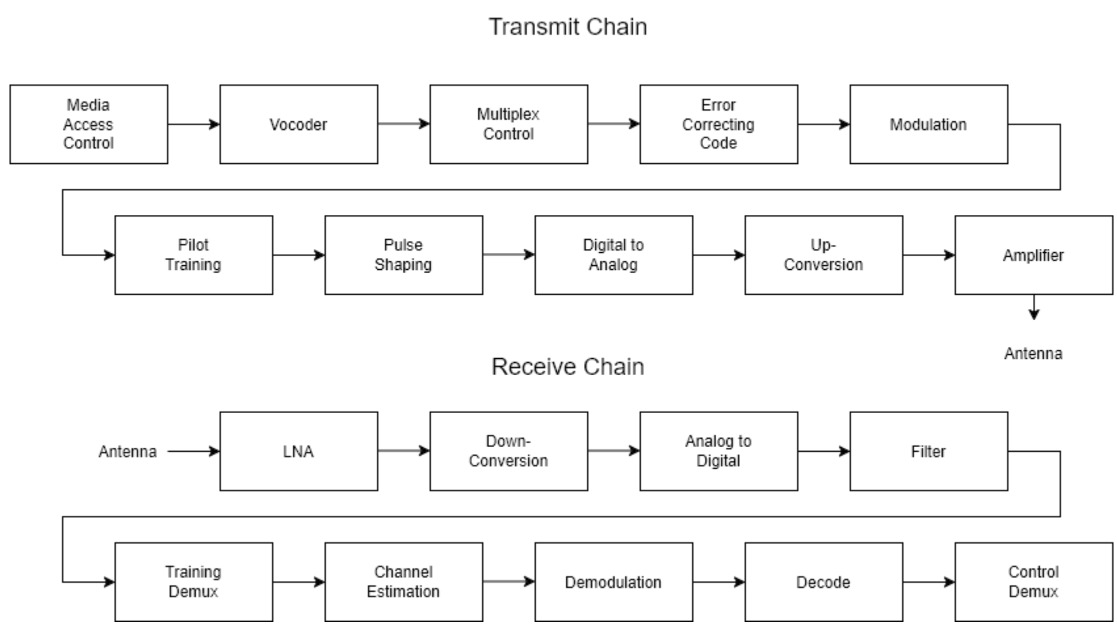


Fig. 27 Transmit and Receive Chains

For command and data handling, the initial system will read data and ensure that all other systems are operating and sustainable. C&DH is responsible for sending the proper data and instructions from the ground station to their proper destination. Moreover, certain information regarding each system is timestamped and either sent into onboard storage or to be interpreted on the ground station. Aphrodite I can rely on most of the computations to be done on ground, meaning the computing power needs to be substantial but nothing unrealistic. The RAD750 from BAE Systems, a radiation hardened CPU, will perform all of the necessary computations onboard. For future stages of the Aphrodite project, this may become an issue for a manned spacecraft. When traveling to other planets, the time it takes the signal to reach Earth and back will be far too long for essential operations. Future technology may have to be implemented during future resupplies that allows more processing power than the current models.

For data storage aboard the spacecraft, both volatile and nonvolatile memory is needed. Mass storage devices preserve all essential information which includes the information from gravity and other various experimentations, as well as the telemetry. The MIL-STD-1553 databus proves to be an effective way to get the information from command to each system because of its efficient management of numerous devices.

H. ADCS / GNC

1. System Requirements

The system requirements for the attitude determination and control system as well as the guidance, navigation, and control system are shown below.

Table 13 ADCS / GNC Requirements

Req. ID	*Mission Requirement*	*V&V*
ADCS.1a	The spacecraft shall have a means of determining translational and rotational motion in space	T/D
ADCS.1b	The ADCS shall employ 2 star sensors and 2 earth sensors.	T/D
ADCS.1c	The ADCS shall incorporate an IMU and GPS	T/D
ADCS.2a	The spacecraft shall have actuators capable of correcting attitude	T/D
ADCS.2b	The spacecraft shall utilize thrusters for initial spinning and momentum dumping	T/D
ADCS.2c	Control moment gyroscopes shall maintain desired angular speed and make small attitude adjustments	T/D

Determining the translational and rotational motion of Aphrodite is extremely important to verify that all other subsystems are operating intentionally. For instance, managing the angular velocity of the station ensures that life support systems behave as intended. Furthemore, Aphrodite will be placed in LEO, which contains other satellites and space debris that can be harmful to the station. Tracking the relative positions of these objects is important, but more so is knowing the trajectory of Aphrodite so early adjustments can be made. For correcting attitude, actuators have to be included on the vessel. Control moment gyroscopes were utilized by the ISS for their powerful torque generating capabilities and power efficiency. For redundancy, RCS thrusters will also be implemented for rapid attitude correction and translational correcting maneuvers.

2. Verification and Validation Methodology

The entire ADCS system shall be thoroughly tested and demonstrated to work in environmental simulations. The sensors shall be calibrated and functionally tested in simulated space conditions (ADCS.1a-c). Actuators such as the CMGs and thrusters will be activated in test environments to observe and confirm their component-wise performance (ADCS.2a-c). Then, the sensors and actuators will be assembled as a system and tested on a rotating platform to ensure the desired performance under operating conditions.

3. ADCS/GNC System Design

Aphrodite will employ six visual sensors, an IMU, and a GPS for attitude detection. These components will then communicate their data with the on board computer in order to calculate the exact position of Aphrodite in space, as well as the trajectory and motion of the space station. The visual sensors selected will be two sun sensors and two earth sensors, as well as two star sensors for determining attitude while eclipsed [16]. Two of each type of sensor are included for redundancy in the case that one sensor is not operational. The GPS and IMU will also need to be specifically designed for spaceflight and be radiation hardened. Units such as the STIM377H inertial measurement unit from Sensonor would be ideal for this mission. The on-board computer will be contracted through Honeywell, with a processing capability of 152 DMIPS with up to 32MB of radiation hardened SRAM and 4MB EEPROM. The main command interface is MIL-STD-1553.

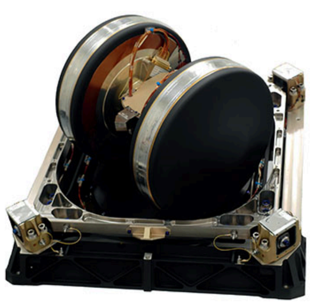
For actuators, CMGs will be employed in a similar arrangement to the ISS. A variety of available CMGs were trade studied, the results of which prove that the Airbus 75-75 S is the optimal choice. This CMG has a maximum torque of 60 Nm, which is well below the capabilities of the ISS CMG system. To make up for this, four 75-75 S CMGs will be arranged in the reaction wheel assembly to increase the torquing capabilities of the actuators. Furthermore, the 75-75 S has a maximum momentum storage capacity of 75 Nms, which means that momentum dumping will have to be considered. RCS thrusters will be incorporated into the ADCS system, however the main purpose of these is for rapid attitude correction or translational avoidance movement. To save fuel, they should only be used for momentum dumping if absolutely necessary.

Table 14 CMG Trade Study

	Weight	Normalized Weight	75-75 S	40-60 S	15-45
Sys. Cost	2	0.1	5	5	5
Size/Mass	2	0.1	4	5	5
Power Usage	4	0.2	4	5	5
Max. Momentum Storage	5	0.25	3	2	1
Max Torque	5	0.25	3	2	1
TRL	2	0.1	5	5	5
Total	20	1	3.7	3.5	3

Table 15 Airbus CMG 75-75 S Specifications

Mass	69 kg
Dimensions (LxWxH)	550 x 390 x 250 mm
Peak Power	160 W
Max Momentum Storage	75 Nms
Maximum Torque	60 Nm



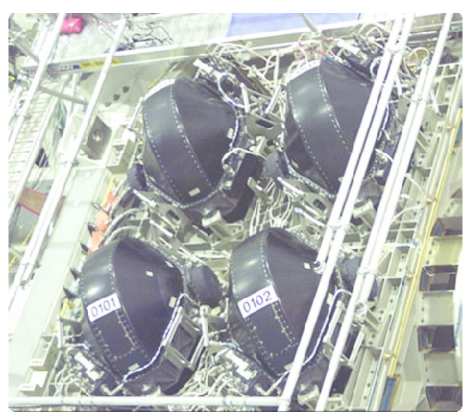


Fig. 28 Airbus 75-75 S (left) and ISS arrangement of CMGs (right)

As mentioned, RCS thrusters will be utilized and incorporated into the ADCS subsystem, however the selection and location of the thrusters is more appropriate under section I.

