Concept Design Report

PATHfinder

(Platform for Aerospace Technology Heritage)

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Abstract

As humanity prepares for sustained deep-space exploration under the Artemis program, the development of reliable, autonomous bioregenerative life-support systems has become a critical technology gap. With the cessation of funding for International Space Station (ISS) biological payloads in 2025 and the station's impending de-orbit, the scientific community faces a stagnation in microgravity plant research. To address this capability gap and overcome the Size, Weight, and Power (SWaP) limitations of previous large-scale demonstrators, this document presents the Critical Design Review (CDR) for the **Pathfinder** mission.

Pathfinder is defined not as a biological experiment, but as a technology demonstrator designed to validate the mechanical and software infrastructure required for space agriculture. Constrained to a 3U CubeSat payload form factor, the system isolates and verifies three critical Environmental Control System (ECS) functions: precision water delivery in microgravity, closed-loop atmospheric climate control, and autonomous fault-tolerant operations. The architecture integrates a central On-Board Computer (OBC) with a dedicated power actuation Controller Board to manage a suite of thermal, fluid, and illumination subsystems within a sealed, 1-atm pressure vessel.

This review details the system design, structural analysis, and operational logic required to raise the Technology Readiness Level (TRL) of these subsystems. Through a comprehensive verification campaign involving laboratory ground testing and High-Altitude Balloon (HAB) flight, Pathfinder aims to de-risk the hardware architecture, ensuring that future biological missions are built upon a validated, scalable, and autonomous platform.

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1. Introduction

1.1 The Problem

NASA’s Artemis program represents humanity’s next major effort to establish a sustained presence beyond Earth. A critical requirement for maintaining crews during deep space missions is the development of reliable bioregenerative life-support systems capable of food production, oxygen regeneration, and psychological stabilization. While the International Space Station (ISS) previously supported this research through facilities such as "Veggie" and the Advanced Plant Habitat, funding for these specific biological payloads ceased in 2025. Consequently, the research platform is no longer operational, and no active science is currently being conducted by on-station astronauts.

This cessation of funding, combined with the planned de-orbit of the ISS, creates an immediate capability gap. Without an active platform to validate biological life-support systems, technological development has stagnated. Furthermore, previous attempts to address this, such as FAU’s 12U "Cube Plant" platform, encountered significant hurdles regarding size, weight, and power (SWaP) constraints. The complexity of attempting a full-scale biological mission without first validating the underlying support subsystems resulted in high implementation costs and integration challenges. Therefore, a need exists for a dedicated, cost-effective platform to validate the mechanical and autonomous infrastructure required for plant growth before full-scale biological research resumes.

1.2 Project Scope

The scope of the Pathfinder project is strictly limited to the design, development, and verification of a research payload compliant with a 3U CubeSat form factor. The project boundaries exclude the development of the satellite bus, propulsion, and attitude determination and control systems (ADCS). The primary directive, defined by the Mission Statement is:

> **MS-1:** Create a CubeSat Payload for testing Environmental Control System (ECS) subsystems to facilitate plant research in space.

The payload is designed to operate within a laboratory setting, a ground-based simulated space environment, or a High-Altitude Balloon (HAB) flight. These environments serve to distinguish testing levels, ranging from single-variable laboratory tests to the multi-variable stresses of a HAB flight. The HAB flight serves as a critical validation step; recovery of the payload after flight allows for the verification of subsystem performance in a near-space environment.

The technical scope is driven by three specific Mission Objectives (MO), defined as follows:

> **MO-1:** Demonstrate water delivery in a space-like environment.

MO-2: Demonstrate climate control in a space-like environment.
MO-3: Demonstrate autonomous ECS operation in a space-like environment.

To satisfy these objectives, the payload design integrates a water delivery system, an Atmospheric Climate Control System, and a custom computer program designed to automatically maintain ECS parameters. Successful completion of this scope is defined by the system's ability to maintain specified climate and hydration ranges autonomously during the testing durations defined in the Mission Success Criteria.

1.2.1 Mission Success Criteria

To validate the achievement of the Mission Objectives defined above, specific success criteria have been established. These are categorized into Minimum Success Criteria (MSC), Full Success Criteria (FSC), and Stretch Success Criteria (SSC).

Mission Objective 1 (MO-1) Success Criteria *Demonstrate water delivery in a space-like environment.*

MSC-1: Perform initial water saturation (IWS) within specified ranges during a 3-day test within a laboratory or ground-based simulated space environment.

FSC-1: Maintain water delivery within specified ranges during a 7-day test within a laboratory or ground-based simulated space environment.

SSC-1: Maintain water delivery within specified ranges during a 14-day test within a laboratory or ground-based simulated space environment.

Mission Objective 2 (MO-2) Success Criteria *Demonstrate climate control in a space-like environment.*

MSC-2: Maintain ECS climate control parameters within specified ranges during a 3-day test within a laboratory or ground-based simulated space environment.

FSC-2: Maintain ECS climate control parameters within specified ranges during a 7-day test within a laboratory or ground-based simulated space environment.

SSC-2: Maintain ECS climate control parameters within specified ranges during a 14-day test within a laboratory or ground-based simulated space environment.

Mission Objective 3 (MO-3) Success Criteria *Demonstrate autonomous ECS operation in a space-like environment.*

> **MSC-3:** ECS operates autonomously in a controlled laboratory environment during a 3-day test, maintaining climate control and water delivery within specified ranges.
>
> **FSC-3:** ECS operates autonomously in a controlled laboratory environment during a 7-day test, maintaining climate control and water delivery within specified ranges.
>
> **SSC-3:** ECS operates autonomously throughout a high-altitude balloon flight, maintaining all climate control and water delivery functions within specified ranges.

1.3 Concept of Operation

The Pathfinder payload operates as a Finite State Machine (FSM) designed to prioritize system safety and power efficiency. The operational logic is strictly governed by a unidirectional promotion protocol for higher-power states: transitions that increase power consumption or initiate irreversible actions require manual commands via the Ground Support Equipment (GSE) interface. Conversely, transitions to lower-power safety states can be executed autonomously by the Onboard Computer (OBC) upon fault detection.

The operational lifecycle is visualized in **Figure 1**, followed by the specific environmental targets per mode in **Figure 2**.

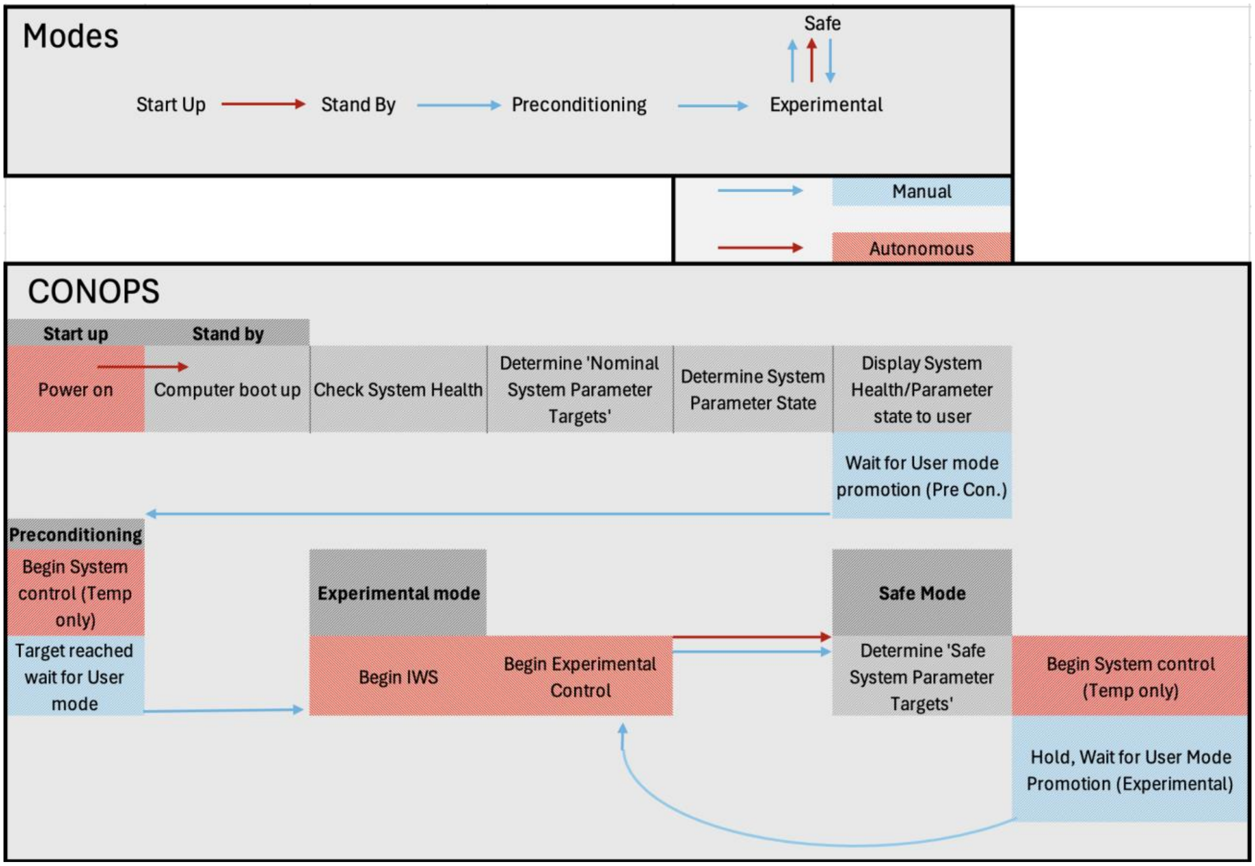


Figure 1: Pathfinder Operational Modes and Concept of Operations Flow. Blue arrows indicate manual user promotion; red arrows indicate autonomous or manual transitions to safety states.

PATHfinder — Modes & Parameters (Target + Band per Mode)

Parameter	Unit	Sensor (generic)	Control	fs (Hz)	Preconditioning		Experimental		Safe		Notes
					Target	Band	Target	Band	Target	Band	
Temperature	°C	Thermistor	PID Heat/Cool	1	20	±2	20	±2	20	±5	Primary chamber temperature.
Pressure	kPa	Barometer	—	0.5	—	—	—	76-101	—	—	
Lighting	$\mu mol \cdot m^{-2} \cdot s^{-1}$ (PAR)	Lux Sensor	PWM Duty Profile	0.25	—	—	120	400 – 600	—	—	Use PPFD (not lux). DLI offline = $\int PPFD\, dt / 10^6$.
CO_2	ppm	CO_2 sensor	—	0.5	—	—	—	400-8000	—	—	
Relative Humidity	%RH	T/RH sensor	—	0.5	—	—	—	20-60	—	—	Monitored; not closed-loop in v1.
Airflow (Wind)	cm/s	Anemometer	PWM Duty Profile	1	—	—	10	±5	—	—	Can be used to diffuse thermal energy
Soil Moisture (VWC)	m^3/m^3	Capacitive probe	Proportional	0.1	—	—	0.6	0.5-0.7	—	—	Discrete watering; volume verified by WDS.

Figure 2: Pathfinder Modes & Parameters Definition Table, detailing target setpoints and control bands for each operational phase.

1.3.1 Operational Phases

The system uses a logic flow that guides the payload from initialization to full experimentation through the following phases:

1. Start-Up and Standby: Operations begin with the "Power On" signal. The OBC initiates a boot sequence, performs a System Health Check to validate sensor connectivity, and loads the "Nominal System Parameter Targets."

- **System Behavior:** Once initialized, the system enters **Standby Mode**. In this state, the payload is passive; no actuators are powered.
- **User Interface:** The GSE Graphical User Interface (GUI) displays the current system state and telemetry using a color-coded status indicator (Green/Red) for rapid visual assessment. The system remains in Standby until a manual "Mode Promotion" command is received.

2. Preconditioning (Thermal Stabilization): Upon manual promotion, the system enters **Preconditioning Mode**. This phase is critical for stabilizing the internal environment if the payload is starting from a "cold-soak" or frozen state.

- **System Behavior:** Control is limited to the thermal subsystem. Heaters actively drive the internal temperature toward the nominal target of 20°C (±2°C). Depending on the initial thermal state, this phase may last from a few minutes to over 12 hours.
- **Constraints:** Hydration and lighting subsystems remain disabled to conserve power. The system holds at the target temperature until the user manually promotes the system to the next phase.

3. Experimental Mode: This mode represents the primary mission activity. Transitioning to Experimental Mode initiates the **Initial Water Saturation (IWS)** sequence.

- **Irreversible Action:** The IWS sequence delivers 25 mL of water to the seed substrate. This is a critical, irreversible milestone; once the seeds are saturated, the biological payload requires strict environmental maintenance to survive.
- **System Behavior:** Following IWS, the system activates full closed-loop control. It maintains temperature, lighting, airflow, and soil moisture according to the "Experimental" targets defined in **Figure 2**.

4. Safe Mode (Fault Protection): Safe Mode is a fallback state designed to preserve the biological subject while minimizing power draw.

- **Triggers:** This mode is entered autonomously if the OBC detects a critical fault (e.g., thermal runaway, sensor failure) or manually by the user.

- **System Behavior:** Non-essential subsystems (such as lighting) are disabled. Thermal control bands are widened from ±2°C to ±5°C to reduce heater duty cycles. The system maintains these "keep-alive" parameters until the operator assesses the telemetry and manually commands a return to Experimental Mode.

1.4 System Level Requirements

The System Level Requirements represent the technical translation of the Mission Objectives into quantifiable engineering specifications. These requirements serve as the primary criteria for determining mission success.

It is noted that the requirements listed in **Figure 3** are presented in no particular order of importance. All entries are considered critical to mission success; failure to meet any single requirement or constraint constitutes a failure to meet the system design intent and mission assurance standards. Each requirement has been formulated to be Specific, Measurable, Achievable, Relevant, and Traceable (SMART). To ensure full traceability throughout the project lifecycle, verification methods and status tracking are maintained for every entry.

System Requirements							
Number	**Requirement**	**Source**	**Type**	**Verification Method**	**Status**	**Verification Document**	**Comments**
SYSr-1	The system shall maintain all environmental parameters (temperature, pressure, humidity, CO_2, soil moisture and lighting) within the defined target ranges for each operational mode.	MO-1, MO-2	Functional	Testing	Not Complete	Modes & Parameters Table	Defines baseline environmental control capability.
SYSr-2	The system shall measure and record all environmental and actuator data at or above the minimum sampling frequency defined for each parameter (≥ 0.25 Hz).	MO-2, MO-3	Functional	Testing	Not Complete	Modes & Parameters Table	Enables closed-loop control and verification of environmental stability.
SYSr-3	The system shall only promote to higher-power operational modes (Preconditioning or Experimental) upon valid manual command from the onboard computer interface.	MO-3	Safety	Testing	Not Complete	CONOPS	Prevents unintended mode transitions or over-power conditions.
SYSr-4	The system shall autonomously enter Safe Mode within 5 s of detecting a fault or uncontrolled parameter deviation beyond safe limits.	MO-3	Safety	Testing	Not Complete	Fault Response Plan	Defines automatic fallback protection and ensures ECS survivability.
SYSr-5	The system shall deliver 25 ± 2 mL of water to the substrate during Initial Water Saturation at the start of Experimental Mode.	MO-1	Functional	Testing, Inspection	Not Complete	Water Delivery Test	Supports initial plant substrate conditioning for controlled experimentation.
SYSr-6	The system shall maintain nominal operation for a continuous minimum of 7 days under stable laboratory conditions.	MO-1, MO-2, MO-3	Functional	Testing, Analysis	Not Complete	Endurance Test Plan	Demonstrates system stability and environmental control endurance.
SYSr-7	The system shall provide a user interface displaying real-time environmental parameters, target setpoints, and mode status through a graphical interface.	MO-3	Functional	Inspection, Testing	Not Complete	Interface Control Document	Enables user monitoring and com

Figure 3: Pathfinder System Functional Requirements Matrix, detailing the specific performance criteria derived from Mission Objectives.

1.5 Constraints

The System Design Constraints define the strict boundary conditions within which the payload must be designed. These are driven by physical limitations, safety mandates, and compatibility requirements with the 3U form factor and launch providers.

As detailed in **Figure 4**, these constraints encompass the mass, volume, material, and safety restrictions required to ensure compliance with NASA CSLI and University Nanosatellite Program (UNP) standards. Adherence to these constraints is mandatory for payload integration and launch eligibility.

System Constraints						
Number	**Requirement**	**Source**	**Verification Method**	**Status**	**Verification Document**	**Comments**
SYSc-1	The ECS payload shall not exceed [100 × 100 × 160 mm] external dimensions, consistent with a 3U CubeSat form factor.	Mission Constraint	Inspection, CAD	Not Complete	CAD Model Verification	CubeSat envelope constraint.
SYSc-2	The total mass of the ECS payload shall not exceed 3 kg.	Mission Constraint	Mass Budget	Not Complete	Mass Budget Sheet	Limits overall payload weight for balloon or CubeSat integration.
SYSc-3	ECS shall not incorporate steel, lead, tungsten, or other high-density or high-melting-point metals, except where explicitly approved for structural or thermal purposes.	UNP Nanosatellite User Guide – Materials Restrictions	Inspection, Materials Certification	Not Complete	Materials Log	Restricts use of materials that pose integration or safety issues during environmental testing or launch. Ensures compatibility with UNP and launch provider standards.
SYSc-4	The ECS shall not contain sealed or pressurized volumes exceeding 1 atm relative to ambient conditions.	Safety Constraint	Inspection	Not Complete	Pressure Compliance Check	Prevents pressure hazard during ascent or vacuum exposure.
SYSc-5	The ECS shall not use welding as a structural joining method.	Manufacturing Constraint	Inspection	Not Complete	Assembly Plan	Enables modularity and re-assembly for subsystem testing.
SYSc-6	The ECS will be exposed to vacuum conditions during environmental testing.	MO-2	Testing	Not Complete	Environmental Test Procedure	Simulates operational environment for ECS validation.
SYSc-7	The ECS will be subjected to cold-soak temperatures down to −60 °C during environmental testing.	MO-2	Testing	Not Complete	Thermal Vacuum Test Report	Confirms survivability under relevant temperature extremes.
SYSc-8	The ECS shall comply with NASA CSLI payload environmental and safety guidelines.	MS-1	Inspection	Not Complete	NASA CSLI Compliance Checklist	Ensures payload readiness for future CubeSat launch heritage.
SYSc-9	The ECS shall not use epoxies, adhesives, or tape as a primary load-bearing structural joining method.	UNP12-14	Inspection	Not Complete	Nanosatellite 12 User Guide	
SYSc-10	The ECS shall use threaded fasteners with torque control and a secondary method of back-out prevention (Loctite, helicoil, staking, etc.).	UNP12-22	Inspection	Not Complete	Nanosatellite 12 User Guide	Ensures retention integrity under vibration.

Figure 4: Pathfinder System Design Constraints Matrix, defining the physical and environmental limitations of the payload.

2. Design Conceptualization

2.1 Functional Analysis

The Environmental Control System (ECS) payload is designed to autonomously regulate and monitor the environmental conditions necessary for plant research within a controlled, sealed environment. Its primary function is to enable the testing of Environmental Control Subsystems

(ECS subsystems) that together replicate the critical life-support parameters a plant would experience in a space environment.

This analysis identifies the key system functions, allocates them to subsystems, and traces them to the operational modes defined in the Concept of Operations (Section 1.3). The ECS operates through five sequential modes—Startup, Standby, Preconditioning, Experimental, and Safe Mode—each of which engages specific subsystem functions to achieve mission objectives.

System-Level Functional Overview

At the system level, the ECS performs three major functions derived from the mission objectives:

1. ***Environmental Regulation:*** Maintain temperature, lighting, and soil moisture within target ranges defined in the Modes & Parameters definition.
2. ***Water Delivery:*** Deliver precise volumes of water to the plant substrate during Initial Water Saturation (IWS) and maintain soil moisture during long-term operation.
3. ***Autonomous Operation and Data Handling:*** Monitor all environmental and actuator parameters, execute control commands, log and store data, and enter Safe Mode when deviations occur.

Each major function is supported by a dedicated subsystem, detailed in 2.1.1.

2.1.1 Subsystem Functional Breakdown

1. On-Board Computer (OBC):

Acts as the central controller for all ECS operations, responsible for command execution and user feedback.

- **Graphical User Interface (GUI):** Generates a high-legibility interface designed for rapid situational awareness. The GUI displays critical telemetry—including Mission Elapsed Time (MET), current Operational Mode, and real-time sensor data—alongside their target setpoints. It utilizes clear visual indicators (e.g., Green/Red color coding) to immediately relay System State (Nominal vs. Off-Nominal) to the operator.
- **CONOPS Execution:** Manages the finite state machine logic, controlling transitions between Startup, Standby, Preconditioning, Experimental, and Safe modes.
- **Sensor Interface:** Reads data from the Climate Control and Water Delivery subsystems at defined sampling frequencies.
- **Actuator Control:** Sends control signals (PWM or digital) to heaters, fans, LEDs, and pumps based on closed-loop logic.

- **Data Logging:** Performs timestamping and storage of all environmental and actuator data for post-mission analysis.
- **Fault Protection:** Implements Safe Mode protocols by disabling non-critical functions if parameters deviate from safety thresholds.

2. Climate Control System (CCS):

The CCS is responsible for atmospheric regulation and monitoring gas exchange.

- **Thermal Regulation:** Regulates temperature through two heating elements (one near the water reservoir and one in the air chamber).
- **Lighting Control:** Controls lighting through a PWM duty-cycle profile to provide the target photosynthetic photon flux density (PPFD).
- **Air Circulation:** Utilizes two counter-rotating fans to achieve three critical functions:
  - Ensuring thermal uniformity within the volume;
  - Disrupting the leaf boundary layer to prevent oxygen stagnation and ensure adequate CO_2 delivery to the stomata; and
  - Canceling angular momentum to ensure zero net torque is imparted to the host satellite.
- **Monitoring:** measures temperature, humidity, CO_2 concentration, and lighting intensity, reporting to the OBC at greater than 0.25 Hz.

3. Water Delivery System (WDS):

The WDS stores and delivers water from a flexible reservoir to the plant substrate via tubing and a miniature peristaltic DC pump.

- **Initial Water Saturation (IWS):** Performs the critical one-time wetting event at the start of Experimental mode.
- **Moisture Maintenance:** Maintains soil volumetric water content (VWC) within the defined range (0.5–0.7 m^3/m^3) using feedback from a capacitive soil-moisture probe.
- **Telemetry:** Reports delivery events and reservoir temperature to the OBC.

4. Electrical Power System (EPS):

The EPS acts as the power distribution unit and physical actuation interface for the payload.

- **Distribution:** Distributes regulated 12 V, 5 V, and 3.3 V power rails to all subsystems.
- **Controller Board:** Integrates a dedicated PCB that houses the power MOSFETs and driver circuitry. This board serves as the bridge between the OBC and the physical hardware; the OBC sends logic-level signals to the Controller Board, which then gates the necessary power to actuate heaters, pumps, and fans.

- **Protection:** Provides power conditioning, active current-limiting, and physical fusing to protect against over-current events. Includes reverse-polarity protection for integration safety.
- **Budget Management:** Ensures total ECS power consumption remains within the defined power budget (≤ 3.5 W continuous).

5. Structural Assembly

The structure provides mechanical support and environmental isolation.

- **Manufacturability:** Designed for rapid production using standard stock materials to minimize machining time and complexity.
- **Integration:** Integrates feedthrough ports for power and data lines between internal components and external interfaces while maintaining hermetic sealing of the internal environment.
- **Compliance:** Ensures compliance with CubeSat form-factor and mass constraints (3U, ≤ 4.5 kg).
- **Survivability:** Supports environmental survivability under vacuum and thermal cycling (down to –60 °C).

2.1.2 Functional Interactions and Control Logic

The subsystems function as an integrated control loop managed by the OBC. As illustrated in **Figure 5**, the system operates on a continuous "Sense-Decide-Actuate" cycle:

- **Sense:** CCS and WDS sensors measure environmental conditions and send data to the OBC.
- **Decide:** The OBC processes inputs, compares them against the target parameters defined in Section 1.3, and determines necessary control actions.
- **Actuate:** The OBC commands the EPS to power actuators in the CCS and WDS as required to restore nominal conditions.
- **Protect:** The OBC continuously enforces safety constraints across all modes. As defined in the CONOPS, if the Temperature drops below <15 degrees Celsius during initialization, the system enters the Preconditioning loop (Heating). If this deviation occurs during Experimental Mode, the system flags a fault and transitions to Safe Mode.

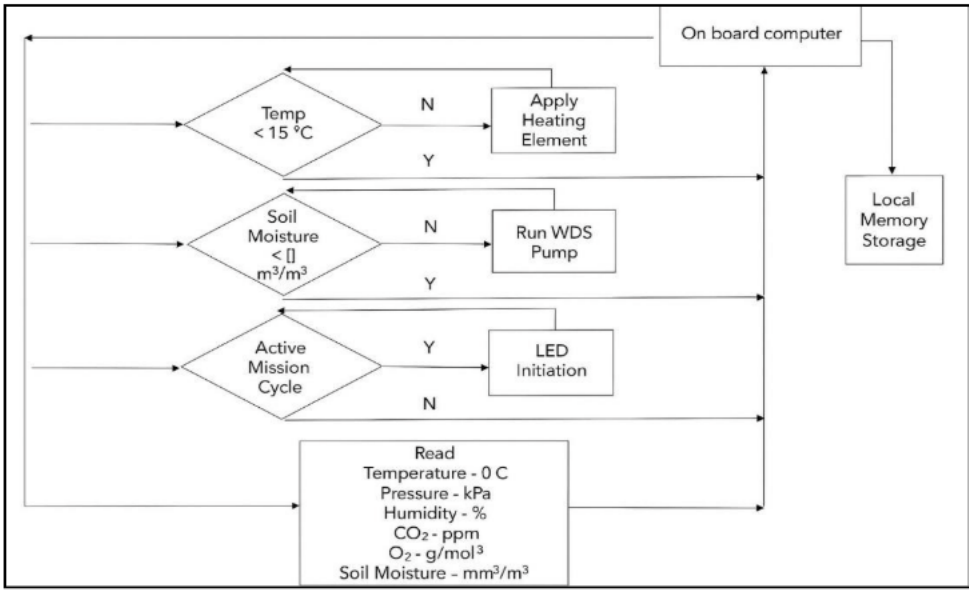


Figure 5: Experimental Mode Closed-Loop Logic Flow. This diagram illustrates the autonomous decision-making process for thermal, hydration, and lighting control.

