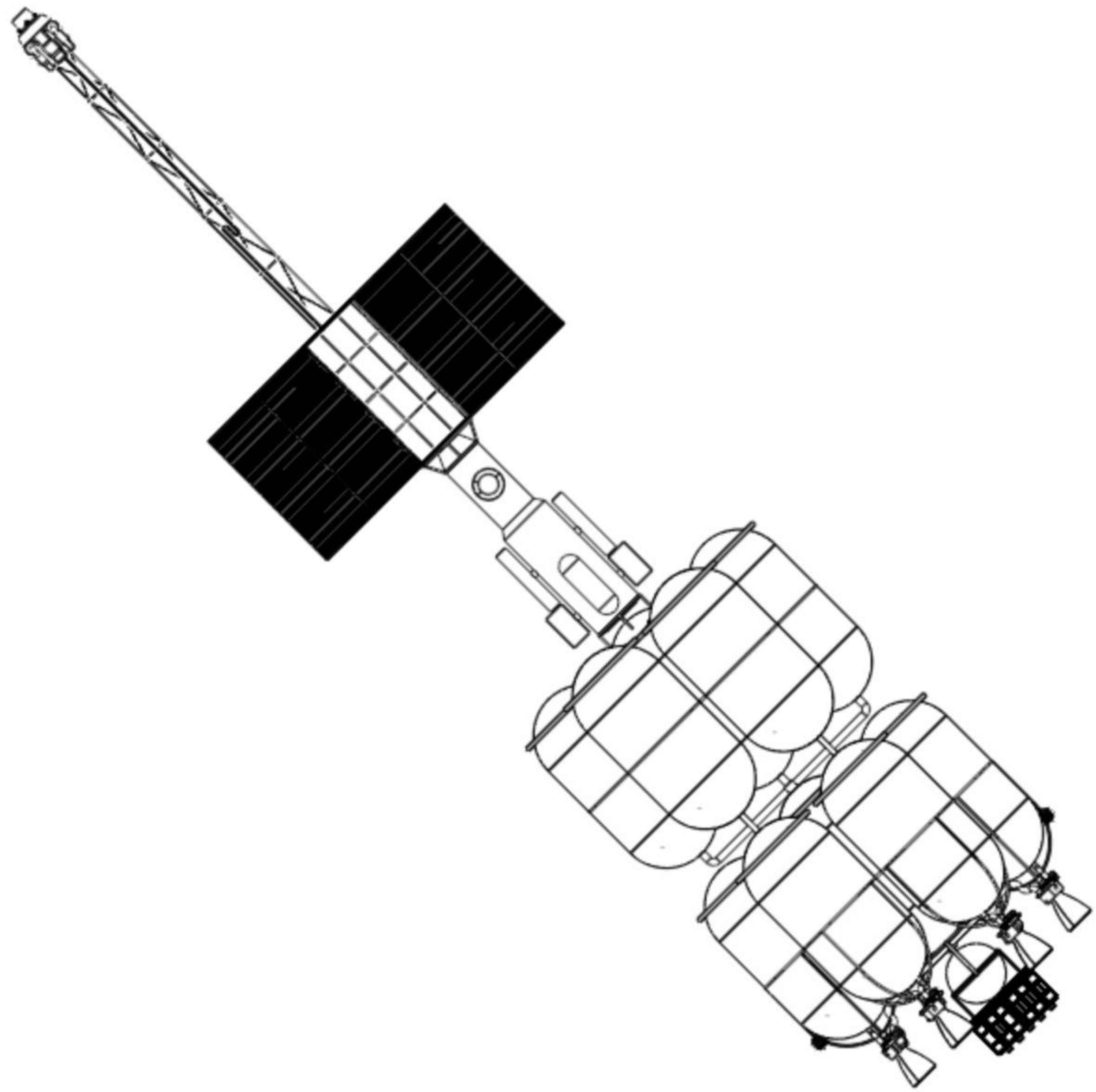
Final Design Review



The Warden

By ER Rocket Inc.

April 18th, 2025

I. Interplanetary Trajectory

The goal of the trajectory is to find the fastest transfer from Earth to Mars utilizing both a chemical and electrical propulsion system. To accomplish this, it was assumed that the Earth, Mars, and Moon orbits were co-planar and circular.

To achieve this goal, the novel approach of launching from the moon will be utilized. Beginning an interplanetary transfer to Mars from the Moon significantly reduces the ΔV expenditure required for the mission. Lower ΔV means that less fuel is required, and therefore less tanks, which helps reduce the overall weight of the spacecraft and increases low-thrust propulsion efficiency.

Table 1: Mass of Spacecraft Stages.

	Stage 0 (Transfer from Assembly Orbit to Moon Orbit)	Stage 1 (Impulsive Escape from Moon Orbit)	Stage 2 (Electrical Interplanetary Transfer)	Stage 3 (Impulsive Insertion to Mars Orbit)
ΔV (km/s)	3.9415	3.9168	-	8.4840
Mp (kg)	293001	1976284	8614	1180812
Mb (kg)	204749	1394175	1385561	204749
Mtot (kg)	497750	3370459	1394175	1385561

Table 1 above demonstrates that the overall mission can be split into 4 primary transfers, referred to as stages. Stage 0 encompasses the transfer of the *Warden* after its assembly in the orbit of the International Space Station (ISS) to an ecliptic low lunar orbit of 100 km altitude using impulsive, chemical propulsion. The ISS currently orbits the Earth in an approximately circular orbit of 407 km, at an inclination of 51.6° [1]. The transfer from the assembly orbit to the lunar orbit is a one-time expense and is modeled as a Hohmann transfer to reduce the initial mass of fuel that is required upon launching the components into space. Also, the *Warden* will be unmanned throughout stage 0, so the transfer is free of any time restraints that would be present if crew were aboard. After the *Warden* successfully inserts itself into the low lunar parking orbit, the spacecraft will receive its 4-person crew from the proposed GATEWAY station and will be refueled via fuel shuttles sent from the lunar surface, which will be filled with hydrogen and oxygen propellant synthesized on the Moon. After the spacecraft is transitioned into the lunar orbit it will not return an Earth orbit. Instead, it will always begin and end all future interplanetary missions from the same ecliptic 100 km lunar orbit.

Stage 1 encompasses the first step in the interplanetary transfer: a hyperbolic escape trajectory from the low lunar parking orbit to a direct transfer to Mars using impulsive, chemical propulsion. Stage 2 occurs after the *Warden* leaves the sphere of influence of the Earth and is thus assumed to only be affected by the gravitational forces of the Sun. This stage will rely solely on electrical propulsion to gradually increase the velocity of the *Warden* and reduce the time of flight required for the interplanetary transfer. The *Warden* will utilize 7 electrical engines that fire at an angle of 40 degrees tangent to the interplanetary flight path. Finally, stage 3 will encompass the insertion of the *Warden* to an ecliptic Martian orbit of 400 km altitude using impulsive, chemical propulsion. Overall, stages 1-3 will consume 3,157,096 kg of chemical propellant and 8614 kg of electrical propellant. The total transfer time will be 114.07 days.

II. Launch Vehicle

The launch vehicle chosen was the Extended Payload Starship. This was chosen due to the large payload bay with a height of 22 m and a weight capacity of 150,000 kg, making it very flexible to account for the required items to launch for the rocket. It was determined the launches would cost $75 million each, so a total of $1.35 billion for 18 launches. Note that the launch containing the astronauts is not included in the cost estimation, due to the astronauts being launched by NASA. The most hazardous item being transported is the nuclear reactor. This is being contained in the TRUPACT-II vessel to ensure safety within the rocket, and to the environment in the event of an emergency. It will cost $410,000. The launch sequence details the launch order for every piece of the rocket needed as shown in Table 2 below. See Launch Vehicle Report for further information on vehicle selection and launch sequencing.

Table 2: Summary of Launch Sequence and Key Items.

Launch No.	Content
1	Booms
2	Electrical Power Assembly
3	Life Habitat Assembly
4	Top Central Oxygen Tank
5	Top Oxygen Tank #1
6-7	Top Hydrogen Tanks #1 and #2
8	Bottom Central Oxygen Tank
9-11	Bottom Hydrogen Tanks #1, #2, and #3
12	Top Oxygen Tank #2
13-14	Top Hydrogen Tanks #3 and #4
15-17	Bottom Hydrogen Tanks #4, #5, and #6
18	Rocket Engines and RCSs
19	Astronaut Crew

III. Certifications

The Earth-Mars transfer vehicle mission has undergone extensive certification processes across multiple critical systems:

1. RS-25 Engines: Certified for safety and performance, complying with CFR Title 14 Part 420.66 for propellant handling and Part 417.129 for debris mitigation
2. VASIMR Thrusters: Safety protocols established for ground operations, launch, and orbital use, with FAA approval pending detailed safety case presentation.
3. Special Purpose Nuclear Reactor (SPNR): Certified for transport using TRUPACT-II packaging, complying with DOT and NRC regulations. Launch safety measures include specialized containment and monitoring systems.
4. Astronaut Food System: Certified under FDA, USDA, NASA standards (NASA-STD-3001), and CFR Title 21 (Part 117, 1240, and 1250) including facility certification, personnel training, and rigorous food testing protocols.
5. Launch Operations: Certified under CFR Title 14 Part 417.113, addressing public safety, flight commit criteria, and flight termination rules.
6. Zvezda Module: While specific certifications are not documented, it undergoes continuous safety monitoring and upgrades to meet human spaceflight standards.

