

# Design Description and Requirements

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*Project Title:* Cryogenic Superconducting Film Characterization Apparatus

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## Table of Contents

I.	<b>EXECUTIVE SUMMARY .....</b>	<b>II:2</b>
II.	<b>TECHNICAL REQUIREMENTS.....</b>	<b>II:3</b>
III.	<b>HIERARCHICAL DESCRIPTION OF DESIGN .....</b>	<b>III:10</b>
A.	<b>High-level System Description .....</b>	<b>III:10</b>
B.	<b>Sub-System Description.....</b>	<b>III:11</b>
1.	Vacuum Chamber .....	III:11
2.	Cold Finger.....	III:12
3.	Magnets and Magnet Holders.....	III:14
4.	Sample Carrier & Interface .....	III:14
5.	Edge Computing Subsystem (EGS).....	III:16
6.	Temperature Sensing Subsystem (TSS) .....	III:16
7.	System Software: Measurement Automation and UI .....	III:18
IV.	<b>DESIGN DECISION JUSTIFICATION: .....</b>	<b>IV:23</b>
A.	<b>Case 1: Permanent vs. Electromagnets .....</b>	<b>IV:23</b>
1.	Decision Context .....	IV:23
2.	Design Options & Decision Matrix.....	IV:23
3.	Design Decision .....	IV:24
B.	<b>Case 2: Temperature Sensors.....</b>	<b>IV:24</b>
1.	Decision Context .....	IV:24
2.	Design Options and Decision Matrix .....	IV:25
3.	Design Decision .....	IV:26
V.	<b>REFERENCES.....</b>	<b>V:27</b>

## I. Executive Summary

Our project is to design and build a testing apparatus for superconducting thin films for Dr. Nicole Pfiester at Rose-Hulman Institute of Technology. The nanoengineering faculty and students at Rose-Hulman are fabricating superconducting thin films for research and lab project purposes. Superconducting thin film technology has a large application in the field of quantum information science and engineering. It can be used to build devices such as a Josephson Junction, which serves as qubits in superconducting quantum computers. The faculty at Rose needs this apparatus to properly test and characterize the fabricated superconducting thin films for research and to educate the students interested in this field.

A variety of tests will be administered using the device under liquid nitrogen level temperatures of approximately 77 K to characterize the electrical properties of high-temperature superconducting films. These tests include measurements for material properties such as resistivity and Hall measurements. Commercially available solutions for performing these tests require expensive and complex bath cryostats to manage the sample temperature and liquid nitrogen flow, but they are over the budget that Rose-Hulman can provide.

With this project, we aim to cut down the cost of this device by making only the necessary components for the purpose of our client. The thin film samples will be packaged onto a PCB that we designed to be loaded onto a cold finger cryocooler in a vacuum chamber. The apparatus will use liquid nitrogen to cool the sample down to the required temperature of 77 K to perform the tests. For Hall measurements, permanent magnets can be inserted into the apparatus to provide the necessary magnetic field. The input and output to and from the sample are wired out of the cryogenic part of the device to standard connectors that can be connected to external devices such as function generators, power supply, ammeter, voltmeter, and oscilloscopes. We are also providing software that automates the data collection process of the external signal processing equipment, so users can perform standard tests such as the Van der Pauw method efficiently.

## **II. Technical Requirements**

*Table 1: Technical Requirements*

Feature(s)	ID	Requirements	We need this requirement because...(Validation)	We will test this feature in our prototype by (Verification)	Design for test (if necessary)
Safe (Cryogenic)	SAFE-1	During operation, liquid nitrogen must remain in the container, with no leakage to areas outside the cold finger. The LN2 container also needs to exhaust the evaporating nitrogen gas.	Prevents cold burns/icing and ensures safety of the user and the environment.	Pour dyed water into the cold finger to see if there is any observable leakage into the rest of the system or the environment.	N/A
Safe (Cryogenic)	SAFE-2	The LN2 container shall provide an opening that is at least 5 mm in diameter to exhaust the evaporating nitrogen gas.	Prevents pressure from building up in the system, which can be dangerous.	Visually verify a means for LN2 gas to exhaust out of the system is provided.	N/A
Flexible	FLEX-1	The system shall provide functionality to swap the samples in less than 10 min.	Fast turnaround increases throughput, reduces downtime for classes/research, and adds flexibility to the types of samples that can be tested.	Recording the amount of time it takes for a user to swap samples given the relevant documentation.	N/A
Flexible	FLEX-2	The wire bonding distance between the sample and PCB pin should not exceed 3 mm.	Wire bonding distance must be kept short so that the sample can be easily packaged onto the PCB to be	Measuring and verifying that all wire bonding connections between the PCB and the sample	N/A

			loaded onto the cold finger. This allows users the flexibility of testing multiple samples with the system with more ease.	have distances less than 3 mm.	
Functional, Precise & Accurate	FUNC-1	The sample must reach a temperature of 77 K.	<p>The sample must be cooled below its critical temperature to be superconducting.</p> <p>The critical temperature for YBCO is 92 K, so the client prefers that we can bring the sample temperature below that to 77 K.</p>	Measuring the sample temperature in a trial run using an external temperature measuring device.	<p>The vacuum chamber must be able to be opened so the sample/sample holder can be accessed externally, even when the cold finger is working.</p> <p>The vacuum chamber is designed to have ConFlat flanges on each face, which can be detached for accessibility.</p>
Functional, Precise & Accurate	FUNC-2	The sample temperature reading at 77 K must be accurate to $\pm 0.5$ K.	Reliable temperature measurement is crucial in studying superconductor behavior; it is a crucial piece of information for the users conducting research.	Compare temperature sensor value against the reading of an external temperature measuring device at 77 K.	Same as FUNC-1