2.2 Functional Flow Diagram

The Environmental Control System (ECS) functions as a closed-loop network centered on the On-Board Computer (OBC), which continuously monitors, evaluates, and adjusts the environment within the experimental chamber. As illustrated in **Figure 6**, the system architecture combines a centralized electrical topology with a nested physical configuration.

System Logic and Control: Sensor data from the Climate Control System (CCS) and Water Delivery System (WDS) are sampled at the frequencies defined in the Modes and Parameters definition and relayed to the OBC for processing. The OBC compares each measurement against mode-specific targets and issues corrective commands (PWM or digital) to the heaters, fans, lighting array, and water pump to restore nominal conditions.

Physical and Functional Hierarchy: The system is physically structured as a set of isolated environments, represented by the nested relation in **Figure 6**:

- **Inner Loop (WDS):** The Water Delivery System manages the interactions between the water pump, water bladder and the plant bay containing the growth-soil-medium and test seeds.
- **Middle Loop (CCS):** The Climate Control System creates the atmospheric volume that encapsulates the biological subject.
- **Outer Loop (Structure):** The ECS Structure provides the physical barrier, hermetically sealing the inner environments from external conditions.

Power and Interaction: Power is distributed by the Electrical Power System (EPS), which supplies regulated voltage to all subsystems while monitoring current draw. The OBC serves as the central processor for this flow, interpreting environmental data and commanding actuators to maintain experimental stability. If parameters deviate beyond safety limits, the OBC executes a fallback response by entering Safe Mode.

Subsystem interactions are defined as follows:

- **CCS ↔ OBC:** Bidirectional flow of sensor data (Temp, Light, Airflow, CO_2) and actuator commands (Heaters, LEDs, Fans).
- **WDS ↔ OBC:** Bidirectional flow of moisture feedback and pump actuation.
- **EPS → System:** Power delivery and voltage regulation for the OBC and actuators.
- **OBC ↔ GUI:** Live telemetry visualization and manual mode override interface.

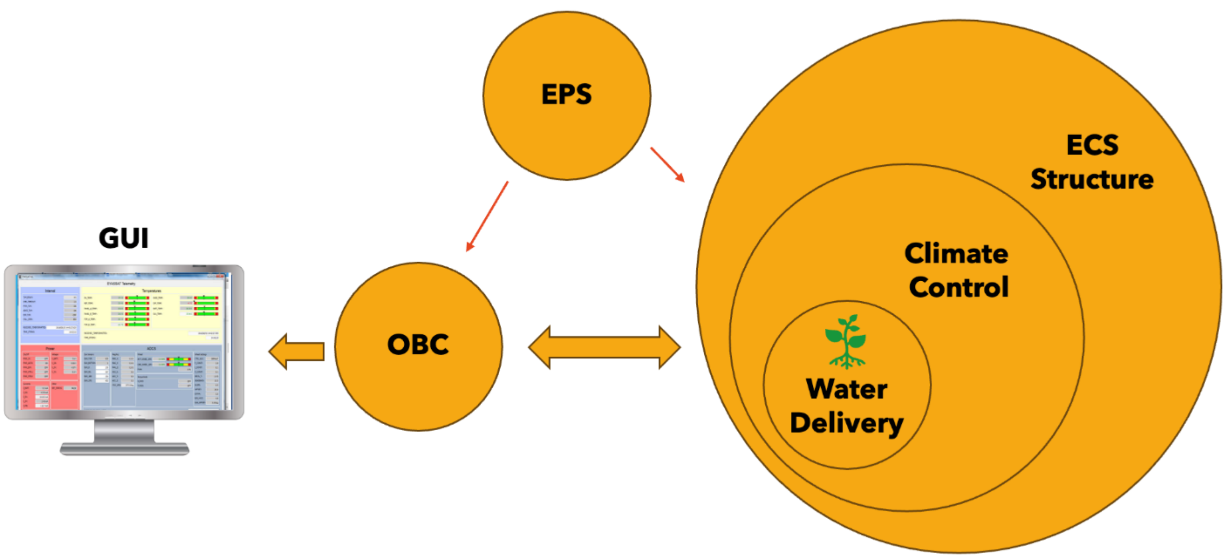


Figure 6: Visual Representation of Subsystem Operation Relations. The diagram highlights the central role of the OBC and the physical nesting of the Water Delivery and Climate Control Systems within the ECS Structure.

2.3 Preliminary Design

2.3.1 Preliminary Design 1

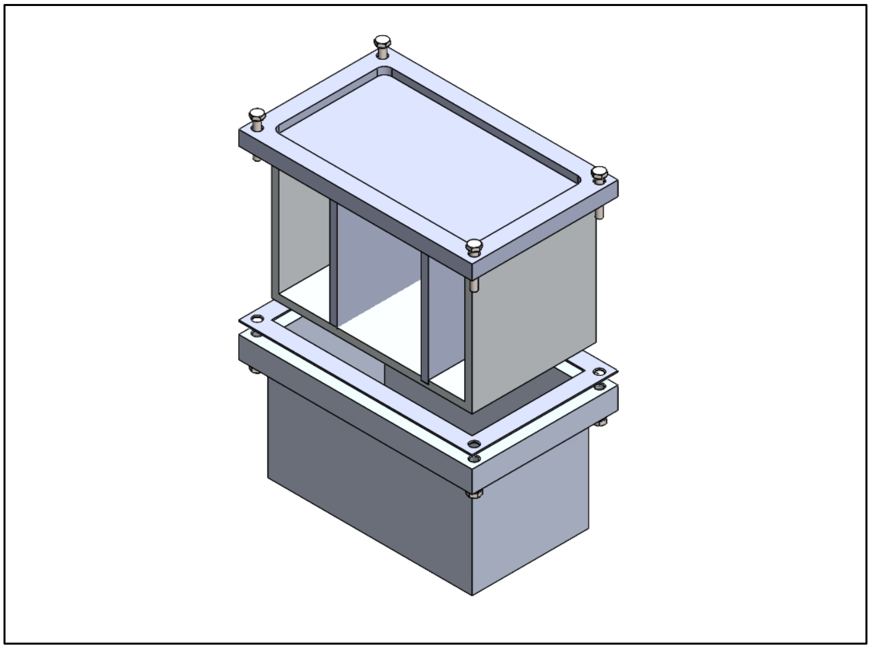


Figure 7 : Preliminary **Design Concept #1**

The first preliminary design conceptualized is shown in figure _. This design consisted of a rectangular housing and drop-in system with flanges to mount a top cover on to. It also utilized a rectangular metal gasket to seal the internal pressure of the chamber. Problems with this design include the unused volume by incorporating the flange design of the housing and the machinability of this configuration.

2.3.2 Preliminary Design 2

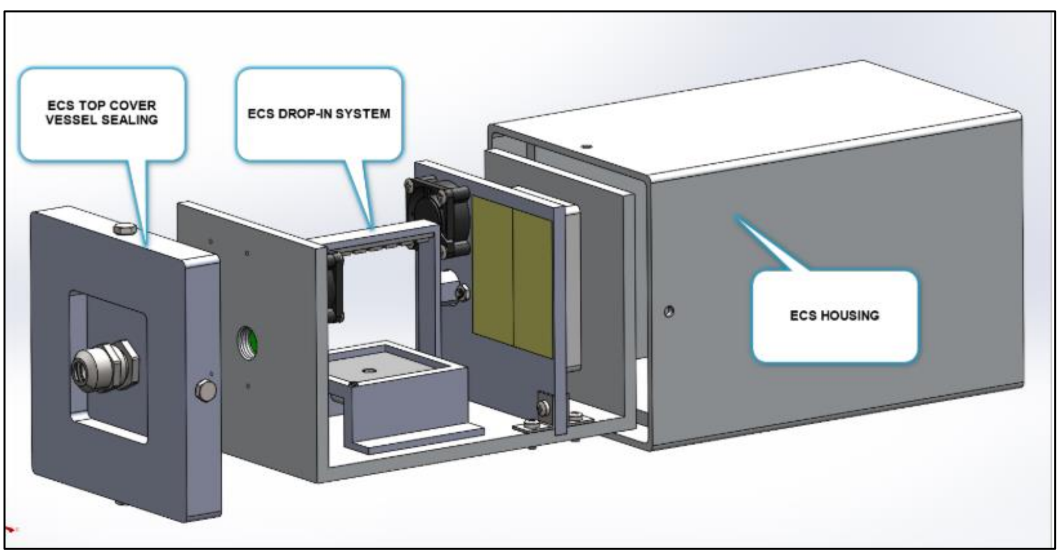


Figure 8: Preliminary Design Concept #2

The second preliminary design concept improves on the first iteration of the ECS structure. This design consisted of three structural components including the Housing, Drop-in System, and Top cover seal. It aimed to incorporate a machined aluminum solid block for the Housing and aluminum U-channel stock for the Drop-in System, the top-cover seal was made of aluminum stock. Issues with this design are there was no method to easily disassemble and remove the drop-in system from the housing. Additionally, the machinability of the housing to the depth needed required external outsourcing and was not feasible.

2.3.3 Preliminary Design 3

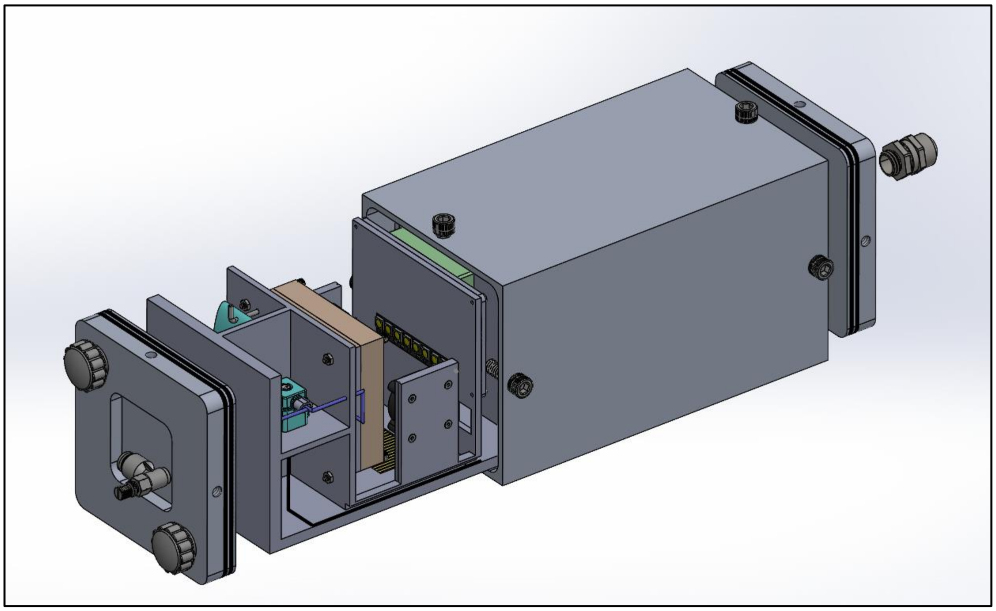


Figure 9: Preliminary Design Concept #3

The third preliminary design concept leads into the proposed design for the ECS structure. This design iterates on the 2nd preliminary design concept by utilizing an aluminum extrusion instead of a solid block for the ECS housing. Naturally, this change prompts the use of two seal covers instead of one. The seals in this design were also upgraded by incorporating grooves for O-rings to fit into. This design maximizes the use of the ECS internal volume and structurally acts as a pressure vessel capable of sealing a 1 bar atmosphere. A final change was to design the Drop-in System to be 3-D printed instead of using an aluminum U-channel stock. This change allows for continuous and fast iteration of the Drop-in System and reduces the mass in the overall weight of the structural system.

2.4 Trade Studies

2.4.1 Pressure Vessel Sealing Method

The figure below shows two practical methods of sealing a pressure vessel. Since the ECS is an enclosed chamber operating at an atmospheric pressure of 1 bar, it may be classified as a pressure vessel [1]. Drawing (a) in the figure shows a flanged type of pressure vessel which may be circular and secured by bolts aligned circularly. Potential issues with this design include the excess diameter needed to secure and close the pressure vessel, additionally the bolts securing the flange are in tension constantly due to the pressure force. Drawing (b) demonstrates a similar flanged design requiring less diameter than drawing (a). Notice the bolts to secure the seal/cover in this drawing are on the sides of the pressure vessel which puts the bolt shanks in shear rather than tension. The ECS aims to follow a similar design to that of drawing (b), implementing a top cover with bolt holes on the thickness of the cover rather than the top. This design also allows for more usable volume within the ECS which is a critical parameter in this design. The new design iteration for the ECS includes O-rings to seal the controlled atmosphere within the ECS.

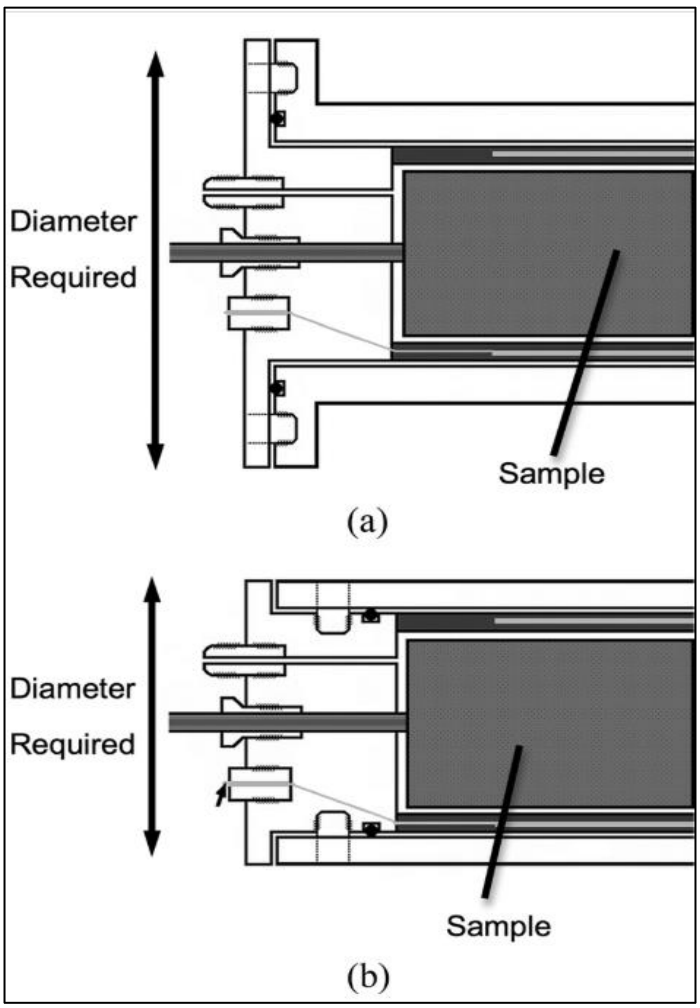


Figure 10: ECS Pressure Sealing

2.4.2 Through-Hole Method

Another challenge of the ECS design is implementing a through hole for internal component wiring to pass through. Element such as the peristaltic pump, various sensors, heaters, and fans require control from the ECS's proposed microcontroller which will be stationed outside of the ECS housing. This is a common engineering problem for pressure vessels and practical solutions have been found for the design. The first method involves sealing the through hole with epoxy which is used commonly on underwater pressure vessels. This method would provide a tight seal to the ECS; however, it is a permanent solution and limits the ability to perform maintenance on the ECS. The next method is the proposed method of sealing the ECS, it involves using a cable gland for the through hole wiring. A cable gland works by using a compression ring tightened by a nut to create a seal between the wire sheathing passing through the gland and the compression ring itself. This method is widely used in machinery applications, electrical installations, etc. A cable gland is threaded into a hole and tightened by a nut on both ends, one nut for securing the piece and one for tightening the compression ring. Figure 7 shows the design of the ECS top cover seal with a threaded hole for the cable gland to enter.

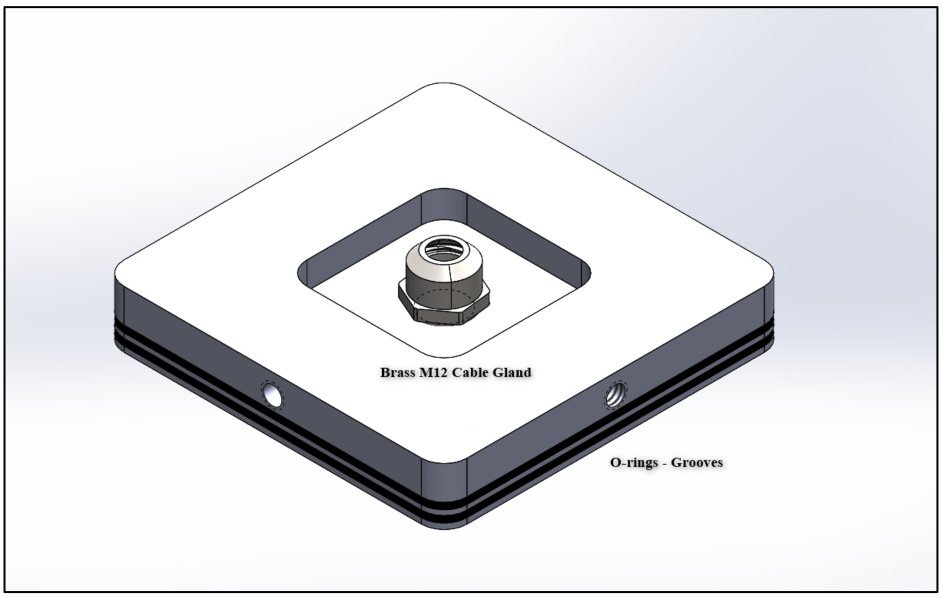


Figure 11: ECS Thread

2.4.3. Climate Sensors

Figures 12, 13, and **14** below shows the trade studies to determine the ambient temperature, humidity, and pressure sensors. The trade studies were performed using the weighted score method; the selection criteria were separated into the following. The first criterion was specifications, encompassing variables such as measurement ranges, accuracies, and refresh rates; this was assigned a weight of 0.2. Additionally, to have been considered a candidate, the component must be in some manner compatible with the onboard computer (OBC). In payloads meant for CubeSat research, power consumption is a considerable constraint as there is a limited source of power, being a battery source and solar panels if used. Therefore, the power consumption of the sensors was the second selection criterion. Being that the internal volume of the payload and, in particular, the plant chamber volume is small, a sensor with the capability of measuring temperature, relative humidity, and pressure, or a combination of these (i.e., multitasking) and with a small surface area is important. Leading to the third and fourth criteria's, also weighted at 0.2. For CubeSat research, based on the CubeSat size, there is a maximum amount of mass allowable. This naturally provided the fifth criterion of mass. The final criterion was price. These two final criteria each carried a weight of 0.1.

Temperature Sensor							
Weight	0.2	0.2	0.2	0.2	0.1	0.1	1
Selection Criteria	Specifications	Power Consumption	Multitasking	Area	Mass	Price	
Bosch: BME280	0.95	0.9	1	0.9	1	0.8	0.93
Adafuit: Si7021	0.7	0.75	0.666666667	0.85	0.9	0.65	0.748333333
Adafruit: DHT22	0.9	0.7	0.666666667	0.6	0.85	0.65	0.723333333
Adafruit: BMP390	0.9	0.85	0.333333333	0.95	0.75	0.6	0.741666667

Figure 12: Ambient Temperature Trade Study

Ambient Humdity Sensor							
Weight	0.2	0.2	0.2	0.2	0.1	0.1	1
Selection Criteria	Specifications	Power Consumption	Multitasking	Area	Mass	Price	
Bosch: BME280	0.95	0.9	1	0.9	1	0.8	0.93
Adafuit: Si7021	0.9	0.75	0.666666667	0.85	0.9	0.65	0.788333333
Adafruit: DHT22	0.91	0.7	0.666666667	0.6	0.85	0.65	0.725333333

Figure 13: Relative Humidity Trade Study

Pressure Sensor							
Weight	0.2	0.2	0.2	0.2	0.1	0.1	1
Selection Criteria	Specifications	Power Consumption	Multitasking	Area	Mass	Price	
Bosch BME280	0.9	0.9	1	0.9	1	0.8	0.92
Adafruit BMP390	1	0.85	0.333333333	0.95	0.75	0.6	0.761666667

Figure ***14: Pressure Trade Study***

Similarly, **Figures 15 and 16** below are the trade studies for soil moisture and O_2 sensors. For these studies, multitasking was removed as a criterion, as soil humidity would not require multitasking, and there were no reasonable candidates that could read both gas concentrations.

As such, the weights were redistributed as 0.3 for specifications and power consumption, 0.2 for area, and 0.1 for mass and price.

Soil Humdity Sensor						
Weight	0.3	0.3	0.2	0.1	0.1	1
Selection Criteria	Specifications	Power Consumption	Area	Mass	Price	
Gravity: Soil Moisture Sensor	0.9	0.4	0.6	0.5	0.75	0.635
Grove: Soil Moisture Sensor	0.9	0.4	0.7	0.55	1	0.685
Adafruit: STEMMA Soil Sensor	0.9	0.5	0.6	0.75	0.7	0.685

Figure 15: Trade Study for Soil Humidity Sensor

Y

O2 Sensor						
Weight	0.3	0.3	0.1	0.2	0.1	1
Selection Criteria	Specifications	Power Consumption	Mass	Area	Price	
Gravity O2 Sensor (25%)	0.85	0.5	0.4	0.65	0.3	0.605
Gravity O2 Sensor (100%)	0.9	0.45	0.4	0.7	0.15	0.6

Figure 16: Oxygen Sensor Trade Study

2.4.4. Peristaltic Pump

As the primary driver of fluid within the ECS, the selection of an appropriate pump was crucial to the viability of the water delivery subsystem. Peristaltic pumps were primarily considered for their ability to deliver precise, low-volume fluid flow without exposing the water to internal pump components. Further, these pumps are very lightweight and have a small footprint, helping to satisfy the strict size and mass constraints of the overall CubeSat design [1].

Two specific peristaltic pump models were evaluated: the RP-QIII and the Boxer 9QX with an encoder. The RP-QIII provides a high degree of flow accuracy, compact form factor, and low power consumption, making it well-suited for continuous operation in small environments. The Boxer 9QX, while also compact and capable of precise flow delivery, has a slightly larger footprint and higher power requirements for similar flow rates. As both pumps met the minimum functional requirements demanded by the ECS, a side-by-side comparison was performed considering their key criteria as shown by Figures 8 & 9, where values of 1 were assigned to the pump with the more favorable condition for each parameter.

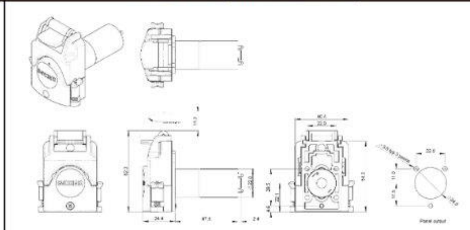
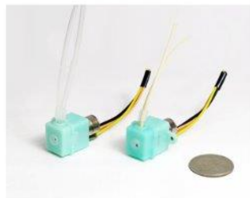
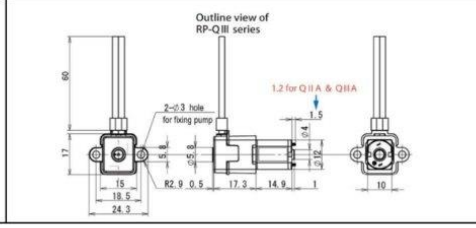
Pump	Price	Picture	Schematic (mm dimensions)	Flowrate (ml/min)	Weight (g)
Boxer 9QX w/ Encoder	$188.82			3.2-6.4	135
RP-QIII	$136.00			0.45-3.00	13

Figure 17: Summary of Pump Features

Pump Trade Study		
Parameter	**Boxer 9QX**	**RP-QIII**
Volume	0	1
Weight	0	1
Ease of Mounting	0.5	0.5
Cost	0	1
Flow Rate / Time of Water Delivery	1	0
Power Consumption	0	1
Totals	**1.5**	**4.5**

Figure 18: Pump Trade Study

As highlighted by the above tables, the RP-QIII demonstrated more favorable characteristics in terms of size and operational simplicity. As such, the RP-QIII peristaltic pump was selected as the preferred option for the ECS water delivery system.

2.4.5. Water Distribution Method

The final trade study conducted evaluated three different plant bay layouts to determine the most efficient method of water distribution within the soil. The first design utilizes a single inlet where water passes through one central hole and then splits into multiple branching pathways to reach the entire soil platform, ensuring minimal dry spots and even coverage. While this design is simple and space-efficient, the multiple flow splits may introduce higher resistance and uneven distribution if blockages occur. The second design implements four evenly spaced inlets across the soil platform, providing uniform hydration through multiple entry points. This configuration allows for consistent moisture levels but requires additional plumbing connections, increasing both system complexity and the potential for leakage. The third design incorporates a spiral-shaped channel that distributes water across the soil in a continuous, curved path. This design minimizes head loss and promotes smooth water flow but introduces greater manufacturing challenges due to its intricate geometry. Overall, each configuration offers a unique balance between efficiency, manufacturability, and maintenance considerations for optimal soil hydration performance.