These certifications confirm that the mission complies with federal regulations and industry standards, guaranteeing safety and reliability throughout every mission phase. For more details, see the Mission Certifications Report.

IV. Chemical Propulsion Method

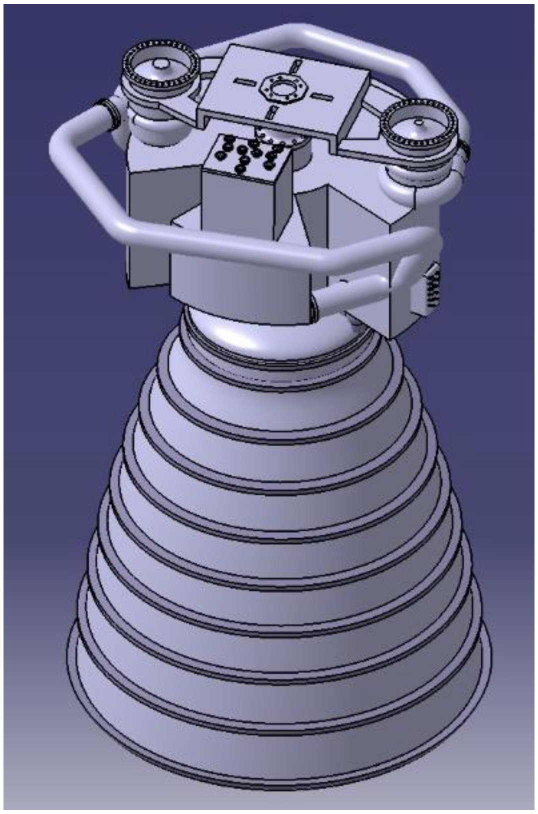


Fig. 1 RS-25 CAD Assembly

A. RS-25 Engine

The RS-25 engine was chosen as the main propulsion system for the Mars transfer vehicle. Initially, the RL-10B-2 was selected due to its high efficiency and lower dry mass, but further analysis showed that the long burn times required would exceed the engine's safe operational limits. This led to a redesign, where six RS-25 engines were selected to reduce burn time and improve overall mission performance.

To integrate the RS-25 engines into the vehicle, both the engine components and mounting system were modeled in CATIA V-5. The CAD modeling process focuses on accurately representing the engine's external geometry and connection points to ensure proper integration with structural and propellant systems. While internal engine details were not necessary for modeling, the external interfaces were given more attention to aligning with assembly and structure requirements.

B. Engine Mounting

The engine mounting system was designed to provide a secure connection between the RS-25 engines and the spacecraft while distributing thrust forces efficiently. The mount system is made up of three key parts: the thrust adapter, which holds most of the load, the gimbal mount plate that bolts directly to the top of the RS-25's gimbal, and another plate that connects the mount to the tank's truss structure. This setup keeps the engine locked in place and prevents it from shifting around when firing at full power. The design also makes assembly in space simple; some parts are pre-attached before launch so that once in orbit, the final connection is just bolted together, and the engine is hooked up to the fuel system. A complete CAD model of the assembled mounting system provides a clear view of how the RS-25 engines will be attached to the mount.

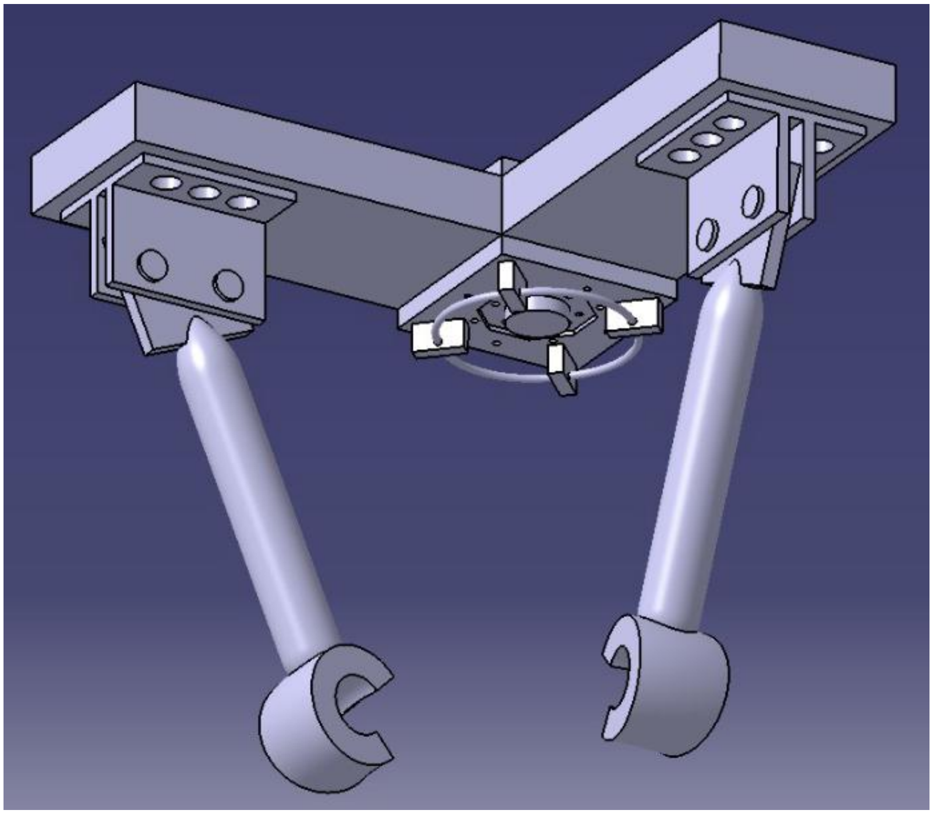


Fig. 2 Engine mount CAD assembly

C. Seals

Seal selection is vital for making sure any system design has resilience and does not undergo any consequences of fluid leakage. Seals for system designs for space applications include spring back resilience, installation load, a sealed environment of media, temperature, pressure, and cost. It must also be ensured they are compatible with all engine fluids such as propellant hydraulic fluids, combustion gases, and low-cost fluids. Pressure-assisted seals were developed to attain a deflection that would better handle deformation of the flange-joint under working loads. Teflon-coated seals are effective for cryogenic services as they can bear a low temperature of –430 degrees Fahrenheit but are limited to 3000psi. The spring effect incorporates a metal circular seal having a U-shaped cross-section. The seal orientation and details include tapered legs to provide uniform stress in material and permits seal legs to follow the flange deflections. They are installed in a concentric groove cut into one of the flanges, which limits the amount of total flange preload transmitted through the contact points of the seal. The contact surfaces will be coated with a material with a lower elastic modulus than the seal material. The seal structural material will be chosen for maximum deflection.

D. RCS System

Precise attitude control is essential for stability, trajectory corrections, and docking with the Martian space station. The Reaction Control System (RCS) enables necessary rotational and translational maneuvers for thermal regulation, realignment, and docking precision. An active center of gravity (CG) monitoring system compensates for shifting mass by adjusting thruster impulses in real time, optimizing stability and fuel efficiency. Bipropellant thruster packs, similar to the Ariane Group 200N, use Unsymmetrical Dimethylhydrazine (UDMH) with a compatible oxidizer, reducing system complexity. Thrusters are positioned at structurally optimal locations, including the aft, boom, and a central halo structure, to maximize control authority. High-specific impulse (Isp) thrusters ensure efficient fuel consumption and sustained maneuvering capability. The integration of CG monitoring, optimized thruster placement, and high-efficiency propellants establishes a controlled and fuel-efficient RCS, ensuring mission success in Martian orbit.

V. Tanks and Piping

The design of the propellant tanks must provide an optimal balance of multiple factors including size, strength, mass, and cost, while maintaining the ability to be launched into space within the proper packaging constraints. It must be sized large enough to carry a significant amount of propellant while still fitting within the starship payload bay. It must also be strong enough to bear the pressure of the propellant, while doing so in a structurally efficient manner, to maximize structural efficiency. Doing so can ensure that the bulk of propellant within each tank is used mostly for changing spacecraft velocity rather than counteracting the additional dry mass of each tank. There are two types of tanks, one for each propellant: the fuel and oxidizer for the chosen propulsion system. Cryogenic liquid hydrogen (LH2) is used for the fuel and cryogenic liquid oxygen (LOx) is used for the oxidizer. Each propellant will be held at a pressure of 15 atmospheres to ensure an operational margin to maintain the liquid state of each propellant. The thickness of the propellant tank is a function of the allowable stresses of the materials used, the shape of the tank, and the pressure inside the vessel. It is then ensured that the geometric properties of the tank can withstand the forces endured throughout the mission without buckling or bursting. The two load bearing materials used for the walls of the vessel are Ti-6Al-4V and CFRP. Each has a specific function as CFRP bears the majority of the load, and the titanium is treated as a liner for the inside of the tank to reduce the permeation of liquid hydrogen.