I. Propulsion

1. System Requirements

The propulsion system requirements of Aphrodite are as follows,

Table 16 Propulsion Requirements

Req. ID	*Mission Requirement*	*V&V*
P.1	Spacecraft shall utilize thrusters to reach desired angular velocity.	T/D
P.2	Spacecraft shall have thrusters to avoid major collisions with other satellites and debris.	S/M
P.3	Each component shall have thrusters enabling movement in 3 translational degrees of freedom.	T/D
P.4	The spacecraft shall have 60 m/s of DV partitioned to maneuvering per 100 days.	S/M
P.5	The fuel temperature shall be maintained between 10℃ and 50℃ while in storage.	T/D

Essentially, Aphrodite will be utilizing RCS thrusters to make quick rotational and translational maneuvers when needed. Since Aphrodite will be operational in LEO, the threat of collisions with other satellites or space debris is probable. The use of thrusters allows Aphrodite to independently alter its orbit and avoid dangerous impacts. Furthemore, the thrusters will be utilized in the initial spinning of the station. Since Aphrodite will only contain fuel for a maximum velocity increment of 60 m/s, the propulsion system will not actively participate in the orbit raising procedure. The temperature requirement in P.4 is derived from the RCS thrusters and fuel described in G.

2. Verification and Validation Methodology

P.1 shall be tested by prolonged engine firing in a vacuum chamber until the hypothetical angular velocity has been reached. This verifies that each engine is capable of making the necessary maneuver. P.2 can be verified by simulating maneuver capabilities using orbit prediction and maneuver planning tools. This can be tested by executing planned avoidance maneuvers in a virtual environment simulation. P.3 is verified by inspection of the schematics and ensuring thrust vectoring along all six translational degrees of freedom. P.4 is verified through the use of propulsion performance data and budget calculations. Finally, P.5 is verified through vacuum and thermal testing of the insulated fuel tank.

3. Propulsion System Design

Monopropellant thrusters are utilized to reduce the storage space of propellant onboard the craft. A trade study of three high thrust engines are below,

Table 17 RCS Trade Study

	Weight	Normalized Weight	RACS 220N	22N HPGP	200N HPGP
Sys. Cost	2	0.1	4	4	4
Fuel Cost	5	0.25	4	4	4
Max Thrust	4	0.2	5	1	4
ISP	5	0.25	3	3	5
Mass	2	0.1	3	5	5
TRL	2	0.1	5	5	5
Total	20	1	3.95	3.35	4.45

Among the three chosen, the ECAPS 200N HPGP RCS thrusters are the best fit. The specifications of this thruster are as follows,

Table 18 RACS 200N RCS Specifications

	Thruster Properties		Fuel Properties
Thrust	50-200 N	Fuel Type	LMP-1035
I_{sp}	206-234 Ns/kg	Freezing/Boiling Point	-90/120 C
Steady State I_{sp}	2020 - 2300 Ns/kg	Qualified Operating Range	10 to 50 C
Min. Impulse Bit	9 Ns	Density	1292 kg/m^3
Length	390 mm		
Mass	6 kg		

Aphrodite will incorporate the 200N HPGP thrusters in omni-directional RCS blocks. The blocks will be placed along the CCM in four-way symmetry with the line of thrust running longitudinally and latitudinally along the station. While rotating, these thrusters are utilized purely for the sake of maneuvers in the nadir or zenith directions. Since the station is constantly spinning, the timing required for prograde, retrograde, port or starboard translational maneuvers requires an advanced propulsion control algorithm. In order to save fuel, energy, and points of failure, Aphrodite will be restricted to nadir and zenith burns once spinning unless it is deemed necessary to avoid an obstacle. Likewise, these blocks will be placed along the OCMs. The blocks will be responsible for the initial spinning of the station as well as providing rotational thrust vectoring if necessary.

The HPGP thrusters utilize LMP-1035 monopropellant. This fuel is required to be kept at a temperature between 10 and 50 C. Therefore, the fuel must be kept in a thermally insulated and temperature regulated fuel tank. This fuel tank is isolated within the CCM with a propellant feed system connecting each RCS block to the main tank.

Like the main tank, these pipes are thermally insulated to prevent the propellant from reaching a dangerously high or low temperature while being partitioned.

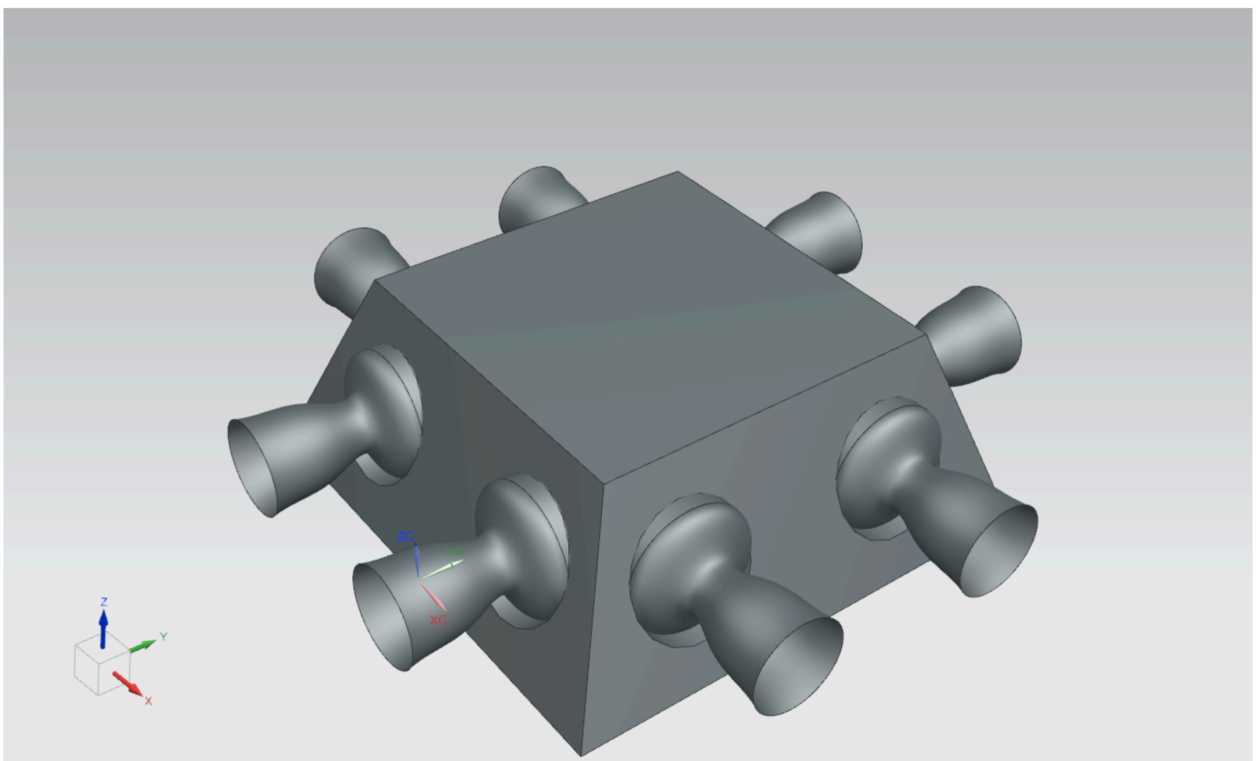


Fig. 29 RCS Block Assembly, featuring 8 200N HPGP Thrusters

The size of this tank must be large enough to store at least 60 m/s of ΔV for the 100 day mission lengths. This is calculated through the Tsiolkovsky rocket equation,

$$\Delta V = V_{eq} ln(\frac{M_f + M_p}{M_f}) \tag{2}$$

Solving for M_p, the required mass of the propellant, yields 24,140 kg. From the density of LMP-1035, this mass can be contained with a cylindrical tank with a diameter of 5 meters and height of 1 meters. As previously stated, this will be housed within the CCM.

