Microcontroller-based Capacitor Discharge Circuit with Configurable Setpoints

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Chapter 1: Executive Summary

In partnering with the University of Central Florida, NextEra Energy set out to sponsor a group of undergraduate students in developing a system that can safely and quickly discharge high voltage capacitors in a laboratory setting. These capacitors undergo various kinds of testing, and it is crucial for safety that they are properly discharged of any residual voltage before and afterwards. The system developed in this senior design project is designed to connect in capacitors charged to upwards of 1200V, sense and communicate the current voltage level to user, and undergo a configurable and staged discharge sequence over bleeding resistors such that a safe voltage level can be reached in under 30 seconds.

This design is achieved in two ways: a dedicated discharge chassis and a control PCB. The discharge chassis consists of aluminum housed power resistors wired in parallel stages. The stages effectively dissipate power while also gradually lowering the effective resistance seen by the capacitor to speed up the discharge process. To control the stages, contactors were employed which are switched on and off by an ESP32-WROOM Microcontroller on a control PCB. The control PCB also monitors the capacitors voltage by way of a voltage divider, isolation amplifier, and ADC signal chain. An AMC3330 isolation amplifier is used to keep the high voltage measurement isolated from the low voltage circuitry. The measured voltage is then both communicated to the user and used to make decisions on when to switch certain stages of the discharge cycle. The main interface with the user comes in the form of a five-inch graphic LCD display which allows for the configuration of voltage setpoints that determine when each stage in the discharge cycle activates. During discharge, the display shows the total elapsed time and the current voltage level in the system. Lastly, an RTD and RTD to digital converter are used to allow the MCU to monitor thermal conditions of the discharge chassis.

The following document is a record of the design process that went into this senior design project. This includes but is not limited to general research, component selection, hardware design, and software design. An overall description of the project is first presented, which outlines major goals and objectives. Then technology research and component selection is conducted, along with a discussion of relevant standards and tools that may apply to this project. Major hardware and software design, followed by manufacturing and testing, is also discussed alongside relevant theories and rationales for specific decisions taken throughout the course of the project. The conclusion highlights potential areas for improvement, and subsequent appendices provide additional information on technical references, code, etc.

Chapter 2: Project Description

2.1 - Project Motivation and Background

Throughout the power industry, capacitors and capacitor banks are used in a wide variety of applications. At its simplest level, a capacitor bank is a group of capacitors, connected in either series or parallel or with a combination of both, that are designed to store electrical energy for later uses. [1] This is evident when capacitors are utilized for power factor correction, where local capacitor banks supply reactive power to inductive loads, such as motors. In doing so, real power output, system efficiency, and system capacity can be increased. [2] Additionally, capacitors can aid in smoothing out voltage and power fluctuations in a system. This becomes especially important within renewable integration since most renewable energy sources produce nonconstant power over the course of a day. During brief changes in production, capacitors can help the system ride through power fluctuations. Finally, capacitors can act as key components in filtering out unwanted frequencies for a system. This helps aid overall power quality and also becomes very useful for communication systems. One such example in the power industry would be the use of power line carrier communication which takes advantage of already existing high voltage powerlines as a medium to send control signals between substations. In such systems, capacitors are utilized as filters to protect substation equipment from damage associated with higher frequency signals.

While capacitor banks provide a variety of advantages and useful applications within a power system, disadvantages can come with the process of charging and discharging the bank itself. A capacitor bank can hold a high and hazardous amount of residual voltage after it is disconnected from a power system. [3] This can pose a safety risk to any workers present near the bank due to the potential for electric shock. Additionally, reconnecting a capacitor bank into a power system while residual voltage is present can be problematic as higher than expected inrush currents can occur. This can lead to equipment breakdown as well as potential tripping within relays. Within parallel capacitors further inrush issues can be caused if one capacitor bank is already charged and another parallel bank that is not fully charged is connected on the same parallel bus. The voltage difference between the first bank and the second bank produces high currents that go back and forth between the two banks, which places immense stress on the system. [4]

The standard solution within the power industry to these issues would be to employ bleeding resistors at the terminals of a capacitor bank to safely discharge the circuit. The resistors can be in a switching topology, or permanently connected, although the latter choice would result in power loss and potential overheating. NextEra Energy, an American energy company specializing in energy utility and efficiency, wanted to pursue a switching resistor-based capacitor discharge tool to safely discharge high voltage capacitor banks that are utilized in conjunction with PVS980 inverters. More specifically, NextEra wanted a tool that could be utilized in a laboratory setting where, after undergoing certain testing, capacitor banks can be brought in and easily discharged. As a result, this senior design project was formed to explore potential solutions and provide NextEra with a design that can safely discharge their capacitor banks while also meeting various constraints and requirements. Due to the dangers of high voltages, however, NextEra agreed to allow the team to develop a prototype of the system that was only be tested at low voltage and that can then be potentially scaled to and operate at higher voltages.

2.2 - Existing Products and Projects

This project's product classification would fall under the umbrella of Photovoltaic Rapid Shutdown Systems or PVRSS, which are a group of products used to safely disconnect the photovoltaic panels from their inverter and swiftly drain the power stored in the system. Use cases for PVRSS range from residential solar installations to multi-Megawatt photovoltaic fields used by electric utilities.

One of the major considerations when installing a photovoltaic array is the safety of maintenance personnel for routine inspections and first responders in emergency situations, and the National Electric Code has a section addressing the standards that products of the category must adhere to, under NEC Section 690.12: Rapid Shutdown of PV Systems on Buildings [5]. Because the PVS980 inverter this project is working with is designed to be a modular system, it requires the installation of a PVRSS to meet the standard. Below are a few examples of products that are either modules in a PVRSS system or have such a system integrated into the product.

2.2.1 - Beny BFS-A1

A current product that fulfills a similar purpose is the Beny BFS-A1, which is a "rapid shutdown switch for connection to PV panel arrays to achieve compliance with 2020 NEC 690.12" [6]. This product shuts down panels and dissipates energy stored in its connected inverter. While the function of this device is similar to this project's motivation, it appears to be designed for smaller scales, such as a residential installation that would have a far smaller capacitance to discharge than the scope of this project.

The main selling point of the BFS-A1 is its simplicity of installation and per-module shutoff for lower-power systems. Because this product is designed to be installed onto the back of a photovoltaic module and control its output to the inverter, it is optimal for smaller installations such as a residential solar array. However, one of the main downsides of the BFS-A1 would be that it only disconnects the photovoltaic panel from its inverter, rather than discharging the capacitors in the inverter.

2.2.2 - EG4 18kPV

On the residential-scale inverter side, the 18kPV inverter by EG4 electronics is designed to be installed on a house and provide supplemental power while the solar panels are active. The 18kPV "includes a rapid shutdown system that complies with 2017 and 2020 NEC 690.12" that can be connected to an E-stop button and activated if emergency personnel need to cut power to the home [7].While the 18kPV does have a rapid shutdown feature that complies with the past two iterations of NEC 690.12, its main drawback is the fact that its discharge system is only designed to work at the scale of a residential solar installation, with a maximum input of 21kW at 600V. As such, the PVRSS in the 18kPV would not be able to work at the utility-scale requirements specified for this project.