Functional, Precise & Accurate	FUNC-3	The critical current of the sample measured using this system must be within 5% of the actual values.	Users need reliable data to conduct research.	The critical current measurements of a test sample using the system must be within 5% of the values provided in its datasheet.	N/A
Functional, Precise & Accurate	FUNC-4	The surface resistivity of the sample measured using this system must be within 5% of the actual values.	Users need reliable data to conduct research.	The surface resistivity measurements of a test sample using the system must be within 5% of the values provided in its datasheet.	N/A
Functional, Precise & Accurate	FUNC-5	The apparatus must provide at least 10 mT of magnetic field to the sample.	A strong enough magnetic field is needed to perform Hall measurements on the sample.	Measure the magnetic field provided by the magnet with a gaussmeter.	Same as FUNC-1
Functional, Precise & Accurate	FUNC-6	The system will perform Van der Pauw measurements (including Hall measurements) semi-automatically through the web UI. That is, the user only needs to interact with external equipment when rewiring the probes; the	An automated data collection system can make research more efficient.	Run a full test trial and verify the only interaction between the user and the external equipment is when the probes need to be switched.	N/A

		software should dial in all the appropriate settings to the external equipment and save the relevant data.			
Functional, Precise & Accurate	FUNC-7	During Van der Pauw measurements, the system shall take voltage measurements with microvolt-level precision.	Van der Pauw measurements for YBCO samples are in the order of microvolts.	Verifying that the system, working with the signal processing equipment, can provide voltage measurements at the microvolts level.	N/A
Functional, Precise & Accurate	FUNC-8	During Van der Pauw measurements, the system shall source 10mA of current within $\pm 1\text{mA}$ of accuracy.	The Van der Pauw method requires an accurate and precise amount of current to be injected into the sample. The current amount is used to perform calculations on the measurements.	Verifying that the system, working with the signal processing equipment, can source current at 10mA within $\pm 1\text{mA}$ of accuracy.	N/A
Affordable	COST-1	The cost of building the system (not including the vacuum chamber) shall be under a 2000-dollar budget.	The client of the project has limited budget.	Maintain BOM with pricing and saved receipts. The sum of all costs must be less than \$2,000.	N/A

Reliable	REL-1	The system must be able to complete at least 5 consecutive cool-down/measure/warm-up cycles without failure/error.	Users need reliable operation during labs; a series of constant failures will damage the expensive samples and potentially affect experimental outcomes.	Run 5 complete trials back-to-back. If the system is still fully operational, then it meets the reliability requirement.	N/A
Documented	DOC-1	The documentation must include detailed information about the individual parts of the system, their functionalities, and the assembly and functionalities of the overall system.	Users should be able to understand the workings of the system using the documentation alone.	Ask a user without any prior knowledge of the system to read through the documentation and check their understanding of the apparatus on a system-level and a parts-level.	N/A
Documented	DOC-2	The documentation shall include detailed instruction, so that users can learn how to operate the system without the presence of a design team member.	Users need clear instruction to learn how to operate the apparatus.	Providing instructions to users who are unfamiliar with the system and seeing if they can learn to operate the apparatus by themselves.	N/A
Documented	DOC-3	The documentation shall include a maintenance guide.	Since the system should be operational in the long-term, users	Providing a maintenance guide to users unfamiliar with the system	N/A

			need to be able to maintain the system.	and seeing if they can identify which parts of the system may need maintenance and how to maintain them.	
Resourceful	REC	The apparatus will use at most 1 liter of LN2 per trial.	Cost of operation and environmental impact must be minimized.	Measure the total amount of LN2 used for a full trial with a test sample.	N/A

### III. Hierarchical Description of Design

#### A. High-level System Description

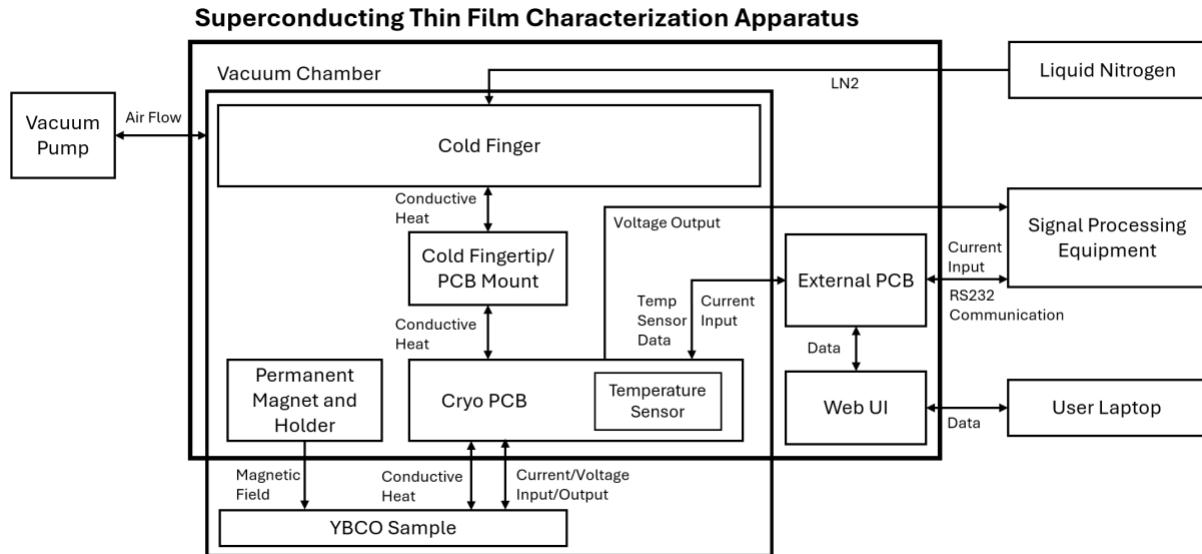


Figure 1: White Box Diagram

Most of the system is located within a vacuum chamber. In the chamber, the cold finger, filled with liquid nitrogen inside, cools down the PCB mount and cryostat PCB, which the YBCO sample is loaded onto. When needed, permanent magnets are loaded into the chamber to apply a uniform magnetic field to the YBCO sample. A temperature sensor is also used to measure the sample temperature. The sensor data and I/O signals from the sample are relayed through the cryostat PCB out of the vacuum chamber to an external PCB and external signal processing equipment (multimeter and power supply). The external PCB processes and displays the temperature sensor data, automates the data collection process with the signal processing equipment using RS232, and communicates with the web UI that the user interacts with. See the diagram on the next page for a better understanding of the physical structure of the system.

