CDR Report

TEAM THERMOCLINE

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Project Description

Customer Requirements

The customer requires the development of a controlled temperature chamber for evaluating the performance of electronic components under varying thermal conditions. The chamber must accommodate a 12"×12" printed circuit board and incorporate a sealed port for routing external electrical connections needed for stimulus and measurement. It must be constructed with appropriate insulation to minimize thermal losses and equipped with the ability to heat and cool the internal volume across the commercial operating range of 0°C to 70°C while maintaining the temperature within ±3°C of the setpoint. In addition, the system must include internal temperature monitoring and provide recorded data. These capabilities are necessary to support reliable and repeatable component testing as specified by the project sponsor, Dr. Monk.

Solution Description

The solution will be in the form of a labratory appliance. It will be installed on a table no deeper than 30" to accommodate labratory table depth. It will be no wider than 30" to take up excess space. The system will run indoors, use standard AC wall power (120V, 60HZ). Will not require external ducting or pumbing. And will not require (but may optionally include) external, remote or computer control.

ConOps Summary

The Concept of Operations (ConOps) outlines the intended function, environment, and operational behavior of the thermally controlled PCB testing chamber. The system is a tabletop, insulated chamber designed to accommodate 12"×12" PCBs and regulate internal temperature within the commercial range of 0–70°C while maintaining ±3°C accuracy. It operates in an indoor laboratory environment with stable power, proper ventilation, and access to PC-based data logging. The chamber supports multiple operating modes—including Shutdown, Standby, Start, and Safe states—and allows users to insert test boards, connect measurement cables, and monitor temperature performance locally or remotely. The ConOps identifies primary stakeholders such as engineers, maintenance personnel, faculty, and material suppliers, all of whom contribute to system design, operation, and lifecycle support. It also evaluates operational impacts, including thermal hazards, electrical safety concerns, ventilation requirements, spatial constraints, and data management needs. Finally, the ConOps provides a structured risk assessment addressing potential failures in design, fabrication, operation, and maintenance, assigning likelihood and consequence values to prioritize mitigation efforts. Collectively, the ConOps establishes a clear operational framework that informs system requirements, guides engineering decisions, and ensures safe, reliable, and traceable thermal testing of electronic components.

Subsystem: Structural - Mechanical

System Requirements

The structural subsystem requirements are strict guidelines for the final system that must be adhered to for a successful project. The product must satisfy both customer and team design specifications – arising from design considerations, project timelines, available resources, financial budgets, or product needs. The following database in Table 2.1 represents the team's structural subsystem requirements as of the Preliminary Design Review, which specifics are subject to change later depending on customer modifications, team discussions, or design updates from testing.

Number	Requirement	Performance	Margin	Verification
STR-01	The system shall have external base dimensions of no more than 30x30 inches.	30x30 in	-2x2 in	Inspection
STR-02	The system shall have internal base dimensions of no less than 12x12 inches.	12x12 in	+2x2 in	Inspection
STR-03	The chamber opening(s) shall	Complies	N/A	Inspection

	include proper thermal sealing according to ASTM F1886			
STR-04	The internal thermal control components shall include proper thermal sealing according to ASTM C633-01.	Complies	N/A	Inspection

Table 2.1 Structural Requirements

The following notes provide further detail on each requirement:

STR-01 is a customer-provided requirement. Considering the product's end-usage will be a local operating table-top system, it should be able to fit conveniently on most SNHU tables, desks, and benches without protruding from their edge; having a requirement that limits the external base dimensions of the system will satisfy the customer's desire to have an easily accessible, movable, and safe system. The margin of -2x2 inches, although relatively small, can be modified with both a customer- and team-agreement since the lower bound is more flexible, as it constricts dimensions below 30x30 inches. Although smaller dimensions will constrict internal area and component-arrangements, this design decision will most likely save costs, material, and fabrication time. The final system's external base dimensions shall be measured and inspected to verify if the requirement is met.

STR-02 is also a customer-provided requirement. In order for the final product to evaluate PCB performance, it must first adequately fit the PCB without mechanical/electrical damage or complicated installation. Thus, the system should incorporate an internal floor space of at least 12x12 inches. Tighter areas could satisfy smaller PCBs, but would fail at incorporating the largest. Designing an area larger than this provides room for possible extruding components from the PCB, as the "tester" dimensional specifications are contemporarily unknown at the time of this design report. The margin for this requirement of +2x2 inches is stricter than STR-01—where the team aims closer to the performance value, as larger than 12x12 inches could reduce insulation and prompt larger external dimensions.

STR-03 is a team-determined requirement, derived from Design Requirement 1.2: Included Insulation. Since the system will have external wiring for its power supply and connections to the tested-PCB, structural openings are inevitable. These ports must thus be properly sealed in order to still satisfy being insulated and safe. ASTM F1886 outlines a visual inspection test procedure for seal integrity to ensure the system complies (1).

STR-04 is also a team-determined requirement derived from several of the system's safety design requirements. The internal components are concerning the thermal-fluid cooling system, resistive heating process, electronic controls, and other mechanical elements. ASTM C633-01 is a "Standard Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings", which can be used to determine if the requirement is met (2).

System Design

Trade Studies

The system design and subsystem design requirements are holistic enough to outline important dimensional, functional, operational, manufacturing process, budget, and resource constraint details. However, these regard not the system in its entirety nor account for every project detail. Therefore, numerous trade studies are carried out with the team and stakeholders—if applicable— to further progress design specifications. These trade studies can be simple through small verbal discussions, or highly detailed spanning weeks of research, testing, and analysis to provide insights into the design. The trade study determining the primary material for the system's external framework, internal support, and housing compartments was completed through a team discussion. This study was finalized early in the design process as the team understood its implications would drive several other design considerations such as insulation, fixture attachments and joint connections, and the arrangement of other components and subsystems. Ultimately, using a 0.063" 5052 H32 Aluminum-based alloy would provide the greatest success for the final product. Its critical material property specifications are outlined in Table 2.2 below (3).

5052 PROPERTIES	
Material Composition	Aluminum (Al): 95.8 – 97.7 Magnesium (Mg): 2.2 – 2.8 Chromium (Cr): 0.15 – 0.35 Iron (Fe): 0 – 0.4 Silicon (Si): 0 – 0.25 Manganese (Mn): 0 – 0.1 Zinc (Zn): 0 – 0.1 Copper (Cu): 0 – 0.1 Residuals: 0 – 0.15
Density	169.344 lb/ft^3
Heat treatments process	N/A
ASTM	B209-14
Tensile Strength (Ultimate)	34 ksi
Tensile Strength (Yield)	26 ksi
Shear Strength	20 ksi
Shear Modulus	3700 ksi
Fatigue Strength	17 ksi
Brinell Hardness	60
Elongation at Break	12%
Elastic Modulus	9900 ksi
Poisson's Ratio	.33
Thermal Conductivity	138 BTU/h-ft °F
Melting Point	1120 °F
Magnetic	No
Does it Rust	No

Table 2.2: 5052 H32 0.063" Aluminum Material Properties (Send-Cut-Send)

Through numerous discussions, this Aluminum alloy beat several other material candidates such as Carbon-Steel, Titanium alloys, glass composites, and heavy-duty plastics. The team found its general low-costs – in manufacturability, installation and repairability – to work within the given budget constraints. Its lightweight property promotes greater usability during operation and maintenance procedures, while contributing less to mechanical stress/strain for load-bearing structures. The Aluminum would also be able to withstand the mechanical and thermal conditions within the system, making it suitable for the system's designated environmental condition range. Most prominently, Send-Cut-Send is a well-reputable manufacturer, able to fabricate the designed pieces, provide consistent and strong customer support, hold efficient lead times, perform solid quality inspections, and provide precise and highly reliable parts. Outsourcing these pieces pre-cut and bent is more feasible and cost-efficient than performing these operations in-house with parts sourced elsewhere. Moreover, for the structural subsystem, the only heavily analyzed trade study was in regard to the use of insulation material. This comparisons between several known candidates are outlined in Table 2.3.

	Fiberglass	*Polyurethane Foam*	*Polystyrene*	*Silica Aerogel*
Thermal Conductivity $\left(\frac{W}{m \cdot K}\right)$	0.032-0.036	0.02-0.03	0.025-0.04	0.0032-0.015
Nominal Thickness (in)	6-12	1.18	3	0.2-0.4
Malleability	Most malleable	Malleable depending on type	Malleable when molten	Not malleable
Cost	\$1.00-4.50/ft^2	\$0.50-4.50ft^2	\$1.00-4.50ft^2	\$10,000ft^3

Table 2.3: Insulation Trade Studies

These categories shown on the left-hand side of the table were chosen due to being ranked as highly impactful to the success of the insulation itself along with the final product. In conducting a thorough analysis, fiberglass insulation was seen as superior and would contribute to the greatest success for the overall system. Although out of the most accessible and well-known types of insulation studied it had one of the highest thermal conductivities, this value was sufficient enough to properly insulate the system/components – where the other categories increased its worth. Having a large nominal size would fit well for the system the team is designing given the large amounts of empty volume needed to be filled with insulation; this process would be simpler with how fiberglass insulation is manufactured and installed. Similarly, its higher malleability over the other candidates would simplify the installation, maintenance, or "plugging" processes, especially in smaller ports and non-uniform spaces. Lastly, being widely available and simpler to manufacture decreases its cost, reducing possible financial burdens on the team and opening room for other purchases throughout the project. Strategically weighing these four categories convinced the team to use fiberglass insulation for producing a highly effective thermally-sealing structure to the system.