2.2.3 - SMA Sunny TriPower CORE1

While the Sunny TriPower CORE1 from SMA Solar Technology is smaller than the inverter in this project, with a maximum output power of 62.5kW on its highest specification model (compared to the minimum specification model PVS980 capable of output in the multi-Megawatt range). CORE1 does include a self-discharge feature that is activated with its PVRSS. The CORE1 does not include capacitance on its datasheet, it has a maximum voltage of 1000V when it starts discharging, which is lower than the 1200V maximum for the scope of this project [8].The primary use case of the CORE1 is for integrating a commercial-scale roof or parking lot solar array into a building's electrical systems. As such, the CORE1 is designed to have plenty of safety and convenience features, including self-discharge in emergency situations, without the customer having to make any further modifications. Where it falls short is its scale, as the CORE1 is intended to be installed on a building to augment the power consumption, versus the utility scale needs presented by the PVS980's utility-scale use case.

2.2.4 - Summary

As far as current projects and commercially available products go, there are standalone devices that operate at lower voltages, and there are smaller inverter systems that offer features like the purpose of this project, albeit already integrated with the system being sold and therefore not scalable to the requirements. There did not appear to be any products that operate at these high voltages available as an individual module rather than already being integrated into a larger inverter system, which presents an opportunity to innovate a new solution.

2.3 - Goals and Objectives

Based on the background of the project, along with inspiration from existing products, the following goals and objectives were outlined by the team. It is worth noting that goals were defined as broad, high-level aspirations for our project. Objectives, on the other hand, were specific, measurable outcomes that work towards the set goals. They also provided a foundation for further developing system requirements and specifications. Both goals and objectives can be further broken down into three categories: basic, advanced, and stretch. Basic goals/objectives were a required part of the design implementation, often being dictated directly by NextEra. Advanced goals/objectives included scope that was not directly specified but was beneficial to include in the final design. Stretch goals/objectives were also beneficial to the final design but were considered out of scope for the project due to the time or complexity required to implement them.

2.3.1 - Goals

Below are the basic goals outlined for this project, which all were derived based on requirements coming directly from NextEra:

- The discharge tool shall be safe and reliable.
- The discharge tool shall fully discharge the capacitor quickly.
- The discharge tool shall visibly indicate the discharge stages to the user.
- The discharge states shall be configurable based on specific voltage setpoints.
- The overall design shall be scalable to higher voltages.

Below are the advanced goals outlined for this project produced by the team, which were in scope for the project:

- The discharge tool shall communicate the real time voltage of the capacitor to the user.
- The discharge tool shall communicate the total elapsed discharge time to the user.
- The discharge tool shall monitor thermal conditions for potential overheating.

Below are the stretch goals for this project that were out of scope for the design:

- The discharge tool shall log/store measured data over time for future access and/or analysis.

- The discharge tool shall telemeter data to, and allow controllability via, a remote station.

2.3.2 - Objectives

Below are the basic objectives outlined for this project, which were all derived from information provided by NextEra:

- The discharge tool shall fully discharge a 1650uF capacitor in less than 30 seconds.
- The initial voltage across the capacitor to be discharged shall be 12V, but the system must be scalable to an initial voltage of 1200V.
- The discharge tool shall include four configurable logic alarms to activate at specified voltages.
- One of the four logic alarms shall be activated when the voltage is <0.1V for low voltage testing, and <10V when the system is scaled to high voltage
- The discharge tool shall utilize relays and a microcontroller to control the discharge process.
- The discharge tool shall utilize resistive networks for the discharge process.
- Device should be able to provide a visual indication of the discharge state.
- The discharge tool shall be powered by a 24V DC source.
- A bill of materials for high voltage scalability shall be provided alongside relevant high voltage calculations.

Below are the advanced objectives produced by the team:

- The discharge tool shall display capacitor voltage measurements with an error tolerance of 5%
- The discharge tool shall display total elapsed discharge time with an error tolerance of 5%
- The discharge tool shall display internal device temperature in degrees Celsius with an error tolerance of 10%
- The prototype should be able to display a response time within 500 ms

Below are the stretch objectives that were out of scope for the design:

- The discharge tool shall be able to record up to 30 seconds of data while discharging
- The discharge tool shall be able to log real time data over USB

2.4 - Specifications

This project seeks to address the main issue of not having a safe and reliable system for discharging large capacitors used in electrical power inverters. The team designed a prototype system that is, to the best of our ability, rated for HV input, but was only tested at a scaled lower voltage. However, simulations and calculations were run quantify theorized high voltage performance.

The engineering specifications listed below were selected to inform the user and operators of the general system and specific component capabilities. The most important specifications are for the system to have a less than 30 second discharge rate, 3 discharge stages, and a scaled safe threshold voltage indication of less than 0.1V. These define the heart of the system and its purpose. The additional information provided is given to show the operator this prototype's specific capabilities and use case based on our design and internal component selection. However, these specifications also serve the purpose of summarizing our design, allowing for future modifications and development based on our prototype. The overall system and component specifications are listed below, with specifications that the team feels can be demoed to reviewers highlighted in yellow:

Table 1: Specifications

Parameter	Specification
Capacitor Discharge System Specifications	
Input Capacitance	1650 µF ± 10 %
Input Capacitor Voltage (LV)	12 V ± 15 %
Input Capacitor Voltage (HV)	1200 V ± 15 %
Discharge Time from Full to Safe	≤ 30 seconds
Number of Discharge Stages	3
Stage 2 Voltage Setpoint Range (LV)	8 V to 6 V
Stage 2 Voltage Setpoint Range (HV)	800 V to 600 V
Stage 3 Voltage Setpoint Range (LV)	4 V to 2 V
Stage 3 Voltage Setpoint Range (HV)	400 V to 200 V
Discharge System Temperature	< 120 ˚F
Voltage Measurement Accuracy	± 5 %
Voltage/Current Sampling Rate	25 – 50 Hz
Temperature Measurement Accuracy	± 10 %
Safe Indication Threshold (LV)	< 0.1 V
Safe Indication Threshold (HV)	< 10 V
Power Consumption	5 – 35 W
System Area	≤ 24 inches by 36 inches
Unit Cost	< $2000
Component Specifications	
Microcontroller	
Clock Frequency	≥ 160 MHz
Number of GPIO pins	≥ 15
Logic Rail Voltage	3.3 V
Relays	
Coil Voltage	≤ 24 V
Contact Switching Voltage	≥ 1200V DC
Resistors	
Type	Chassis-mount Power
Power Rating	25 – 100 W

In addition to engineering requirements, it is important that the design be marketable and satisfactory to the sponsor. Based on the sponsor's input, the design use case, and hard specifications, the following list of marketing requirements was developed. Care was taken by the team to try and maximize these requirements in the final design of the system.