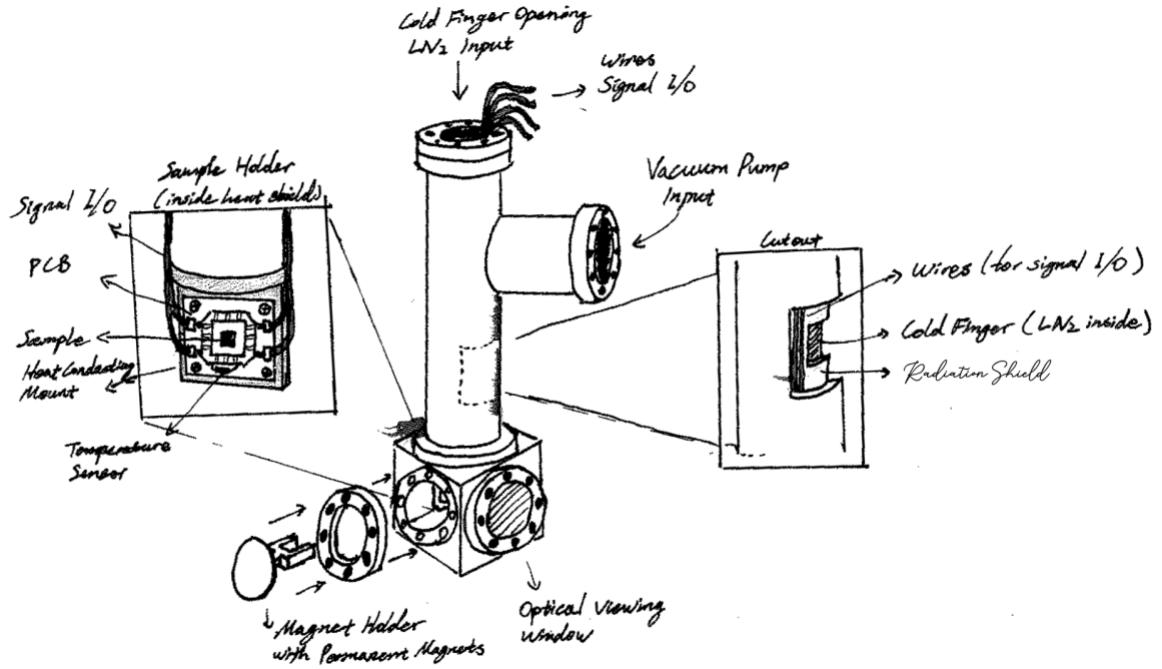


Figure 2: System Sketch

**Note:** The optical viewing window is included in the parts ordered for constructing the system. It adds the feature of performing optical tests on the sample, which is not a requirement but an additional benefit to the client. Since it was not a requirement, it was not included in the white box diagram. Similarly, the radiation shield was included in the purchase with the function of protecting the cold finger from infrared radiation noise of the surrounding warmer environment. It was also not a requirement and thus not included in the white box diagram.

## B. Sub-System Description

### 1. Vacuum Chamber

#### a) Subsystem Function

The vacuum chamber provides the vacuum that the sample must be in when the tests are being conducted. It isolates the sample from air particles and environmental thermal noise. The chamber also interfaces with many of the other subsystems. The tip of the cold finger, along with the sample holder, the magnets and magnet holders, electrical interface (PCB), and electrical feedthroughs must be in the chamber as well.

### b) System Design



*Figure 3: Vacuum Chamber (with faces to be modified)*

Though the client provides the vacuum chamber, many of the features/parts of the chambers are still decided by the design team. Thus, we are including it as a subsystem and considering it as part of our design.

As shown in Figure 3, the vacuum chamber is a cube with a ConFlat flange interface on each face. The cube has an edge length of 7 cm. In our design, the top flange will connect to a tube that interfaces with both the cold finger and the vacuum pump (see Figure 2). The cold finger will enter the chamber from the top, and the gas in the chamber will be pumped in and out of the chamber through the top as well. Electrical feedthroughs follow the path of the cold finger to relay signal in and out of the system. The front side, as shown in Figure 3, will be an optical viewing window for optical characterization of the sample. One of the side flanges will be used to attach the magnet holders and the magnets (see section 3 of the Sub-System Description). The rest of the cube faces will be sealed with blank flanges.

**Note:** We did not design the vacuum chamber itself. Our design is on how to modify/interface with it for our specific purpose.

## 2. Cold Finger

### a) Subsystem Function

The function of the cold finger is to cool the sample down to the required temperature of 77 K. Mechanically, it also supports the sample in the vacuum chamber. Thus, it needs to be able to thermally conduct heat from the sample to the LN<sub>2</sub> reservoir efficiently, and its sample holder must be within the vacuum chamber.

### b) System Design

As shown in the System Sketch (Figure 2), the entire cold finger will be encased in the vacuum chamber, leaving only an opening on the top for LN<sub>2</sub> input and gas exhaust. Figure

4 below is an image of the cold finger that we will use for the system (found on eBay). The cold finger body, a hollow cylinder, is designed to hold LN<sub>2</sub> inside to remove as much heat from the sample as possible. It can be filled through the top opening on the left of the image. We will be modifying it by connecting the opening to a funnel, so we can easily pour in the LN<sub>2</sub>. Below it, the side opening is the gas exhaust, designed to release the evaporated nitrogen gas from the cold finger. The flange (flat disk) below the exhaust will attach to the vacuum chamber and create a vacuum seal. It also ensures the mechanical stability between the cold finger and the vacuum chamber. The gold-coated brass tube on the right is the radiation shield, which reduces thermal radiation noise.



*Figure 4: Cold Finger*

Encased within the radiation shield, at the tip of the cold finger, is the sample holder shown below (Figure 5). With a copper section, it can ensure the highest possible thermal conductivity from the sample to the cold finger. The screw holes will allow us to attach our cryostat PCB along with the sample to the holder. Lastly, electrical inputs and outputs to and from the PCB mount will be relayed by wires that trace along the cold finger to the exterior of the system.



*Figure 5: Cold Fingertip/PCB Mount*

**Note:** We did not design the cold finger itself, but it is our responsibility to modify the cold finger opening (top part) and the cold fingertip/PCB mount for our purposes.

### 3. Magnets and Magnet Holders

#### a) Subsystem Function

A uniform magnetic field of at least 10 mT must be applied to the sample to perform Hall measurements. The direction of the magnetic field also needs to be flipped to complete the thin film characterization process.

#### b) System Design

The high magnetic field strength requires the use of permanent magnets, given the size constraint of the vacuum chamber. We will be using neodymium disc magnets with a diameter of 1 inch, a height of 1/4 inch, and a surface field of 0.33 T. As shown in Fig. 6, to ensure the uniformity of the field, two magnets will be used, with one at the front and one at the back of the sample. The magnets will be held by a Y-shaped structure made by non-magnetic materials, so the field will have no disruption. The Y-shaped rig will be attached to a ConFlat flange that can connect to the side of the vacuum chamber cube.