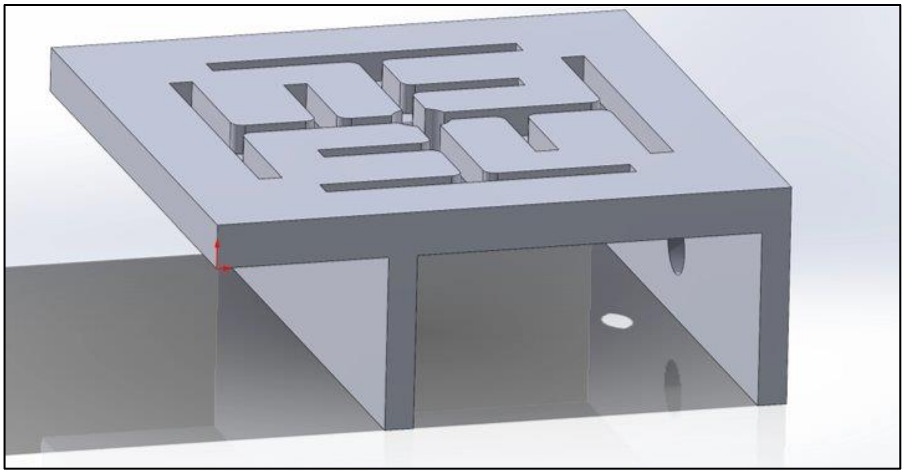


Figure 19: Central Split Flow Layout

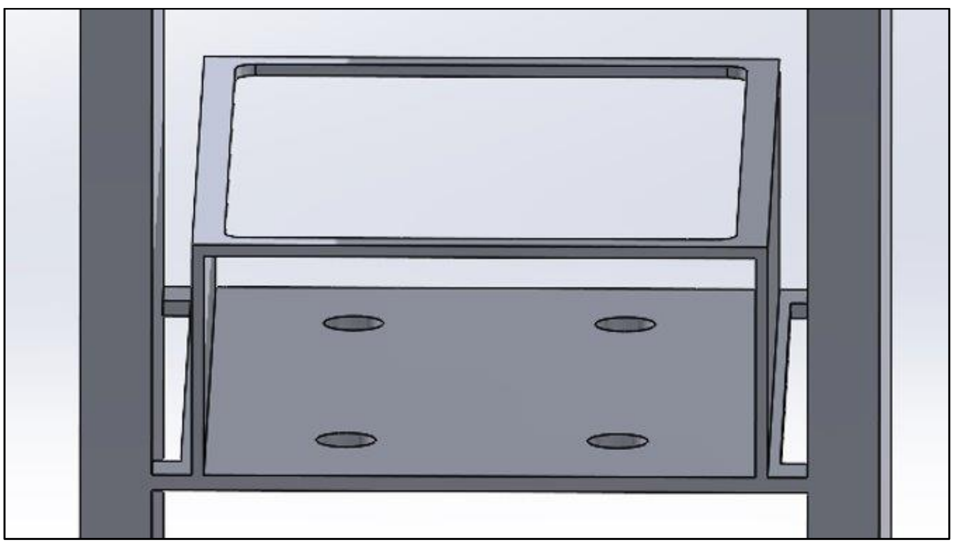


Figure 20: Multi-Inlet Grid Layout

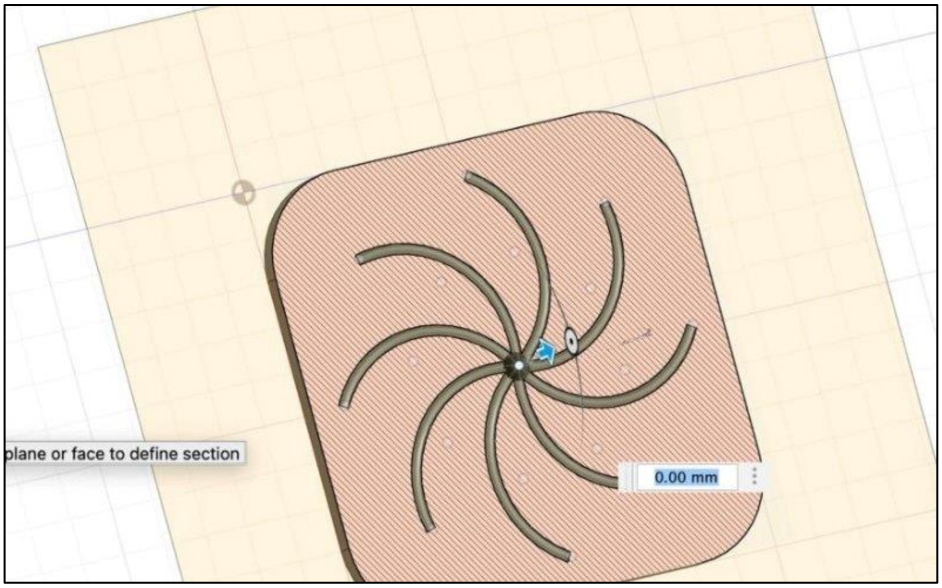


Figure 21: Spiral Spread Layout

2.5 Components Selected

Table 1 below shows the major electrical components selected based on the aforementioned trade studies. Additional components not mentioned in trade studies have been selected based on their proven heritage, i.e., previous iterations of senior design CubeSat payload projects.

Table 1: Components Selected and Respective Descriptions

Component	Description
Raspberry Pi 3 Model B+	On-board computer shall record and store all environmental and actuator data. Allow for autonomous functions and stand-by modes.
Bosch Sensortec Sensor BME280	Sensor to measure ambient pressure, temperature, and relative humidity values.
Gravity Electrochemical Oxygen / O_2 Sensor	Measure oxygen concentration as a percentage of volume.
Apollo SCD-40 NDIR CO_2 Temperature and Humidity Sensor	Measure carbon dioxide concentration within the ambient, also backup for temperature and humidity.
Adafruit STEMMA Soil Sensor - I2C Capacitive Moisture Sensor	Measure soil moisture for water delivery.
DC Fans	Facilitate heat transfer for cooling, promote evaporation, and prevent stagnant condensation.

Film Heater Plates	Ensure ambient temperature does not fall below the minimum target value, and water is at an acceptable value.
LED Light Strips	Provide light for plant development.
RP-QIII Peristaltic Pump	Deliver water from the reservoir to ensure target soil saturation.
Lux Sensor	Measure Lux (then converted to PAR) delivered by LED strips.
Thermistor(s)	Monitor water temperature.

3. Design

3.1 Detailed Description of the Design

The Pathfinder design utilizes a modular, integrated architecture developed to verify autonomous bioregenerative technologies within a 3U CubeSat form factor. The system is engineered as a sealed, atmospheric pressure vessel capable of maintaining 1 atm while isolating biological experiments from the vacuum of space. The architecture is defined by three primary functional domains—Mechanical, Electrical, and Software—which interact to create a closed-loop control environment.

Mechanical Architecture: The mechanical design is centered on a "Housing-and-Insert" philosophy. The primary structure is a sealed aluminum 6061-T6 pressure vessel (ECS Housing) that manages structural loads and environmental isolation. Inside this vessel resides the "Drop-in System" (DIS), a removable independent chassis that houses the fluid reservoir, plant growth bay, and sensor suite. This separation allows for bench-top integration and maintenance of the delicate subsystems (Water Delivery and Climate Control) before they are sealed within the ruggedized outer housing.

Electrical Architecture: The electrical topology utilizes a Centralized Control architecture. The system is powered by a dedicated Power Distribution Board (PDB) that conditions input power into regulated 12V, 5V, and 3.3V rails. Command and control are handled by the On-Board Computer (Raspberry Pi 3B+), which acts as the central brain. To isolate sensitive logic from noisy high-current loads, a separate Controller Board is utilized. This board receives logic-level signals from the OBC and utilizes MOSFETs to gate power to the heaters, fans, and pumps.

Software Architecture: The system logic is governed by a Finite State Machine (FSM) implemented in Python. This software continuously monitors environmental sensors via an I^2C bus and autonomously modulates actuators to maintain homeostasis. The system prioritizes safety through a unidirectional mode-promotion protocol, ensuring high-power states are only entered via valid command or nominal condition checks.

3.1.1 Consideration of Specific Codes and Standards

To ensure mission success, safety, and future launch eligibility, the Pathfinder design adheres to specific aerospace and engineering standards:

- ***NASA CSLI Compliance:*** The mechanical envelope and materials selection conform to NASA CubeSat Launch Initiative (CSLI) payload environmental and safety guidelines. This includes strict adherence to mass budgets ($\leq$ 6 kg) and venting/pressure vessel safety factors. [2]
- ***University Nanosatellite Program (UNP):*** The system design complies with UNP user guides regarding materials restrictions (e.g., prohibition of outgassing materials like localized epoxies) and the use of locking mechanisms (secondary retention) on all threaded fasteners.
- ***SAE AS568 O-Ring and Seal Sizing:*** Standardized SAE AS568 O-ring sizes are used with properly sized grooves to ensure reliable sealing in microgravity conditions, accounting for thermal expansion, vibration, and material compatibility. [8]
- ***IPC-A-610 (Acceptability of Electronic Assemblies):*** All custom PCB fabrication (Power Distribution and Controller Boards) and harnessing adhere to Class 2 reliability standards for dedicated service electronic products. [3]
- ***PEP 8 (Python Enhancement Proposals):*** The flight software (FSW) is developed in accordance with PEP 8 style guides to ensure code readability, maintainability, and successful transfer of the codebase to future teams. [4]

3.2 Sub-Systems

3.2.1 ECS Structure

The ECS structure shall provide mechanical support and mounting interfaces for all the ECS subsystems. The ECS structure is divided into three mechanical components that will provide the ability for subsystem integration including the ECS housing, Drop-in System, and housing seals. The ECS housing and housing seals provide a hermetic internal volume capable of maintaining a pressurized ECS environment up to 1 atm without leakage. The Drop-in System (DIS) is a removable structure that provides mounting interface for the instrumentation devices of the ECS. The Drop-in System is the piece of the assembly that will integrate the Water Delivery System (WDS), and Climate Control System (CCS) into the ECS. Figure 13 provides an exploded view image of the ECS structural assembly.

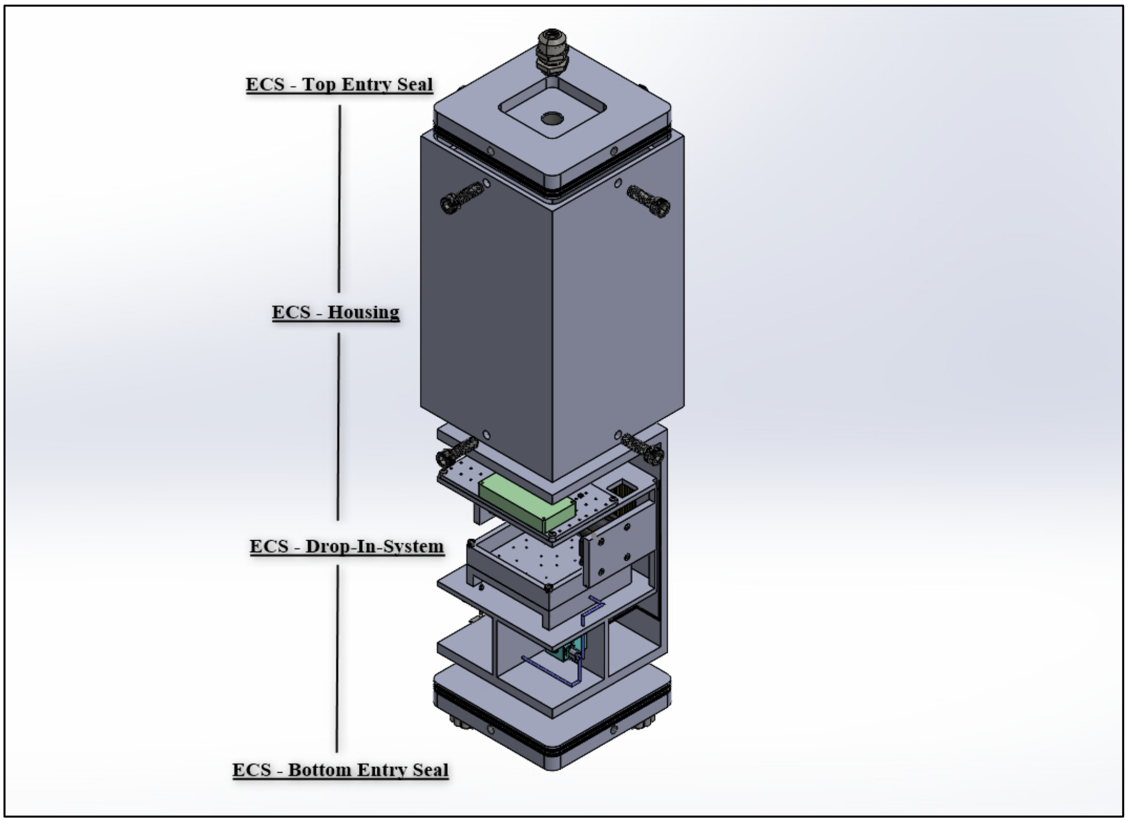


Figure 22: ECS Exploded View

3.2.1.1 ECS Housing

The ECS Housing is derived from a 4 x 4-inch profile T6-6061 aluminum extrusion. The ECS housing spans 7.125 inches in depth and will provide structural support for the ECS drop in system. The profile extrusion will be milled to a depth of 5/8" on each end for the top and bottom entry seals to be integrated into the assembly. The extrusion utilized for the housing shall be milled down to 1/8" on each side of the ½" thick profile walls. Figure 14 provides a mechanical drawing of the ECS housing.

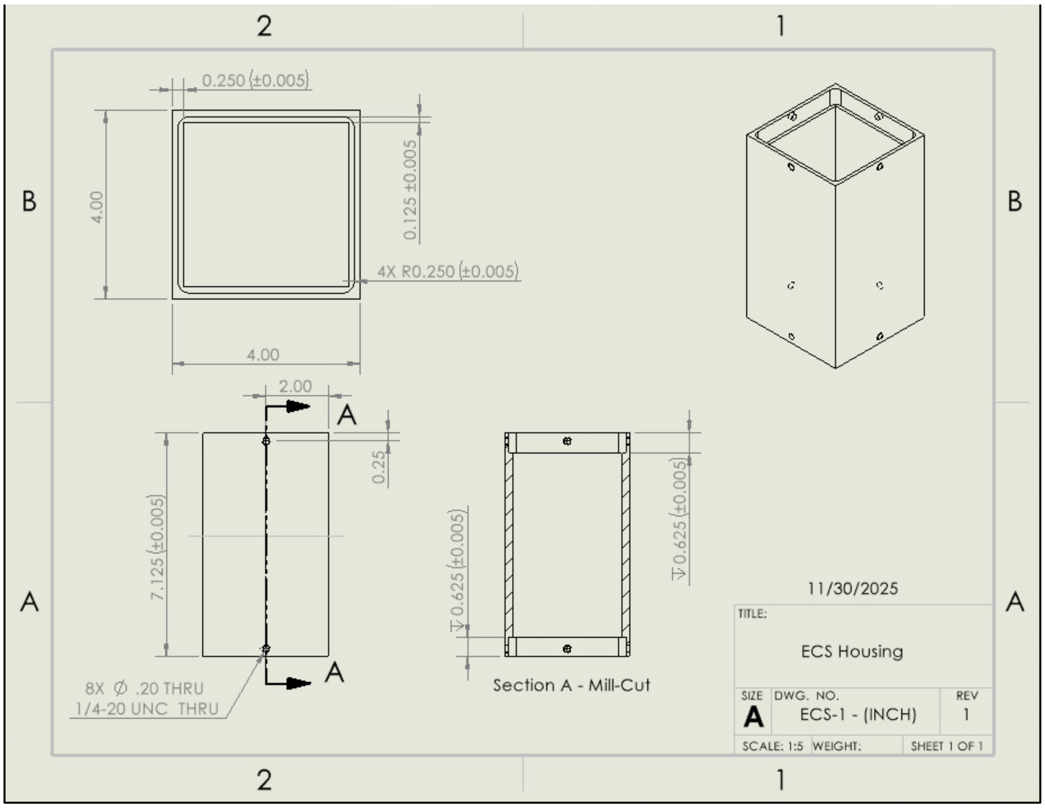


Figure 23: ECS Housing Drawing

3.2.1.2 ECS Drop-in System

The ECS Drop-in System (DIS) will serve as a removable structure that is press-fit into the aluminum extrusion once the top and bottom seals are bolted to the ECS Housing. The Drop-in System provides structural support for the ECS subsystems including the Water Delivery System, Climate Control System, and system control board. The DIS attempts to maximize usable volume and separate the respective subsystems. Figure 15 provides a mechanical drawing of the ECS Drop-in System.

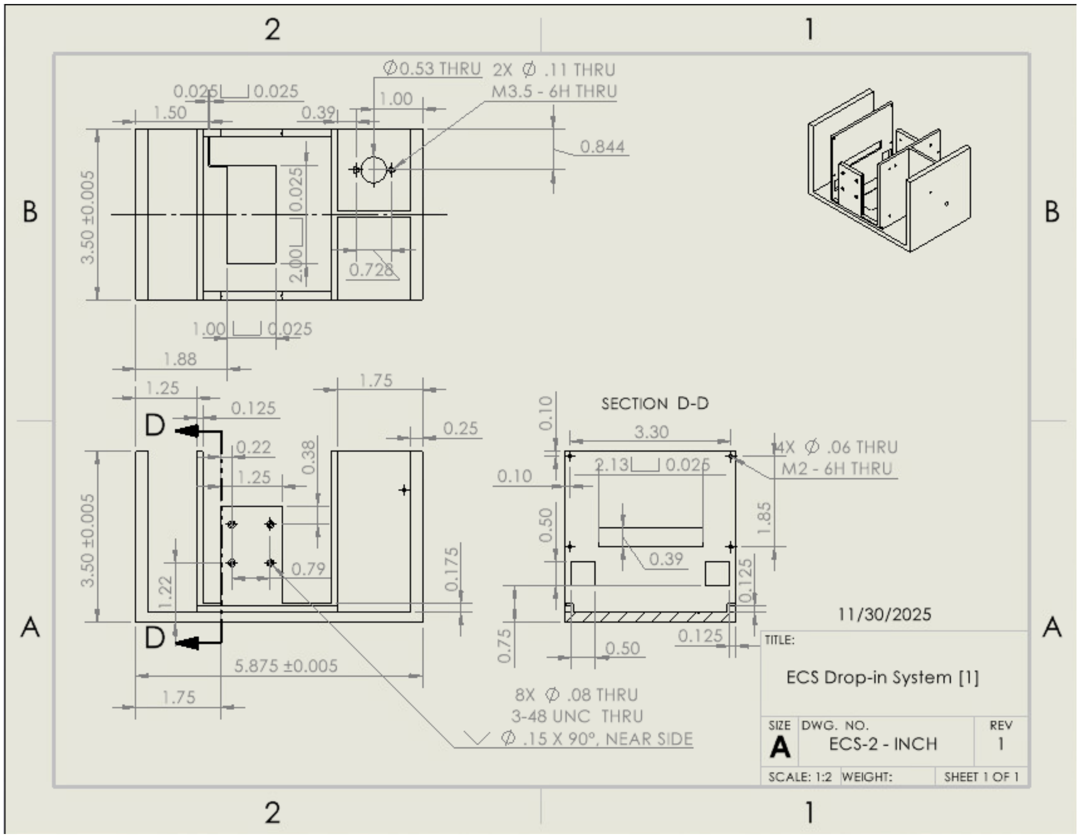


Figure 24: ECS Drop-in System Drawing [1]

The DIS separates the sensor bay from the grow chamber and climate control system. 1/8" mounting plates are the physical piece that separates each subsystem and respective components. Figure 16 shows a top-view of the DIS, towards the top of the figure is where the system sensors and circuit board will be mounted. Square cut-outs are made on the sensor bay mounting plate to allow airflow from the grow chamber to contact the respective climate control sensors. The mid-section of the DIS integrates the grow bed, circulating fans, heaters, and LEDs. The bottom-section of the DIS integrates the Water Delivery System which consists of the water reservoir and peristaltic pump. Through-holes are made on the lower mounting plates to allow for pump tubing to pass through. The pump tubing connects to the water reservoir and gets routed to the grow bed.

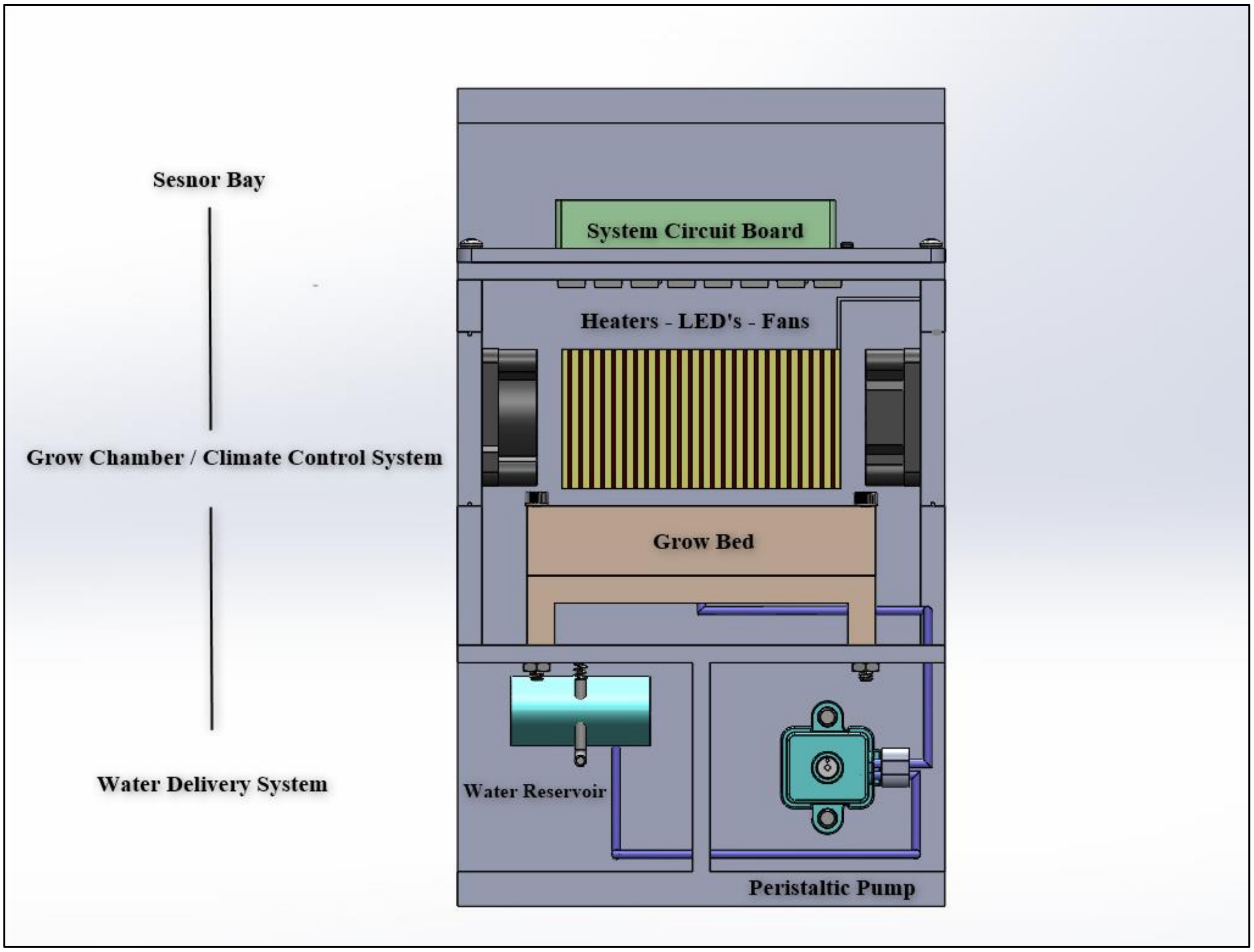


Figure 25: Drop-in System Component Layout

3.2.1.3 ECS Top/Bottom Entry Seal

Two critical components of the ECS design are the top and bottom entry seals, these mechanical components shall aid in maintaining an internal atmosphere of 1 bar. The seals are designed to slot into the ECS housing and will interface with the mill cut to a depth of 5/8". The seals will be machined to incorporate two 0.07 x 0.07-inch grooves around the thickness of the part. With the milled grooves, 0.07-inch-thick O-rings will be placed around the grooves to prevent internal atmosphere leakage. The O-ring grooves are placed below the bolt holes to prevent leakage from the bolt hole and bolt interface. The top entry seal is designed to include a threaded through on the top-surface. The through-hole will mate with a brass M12 cable gland to allow for internal component wiring to pass through to the user interface. The M12 cable gland will create an airtight seal around the thickness of the wires passing through it. Figure 17 shows the mechanical drawing for the ECS top entry seal.