The propellant feed system has three main purposes other than providing propellant to the engines. These include maintaining propellant tank pressures, purging feed lines pre-burn (for clearing), and cryogenic pre-conditioning pre-burn (directly after purging). The pressurants for the system are Helium and GH2 for the oxidizer and fuel, respectively. Helium is pre-stored in a tank and gradually fed into the three auxiliary oxygen tanks as they empty into the main feeder LOx tank. GH2 is continuously fed into each fuel tank with exhaust from the RS-25 pre-burners. Each tank feeds a single engine, with four of them equipped with an auxiliary tank as only four tanks of fuel are left over after the first burn. The purging system uses the same Helium supply from the LOx and is used for each propellant main feed line. The helium is routed from the supply to two separate manifolds, one for the LOx feed lines and one for the LH2 feed lines. Each manifold then branches into each individual feed line for purging post burn. The pre-cryogenic conditioning cycle (chilling) loop prevents flash vaporization during burn as well as cavitation and other undesirable effects by cooling the feed lines that the propellants travel through. In each engine's feed line for both propellants, a small parallel branch is added with another actuator and flow restrictor which can be opened to allow a trickle flow directly after purging. Please refer to the appendix for the diagram overview.

The cryocooler-mount system is designed to place the cryocooling components in close proximity to the tubes on the Liquid Oxygen and Hydrogen tanks. The manifolds rings placed on the mount distributing the respective hot and cold He gas flows within each cooling tube stage that is wrapped around the tanks. The 1-stage design cools to 85K and is placed on the liquid oxygen tanks, while the 2-stage design cools to 18 K and features two layers of cooling placed on hydrogen tank. Out of the 10 fuel tanks, 6 will being concentric around the bottom layer near the engines and 4 will be in the same form on the top layer with reserved space for 2 tanks. 9.3 tanks worth of fuel will be prepared when lifting off the moon and will be reduced to 3.5 after the first burn. Fuel lines will run top down from the top layer of tanks into the bottom layer. Tanks with no respective top layer will be empty after the first burn. From 4 oxidizer tanks, 2 will being centered in the bottom layer and top layers, the remaining 2 will be in reserved slots concentric to the top layer. 3.5 tanks worth of oxidizer will be prepared when lifting off the moon and will be reduced to 1.3 after the first burn. Fuel lines will run into the center and then top down from the top layer into the bottom layer. Tanks not in the center of a layer will be empty after the first burn. Each tank will have a dedicated sensor suite and a DAS computing unit that will relay to the Zvezda module. They can all be seen to have outer dimensions of 16.9m in height and 3.9m in radius with corner radii of 3.9m on the cylindrical body.

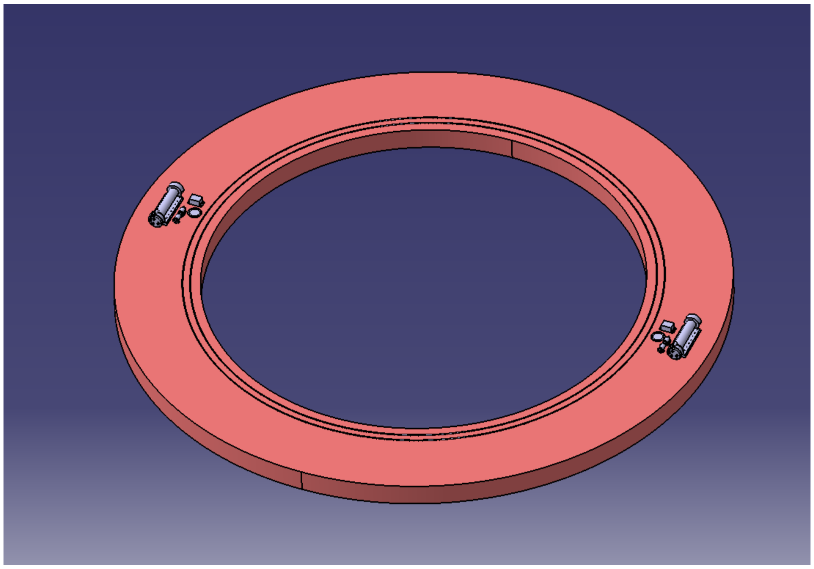


Fig. 3 1-stage Cryocooler Mount CAD Assembly

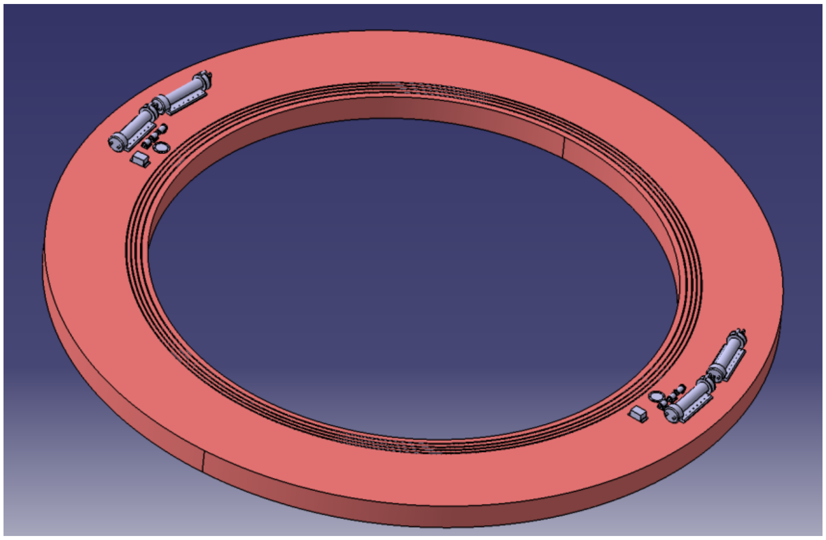


Fig. 4 2-stage Cryocooler Mount CAD Assembly

VI. Electrical Propulsion Method

The electrical propulsion system selected revolves around the TLR-5 VASIMR VX-200SS system. The configuration includes its integrated thermal management system, propellant delivery system, a high-level power delivery system, and a detailed flight control system. The goal of the electrical propulsion system is to decrease the time of flight as much as possible with the allocated 1401 kW provided for maximum electric propulsion influence, while maintaining an efficient structural configuration and power management for the long duration transit.

A. Power Delivery Configuration

The power delivery system is designed to deliver power from the main and secondary redundant electric propulsion bus to the seven VASIMR VX-200SS systems. The configuration addresses and include desired sensors and control systems, thermal management systems, and flight telemetry data to be relayed to the crew capsule flight computer.

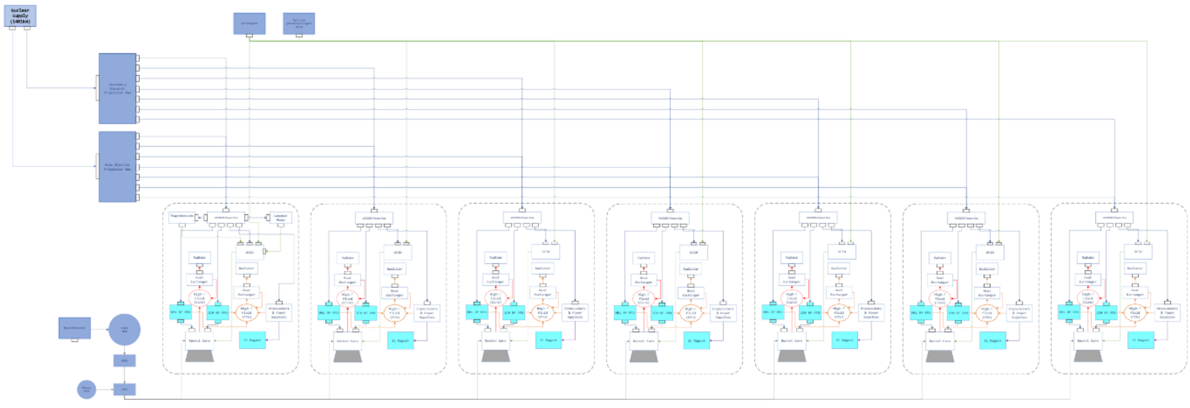


Fig. 5 Entire Electric Propulsion Power System with Seven VX-200SS Systems Included

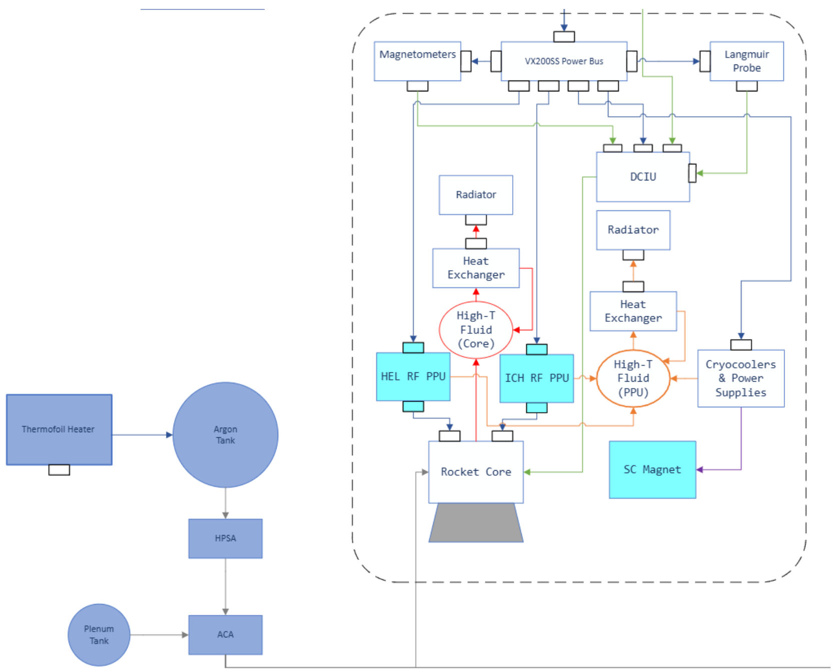


Fig. 6 VASIMR VX-200SS Individual Power System

As presented in Figure 1 and 2, the overarching electrical system distributes the allocated 1401 kW power to each of the seven VX-200SS systems. Included in these systems are the modes for thermal management, the sensors for gathering telemetry data, and controls for regulating operational conditions for the propellant delivery system, argon tank, and the VX-200SS engines.
For wiring specifics, the GORE Space Cables Type SPP (AWG 0) were selected for delivering 200 kW of power to each of the seven engines. They are designed for high-current applications and are authorized through ESA's qualified parts list for deep space transit.