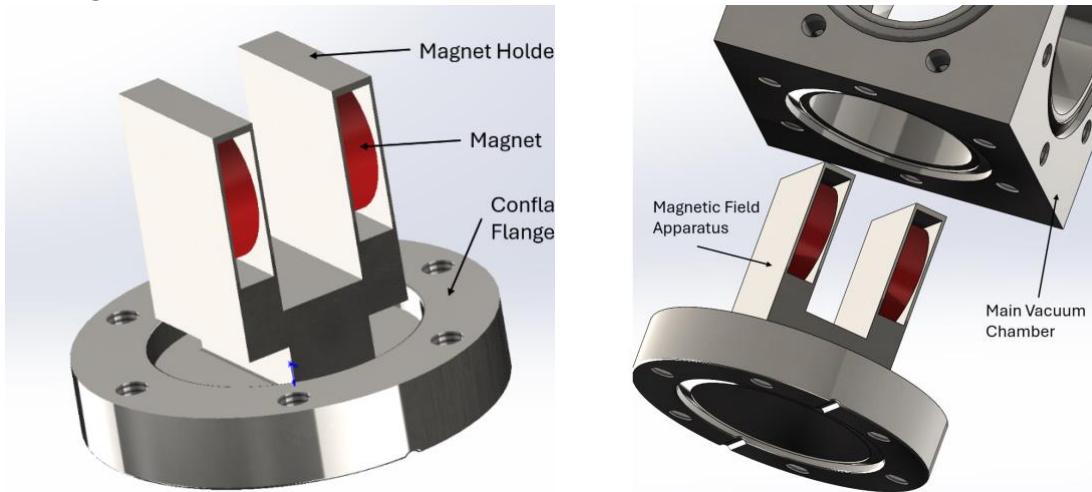


Figure 6: Magnets and Magnet Holders

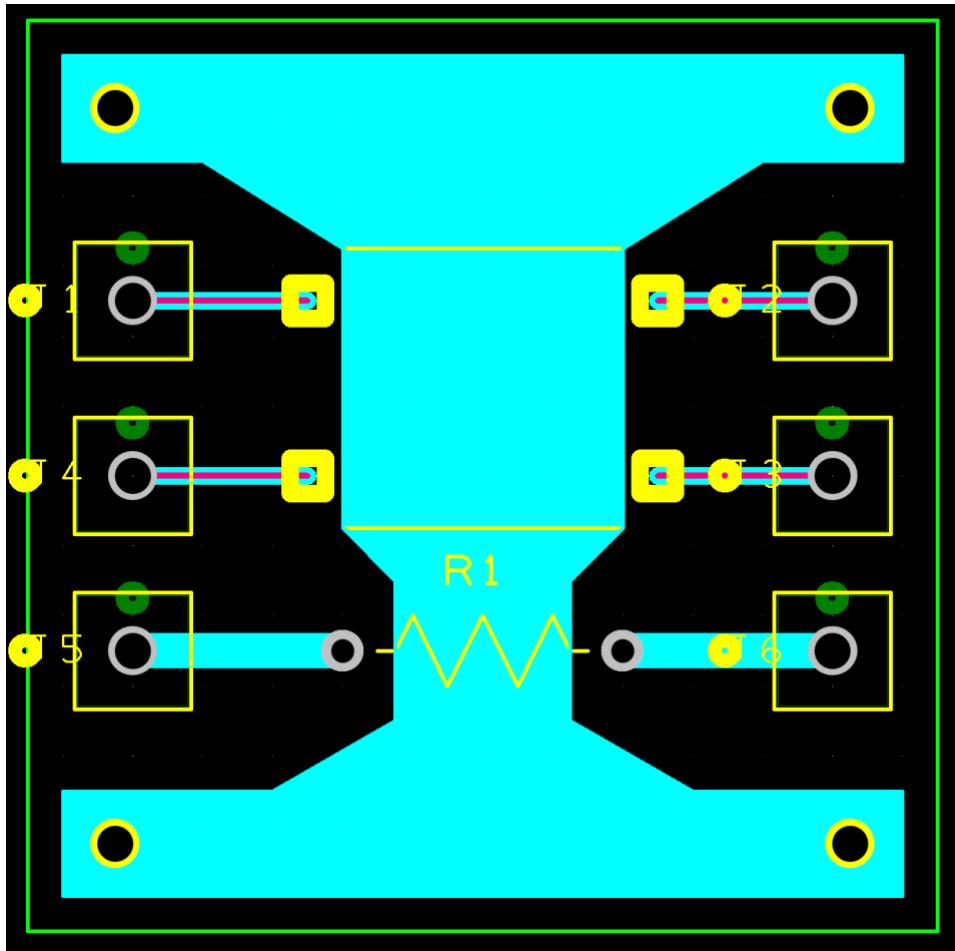
### 4. Sample Carrier & Interface

#### a) Subsystem Function

The sample must be mounted to the cryostat PCB so that electrical connections can be made for testing as well as to provide a thermal pathway to cool the sample down to 77K. Temperature readings of the sample should be taken, and electrical wiring must be routed out of the vacuum chamber without interfering with other subsystems.

#### b) System Design

The sample will be attached to the cryostat PCB with vacuum grease and wire bonded to copper pads as seen in yellow below (Figure 7). To increase the thermal conductivity of the device, a copper pour region has been added between the screws and the device. This region also runs under the temperature sensor to try to keep the temperature of the sample and the sensor as close as possible. The temperature sensor is through-hole mounted at the bottom of the PCB.



*Figure 7: Cryo-PCB Schematic*

Because the cryostat PCB must be thermally conductive, all parts on the PCB must not fail at 77K. This leads to copper screws (Figure 8) which will remain mechanically strong at this temperature while also increasing thermal conductivity between the cold finger and the device. The binding posts (Figure 7) for the temperature sensor and device will be made of brass due to its strong mechanical properties at 77K.