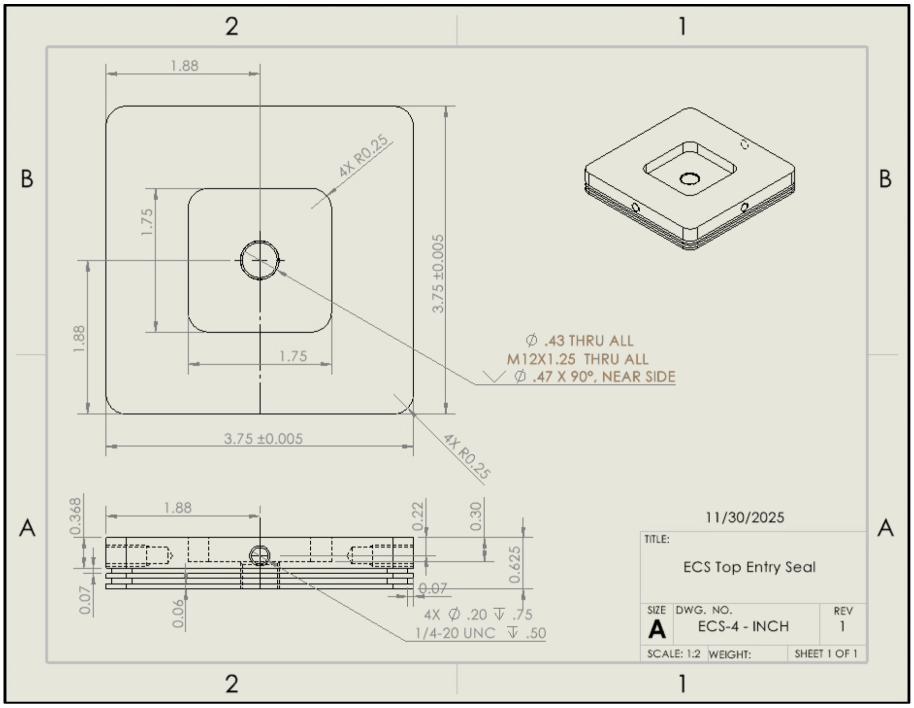


Figure 26: Top Entry Seal Drawing

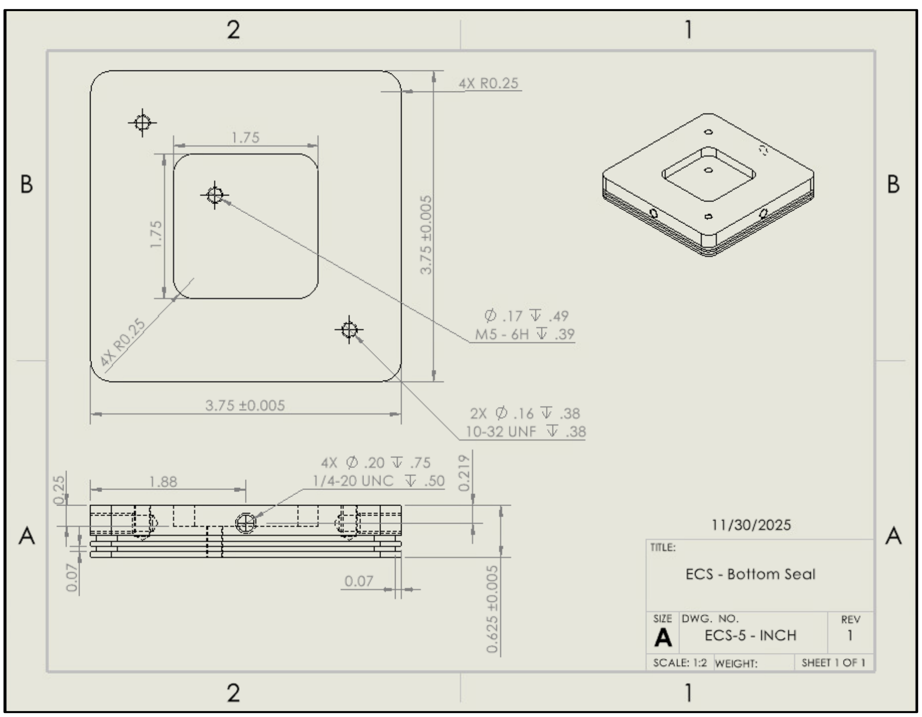


Figure 27: Bottom Entry Seal Drawing

The bottom entry seal is designed with three holes on the top-surface of the part. The hole integrated to the milled surface of the seal is for an adjustable air-bleed valve. The air-bleed valve allows for a user to release the internal pressure of the chamber to the surrounding atmosphere. This feature was designed and added to assist the release of the top and bottom entry seals from the housing when maintenance is needed on the internal components. Two holes on the upper surface are sized for threaded knobs to be used for opening the ECS structure once the internal pressure of the ECS has been released. Figures 19 and 20 showcase the ECS top and bottom seal features.

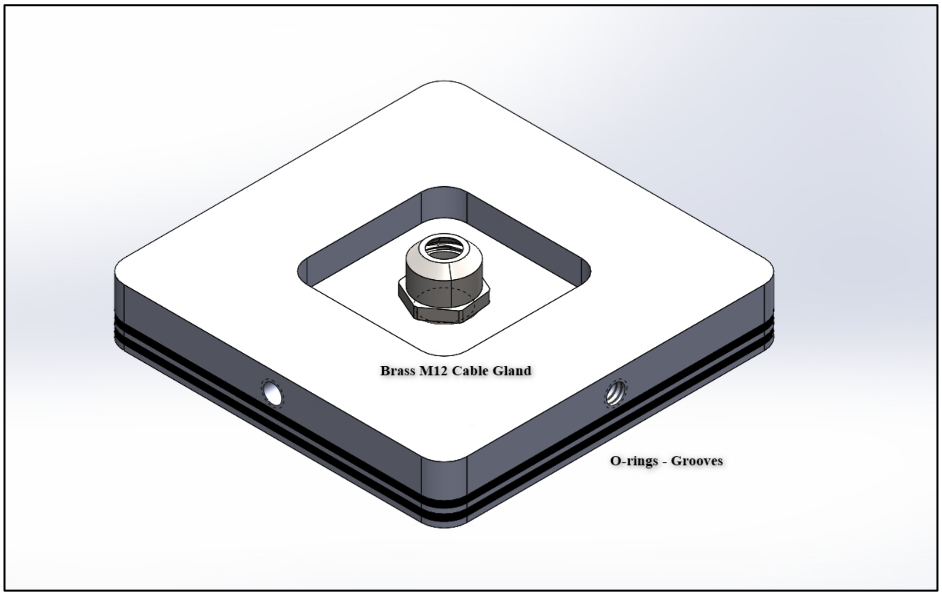


Figure 28: Top Seal Features

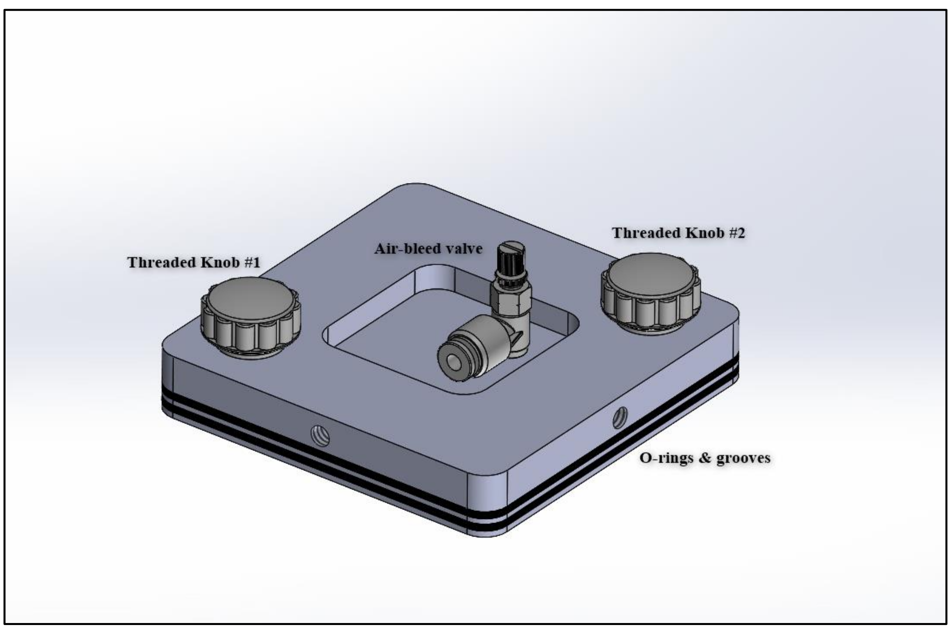


Figure 29: Bottom Seal Features

3.2.2 Climate Control System

The goal of the climate control subsystem is to maintain an optimal environment for subject growth within the payload. Sensors are utilized to monitor ambient pressure [kPa], ambient temperature [°C], soil moisture [$\frac{m^3}{m^3}$] , lighting delivered [Photosynthetically Active Radiation (PAR)] relative humidity [%], and as concentrations such as CO_2 [parts per million (ppm)] and O_2 [% volume]. The controlled conditions are ambient pressure, temperature, soil moisture, and lighting. Solely monitored conditions are comprised of gas concentrations and relative humidity, although it is noted that relative humidity will be affected by the ambient temperature.

In addition, components such as heaters, fans, and light-emitting diodes (LEDs) will be utilized. Most sensors shall be soldered onto a printed circuit board (PBC) located along the plant bay drop-in walls. The sensors for lighting and soil moisture shall be normal to the LEDs (facing towards the LEDs) and placed directly into the soil, respectfully. **Figure 30** below is a diagram of the layout.

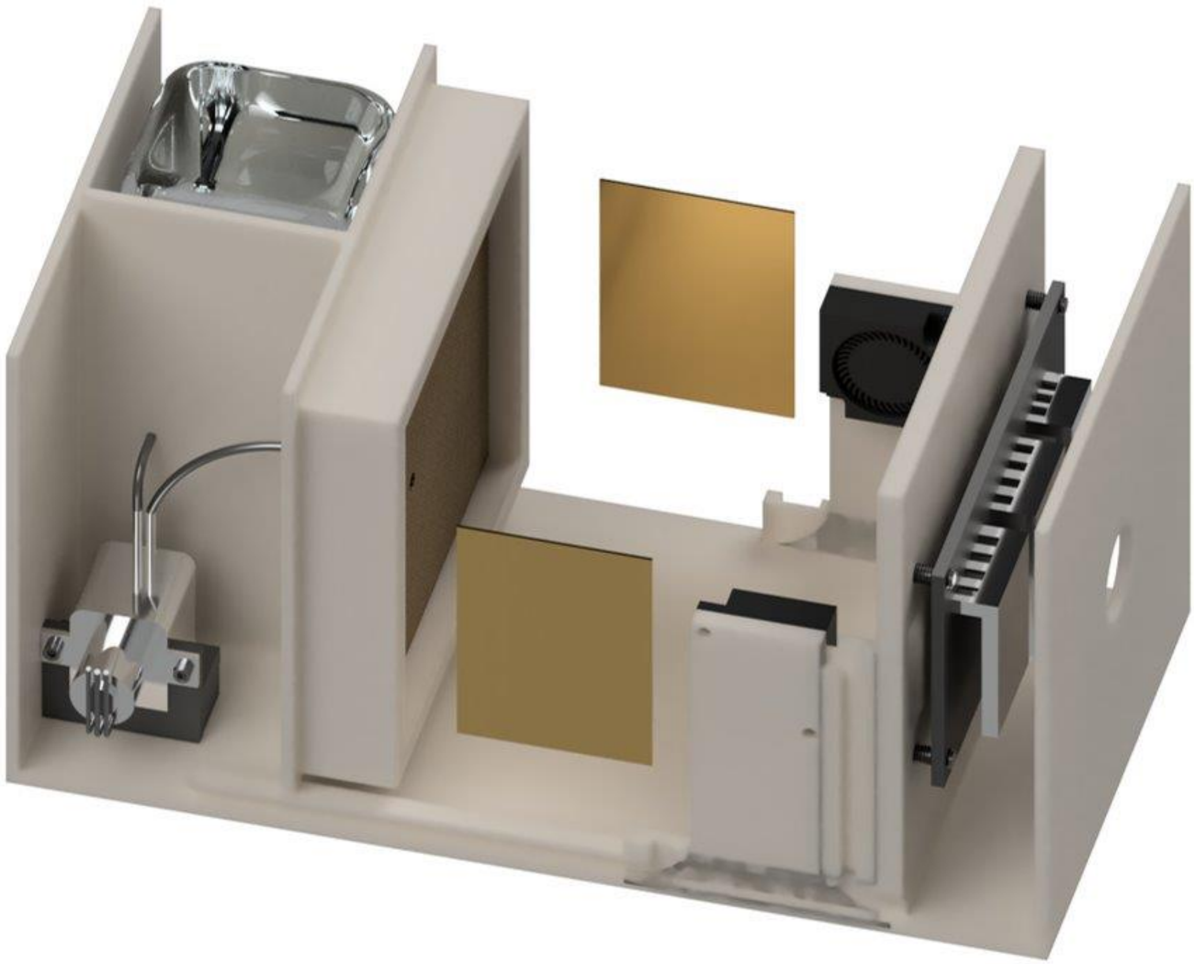


Figure 30: ECS Diagram

As mentioned in section 2.2, functional flow diagram, during experimentation, the on-board computer will follow closed-loop logic to control, monitor, or both, pressure, temperature, relative humidity, lighting, CO_2, O_2, and soil moisture, and autonomously decide how to proceed. The on-board computer will activate the dedicated heater when the ambient temperature or pressure is lower than the target band and deactivate it when the temperature or pressure exceeds the target band. Similarly, when relative humidity is low to acceptable values, the fans will remain deactivated; once relative humidity is high, the OBC will activate the fans used to propel airflow. The airflow shall promote evaporation and convection and prevent condensation buildup. Additionally, the temperature could be increased to increase the saturation vapor pressure.

Grow light LEDs are utilized to provide the light required for growth and photosynthesis. The light sensor utilized will measure in units of Lux; however, this measurement shall be converted to PAR. Once the OBC interprets the measured PAR as being in target ranges, for the target light duration, the LEDs shall be deactivated. This manner of operation is intended to simulate the day and night cycle. Finally, to ensure proper soil saturation, the soil moisture sensor will monitor the water content in the soil. When low soil moisture is detected, the OBC shall prompt the peristaltic pump to actuate. Additionally, a second heater will be dedicated to the water reservoir along with a thermistor, ensuring the water remains unfrozen and is delivered at an acceptable temperature for the subject.

3.2.3 Water Delivery System

The water delivery system is responsible for transferring controlled volumes of water from a reservoir to the plant growth bay. Using a peristaltic pump, selected for its compact form factor and flow-rate precision, the closed-tube design enables the system to operate reliably within the CubeSat's confined environment.

A Raspberry Pi-based controller will regulate the pump's operation, enabling precise control over both the volume and timing of each watering cycle. Water is drawn from a medical-grade IV drip bag (reservoir) secured within the payload enclosure and transported through flexible tubing into the plant bay. The IV bag functions as a collapsible reservoir, ensuring consistent suction pressure while preventing air entrapment during dispensing.

To manage soil moisture and prevent over-saturation, a capacitive moisture sensor embedded within the soil will provide real-time feedback to the Raspberry Pi. This sensor will detect the water content within the soil and relay data to the control algorithm, which will initiate or terminate the pumping cycle based on predefined thresholds. This feedback loop, demonstrated by Figure 31, will maintain a consistent environment for plant growth while minimizing excess free water formation in microgravity conditions.

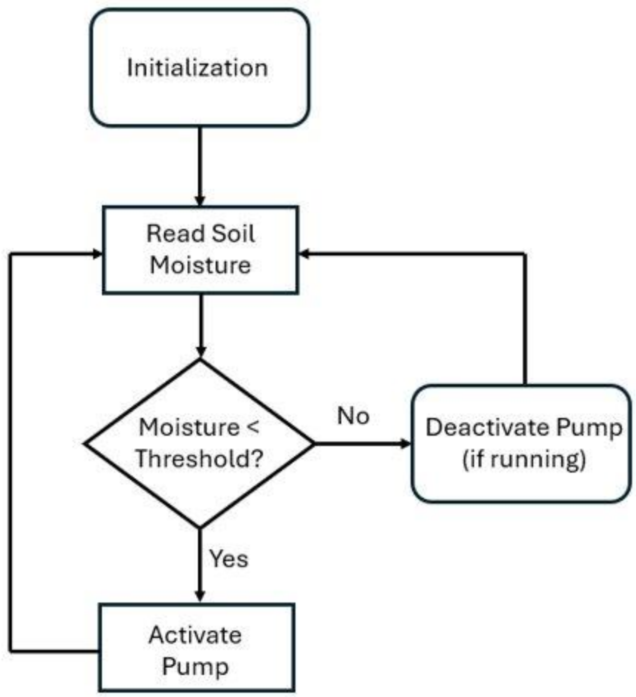


Figure 31: Operational Feedback Loop of Water Delivery System

The combination of a peristaltic pump and responsive moisture sensing enables precise saturation control, ensuring efficient water use, system reliability, and containment of all fluids within the payload. Figure 32 highlights a general schematic representing the components involved with driving the fluid from its reservoir to the plant bed.

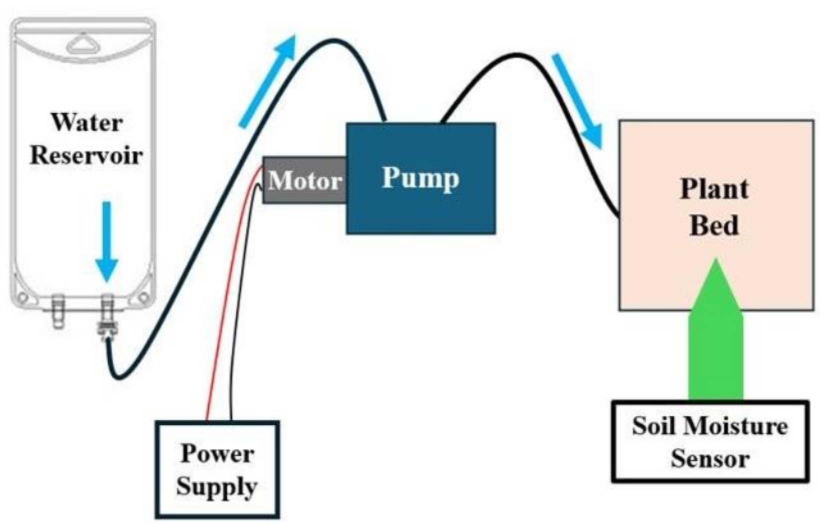


Figure 32: Water Delivery System Component Schematic

3.2.4 On-Board Computer (OBC) Design

The OBC utilizes a **Centralized State Architecture** implemented in Python on a Raspberry Pi 3B+. Unlike distributed systems, all subsystem logic (Climate Control, Power Management, Payload) is managed by a single central process which maintains a unified system state dictionary.

<u>Flight Software (FSW) Modes:</u> The software is organized into distinct CONOPS modes verified via SITL testing:

- **SAFE_MODE (Implements CONOPS 'Standby' & 'Safe'):** The default system state. To reduce architectural complexity, the software treats the CONOPS "Standby" phase and "Safe Mode" as a single, high-integrity-idle state. In this mode, actuators are disabled, and the system listens for ground commands while performing thermal survival checks.
- **PRE_CONDITIONING_MODE:** Corresponds to the "Preconditioning" phase. The software autonomously regulates heaters to bring the water reservoir and internal atmosphere to the target 20 degrees Celsius before allowing the experiment to proceed.
- **EXPERIMENT_MODE:** The primary mission phase. This mode automatically sequences the "Initial Water Saturation (IWS)" event followed by the continuous 1.0 Hz closed-loop control of lighting and soil moisture.
- **LAST_RESORT_MODE:** An additional software-level safety state (beyond baseline CONOPS) that sheds all non-essential loads if battery voltage drops below critical thresholds.

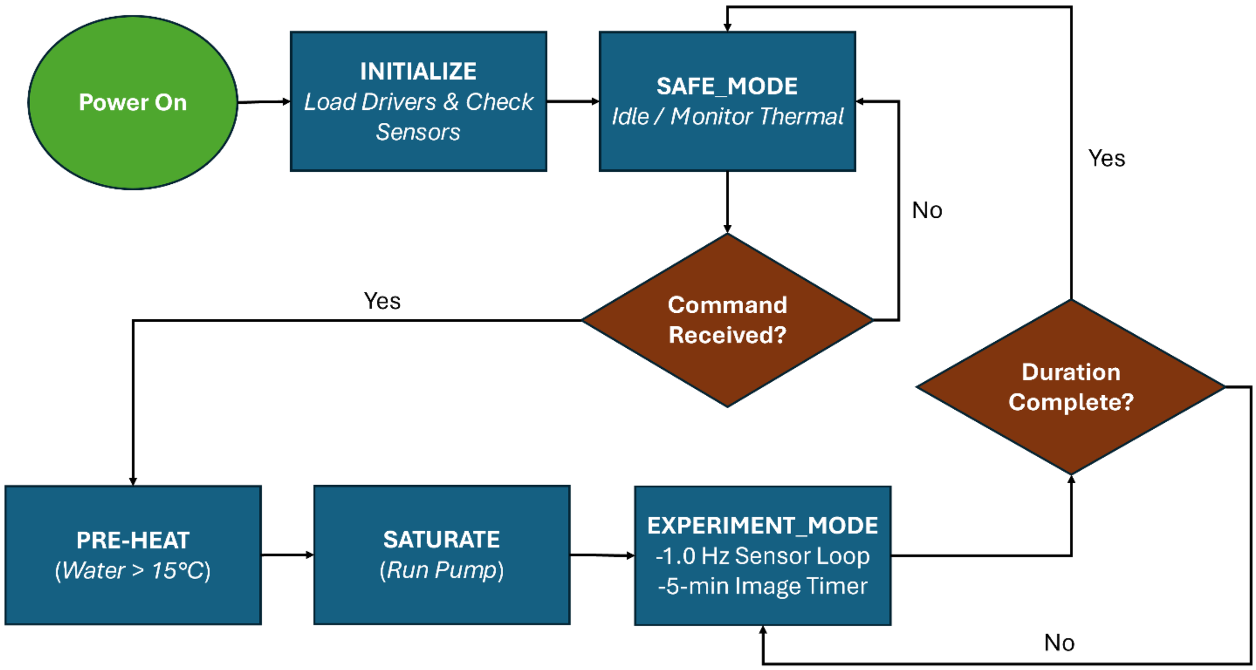


Figure 33: Pathfinder Flight Software (FSW) Flowchart. Note: The "SAFE_MODE" block encompasses both the "Standby" and "Safe" operational phases defined in Section 1.3. "SATURATE" represents the Initial Water Saturation (IWS) event that occurs upon entry into Experimental Mode.

3.3 Product Breakdown

The Environmental Control System is a monitored control system that will be tested to germinate a seed and provide plant life. The ECS is designed to integrate into a 3U form factor CubeSat and is comprised of three main structural components. The ECS housing is the primary structural component, it provides structural support for the ECS Drop-in System. The housing is a derivative of an aluminum tube extrusion and will allow the ECS Drop-in System to slide and press-fit into the housing walls. The ECS Drop-in System is the structural support for the ECS subsystems and the subsystems' respective components. The Drop-in System will be made of PETG 3-D printed material. The Drop-in System is designed to be modular and can support various plant life monitoring sensors or grow-house components. The final structural component is the ECS entry seals which close and seal the ECS from external atmospheric pressure. The seals are designed to maintain the internal atmospheric pressure of the ECS and Climate Control System.

3.3.1 Overall Design

The figure below provides a schematic exploded-view of the ECS. It highlights the ECS structural components and internal subsystems within the ECS Drop-in System.

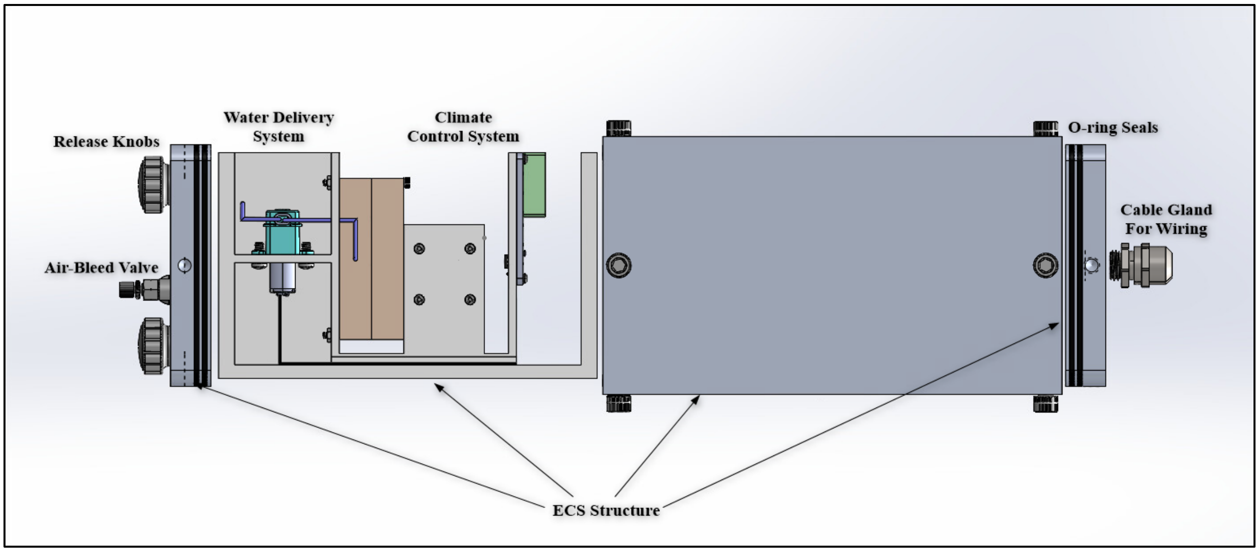


Figure 33: Overall Design

Starting from the right side of the figure, the ECS Top Entry Seal is shown. The top seal includes a brass M12 cable gland to allow for internal component wiring to pass through. The wiring will then be directed to the Electrical Power System and OBC user interface. The top seal is designed with O-rings and grooves to fit for sealing the internal atmosphere of the ECS. The top seal then mates with the ECS Housing (middle right of figure). The ECS Housing is the primary structural component and will interface with the ECS Drop-in System. The Drop-in System contains ECS subsystems including the Water Delivery System and Climate Control System (CCS). The Water Delivery System (WDS) will integrate a peristaltic pump and water reservoir to deliver water to the CCS grow bed. The grow bed is where the subject of the ECS experiment will be stationed and testing of this subject will be monitored by the Climate Control System. The CCS contains two fans to circulate air, LEDs to provide light to the subject, heaters to warm the circulating air, and grow bed. The CCS will monitor parameters including temperature, pressure, soil moisture, light intensity, C02, and oxygen using sensors staged on the CCS sensor bay. Finally, the bottom entry seal, the final structural component of the ECS. This component includes an air-bleed valve that can vent the internal atmosphere of the ECS to the surrounding external atmosphere. The air-bleed valve is positioned to draw air from the Drop-in System, specifically where the peristaltic pump is stationed. The bleed-valve can be manually open or closed with a screwdriver and may release internal atmospheric pressure when needed. The seal also integrates two release knobs that ease the process of disassembling the bottom seal from the ECS housing. Like the top seal, the bottom seal is lined with O-rings to maintain the internal atmosphere of the ECS and will be bolted to the ECS Housing like the top seal.