B. Propellant Tank

This propellant tank is designed to meet safety standards of a pressurized vessel with extra caution, while considering the security of the argon propellant in its high-pressure state. To achieve optimum operation parameters, the argon propellant tank is designed to contain 50 atm argon gas at 180 K and is designed to withstand buckling at maximum g loads. The material selected is the titanium aluminum alloy Ti-6Al-4V which boasts high strength and a low density of 4,430 kg/m³. The dimensions and necessary thickness were then formulated with a targeted factor of safety of 2.4 and ultimate stress of 827 MPa.

Fig. 7 Argon Tank Isometric View

The tank was designed to be refueling capable, with a 4-inch nominal diameter inlet nozzle flange, and a ¼ inch diameter outlet nozzle flange to the propellant delivery system. The finalized tank dimensions were calculated to be a thickness of 16.92 mm, an outer radius of 2.317 m, and a total mass of 4986.31 kg. The argon tank will be situated above the VX-200SS assembly configuration with the outlet nozzle directed toward the engines. For more details, reference the Electric Rocket Accessory and Components Report.

C. Propellant Delivery System

The propellant delivery system was designed specifically for the VASIMR engine, and the intended configuration will be run at. It includes a whole redundant and robust system to mitigate the possible failures of different parts. The pressure of the final delivery was checked with FluidFlow3 to ensure that the correct parameters are reaching the engines as needed since they require extremely low mass flow and pressures.

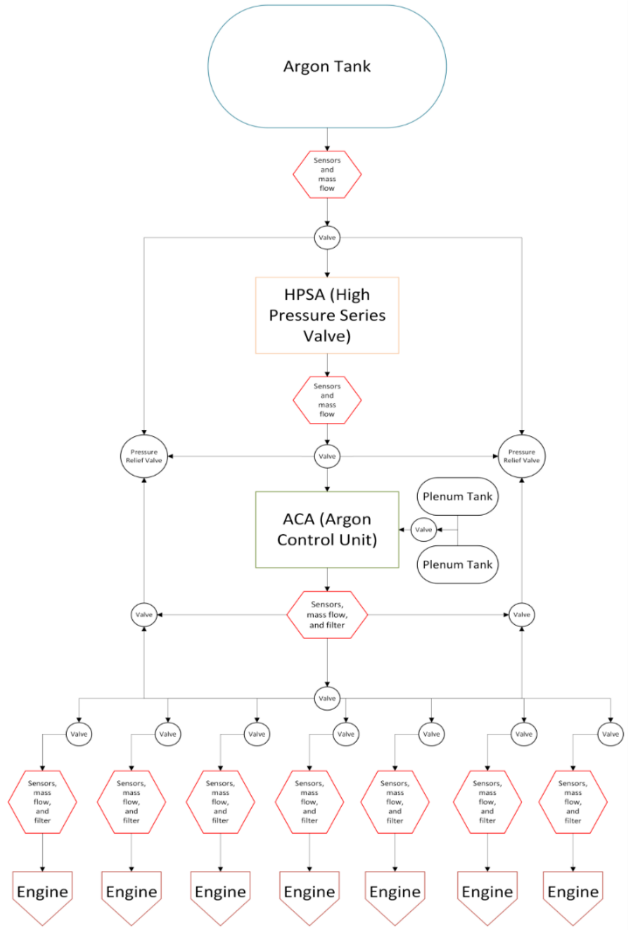


Fig. 8 High Level Propellant Delivery System Diagram

The overall diagram can be seen in Figure 8, where it shows the main components of the whole system. Moreover, various design failure mode analysis was created for the components in the system. It was determined that the chance of failure of the propellant delivery system is extremely low. Nonetheless, mitigations were added in place for every single possible event that might occur in the trajectory. Moreover, a control system for the whole propellant delivery was designed using FluidFlow3, however the software itself still needs to be designed by engineers. Further improvements will include ensuring all system parts will be tested accordingly, integration with other systems, and final detail additions. For more details, reference Electric Rocket Accessory and Components Report.

D. VASIMR VX-200SS Assembly

The selected assembly configuration consists of seven VASIMR VX-200SS engines arranged in a hexagonal configuration with one in the center. This symmetric design allows for simple assembly, and simplified emergency control measures. The design background is based on the consideration that if one engine is lost, the symmetric geometry of the configuration allows for simple throttling of the opposite engine to maintain the flight trajectory autonomously. Refer to the Electric Rocket Accessories and Components Report for details on its control system schema.

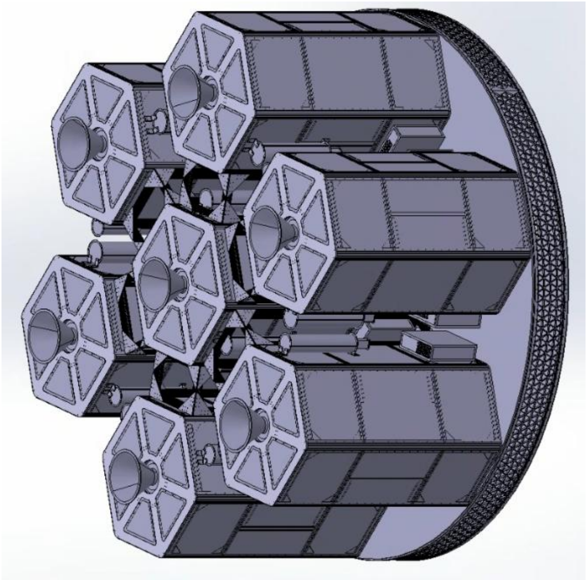


Fig. 9 VASIMR VX-200SS Assembly with Bulkhead

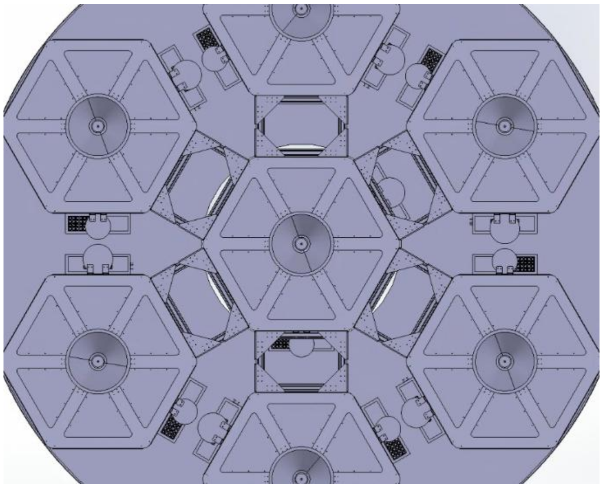


Fig. 10 VASIMR Assembly Front View with T-Slot Beams

The assembly in Figure **9** includes a bulkhead attachment for structural integrity and piping/wire management. Standardized 6063-T6 aluminum t-slot beams, seen in Figure 10**,** are used to attach each engine to each other to prevent knocking during high vibrational sections of the flight, maintaining a stiff rigid assembly.
Structural FEA on the 3g max g-load suggests high structural integrity in the design and can be further proven in the Electric Rocket Accessories and Components Report.

E. Sensors and Control

The VASIMR engine system for a Mars mission requires precise control over key operating variables to ensure efficient propulsion, energy management, and astronaut safety. To achieve this, several advanced sensors and control systems will be integrated into both the engine and the argon propellant tank. Magnetometers will measure the strength and direction of the magnetic field within the plasma environment, helping maintain stable plasma confinement. Each engine will be equipped with a high-sensitivity three-axis fluxgate magnetometer, which will send real-time data to the Digital Control and Interface Unit (DCIU) for precise magnetic field adjustments.

Additionally, Langmuir probes will monitor plasma properties, including electron temperature, density, and potential, to ensure optimal ionization of the argon propellant. These probes will provide real-time diagnostics and alert the central control system to any anomalies that require corrective action.

The Astrix 1090 Gyroscope will also be integrated into the spacecraft's attitude control system to provide accurate inertial measurements, helping align the thrust vectors with the spacecraft's orientation. Known for its reliability, low noise, and quick startup time, this gyroscope will enable real-time feedback on the spacecraft's attitude and any necessary thrust adjustments.

Finally, a thermofoil heater will regulate the temperature of the argon propellant tank to maintain ideal conditions for ionization and plasma generation. Made from a flexible foil material, this heater will incorporate temperature sensors to ensure even heat distribution. The data from these sensors will be processed by the spacecraft's thermal control system, allowing for automatic adjustments to maintain the required temperature throughout the mission. Further analysis on the implementation of these sensors is addressed in the Electric Rocket Accessories and Components Report.