*Figure 8: Copper screws and brass binding posts*

## 5. Edge Computing Subsystem (EGS)

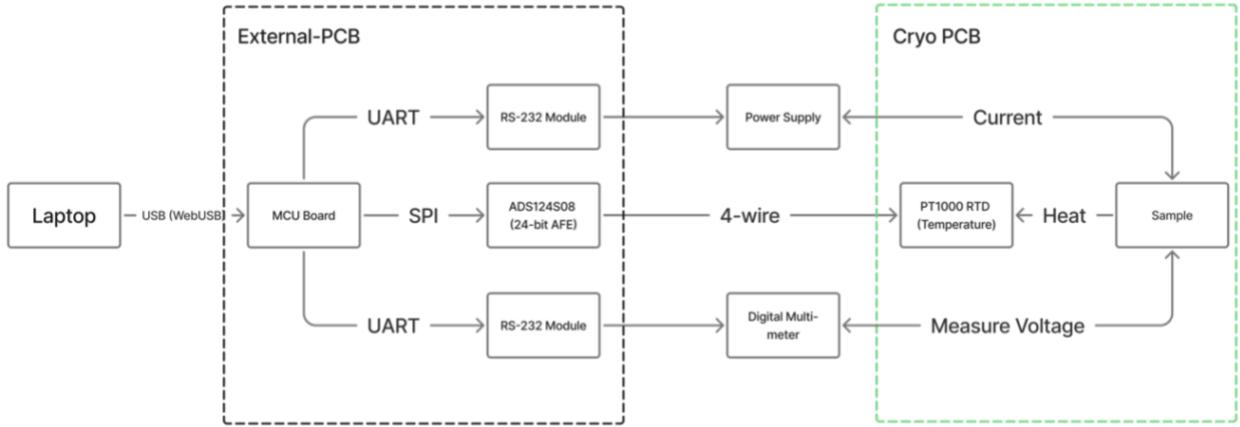


Figure 9: EGS High-Level Interconnect

### a) Subsystem Function

The Edge Computing Subsystem performs closed-loop measurements locally. It sends out commands and receives measurement data from the external signal processing equipment (power supply and DMM) for the Van der Pauw measurements. It also takes temperature measurements directly from the temperature sensor on the cryostat PCB.

### b) System Design

The ESP32-P4 microcontroller manages the bench power supply and digital multimeter over isolated RS-232 (SCPI) connections. It acquires temperature data via the ADS124S08 (SPI, PT1000 4-wire) and provides a USB link to the laptop for configuration, startup/shutdown, live telemetry, and data export. By ensuring precise timing and safety logic on the microcontroller, the system maintains a deterministic nature and independent of enterprise network constraints.

## 6. Temperature Sensing Subsystem (TSS)

### a) Subsystem Function & Design

The TSS converts the voltage readings of the cryogenic Resistance Temperature Detector (RTD), the temperature sensor on the cryostat PCB, to digital temperature data and transmits that data to the Main MCU. The system will use PT1000 RTD (Model Number: ERTD2-PT-1000-A-3850 from Variohm) and delta-sigma ADC (Model Number: ADS124S06 from TI) for data read out. The PT1000 is connected to the ADS124S06 via a four-wire Kelvin connection, which reduces noise and enhances accuracy. The ADS124S06 communicates with the Main MCU over SPI. The system should be able to meet requirement ACC-1 ( $\pm 0.5$  K accuracy at 77 K,  $\leq 0.2$  K drift over 10 minutes) after calibration.

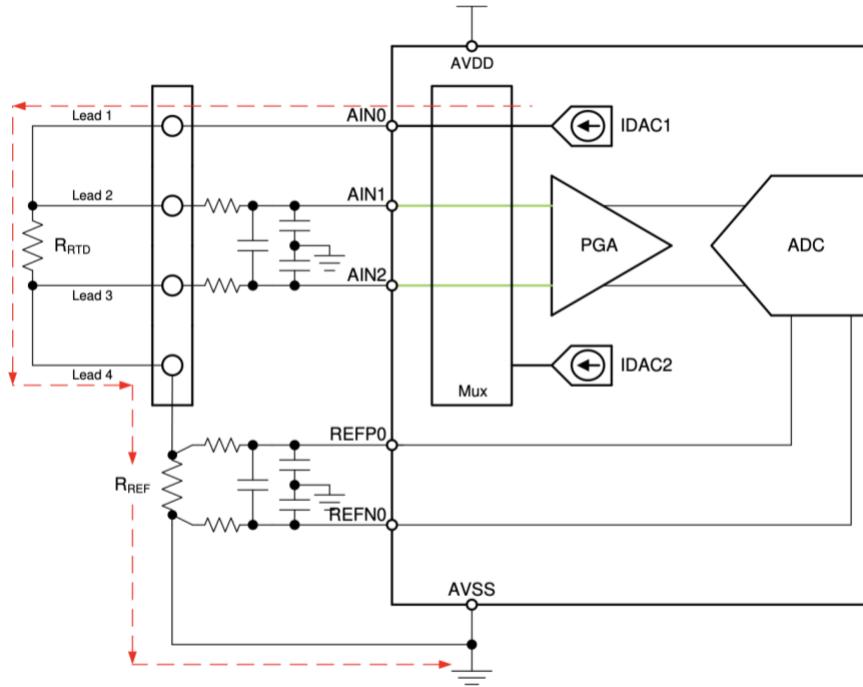
### b) System Interface

The TSS interfaces thermally with the cryostat environment via the sample holder and electrically with the main MCU as summarized below in Table 2.

Table 2: Temperature Sensing Sub-System Interface

Cryostat Environment	Transfer Thermal Energy
Main MCU	be configured by; report data to

c) Circuit Diagram



**Figure 2-6. Four-Wire RTD, Low-Side Reference Measurement Circuit**

*Figure 10: Four-Wire RTD, Low-Side Reference Measurement Circuit [1]*

Figure 10 shows the four-wire, low-side reference configuration used for the PT1000 and ADS124S06. The ADS124S06 provides a programmable excitation current (nominal 500  $\mu$ A) through the RTD and a precision reference resistor,  $R_{REF}$ . The differential voltage across the RTD is detected via a Kelvin connection and converted by the internal PGA and delta-sigma ADC.