The figure below shows a 3U form factor CubeSat which is where the ECS may be placed once reaching a technology readiness level of 6 as defined by NASA [7]. The ECS was designed to integrate into a 3U CubeSat, and its dimensions allow for such purpose.

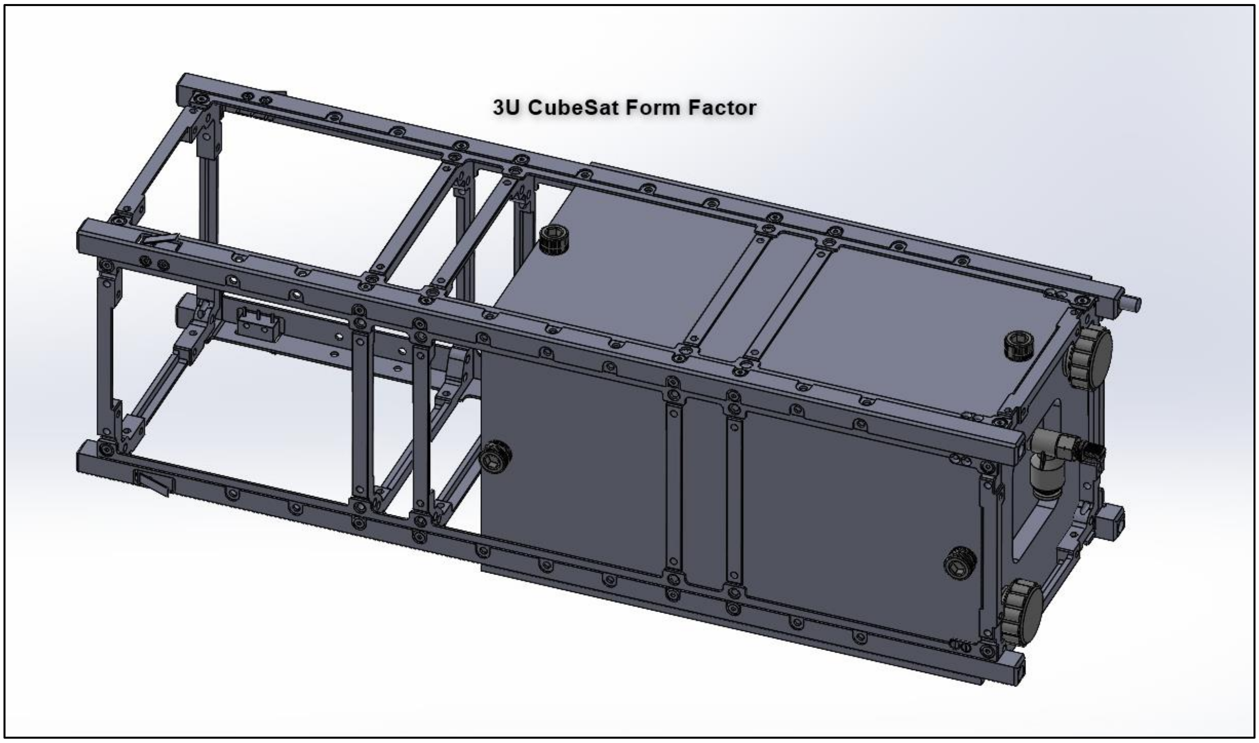


Figure 34: 3U CubeSat Structure

3.3.2 Plant Bay

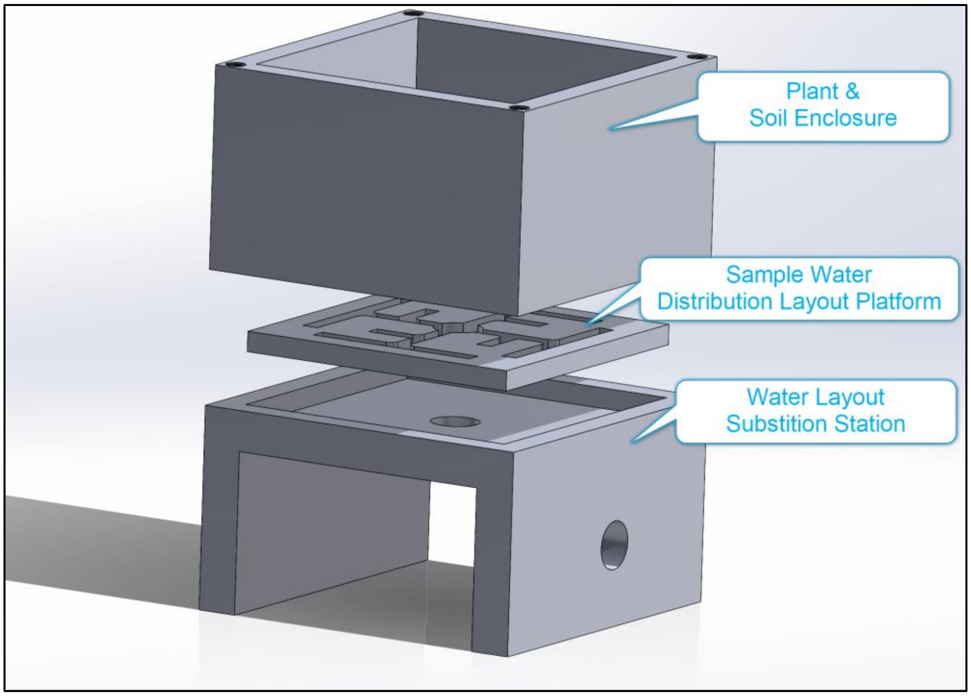


Figure 35: Plant Bay Configuration

In the figure above, a SolidWorks model of the plant bay is shown. The bottom section features the **water layout substitution station**, which redirects tubing from the water-supply bay throughout the plant bay. This station also provides an interface for trade studies, allowing different water-distribution platforms to be inserted into the square slot at the top and tested interchangeably. All tubing ports throughout the plant bay must be sized to 1.5 mm in diameter to meet the pump and piping design requirements.

The middle component in the figure represents a **sample water distribution platform**. This platform enables controlled water dispersal in multiple directions toward the soil enclosure, using a central inlet designed for seamless integration with the tubing.

At the top of the model, the **plant and soil enclosure** is shown. This enclosure houses the soil and the biological specimen selected for testing. As seen in the figure below, the enclosure includes small perforations that allow water delivered from below to spread evenly throughout the soil and rise vertically toward the root zone. The four screw holes at the top where brass threaded inserts are designed to secure a plant divider plate, which ensures that each plant grows uniformly within its designated section.

Soil Enclosure: 6.35 [cm] x 6.35 [cm] x 1.3 [cm]

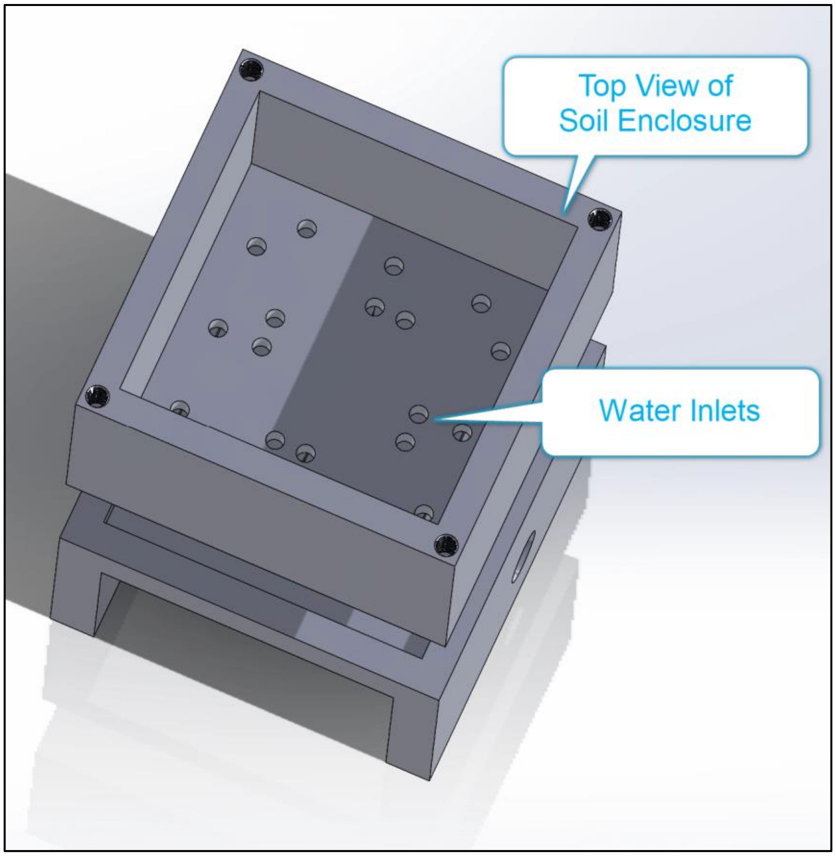


Figure 36: Top View of Plant Bay

3.4 Electronic Diagrams

This section presents the complete electrical and electronic schematics for the Environmental Control System (ECS). Each subsystem diagram illustrates the logical connections between components, including power distribution, signal interfaces, and control routing between the On-Board Computer (Raspberry Pi 3B), Controller Board, sensors, and actuators. The intent of this section is to provide a detailed view of how power and data flow through the system, supporting both functionality and reliability of the overall design.

The following figures outline each major EPS subsystem and its respective circuit implementation.

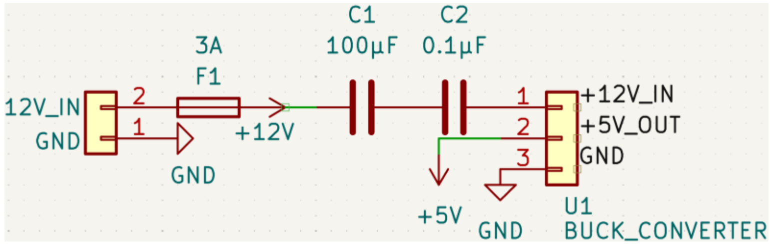


Figure 37: Power Distribution Board

- The Power Distribution Board provides the main 12 V supply to all actuators and the Controller Board.
- It includes a 5 V buck converter that powers the On-Board Computer (Raspberry Pi 3B) and all low-voltage peripherals.
- The 12 V line feeds all loads (fans, heaters, LEDs, and the water pump), while the Controller Board regulates their activation through low-side switching MOSFETs.
- A 3 A fuse and decoupling capacitors stabilize and protect the main input line.

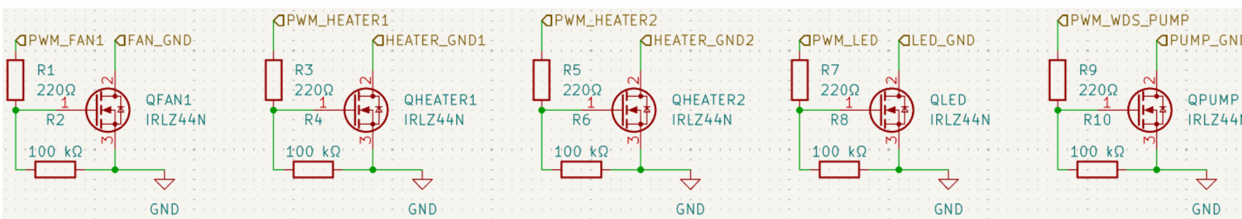


Figure 38: Controller Board

- The controller board houses all IRLZ44N MOSFETs used to modulate ground return for actuators via PWM control from the Raspberry Pi.
- Controls:
    - **Fans (2 total)** — connected in parallel, low-side switched.
    - **Heaters (3 total)** — two grouped, one independently switched.
    - **LED Array (1 strip)** — controlled as one channel.
    - **Water Delivery System (1 pump)** — independently switched.
- Each MOSFET gate includes a 220 Ω gate resistor and 100 kΩ pull-down resistor for noise suppression and safety.

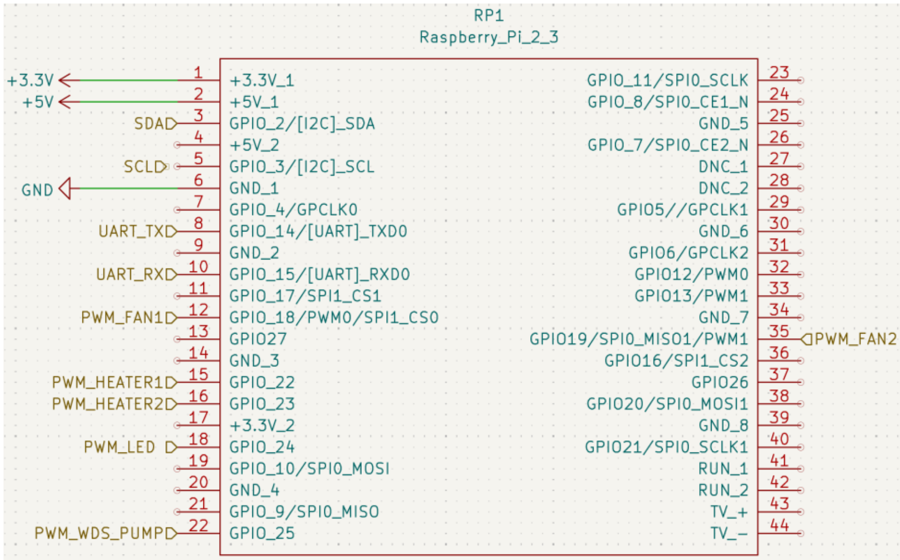
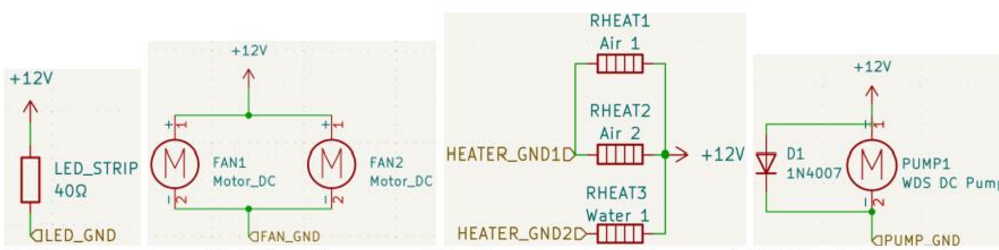


Figure 39: On-Board Computer (Raspberry Pi 3B)

- Acts as the main control and data acquisition unit.
- Communicates via:
  - **I²C (SDA/SCL)** with all digital sensors and ADCs.
  - **PWM GPIO lines** to the Controller Board for fan, heater, LED, and pump control.
  - **UART (TX/RX)** if debugging or data logging is needed.
- Supplies logic-level 3.3 V and provides ground reference to all peripherals.



LEDs | Air Flow Fans | Heating elements (2 zones) | Water delivery pump

Figure 40: Actuator Assemblies

- **Fans:** 12 V parallel pair for air circulation, PWM controlled by MOSFETs.
- **Heaters:** 12 V resistive pads; two grouped, one independently switched.
- **LED Strips:** 12 V lighting array used for plant growth illumination.
- **Water Pump:** 12 V DC pump, individually switched via MOSFET.

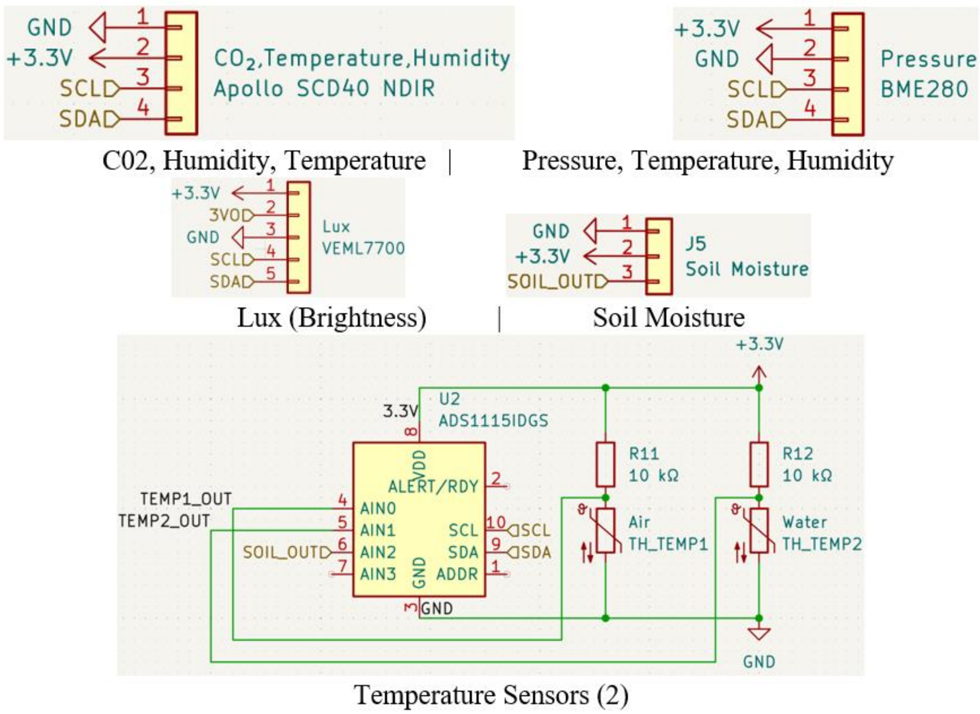


Figure 41: Sensors

Grouped under a single "Sensors" subsystem. Each connects via common 3.3 V, GND, and shared I²C (SDA/SCL) bus.

- **VEML7700 (Lux Sensor):** Monitors light intensity.
- **BME280 (Pressure):** Reports relative humidity, barometric pressure, and temperature.
- **SCD40 (CO_2, Temperature, Humidity):** Provides environmental data for CO_2 regulation and climate feedback.
- **Thermistors (2× 10 kΩ NTC):** Connected through ADS1115 ADC channels for analog temperature measurement.
- **Soil Moisture Sensor:** Outputs an analog voltage read by the same ADC as thermistors.

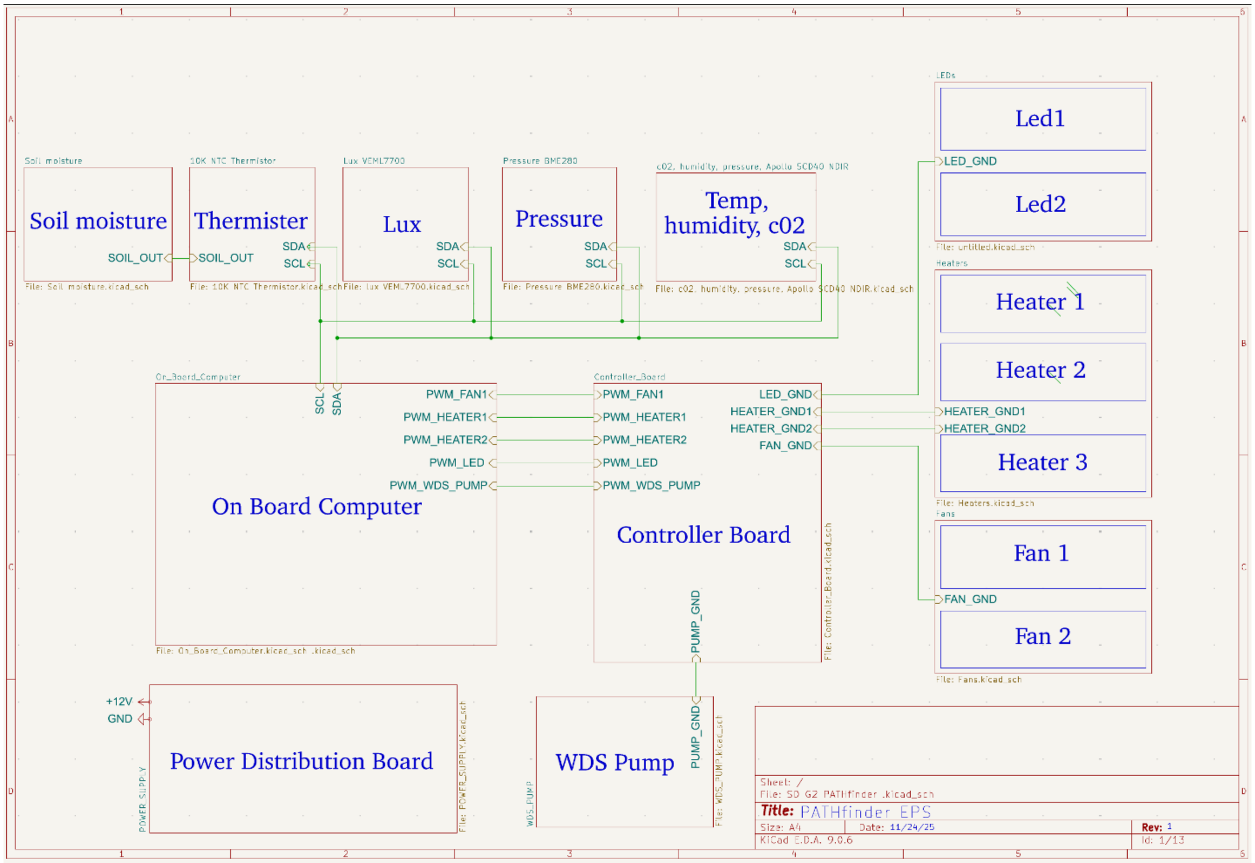


Figure 42: System Integration

- The Power Board supplies 12 V and 5 V.
- The Controller Board regulates all high-current paths.
- The On-Board Computer performs logic, sensing, and control.
- Sensors provide environmental feedback for closed-loop climate control logic.
- Only the controller, OBC, and power boards are inside the ECS enclosure; actuators and sensors remain external to the pressurized environment.

3.5 System Construction and Assembly

The manufacturing strategy for the Pathfinder payload prioritizes rapid prototyping techniques and minimized machining operations to reduce lead times while maintaining strict dimensional tolerances required for hermetic sealing.

3.5.1 Structural Fabrication (Housing and End Caps)

The primary pressure vessel components are constructed from 6061-T6 aluminum alloy using standard milling operations.

ECS Housing Fabrication: The housing is derived from standard 4-inch square aluminum extrusion stock.

1. **Cut to Length:** The extrusion is saw-cut to the required 7.125-inch length, and both ends are faced on a mill to ensure parallelism and perpendicularity.
2. **O-Ring Lead-in:** A critical machining step involves milling the internal faces of both ends to a depth of approximately 0.5 inches. This operation creates a smooth internal radius (fillet) that matches the end cap profile, ensuring the O-rings transition smoothly into the bore during assembly without shearing or tearing.
3. **Mounting Pattern:** Four drill centers are located on each face of the extrusion to accept the threaded fasteners used to retain the end caps under pressure loads.

End Cap Fabrication: The top and bottom end caps are machined from 0.75-inch aluminum plate stock.

1. **Profile Machining:** Square blanks are milled to match the precise internal dimensions and corner radii of the housing extrusion, ensuring a close-tolerance fit.
2. **O-Ring Grooves:** Using a CNC mill, two precision grooves are cut into the perimeter of each cap to house the dual O-ring seals. The depth and width (nominally 2mm) are finalized based on fit-check testing to ensure optimal compression.
3. **Feedthrough Port:** The top end cap receives an additional milling operation to create a central bore designed to interface with the hermetic cable gland, allowing power and data pass-through without compromising the pressure boundary.

3.5.2 Internal Component Fabrication (Drop-in System)

To minimize mass and maximize design flexibility, the internal "Drop-in System" (DIS) chassis is fabricated entirely via additive manufacturing (3D printing).

Utilizing engineering-grade thermoplastics (e.g., PETG or PEEK), the DIS is printed as a unified structure. This manufacturing approach allows for the creation of complex internal geometries that would be impossible to machine, including integrated sensor mounting brackets, secure cradles for the fluid reservoir, and intricate, non-conductive routing channels designed to manage internal wiring harnesses safely. The use of 3D printing ensures high dimensional consistency for a repeatable interference fit within the housing while significantly reducing the overall payload mass versus a metallic internal structure.

Table 2: ECS Bill of Materials

ECS Structural Bill of Materials			
Component:	**Quantity:**	**Supplier:**	**Cost:**
Multipurpose 6061 Aluminum Rectangular Tube, 1/4" Wall Thickness, 4" High x 4" Wide Outside	1 ft.	McMaster-Carr	$82.17
Multipurpose 6061 Aluminum, 3/4" Thick, 4" x 48" Sheet	(1) 4" x 48" Sheet	McMaster-Carr	$122.99
Brass Submersible Cord Grip, Metric Threads, for 0.14"-0.28" Cord OD, M12 Knockout	1	McMaster-Carr	$7.33
Aluminum Socket Head Screw, 1/4"-20 Thread Size, 3/4" Long	8	McMaster-Carr	$35.68
Passivated 18-8 Stainless Steel Pan Head Phillips Screws, M3 x 0.5mm Thread, 8mm Long	8	McMaster-Carr	$5.51
Black-Oxide Alloy Steel Socket Head Screw, 3-48 Thread Size, 1-1/4" Long	4	McMaster-Carr	$19.86
Zinc-Plated Low-Strength Steel Hex Nuts, 3-48 Thread Size	4	McMaster-Carr	$3.36
Oil-Resistant Buna-N O-Ring Cord Stock, 1/16 Fractional Width, 0.07" Actual Width	3 ft.	McMaster-Carr	$0.34
			$277.24

4. Engineering Analysis

4.1 ECS Housing Stress

For this analysis, ANSYS 2023 was utilized to model the ECS housing with precise dimensions of 4 [in] × 4 [in] × 7.125 [in]. The internal volume was carefully designed to replicate the actual operational component. The simulation examines the structural response of the pressure vessel when exposed to the extreme conditions of a vacuum environment while containing an internal pressure of 1 atmosphere (14.7 [psi]), replicating the challenges it would face during space operation.