Proof of Concept / Feasibility Testing

Early in the team's research phase, the system's structure was identified as a crucial aspect not only the final system's success, but in conducting trade studies, developing design models, building prototypes, and optimizing subsystems. Therefore, it was important to analyze the subsystem, determine a ph.

List of Applicable Standards

The following is a list of two standards relevant to the structural subsystem. Both pertain to the insulation and its process of being properly applied to the system in accordance with national rules – ASTM stands for "American Society for Testing and Materials". This organization is especially pertinent to Thermocline's system, ensuring the team's fabrication process, resources, and tools are all efficient, adhere to proper safety, and promote the success of the final product.

1. ASTM F1886: "Standard Test Method for Determining Integrity of Seals for Flexible Packaging by Visual Inspection"
2. ASTM C633-01: "Standard Test Method for Adhesion or Cohesion Strength of Thermal Spray Coatings"

Analysis

Based on the law of heat conduction, the thickness of insulation is a function of the insulation's thermal conductivity (k_{ins}), surface area (A_{sur}), internal temperature (T_{int}), external temperature (T_{ext}), and the heat transfer rate ($\dot{Q}_{cod}$) (Equation 1).

$$\Delta x_{ins} = \frac{k_{ins} A_{sur} (T_{int} - T_{ext})}{\dot{Q}_{cod}} \tag{1}$$

In using estimated and expected values for each variable, the minimum insulation needed to maintain a safe-touch temperature of 50°C during heating is 0.095in (Equation 1).

$$\Delta x_{ins} = \frac{(0.036 \frac{W}{m \cdot K})(810 in^2)(70^o C - 50^o C)}{156W} \left[\frac{0.0254m}{1in}\right] \tag{1}$$

$$\Delta x_{ins} = 0.095in$$

The results of this analysis, albeit rudimentary and include numerous underlying variable/value assumptions, provide insight into critical layers of insulation needed throughout the system during heating operations. Cooling will require less insulation to maintain a safe-touch temperature as the temperature-difference between the internals and externals of the chamber will be smaller. These conclusions also assist the design of the chamber regarding the redirection of airflow in order to maintain temperature uniformity, arrangement of components, and the level of safety needed to be present – satisfying defined and ancillary requirements. The insulation design is to include a large factor of safety, with excess amounts of fiberglass insulation material used to protect internal components and hold a touchable external temperature. Ensuring no air gaps and tight seals conforming to the structure will reduce thermal leakage within the system, and uphold the level of safety desired by the team.

A critical analysis needed for the structural subsystem is also the total weight. For this directly influences operator usability and convenience, while also necessitating certain brackets, fixtures, and joints to maintain mechanical stability. Therefore, an analysis was conducted to explore the current best estimate ("CBE") for the primary structural weight. The team used both property tools and direct measurements from *Inventor* and *Onshape* CAD to calculate the volume, converting this to weight given an approximated density of the material. The relevant formula was based on weight (W) being a function of density (ρ) and volume (V) (Equation 2). The results can be seen in *Table 4*.

$$W = \rho V \tag{2}$$

	Volume (m^3)	Density (kg/m^3)	CBE for Weight (kg)
Skeletal Frame	7.93E-03	2700.00	21.42
External Body Panels	4.01E-03	2712.63	10.88
Chamber Door & Handle	4.58E-04	2712.63	1.24
PCB Testing Chamber	9.06E-04	2712.63	2.46
Airflow Management Chamber	7.83E-04	2712.63	2.12
Thermal Insulation	*Unknown	12 - 48	< 3.00
Total			41.12

Table 2.4; Current Best Estimate for Structural Weight

Component Design Detail

The design of the structural subsystem primarily consists of the body's frame, body panels, alongside internal housings and external mechanisms. These constitute the assembly of the materials, components, and design specifications for the structure and its function. When fully assembled, the external view of the product appears to be a solid metal structure, roughly 22(in) by 31(in) at the base, and 24(in) tall. It consists of jointed panels, revealing only a mounted HMI display, chamber door, and the internal access of the PCB testing chamber, as shown in Figure 2.1.

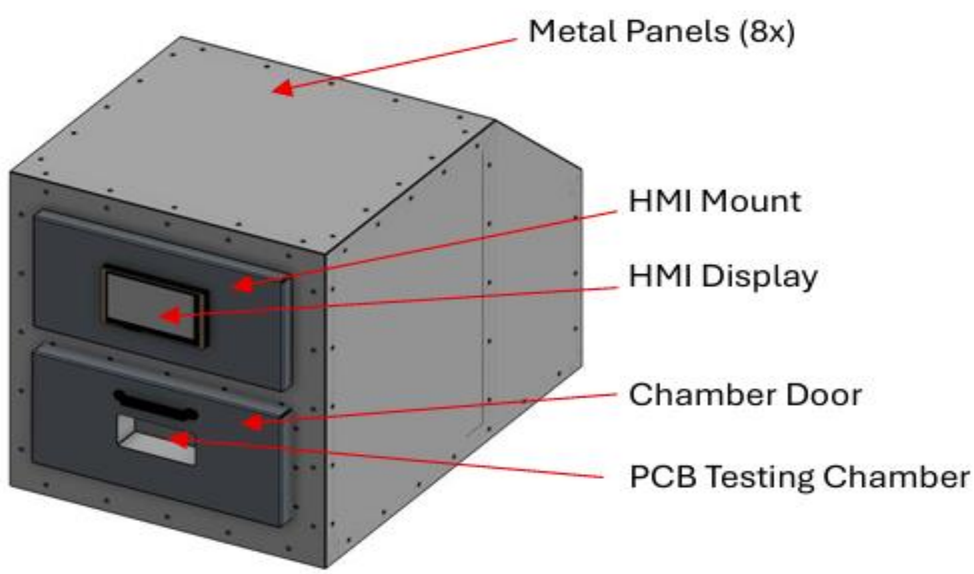


Figure 2.1: Chamber External Assembly

80-20 aluminum-extrusion parts make up the body's frame – providing the "skeleton" for the system. These are strategically designed to not only support the structural loads and material stresses, but serve as attachment pillars for the external panels and insulation. L-brackets will connect these in the assembly in order to maintain their structural integrity and keep the system properly aligned. Several viewpoints are shown in Figure 2.2.

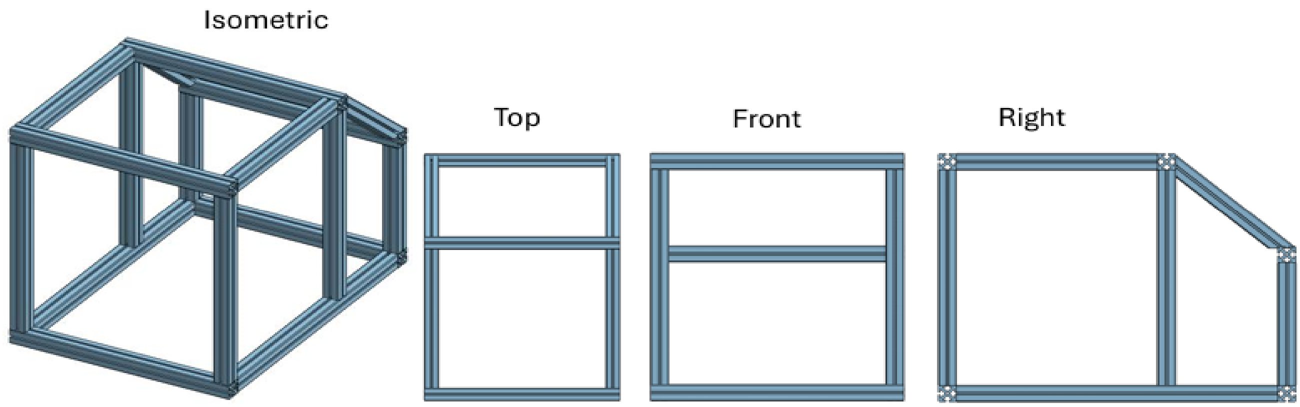


Figure 2.2: Frame Assembly Views

The 8 body panels, directly mounted to these frame pieces, consist of 6 external (left and right sides are duplicates) and 1 internal. All will be individually-cut from the Send-Cut-Send manufacturer, and are designed to provide easy installation and removal for necessary maintenance purposes. All panels will have laser-cut holes, allowing screws to mount the panel to the respective frame. Other holes are designed for "rivnuts" that connect to other components of the system; these joints are an integral part of the system, ensuring all structural connections are secure, able to withstand internal stresses caused by mechanical vibration, and can be easily attached to the thin Aluminum pieces which constitute most of the structural frame and body. All panels are shown in Figure 2.3.