J. Orbital Logistics

1. System Requirements

The orbital requirements for Aphrodite I are as shown in table X.

Table 19 Orbital Requirements

Req. ID	*Mission Requirement*	*V&V*
OP.1	The station shall be assembled in circular orbit at an altitude of 390 km.	S/M
OP.2	Aphrodite shall have an inclination of 35 degrees to enable rendezvous with starships launched from Boca Chica.	S/M
OP.3	The station shall be assembled within 6 months (180 days).	T/D
OP.4a	After assembly and operation verification, Aphrodite I will be raised to a circular orbit of 450 km.	S/M
OP.4b	The orbit raising and station keeping of Aphrodite I shall be performed by an auxiliary spacecraft	T/D

The main constraint for the orbit is based on the in-space assembly of the station. Aphrodite will be launched on four separate launch vehicles and berthed in LEO. This results in 3 separate docking procedures, which will take at least 6 months to complete (OP.3). Thus, the station must be launched to a height that its altitude will not recede towards the Karman line during its assembly. The predicted orbital decay of the overall station is conducted below, in H.4. This, along with mission requirement MR. 1, justifies the station orbital altitude of 450 km. However, the discrepancy between the assembly altitude and operational altitude is significant. Due to Aphrodite's lack of a main thruster, an auxiliary spacecraft will be commissioned to boost the station via a hohmann transfer.

Because of the partnership and decision to utilize the Starship Cargo configuration as the launch vehicle, the inclination of the space station is one that facilitates easy launch trajectory and rendezvous from Starbase in Boca Chica. This reduces the cost of fuel needed to adjust inclination, since the Starships will be able to launch into the orbital plane. This allows the assembly altitude to be higher than otherwise. This is also beneficial for the post-assembly hohmann transfer, as the velocity increment to raise the orbit is reduced.

2. Verification and Validation Methodology

All requirements pertaining to the orbital characteristics of Aphrodite are verified through the use of S/M. Specifically, OP.1, OP.2, and OP.4a can all be verified through the orbital maneuvering calculations. OP.3 will undergo T/D to verify that the AAA is capable of maneuvering the components from the launch vehicle and to the Aphrodite core in the appropriate time. This will be conducted in a simulated zero gravity environment so the AAA is in as relevant environmental conditions as possible. Furthermore, the assembly schedule is also reliant on the rate at which the Starships are able to be loaded, fueled, and launched. SpaceX will need to demonstrate their capability to achieve this within the allotted time. Likewise, OP.4b's verification relies on the commissioned orbit raising spacecraft. It needs to be demonstrated that this spacecraft has the means to reach Aphrodite's orbit, dock, and perform the desired burn. The specific velocity increment of this meaneuver is calculated in I.4.

3. Launch

Due to the enormous mass of the station, Aphrodite will be launched in five separate pieces on four separate launch vehicles. The initial launch will consist of the central control module and AAA. Then, the four crew modules will be launched over the course of two launches. The launch vehicle will dock with the CCM and be guided to its corresponding berthing port with assistance from the AAA. Finally, the fourth launch will contain the external reactor and collapsable radiators.

Over the course of four launches, each launch vehicle must be capable of moving at least 120000 kg. This heavily restricts the available launch vehicles to only two options. The SLS Block 2 and the SpaceX Starship. These underwent a trade study depicted below. The chosen study factors are weight, payload diameter bay, availability, reusability, and maximum payload weight.

Table 20 Launch Vehicle Trade Study

	Weight	Normalized Weight	Starship	SLS B2
Cost	5	0.28	5	2
Diameter	5	0.28	5	4
Availability	3	0.16	4	3
Reusability	3	0.16	5	3
Max Payload Weight	2	0.11	5	4
Total	18	1	4.79	3.08

The SpaceX starship is a better option for the aphrodite launch vehicle due to its reduced cost, larger diameter, and higher maximum payload to orbit weight. It is this trade study and the decision to utilize the Starship that facilitates the emphasis on establishing a partnership with SpaceX for the Aphrodite program. The diameter of the launch vehicle is an important factor as the launch configuration of the second and third starships will include two outer crew modules per vehicle bay. The Starships' nine meter diameter allows for this and reduces the number of launches by two, reducing the financial and environmental cost of the project.

4. Orbital Path / Station Keeping

As previously mentioned, Aphrodite will be assembled in LEO before being raised to a higher orbit. This will be done over the course of 6 months, which means that Aphrodite will need to be launched at a sufficiently high orbit to avoid orbit decay below the Karman line. According to Dr. Mathew Peet, the degradation of the semi major axis of an orbiting body due to drag is defined by,

$$\dot{a} = -\sqrt{a\mu}\frac{\rho}{B} \tag{3}$$

Where B is the ballistic coefficient,

$$B = \frac{m}{C_D A} \tag{4}$$

Assuming a constant ρ and integrating with respect to time yields [29]

$$a(t) = \left(\sqrt{a(0)} - 2\sqrt{\mu}\frac{\rho}{B}t\right)^2 \tag{5}$$

While ρ is assumed to be constant, the density of the exosphere is heavily dependent on various factors, including solar flux. As a result, the value of the density is difficult to predict. In order to get a safe estimate of the rate at which Aphrodite's orbit will decay, three separate densities are used which correspond to "low", "mean", and "extremely high" solar activity [14]. These tables are updated every 20 km in altitude, so once the altitude falls by 20 km, a new ρ is used from equation __, which reduces error in the calculation. The results of this exercise are in figure X below.

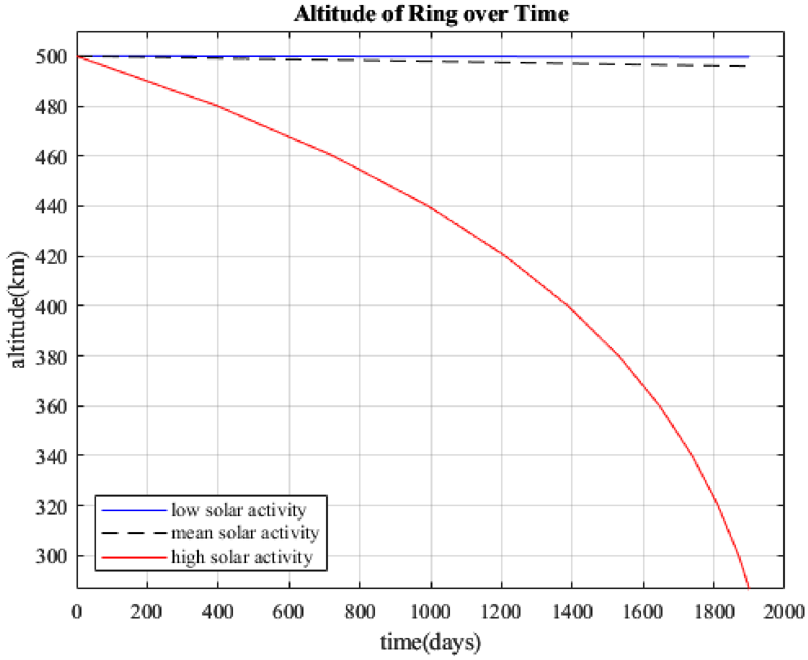


Fig. 30 Orbital Decay of Aphrodite during Various Levels of Solar Activity

Table 21 Atmospheric Density Values

Altitude (km)	Low Solar activity (10^{-13} kg/m^3)	Mean Solar Activity (10^{-13} kg/m^3)	High Solar activity (10^{-13} kg/m^3)
300	27.2	25.8	17.1
320	42.1	17.2	13.2
340	25.0	11.6	10.3
360	15.1	7.99	8.05
380	9.20	5.55	6.35
400	5.68	3.89	5.04
420	3.54	2.75	4.02
440	2.23	1.96	3.23
460	1.42	1.40	2.60
480	.920	1.01	2.10
500	.603	.730	1.70

The “extremely high” solar flux is not a common occurrence, but it is important to consider it for the assembly of the ring. During this six month period, orbit raising should be avoided if possible. This means that the solar wind should be monitored and the launch should be delayed if the atmospheric density is too high. In the case that the wind unpredictably reaches critical levels while assembly is occurring, the 390 km assembly altitude should prove high enough to prevent the orbit from falling below 340 km.