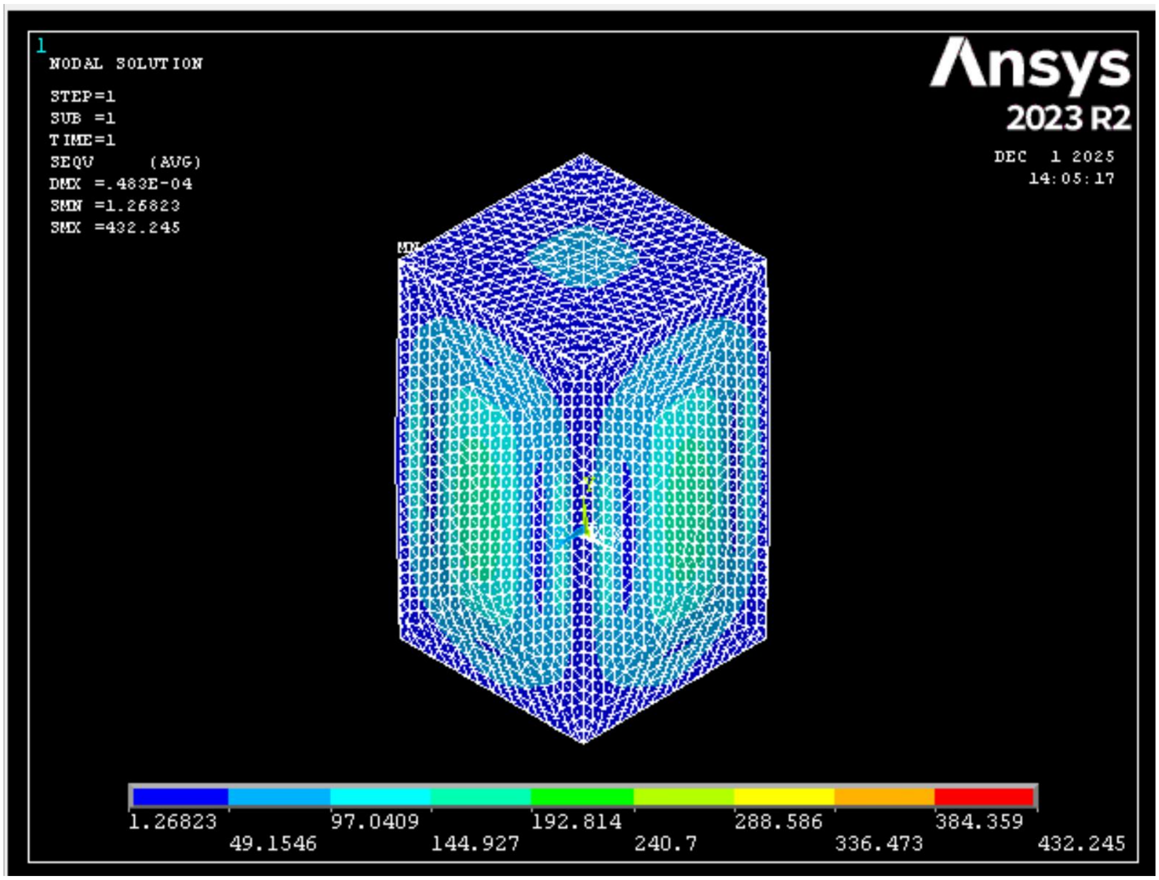


Figure 43: Von-Mises Stress

As shown in Figure 44, the Von Mises stress analysis of the ECS housing reveals that the highest stresses occur on the center of each face, with the maximum stress reaching approximately 192 [psi] on the 4 × 7.125 [in] faces. Interestingly, the corners and edges of the outer housing experiences significantly lower stresses, close to the minimum value of 1.27 [psi], which was unexpected by the team.

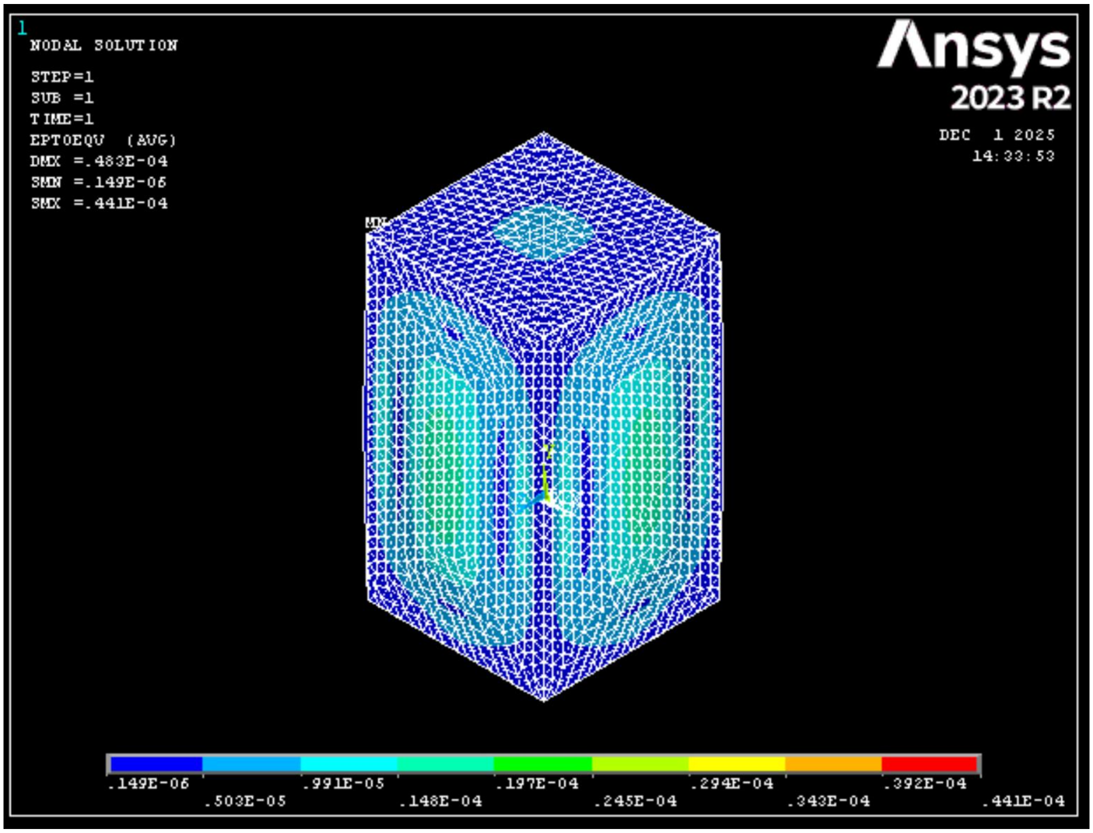


Figure 44: Overall Strain

As shown in Figure 45, the total strain analysis of the ECS housing mirrors the stress distribution, as stresses and strains are directly proportional. The highest strains are observed at the center of each face, with a maximum value of approximately 0.197×10^{-4} on the 4×7.125 [in] faces.

To validate the FEA results, hand calculations were also performed to determine the stress distributions in the structure. For this analysis, the internal volume of the enclosure was taken as $3.5 \times 3.5 \times 6$ inches, which gives a plate surface area of 3.5×3.5 inches exposed to the internal pressure. The enclosure uses a total of eight 1/4-inch-20 aluminum bolts for four bolts per plate to hold the two end plates in place. These bolts are responsible for resisting the outward force produced when the interior is pressurized. Using the pressure acting on the plate area, the total force on each plate was calculated, followed by the load carried by each individual bolt. With the bolt size and material known, the corresponding shear stress was determined and compared to the shear strength of the aluminum bolts to establish an appropriate factor of safety.

Plate Dimensions on one of the ends:

$$\boldsymbol{L = 3.5\ in = 0.0889\ [m]} \quad (1)$$

$$\boldsymbol{\Delta P = 1\ atm = 101,325\ [Pa]} \quad (2)$$

Force on 3.5 x 3.5-inch plates:

$$\boldsymbol{F_{plate} = \Delta P \cdot A = 101.325\ [Pa] \cdot 0.007903\ [m^2] = 801\ [N]} \tag{3}$$

Since the 801N force is shared by 4 bolts per side:

$$\boldsymbol{F_{per\ bolt} = \frac{801}{4} \approx 200\ [N]} \tag{4}$$

For ¼-20 bolts with an approximate diameter of 6.35mm:

$$\boldsymbol{A_{bolt} = \frac{\pi d^2}{4} = \frac{\pi(6.35)^2}{4} \approx 31.7\ [mm^2]} \tag{5}$$

$$\boldsymbol{\tau = \frac{F_{per\ bolt}}{A_{bolt}} \approx \frac{200[N]}{31.7[mm^2]} \approx 6.3\ [MPa]} \tag{6}$$

Factor of safety calculation: (6061-T6) [5]

$$\boldsymbol{\tau_y = 0.577\sigma_y = 0.577(276[MPa]) \approx 159\ [MPa]} \tag{7}$$

$$\boldsymbol{N = \frac{\tau_y}{\tau} \approx \frac{159[MPa]}{6.3[MPa]} \approx 25} \tag{8}$$

In a similar manner, utilizing the maximum shear-stress theory:

$$\boldsymbol{S_{ys} = 0.5\sigma_y = 0.577(276[MPa]) \approx 159\ [MPa]} \tag{9}$$

$$\boldsymbol{N = \frac{S_{ys}}{\tau} \approx \frac{138\ [MPa]}{6.3\ [MPa]} \approx 22} \tag{10}$$

4.1.1 Fastener Analysis

The structural analysis of the 1/4-20 6061-T6 aluminum fasteners yielded a Factor of Safety (FoS) of approximately 25. This value is derived from the pressure differential between the 1 atm internal environment and the external vacuum. The end plate, possessing an internal surface area of 3.5 x 3.5 inches, withstands a total pressure load of approximately 180 [lbf]. Distributing this load across the four retaining bolts results in a tensile load of 45 [lbf] per fastener.

Given the substantial cross-sectional area of a 1/4-20 bolt relative to this load, the resulting shear stress is calculated at approximately 900 [psi]. When compared against the shear strength of 6061-T6 aluminum (~23,000 [psi]), the margin is significant. The resulting high FoS indicates a mechanically conservative design where the fastener size is driven by manufacturing standards and handling requirements rather than minimum stress limits.

4.1.2 Housing and End Plate Analysis

To verify the structural integrity of the payload housing, a static stress analysis was performed on both the end plates and the main housing walls. The loading condition assumes a maximum pressure differential of 14.7 [psi] acting uniformly on all internal surfaces. While this pressure magnitude is low relative to standard pressure vessel applications, verification is required to ensure that the aluminum structure remains within the elastic region and that deformation remains negligible.

4.1.3 Geometric Assumptions

The analysis utilizes the following geometric parameters:

- **External Dimensions:** 4.0 x 4.0 x 7.125 inches
- **Internal Dimensions:** 3.5 x 3.5 x 6.0 inches
- **Wall Thickness:** 0.25 inches

For this calculation, the walls and end plates are approximated as beams of unit width under a uniformly distributed load. This method provides a conservative estimate of the bending stresses induced by internal pressure.

Span of plate:

$$\boldsymbol{L = 3.5\ [in]} \tag{11}$$
$$\boldsymbol{h = 3.5\ [in]} \tag{12}$$

Plate thickness:

$$\boldsymbol{t = 0.25\ [in]} \tag{13}$$

Yield strength of 6061-T6 aluminum: ***[5]***

$$\boldsymbol{\sigma_y = 40{,}000\ [psi]} \tag{14}$$

Line load calculations:

$$\boldsymbol{w = P * h = 14.7\ [psi] \cdot 3.5\ [in] = 51.45\ [\frac{lb}{in}]} \tag{15}$$

Maximum moment for a fixed- fixed beam

$$\boldsymbol{M_{max} = \frac{w \cdot L^2}{12} = \frac{51.45 \cdot (3.5)^2}{12} = 52.52\ [lbf \cdot in]} \tag{16}$$

Modulus of plate strip:

$$\boldsymbol{Z = \frac{bt^2}{6} = \frac{1 \cdot (0.25)^2}{6} = 0.0104\ [in^3]} \tag{17}$$

Bending stress:

$$\sigma_{plate} = \frac{M_{max}}{Z} = \frac{52.52}{0.0104} = 5042\ [psi] \tag{18}$$

Factor of Safety:

$$N_{plate} = \frac{\sigma_y}{\sigma_{plate}} = \frac{40000}{5042} = 7.9 \tag{19}$$

The end plate factor of safety if about 8 in bending under a 1 atm internal pressure.

<u>Housing Wall Factor of Safety (Side panel 3.5x6 [in])</u>

Wall span:

$$L = 6\ [in] \tag{20}$$

Wall height:

$$h = 3.5\ [in] \tag{21}$$

Thickness:

$$t = 0.25\ [in] \tag{22}$$

Line Load Calculation:

$$w = P \cdot h = 51.45\ \left[\frac{lb}{in}\right] \tag{23}$$

Maximum moment:

$$M_{max} = \frac{wL^2}{12} = \frac{51.45 \cdot 6^2}{12} = 154.35\ [lb \cdot in] \tag{24}$$

Bending stress:

$$\sigma_{wall} = \frac{M_{max}}{Z} = \frac{154.35}{0.0104} = 14818\ [psi] \tag{25}$$

Factor of safety:

$$N_{wall} = \frac{\sigma_y}{\sigma_{wall}} = \frac{40000}{14818} \approx 2.7 \tag{26}$$

Component Analysis Results

Both the end plate and the housing wall exhibit positive structural margins when subjected to the maximum design pressure of 1 atm (14.7 psi).

- **End Plate:** This component demonstrates the higher margin of the two, with a calculated Factor of Safety (FoS) of approximately **8.0**. This high safety factor is attributed to the relatively short unsupported span (3.2 inches), which significantly limits the bending moment generated by the internal pressure.
- **Housing Wall:** The housing wall yields a lower, yet sufficient, FoS of approximately **2.7**. This reduction compared to the end plate is a direct result of the increased unsupported span (6.0 inches), which increases the bending stress under the same uniform load.

Design Validation

The calculated margins validate the selection of 0.25-inch thick 6061-T6 aluminum for the pressure vessel. While flat-walled pressure vessels typically experience higher stress concentrations as span lengths increase, the selected wall thickness provides significant stiffness relative to the low operating pressure.

The results indicate that the design remains well within the elastic regime of the material. There are no indications of realistic failure modes under nominal loading conditions; the housing is sufficiently robust to prevent excessive deformation or yield.

4.2. Water Delivery

4.2.1 Pressure Drop

A hydraulic analysis was performed to assess the expected pressure drop in the water delivery system due to the selected pump's flowrate parameters. Provided that the system is designed for operation in space-like, microgravity conditions, flow relationships were analyzed in terms of pressure (as opposed to head) to factor out explicit gravitational effects. To determine the range of pressure drops expected within the water delivery system, the flow was characterized at the minimum and maximum possible flowrates produced by the peristaltic pump. The following set of expressions walk through this process for the maximum pump flowrate.

To maintain dimensional homogeneity, the provided pump flowrates were first converted to standard units using the conversion expressed by Equation 27.

$$\mathbf{1.100}\left[\frac{\boldsymbol{mL}}{\boldsymbol{min}}\right]\times\frac{\mathbf{1}\,[\boldsymbol{min}]}{\mathbf{60}\,[\boldsymbol{s}]}\times\frac{\mathbf{1\times10^{-6}}[\boldsymbol{m}^{\mathbf{3}}]}{\mathbf{1}\,[\boldsymbol{mL}]}=\mathbf{1.83\times10^{-8}}\left[\frac{\boldsymbol{m}^{\mathbf{3}}}{\boldsymbol{s}}\right] \qquad (27)$$

Given an inner pipe diameter of 0.5 [mm], the flow velocity was determined by Equation 28 where V is the flow velocity, Q is the flowrate, and A is the cross-sectional area of the pipe.

$$V = \frac{Q}{A} = \frac{1.83 \times 10^{-8} \left[\frac{m^3}{s}\right]}{\frac{\pi}{4}(\frac{0.5}{1000})^2 \ [m^2]} = 0.09337 \ [\frac{m}{s}] \tag{28}$$

With the flow velocity known, the Reynolds number (Re) was calculated by way of Equation 29 to characterize the resulting level of turbulence, where ρ is the air density, d is the inner pipe diameter, and μ is the dynamic viscosity of the air.

$$Re = \frac{\rho V d}{\mu} = \frac{(998 \left[\frac{kg}{m^3}\right])(0.09337 \left[\frac{m}{s}\right])(0.0005[m])}{1 \times 10^{-3}[\frac{kg}{m \cdot s}]} = 46.592 \tag{29}$$

Having determined a Reynolds number of less than 2300, the internal flow was characterized as extremely laminar, representing smooth flow throughout the pipe system. The friction factor (f) could therefore be determined for explicit laminar flow, as shown by Equation 30.

$$f = \frac{64}{Re} = \frac{64}{46.592} = 1.373 \tag{30}$$

To determine the magnitude of the pressure drop between the inlet and outlet of the pipe system, Bernoulli's Principle was applied as highlighted by Equation 31, including pressure losses (P_L) which result from pipe geometry characteristics. For reference, the subscript 1 represents the inlet of the pipe whereas the subscript 2 represents the outlet of the pipe.

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 + P_L \tag{31}$$

Within this system, the pipe diameter remains unchanged, meaning that the velocity remains constant along its length as defined by the Conservation of Mass and expressed by Equation 32, where.

$$Q_1 = Q_2; V_1 A_1 = V_2 A_2 \tag{32}$$

By applying the Conservation of Mass to Bernoulli's Principle, Equation__ can be rearranged to represent the pressure drop as a function of the pressure losses in the pipe. This modified expression is represented by Equation 33, where L is the characteristic length of the pipe.

$$\Delta P = P_L = f\frac{L\rho V^2}{2d} \tag{33}$$

To account for variations in the pipe length, the pressure drop was modified slightly to represent the pressure lost on a per unit length basis. Equation 34 highlights the maximum pressure drop calculated.

$$\frac{\Delta P}{L} = f\frac{\rho V^2}{2d} = 1.373 \frac{(998 \left[\frac{kg}{m^3}\right])(0.09337 \left[\frac{m}{s}\right])^2}{2(0.0005[m])} = 11.945 \ [\frac{kPa}{m}] \tag{34}$$

By applying the same procedure to the minimum pump flowrate of 0.060 $[\mu L/min]$, a minimum pressure drop of 0.001[kPa/m] was determined. As such, the water delivery system is expected to exhibit pressure drops ranging from **0.001-11.945 [kPa/m]**.

4.2.2 Delivery Timing

In addition to hydraulic analysis, a water flow analysis was performed for time assessment. The following list entails the known parameters, being the water reservoir, soil moisture ranges, and their notations to be used.

- Volume of Water Within Reservoir, $V_{reservoir}$ = 0.00035[m^3]
- Minimum Soil Moisture, θ_{min}= 0.5 $[\frac{m^3}{m^3}]$
- Maximum Soil Moisture, θ_{max}= 0.7 $[\frac{m^3}{m^3}]$

The following analysis utilizes the maximum flow rate, beginning by determining the soil volume, V_{soil} [m^3], which is simply calculated using the plant bay dimensions, as outlined in Section 3.3.2.

$$\boldsymbol{V_{soil} = 6.35 * 6.35 * 1.3\ [cm^3] \approx\ 5.24 * 10^{-5}\ [m^3]} \tag{35}$$

Following this, the amount of water to be delivered to bring the soil saturation from a minimum soil moisture value to a "maximum" soil moisture value. Soil moisture is simply the ratio of water volume within the soil and soil volume (Equation 36). Using this concept, the maximum and minimum volumes of water in the soil, $V_{ws,\ min}$ and $V_{ws,\ max}$ [m^3] are determined. Taking the difference yields the volume of water that encompasses a single "full" delivery of water, ΔV_{ws} [m^3].

$$\boldsymbol{\theta = \frac{Volume\ of\ water\ within\ soil}{Soil\ Volume}} \tag{36}$$

$$\boldsymbol{V_{ws,min} = \theta_{min} * V_{soil} \approx\ 2.7 * 10^{-5}\ [m^3]} \tag{37}$$

$$\boldsymbol{V_{ws,max} = \theta_{max} * V_{soil} \approx\ 3.7 * 10^{-5}\ [m^3]} \tag{38}$$

$$\boldsymbol{\Delta V_{ws} = V_{ws,max} - V_{ws,min} \approx\ 1.05 * 10^{-5}\ [m^3]} \tag{39}$$

After determining the volume of water for a full delivery, the number of full deliveries, n is determined by rounding down the ratio of total water volume and $\Delta V_{ws.}$ This value is then used to determine the amount of water left within the reservoir 'n' delivieres, or the final volume of water to be delivered, ΔV_w [m^3]. Rather than rounding 'n' deliveries up, this method was preferred to reduce power consumption, as it allows the final delivery to be operated for a more power efficient time frame.

$$\boldsymbol{n = \frac{V_{reservoir}}{\Delta V_{ws}} = 33} \tag{40}$$

$$\Delta V_w = V_{reservoir} - n * \Delta V_{ws} \approx 4.03 * 10^{-6} [m^3] \tag{41}$$

By utilizing equation _ and the difference in water volume along with the known flow rate as per the pump specifications, the time required for a full delivery, t_{pump}[s], is determined. Likewise, the total time for water delivery, t_{max} [s], is determined by taking the ratio of the water within the reservoir and the flow rate. These times in addition with the number of full deliveries, yield the final time for pump actuation, t_{final} [s].

$$Q_{pump} = \frac{\Delta V}{t} \left[\frac{m^3}{s}\right] \tag{42}$$

$$t_{pump} = \frac{\Delta V_{ws}}{Q_{pump}} \approx 572 [s] \tag{43}$$

$$t_{max} = \frac{V_{reservoir}}{Q_{pump}} \approx 1.\overline{90} * 10^4 [s] \tag{44}$$

$$t_{final} = t_{max} - n * t_{pump} \approx 220 [s] \tag{45}$$

This analysis while incorporating the minimum flow rate yielded the same total of full water deliveries; however, t_{max} and t_{pump} were, 3.5 * 10^8 [s] and 1.05 * 10^7 [s] respectively. By comparison, it is clear that to provide prompt water saturation, the pump should operate at maximum.

4.3 Heat Transfer

The thermal behavior of the Environmental Control System (ECS) was evaluated using a lumped parameter heat transfer model in MATLAB. Since the CubeSat has relatively small dimensions and is primarily contracted from 6061-T6 aluminum, the entire structure is treated as a single thermal mass whose temperature changes uniformly with time. The external housing dimensions of $4 \times 4 \times 7.125$ inches and the actual mass of 4.4[lb] (≈ 2 $[kg]$) were used to determine both the surface area of the satellite exposed to the environment and its overall heat capacity. The specific heat of aluminum (≈ 900 $\left(\frac{J}{kg \cdot k}\right)$) was used to calculate how quickly the system responds to changes in heat input and radiation to space.

The model simulates the satellite passing through a 90-minute low Earth orbit consisting of a 60-minute sunlit period followed by a 40-minute eclipse. During sunlight, the exposed 4 × 4-inch face absorbs incoming solar radiation based on the solar constant (1361 [W/m²]), the absorptivity of the anodized aluminum surfaces (0.3), and the effective area of the deployable components. Internal heat generation from the Raspberry Pi, the battery system, and the ECS heater were included in both phases of the orbit. Radiative cooling to deep space was calculated continuously using the Stefan-Boltzmann law with an emissivity of 0.3.

To better reflect realistic spacecraft operation, the heater was controlled using a simple temperature-based switching logic. The heater activates when the temperature falls below 10°C and turns off once the system warms above 20°C. This allows the system to maintain temperatures within an acceptable range without adding unnecessary heat.

After multiple orbital cycles, the model converged to a repeating temperature pattern. Over the final orbit, the ECS temperature ranged from 12.01°C during eclipse to 22.53°C during sunlight, with an average temperature of 19.36°C. The resulting temperature profile shows the expected oscillatory behavior, where the system warms when exposed to the Sun and cools during eclipse. The heater engages only briefly when temperatures approach the lower threshold, indicating that natural solar input and internal loads are sufficient to maintain the system above the minimum required temperature for operation.

Overall, the predicted temperature range of approximately 12–22°C is well within acceptable limits for the onboard electronics and for maintaining a stable environment inside the ECS. The results suggest that the system's thermal balance is adequate for low Earth orbit and does not require continuous heating to remain within the desired temperature band.