Table 2: Marketing Requirements

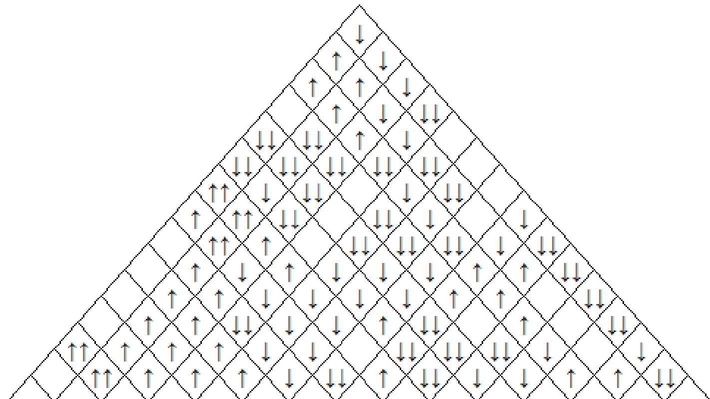
Marketing Requirements	
Parameter	Description
Safety	The system should prevent accidental HV exposure with safety systems, E-stop, and only show safe voltage level when system is truly below the threshold
Ease of Use	A new user and technician should be able to setup the discharge with minimal training and be confident in their operation
Affordability	The system should be affordable and be worth implementing for companies.
Reliability	The system should be robust and be able to complete many discharge cycles throughout its lifetime without needing replacement
Ease of Maintenance	The system should be easily serviceable if it needs repairs
Configurability	The system should be compatible with any reasonable voltage level configured or set by the operator during use
Deployability/Portability	The system should be manageable in size and weight and easily integrable into existing systems if permanent installation is desired

2.5 - House of Quality

The House of Quality (HOQ) is a common diagram format used in engineering design plans to show the connections and correlations between engineering and market/sponsor/client requirements as well as the desired direction or target for each of these requirements. Using the requirements previously discussed in the previous section, we filled out the table accordingly. The tradeoffs between engineering requirements are listed in the “roof” (upper triangle) portion of the house. The direction of desirability shows whether it is best to increase, decrease, or hit a specific requirement. The inner arrows show the strength and the type of correlation between engineering and marketing requirements.

Relationships	
Very Positive Correlation	↑↑
Positive Correlation	↑
No Correlation	
Weak Correlation	↓
Very Weak Correlation	↓↓

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



Column #		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Customer Requirements (Explicit and Implicit) / Engineering Requirements	Direction of Desirability	Input Capacitance	Input Capacitor Voltage (LV & HV Models)	Discharge Time from Full to Safe	Number of Discharge States	Stage 2 Voltage Range (LV & HV Models)	Stage 3 Voltage Range (LV & HV Models)	Safe Indication Threshold (LV & HV Models)	Discharge System Temperature	Resistor Power Rating	Voltage Measurement Accuracy	Voltage Sampling Rate	Temperature Measurement Accuracy	Power Consumption	System Size	cost
Direction of Desirability		◇	▲	▼	◇	◇	◇	◇	▼	▲	▲	▲	▲	▼	▼	▼
Safety	▲	↓	↓↓	↑		↑	↑	↑↑	↓↓	↑↑	↑↑	↑	↑↑			↓
Ease of Use	▲		↓	↑	↓	↓	↓	↑	↓				↑	↓	↑	↓
Affordability	▲	↓	↓↓		↓	↓	↓	↓	↓	↓	↓↓	↓↓	↓	↓	↓	↑↑
Reliability	▲		↓	↓	↓	↓	↓	↓	↓↓	↑			↑			↓
Ease of Maintenance	▲		↓		↓↓	↓	↓	↓	↓	↑			↓		↑	↓
Configurability	▲	↓	↓		↑↑	↑↑	↑↑	↑		↑	↑	↑	↑	↑		↓
Deployability/Portability	▲	↓	↓↓		↓				↓						↓↓	↓
Target		1650uF +/- 20%	12V / 1200V +/- 15%	<= 30 seconds	3	8-6V / 800-600V	4-2V / 400-200V	<0.1V / <10V	<120 C	25-100W	+/- 5%	25-50Hz	+/- 10%	5-35W	<24" x 36"	<$1200

Figure 1: House of Quality

2.6 - Features and Functionality

2.6.1 - Hardware Features and Functionality

The previously defined objectives and goals dictate our system's target features and operation. The system can be broken into a few main subsystems: computing and I/O, power delivery, sensing and isolation, and staged capacitor discharge. Each group member claimed the main responsibility for one of these subsystems.

Computing includes the microcontroller and user I/O. There are three input buttons (Up, Down, and Select) on the outside of the device to allow users to set the voltages of the various discharge stages. A screen display shows the discharge-to-safe time, current voltage current temperature level, and the user settings. The screen's various settings are navigable by the previously input buttons. The microcontroller is responsible for gathering voltage and temperature data and switching the relay stages according to the user's defined set points. Included on the device are five indicator lights showing when the three discharge stages are activated, when the defined safe voltage is reached, and when the system is powered on.

The power delivery subsystem includes a connection to a 120V AC wall outlet, an external power supply to convert the AC voltage into a 24V DC source, and two regulators (3.3 and 5V) to power various electronic components.

The sensing isolation subsystem includes all the various sensors and devices that measure the data and report it to the microcontroller. This includes the main voltage sensor, the temperature sensor, and their conversion to digital signals with a dedicated ADC. The ADC feeds the microcontroller with the data gathered from the sensors. The sensor data is used to control the current discharge state by driving relays from an MCU control signal and other relay driving circuitry. Isolating the low voltage circuitry needed to sense, process, and make control decisions for the system from potential high voltage connections was also crucial for safety. This was done through a dedicated voltage divider and isolation amplifier combination.

The staged capacitor discharge subsystem includes the resistor stages activated by relays, the sequence and calculations for the discharge cycle, and how to safely contain the high voltage connections on an external chassis for isolation purposes. The various resistance values of the discharge stages were calculated based on the input capacitance, the voltage setpoints, and a desired optimal discharge speed. The customizable voltage setpoints determine the points at which the rate of discharge can safely change.