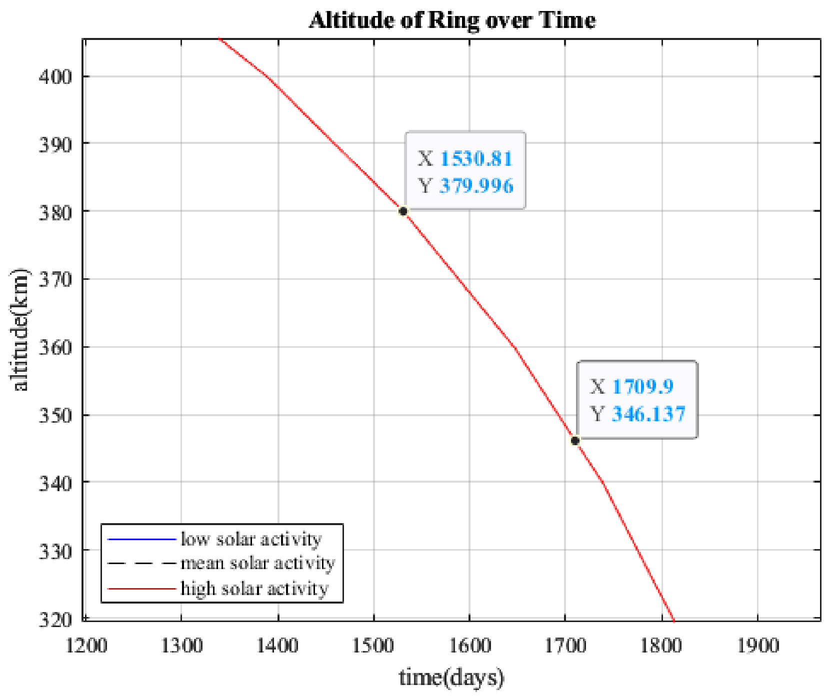


Fig. 31 Altitude of Aphrodite over six months (180 days) during high solar activity.

The velocity increment of a hohmann transfer is calculated in appendix III.D. Assuming that the ring remains at an altitude of 390 km during its assembly, it will need a velocity increment of 2.2 km/s to perform a hohmann transfer to the desired operational orbit of 450 km. Aphrodite’s propulsion system lacks the fuel capacity required to raise its own orbit by that amount, meaning an auxiliary spacecraft will have to dock with Aphrodite and help raise its orbit. This process will be similar to the ISS’s orbit raising procedures. The altitude of Aphrodite shall not fall below 400 km, which would happen the soonest after 500 days (at extremely high solar flux). Since a resupply vessel will rendezvous with Aphrodite every 100 days, this means that every fifth rendezvous will raise the orbit to the desired altitude. This vehicle must be capable of a 1.04 km/s burn, which is the velocity increment required for a hohmann transfer from 400 to 450 km.

III. Mission Management

A. Risk Mitigation

A risk matrix was created to visualize the critical mission points.

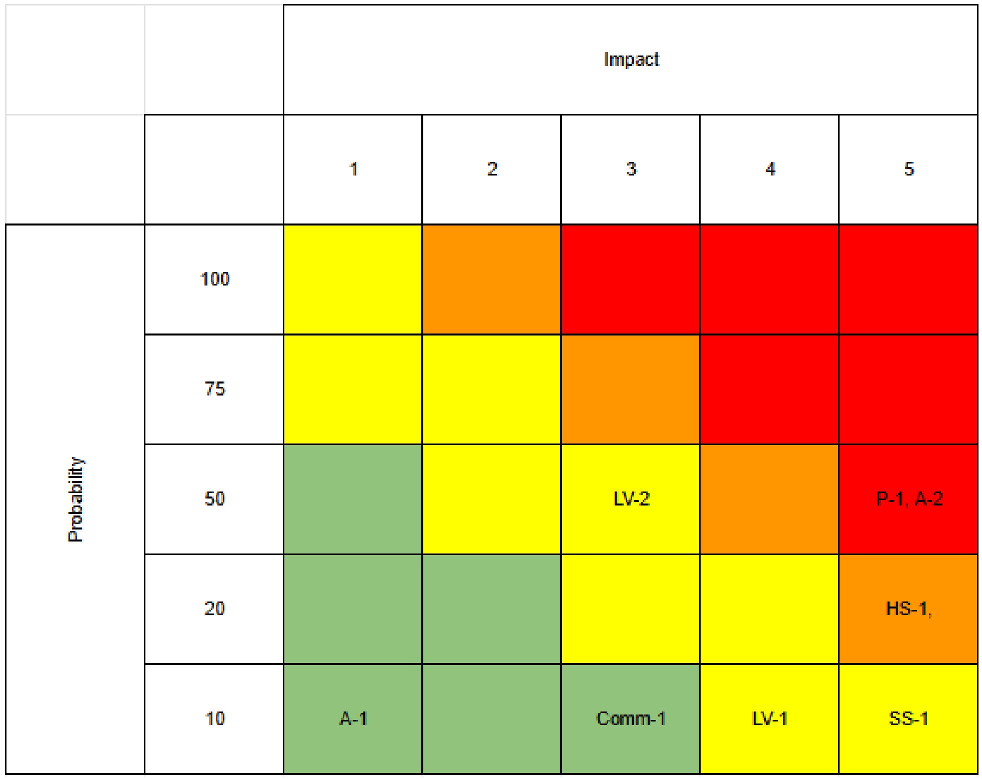


Fig 32. Aphrodite I Risk Matrix

Table 22 Risk Matrix Legend

Event Letter	*Event Description*
A-1	Spacecraft is unable to determine its attitude in space
LV-1	Launch Vehicle is not capable of moving payloads to orbit
SS-1	Spacecraft is unable to effectively dock
Comm-1	Spacecraft loses communications with Earth's station
LV-2	Launch vehicle over budget
HS-1	Human Systems failure results in dangerous living conditions for astronauts
P-1	The station cannot generate enough power
A-2	The station has an unintentional collision with debris or another satellite

To mitigate the higher probability and impact critical points, the team has decided on the following major actions for critical points P-1, A-2, HS-1, SS-1, and LV-2. Solar panels have been replaced with a nuclear reactor, which allows constant and consistent uptime of power generation, even during eclipse periods. This will lower the probability and impact factors of P-1. The nuclear power aspect does present alternate risks, such as radiation and power control. However, these can be mitigated in design by use of shielding and transformers. RCS has been implemented to provide the station means of evasion. Additional ground stations have been researched to provide constant communication uptime and ample warning time. This action lowered the probability of A-2. Redundancy and airlocks have been put in place in the event that life support or structural failure in one segment of the station occurs. This action lowered the probability of HS-1. The AAA has been developed in order to align and berth the components as they are launched. This lowered the impact for critical point SS-1. In order to reduce the number of launches, the components will be launched 2 at a time, halving the total number of launches. This lowered the impact and probability of critical point LV-2.