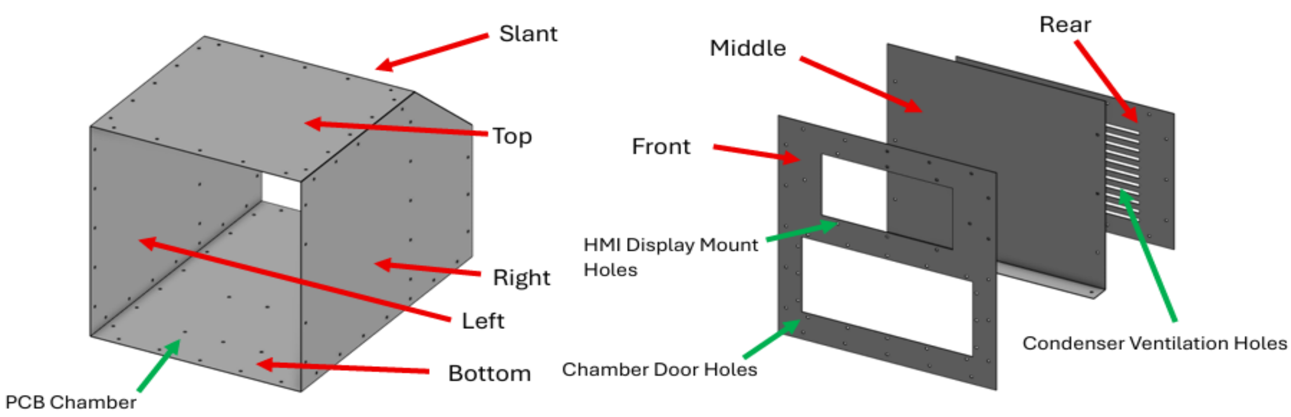


Figure 2.3: 8 Panel Design

The PCB testing chamber, mounted to the rear of the front panel, is outlined in Figure 2.4. There are 4 pieces, including 1 top, 1 bottom, and 2 sides. The parts will be made from the same material, and primarily due to the complex shapes, manufactured from Send-Cut-Send. They are designed for simple installation and maintenance. The chamber shall also have a subjacent "stand" serving for structural support and mitigation of vibrations during operation – mounted to the bottom panel.

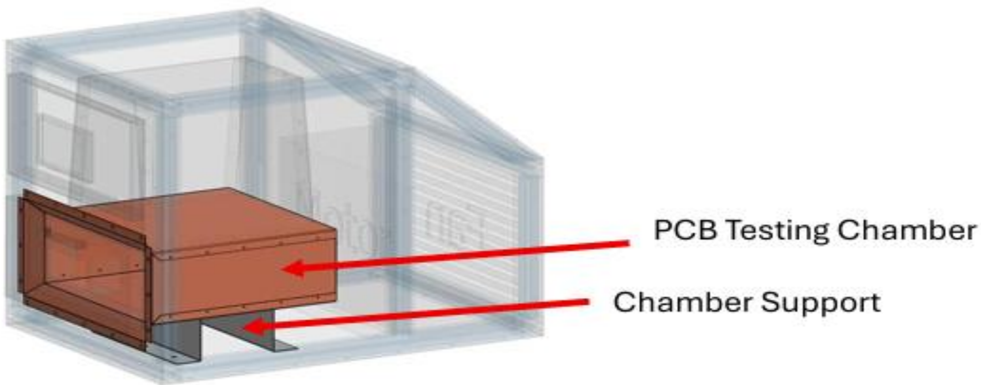


Figure 2.4 PCB Testing Chamber & Support

The air management compartment redirects airflow throughout the PCB testing chamber, being mounted to the top, and is outlined in Figure 2.5. The 3-panel design consists of 1 front, 1 rear, and 1 top piece. This allows the respective personnel to have easy access to the internal components, while providing room for the thermal-fluid and electrical components to reach the rest of the system. These pieces will be fabricated with the same material and manufacturer described aforehand.

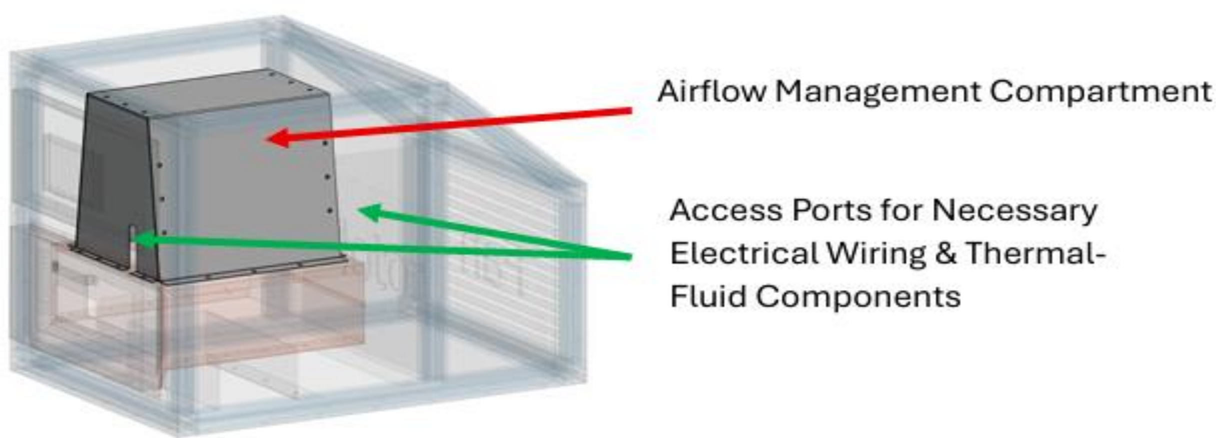


Figure 2.5: Airflow Management Compartment

The HMI Display Mount is to be fabricated with the same material and manufacturer, and mounted on the front panel. Its features were designed for aesthetics, ease of HMI-installation, and a proper cavity for all necessary electrical wiring to protrude from the back. The HMI mount is shown in Figure 2.6.

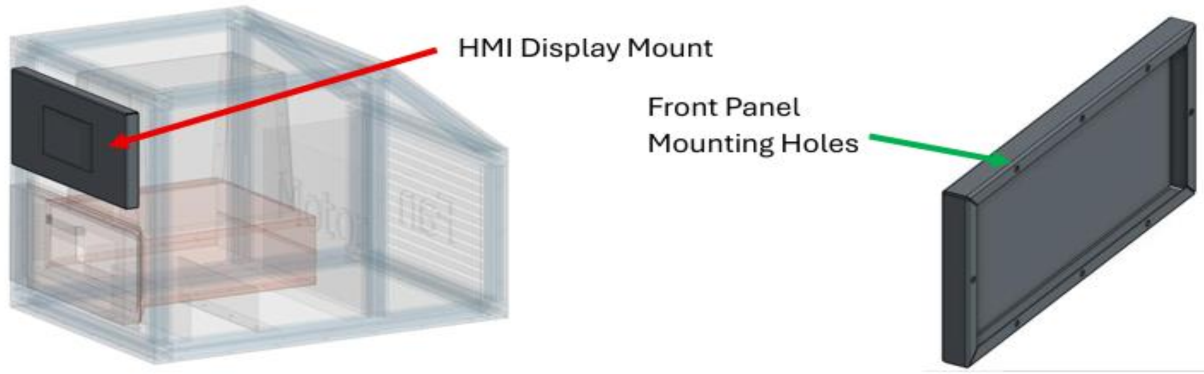


Figure 2.6: HMI Display Mount

The external door, shown in Figure 2.7, is to be made of 3 primary parts, including a front piece, rear piece, and handle. Each is to be fabricated with the same material and manufacturer. The door will be hinged to the front panel, ensuring a smooth opening-mechanism. There shall also be a glass window housed between the front/rear pieces to provide viewing access into the chamber, reducing the need to open the door mid-operation.

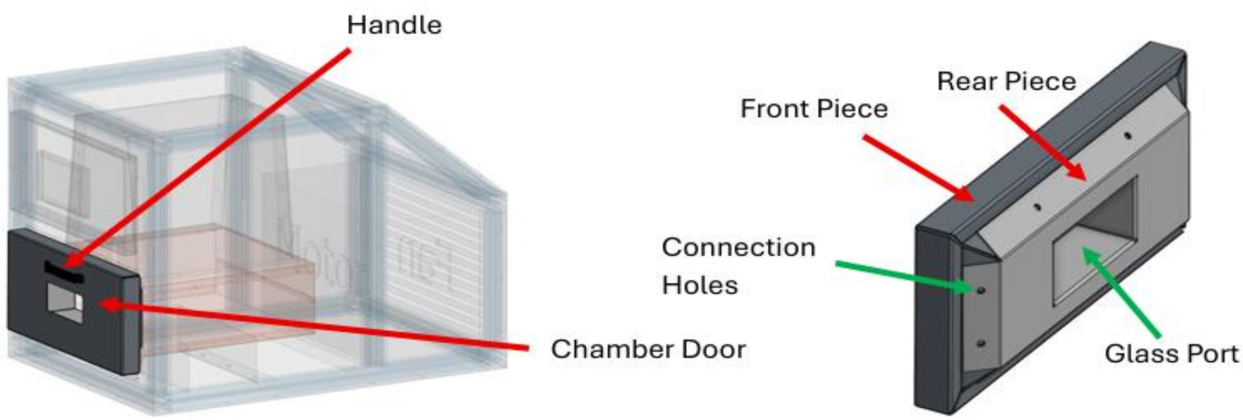


Figure 2.7 Chamber Door Handle Design

Last of all, fiberglass insulation fills most of the empty space in the system – within the panels – providing sufficient protection to satisfy the “proper thermal sealing” requirement for both chamber openings and components; this increases human safety, material longevity, and maintains proper system operation.