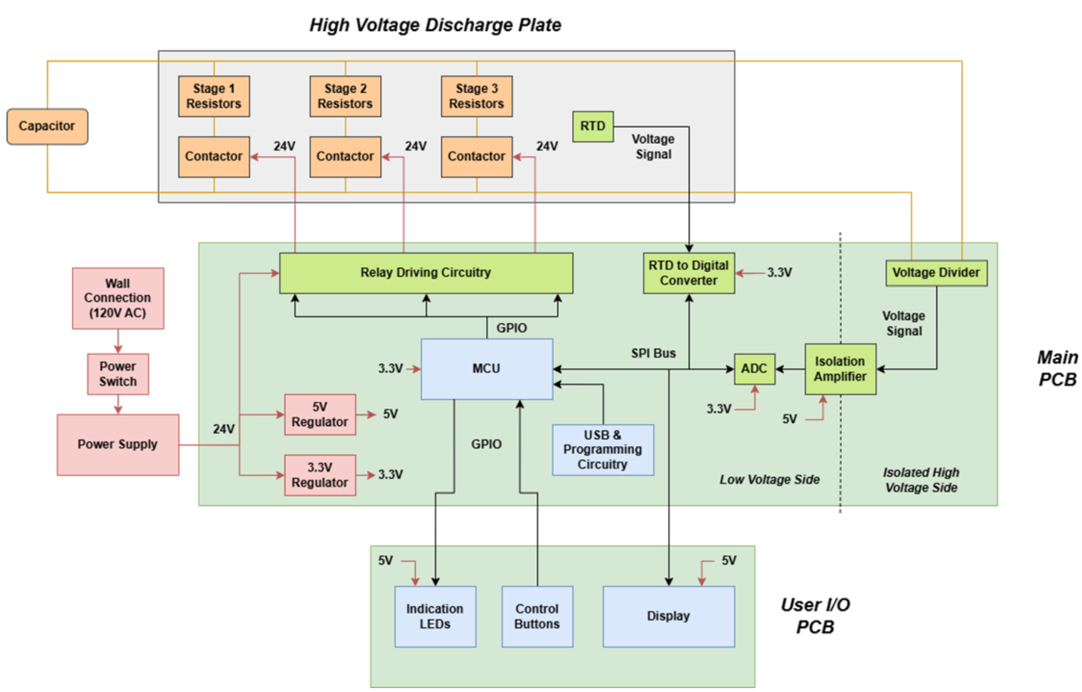


Figure 2: Hardware Diagram

2.6.2 - Software Features and Functionality

The software for this project has a few main principles provided by our sponsor, NextEra, that can be divided into the categories of configuration, control & communication. Since this code runs on a microcontroller, it will perform the initial I/O setup and other configuration before starting its main loop, which will continue until the microcontroller is reset or powered off.

2.6.2.1 Configuration

Part of the project objectives provided by NextEra include four configurable logic alarms based on voltage thresholds. After the initial input and output configuration is run, the software will accept these thresholds as input, either from a user or another source. Once these thresholds have been read into the program, they will be saved until the program is reconfigured.

2.6.2.2 Control

Once the program enters its control loop, it will wait until it receives a signal to start the staged discharge. The scaled voltage will be read through the ADC on each iteration of the control loop, which then will be used to determine the corresponding discharge stage by comparing it to the configured voltage thresholds. The program will then output the corresponding logic alarm and activate the three relays in the optimal dissipation for each given discharge stage. Finally, when the voltage has dropped below the final alarm’s threshold, the program will activate the logic high output to indicate that the capacitors have been discharged to a safe voltage.

2.6.2.3 Communication

Even before the staged discharge control loop has been started, the program will monitor the voltage through the ADC. After the alarm configuration is complete, the program then displays its state to the user. Starting before the program receives the signal to discharge, it will indicate that it is idle. Once the staged discharge sequence is started, the program will show its current state, and which alarm is activated. Finally, along with the logic high output, the program will also display an indication of safe voltage when the discharge sequence has been completed.

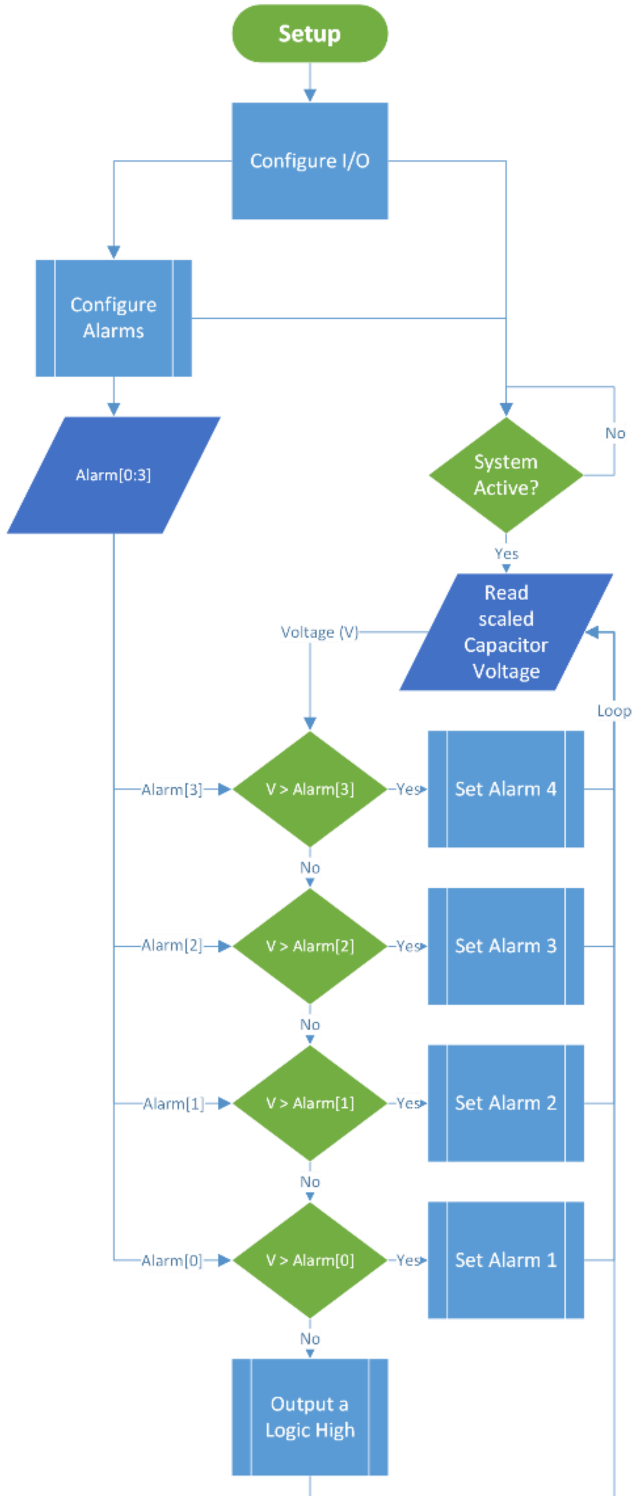


Figure 3: Initial Software Flowchart

Chapter 3: Research and Investigation

3.1 - Resistor Technology

Resistors are an especially crucial component for the scope of this project. The heart of the project depends on bleeding resistors that are dissipating energy from the capacitor over time, but resistors also form the backbone for the low voltage portion of the system as well. A resistor divider network helps monitor the voltage across the capacitor, and resistors were necessary for much of the low voltage circuitry. As a result of all these uses, it became especially important to understand different resistor technologies and select components on a use case basis. It does not make sense, for example, for a pull up resistor to be the exact same make/model as a bleeding resistor. So, to support this effort, the following technologies were researched and explored to understand their capabilities for potential use in the final system.

3.1.1 - Carbon Composition Resistors

Carbon composition is one of the oldest resistor manufacturing technologies dating back to the early 1900s. The manufacturing process involves making the entire resistor body out of a mixture of carbon particles and an insulator such as ceramic. The mixture is then held together with a binder such as resin. Since the carbon particles are conductive, the final resistance value is determined by the concentration of carbon in the final mixture. More carbon results in a higher conductivity and lower overall resistance. Once the mixture is baked, a protective coating is applied over the body, which can then also be painted over with resistor color codes. [9]

The manufacturing process of carbon composition resistors does provide some unique benefits to the final product. Because the resistive element comprises the entire body of the resistor, there is more volume to conduct current, and as a result, conduct heat. The solid body is also noninductive by nature. On the surface, this makes carbon composition resistors good for handling high pulses of energy. As will be discussed later on, however, some instability issues prevent the technology from fully taking advantage of this [10]. In addition to handling high energy pulses, the manufacturing process for these resistors makes it easy to create high resistance values in a cheap manner.