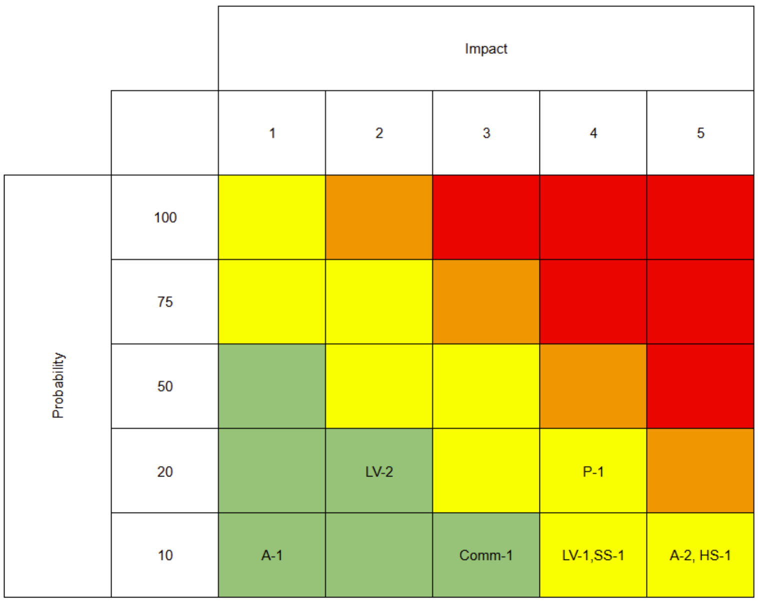


Fig 33. Updated Risk Matrix

The actions taken have reduced the overall impact and probability of our critical mission points. We feel confident in maintaining these positions if not lowering the outliers further. Life support or structural damage will always have an impact of the highest level due to the seriousness of the scenario and the fact that they will be in effect for the life of the station. The most effective means of mitigation for these critical points is lowering and maintaining a low level of probability.

B. Cost Estimation

The cost of Aphrodite is spread among various factors such as launch vehicles, ground facilities, operations and maintenance, and labor. At this stage in the design process, parametric modeling can be utilized to get a rough estimate of the cost of the program. By performing a linear regression analysis of the costs of other space stations and their weight, the cost of Aphrodite can be estimated. The selection of available space stations are limited, however there is a reasonably large sample size to perform this analysis.

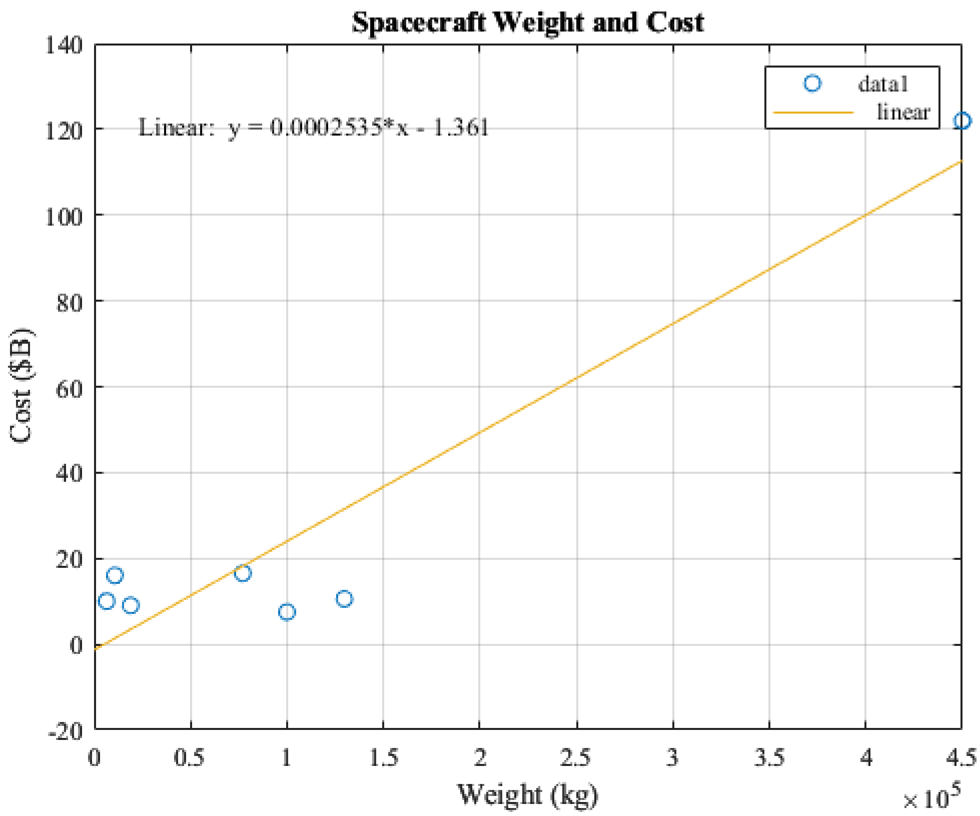


Fig. 34 Linear Regression of Space Vehicle Weight and Cost

Table 23 Space Vehicle Weights and Cost

Station	Weight (kg)	# of Launches	Adjusted Cost ($B)
Skylab	77,088	1	15
Hubble	10,800	1	16
JWT	6,500	1	10
Salyut 6	19,000	1	9
Mir	129,700	6	10.54
Tiangong Space Station	100,000	xxx	7.5
ISS*	450,000	40	122

* The price has been adjusted for 40 launches at a cost of $500M per launch [11]

The cost of each station is inclusive of wages, R&D, launch vehicle, and material costs. Naturally, the launch vehicle costs for the ISS will be a considerable portion of the overall cost. Since LV costs are already determined, these are factored out based on the number of launches each station needed to reach operational status, where applicable. Since the Aphrodite I incorporates new technologies, the inclusion of the Hubble and JWT functions to naturally skew the data to account for the R&D and V&V to reach flyable status. On top of this, the WBS is ranked according to its TRL and given a complexity factor. This is used to scale the importance of engineers within their jobs and how many engineers to delegate to each subsystem. Each engineer will be paid for an average of 2080 hours of work over the 10 year project at a rate of $160/hr. Using the weighted averages of engineer:complexity level, the overall complexity of the station is evaluated and scaled with the parametric modeling, excluding the launch vehicle.

Table 24 WBS Labor Assignment and Complexity level

CODE	Complex. Level	# of Engineers	Average CL	Sum of Salary ($M)
1.1 Propulsion	0.7	15	1.284	732.16
1.2 ADCS	1	15		
1.3 C&DH	0.7	5		
1.4 Structural	1.7	40		
1.5 Thermal	1.3	15		
1.6 Power	1.3	25		
1.7 TT&C	0.7	5		
1.8 Human Sys	1.3	100		

By totaling the weight of structures and components within the station and multiplying it by the overall complexity level, an upper estimate of the cost of the space station is achieved. This is represented through Eq. (6),

$$C_{total} = CL(W0.0002538 - 1.361) + C_{LV} + C_{labor} \quad (6)$$

The total weight of the structures and components, as well as the cost of the launch vehicle and labor are tallied below. For additional information, see the table in appendix II.A.

Table 25 Structural Weight and Cost Estimate

	Weight (kg)		Cost ($B)
Structures	205792	Labor	.73216
Components	100295	Launch Vehicle	0.4
Total	310489	Weight Cost	99.44
		Total	100.56

Once again, this is an upper estimate that factors in the cost of labor, ground stations, R&D, launch vehicles, maintenance, and more. Furthemore, the linear regression is over a very small number of space stations that had available weight and costs. Likewise, the cost of the MIR and Tiangong Space Station are reported from Russia and China respectively, which may have incentive to lie about the actual cost of their station to boost their perceived reputation.