The structural subsystem, falling under the “mechanical” category of the product, focuses mainly on the intricates of the framework design, and its supporting impact for other subsystems. Its primary purpose is to maintain the integrity, alignment, and stability of itself and other components. Its design is made for efficient connections and organized integration of wiring that ensure a mechanically solid and highly functioning system; the support provides mounting points for fixtures and devices, maintaining positioning, solid connections, and mechanical stability during loading/unloading boards and reliability during PCB testing. It ensures a rigid enclosure for all heating/cooling elements and electronic components, promoting efficient dynamic functioning of other parts. Its secondary purpose is to be designed with proper material usage – ensuring long-lasting quality. A thorough material selection process enables the final structure to withstand thermal heat transfer rates throughout the system, protecting the integrity and performance of other components under natural environmental conditions. During operation, a well-built structural subsystem also reduces mechanical stresses encountered on other components by distributing and dampening loads uniformly, preventing deformation of other internal housings and connections. This ensures other subsystems operate effectively while maintaining safety and precision required for evaluating the performance of the PCB. Overall, the structural subsystem is an integral part of the entire system design, ensuring reliability in itself and other components, alongside high-performance of other subsystems. It is able to satisfy the requirements with a strategic design that accounts for external/internal dimensions (STR-01, STR-02), while also including proper thermal sealing for openings (STR-03) and necessary components (STR-04).

Subsystem: Structural – Thermo-Fluid

System Requirements

Table 3.1: Thermo-Fluid Requirements

System Design

Trade Studies

Proof of concept or feasibility testing

List of Applicable Standards

Analysis

Component Design Detail

Subsystem: Safety

System Requirements

The following section details the Safety Subsystem requirements and their compliance information. Requirements are grouped by category to align with system-level safety goals. Each table provides traceability between the requirement, associated rationale, applicable standards, and planned verification methods for PDR.

Table 4.1: Internal Safety Requirements

Number	Requirement	Rationale	Stand/Source	Verification Method	Status
SAF-01	The internal surfaces shall be safe for electronics according to ASTM D3874-20	Ensures internal chamber surfaces do not cause thermal or material degradation of sensitive electronics	ASTM D3874-20	Test- Measure internal surface temperatures while chamber operates at maximum thermal load	Planned

Table 4.2: External Safety & User-Contact Requirements

Number	Requirement	Rationale	Standard/Source	Verification Method	Status
SAF-02	External System surfaces shall not exceed the safe-touch temperature of 50°C per ASTM C1055	Prevents user injury from unsafe contact temperatures during operation	ASTM C1055	Test – Measure exterior surfaces at thermal steady-state during high temperature operation	Planned

Table 4.3: Operation & Fault-Response Requirements

Number	Requirement	Rationale	Standard/ Source	Verification method	Status
SAF-03	The system shall be capable of operating in normal environmental conditions of 21°C.	Ensures reliable performance under expected laboratory ambient conditions.	System Environmental Requirements	Analysis/Test - Validate thernal stability and control while operating at 21°C ambient	Planned
SAF-04	The system shall include a	Prevents overheating,	System Safety Requirements	Test/Inspection - Induce fault	Planned

	safety measure if internal temperature range or tolerance is exceed	thermal runaway, and hazardous internal conditions		condition and verify that safety mechanism activates as intended	

Table 4.4: Safe-State Requirements

Number	Requirement	Rationale	Standard/Source	Verification Method	Status
SAF-05	The system shall incorporate a defined “safe-state” that engages during abnormal or unsafe conditions	Ensures chamber transitions to a non-hazardous state to protect users and hardware	System Safety Requirements	Analysis/Test - Simulate fault conditions and verify that the system enters and maintains safe state	Planned

System Design

While safety is a very important subsystem there was many overlaps in the Trade Studies we have done. S0 Although there is no trade study specifically in this section the insulation trade study is very valuable to consider for safety. It will help to determine the most suitable option to keep the chamber a resonable temperature to touch because the insulation will limit the amount of heat loss.

List of Applicable Standards

ASTM D3874-20

ASTM C1005

Analysis

The thermal resistance, R, is a function of the thickness of the insulation, L, divided by the thermal conductivity of the insulation, k. (Equation 4.1)

$$R = \frac{L}{k}$$

$$R = \frac{0.1524m}{\left(0.032\,\frac{W}{m \cdot K}\right)} = 4.76$$

$$R = \frac{0.1524m}{\left(0.034\,\frac{W}{m \cdot K}\right)} = 4.48$$

Where

L = thickness(m)

K = Conductivity (W/m*K)

I have used 2 different values because in the specifications of this material there was a range so I checked both sides of the spectrum for these values to get a range.

Component Design Detail

The safety subsystem is integrated throughout the entire system rather than being represented by a single physical component. Its purpose is to ensure safe operation of the device under all expected environmental and load conditions by mitigating thermal, structural, electrical, and operational hazards. The safety design relies on coordinated interactions with the Structural, Thermo-Fluid, Electrical Components, and Control System subsystems to maintain safe limits, prevent equipment damage, and protect personnel.

Interface With Structural and Thermo-Fluid Subsystems: Insulation and Safe-Touch Temperature

A primary safety feature is the installation of thermal insulation, which provides a barrier between hot internal components and the external structure. The insulation physically interfaces with the structural subsystem by attaching directly to the interior surfaces of the housing. Structurally, the insulation must comply with thickness, compressive strength, and mounting constraints, ensuring that it does not interfere with internal clearances or cause deformation of panels.

From a safety standpoint, the insulation ensures the external surface temperature remains within safe-touch limits. This prevents burn hazards and reduces the risk of unintentional thermal exposure during handling or maintenance. The thermo-fluid subsystem provides the heating and airflow conditions which determine internal temperatures; the insulation enables this subsystem to operate effectively by limiting heat loss, controlling thermal gradients, and maintaining predictable external temperature profiles. Together, the insulation and thermo-fluid subsystem form a coupled safety barrier that protects users while preserving structural integrity.

Interface With Electrical Components: Current Transformer for Electrical Protection

The safety subsystem also interfaces closely with the electrical components through the inclusion of a current transformer (CT**)**. The CT is used to monitor real-time current draw from critical components. Its primary safety function is to detect abnormal electrical conditions—such as overcurrent, short circuits, or unexpected load spikes—that could generate heat, damage components, or create fire hazards.

Figure 4.1: Current Transformer

The CT sends continuous current measurements to the electrical subsystem and, more importantly, to the control system. When the sensed current exceeds a predefined safety threshold, the CT enables the system to trigger protective circuitry, initiate controlled shutdown procedures, alert users through system indicators, and prevent overheating in wiring or power electronics. Because electrical faults are often precursors to thermal or structural hazards, the CT acts as a key interface point linking electrical safety to the overall system health. It ensures compliance with safety limits and provides the data necessary for automated protective actions.

Interface With Control System

The control system integrates all safety data including temperature readings, CT feedback, and environmental monitoring into a unified logic framework. It uses these inputs to enforce safety rules, initiate alarms, and command subsystem shutdowns when necessary. This makes the control system the enforcement mechanism for the safety subsystem's requirements.

Subsystem: Electrical Components

System Requirements

The electrical components subsystem contains six requirements, including rules dictated by NEC (National Electrical Code) and UL (Underwriters Laboratories), as well as requirements per the project.

Table 5.1: Electrical Components Requirements

Number	Requirement	Rationale	Standard/Source	Verification Method	Status
COM-01	The PCB shall be operatable while temperature is controlled	Ensures the electronics under test can function reliably during thermal testing without interruption or damage due to active temperature control	System ConOps; Functional Performance Requirement	Measure (Demonstration)	Planned
COM-02	System will adhere to NEC rules on grounding	Proper grounding reduces the risk of electric shock, equipment damage,	NEC Article 250	Inspection	Planned

	according to Article 250	and fire hazards, ensuring safe operation for users and equipment			
COM-03	System will adhere to NEC rules on appropriate fuses and load wire sizes	Correct fuse ratings and conductor sizing pretext the system from overcurrent conditions and prevent overheating or fire.	NEC (Overcurrent Protection and Conductor Sizing Requirements)	Inspection	Planned
COM-04	System will adhere to UL 61010 for test and measurement equipment	Compliance ensures the system meets recognized safety requirements for laboratory and test equipment operation	UL 61010	Inspection	Planned
COM-05	The sensors shall be properly rated to withstand internal environment conditions.	Ensures sensor accuracy, reliability, and longevity when exposed to expected temperature ranges inside the chamber	Manufacturer Datasheets; System Environmental Requirements	Inspection	Planned
COM-06	The system shall support PC connection for datalogging	Enables data collection, analysis, traceability, and verification of system performance during testing	System ConOps; Data Logging Requirements	Inspection	Planned

System Design

Trade Studies

The primary trade study for this subsystem is the heating element. A trade study was conducted via four possible options:

Table 5.2: Heating Trade Studies

	Resistive	Inductive	Convection	Reversible Heat
Description	Current Passes through a resistive element which converts energy into heat through	A quickly alternating magnetic field that induces eddy currents	Transfers heat through circulating air/fluid, heated by resistive elements.	Add a reversible heat valve to allow recycling heat from the thermal hot side for use in heating.

	the element's resistance			
Price	~$100	~$800	~$600	~$500
Risk	Overheating/fire hazard	Electromagnetic Interference (EMI)/ magnetic fields	Temperature non-uniformity/runaway airflow heating	Adds failure points to the thermal system, risks overheating the oil.

Proof of concept or feasibility testing

For testing, the relays with the flyback protection were breadboarded to ensure that the design worked as is intended.