Over the years, carbon composition resistors have largely been replaced by other resistor technology types. This was mainly fueled by issues that are derived from the way they are made. Firstly, the technology does not create very tight tolerances for resistor values in general (usually around 10%). Additionally, the mixture of different materials creates instability in the resistor body. This instability causes conditions like temperature, humidity, long use, and overvoltage to alter the resistance value quite a bit. Depending on the environment, a shelf life of one year could see the resistance value change by as much as 5% [9]. Finally, different materials in the resistor body also contribute to the resistor being more noisy than other technologies [11]. Altogether, these factors made carbon composition resistors unsuitable for high precision applications and newer technologies have largely taken over most of the resistor market by offering better performance.

3.1.2 - Film Resistors

Film resistors are a broad category of resistor technology that encompasses a large portion of the through hole resistor market. They represent a step up in performance in almost every category compared to carbon composition resistors. At their core, film resistors are comprised of an insulating substrate (usually ceramic) and a conductive material that is then deposited around the substrate. This conductive material can be carbon, a metal, or a metal oxide. Once deposited, the conductive material is then cut in a helical pattern which helps control the overall resistance value. Utilizing a higher pitch for the cut results in a larger area and shorter distance in the resistor for current to flow which corresponds to a smaller resistance value. A lower pitch results in the opposite and creates higher resistance value. Once the cuts are made, a mold is typically applied over the resistor body for protection [12].

Due to a controlled and precise cutting process, film resistors are available in resistances ranging from as low as 1 ohm to as high as several megaohms. Tolerances also become tighter compared to carbon composition resistors, with typical values being 2, 5, and 10%. Of the different types of film resistors, carbon film is considered as a good general-purpose technology when high precision is not required. Metal film offers higher performance in multiple categories over carbon film for only a small price increase. These resistors generally have typical tolerances of 1% but can have a tolerance of as low as 0.1%. Additionally, their temperature coefficient is lower than carbon film and they produce less noise. All of these factors make them a much more precise resistor technology when compared to carbon film. Finally, metal oxide resistors are the best of the three when it comes to power rating, voltage rating, overload capability, and thermal performance [10]. Their noise, however, is comparable to that of a carbon film resistor and they may be less precise than metal film resistors at higher power ratings [11]. Another trait worth noting for all of these film resistors, is that they will naturally have parasitic inductance and capacitance associated with them. So, depending on the application, these effects may need to be taken into account.

3.1.3 - Thick and Thin Film

When it comes to SMD packaging, thick and thin film resistors are the dominant technology. Unlike other film resistors, the manufacturing process of thick and thin film resistors is much more planar. This involves a resistive layer of material being either sputtered (a method of vacuum deposition) or screen printed onto a ceramic base. The amount of resistive material determines the resistance value once photoetching or laser trimming is used to calibrate the resistance value. For thin film resistors, the thickness of the resistive material is typically less than one micron. Thick film resistors, as the name suggests, have much thicker resistive material, typically measuring anywhere between 1 and 100 microns. [13]

The main advantage of thin/thick film resistors would be their size. In an SMD package, these resistors can be smaller a tenth of an inch and follow very standardized sizing codes. Both also offer tight tolerance on their resistance values, but to varying degrees. Thick film resistors offer tolerances between 1% and 5% while thin film offer much tighter values between 0.01% and 1%. In addition to this, thin film resistors also have lower temperature coefficients, lower noise, and lower parasitic capacitance and inductance when compared to their thick film counterpart and also when compared to other resistor technologies in general. However, this usually comes at a higher cost as thick film resistors are typically cheaper since they are easier to make and are designed to be more general purpose oriented.

Having so many benefits within a very small package, however, does come with its downsides. Power handling in general will be less when compared to technologies like metal-oxide film and wire wound, although special packages designed to be incorporated with heatsinks to allow for higher wattage use are available. They can also be more sensitive to moisture and the potential effects of ESD. [10]

3.1.4 - Wire wound Resistors

Wire wound resistors are another technology that date back to the early 1900s. Unlike carbon composition resistors, however, wire wound resistors still see a fair amount of use today. The technology is comprised of wire with high resistivity which is wrapped around a non-conductive core. Based on a variety of variables, such as the resistivity of the wire, the size of the wire, and the length of the wrapping, the resistance value can be tuned. By using very thin wire with low resistivity, low power and low resistance can be achieved. For higher power applications, thicker wire with special coatings and insulation are used and the resistor itself can be encased in a metal-finned chassis to help with heat dissipation. [14]

Due to their simplicity, wire wound resistors can be produced accurately at low resistances for precision applications. This makes them a popular choice for fuse applications. On the other end of the spectrum, they can also exhibit the highest power ratings out of all available resistor technologies. This often comes at the cost, however, of being bulky and requiring a dedicated heat sink to utilize the full power rating. Another disadvantage that wire wound resistors have is that their construction is essentially that of a conventional inductor. This means they have higher parasitic inductance than other resistor types. Specific winding patterns, however, have been developed to minimize this effect, although these resistors still typically have the poorest frequency performance. [10] [15]

3.1.5 - Technology Comparison and Selection

The following table compares some key parameters between all the discussed resistor types:

Table 3: Comparison of Various Resistor Technologies

	Carbon Composition	**Carbon Film**	**Metal Film**	**Metal Oxide Film**	**Thick Film**	**Thin Film**	**Wirewound**
Typically Used Package	Through Hole	Through Hole	Through Hole	Through Hole	SMD	SMD	Through Hole or Chassis Mount
Typical Resistance Range	Ω to MΩ	Ω to MΩ	mΩ to MΩ	Ω to MΩ	mΩ to MΩ	mΩ to MΩ	mΩ to MΩ
Typical Tolerances	5 to 20%	2 to 10%	0.1 to 5%	0.1 to 5%	0.1 to 5%	0.01 to 5%	0.1 to 5%
Typical Temp. Coefficient	+2000 to -1400 ppm/°C	±400 to -1500 ppm/°C	±10 to ±100 ppm/°C	±200 to ±350 ppm/°C	±100 to ±400 ppm/°C	±10 to ±50 ppm/°C	-80 to 900 ppm/°C
Typical Power Ratings	1/4 to 1W	1/8 to 2 W	1/8 to 2 W	1/2 to 7 W*	1/20 to 3.5 W*	1/20 to 2/5 W	1/2 to 50W*
Relative Noise/Parasitics	Noisiest	Moderate Noise	Low Noise	Low Noise	Moderate Noise	Low Noise	Low Noise High inductance
Relative Cost	Low	Low	Moderate	Moderate	Lowest	Moderate	Highest
Typical Applications	Legacy Electronics Absorbing High Energy Pulses	General Purpose/Low Cost Electronics	Precision Analog, Audio, and Measurement	Power Surge and Overvoltage absorbtion	General Purpose SMD	High Precision SMD	High Power Dividers/Bleeders
Notes:	*Specialty products/packaging may provide higher wattage (Ex: chassis mount, package design, heatsink use, etc.)						