d) System Sequence Diagram

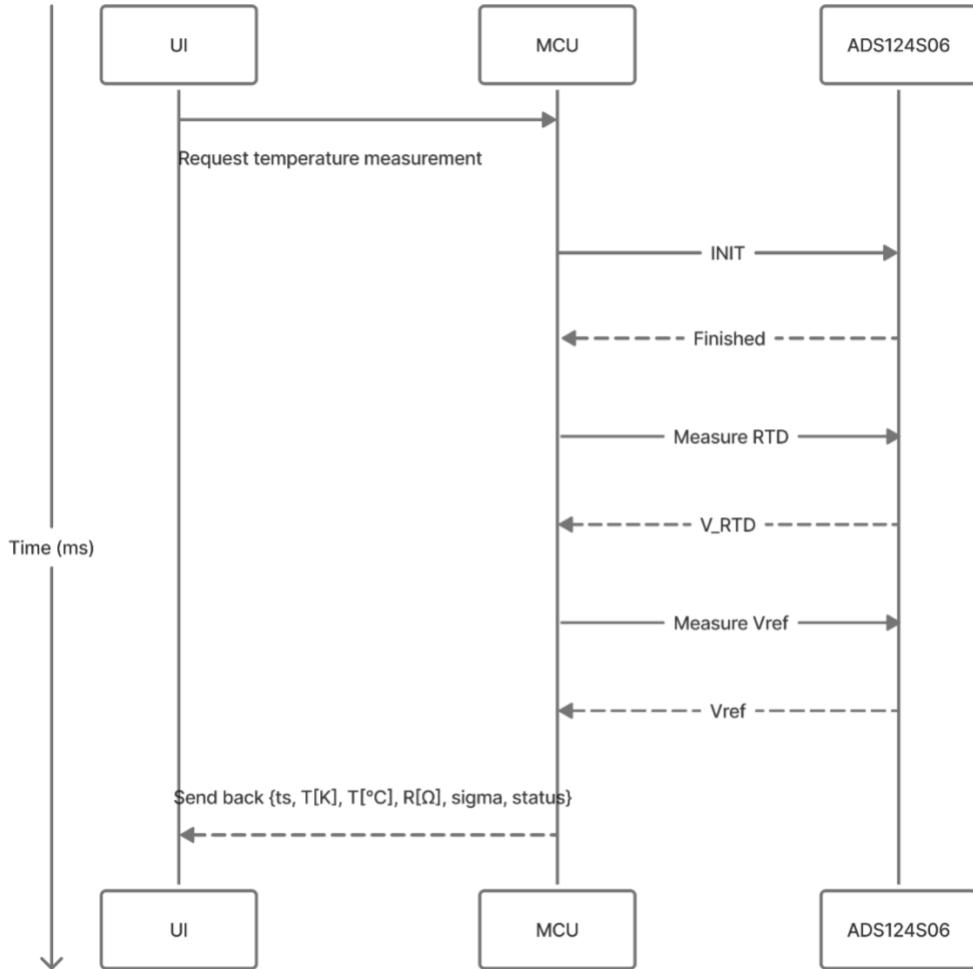


Figure 11: TSS One-Shot Measurement Sequence

Figure 11 illustrates the one-shot temperature measurement sequence of the TSS. The measurement can either be requested by the user through the UI or self-initialized through MCU control program if needed. Upon requirement the MCU configures the ADS124So6 by writing its configuration registers (input multiplexer, IDAC magnitude, PGA gain, reference selection, and data rate) over the Serial Peripheral Interface (SPI). Then, the MCU waits for the ADS124So6 to send the data-ready signal. Upon the detection of the ready signal, the MCU transmits an RDATA command to get the 24-bit RTD conversion result and converts the raw code to a calibrated temperature value. Finally, the MCU stores and, if needed, returns the temperature sample (and optionally, status/meta-data) to the UI for display.

## 7. System Software: Measurement Automation and UI

This section provides an overview of the current design of the semiautomatic measurement software and its interface. Note that the measurement is semiautomatic because the user still has to manually rotate the wiring connections to the power supply and multimeter during the Van der Pauw measurement sequence.

a) Subsystem Decomposition

Table 3: Software Components

Component	Platform	Role
User Interface	PC (Win/macOS/Linux)	Start/stop runs, show plots, export CSV/Parquet
Protocol Client	PC	Frames commands/telemetry over USB
Protocol Server	MCU	Parses commands, acks, streams telemetry
Test Executor	MCU	Run required test
ADS124So8 Driver	MCU (SPI)	Configure, calibrate, sample, filter
SCPI Drivers (PSU/DMM)	MCU (UART→RS-232, isolated)	Vendor-specific SCPI send/parse
Guards & Interlocks	MCU	Temp/over-V/over-I protection
Log Buffer	MCU (+uSD)	Save the Test Result before User download it

b) PC and MCU Connection

The PC communicates with the controller via a single USB link. By using the TinyUSB Project and webUSB, the system establishes a WebUSB interface as the primary channel for control and user interface while retaining a CDC-ACM virtual COM interface for debugging and backup. This USB-only design addresses enterprise network constraints by eliminating the need for Wi-Fi and network credentials. It also ensures deterministic latency and maintains stable and easy interface experiences as it also prevented host-side port confusion.

c) User Interface

The User Interface is a WebUI that operates locally within Chrome/Edge/Safari and establishes a connection to the device via WebUSB (primary) with WebSerial/CDC as a backup. This is where the user interacts with the measurement automation system by sending in commands and receiving measurement results.