A. Power Generation and DistributionPower Generation

The primary source of power generation will come from a Special Purpose Nuclear Reactor (SPNR) designed by the Idaho National Laboratory (INL) & the Los Alamos National Laboratory (LANL). This system involves a complex and unique combination of TRL 3 – 5 components to provide the massive amounts of energy required for the VASMIR thrusters, crew and habitat life support, and propellant cryocoolers. The SPNR was initially designed to produce 5 MW of power, making it capable of powering neighborhoods or small cities, which makes it ideal for generating the power requirements of a long duration mission through space. The SPNR will be purchased from the INL & LANL and therefore will be considered an off-the-shelf component/system. As an off-the-shelf component, a detailed CAD model of the SPNR will not be generated, as the assumption is that the manufacturer would provide the detailed model. Until the manufacturer provides the detailed CAD model, a cylinder with the accurate overall dimensions will be used to represent the reactor. The simplified cylinder shown below has a height of 1 meter and a diameter of 1.5 meter.

Fig. 11 SNPR Simplified CAD from Front View

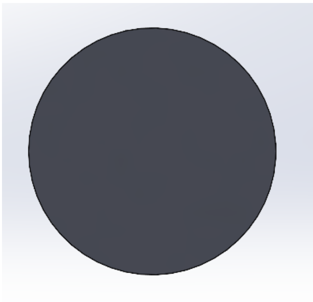


Fig. 12 SNPR Simplified CAD from Top View

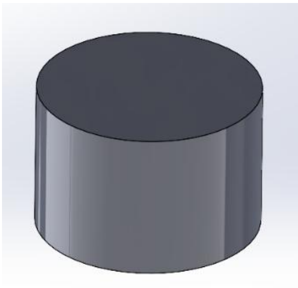


Fig. 13 SNPR Simplified CAD from Isometric View

The chosen PCS would be a Brayton-Loop cycle with a Turbine-Alternator-Compressor. This system would produce AC power to the VASIMR engines and other electrical systems. However, it was determined that both the VASIMR engines and all electrical systems on the spacecraft will operate on DC power, rather than AC. Initially, it was assumed that an AC to DC rectifier would be used to convert the power for use with electrical systems. However, research concluded that a rectifier capable of converting 1.4 MW to DC would be large and inefficient. As an alternative, the alternator on the Brayton-Loop will be replaced with a DC generator capable of outputting the same power as the alternator. Ashman Technologies has developed a turbogenerator for use in space, capable of producing 365 kW from a Brayton-Loop like that which will be used. This generator will be used on each of the four Brayton-Loops and will provide over 1.4 MW of DC power directly to the electrical buses. A rough CAD model was created to represent an "off the shelf" Brayton loop shown in the figures below.

Fig. 14 Front View

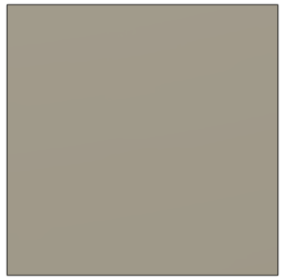


Fig. 15 Top View

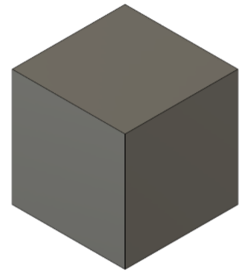


Fig. 16 Isometric View

The ISS Roll Out Solar Array (iROSA), shown in Figure 17, is intended to supply additional auxiliary power where needed and provide redundancy to the power generation system. The iROSA provides 28 kW BOL and 12.1 kW at Mars. It costs 16.67 million per unit and is 34% efficient. A crucial feature of the iROSA is its ability to stow and deploy. This is ideal for minimizing moments during chemical burns.

Multiple fuel cells (Figure 18) are implemented to provide extra power during shutdown of the reactor. During the Time of Flight to Mars, the fuel cells would only occasionally be turned on to generate the amount of water the Zvezda habitat needs for human sustainability. It was determined the consumption of the Fuel cell was 0.43kg/hr of H_2 and 3.46kg/hr of O_2, outputting 3.89kg/hr of H_2O. With an assumption that the four astronauts on board require 3.8 kg/day of water, it was determined that the Zvezda fuel cell needed to run for slightly over an hour a day. With the ToF to Mars being around 111 days, the amount of H_2 and O_2 required for the mission was calculated to be 48.5kg and 390.4kg, respectively. For more detailed calculation and information on the PEM Fuel Cell, reference section I-D on the Power Generation and Electrical Diagram report.

Fig. 17 iROSA deployed on ISS.

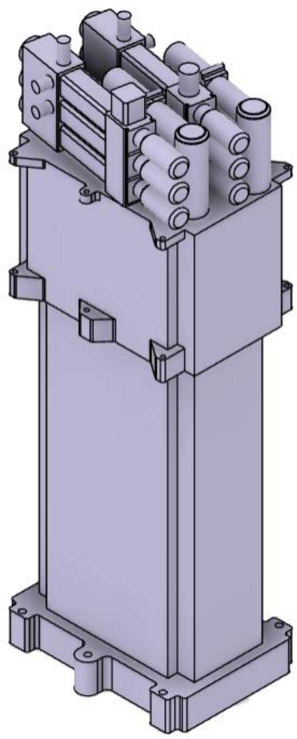


Fig. 18 iROSA CAD

B. Shadow Shield

The shadow shield subsystem in its entirety is less of a functioning system and more of a solitary device. While not including any electrical components, it is a necessity to achieve the goals of this mission. The shield itself has undergone many simulations by different groups, and while this is not as useful as physical tests, the low TRL of different shadow shields in the industry allows the reasonable comparison of simulated tests for a future mission to Mars.

Fig. 19 Front View

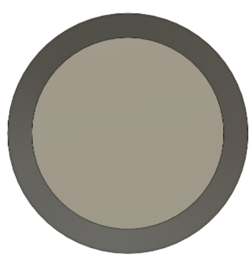


Fig. 20 Top View

Fig. 21 Isometric View

C. Electrical Diagram and Wiring

In Figure 22. this is the high-level system design specifically for Phase 9, meaning that any switches that are open or closed represent how the system will look during the mission. During the duration of the mission, a Flight Phase has been determined for each time the electricity needs to be connected, redirected, or disconnected. Refer to the Power Generation and Electrical Diagram Report for additional information about the phases of flight. The main reason for deciding on explicitly showcasing Phase 9 was so that a clear distinction could be made in what was delivering power and what did not need power supplied to it, and the distinctness of Phase 9 is only applicable to the switches, the same block diagram will be used for all the rest of the phases of flight, just with the switches in different orientations. Important power generation and consumption notations are placed where needed, as well as switch designations. Subsystem diagrams were created for the respective buses, and a switch diagram to determine which switches needed to be opened and closed during specific phases. Information on the subsystem diagram and switch diagram are located inside of the Power Generation and Electrical Diagram Report.

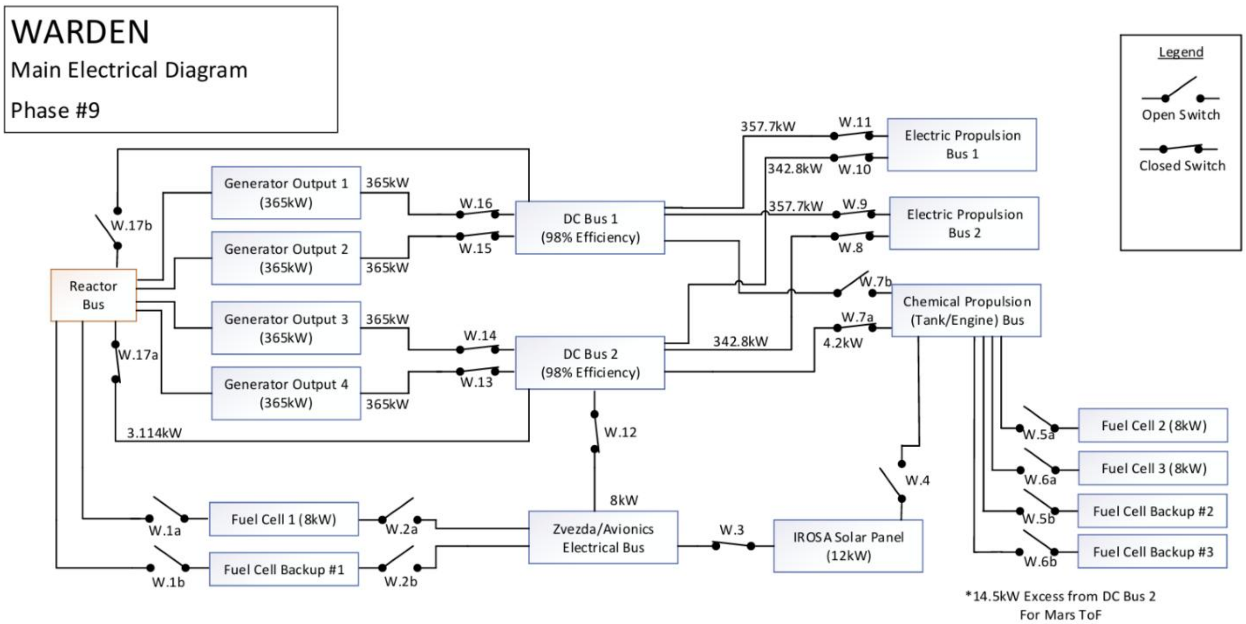


Fig. 22 Phase #9 Main Electrical Diagram

The power output from Warden's various power sources provides electrical input for all the vehicle's subsystems. All systems from Zvezda's thermal control system to the VASIMR engines use this electric power to operate. The output of Warden's power sources must be transported and distributed to all systems. This is done through a system of wires to transport energy, along with electrical buses for all subsystems. These buses collect the system's inputs from multiple wire sources and distribute energy to all necessary outputs. The design of these systems came with several challenges, and some compromises on mass and efficiency had to be made for the wiring and power distribution systems to interface with Warden's other systems.