For the scope of this senior design project, there are two main uses for resistors: high power dissipation and integration of low voltage electronics (sensor circuits, regulator circuits, etc.). Since these uses differ drastically, the choice of resistor technology used for them should also be different. Based on the available technologies, wire wound resistors seem to be the most suitable for high power applications such as the discharge circuits bleeder resistors. They offer the highest base power ratings while also providing a good range of typical resistance value with sufficient tolerance. For low voltage applications, thick and thin film resistors seem to be best suited since they are very widely available at low costs with a variety of resistance values. They also offer great tolerance, little noise, and low TCR.

3.2 - Resistor Component Selection

In terms of wire wound resistors utilized for high power/voltage applications, a large part of the market consists of aluminum housed, chassis mounted resistors. There are, however, other unique options that don't fit that category as well. Below are some options from various market leaders followed by specific comparisons of individual products:

3.2.1 - TE Type HS Series

TE connectivity offers a wide range of passive electronics products within their portfolio. This includes high power wire wound resistors, most notably through the type HS series. This series includes power resistors that range from 5 W to 500 W, which is marketed as the largest range for a single product series on the market. The resistance value range for this series is also large, but specifics differ depending on the specified power rating. Additionally, these resistors are suitable for use in pulse and high voltage applications. This includes but is not limited to, braking and balancing resistors, electric machinery use, and, most importantly, capacitor charging and discharging. Depending on the specific power rating specified, various mounting options are available. Lower power options utilize two mounting holes, while resistors with rated power above 50 W utilize four mounting holes. Additionally, the standard terminal for these resistors is a solder lug suitable for soldering wire or securing ring terminals.

3.2.2 - Arcol HS Series

Arcol is a known quality manufacturer of power resistors based in the United Kingdom. As of 2015, they were purchased by Ohmite, another leader in resistive technology. Their HS series of power resistors has many similarities with those produced by TE connectivity. They are specifically wound to maximize high pulse capability and are marketed as having a high power to volume ratio. As a series, when compared to TE, the available power range is less, only running from 10W to 300W. The resistance range for various power ratings is still large and many of the mechanical aspects in terms of housing and terminal style is similar to TE. The only major difference mechanically is the use of six mounting holes instead of four for higher power ratings.

3.2.3 - Ohmite 270 Series

As mentioned before, Ohmite is another major player when it comes to resistive technologies. Their acquisition of Arcol added a strong aluminum chassis power resistor product line to their portfolio, but they also offer other wire wound resistor packages. A notable one is their 270 series of vitreous enamel coated wire wounds. This kind of packaging offers the benefit of not needing to be mounted specifically to a heatsink and providing a flame-resistant coating. The downside is typically taking up more space and being more costly. With that being said, the 270 series offers wattage ratings from 12 to 1000W and include a hollow core for various types of mounting hardware (through bolt, spring-type brackets, etc.). A wide range of resistances are available and the included lug terminals are suitable for soldering or bolt connection.

3.2.4 - StackPole KAL and Bournes UAL Series

Circling back to aluminum chassis mount resistors, StackPole Electronics and Bournes Incorporated also provide many resistive products of this type. In fact, their KAL and UAL product lines have many similarities between them. They both offer a much smaller range of power ratings, maxing out at 50W. Additionally, their construction/mechanical attributes are nearly identical within a smaller package compared to TE and Arcol options. Both are also marketed for good pulse handling capabilities. The only downside is that limited power ratings also limits the potential working voltage of this series, which was a crucial parameter for the high voltage applications of this project.

3.2.5 - Comparison and Selection

Of the discussed product series, the most suitable model was selected from each one in order to determine the best option for this project's application. Based on preliminary design work, one of the key component parameters was the resistor's voltage handling capabilities, which is also related to its power handling capability. Additionally, it is worth noting that the rated power for most of these resistors assumes a fairly idealized and well-designed heatsink. To avoid fully depending on heatsink design for the performance of the discharge resistors, it is more conservative to utilize the free air power rating of these resistors for design calculations. As a result, voltage capability and free air power were the most important parameters for comparison. For similar performance, cost was ultimately be the deciding factor.

Table 4: Comparison of Power Resistor Options

	TE HSC100 Series	Arcol HS100 Series	StackPole KAL Series	Bournes UAL50 Series	Ohmite 270 L50 Series
Max Rated Power	100W	100W	50W	50W	50W
Max Free Air Power	50W	30W	20W	20W	N/A
Withstand Voltage	1900V DC	1900V DC	3000 VAC	3500 VAC	1625 V DC
Tolerance	5%	5%	5%	5%	5%
Range of Values	5Ω to 100kΩ	1Ω to 70kΩ	0.05Ω to 75kΩ	0.01Ω to 250kΩ	0.38Ω to 260kΩ
Length	3.44 in	3.46 in	2.78 in	2.72 in	4 in
Cost	$17.83	$14.54	$6.44	$8.47	$24.15

Based on the comparison, the highest free air power was between the TE and Ohmite option. Since the TE option offers a higher withstand voltage for a lower price while also being about half an inch smaller, it was a better choice for this application. The Arcol HS100 series could be a good secondary option since it has the second lowest free air power with the same withstanding voltage. In summary, however, the discharge resistor selection was the TE HSC100 series.

3.3 - Relay Technology

Another key component of this project are the relays, which switch on the various stages of the discharge process. They are also one of the main isolation points between the low voltage portion of the system and the high voltage capacitor, allowing the microcontroller to dictate the discharge order while not coming into direct contact with high voltage. The following research looks at different relay technologies that are currently available in order to have a complete understanding of each one's strengths and weaknesses. From there, a reasonable selection for the projects scope can be made.

3.3.1 - Electromechanical Relays

Electromechanical relays are the oldest type of relay technology with their use dating back to the 1800s in telegraph systems. Despite their age, they still see much use today in a variety of applications such as industrial control and automotive electrical systems. In its simplest form, the key parts of an electromechanical relay consist of a coil, an armature, and a set of contacts. When current from a control signal flows through the coil on one side of the relay, a magnetic field is produced which attracts the metal armature. When the armature moves towards the coil, a set of contacts come together to connect a circuit on the opposite side of the relay. When current stops flowing through the coil and the magnetic field dissipates, a spring returns the armature to its original position and causes the contacts to break the circuit. [16]

Based on the basic construction of an electromechanical relay, alongside the 200 years that the technology has had to develop, a number of advantages become clear. Firstly, this relay type is rugged and many years of technological development have made them quite reliable. The electrical life for electromechanical relays are often in the hundreds of thousands of switching cycles, and it is not uncommon for lightly loaded relays to reach a million switching cycles before failing [17]. Additionally, electromechanical relays have become very general purpose and unique types exist for a variety of applications. These include signal relays, power relays, contactors, etc. [18] The coil-armature system in these relays also provides true galvanic isolation between the control circuit and the load circuit which is critical for high voltage applications.