C. Mission Timeline

The Aphrodite I design process spanned 9 months, from August 26th, 2024 until May 2nd, 2025. During this time, a few critical deadlines approached, specifically the Preliminary Design Review (PDR), scheduled near the end of the fall semester, and the Critical Design Review (CDR), which marked the culmination of the academic year. These reviews served as academic checkpoints as well as internal deadlines to ensure meaningful progress and validate the engineering decisions made up to those points. To navigate the complexities of the design process and maintain an organized workflow, the team implemented a Gantt chart. This visual planning tool allowed for a clear breakdown of tasks, assigned responsibilities, and an effective timeline that helped track progress, identify potential bottlenecks, and coordinate team efforts efficiently throughout the duration of the project.

ID#	Task	Assigned To	Progress	Start	End
1	Project Formulation		100%	8/26	10/9
1.1		INDIVIDUAL	☑	8/26	9/6
1.2	Team Org Chart	MANAGER	☑	9/4	9/11
1.3	Initial Design Discussions	TEAM	☑	9/6	9/17
1.4	Gantt Chart	TEAM	☑	9/9	9/18
1.5	Risk Chart	TEAM	☑	9/9	9/25
1.6	Requirement Chart	TEAM	☑	9/9	9/25
1.7	Preliminary Research	TEAM	☑	9/9	9/30
1.8	Schedule Margin			9/30	10/9
1.9			☑	10/9	10/9
2	Design		100%	10/7	11/4
2.1	Power Design Consideration		☑	10/7	1/30
2.2	TT&C/C&DH Design Consideration		☑	10/7	1/30
2.3	Structual Design Consideration		☑	10/15	1/30
2.4	Human Sys. Design Consideration		☑	10/15	1/30
2.5	Propulsion Design Consideration		☑	10/15	1/30
2.6	Thermal Sys. Design Consideration		☑	10/15	1/30
2.7	ADCS Design Consideration		☑	10/15	1/30
2.8	N^2 Diagram		☑	11/1	2/4
2.9	Human Sys. Flow Diagram		☑	11/1	2/4
2.10.	Work Breakdown Structure		☑	11/1	2/4
2.11	Physical Architecture		☑	11/1	2/4
2.12	Schedule Margin		☑	2/4	2/5
2.13	◆ PDR Presentation		☑	2/7	2/7

Fig. 35 PDR Schedule

Task	Assigned To	Progress	Start	End	Days	Margin
Analysis		100%	2/8	5/5	77	3
PDR Feedback	TEAM.	☑	2/14	2/17	3	1
Storage module design	STR.	☑	2/17	2/24	7	1
Final component selections	TEAM	☑	2/17	2/24	7	1
Final subsystem designs	TEAM	☑	2/24	3/10	14	1
Subsystem CAD models	TEAM	☑	2/24	3/10	14	1
System implementation	TEAM	☑	3/10	3/24	14	1
Full system CAD	TEAM	☑	3/10	3/24	14	1
Power and Heat Estimates	POW. THERM.	☑	3/24	3/31	7	1
ANSYS Structural	STR.	☑	3/24	4/14	21	1
ANSYS Thermal	POW. THERM.	☑	3/24	4/14	21	1
Future mission objectives	SYS.	☑	2/24	3/10	14	1
Risk Management	SYS.	☑	2/24	4/21	63	1
CDR Report	TEAM	☑	3/3	4/23	58	1
Create CDR Presentation	TEAM	☑	4/14	4/30	16	1
Schedule Margin		☑	4/30	5/2	2	2
◆CDR		☐	5/2	5/2	1	

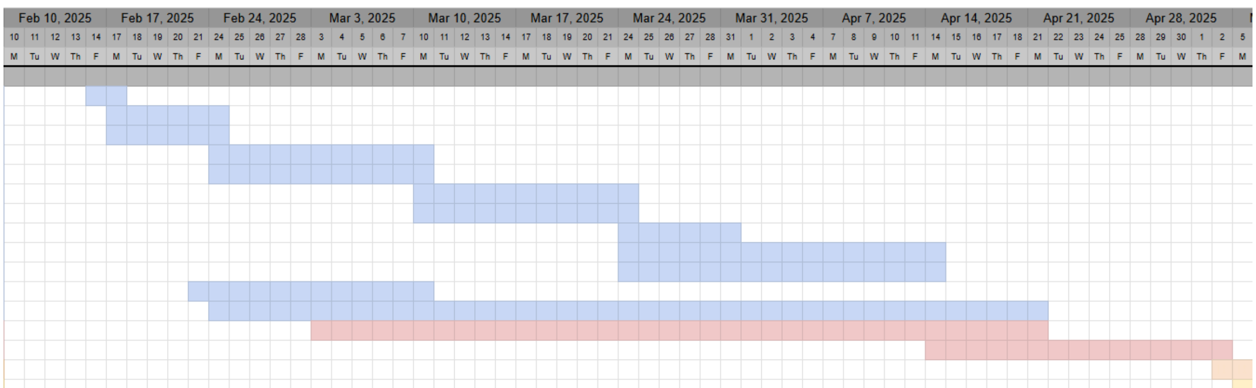


Fig. 36 PDR-CDR Schedule

In the future, the Aphrodite program plans to expound upon the lessons learned with Aphrodite I with more ambitious crewed missions. Aphrodite II, tentatively scheduled for 2045, will send astronauts on a highly elliptical orbit beyond the moon. This will be useful in verifying the radiation shielding and life support systems beyond earth's magnetic field. In later years, once the life support systems and radiation shielding is perfected, Aphrodite III will send astronauts on the first ever crewed flyby of a foreign planet. Specifically, Venus is chosen due to its relatively close proximity to Earth, as well as its low amount of fuel and time requirements to reach it. This will be the final verification of the Aphrodite program before Aphrodite IV, which will be a crewed mission to mars with the intent of establishing permanent orbital habitation infrastructure. It is the dream of Aphrodite to see mankind rebirthed into a space faring race and the first steps are in Aphrodite I and mankind's mastery over microgravity.

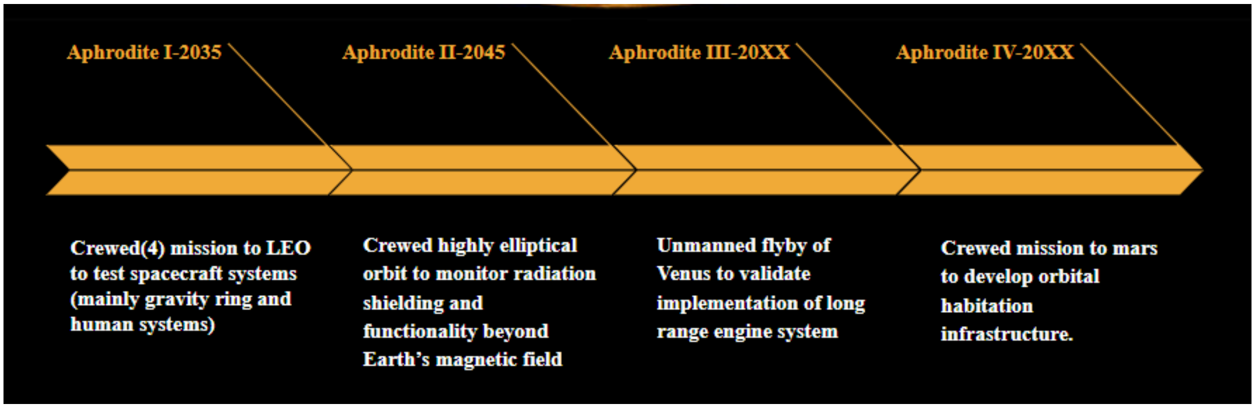


Fig. 37 Future Aphrodite Mission Schedule

D. Future of Aphrodite

This comprehensive report of Aphrodite I is not the final version of the project, but simply a proof of concept that the team can use to begin working. Many of the subsystems require large teams and thousands of hours of research and development before they can even be built. All of the subsystems, with an emphasis on structures, power, and human support, are nowhere near the level of detail that must be emphasized for this project to work. Going forward, the Aphrodite I team will fully split into sub teams and communicate with each other as needed. Handbooks will be created for each system, and each subsystem within that system. Everything down to the bedding thread count, light luminosity, and manufacturing technical drawings will be meticulously recorded. By the end of this project every detail will be completely fleshed out and ready for construction.