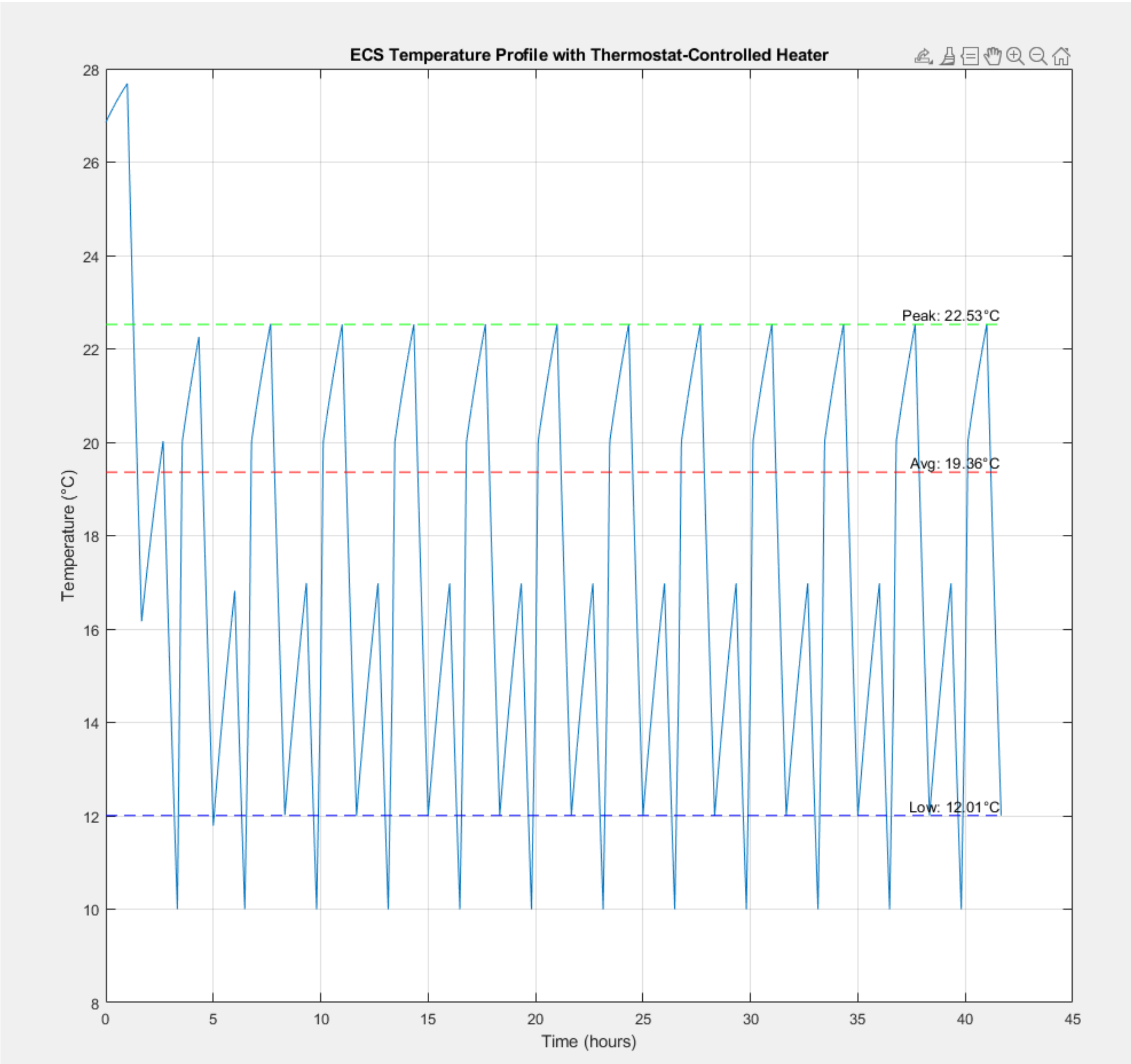


Figure 45: Converged Orbital Temperature Range for ECS

```
>> Thermal_Calcs_ECS_HEATER_Tweak
Average converged temperature over the last orbit: 19.36 °C
Peak temperature over the last orbit: 22.53 °C
Lowest temperature over the last orbit: 12.01 °C
>>
```

Figure 46: MATLAB Output for Thermal Analysis

4.4 Data Budget Analysis

The Pathfinder Data Budget was derived using a Software-in-the-Loop (SITL) simulation running on the flight hardware. This method provides a verified estimate of data generation based on the sensor polling rates defined in the Mission Experiment Plan.

Table 3: Data Budget

Subsystem	Description	Size (Bytes)	Frequency (Hz)	Duration (s)
PAY	Temperature	4	1.0	86400
PAY	Airflow	4	1.0	86400
PAY	Pressure	4	0.5	86400
PAY	CO2	4	0.5	86400
PAY	Rel. Humidity	4	0.5	86400
PAY	Lighting	4	0.25	86400
PAY	Soil Moisture	4	0.1	86400
Total	**Mission Data (24 hrs.)**			~1.7 MB

Link Budget & Transmission Strategy: The total daily data volume is approximately **~1.7 [MB]**. With a telemetry radio rate of **57.6 [kbps]**, the system has sufficient bandwidth to downlink all sensor data in real-time during the flight.

- **Transmission:** 100% of generated data is transmitted live for ground monitoring.
- **Storage:** The onboard SD card serves purely as a redundant backup in case of radio link loss.

4.5. Power Budget

A comprehensive power budget was developed to organize and quantify the electrical demands of each subsystem across Pathfinder's operating modes. Figure 48 summarizes the maximum power and duty cycles for all subsystem components utilizing a spreadsheet retrieved from the University of Nanosatellite Program (UNP) [6]. It includes the Water Delivery System, Onboard Computer, and Climate Control System. By multiplying each component's peak load by its expected duty cycle in the Standby, Preconditioning, Experiment, and Safe modes, the mode of power was able to be determined in aggregate for the entire system.

POWER DRAW													
Spacecraft Subsystem, Unit, Quantity and Power Consumption						Power Consumption by Spacecraft Mode							
						Standby		Preconditioning		Experiment		*Safe*	
Subsystem	Component/ Use Case	Peak Power(W)	Qty	Comment	Total Power (W)	Duty Cycle	Mode Power (W)	Duty Cycle	Mode Power (W)	Duty Cycle	Mode Power (W)	Duty Cycle	Mode Power (W)
ECS													
					0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00
					0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00
WDS	Pump	0.35	1		0.35	0.00%	0.00	0.00%	0.00	25.00%	0.09	10.00%	0.04
	Heater 1	7.00	1		7.00	0.00%	0.00	50.00%	3.50	25.00%	1.75	0.00%	0.00
					0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00
					0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00
OBC	Raspberry Pi 3B	2.50	1		2.50	25.00%	0.63	70.00%	1.75	75.00%	1.88	25.00%	0.63
Sensors					0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00
	Combined	0.10	1		0.10	0.00%	0.00	25.00%	0.03	100.00%	0.10	0.00%	0.00
					0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00
CCS	Heater 2	7.00	2		14.00	0.00%	0.00	25.00%	3.50	25.00%	3.50	10.00%	1.40
	LEDs red	0.40	8		3.20	0.00%	0.00	0.00%	0.00	40.00%	1.28	0.00%	0.00
	LEDs blue	0.12	4		0.48	0.00%	0.00	0.00%	0.00	40.00%	0.19	0.00%	0.00
	Fans	0.60	2		1.20	0.00%	0.00	0.00%	0.00	50.00%	0.60	0.00%	0.00
					0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00	0.00%	0.00
					Total Mode Power (W)	0.63		8.78		9.38		2.06	

Figure 47: Power Budget

The minimum power draw of **0.63 [W]** occurs during the Standby mode, while maximum power draw of **9.38 [W]** occurs during the Experiment mode. During Preconditioning, the system reached an intermediate load of **8.78 [W]** as the heaters and control electronics ramp up to operating conditions. Safe mode reduces power to **2.06 [W]**, limiting operation to only the essential components necessary to maintain system health.

4.6. Mass Budget

A design goal of the Environmental Control System was to keep the total mass of the system under 6 [kg]. This design goal was in fact met. The biggest contributor to the total mass of the system would be the structural components including the ECS Housing, Drop-in System, and Entry Seals. Sensors and climate control components in total weigh less than 1 [kg] while the pump and water reservoir weigh around 0.473 [kg] combined. Like the power budget, mass sheet also retrieved from UNP. [6]

Table 4: Mass Budget

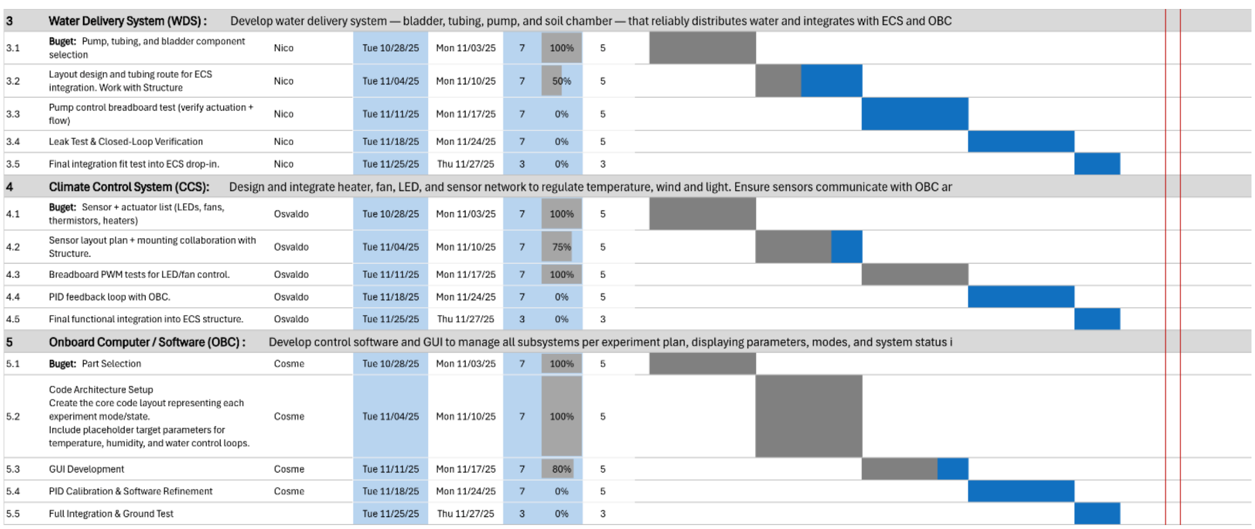
PATHfinder Mass Budget				
Component	**Material**	**Quantity**	**Mass (kg)**	**Total Mass (kg)**
Structure				**2.1**
ECS Housing	Aluminum	1	1.08	1.08
ECS Drop-In System	PETG	1	0.34	0.34
ECS Top Entry Seal	Aluminum	1	0.34	0.34
ECS Bottom Entry Seal	Aluminum	1	0.34	0.34
CCS				**0.09161**
Cooling Fans	Metal	2	0.006	0.012
Lux Sensor	FR-4 PCB	1	0.001	0.001
CO2 Sensor	FR-4 PCB	1	0.01361	0.01361
Soil Moisture	FR-4 PCB	1	0.004	0.004
LED's	LED	2	0.001	0.002
Heaters	Polyimide	3	0.003	0.009
Pressure, Temperaure and Humidty Sensor	FR-4 PCB	1	0.05	0.05
EPS				**0.3**
Power Supply	-	1	0.3	0.3
WDS				**0.473**
Pump	Metal	1	0.013	0.013
Water	-	1	0.35	0.2
Water Reservior	PVC	1	0.26	0.26
OBC				**0.12**
Raspberry Pi 3	FR-4 PCB	1	0.06	0.06
Controller Board	FR-4 PCB	1	0.06	0.06
			Total	**3.08461**
			Total + 25%	**3.8557625**
			Max Allowable	**6**

5. Project Plan

5.1 Timeline

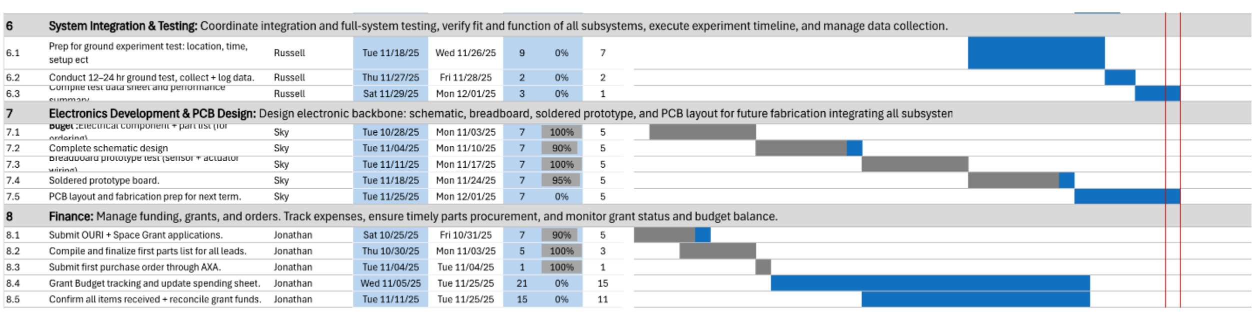
WBS	TASK	LEAD	START	END	DAYS	% DONE	WORK DAYS
1	**General:** Be a team player			-			-
1.1	BWR 5 – Submit	Team	Tue 10/28/25	Tue 10/28/25	1	100%	1
1.2	PDR & Presentation Prep	Team	Thu 10/30/25	Tue 11/04/25	6	100%	4
1.3	PDR Presentation	Team	Tue 11/04/25	Tue 11/04/25	1	100%	1
1.4	BWR 6 – Submit	Team	Mon 11/10/25	Tue 11/11/25	2	100%	2
1.5	Final Presentation Prep	Team	Tue 11/25/25	Mon 12/01/25	7		5
1.6	Final Presentation & Demo	Team	Tue 12/02/25	Tue 12/02/25	1	0%	1
1.7	Party Time	Team	Fri 12/05/25	Fri 12/05/25	1		1
2	**ECS Structure / Shell / Drop-In Integration :** Design and 3D print ECS shell and drop-in system that supports all subsystems, minimizes weight, and provides hermetic acce						
2.1	**Bugetr :** Component + material list (PLA/PETG, O-rings if needed).	Frank	Tue 10/28/25	Mon 11/03/25	7	100%	5
2.2	CAD update — ECS Shell v2 (structural layout, access port).	Frank	Tue 11/04/25	Mon 11/10/25	7	50%	5
2.3	Print and fit-test Drop-In v2.	Frank	Tue 11/11/25	Mon 11/17/25	7	0%	5
2.4	Integration edits with CCS + WDS leads (mount points, wire routing).	Frank	Tue 11/18/25	Mon 11/24/25	7	0%	5
2.5	Final structure print ready for subsystem mounting.	Frank	Tue 11/25/25	Thu 11/27/25	3	0%	3

Figure 48: First Section of Gantt Chart



WBS	TASK	LEAD	START	END	DAYS	% DONE	WORK DAYS
3	**Water Delivery System (WDS) :** Develop water delivery system — bladder, tubing, pump, and soil chamber — that reliably distributes water and integrates with ECS and OBC						
3.1	**Buget:** Pump, tubing, and bladder component selection	Nico	Tue 10/28/25	Mon 11/03/25	7	100%	5
3.2	Layout design and tubing route for ECS integration. Work with Structure	Nico	Tue 11/04/25	Mon 11/10/25	7	50%	5
3.3	Pump control breadboard test (verify actuation + flow)	Nico	Tue 11/11/25	Mon 11/17/25	7	0%	5
3.4	Leak Test & Closed-Loop Verification	Nico	Tue 11/18/25	Mon 11/24/25	7	0%	5
3.5	Final integration fit test into ECS drop-in.	Nico	Tue 11/25/25	Thu 11/27/25	3	0%	3
4	**Climate Control System (CCS):** Design and integrate heater, fan, LED, and sensor network to regulate temperature, wind and light. Ensure sensors communicate with OBC ar						
4.1	**Buget:** Sensor + actuator list (LEDs, fans, thermistors, heaters)	Osvaldo	Tue 10/28/25	Mon 11/03/25	7	100%	5
4.2	Sensor layout plan + mounting collaboration with Structure.	Osvaldo	Tue 11/04/25	Mon 11/10/25	7	75%	5
4.3	Breadboard PWM tests for LED/fan control.	Osvaldo	Tue 11/11/25	Mon 11/17/25	7	100%	5
4.4	PID feedback loop with OBC.	Osvaldo	Tue 11/18/25	Mon 11/24/25	7	0%	5
4.5	Final functional integration into ECS structure.	Osvaldo	Tue 11/25/25	Thu 11/27/25	3	0%	3
5	**Onboard Computer / Software (OBC) :** Develop control software and GUI to manage all subsystems per experiment plan, displaying parameters, modes, and system status i						
5.1	**Buget:** Part Selection	Cosme	Tue 10/28/25	Mon 11/03/25	7	100%	5
5.2	Code Architecture Setup Create the core code layout representing each experiment mode/state. Include placeholder target parameters for temperature, humidity, and water control loops.	Cosme	Tue 11/04/25	Mon 11/10/25	7	100%	5
5.3	GUI Development	Cosme	Tue 11/11/25	Mon 11/17/25	7	80%	5
5.4	PID Calibration & Software Refinement	Cosme	Tue 11/18/25	Mon 11/24/25	7	0%	5
5.5	Full Integration & Ground Test		Tue 11/25/25	Thu 11/27/25	3	0%	3

Figure 49: Second Section of Gantt Chart



WBS	TASK	LEAD	START	END	DAYS	% DONE	WORK DAYS
6	**System Integration & Testing:** Coordinate integration and full-system testing, verify fit and function of all subsystems, execute experiment timeline, and manage data collection.						
6.1	Prep for ground experiment test: location, time, setup ect	Russell	Tue 11/18/25	Wed 11/26/25	9	0%	7
6.2	Conduct 12–24 hr ground test, collect + log data.	Russell	Thu 11/27/25	Fri 11/28/25	2	0%	2
6.3	Compile test data sheet and performance summary	Russell	Sat 11/29/25	Mon 12/01/25	3	0%	1
7	**Electronics Development & PCB Design:** Design electronic backbone: schematic, breadboard, soldered prototype, and PCB layout for future fabrication integrating all subsysten						
7.1	**Buget :**Electrical component + part list (for ordering)	Sky	Tue 10/28/25	Mon 11/03/25	7	100%	5
7.2	Complete schematic design	Sky	Tue 11/04/25	Mon 11/10/25	7	90%	5
7.3	Breadboard prototype test (sensor + actuator wiring)	Sky	Tue 11/11/25	Mon 11/17/25	7	100%	5
7.4	Soldered prototype board.	Sky	Tue 11/18/25	Mon 11/24/25	7	95%	5
7.5	PCB layout and fabrication prep for next term.	Sky	Tue 11/25/25	Mon 12/01/25	7	0%	5
8	**Finance:** Manage funding, grants, and orders. Track expenses, ensure timely parts procurement, and monitor grant status and budget balance.						
8.1	Submit OURI + Space Grant applications.	Jonathan	Sat 10/25/25	Fri 10/31/25	7	90%	5
8.2	Compile and finalize first parts list for all leads.	Jonathan	Thu 10/30/25	Mon 11/03/25	5	100%	3
8.3	Submit first purchase order through AXA.	Jonathan	Tue 11/04/25	Tue 11/04/25	1	100%	1
8.4	Grant Budget tracking and update spending sheet.	Jonathan	Wed 11/05/25	Tue 11/25/25	21	0%	15
8.5	Confirm all items received + reconcile grant funds.	Jonathan	Tue 11/11/25	Tue 11/25/25	15	0%	11

Figure 50: Final Section of Gantt Chart

In terms of the coming semester, a rough timeline is as follows:

December - January: Manufacturing & Physical Integration of ECS

February: Ground test in freezer/vacuum chamber

March/April: High-Altitude Balloon Launch Test

May: Senior Showcase & Graduation

5.2 Achievements

5.2.1 Mechanical Achievements

- ***Developed Complete ECS Structure:*** Designed and modeled a complete structure for the Environmental Control System. A total of four major iterations were made on the ECS mechanical structure. Each iteration tackled issues with the previous design and improved those issues to refine the design. The ECS structure has been optimized to perform success criteria and mission plan.
- ***Developed ECS Fabrication Plan:*** Developed a fabrication plan for the Environmental Control System mechanical structure. ECS design will require three machined parts and one 3-D printed part. The machining process for structural parts will be completed on a CNC mill with dimension tolerances of ± 0.005-inch. The Drop-in System will be a 3-D printed component and may be further optimized in terms of the component/sensor layout during fabrication.
- ***Developed ECS Pressure Sealing and Bleed Feature:*** The final design of the ECS structure will include a pressure sealing and bleed feature. To maintain the internal atmosphere of the system, a piston-like O-ring design has been made for the entry covers of the ECS. The O-rings will be placed below the bolts that mate the ECS Housing and Top/Bottom entry seals. To relieve the internal atmosphere of the ECS, an air-bleed valve has been integrated into the bottom entry seal. The air-bleed valves inlet may draw air from a hole cut-out of the Drop-in System. This feature makes disassembly of the ECS easier and reduces the force required to open the Top/Bottom entry seals.
- ***Developed Through-Hole Feature:*** An imperative design feature needed for the ECS structure was to develop a sealed through-hole to allow component wiring to pass through. This feature is needed since the ECS user interface and OBC will be outside of the ECS structure, and internal pressure of the system must be maintained. A method of achieving this was to use a cable gland which creates a seal between an O-ring and the wires passing through it. The cable gland is threaded and can be tightened with a nut to create a tight seal around the thickness of the wires.

5.2.2 Electrical Achievements

- ***Requirements Definition & Component Selection:*** Successfully identified and procured the complete sensor and actuator suite required to meet Climate Control and Water Delivery objectives. This includes the selection of specific MOSFETs, resistors, DC motors, full-spectrum LEDs, brushless fans, and the peristaltic pump, ensuring compatibility with the Raspberry Pi 3B+ logic levels.
- ***Schematic Design & Safety Integration:*** Developed comprehensive electrical schematics for the Power Distribution Board and Controller Board. The design incorporates critical safety features, including fusing over-current protection and discharge paths to prevent electrostatic charge buildup, ensuring the system cannot damage itself during operation.
- ***Prototype Fabrication:*** Transitioned from theoretical design to physical hardware by fabricating a solder-in-place prototype (perfboard) of the Controller Board. All components have been soldered and integrated into a compact form factor that adheres to the payload's spatial constraints.
- ***Power Distribution Verification:*** Validated the stability of the three required voltage rails. Confirmed that the system correctly regulates and distributes **12V** for high-power actuators, **5V** for the On-Board Computer, and **3.3V** for environmental sensors.
- ***Component-Level Testing:*** completed functional verification of all individual subsystems. Each sensor and actuator has been powered and tested independently to ensure operational readiness prior to full system integration.

5.2.3 Software Achievements

- ***Developed Centralized State Architecture:*** Designed and implemented a unified Python-based control architecture (main.py) that aggregates state-of-health telemetry and sensor data into a single verified data packet, simplifying the downlink requirements.
- ***Verified CONOPS Logic via SITL:*** Successfully created a Software-in-the-Loop (SITL) simulation environment to validate the autonomous transition logic between **Safe Mode** and **Experiment Mode** before physical integration.
- ***Validated Data Budget*:** Utilized the flight software execution to generate a precise, line-by-line data generation model, confirming that the mission produces ~1.7 MB/day and fits within the 57.6 kbps telemetry link margin.
- ***Implemented Data Regulation:*** Programmed non-blocking timer logic to strictly enforce sensor polling rates, prevent data saturation, and ensure 100% compliance with the onboard storage constraints.

5.3 Role and Tasks

To ensure the success of this project, each group member has been assigned a distinct role that aligns with their individual strengths and expertise. These responsibilities are designed to complement one another, allowing the team to address the research questions effectively while maintaining a clear division of tasks. The following outlines each member's specific contributions and how they support the overall objectives of the project:

Frank Borkowski – Structural Design/Fabrication Lead

Project role is focused on developing/fabricating the Environmental Control System structure and drop-in system. Several design iterations of the ECS will be performed, optimizing each throughout the design phase. This role is responsible for fabrication of the ECS structure and drop-in system. 3-D printed models will be utilized to optimize design for ease of maintenance and use. This role will be directly integrated with other sub-system leads, providing proper design iterations for necessary system layout changes. This role is responsible for purchasing the correct materials needed for structural fabrication. This role shall also fabricate the ECS in the machine shop throughout the development process.

Sebastian Bosa – Climate Control Team, Thermal Analysis and Pressurization

Project role is focused on developing and integrating the control logic required to maintain stable environmental conditions within the Environmental Control System (ECS). Responsibilities include helping design feedback and control architectures that will regulate internal variables such as temperature, humidity, and atmospheric pressure. This involves determining desired environmental conditions and assisting with the selection and integration of sensors, actuators, and control hardware needed to maintain target values for the biological payload. In addition to control integration, this role also includes performing the thermal and structural analyses necessary to verify that the ECS can operate safely in a space-like environment. This includes conducting heat-transfer calculations, developing a MATLAB thermal model to evaluate temperature behavior through sunlit and eclipse periods, and assessing the performance of the heater and radiative surfaces. Structural responsibilities include calculating the forces on the pressurized ECS housing, evaluating the loading on the end plates, and determining factors of safety for the bolts and structure under 1 atm internal pressure. In collaboration with the OBS and CCS leads, this role contributes to developing sensor calibration procedures, defining signal routing, and outlining control algorithms that automate environmental stability. The pressurization portion of the role involves researching effective sealing methods and ensuring that the ECS maintains an Earth-like internal atmosphere with minimal leakage over the mission duration. Altogether, these contributions support the development of a stable, controlled environment capable of sustaining plant growth inside the CubeSat.

Nicholas Caggiani – Structural Design & Water Delivery System Lead

Project role is focused on developing and testing the structural design of the Environmental Control System. The responsibilities of this role include supporting Frank and Russell in iterating on CAD depictions of the physical structure by using engineering principles to guide critical design decisions. Further, these responsibilities encapsulate analyzing the various model iterations using free body diagrams, strength of materials principles, and finite element analysis to validate important design choices. Water Delivery System operations primarily involve ensuring that the research and integration of all components related to the delivery of water from the reservoir to the plant bed is performed thoroughly, thereby ensuring its operational viability within the overarching system. These efforts will support the mission by ensuring structural and system integrity and stability.