There are, however, some drawbacks to such a rugged technology. The mechanical nature of this relay type does make them larger than other relay technologies. Additionally, when the contacts break the load circuit there is a possibility for arcing to occur between them. Over time, this arcing can create residue on the contact surfaces which can increase resistance in the load circuit and, if severe enough, can cause electrical failure of the relay. In fact, power limitations of these relay models typically are derived by how much arcing the contacts can handle before they weld together and fail. Even when arcing is not factor, the switching of the contacts themselves can be both physically and electrically noisy, which could affect sensitive circuitry if not considered. Moving away from the contacts on the load side, the coil on the control side can also provide some issues. Essentially acting as an inductor, the coil can add unwanted inductance to a circuit and its switching behavior can lead to transient effects. To account for these effects, driving/protective circuitry is typically required around the coil to effectively switch the relay on and off.

3.3.2 - Reed Relays

Reed relays are a newer technology when compared to electromechanical relays, with their earliest uses dating back to the 1930s Reed relays are also mechanical in nature, but their construction and properties differ enough from conventional electromechanical relays to warrant dedicated research. Rather than having a dedicated armature and contacts, reed relays utilize strips of flexible ferromagnetic metal which are hermetically in a glass tube. In the presence of a magnetic field, the metal strips are attracted towards each other and make electrical contact. In order to make such a scheme controllable, a coil of wire is wrapped around or near the glass tube, which generates the necessary magnetic field to close the contacts when current flows through it. [19]

This difference in construction for a reed relay does provide unique benefits. The most obvious one is that since the contacts are sealed off from the environment, they are less susceptible to degradation and oxidation that can come from factors such as humidity. Such protection translates to increased electrical life and thus more switching cycles before failure. The isolation of the contacts can also make reed relays able to be more easily designed to sustain high voltages as well. The tradeoff for this is that the lightness and flexibility of the contacts makes their current carrying capacity significantly less than conventional electromechanical relays. And yet, that same lightness and flexibility also provides generally higher switching speeds alongside less switching noise. [19]

Due to the mechanical nature of the reed relay, some disadvantages that are shared with general electromechanical relays remain and may even be amplified. Arcing, for example, is still a phenomenon that occurs and can be more of issue due to the delicate nature of the contacts. In fact, most of the power ratings for such reed relays will be limited by contact arcing and risk of the contacts welding together when they connect the load. Additionally, the main driver for the relay is still a magnetic coil that will act as an inductor on the control side circuit, bringing unwanted transients. Driving/protection circuitry would still be required to adequately control the coil voltage.

3.3.3 - Solid State Relays

Solid state relays represent a large advancement in relay technology and offer a completely different way of controlled switching when compared to their mechanical counterparts. Solid state relays rely completely on semiconductor devices for switching and isolation. While specific details and schemes may differ, in general solid-state relays utilize an LED on its control side. When the LED is biased by a control signal, photons are detected on the other side of the relay by a photodiode. The photodiode then activates an electric switch, typically some kind of MOSFET, which closes the connection for the load circuit to operate. So, rather than the magnetic field providing a medium for galvanic isolation between the control and load side, in solid state relays light is what helps provide the galvanic isolation [16].

Utilizing semiconductor devices in lieu of mechanical parts does provide solid state relays with a number of advantages. No mechanical contacts results in zero arcing and no forms of mechanical failure, which translates to longer operational life. The switching speed for semiconductor devices is also much faster than any mechanical switching and provides very little noise. The lack of a inductive coil on the control side also means that driving/protection circuitry is not needed. It may even be possible to drive the control signal directly from a microcontroller pine. Taking advantage of current semiconductor manufacturing techniques also allows for solid state relays to come in very small packages [20].

Some unique downsides of using semiconductor devices are also present. One downside that was not present in prior relay technologies has to do with leakage current. Even when the load side of the relay is in its off state, leakage current will still flow through the MOSFET and into the rest of the load circuit. Despite it being in the order of microamps, this does mean that load circuit isn't as fully disconnected as it is with electromechanical relays. Additionally, semiconductor devices can be more susceptible to being damaged from transients and overvoltage in addition to potentially being sensitive to noise. Lastly, most solid-state relays are made for low power applications, but there are a number of AC high-power options on the market that utilize silicon carbide MOSFETS/IGBTS in order to safely switch high voltages [20].

3.3.4 - Contactors

At this point, it is worth noting that another category of electromechanical relays exists when operating voltages and currents get high enough. These relays are known as contactors, and they are essentially electromechanical relays that are built to be larger, more robust, and better equipped to handle the arcing that can occur when switching high power loads. Where the line is drawn to differentiate a relay from a contactor can differ depending on the source, but generally contactors are defined as having a carry current of more than 10 amps.

As a result of their construction, contactors are often designed to be mounted onto a chassis or electrical panel as opposed to integrating directly onto a PCB, although some rare PCB options do exist. This makes them more expensive when compared to other relay options. The increased size can also require a greater coil current to drive the switching action for the same coil voltage when compared to smaller relays. Despite all of these differences and potential downsides, when its comes to effectively switching under high power conditions, contactors are the industry standard.

3.3.5 - Technology Comparison and Selection

The following table compares some key parameters between all the discussed relay types:

Table 5: Comparison of Various Relay Technologies

	Electromechanical	**Reed**	**Solid State**	**Contactors**
Typical Switching Voltage	V to kV	V to kV	V to kV	KV
Typical Load Current	mA to 30A	mA to 3A	mA	A
Typical Switching Speed	ms	ms	μs to ms	ms
Switching Characterstics	Noise Bouncing Arcing	Less Noise Less Bouncing Arcing	Off State Leakage Current	More Noise Bouncing Possible Arc Supression
Typical On Resistance	mΩ	mΩ	mΩ to Ω	mΩ
Typical Lifetime (In Switching Cycles)	10^4 to 10^7	10^6 to 10^7	10^7 to 10^9	~10^6
Relative Cost	Low to Moderate	Moderate	Moderate to High	High

For this senior design project, the discharge system is seeing high voltage (1200V) but the current coming from the capacitor is not expected to exceed half an amp. Despite this much lower current, the overall switching power is still be very high. Switching 1200V at even 0.1A results in a switching power of 120W, which can bring heavy arcing at the relay contacts. Most standard electromechanical and reed relays aren't rated for this high of switching power, and those that will see a substantially reduced lifetime by operating near their maximum capabilities. Higher power solid state relays are typically rated for AC voltages, and those designed for high DC voltages are typically more expensive than equivalent contactors. As a result, contactors were chosen as the relay technology for this project, even if most of the options on the market may be over required specifications.

3.4 - Relay Component Selection

Navigating the contactor market for this project did prove to be challenging. As stated before, many options on the market have far higher capabilities than what are needed for this project. As a result of that, the cost also increases. Some options, however, were found that were not extremely unreasonable when it came to cost versus performance.

3.4.1 - TE ECP40B Series

TE connectivity offers a contactor option that is designed for use in 1500V DC systems. These include applications such as EV charging, battery storage, and solar inverter systems. Like most the contactors that will be discussed, its 40A current rating is much higher than this project's system would ever need, but it is a lower cost option at $66. In terms of packaging, this contactor is chassis mounted and utilizes M3 screw holes for the main contacts. The coil wires are a fixed length, and would likely need some form of extension for use in this project. Additionally, both 12 and 24V coil voltages are available.