It was decided that for the high-power lines running from the Brayton Loops to the VASIMR engines, lines would be run in parallel. This would allow the current through each line to be decreased, resulting in a small wire diameter. This allowed the mass of the high-power wiring to be reduced. Throughout the vehicle, radiation resistant wiring supplied by Axon will be used. This is particularly useful for lines that will need to run outside the Warden vehicle and will be directly exposed to the space environment. This wire uses tin-plated copper as a conductor, allowing for high efficiency; different sizes of this wire will be used as necessary. The total mass of wiring throughout the vehicle is 2806.5 kg; this mass will be updated as the design of the vehicle's wiring progresses.

Warden's wiring will be routed throughout the vehicle, with most lines running through the walls of the Zvezda module. Some lines, however, will run on the outside of the vehicle. This is the case for the lines running from the Brayton loops to the VASIMR engines. Such high-power lines would present safety issues if run within the Zvezda module. These lines will run along the outside of the Zvezda module, then run through the center of the tank assembly to reach the VASIMR engines. A structure will need to be made to support these tank assembly lines. Additionally, the total length of these tank assembly wires is close to 60 meters. A single line of this length could not practically be transported to LEO, so wiring in smaller sections will be transported to and assembled in LEO.

At locations where lines are run in parallel, there is a necessity to run multiple lines side by side. These wire groups will be held together using wire harnesses made from Perfluoroalkoxy (PFA). This material allows for added protection for the wiring it surrounds. This material also allows the wire group to be easily installed on the Zvezda vehicle and on the tank assembly support. A 3D model of one of these wire harnesses is shown in Figure 23.

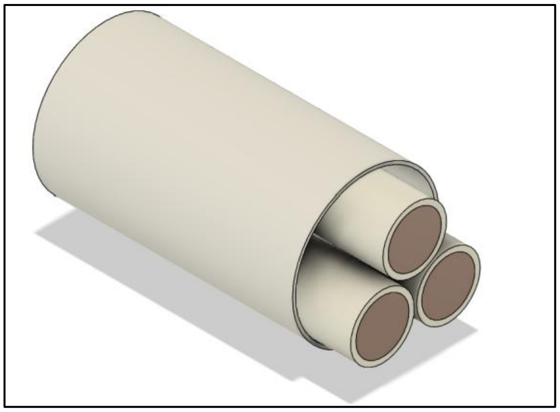


Fig. 23 Wire Harness for Three 400 KCMIL Wires

In cases where multiple wires need to be connected, an easily installable connection is needed. The shorter sections of wire running through the tank assembly will need to be connected in orbit. Because of this, a connector that can attach these wires quickly and efficiently is needed. NSI Industries' IPLD750 series connectors will be used to make this connection. These connectors allow for wiring to be connected efficiently in LEO.

The extendable boom on the forward end of the Warden vehicle allows the reactor to be moved away from the Zvezda module. This extendibility increases the safety of the Zvezda crew, reducing the possibility of the crew being exposed to radiation. As the boom extends and retracts, the wiring running from the reactor must also extend and retract. Winding the wire on spools was considered but was rejected for several reasons. The final solution implemented to the vehicle was a cable chain. This cable chain would allow the wiring to extend and retract freely with the boom, without risk of the wire being pinched or wound out of place. Two sets of rollers guide the cable chain as it extends and retracts. As the three pieces of the boom nest together, small notches needed to be made in the wall of the two forward boom sections. These notches ensure that the rollers of the aft boom section will not interfere with the walls of the forward two sections. 3D models of the cable chain when extended and retracted are shown in Figures Figure 24 and 25.

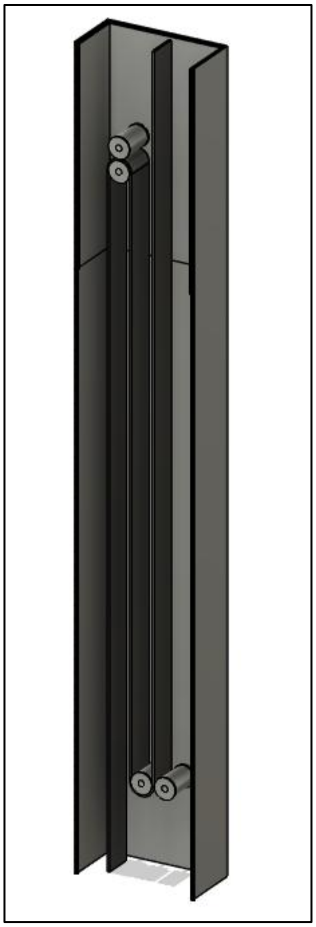


Fig. 24 Retracted Cable Chain-Boom Assembly.

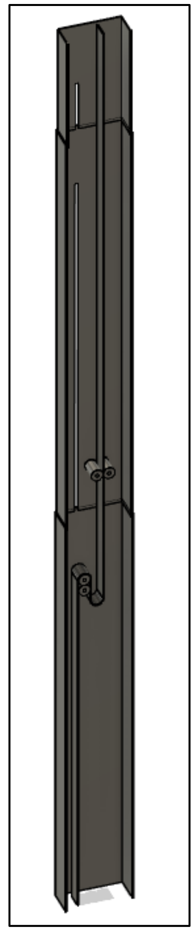


Fig. 25 Extended Cable Chain-Boom Assembly

The electrical buses on Warden take the inputs for a system and distribute that energy to its outputs. These junctions are useful for distributing energy throughout the vehicle. When designing Warden's electrical buses, copper was chosen as the material as it is readily available, relatively easy to manufacture, and will maximize efficiency. The cross-sectional area and length of the buses was determined based on each bus's input power, voltage, current, and number of connections. The total mass of the buses on the vehicle is 21.12 kg. More buses will be designed and sized as the design of the vehicle progresses. For more information on bus design, connection, and assembly, see the Wiring and Power Distribution report.

As the design of the wiring and distribution system progresses, there are several next steps that need to be taken. More wiring and buses will be sized and designed, and thermal analysis will be performed on these components. Structures will need to be designed to support wiring in the tank assembly and housing structures will be designed for the spacecraft's buses. Finally, the length of the wire sections in the tank assembly will be determined, and the total mass and cost of the wiring and power distribution system will be determined.

Information on all systems described in this section of the report is given in more detail in the Wiring and Power Distribution report.

D. Thermal Control

Heat dissipation is an extremely critical component of the mission design; without an adequate heat disposal system, the excess heat from the reactor would cause undue problems and jeopardize the mission before it even starts. With the incoming 3.45 MW of waste heat and space environmental considerations, the radiators must be sturdy enough to withstand the moment generated during the initial chemical burn, be resistant to the space environment, have a long lifecycle, and consist of materials capable of withstanding extreme temperatures. An important consideration for radiator design was a deployment mechanism as it solves two major issues posed by a rigid array. A deployment mechanism is necessary to fit within the Starship payload-bay fully assembled. This minimizes in-space assembly. During chemical burns, the power generation system will not be operating, and the radiators can be stowed. This saves on structure weight as the stowed modules have a minimal moment arm. Four modules of deployable radiators will be mounted on the sides of the spacecraft in a cruciform pattern shown in figure 29 below.

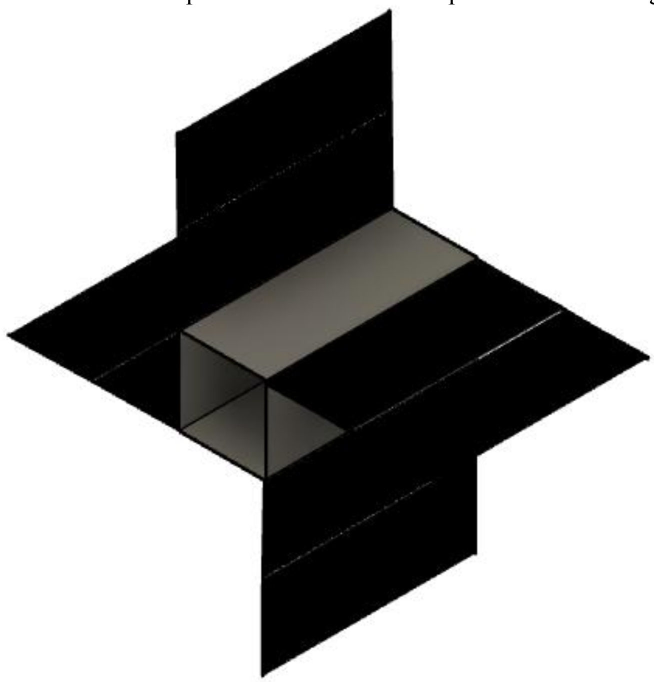


Fig. 26 Four Radiators Modules in Fully Deployed state.