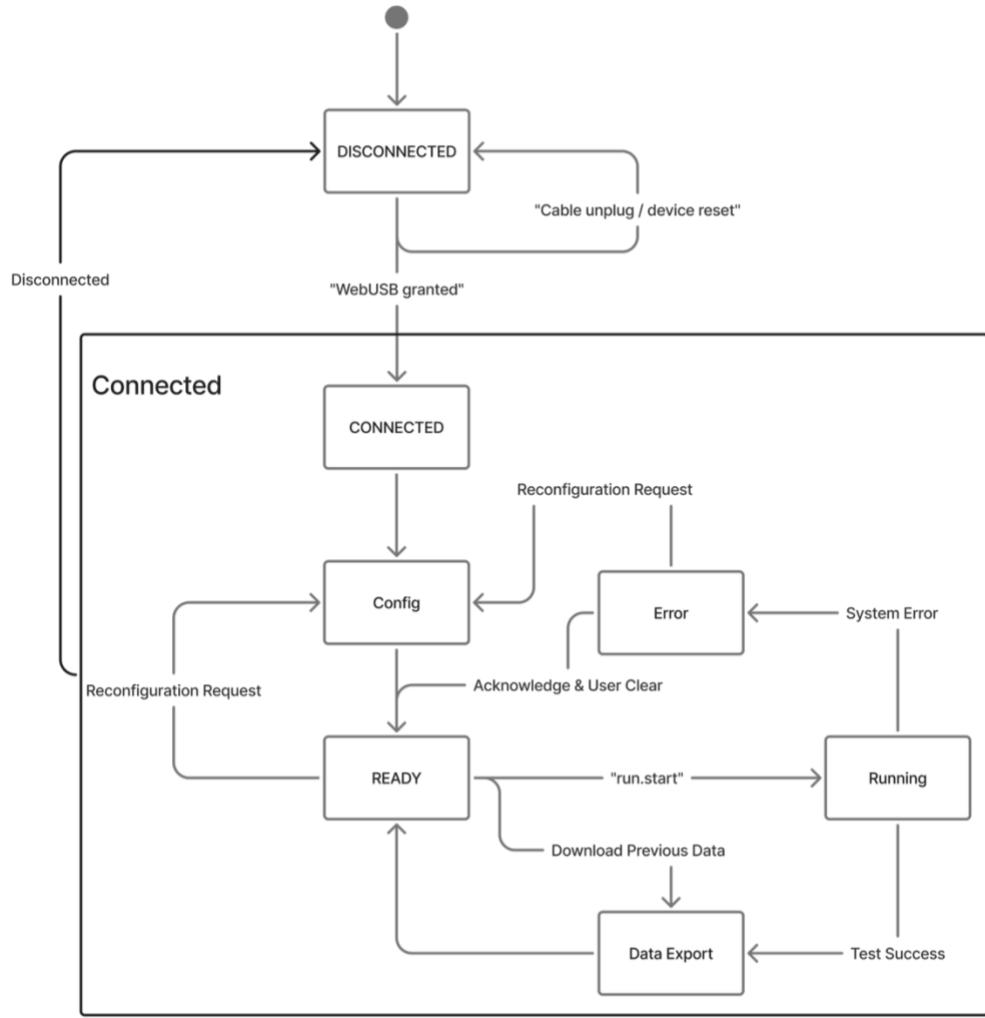


Figure 12: UI State Machine

The user interface uses a streamlined workflow comprising of the following steps: connect, configure, ready, run, and export. Upon connecting the device to their computer and browser, the user can configure the test flow and subsequently initiate an autonomous run that is executed entirely on the microcontroller unit (MCU) with real-time charts display of  $V_{set}$ ,  $V_{meas}$ ,  $T_K$ , and other parameters. Previous and current results can be exported to CSV (in addition to a sidecar JSON containing firmware hash, instrument IDN strings, recipe, and UTC timestamps for audit purposes).

#### d) Measurement Plan Instruction

In order to create a measurement plan instruction that is both code and user friendly, we have designed a compact, MCU-executed plan that encapsulates an entire measurement acquisition process. This plan is expressed in YAML format and defines global guards (e.g., temperature and timeouts), instrument settings (PSU/DMM ranges and limits), and a sequence of actions (set PSU, settle, DMM read, ADS batch/median, log). The example in Figure 13 defines global guards ( $temp_k$  window and timeout), per-instrument settings (PSU/DMM limits and ADS124So8 configuration), and an ordered sequence of actions

(*init*, *psu\_on*, voltage sweep with dwell, *dmm\_read*, *ads\_collect*). The logging section then specifies which fields (e.g., *t\_us*, *Vset*, *Vmeas*, *T\_K*) are recorded for each sweep point.

```

meta:
  name: YBCO_IV_TempSweep
  version: 1
guards:
  temp_k:
    min: 65.0
    max: 90.0
  timeout_ms: 2000
instruments:
  psu:
    baud: 9600
    channel: 1
    v_limit: 6.0
    i_limit: 0.10
  dmm:
    baud: 9600
    channel: 1
    range_vdc: 10
ads124s08:
  sps: 20
  pga: 16
  mux: "AIN0/AIN1"
  sys_cal: true
sequence:
  - do: init
  - do: psu_on
  - sweep:
      var: Vset
      dwell_ms: 150
      points: [0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1.00]
      actions:
        - psu_set_v: "${Vset}"
        - wait_ms: 100
        - dmm_read: "Vmeas"
        - ads_collect:
            samples: 20
            reduce: "median"
            out: "T_K"
  - do: psu_off
logging:
  fields: [t_us, Vset, Vmeas, T_K]
```

*Figure 13: Example YAML Measurement Recipe YBCO\_IV\_TempSweep for a PSU Voltage Sweep with Temperature Logging*

e) MCU Measurement State Machine

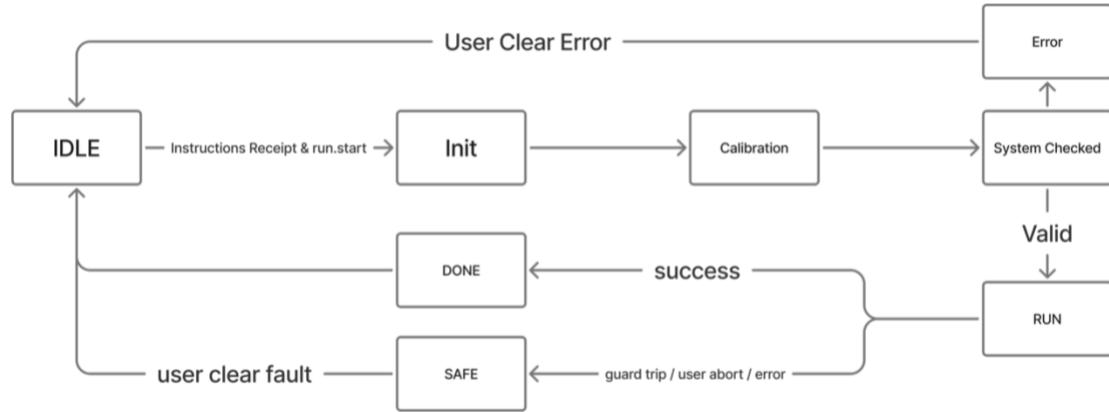


Figure 14: MCU measurement state machine

The MCU firmware is structured as a finite-state machine. The controller initiates in the IDLE state, awaiting a valid Measurement Plan Instruction and a valid command. Subsequently, it transitions to the Init state, during which hardware interfaces are established and configuration data is loaded. This is followed by the Calibration state, which conducts ADC/self-checks and instrument sanity checks. Upon successful completion of all checks, the system proceeds to the System Checked state, transitioning to the RUN state, where the active Measurement Plan Instruction is executed. Any failed check at this stage redirects to the Error state, reporting the fault to the PC. A normal completion of the Measurement Plan Instruction results in the DONE state, while guard violations or user aborts lead to the SAFE state, which deactivates the PSU to make the sample safe. Both the DONE and SAFE states return the controller to the IDLE state for the subsequent run.

## IV. Design Decision Justification:

### A. Case 1: Permanent vs. Electromagnets

#### 1. Decision Context

To fulfill requirement FUNC-5, we must design a way for the system to provide 10 mT of uniform magnetic field to the sample area. This function is crucial for building a system that can take the Van der Pauw measurements of the thin film sample as required by the client. The three options we have are to purchase a set of Helmholtz coils (a type of air-core electromagnet), make our own electromagnet, or use permanent magnets. These options relate to many of our requirements and affect many aspects of the system design. For example, choosing between electromagnets and permanent magnets will affect the size of the vacuum chamber that needs to house them and the PCB, which must be designed to accommodate the electromagnet control circuits. Purchasing the magnet or building our own magnet would also greatly affect the cost of the system. The pros and cons of each option and their effects on the design requirements are tabulated in the section below.