This is just the beginning of the Aphrodite Project. The first mission in pursuit of interplanetary habitation. Once Aphrodite I is built, the crew can begin research in artificial gravity. The artificial gravity generated by Aphrodite I should remove one of the largest problems posed by sustained space habitation - biological degradation. Aphrodite I will also provide an opportunity to do extensive research on state of the art radiation shielding, nuclear reactors, inflatable modules, and more. The applications of these technologies in space could prove to be boundless, and ensuring that the mission is handled one step at a time will guarantee long term success.

The Aphrodite team expects to see great success with the implementation of new space technologies once the station is constructed. Successful systems will be primed and ready to be implemented into spacecraft that will leave Earth's sphere of influence. The team already has plans to send a crew of astronauts into a highly elliptical orbit on a spacecraft that will be made using the best characteristics of Aphrodite I. Systems that prove to be lackluster or more problematic than initially expected will be revised and tested again, either on Aphrodite I or on a new craft. All the testing on Aphrodite I will enable the team to move forward towards Aphrodite II, III, and IV. The final goal of this ambitious project is to create a reliable means for humans to travel and inhabit Mars, and possibly orbits as well.

The original Aphrodite mission was a manned flyby of Venus, a goal that still seems far away. However, the current vision of Aphrodite will make calculated steps towards reaching that goal. With a road map in sight, the initial mission will be conquered by Aphrodite III, with plans to go even further during Aphrodite IV. Although Aphrodite was not able to accomplish what it was originally intended to do, the timeline and approach that has been adopted is much more reliable and appropriate for the current understanding of manned space travel. The Aphrodite project will continue to adapt as it progresses, doing everything one step at a time.

IV. Summary

Aphrodite I will be a habitable, rotating space station that will be assembled over the course of four launches at an approximate altitude of 390 kilometers. The AAA will completely assemble all of the major structures prior to crew arrival. The station will then enter a Hohmann transfer and elevate its orbit to 450 kilometers, where it will be kept. The primary highlights of this concept design are the human systems, structural systems, power systems, thermal control systems, C&DH/TT&C, ADCS/GNC, and propulsion systems. These pieces will all work harmoniously to enable a comfortable internal environment for a crew of four highly trained astronauts. After the completion of the station and the orbital raising, the crew will be sent to the station and conduct all the final checks and assemblies. Once everything is ready, Aphrodite I will slowly be accelerated to 9.8 meters per second squared, or “1g”. If necessary, the station will also be able to accelerate to nearly any factor of Earth’s gravity, providing more adaptability for research. Resupply will rendezvous with the station every 100 days, with every fifth resupply being able to attach to the station and restore the original orbit height. Inside of the station, research will be done primarily on the effects of artificial gravity for humans and other life forms. Aphrodite I will be a beacon of inspiration and progress as humanity approaches interplanetary habitation.

V. Appendix

I. Human System Requirements Additional Tables

Table 26 Human System Training Requirements

Req. ID	*Mission Requirement*	*V&V*
HS.CT.1	Crewmembers, flight surgeons, support personnel and mission control personnel shall be provided medical training	T/D
HS.CT.2a	Crew Members shall have training in general medical practices involving first aid, CPR, altitude physiological training, carbon dioxide exposure, familiarization with medical issues, procedures of spaceflight, physiological training, toxicology, and medical equipment	T/D
HS.CT.2b.1	Mission shall have two trained crew members assigned at Crew Medical Officers (CMO)	T/D
HS.CT.2b.2	CMOs shall be trained with specific medical training to deal with health issues, space physiology, behavioral health, medical procedures, medical equipment, toxicology, and countermeasures.	T/D
HS.CT.2c	Crew training shall be verified	T/D
HS.CT.3a	Flight surgeons shall receive necessary training and certification for mission-specific aspects	T/D
HS.CT.3b	Mission Control Center personnel shall receive necessary training and certification for mission-specific aspects	T/D
HS.CT.3c	Support personnel shall receive necessary training if required knowledge of medical procedure is deemed appropriate for job	T/D
HS.CT.4	Pre-mission briefing and trainings shall be provided concerning the significant psychological and social phenomena that may arise in all phases of the mission to all appropriate personnel	T/D
HS.CT.5	Physiological training shall be provided to crew members regarding inflight exposure to CO_2, hypoxia, centrifuge, and microgravity adaptation	T/D

Table 27 Human System Health Record Requirements

Req. ID	*Mission Requirement*	*V&V*
HS.HR.1	Crew health records shall be stored in a permanently retrievable format.	T/D
HS.HR.2	A method for communicating crew health records shall be instituted, such that medical operational needs of the mission are met	T/D
HS.HR.3	Security of crews health records shall be maintained during handling, storage and communication	T/D

Table 28 Human System Health Sustainment Requirements

Req. ID	*Mission Requirement*	*V&V*
HS.HHS.1	All crew members shall be examined physically and mentally to exceed those presented in the NASA Medical Standards prior to mission commencement.	T/D
HS.HHS.2	Weekly general health check ins shall be conducted with all crewmembers	T/D
HS.HHS.3	At least one certified Flight Surgeon shall be within the crew	T/D
HS.HHS.4	The on-board Flight Surgeon shall communicate weekly with another Flight Surgeon on ground.	T/D
HS.HHS.5	All crew members shall record all exercise and all nutrition intake	T/D
HS.HHS.6	Crew Members shall work a schedule that optimizes productivity and sleeping patterns, putting aside a minimum of 9 hours per day cycle to sleep, with the exception of mission emergencies	T/D
HS.HHS.7	Crew Members shall log all sleep patterns	T/D
HS.HHS.8	Cremembers shall sleep such that at least two crewmembers are awake at all times	T/D

HS.HHS.9	Crew Members shall exercise for a minimum of 2.5 hours per day cycle, with at least one hour contributed to cardio-oriented exercise, and at least one hour contributed to strength-oriented exercise	T/D
HS.HHS.10	[V2 6001] The system shall provide environmental and suit monitoring data in formats compatible with performing temporal trend analyses.	T/D
HS.HHS.11a	[V2 6002] Cabin atmospheric composition shall contain at least 30% diluent gas (assuming balanced oxygen).	T/D
HS.HHS.11b	[V2 6003] The system shall maintain inspired oxygen partial pressure (PIO2) in accordance with Table 6.2-1—Inspired Oxygen Partial Pressure Exposure Ranges	T/D
HS.HHS.11c	[V2 6006] The system shall maintain the pressure to which the crew is exposed to between 34.5 kPa $<$ pressure $\leq$ 103 kPa (5 psia $<$ pressure $\leq$ 15.0 psia) for indefinite human exposure without measurable impairments to health or performance.	T/D
HS.HHS.12a	[V2 6017] The system shall allow for local and remote control of atmospheric pressure, humidity, temperature, ventilation, and ppO_2 (partial pressure of O_2).	T/D
HS.HHS.12b	[V2 6020-6021] The system shall record and display real-time values for pressure, humidity, temperature, ppO_2, and $ppCO_2$ data to the crew locally and remotely.	T/D
HS.HHS.13a	[V2 6026] At the point of crew consumption or contact, the system shall provide aesthetically acceptable potable water that is chemically and microbiologically safe for human use, including drinking, food rehydration, personal hygiene, and medical needs.	T/D
HS.HHS.13b	[V2 6109-6110] The system shall provide a minimum water quantity and temperature as specified in Table 6.3-1— Water Quantities and Temperatures, for the expected needs of each mission, which are considered mutually independent.	T/D
HS.HHS.13c	[V2 6039-6040] To prevent overflow, water shall be dispensable in specific increments and rates that are compatible with the food preparation instructions and time demands of the allotted meal schedule.	T/D