Russell Caton – System Integration/Testing & Structural Design/Fabrication

Project role focuses on the structural development, integration, and experimental validation of the Environmental Control System (ECS). Responsibilities include designing and fabricating the ECS outer shell and internal drop-in frame to ensure proper fit within the 1.6U CubeSat bus, as well as coordinating and conducting system-level ground testing. This includes preparing test setups, executing 12–24 hour ground tests, collecting and logging performance data, and compiling detailed test reports. Additional tasks involve performing finite element analysis (FEA) to assess structural integrity and developing pressure sealing solutions to prevent thermal and atmospheric losses. These combined efforts ensure that the ECS is both structurally robust and fully verified for mission operation.

Osvaldo Gonzalez – Climate Control System Lead and Water Delivery

Project role focuses on development, integration and implementation of the climate control subsystem. For this role, performed trade studies on primary sensors such as pressure, temperature, humidity, and soil moisture sensors, and gas concentration sensors, and studies for various optimal plant parameters. After selection of sensors, breadboard tested additional climate components, heaters, fans, and grow light LEDs.

Additionally, collaborated with the team regarding layout plan and mounting plan. Also, completed delivery timing calculations, LED, preliminary heat transfer calculations, and calculations to interpret atmospheric conditions, such as relative humidity and assisted in fastener stress calculations. Helped outline functional logic of water delivery method.

Cosme Penney – Software & Electrical

Project role focuses on the development, verification, and integration of both the software and electrical systems that support the Environmental Control System (ECS). Responsibilities include designing and implementing the control architecture that governs autonomous operation and environmental regulation in accordance with system and subsystem requirements. This encompasses developing the logic for sensor data handling, feedback loops, and safety interlocks that enable stable, closed-loop control of ECS parameters. On the electrical side, this role ensures that all powered subsystems operate within the defined power and voltage limits, maintaining a verified power budget that accounts for load, efficiency, and operational margins. Additional responsibilities include managing wire routing, connector selection, and electrical organization to ensure that all connections meet current and voltage specifications while fitting within the tight physical and thermal constraints of the ECS. This role ensures seamless coordination between the control software and electrical hardware, providing reliable system operation under all test conditions.

Jonathan Ramdhanie – Finance Lead & Electrical

Project role focuses on managing funds, grants and orders alongside tracking expenses, ensuring timely parts procurement, monitoring grant status and budget balance. Other responsibilities include providing the Environmental Control System (ECS) with continuous electrical energy. To achieve this, the Electrical and Power System (EPS) must store energy for use when generation is unavailable and ensure stable voltage levels to protect subsystems from overcurrent or undervoltage, with power regulation through DC/DC converters. Emphasis is placed on the budget for design and subsystem choice in the selection of the parameters required for each component as well as the energy and power levels necessary to facilitate its processes.

Sky Rueff – Team Lead & Systems Engineer & Electrical Power Lead

This role oversaw the full technical and organizational development of the Environmental Control System (ECS) mission, ensuring all subsystem efforts aligned with the defined objectives and success criteria. The system hierarchy was established through traceable requirements and constraints, linking mission goals to subsystem functionality. Documentation—including the System Design Verification Matrix (SDVM), subsystem sheets, and budgets—was organized to maintain logical consistency across design phases. A structured team framework was developed, defining subsystem leads for Climate Control, Water Delivery, Structure, Electrical Power, and Software, while coordination between members and mentors ensured timely progress toward integration milestones.

System-level oversight included defining mission modes, verifying requirement coverage, and maintaining system traceability from the concept of operations to functional testing. The Gantt chart was maintained to manage subsystem deliverables, testing, and integration timelines, while technical communication between leads was facilitated through design reviews and requirement verification meetings. Each subsystem's interfaces were validated for compatibility, with attention to environmental, electrical, and software dependencies to ensure seamless operation during ground testing.

In parallel, the electrical system architecture was developed to serve as the backbone of subsystem control. Responsibilities included component selection, schematic design, breadboard prototyping, and development of a soldered control board integrating actuators, sensors, and MOSFET drivers for heaters, lighting, and pumps. Testing confirmed voltage regulation, current distribution, and system reliability under operational conditions. Design refinements were made to prepare the PCB layout for future fabrication, with a focus on modularity, safety, and scalability for future CubeSat adaptation.

6. Detailed Budget

Table 5: Encompassing Budget

Item	Supplier	Quantity	Unit Cost	Total
Structural Subsystem				
Aluminum sheet (6061-T6) for CubeSat housing	McMaster-Carr	1	$238.40	$238.40
100 Pcs M3 Threaded Inserts	Amazon	1	$7.59	$7.59
Total				$245.99
Water Delivery Subsystem				
Peristaltic Pump	TFS	2	$136.00	$272.00
Tubing	Amazon	1	$6.39	$6.39
Water Reservoir Bags	Amazon	1	$11.99	$11.99
Total				$290.38
Climate Control Subsystem				
Bosch Sensortec Pressure and Temperature Sensor	Digikey	4	$4.03	$16.12
Electrochemical Oxygen /O_2 Sensor	DF Robot	2	$53.90	$107.80
NDIR True CO_2 Temperature and Humidity Sensor	Adafruit	2	$58.95	$117.90
STEMMA Soil Sensor - I2C Capacitive Moisture Sensor	Adafruit	4	$7.50	$30.00
6 Pcs DC 20 mm Fan 12V	Amazon	1	$15.99	$15.99
20 Pcs 30 mm x 40 mm Film Heater Plate Adhesive Pad	Amazon	1	$13.99	$13.99
15 Pcs 10 mm x 93 mm Film Heater Plate Adhesive Pad	Amazon	1	$12.99	$12.99
16.4 ft Full Spectrum LED Plant Growth Light Strips	Amazon	1	$22.99	$22.99
VEML7700 Ambient Light Detector	Amazon	1	$17.99	$17.99
4 Pcs NTC 10K Thermistor Probe 15.7 inch	Amazon	1	$8.29	$8.29

10 Pcs NTC 10k Thermistor Probe 3.93 inch	**Amazon**	**1**	**$7.99**	**7.99**
Total				**$372.05**
Electrical Subsystem				
120 Pcs ELEGOO Dupont Wire Kit	**Amazon**	**1**	**$6.98**	**$6.98**
TO-220 Heatsink Kit	**Amazon**	**1**	**$6.99**	**$6.99**
Bojack 3 Solderless Breadboard 4 Pcs	**Amazon**	**1**	**$9.99**	**$9.99**
Rindion 32 Pcs PCB Board	**Amazon**	**1**	**$6.99**	**$6.99**
0.079” Buna-N O-Ring Cord Stock	**Amazon**	**1**	**$15.39**	**$15.39**
0.093” Buna-N O-Ring Cord Stock	**Amazon**	**1**	**$15.39**	**$15.39**
Total				**$61.73**
OBC Subsystem				
Raspberry Pi 3 Model B+	**DigiKey**	**2**	**$40.00**	**$80.00**
4 Pcs Analog to Digital ADC PGA Converter with Gain Amplifier	**Amazon**	**1**	**$12.88**	**$12.88**
4 Pcs DC-DC Buck Converter	**Amazon**	**1**	**$11.99**	**$11.99**
SanDisk 265GB Extreme microSDXC UHS-1 Memory Card	**Amazon**	**1**	**$26.99**	**$26.99**
Total				**$131.86**
Testing				
High Altitude Balloon	**High Altitude Science**	**1**	**$450.00**	**$450.00**
Helium	**All American Balloon**	**2**	**$325.00**	**$650.00**
Total				**$1100.00**
Combined Total				**$2,202.01**

All listed materials are essential for constructing and testing the ECS. The microcontroller and sensors form the autonomous control core. The pump and tubing enable water delivery testing.

The aluminum and acrylic materials provide structural support for the test enclosure, replicating CubeSat environmental conditions. The high-altitude balloon and helium gas is required for testing under space-like conditions. Additional materials, such as software licenses, will be covered through departmental resources.

7. References

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8. Appendix

```
%% ECS Thermal Model for 2U CubeSat in LEO (with thermostat-controlled heater)
%-----------------------------
% Geometry & Material Properties
%-----------------------------
mass = 4.4 * 0.453592; % kg, 4.4 lb converted to kg (~2.0 kg)
specific_heat = 900; % J/kg·K, 6061-T6 aluminum (approx.)
% External dimensions (housing) in meters (4 in x 4 in x 7.125 in)
L = 4 * 0.0254; % m
W = 4 * 0.0254; % m
H = 7.125 * 0.0254; % m
% Surface areas based on housing size
surface_area_sun = L * W; % m^2 (one 4x4 in face facing the Sun)
surface_area_total = 2 * (L*W + L*H + W*H); % m^2 (total external radiating area)
% Deployable areas (radiators / solar panels)
deployable_area_total = 3 * (6 * (10 * 10) * 1e-4); % m^2 (3 deployables, each 6U of
10x10 cm faces)
deployable_efficiency = 0.05; % 5% effective coupling to heat input
deployable_area_effective = deployable_efficiency * deployable_area_total;
% Optical & thermal properties
emissivity = 0.3; % IR emissivity, anodized aluminum
absorptivity = 0.3; % solar absorptivity
%-----------------------------
% Orbital Environment
%-----------------------------
sunlit_period = 60 * 60; % seconds in sunlight (1 hour)
eclipse_period = 40 * 60; % seconds in eclipse (40 minutes)
orbital_period = sunlit_period + eclipse_period; % total orbit duration
solar_constant = 1361; % W/m^2, solar flux at 1 AU
stefan_boltzmann = 5.67e-8; % W/m^2·K^4
%-----------------------------
% Internal Power (ECS Loads)
%-----------------------------
raspberry_pi_power = 0.54; % W, electronics heat (Pi)
battery_power_charge = 5.04; % W, during charge in sunlit
battery_power_discharge = 2.96; % W, during discharge in eclipse
heater_nominal = 20; % W, full heater power
T_heater_on = 10 + 273.15; % K, turn heater ON below 10°C
T_heater_off = 20 + 273.15; % K, turn heater OFF above 20°C
heater_on = false; % initial heater state (off)
%-----------------------------
% Initial Conditions & Time Setup
%-----------------------------
initial_temp = 300; % K, initial temperature (~27°C)
time_step = 1; % seconds
num_orbits = 25; % simulate 25 orbits
```

```
total_time = num_orbits * orbital_period;
time = 0:time_step:total_time; % time vector [s]
temperature = zeros(size(time)); % temperature history [K]
temperature(1) = initial_temp;
% Lumped heat capacity [J/K]
heat_capacity = mass * specific_heat;
%-----------------------------
% Time Marching Simulation
%-----------------------------
for k = 2:length(time)
% --- Thermostat control for heater----
T_prev = temperature(k-1);
if T_prev < T_heater_on
heater_on = true;
elseif T_prev > T_heater_off
heater_on = false;
end
Q_heater = heater_on * heater_nominal; % W
% Time within current orbit
t_orbit = mod(time(k), orbital_period);
if t_orbit <= sunlit_period
% ---- Sunlit Period ----
Q_solar = absorptivity * solar_constant * (surface_area_sun +
deployable_area_effective);
Q_internal = raspberry_pi_power + battery_power_charge + Q_heater;
Q_in = Q_solar + Q_internal;
else
% ---- Eclipse Period ----
Q_internal = raspberry_pi_power + battery_power_discharge + Q_heater;
Q_in = Q_internal; % no solar input in eclipse
end
% Radiative heat loss
Q_out = emissivity * stefan_boltzmann * surface_area_total * T_prev^4;
% Net heat flow
Q_net = Q_in - Q_out; % [W] = [J/s]
% Temperature change (lumped capacitance)
delta_temp = (Q_net * time_step) / heat_capacity; % [K]
% Update temperature
temperature(k) = T_prev + delta_temp;
end
%-----------------------------
% Post-processing
%-----------------------------
temperature_C = temperature - 273.15; % convert to °C
time_hours = time / 3600; % convert time to hours
figure;
plot(time_hours, temperature_C);
```

```matlab
xlabel('Time (hours)');
ylabel('Temperature (°C)');
title('ECS Temperature Profile with Thermostat-Controlled Heater');
grid on;
% Steady-orbit statistics (last orbit)
last_orbit_start_time = total_time - orbital_period;
idx_start = round(last_orbit_start_time / time_step) + 1;
last_orbit_temps = temperature_C(idx_start:end);
avg_temp = mean(last_orbit_temps);
peak_temp = max(last_orbit_temps);
low_temp = min(last_orbit_temps);
fprintf('Average converged temperature over the last orbit: %.2f °C\n', avg_temp);
fprintf('Peak temperature over the last orbit: %.2f °C\n', peak_temp);
fprintf('Lowest temperature over the last orbit: %.2f °C\n', low_temp);
hold on;
x_max = max(time_hours);
plot([0, x_max], [avg_temp, avg_temp], 'r--');
text(x_max, avg_temp, sprintf(' Avg: %.2f°C', avg_temp), ...
'VerticalAlignment', 'bottom', 'HorizontalAlignment', 'right');
plot([0, x_max], [peak_temp, peak_temp], 'g--');
text(x_max, peak_temp, sprintf(' Peak: %.2f°C', peak_temp), ...
'VerticalAlignment', 'bottom', 'HorizontalAlignment', 'right');
plot([0, x_max], [low_temp, low_temp], 'b--');
text(x_max, low_temp, sprintf(' Low: %.2f°C', low_temp), ...
'VerticalAlignment', 'bottom', 'HorizontalAlignment', 'right');
hold off;
```

Heat Transfer Code

Parameter	Symbol	Unit	Value	Formula
ECS Bolt Stress				
Internal Pressure	P	kPa	101.325	
Wall Area	A	in^2	12.25	L*W
		cm^2	79.0321	
		m^2	0.00790321	
Force	F	kN	0.800792753	P*A
		N	800.7927533	
Force per Screw	Fs	N	200.1981883	F/4
Screw Diameter	Ds	in	0.25	
		cm	0.635	
		m	0.00635	
Screw Cross-Sectional Area	As	m^2	3.16692E-05	0.25*pi*Ds
Shear Stress per Screw	τs	kPa	6321.538847	Fs/As
		MPa	6.321538847	
6061 Heat Treated Tensile Yield Strength	Sy_tensile	MPa	276	
Factor of Safety (using yield shear stress theory)	N		25.19196731	0.577*Sy/τs
Factor of Safety (using maximum shear-stress theory)	N		21.83012766	0.5*Sy/τs

Figure 51: Fastener Stress Excel Sheet

Parameter	Symbol	Unit	Value	Formula
Water Delivery RP-QII Minumum Flow Rate (CDR Rendition)				
Volume of Water in Reservoir	V_reservoir	mL	350	
Volume of Water in Reservoir	V_reservoir	m^3	0.00035	
Volume of Soil	V_soil	m^3	5.24193E-05	
Pump Flow Rate	Q_pump	µL/min	0.06	
Pump Flow Rate	Q_pump	m^3/s	1E-12	
Soil Humidty (Min)	θmin	m^3/m^3	0.5	
Soil Humidty (Max)	θmax	m^3/m^3	0.7	
Volume of water in soil (Min)	V_ws_min	m^3	2.62096E-05	V_soil*θmin
Volume of water in soil (Max)	V_ws_max	m^3	3.66935E-05	V_soil*θmax
Volume of water to be delivered for one full delivery	ΔV_ws	m^3	1.04839E-05	V_ws_max- V_ws_min
Time for pump to deliver ΔV_ws	t_pump	s	10483850	ΔV_ws/Q_pump
reservior	t_max	s	350000000	V_reservoir/Q_pump
Amount of Full Deliveries	n		33	V_reservoir/ΔV_ws
deliveries	ΔVw	m^3	4.03295E-06	V_reservoir - n*ΔV_ws
Time for final water delivery	t_final	s	4032950	t_max - n*t_pump or ΔVw/Q_pump

Figure 52: Excel Sheet of Water Delivery using Minimum Flow Rate

Parameter	Symbol	Unit	Value	Formula
Water Delivery RP-QII Maximum Flow Rate (CDR Rendition)				
Volume of Water in Reservoir	V_reservoir	mL	350	
Volume of Water in Reservoir	V_reservoir	m^3	0.00035	
Volume of Soil	V_soil	m^3	5.24193E-05	
Pump Flow Rate	Q_pump	mL/min	1.1	
Pump Flow Rate	Q_pump	m^3/s	1.83333E-08	
Soil Humidty (Min)	θmin	m^3/m^3	0.5	
Soil Humidty (Max)	θmax	m^3/m^3	0.7	
Volume of water in soil (Min)	V_ws_min	m^3	2.62096E-05	V_soil*θmin
Volume of water in soil (Max)	V_ws_max	m^3	3.66935E-05	V_soil*θmax
Volume of water to be delivered for one full delivery	ΔV_ws	m^3	1.04839E-05	V_ws_max- V_ws_min
Time for pump to deliver ΔV_ws	t_pump	s	571.8463636	ΔV_ws/Q_pump
reservior	t_max	s	19090.90909	V_reservoir/Q_pump
Amount of Full Deliveries	n		33	V_reservoir/ΔV_ws
deliveries	ΔVw	m^3	4.03295E-06	V_reservoir - n*ΔV_ws
Time for final water delivery	t_final	s	219.9790909	t_max - n*t_pump or ΔVw/Q_pump

Figure 53: Excel Sheet of Water Delivery using Maximum Flow Rate

```python
# main.py - Core Architecture
import time
import conops_modes
import global_config

def main():
    # 1. Initialize Centralized State Dictionary
    system_state = {
        "current_mode": "STARTUP",
        "last_mode": None,
        "battery_voltage": 0.0,
        "payload_temps": {"air": 0.0, "water": 0.0},
        "error_log": []
    }

    # 2. Main Control Loop (1.0 Hz)
    while True:
        # Execute the logic for the current mode
        current_mode = system_state["current_mode"]

        if current_mode == "SAFE_MODE":
            conops_modes.handle_safe_mode(system_state)

        elif current_mode == "EXPERIMENT_MODE":
            conops_modes.handle_experiment_mode(system_state)

        elif current_mode == "LAST_RESORT":
            conops_modes.handle_last_resort_mode(system_state)

        # Maintain loop frequency
        time.sleep(global_config.MAIN_LOOP_DELAY)
```

Figure 54: Centralized State Architecture (main.py)

```python
# conops_modes.py - Experiment Mode Logic
import time
import hardware_drivers

# Timer Variables
last_image_time = 0
IMAGE_INTERVAL = 300  # 5 Minutes

def handle_experiment_mode(system_state):
    """
    Executes Payload Tasks:
    1. Thermal Control (Continuous)
    2. LED Lighting Cycles (16h ON / 8h OFF)
    3. Data Capture (Regulated)
    """
    global last_image_time

    # 1. Run Critical Thermal Loops
    system_health.run_payload_thermal_control(system_state)

    # 2. Check Image Timer (Data Budget Verification)
    current_time = time.time()
    if (current_time - last_image_time) >= IMAGE_INTERVAL:
        print(f"[Mode] EXPERIMENT: Timer hit ({IMAGE_INTERVAL}s). Capturing image.")
        hardware_drivers.capture_image()
        last_image_time = current_time  # Reset Timer
```

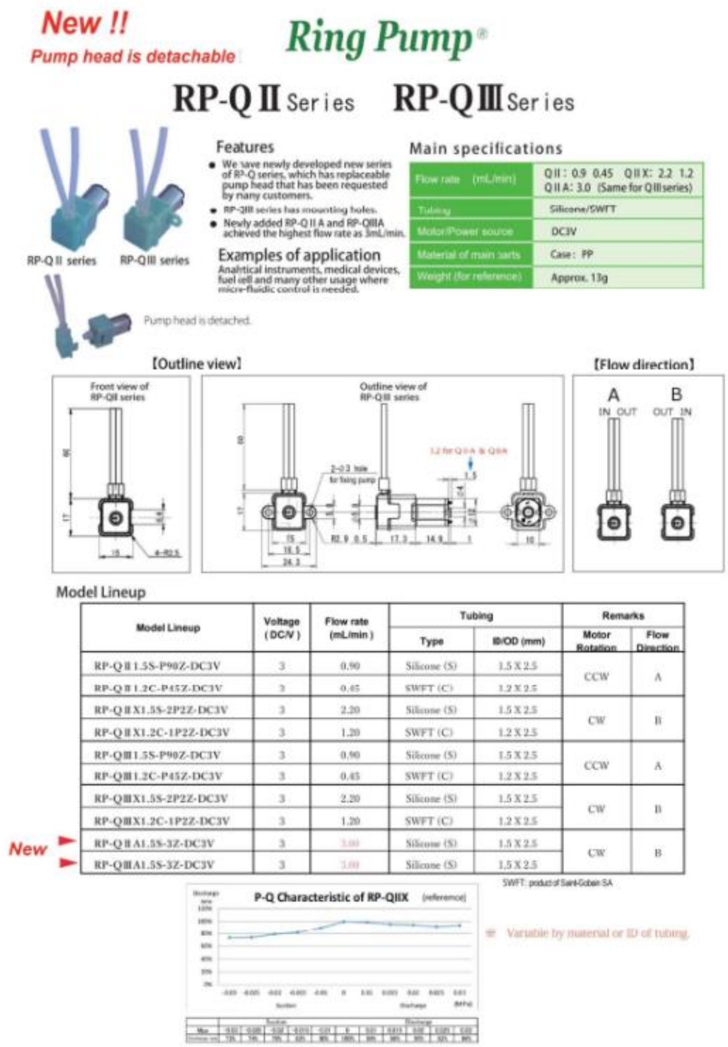
Figure 55: Experiment Logic & Data Regulation (conops_modes.py)

```python
# hardware_drivers.py - Sensor Interface
def read_sensors(system_state):
    """
    Polls all I2C and GPIO sensors and updates the central state.
    """
    try:
        # Read BME280 Environmental Sensor
        temp = bme280.read_temperature()
        humidity = bme280.read_humidity()
        pressure = bme280.read_pressure()

        # Update the State Dictionary directly
        system_state["payload_temps"]["air"] = temp
        system_state["humidity"] = humidity
        system_state["pressure"] = pressure

    except OSError:
        # Log error but do not crash the main loop
        system_state["error_log"].append("Sensor Read Failure")
```

Figure 56: Hardware Abstraction Layer (hardware_drivers.py)



New !!

Pump head is detachable

Ring Pump®

RP-Q II Series RP-Q III Series

Features

- We have newly developed new series of RP-Q series, which has replaceable pump head that has been requested by many customers.
- RP-QIII series has mounting holes.
- Newly added RP-Q II A and RP-QIIIA achieved the highest flow rate as 3mL/min.

Examples of application

Analytical instruments, medical devices, fuel cell and many other usage where micro-fluidic control is needed.

Main specifications

Flow rate (mL/min)	Q II : 0.9 0.45 Q II X: 2.2 1.2 Q II A: 3.0 (Same for Q III series)
Tubing	Silicone/SWFT
Motor/Power source	DC3V
Material of main parts	Case : PP
Weight (for reference)	Approx. 13g

Model Lineup

Model Lineup	Voltage (DC/V)	Flow rate (mL/min)	Tubing Type	Tubing ID/OD (mm)	Remarks Motor Rotation	Remarks Flow Direction
RP-Q II 1.5S-P90Z-DC3V	3	0.90	Silicone (S)	1.5 X 2.5	CCW	A
RP-Q II 1.2C-P45Z-DC3V	3	0.45	SWFT (C)	1.2 X 2.5		
RP-Q II X1.5S-2P2Z-DC3V	3	2.20	Silicone (S)	1.5 X 2.5	CW	B
RP-Q II X1.2C-1P2Z-DC3V	3	1.20	SWFT (C)	1.2 X 2.5		
RP-QIII1.5S-P90Z-DC3V	3	0.90	Silicone (S)	1.5 X 2.5	CCW	A
RP-QIII1.2C-P45Z-DC3V	3	0.45	SWFT (C)	1.2 X 2.5		
RP-QIIIX1.5S-2P2Z-DC3V	3	2.20	Silicone (S)	1.5 X 2.5	CW	B
RP-QIIIX1.2C-1P2Z-DC3V	3	1.20	SWFT (C)	1.2 X 2.5		
New ► RP-Q II A1.5S-3Z-DC3V	3	3.00	Silicone (S)	1.5 X 2.5	CW	B
New ► RP-QIIIA1.5S-3Z-DC3V	3	3.00	Silicone (S)	1.5 X 2.5		

SWFT: product of Saint-Gobain SA

Figure 57: Peristaltic Pump Specifications

BME280
Digital humidity, pressure and temperature sensor

Key features

• Package	2.5 mm x 2.5 mm x 0.93 mm metal lid LGA
• Digital interface	I²C (up to 3.4 MHz) and SPI (3 and 4 wire, up to 10 MHz)
• Supply voltage	V_{DD} main supply voltage range: 1.71 V to 3.6 V V_{DDIO} interface voltage range: 1.2 V to 3.6 V
• Current consumption	1.8 µA @ 1 Hz humidity and temperature 2.8 µA @ 1 Hz pressure and temperature 3.6 µA @ 1 Hz humidity, pressure and temperature 0.1 µA in sleep mode
• Operating range	-40…+85 °C, 0…100 % rel. humidity, 300…1100 hPa

- Humidity sensor and pressure sensor can be independently enabled / disabled
- Register and performance compatible to Bosch Sensortec BMP280 digital pressure sensor
- RoHS compliant, halogen-free, MSL1

Key parameters for humidity sensor

• Response time ($\tau_{63\%}$)	1 s
• Accuracy tolerance	±3 % relative humidity
• Hysteresis	±1% relative humidity

Key parameters for pressure sensor

• RMS Noise	0.2 Pa, equiv. to 1.7 cm
• Offset temperature coefficient	±1.5 Pa/K, equiv. to ±12.6 cm at 1 °C temperature change

Figure 58: Bosch BME280 Specifications