#### 2. Design Options & Decision Matrix

1. Purchase a pair of Helmholtz coils (6" diameter) that provide ~4.80 mT at \$233.50.
2. Build our own electromagnet that provides the required 10 mT.
3. Purchase permanent neodymium magnets (1" diameter, 1/4" thick) with a surface field strength of 331 mT at \$9.24 each.

Table 4: Decision Matrix for Magnet Design

Feature/Requirement	Option 1	Option 2	Option 3
<b>FUNC-3,4,8,9: Accuracy and precision requirement of various electrical measurements</b>	4.8 mT is slightly lower than preferred. We should still be able to get measurements, but maybe not to the accuracy and precision of a higher field.	Can be designed to achieve 10 mT.	331 mT at the surface is more than enough, even if the sample is some distance away.
<b>FUNC-5: Provide at least 10 mT of uniform field</b>	~4.80 mT	10 mT	~120 mT at 1/4" away from surface
<b>FUNC-6: Can switch field direction</b>	Yes (just reverse the current)	Yes (just reverse the current)	Yes (but need to turn off vacuum to physically flip the magnets then turn the vacuum back on)
<b>FLEX-1: Swap sample in 10 min</b>	The large coil size (6" diameter) requires a larger vacuum chamber, which takes longer	The large coil size requires a larger vacuum chamber, which takes longer to pump up/down,	The small size (1" diameter) allows for a smaller vacuum chamber, which takes

	to pump up/down, lengthening the sample swapping time.	lengthening the sample swapping time.	shorter time to pump up/down, decreasing sample swapping time.
<b>COST-1: \$2,000 budget</b>	\$233.50	Undetermined (ruled out this option before a price was determined)	2 * \$9.2
<b>REC-1: 1 liter of LN2 per run</b>	Larger vacuum chamber takes more LN2 to cool down.	Larger vacuum chamber takes more LN2 to cool down.	Smaller vacuum chamber takes less LN2 to cool down.
<b>Additional Notes</b>	Coils with fields that meet 10 mT are sold, but they are not within our budget. This is one where the pricing is reasonable and the field strength is somewhat acceptable.	Manufacturing the coil is complex and precise, which is difficult to make by ourselves. The coil is calculated to need hundreds of turns to achieve our requirements.	None

### 3. Design Decision

Option 3 was chosen for our design. The cheaper price, smaller size, and stronger field strength are benefits that outweighed the inconvenience of physically flipping the magnet direction while using the apparatus. Not only is this an inconvenience that the client deemed to be acceptable, we can take advantage of the flexibility of interfacing with the vacuum chamber in our magnet holder design to minimize this inconvenience.

## B. Case 2: Temperature Sensors

### 1. Decision Context

In our project, we are designing a liquid-nitrogen-cooled test rig for thin film devices (e.g., YBCO) that will routinely operate around 77 K. Accurate and stable temperature measurement of the sample is one of the most critical functions, as all downstream electrical measurements and material characterizations are only meaningful if we know the precise sample temperature.

Early in the term, we faced a design decision for this subsystem: whether to purchase a commercial, cryogenic-rated temperature sensor that is designed to work down to approximately 70 K and costs around \$600, or to design our own temperature sensing solution based on a RTD (Resistance Temperature Detector) (approximately \$3 per sensor) and a precision ADC/AFE (ADS124S08, approximately \$10) that we expect to perform reliably down to about 73 K. The commercial option offers guaranteed performance and extends low temperature range but consumes a significant fraction of our total \$2,000 budget. The in-house option trades some performance margin and requires additional calibration and documentation work but is much cheaper and integrates more naturally

with other parts of our system. The following decision analysis justifies which option better satisfies our stakeholder requirements given the actual operating range (around 77 K) and the constraints of the overall system.

## 2. Design Options and Decision Matrix

Option 1: purchase a commercial, cryogenic-rated temperature sensor that is designed to perform down to approximately 70 K and costs around \$600

Option 2: Build 73 K sensor ourselves with RTD ( $\approx \$3$ ) and ADS124So8 ( $\approx \$10$ ) + passives/PCB, calibrated and validated down to  $\approx 73$  K.

*Table 5: Decision Matrix for Temperature Sensor*

FEATURE / REQUIREMENT	ID	WEIGHT	OPTION A	SCORE	OPTION B	SCORE
Impact on sample access & swap time (< 5 min)	MAINT-1	0.10	Probes or small sensor heads, sometimes bulkier, can be positioned close to samples without major obstruction.	4	We are swapping the cyro-PCB now	4
Accuracy & stability at 77 k	ACC-1	0.30	Vendor-calibrated, cryogenic use, $\pm 0.1\text{--}0.2$ K accuracy at 77 K, stable over time.	5	4-wire RTD + ADS124So8 calibration can achieves $\pm 0.3\text{--}0.5$ K accuracy and $\leq 0.2$ K stability.	4
Budget impact relative to \$2,000 cap	COST-1	0.30	Sensor costs 30% of budget, limiting funds for other components.	1	1% of total budget	5
Reliability over >10 cryogenic cycles	REL-1	0.20	Cryogenic cycling designed, potted, and strain-relieved component survives >10 cycles.	5	PCB-mounted RTD and wiring require careful potting to prevent cracking from mechanical and thermal	3

Documentation (calibration procedures, schematics, etc.)	DOC	0.10	Vendor provides datasheets and calibration tables; document only needs to describe mounting and plugging in.	4	stress. More risk and unknowns. Document RTD circuit, calibration, and uncertainty analysis for transparency and teaching value. Could be slightly harder to write	2

### 3. Design Decision

$$\text{Option 1: } 0.4 + 1.5 + 0.3 + 1 + 0.4 = 3.6$$

$$\text{Option 2: } 0.4 + 1.2 + 1.5 + 0.6 + 0.2 = 3.9$$

Considering the pros and cons of each option, and the weight associated with each requirement, option 2 was decided to be the best design choice. The benefit of the significantly cheaper pricing outweighed the small disadvantages that Option 2 has against Option 1.

## **V. References**

- [1] J. Wu, "A Basic Guide to RTD Measurements," 2023. [Online]. Available: [www.ti.com](http://www.ti.com)