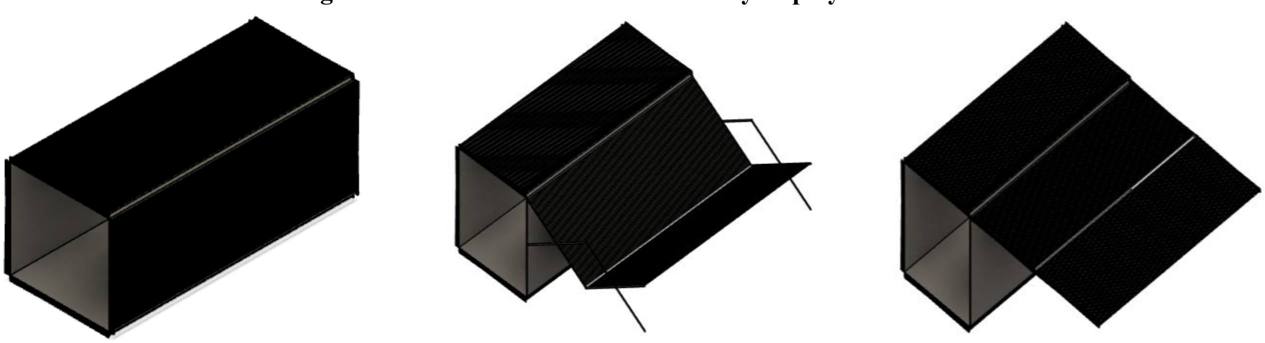


Fig. 27 Stowed, Partially Extended, & Fully Extended Radiator Module.

As shown in figure 30 the radiator modules use a scissor lift mechanism to deploy which provides excellent compaction and extension range between packed and stowed configurations. While stowed during chemical burns, the moment arm of the radiator module is small, greatly reducing structure weight. Consisting of Ti-H_2O heat pipes and carbon fiber polymer panels, the radiators are designed to meet the needs of the mission.

VII. Structural Supports

The structural components of the rocket are split into three sections, the life support trusses, chemical stage trusses, and the electrical stage trusses. The life support structural trusses are comprised of six different exterior attachments: two International Docking Adapters (IDA), Zvezda radiators, ISS Roll Out Solar Array (IROSA), communications antennae, Zvezda to nuclear reactor radiator truss, and the Zvezda to Oxygen tank truss. The structural trusses for the chemical stage components are comprised of four different designs based on the assembly of the tanks. The chemical tanks require two external sets of tank rings, connector beams, tank engine mounts connectors, and interstage piping trusses. Finally, the structural trusses for the electrical stage components are comprised of two different designs based on the assembly of the Argon tank, VASMIR, and O2 tanks. The electrical stage components require two sets of trusses: Argon to VASMIR connection and Argon to O2 connectors. All the structural components listed are manufactured of Aluminum 2090-T83, which is a space-grade aluminum will low density to high strength ratio that can withstand 10.5 MN of thrust. For more information regarding the truss design, placement, material, and structural analysis, see the *Truss Report*.

VIII. Zvezda

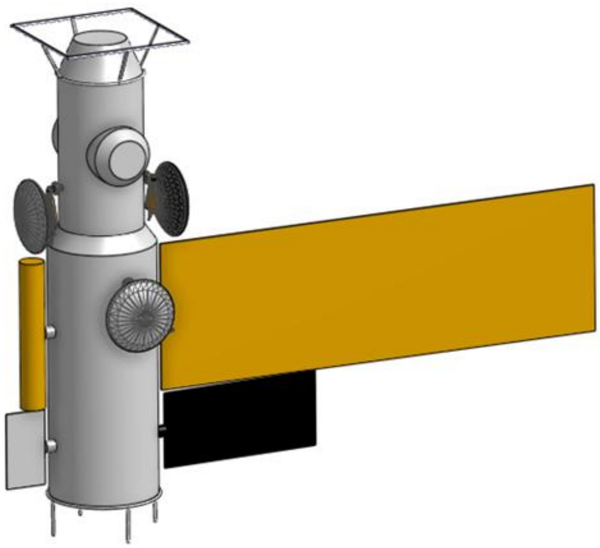


Fig. 28 Zvezda Module

The Zvezda module is the life support habitat for the astronauts on the transfer trip to the Mars station. The goal of a life module is to protect the astronauts from deep space radiation, and to maintain the necessary life-supporting conditions for astronauts, including providing breathable oxygen, regulating temperature, managing waste, filtering air, and supplying potable water, etc. The astronauts must be able to live and work in space during travel.

The Zvezda module design is comprised of four exterior shells to protect the astronauts from deep space radiation: an aluminum inner shell, a Polyethene shell, an aluminum outer shell, and a mylar shell with thickness of 0.25 cm, 9 cm, 0.25 cm, and 0.00045 cm respectively. The radiation shield weighs 25,103 kg. Accounting for the variation in thickness and the internal components, the total mass is 35,939 kg. Accounting for food, water, and oxygen, the total mass is 41,689 kg. Labor cost estimates for the Zvezda were based on commercial spacecraft research, design, and operating costs, where the average percentage of NASA funds used on R&D to be 14.08%. After combining the total project cost to manufacture the Zvezda, and extended logistics modules, an estimated cost was found to be $1.216 billion.

The Zvezda habitat is comprised of five main subsystems, life support systems, flight systems, personal care systems, power systems, and safety systems. Fig – depicts a flow diagram of the Zvezda subsystems.

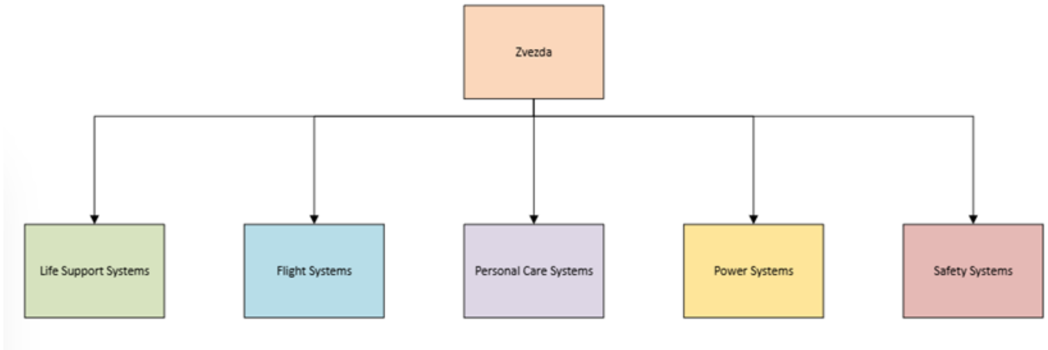


Fig. 29 Zvezda Subsystem Flow Diagram

The life support systems in the Zvezda are comprised of two oxygen generation systems, one water generation system, and one heat distribution system. The two oxygen generation systems are the Advanced Closed Loop System and the Russian Elektron-VM System. Water is primarily generated using products from the onboard hydrogen fuel cells. However, 100 kg of water will also be brought pre-launch to assist in starting the oxygen systems. The flight system is comprised of three main components, communications systems, the flight control system, and the navigation system. The communications subsystem is made up of three main components: the flight computer, Mn553-2000 data bus, and the MRO communications module. The flight control system and navigation systems are designated within the flight computer, but each has different purposes. The flight control system is a dashboard setup where the astronauts can find all information regarding the rocket, including fuel temperature, speed, oxygen levels, etc. The personal care system is comprised of three main components, the galley table, exercise machinery, and the sleeping quarters. The galley table is the main component of this subsystem, since it acts as a water dispenser and a food warmer for astronauts. The exercise machinery consists of a treadmill, the vela ergometer, and the Advanced Resistive Exercise Device (ARED). The living quarters for the astronauts include the sleeping quarters and the bathrooms. The power systems for the Zvezda are comprised of the Roll-Out Solar Array (ROSA), the nuclear reactor supplement, and the fuel cell. Information about the nuclear reactor can be found in the *Reactor Report*. In addition, information regarding the fuel cells can be found in the *Power Distribution Report*. Finally, the safety systems on the Zvezda include, over cabin lights, necessary medical equipment, and a smoke detector. For more information regarding the Zvezda design, specific details of the subsystems, see *Zvezda Report.*

IX. Assembly

The components of the Warden were required to be sent up to the ISS for assembly. This process would take 18 launches as described in the Launch Vehicle Report. While these components would be aboard Starship, unique fixtures needed to be designed for each payload to ensure safe travel to the ISS. These fixtures were designed to hold the payload objects in place through their journey to the ISS, restricting movement in all directions and minimizing vibrations. Stainless steel 304 ½ Hard was chosen for all the fixtures' material because of its high yield strength and manufacturability costs. These fixtures were modeled to fit each payload specifically and can be seen in Figure 32. The contents of each payload can be seen in Table 2.