HS.HHS.14	[V2 6048-6049,6060-63] Systems shall prevent Toxic Hazard Level Four Chemicals from entering habitable volume, System shall provide controls to minimize biological cross contamination, system to provide means to isolate and remove released chemicals/biological contaminants	T/D

Table 29 Human System Flight Requirements

Req. ID	*Mission Requirement*	*V&V*
HS.MR.1	[V2 Section 5] System design shall accommodate human visual, auditory, sensorimotor, and cognitive capabilities and limitations to support effective and efficient human performance.	T/D
HS.MR.1a	System design shall human accommodate visual capabilities and limitation	T/D
HS.MR.1b	System design shall accommodate human visual capabilities and limitation	T/D
HS.MR.1c	System design shall accommodate human sensorimotor capabilities and limitation	T/D
HS.MR.1d	System design shall accommodate human cognitive capabilities and limitation	T/D
HS.MR.2	[V2 10001] System shall provide crew interfaces that result in minimum average satisfaction score or higher of NASA modified System Usability Scale (NMSUS)	T/D
HS.MR.3	[V2 6064] The system shall limit the magnitude, direction, and duration of crew exposure to sustained (> 0.5 seconds) translational acceleration by staying below the limits in Figures 6.5-(27) and Tables 6.5-(1-6) for seated and standing postures.	T/D
HS.MR.3a	[V2 6065] The system shall limit crew exposure to rotational velocities in yaw, pitch, and roll by staying below the limits specified in Figure 6.5-8—Rotational Velocity Limits and Table 6.5-7— Rotational Velocity Limits.	T/D

HS.MR.3b	[V2 6113] The time in which crew members are on back with feet elevated in a launch configuration shall not exceed 3 hours and 15 minutes, excluding subsequent safing and egress time.	T/D
HS.MR.4	[V2 6073] During launch, entry, and abort operations, the noise exposure level (not including impulse noise) at the crewmembers ear, calculated over any 24-hour period, shall be limited such that the noise dose (D) is ≤100:	T/D
HS.MR.4a	[V2 6074-6079] System shall limit sound levels according to defined ceilings	T/D
HS.MR.5	[V2 6089] The system shall limit vibration to the crew such that the frequency-weighted acceleration between 0.1 to 0.5 Hz in each of the X, Y, and Z axes is less than 0.05 g (0.5 m/s2) root mean square (RMS) for each 10-minute interval during prelaunch	T/D
HS.MR.5a	[V2 6090] The system shall limit vibration during dynamic phases of flight at interfaces that transmit vibration to the crew such that the vectorial sum of the X, Y, and Z accelerations between 0.5 and 80 Hz, calculated in 1-s intervals and weighted in accordance with ISO 2631	T/D

II. Supplementary Tables

A. Weights Spreadsheet

Structures	TRL	Structure Weight (kg)	Total Structure Weight (kg)
Mattresses	9	36.85438	205792.3031
Bed Frames	9	54.4310844	
Chairs/bench	9	38.5553514	
Table/operating	9	15.8757329	
Ladders	9	54.4310844	
Toilet	7	100	
Air Tanks	8	272.155422	
CCM	3	39000	
ORCM	3	72000	

RIM	3	32000
ORIM	3	42000
TCS	6	20000

Components	TRL	Weight (kg)	Power (kW)	Total Component Weight
Airbus CMG 75-75 S	9	276	0.64	100295.05
IMU	9			
Sun Sensor	9			
Earth Sensor	9			
GPS	9			
K-band transmitter	9	3	0.003	
High-gain antenna	9	1.35	0.00135	
Low-gain antenna	9	0.4	0.0004	
Modulator/demodulator	9	3.2	0.0032	
Amplifiers	9	2.4	0.0024	
Command/Data handling	9	0.3	0.0003	
Crew Interface devices	9	8	0.008	
ECLSS	7	100000	9.6	

Cabling Length (ft)	Cabling Weight (kg)	Food+Astronaut (kg)	Water (kgs)	Ducting Length (ft)	Ducting Weight (kgs)
687	74.8	1326.75768	1043.26245	170	2032.09382

III. Matlab Code

A. Propellant Mass Calculator

```
clear; clc; close all
%% Spacecraft parameters
Mpayload = 310000; %kg
Mf = Mpayload;
DV = 60; %m/s
Diameter = 5; %m
%% Engine parameters
ISP = 234; %s
T = 200; % N
mdot = 150/(60*10); %kg/s
phi = 0; %Ox;Fuel ratio
oxrho = 1141; %kg/m^3 , 1141 for LO2
fuelrho = 1026*1.26;
%% total propellant mass
Veq = T/mdot;
f = @(mp) Veq*log((Mf+mp)/(Mf)) - DV;
mp = fsolve(f,1);
mox = phi/(phi+1) * mp;
mfuel = 1/(phi+1)*mp;
Vox = mox/oxrho; %kg/m^3
Vfuel = mfuel/fuelrho; %kg/m^3
oxheight = Vox/(pi*(Diameter/2)^2)
fuelheight = Vfuel/(pi*(Diameter/2)^2)
totalmass = mp+Mf
```

B. Orbital Decay Calculator

```
clear;clc;close all;
%% data
RE = 367800;
alt =  [300 320 340 360 380 400 420 440 460 480 500]*10^3;
a = alt+RE;
rholow = [27.2 42.1 25.0 15.1 9.20 5.68 3.54 2.23 1.42 .920 .603]  *10^-13;
%kg/m^3
rhomean = [25.8 17.2 11.6 7.99 5.55 3.89 2.75 1.96 1.40 1.01 .730] *10^-12;
%kg/m^3
rhohigh = [17.1 13.2 10.3 8.05 6.35 5.04 4.02 3.23 2.60 2.10 1.70] *10^-11;
%kg/m^3
mu = 3.986*10^14;
mass = 390000; %kg
Cd = 0.75;
A = 60*4; %m^2
V = 30000; %m/s
days = 1900;
time = linspace(0,days,days); % days
a0 = a(end);
t = time*86400;
```

```
B = mass/(Cd*A);
l = length(rholow);
m = length(rhomean);
n = length(rhohigh);
alow(1) = (sqrt(a0) - 2*sqrt(mu)*rholow(l)/B.*86400).^2 ;
amean(1) = (sqrt(a0) - 2*sqrt(mu)*rhomean(m)/B.*86400).^2 ;
ahigh(1) = (sqrt(a0) - 2*sqrt(mu)*rhohigh(n)/B.*86400).^2 ;
for i = 2:length(time)
   alow(i) = (sqrt(alow(i-1)) - 2*sqrt(mu)*rholow(l)/B.*86400).^2;
   amean(i) = (sqrt(amean(i-1)) - 2*sqrt(mu)*rhomean(m)/B.*86400).^2;
   ahigh(i) = (sqrt(ahigh(i-1)) - 2*sqrt(mu)*rhohigh(n)/B.*86400).^2;
  if abs(alow(i) - a(l)) > 20000
      l = l-1;
  else
  end
if abs(amean(i) - a(m)) > 20000
      m = m-1;
  else
end
if abs(ahigh(i) - a(n)) > 20000
      n = n-1;
  else
end
end
altlow = (alow-RE) *10^-3;
altmean = (amean-RE) *10^-3;
althigh = (ahigh-RE) *10^-3;
figure(1)
plot(time,altlow,'b',time,altmean,'k--',time,althigh,'r');
%plot(time,altlow,'b',time,altmean,'k--');
grid on; title('Altitude of Ring over Time');
xlabel('time(days)'); ylabel('altitude(km)'); ylim([min(althigh)
max(altlow)+10])
legend('low solar activity','mean solar activity','high solar
activity','location','SouthWest')
```

C. Weights and Costs

```
w = [77088 10800 6500 19000 129700 450000 100000];
c = [16.5 16 10 9 10.54 122 7.5];
plot(w,c,'o')
title('Spacecraft Weight and Cost');
xlabel('Weight (kg)');ylabel('Cost ($B)'); grid on
```

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