List of Applicable Standards

IPC-2152

Analysis

To calculate the proper trace width when designing the PCB, four equations were used:

Current Carrying Capacity, where I is the allowable current, k=0.048 for external layers, is the allowable temperature rise, and A is the trace cross-sectional area (width * copper thickness).

$$I_{cc} = k \cdot (\Delta T)^{0.044} \cdot A^{0.75} \quad (1)$$

Trace Width, where W is the required trace width, and t is the copper thickness.

$$W = \frac{A}{t} \quad (2)$$

Trace Resistance Analysis, where R, is the trace resistance. P is the resistivity of copper $1.72 \cdot 10^{-8} \Omega \cdot m$, L is the trace length, t is the copper thickness, and W is the trace width.

$$R = p\left(\frac{L}{t \cdot W}\right) \quad (3)$$

Trace Heating/Performance Margin, where ΔT is the temperature rise of the trace and, I is the current through the trace.

$$\Delta T = 0.024 \cdot I^{1.6} \quad (4)$$

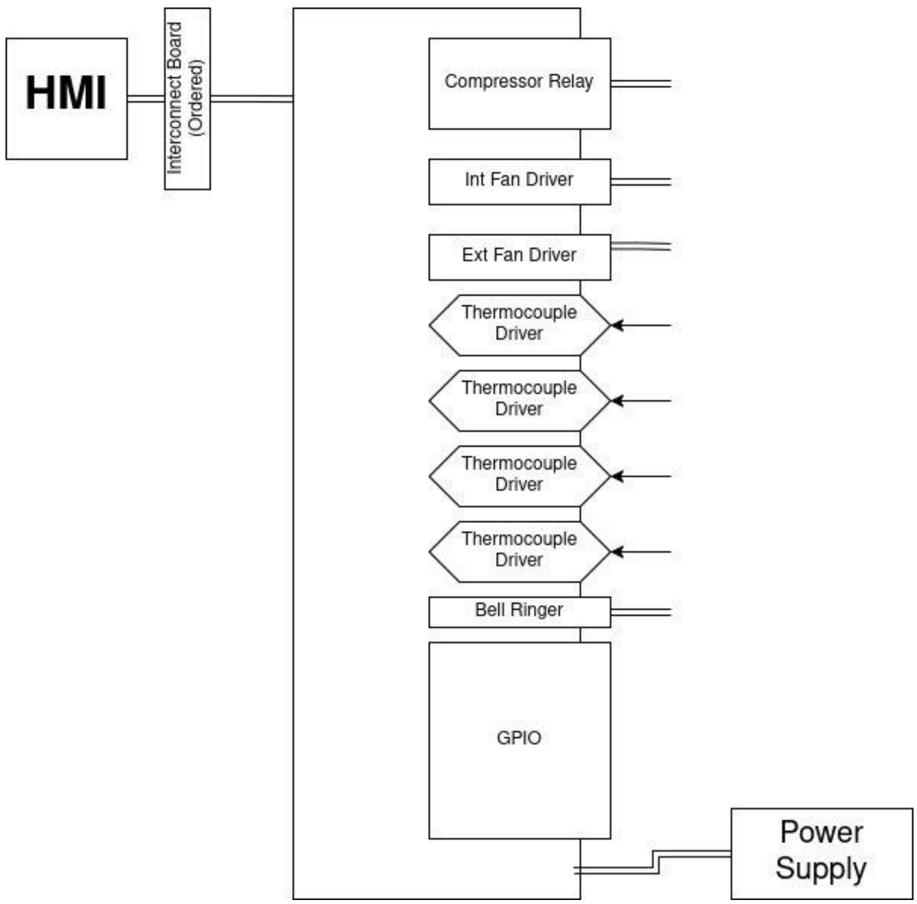
The power traces supplying the relay coil and fans were sized using IPC-2152 (Institution for Interconnecting and Packaging Integrated Circuits) current carrying capacity guidelines. Equation 1 provides the trace current limit as a function of copper cross-sectional area and allowable temperature rise. An allowable temperature rise of ΔT= 10°C is reasonable as the thermal chamber operates over a wide temperature range (-40°C to 85°C), this also ensures that at the extreme case (85°C), the copper, solder joints, and connector plastics remain under 95°C, which is within IPC guidelines material limits and helps to improve longevity. The resulting required trace area is now converted to trace width using equation 2 assuming 1oz Copper (0.35 μm thickness). Equation 3 is used to check that the resulting trace width and

Voltage drops are acceptable for relays and fan loads. Equation 4 is used to confirm that the expected operating current does not exceed the ΔT margin. Based on these calculations, it was determined that the trace widths should be approximately 8mm, with a maximum current carrying capacity of 12-15 amps.

Component Design Detail

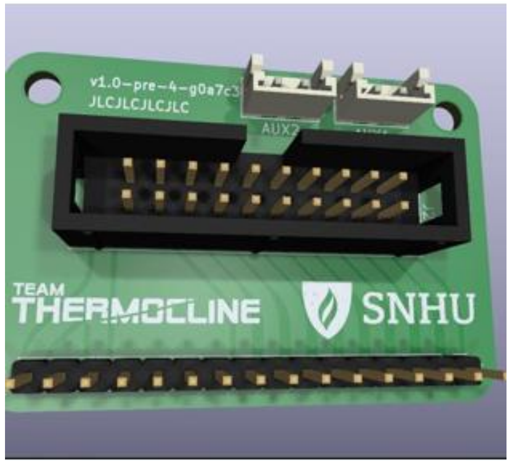
The role of the electrical components subsystem can be understood through the flow chart in Figure 5.1:

Figure 5.1: Electrical Flowchart



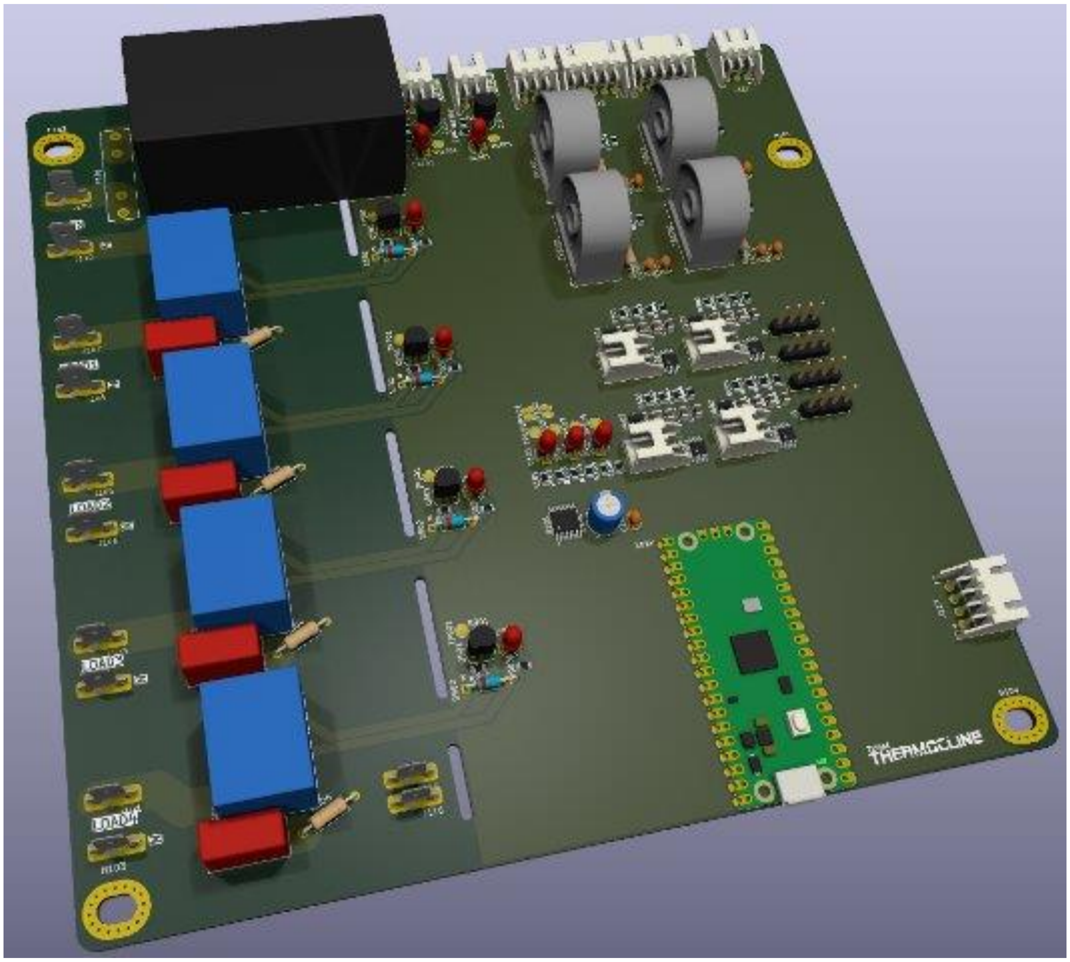
The electrical components subsystem consists of a PCB that provides control and communication throughout the thermal testing chamber. The primary controller is a Raspberry Pi Pico which interfaces with four thermocouple drivers which are used for temperature measurement. The subsystem design, shown in Figure 3, includes relays, a BJT, op-amps, current sense transformers, indicator LEDs, a DHT11 humidity sensor which will be a standalone component, not on the PCB used to measure humidity in the chamber, and an IRM used as the analog-to-digital converter. The interconnect board, shown in Figure #, allows the PCB to talk to the HMI to transmit data to the user.