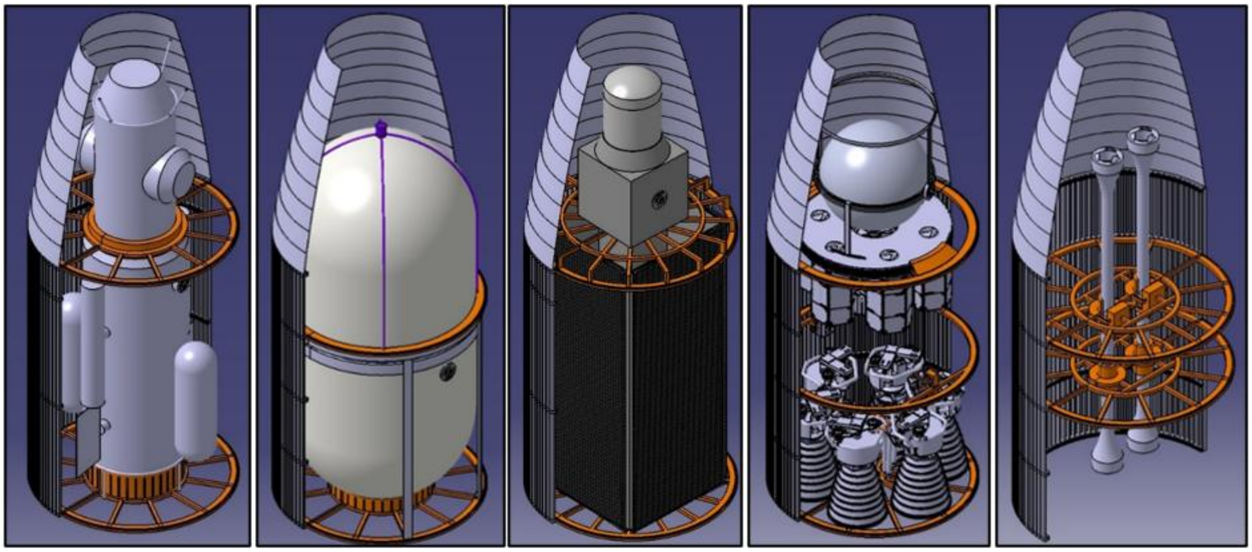


Fig. 30 Models of rocket modules held by their fixtures in Starship payload bay

Once arrived at the ISS, the Canadarm2 and JEMRMS robot arms will be used to unpackage the payloads from Starship, orient them in the correct manner, and assemble them piece by piece. The Flight Ready Grapple Fixture will be welded to each payload to give the robot arms a spot to latch onto and be able to move the objects. Astronauts onboard the ISS would also be involved in the assembly process, primarily using Pistol Grip Tools to drive bolts and laser welding to bond various objects and trusses together.

Before the rocket assembly begins, two booms will be brought to the ISS and mounted at its end and midpoint to provide docking points for the rocket assembly. The first part of the rocket to be launched is the electrical assembly. This module will first be mounted to the boom at the end of the ISS using the aforementioned robot arms. The life habitat module follows, and this will be attached to the bottom of the electrical assembly through a combination of robot arms and welding. The top central oxygen tank would then be welded to the bottom of the life habitat in a similar manner. One oxygen tank and two hydrogen tanks will follow, with all three welded to the central oxygen tank on the side within reach of Canadarm2 (the face between the rocket and ISS). Next, another oxygen tank will be launched and welded to the bottom of the top central oxygen tank. Three more hydrogen tanks will then be brought up and welded to the bottom oxygen tank in the same configuration as the top layer. The RCSs on the Zvezda will then be used to perform a 180 degree rotation of the entire rocket assembly. Once complete, the last oxygen tank and the remaining five hydrogen tanks will be brought up. They will be welded to the centra oxygen tanks to complete a top and bottom layer of a hexagonal pattern of tanks. The last launch includes the VASMIR engine assembly, two RCSs to be mounted to opposite hydrogen tanks, and the RS-25 engine assembly. The VASIMR engines will first be welded to the bottom of the bottom central oxygen tank, followed by the RS-25 engines being bolted to the bottoms of the six hydrogen tanks. Astronauts will mount and weld the RCSs manually. All wiring and piping connections throughout the modules will be completed by the astronauts. For a more detailed assembly process, see the Assembly Report.

X. Mission Expenditures

Part	Subpart	Power (Watts)	Cost($)	Mass (kg)	Quantity	Total Cost ($)	Total Mass (kg)	Total Power (W)
Control System Sensors	ASTRIX Gyroscope		250,000	5	1	250000	5	0
	Fluxgate Magnetometers		35000		7	245000	N/A	0
Valve	Brooks Quantim Coriolis Controller	0	250	0.75	14	3500	10.5	0
Mass flow controller	Brooks Quantim Coriolis Controller	15	4000	2.4	1	4000	2.4	15
Filter	Mott GSP040FF2	0	300	0.35	8	2400	2.8	0
Sensor	Omega PX309-3KG5V Pressure Transducer	0.75	440	0.154	9	3960	1.386	6.75
Sensor	Omega RTD-NPT-72-E Temperature Sensor	0	160	0.12	9	1440	1.08	0
Piping Material	316L Stainless Steel Pipe (1/4" OD)	0	1.51	0.64	23	34.73	14.72	0
Piping Fittings	Swagelok VCR® Fittings (SS-4-VCR-6-600)	0	75	0.15	8	600	1.2	0
Flexible Connections	Swagelok FM series metal hose assemblies	0	150	3.6	8	1200	28.8	0
Sensor	Brooks Instrument Quantim Coriolis Flow meter	15	4000	2.4	9	36000	21.6	135
Wire	GORE Space Cables Type SPP (ESCC 3901/017)	0	1100	2.85	30	33000	85.5	0
Propellant Tank	Ti-6Al-4V tank	0	290000	4986.3	1	290000	4986.31	0
Vasimr Assembly	Total Hex Configuration Mount	0	850000	4283	1	850000	4283.01	0
Electric Engine	VASIMR VX-200SS System	200000	1964285.71	815.2	7	13750000	5706.4	1400000
						15471134.7	15150.706	1400157

Fig. 31 Electrical Propulsion System Bill of Materials

Items	Qty		Cost ea.	Mass ea.	Total Cost	Total Mass
Propellant (liq.) Actuated Valve	22		$ 20,000	12	$ 440,000.00	264
Pressurant (gas) Actuated Valve	9		$ 10,000	5	$ 90,000.00	45
Mass Flow Sensor	20		$ 30,000	8	$ 600,000.00	160
Temperature Sensor	20		$ 5,000	0.2	$ 100,000.00	4
Pressure Transducer	27		$ 5,000	0.4	$ 135,000.00	11
Check Valve	41		$ 8,000	2.5	$ 328,000.00	103
Relief Valve	9		$ 6,000	2	$ 54,000.00	18
Pressure Regulator	9		$ 15,000	3.5	$ 135,000.00	32
Actuated Purge Valve	12		$ 10,000	6	$ 120,000.00	72
Flow Restrictor	12		$ 2,000	1.5	$ 24,000.00	18
3-way port	9		$ 10,000	7.5	$ 90,000.00	68
RS-25	6		$ 146,000,000	3396	$ 876,000,000	20,376
Titanium (h)	1754	*kg/tank*	$ 21	1	$ 365,709	17,540
CFRP (h)	3421	*kg/tank*	$ 100	1	$ 3,421,000	34,210
Titanium (O)	1754	*kg/tank*	$ 21	1	$ 146,284	7,016
CFRP (O)	3421	*kg/tank*	$ 100	1	$ 1,368,400	13,684
Cryocoolers (h)	2	*/tank*	$ 64,000	301	$ 1,280,000	6,020
Cryocoolers (O)	2	*/tank*	$ 17,000	221	$ 136,000	1,768
Manufacturing		*/tank*	$ 2,000,000		$ 28,000,000	
			Chemical Subtotal		**$ 912,833,393**	**101,407**

Fig. 32 Chemical Propulsion System Bill of Materials

Items	Components	Qty	Mass Tot.(Kg)	Cost ea.($)	Total Cost($)
Zvezda Shell	Aluminum T6-2219 Inside (0.5cm)	1	1789.551725	16	28632.8276
	Polyethylene (18 cm)	1	21269.90823	0.9	19142.91741
	Aluminum T6-2219 Outside (0.5cm)		2042.784153	16	32684.54645
	Mylar (0.00045 cm)	1	0.816844	0.51	0.41659044
Zvezda	Plans + Labor + Inside	1			1216000000
Supply	Food	1	5000	262	1310000
	Water Container	1	424	1642	1642
Truss	Tank Rings	8	4086.208	16	65379.328
	Connector Beams	12	281.448	16	4503.168
	Engine Mount	6	9569.232	16	153107.712
Total			44463.94895		1217615093

Fig. 33. Structure and Life Support System Bill of Materials

Part	Quantity	Total Mass (kg)	Cost ea.	Total Cost
Reactor	1	3580	$ 25,000,000.00	$ 25,000,000.00
Radiators	1	2000	$ 3,500,000.00	$ 3,500,000.00
Shield	1	9011.6264	$ 5,118,000.00	$ 5,118,000.00
Wiring	1	2806.5	$ 26,690.00	$ 26,690.00
Buses	1	21.12	$ 300.00	$ 300.00
Boom	1	500	$ 10,000.00	$ 10,000.00
Fuel Cells	6	25.4	$ 50,000.00	$ 300,000.00
Solar Panels	1	325	$ 16,670,000.00	$ 16,670,000.00
temperature sensors	16	Negligeable	$ 99.26	$ 1,588.16
High temp pressure sensors	2	Negligeable	$ 8,000.00	$ 16,000.00
low temp pressure sensors	12	Negligeable	$ 2,000.00	$ 24,000.00
rmp sensors	4	Negligeable	$ 5,000.00	$ 20,000.00
multimeter	6	Negligeable	$ 5,000.00	$ 30,000.00
TOTALS:		18269.6464		$ 50,716,578.16

Fig. 34 Electrical Power System Bill of Materials

XI. References

[1] European Space Agency, "International Space Station Overview."