Figure 5.2: Interconnect board



As of most recent updates, the PCB stands as shown:

Figure 5.3: Current PCB Layout



The functional role of the PCB is to monitor the internal temperature of the chamber and communicate that data to the HMI. It continuously reads temperature, humidity, load conditions, and provides the necessary control for the heating and cooling elements.

Subsystem: Control System

System Requirements

Since the software is so broad reaching in the system, many different requirements fall under its roof, including safety, control, power and interfacing.

Table 6.1: Customer/System Requirements

Number	Requirement
CST-1.1	The system shall include a Human Machine Interface (HMI) for the control system
CST-1.2	The system shall include separate operating/control modes.

Table 6.2: Control System Requirements (Part A)

Number	Requirement	Rationale	Standard/Source	Verification Method	Status
COM-06	The system shall support Personal Computer (PC) connection for datalogging	Enables users to collect, store, and analyze test data for performance verification, traceabilitiy, and reporting purposes	System ConOps	Inspection	Planned
CON-01	The system shall allow local temperature set-point control	Provides users with direct on-site control of chamber temperature to support setup, calibration, and manual testing operations	System ConOps	Test	Planned
CON-02	The system shall allow remote temperature setpoint control	Allows users to control chamber temperature remotely, iimproving usability, safety, and operatoinal flexibility during testing	System ConOps	Test	Planned
CON-04	The system shall prohibit thermal control when teh chamber door is open	Prevents unsafe operating conditions, reduces risk of user injury, and protects hardware from unintended thermal exposure	System ConOps	Demonstration	Planned
CON-05	The system shall prohibit thermal control when a user is handling the	Ensures user safety and prevents damage to the PCB by disabling thermal control	UL 61010	Demonstration	Planned

	Printed Circuit Board (PCB)	during direct user interaction			
CON-06	The system shall log temperature data	Allows verification of system performance over time and supports post-test analysis, troubleshooting, and documentation	System ConOps	Test	Planned

System Design

Trade Studies

Screen Selection

To meet requirements CST:1.1, SAF:04 and CON:01, the HMI for the systems hall need to provide for both graphics and output, as well as numerical and configuration input.

Table 6.3: Control System Requirements (Part B)

Number	*Requirement*	*Rationale*	*Standard/Source*	*Verification Method*	*Status*
CON-07	*The system shall log humidity data*	*Enables monitoring and verification of environmental conditions that may affect PCB*	*System ConOps*	*Test*	*Planned*
CON-08	*The system shall log faults for safety measures*	*Provides traceability of safely-realted events, supports troubleshooting, and enables verification of proper safety subsystem operation.*	*System ConOps*	*Measure*	*Planned*

CON-09	*The system shall have a "shutdown" state*	*Ensures the system can be placed into a safe condition to protect users and hardware during faults, maintenance, ir emergency conditions*	*UL 61010*	*Demonstration*	*Planned*
CON-10	*The system shall have a "standby" mode*	*Allows the system to remain powered while minimizing active thermal control, improving safety, readiness, and energy efficiency*	*System ConOps*	*Demonstration*	*Planned*
CON-11	*The system shall have a normal operating "start" mode*	*Establishes a controlled and repeatable transition into normal operation, reducing the risk of unsafe or unintended system behavior*	*System ConOps*	*Demonstration*	*Planned*
CON-12	*The system shall allow for manual switching between modes*	*Provides user control and flexibiility during testing, setup, and troubleshooting while maintaining defined system states*	*System ConOps*	*Demonstration*	*Planned*

No requirement mandates that the HMI be part of the machine. Therefore, we could satisfy the requirements by using off-board or external computer control. We considered this alternative in our trade study in Table 5. We quickly decided through the trade study that the most desirable HMI option would be something built into the machine itself, and among those two options, using a low-level interface was the most desirable and thus the selection we went with. We experimented with a few models and settled on purchased one for testing. As part of our initial verification experimented with a CrowPanel HMI screen "7 Inch HMI Touch Display- 800x480 LCD for ESP32/Arduino/LVGL", 2023 shown in Figure 1. The screen is programmable in C and uses Light and Versatile Graphics Library (LVGL) for the Graphical User Interface (GUI). Our initial GUI design allows the major operating modes, configuration, and calibration to be separated by tabs along the top bar, with buttons in the center and live status, error, and safety warnings below Figure 6.1.

Table 6.4: Screen Selection Trade Study

	External Computer	LVGL UI	Internal Computer
Boot Time	N/A	Fast	Slow
Size	External device required	Small (under 7")	Medium to Large (Over 7")
Estimated ease of use	Low, Will require at least setting up site or software on user's computer	Medium, all controls integrated and available quickly. LVGL may make animations, tooltips and other graphics somewhat basic	High, Full sized UI with as much complexity you like
Ease of integration	High, we don't worry about integration system-side. Push all the work off to software on a PC that isn't ours	Medium, more work on our end. Installation of a screen on the machine and simple graphics	High, we mut manage whole Operating Systems (OS) and graphics stack, as well as the graphics and control underneath
Ease if programming	High, use anything we like	Medium (embedded C/C++)	Medium, graphics are as easy as with an external machine but we must also manage the single board inside as well

Choosing an MCU was a similar process to choosing a screen. Both are crucial parts of the software stack as the controller and display (Table 6 and Table 7) are what will allow the software to run at all. Our trade study took into account how easy it would be to integrate and use the MCU, but also what safety features were offered, what support was available and how expensive it would be to re-tool or replace. In the end, we selected using the RP2040. Having a solid core with good safety systems and easy integration was the most important and met the requirements best.

Figure 6.1: CrowPanel 7.0 ESP32

Figure 1: CrowPanel 7.0 ESP32

Figure 6.2: Thermocline GUI Prototype, LVGL block

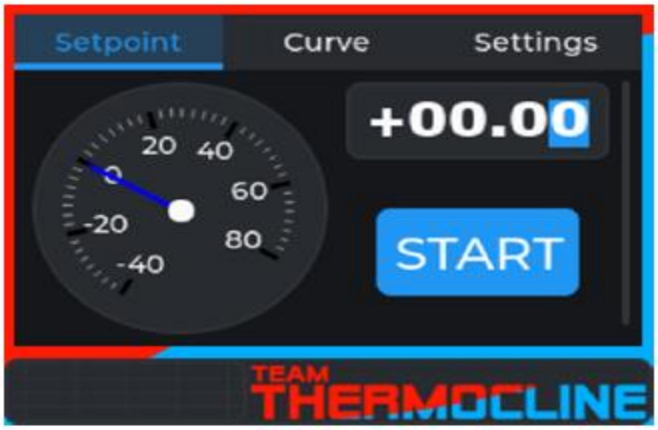


Figure 2: Thermocline GUI Prototype, LVGL blocks

State Machine

A good portion of our design centers around the safety and discrete modes the system can operate in. This is one of the reasons supporting a good Real-Time Operating System (RTOS) was so critical in our selection of an MCU (Table 6.5 and Table 6.6). To this end, our system has several modes, all of which have safety background tasks, control systems tasks, user interface tasks and other functions dependant on the mode you're in or the mode you're transitioning to.

Table 6.5: MCU Trade Study (Part A)

Criteria	CRIO (NI)	RP2040	Arduino (AVR)	Arduino (SAMD)	ESP32
Cost	Very High $2,500	Very Low <$40	Low ~ $40	Very Low < $40	Very Low < $40
Integration	Low, LabView might be easier to develop on but harder to port (and meet Req COM:06)	Very easy, Integration with python, JavaScript Object Notation (JSON) and Universal Serial Bus (USB)	Easy, Integration over serial	Very easy, full USB stack, python, JSON	Easy, integration over serial
Safety Features	Physical hardware safety features like Electromagnetic Interference (EMI) Electrostatic Discharge (ESD)	Hardware watchdogs, Memory debugging, EMI/ESD	Hardware watchdogs, EMI/ESD	Hardware watchdogs, Memory debugging	Hardware watchdogs, Memory debugging

	but limited software ones				

Figure 3 is a flowchart detailing each state the machine can be in. The primary states are:

- Power-On Self-Test (POST): Power on and self test
- Safe Mode: Safe return mode where the suer can examine an error or reset to a known state with all functions in idle or disabled
- Standby: Default standby mode, await user input and allow to move to any other mode
- Configure: Configure the system, make adjustments and view information before or after use
- Follow Curve: Follow a curve, change the chamber setpoint automatically according toa a script, curve or chart
- Follow Setpoint: Follow a setpoint, change the chamber setpoint to a specific value and hold there.

Table 6.6: MCU Trade Study (Part B)

Criteria	CRIO (NI)	RP2040	Arduino (AVR)	Arduino (SAMD)	ESP32
RTOS	Yes (But only NI Linuz RT)	Yes (any)	No	YEs (Zephyr and Free Real-Time Operating System (FreeRTOS))	Yes (FreeRTOS)
Support	Yes (Via NI)	Yes (Most Vendors, RPi, Adafruit)	No (Phasing out)	No (Obscure)	Yes (Some vendors, Esprissif, Adafruit)
Input/Output	Good, Expandable Digital Analog Converter (DAC) and analog-to-digital converter (ADC) operations (at a price)	Good, great General Purpose Input/Output (GPIO) and Programmable Input/Output (PIO) system, only a limited set of analog pins.	Limited poor resolution ADC and limited pin counts and specialized pins	Good, robust ADC and many GPIO on most chips	Good, passable ADC pin counts for most models

Figure 6.3: Thermocline State Machine

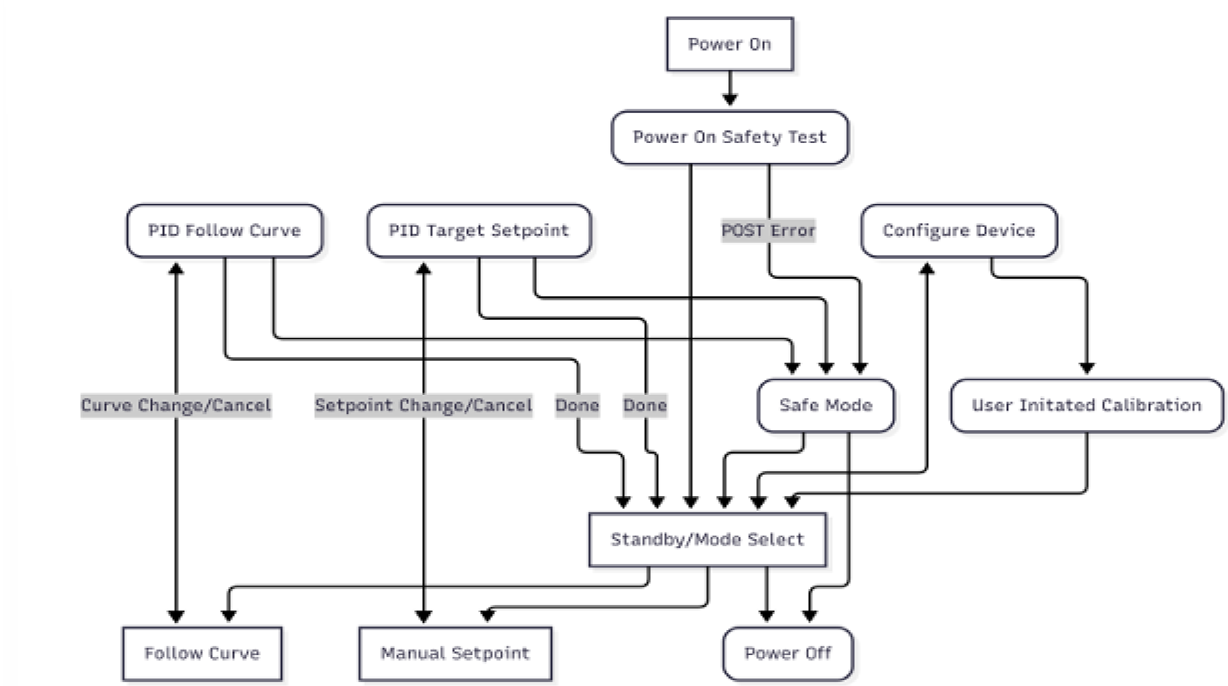


Figure 3: Thermocline State Machine

We don't want to reinvent the wheel; an RTOS on a microcontroller is a common and well-understood task management solution. We chose to use FreeRTOS ("FreeRTOS™- FreeRTOS™", n.d.) for our system as it allows for easy task creation and management. Tasks will be structured to run on a priority system, where tasks that are checking for safety conditions (such as overtemperature, interlocks, overcurrent, undervoltage, etc.) will preempt other tasks running, or cancel them entirely. This RTOS operation also allows "background" tasks to run periodically, and perform low-priority items such as updating the display, syncing the time, saving the data.

Figure 6.4: Overview of Task State Management

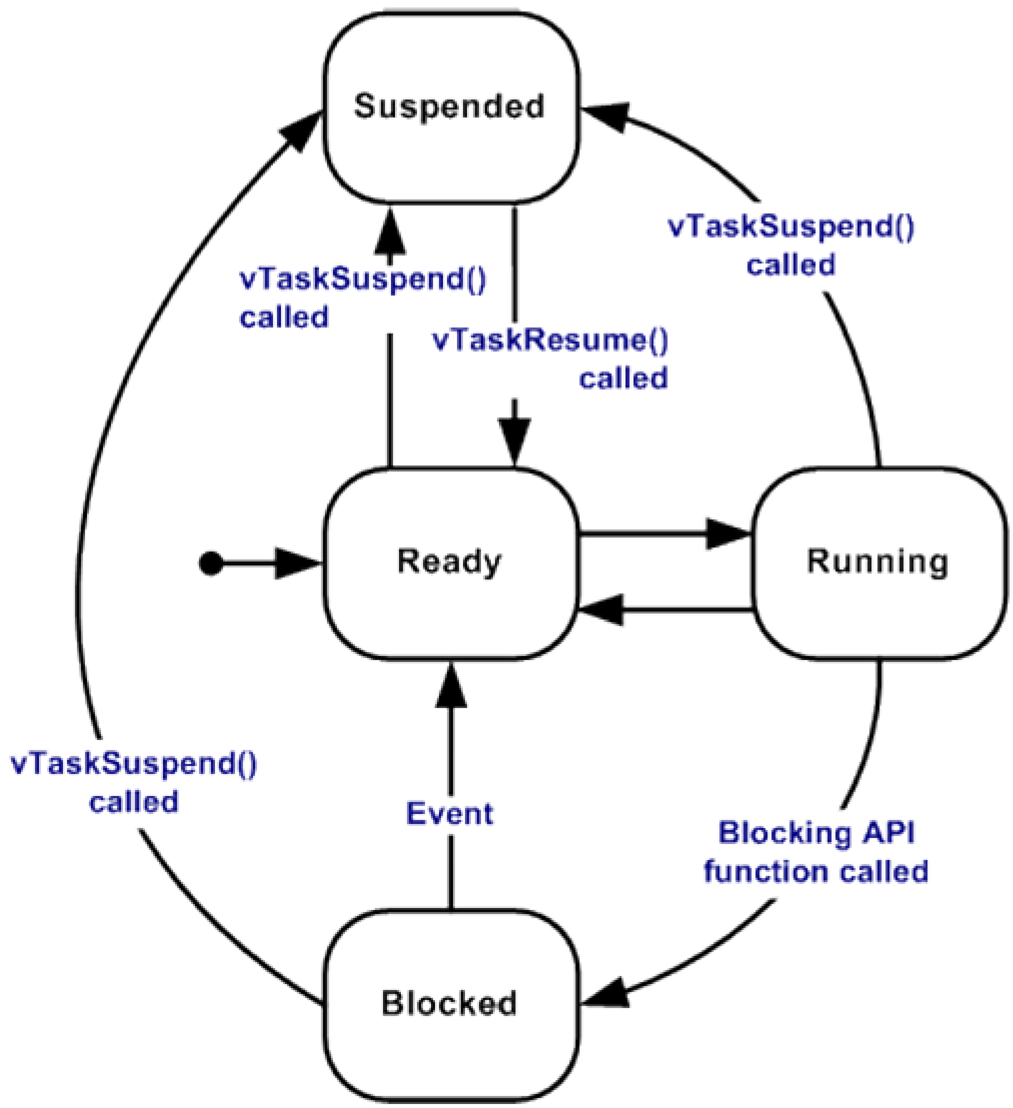


Figure 4: Overview of Task State Management

Proof of concept or feasibility testing

List of Applicable Standards

Analysis

Component Design Detail

Intercommunications

The central software controller stack will include both the built in screen, as well as a potential customer computer. To simplify the amount of work we need to as programmers, and the work the system needs to do in computation, the interconnect language will be the same for both. JSON is a common language for intercommunication between systems, and is a good fit for our needs. By encapsulating the data in JSON objects, we can easily send and receive data between one or more systems, as well as assign types, instructions and names to each packet. Such packets may look like Figure 6.5.

Figure 6.5 Example JSON Packet


```
{
    "command": "none",
    "type": "temperature",
    "value": 25.0,
    "unit": "C"
}
```


Figure 5: Example JSON Packet

Sensors and Inputs

Computers don't come with an awareness of their environment so we need to integrate our own. The implementation of which is largely an electrical one, but what we do with those sensors is all in software. There are two main responsibilities turned over to the software, one is actually reading the data and reacting in a timely manner, the other is pro cessing, filtering and presenting the data. One consideration is under- or oversampling. The analog system on our control board will provide as much data as we need, but once we sample it we could be undersampling and alias ing noise. The mitigation of this example can be found in subsection 6.1. For the storage and presentation of the data, we need to consider what rate is necessary for the storage and what rate is appropriate for the pre sentation. The customer may prefer to see a significant resolution in their saved data, but what is shown on the screen may not benefit from a very high update rate. In fact, oversampling could make the screen flicker or look sluggish. The software will balance what data it sends and at what rate, and allow different rates internally.

Drivers and Outputs

The most critical job of the software is at the very end, the end-effector. The product of the control system is to set, unset and toggle various relays, drivers and devices that will do meaningful and potentially dangerous work. Relays have a finite lifespan, arcing across the contacts as well as me chanical wear from cycles will affect their life and the performance of their switches. The software must self-regulate and prevent overuse of the relays. In addition, there are many more loads controllable by the system than the power budget allows for. The software will need to never exceed the power budget and it must keep track of which loads are running and not cycle incompatible loads on at the same time.

Figure 6.6: Example of electrical arcing across relay contacts. Source: Wikipedia

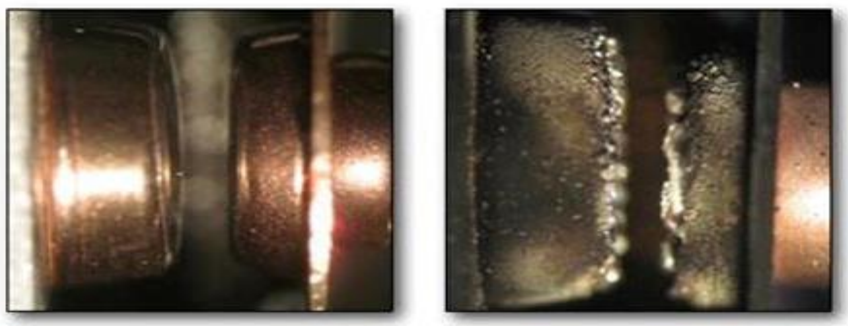


Figure 6: Example of electrical arcing across relay contacts. Source: Wikipedia.

Risks and Mitigation

Letter	Consequence	Description
A	Asset	Mechanical Failure of Components (worn, broken)
B	Asset	Insufficient Dimensions for PCB testing (internal, external, cable port, chamber door)
C	Asset, Human Safety	Internal System is Over Temperature Range (fire, melting components)
D	Asset, Human Safety	Internal System is Under Temperature Range (freezed components)
E	Asset, Performance	System's Safety Measure Fails If Outside Temperature Range
F	Asset, Performance	Internal Heating/Cooling System Can't Reach upper/lower boundaries (poor components, inefficient controller)
G	Asset, Performance	Inconsistent Temperature Control (poorly designed microcontroller or interface)
H	Asset, Performance	Failure to Maintain Toleranced Setpoint ($\pm^{\circ}3C$) (ineffective control system, poor insulation - internal & external)
I	Asset, Performance	Lack of Electronic Protection (excessive moisture buildup)
J	Cost	Spending Past Designated Budget for Equipment & Materials
K	Human Safety	Lack of Human Protection at Critical Temperature Ranges (burns)
L	Human Safety	System Fails to Meet Environmental/Engineering Codes
M	Human Safety	System Fails to Prohibit Temperature Control During Manual User Usage.
N	Human Safety, Performance	Chemical Leaking
O	Human Safety, Performance	Electrical Hazards (short circuits, improper connections)
P	Human Safety, Performance	System Fails to Operate Safely Under Normal Conditions
Q	Performance	Software/HMI Failure
R	Performance	Lack of Refrigerant Fluid in System
S	Performance	Controller not User Friendly (poor HMI design)
T	Performance	Sensor Reading Failure (miscalibration, component issue)
U	Performance	Improper Ventilation (pressure changes, fumes buildup)
V	Performance	Ineffective Insulation (poor materials or design)
W	Performance	Data Measuring, Collecting, and Logging Fail to Work Systematically
X	Performance	System Mode(s) Failures
Y	Schedule	Poor Scheduling for Fabricated Parts or Sourced Materials
Z	Schedule, Cost	Rework of Product (ineffective design from failed systems/components/materials)

Table 7.1: Risk Matrix

Consequence	5	B, L	A, E, P	K, M, O	Z	
	4		Y	N	I	Q, W
	3		F, G	T, U, X	V	
	2	R	J		C, D	H
	1	S				
		1	2	3	4	5
		Likelihood				
Notes:	Combined Risk Scores: 0-9 (Green) --> Minor 10-19 (Yellow) --> Moderate 20-29 (Red) --> Major					

Figure 7.2: Risk Vs. Likelihood

Risk Letter	Risk Score	Description	Effects	Mitigation
Q	**20**	Software/HMI Failure.	Lack of system input and control.	Hardware Watchdogs, implementing secondary/backup control features.
W	**20**	Data measuring, collecting, and logging fail to work systematically.	System lagging, inaccurate measurements.	Repeated calibration and testing, and more sophisticated components.
Z	**20**	Product fails to meet requirements.	Product redesigning, sourcing of new components, falling off schedule.	Early and substantial amounts of research, feasibility testing, and analysis.

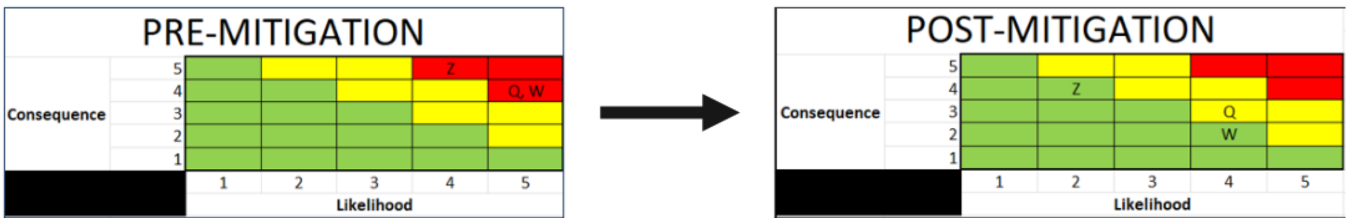


Figure 7.3: Most severe risks and mitigations.

Consequence	5	B, L	A, E, P	K, M, O	Z	
	4		Y	N	I	Q, W
	3		F, G	T, U, X	V	
	2	R	J		C, D	H
	1	S				
		1	2	3	4	5
		Likelihood				
Notes:	Combined Risk Scores: 0-9 (**Green**) --> Minor 10-19 (**Yellow**) --> Moderate 20-29 (**Red**) --> Major					

Verification Matrix

Req. Num	Short Desc.	Status	Margin
STR-01	System Bounds	Current CAD and footprint overall fit in our maximum size.	10%
STR-03	Insulation and seal	Minimum thicknesses for insulation are within our requirements	<5%
THE-01	Min. Temperature	Pre-modification system reached 0°C, r410 boils at –43°C.	50%
THE-02	Sweep Speed	Heat rejection is 2-3 times larger than evaporator requirement	35%
CON-08	Log faults	RTOS logging setup as part of underlying structure	Met
SAF-05	Have a safe state	Implemented in underlying structure	Met

Table 8.1: Verification Matrix

Design Considerations

Global Considerations

The system design reflects awareness of global impacts related to material sourcing, manufacturing practices, and energy usage. Aluminum alloys were selected for structural components due to their abundance, recyclability, and relatively low environmental burden. Manufacturing methods were chosen to minimize material waste and promote responsible supply chain practices. Energy efficiency was also considered across thermal control, insulation, and software logic to reduce overall power consumption in alignment with global sustainability goals.

Cultural and Social Considerations

While the system does not directly interface with culturally sensitive applications, its design emphasizes universal usability and accessibility. The chamber is ergonomically designed for ease of operation, with dimensions and interfaces that accommodate a broad range of users. Safety indicators, warnings, and operational cues rely on intuitive symbols and clear visual feedback rather than language-specific instructions, reducing cultural and language barriers. These choices promote safe and inclusive interaction in diverse laboratory environments.

Public Health, Safety, and Welfare Considerations

Public health and safety are central to the system design. Structural materials and insulation prevent hazardous external temperatures and eliminate sharp edges or unsafe protrusions. Electrical safety is ensured through proper grounding, fusing, relay isolation, and PCB trace sizing in accordance with industry standards. Temperature and current sensors, combined with automated Safety Mode logic, prevent runaway heating, electrical faults, and unsafe operating conditions. Interlocks disable thermal control during unsafe states, protecting users, equipment, and the surrounding environment. These measures fulfill ethical responsibilities to safeguard users and the public.

Economic Considerations

Economic efficiency was balanced with safety, reliability, and performance. The use of repeated structural components reduces fabrication and assembly costs. Material selections were optimized to provide durability and long service life, minimizing maintenance and replacement expenses. Cost-effective electrical protection components prevent catastrophic failures and reduce downtime. Energy-efficient insulation and control logic further reduce operational costs, resulting in a system that provides strong long-term value and return on investment.

Environmental Considerations

Environmental impact was addressed through sustainable material selection, energy efficiency, and long-term system durability. High-performance insulation minimizes heat loss and reduces power consumption. Control software limits unnecessary operation and reduces energy usage during fault conditions. Structural design minimizes the likelihood of thermal-fluid leakage and reduces waste by extending component lifespan. Together, these design choices reduce environmental impact, conserve resources, and support sustainable engineering practices.

Open Design Issues

- Chassis
- Shocks/Vibration Dampening
- Pre-Final Sheet Metal (Laser Cutter)

Budget

Table 11.1: Itemized Purchased Budget

Item	% of Budget	Price
PCB	1%	$ 35.00
Compressor	0%	$ -
SendCutSend	1%	$ 30.00
HMI Screen	2%	$ 50.00
Recovery Pump	13%	$ 388.00
Manifold Gauge	2%	$ 49.00
Reciver Cylinder	2%	$ 66.00
Resistive Heater Core	1%	$ 29.55
9" Fan	1%	$ 23.17
Polycarb Square Sheet	0%	$ 12.69
Total Purchases	23%	$ 683.41
Total Budget	100%	3000
Total Budget Left	77%	$2,316.59

Table 11.2: Overall Budget

#	Category	Original Budget ($	Spent ($)	Balance ($)
1	Materials	600	42.69	557.31
2	Hardware	600	87.72	512.28
3	Software	600	50	550
4	Management Reserve	600	0	600
5	Other	600	503	97
	Total ($):	3000	683.41	2316.59

Conclusion

The thermal testing chamber is comprised of 5 major subsystems: safety, structural, thermo-fluid, electrical components, and software. (https://team-thermocline.github.io/)

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