3.4.2 - Sensata-Gigavac P125 Series

Sensata-Gigavac provides a 30A contactor option that is also utilized in charging and solar applications. The reduced current, however, also brings a reduced operating voltage of 1200V. While this does match the operating voltage of this project's system, it does not leave any potential margin. The cost also ends up being higher for this option at 91$. This is likely due to the products packaging. Compared to the TE option, this product is smaller and designed to be incorporated on a larger PCB as opposed to a separate chassis. This PCB mounting comes in the form of M4 and M3 studs for the power and coil contacts respectively. Integrating a product with these terminals onto a PCB for this senior design project may prove challenging.

3.4.3 - Sensata-Gigavac P115 Series

Another option from Sensata-Gigavac provides a more traditional chassis mount design. In terms of performance, the P115 matches or outdoes the other options in many categories. The max switching voltage is 1500V and the current carrying capacity is 50A. Being part of the same minitactor series as the P125, it also retains a smaller packaging despite being chassis mounted. Unlike the TE option, both the main contacts and the coil contacts are stud terminals of either M3 or M4 sizing. Coil options include both 12 and 24V.

Table 6: Comparison of Contactor Options

	TE ECP40B	Sensata-Gigavac P125BDA	Sensata-Gigavac P115CDA
Max Contact Voltage	1500 V	1200V	1500 V
Max Carry Current	40 A	30 A	50A
Max Operate Time	30 ms	25 ms	25 ms
Max Release Time	10 ms	8 ms	8 ms
Nominal Coil Voltage	24 V	24 V	24 V
Nominal Coil Current	125 mA	85 mA	85 mA
Coil Power	3 W	2 W	2 W
Coil Resistance	192Ω	280Ω	280Ω
Mechanical Life	500,000 cycles	1,000,000 cycles	1,000,000 cycles
Cost	$66.03	$91.00	$108.36

3.4.4 - Comparison and Selection

In terms of the P125, both the ECP40 and the P115 provide better contact voltage performance with margin for the expected voltage levels of this project. When comparing just the ECP40 and the P115, it is clear that the P115 has slightly better operate and release times and requires one less watt of power to operate the coil. The mechanical life is also double that of the ECP40. The real question, however, is whether this better performance really justifies the cost. In normal circumstances, probably not, but part availability is also worth considering. In this regard, the P115 is much more widely available and should not experience potential stocking issues, so it was the contactor selected for this project.

3.5 - Wire Technology

As discussed previously, the high voltage nature of this project requires carefully designed isolation and the use of chassis mounted components to handle the expected power dissipation. As a result, the use of suitable wire is required to connect the various resistors and relays, along with interfacing with the external capacitor and control PCB. The following research seeks to establish a better understanding of wire technology, specifically when it comes to material, current carrying capacity, and insulation. From this information, a more informed decision can be made as to not over or under spec the selection of wire for the project.

3.5.1 - Conductor Material

The backbone of any wire is the material of the conductor itself. The conductor must excel in three key parameters: conductivity, malleability, and cost. Today, copper is the baseline for conductor performance in these three categories, and alternatives to copper are directly compared to it for evaluating their own performance. Some common alternatives to bare copper that were further studied include tinned copper, and aluminum.

Starting with bare annealed copper, it has a conductivity of 5.8×10^7 siemens per meter at 20 degrees Celsius [21]. As implied before, this conductivity is used as a baseline for comparing the conductivities of other metals. This is done through the International Annealed Copper Standard, which gives this conductivity a value of 100%, and gives all other metals' conductivities a value relative to it. There are few materials with higher conductivity to copper, and those that do typically have a much higher cost. Additionally, bare copper is very workable, available, and has a high thermal conductivity as well, which prevents overheating.

Tinned copper has one added feature to traditional copper. Rather than the copper core of the wire being left bare, it is covered in a thin layer tin for protection. The tin prevents potential oxidation of the copper core, which can decrease electrical performance. Additionally, this protection can make the wire have better solderability since the reduction of copper oxides allows for better heating of the material with a soldering iron and the tin enhances solder flow and adhesion [22]. Surprisingly, the tin coating also has a very negligible effect on overall conductivity and final wire pricing.

Moving away from copper-based technologies, aluminum is the only other metal that is used in the same amounts as copper. This is mainly due to cost and weight. Aluminum is significantly cheaper than copper and is much lighter. This becomes evident in their cost per kilogram, with copper costing between $8-10/kg and aluminum only costing between $2-3/kg. An important caveat, however, is that aluminum only has about 61% the conductivity of aluminum [23]. Practically this implies that for the same load carrying capacity, you would need an aluminum conductor that's nearly double the size of its copper counterpart. Additionally, aluminum can be harder to solder, and can be more prone to corrosion compared to copper. So, the cost and weight savings become very beneficial when considering large infrastructure projects such as those undertaken by electric utilities.

3.5.2 - Effects of Insulation and Wire Guage on Ampacity and Voltage Rating

A wires ampacity is defined as the conductor's current carrying limit. The main limiting factor when it comes to a wires ampacity is heat. If too much current runs through an improperly rated wire, then an excess of heat is generated which will end up burning the wire. This heat is a manifestation of the power dissipated in the conductor, which is equal to I^2R, where I is the current and R is the resistance, according to Ohm's Law. Additionally, the resistance of the wire can be expressed as a function of conductivity via the equation $\frac{L}{\sigma A}$, where L is the length of the conductor, A is its cross-sectional area, and sigma is its conductivity. Based on this logic, there are really two ways to increase a conductors current carrying capacity for a fixed current: Either decrease the resistance to minimize power dissipation, or improve the insulation to better handle the subsequent heat. First, various common insulation technologies will be discussed with their effects on temperature and voltage ratings. Then, wire gauges will be briefly discussed along with ampacity charts.

Wire insulation typically falls into one of two categories of polymer plastics: thermoplastics and thermosets. Thermosets are materials that can be molded and strengthened when heated, but once reheated they do not melt, rather they tend to char, and cannot be remolded. Thermoplastics, on the other hand, can be remolded, will melt when exposed to heat, and remain quite flexible after setting [24]. The most popular thermoset insulation is cross-linked polyethylene (XLPE), while the most popular thermoplastic insulation is polyvinyl chloride (PVC). [25] Other options include silicone rubber insulation (a thermoset) and polytetrafluoroethylene (PTFE) (a thermoplastic). The key parameters when it comes to comparing these materials are their dielectric strength, and maximum operating temperatures. Dielectric strength directly determine the voltage rating of the wire and is measured per millimeter of insulation. The insulation temperature capability also effects ampacity as will be discussed soon. Typically, thermoset type insulation will have better temperature performance and can be made to be more flame retardant since it doesn't melt. This is more suitable for cases of failure in high voltage applications. Dielectric strength can be more variable across specific insulation types, with options in both thermosets and thermoplastics having suitable performance for high voltages [26].

Moving away from insulation, the gauge of a wire is also an important factor. A wire's gauge is nothing more than a representation of its diameter. Gauges that are associated with a larger diameter have more cross-sectional area, which decreases the overall resistance of a wire. This can then increase ampacity. Combining this with the temperature rating of a wire that is based on its insulation can be used to derive the ampacity of the wire. In fact, multiple sources of ampacity tables are available for reference to make design decisions based on a wires gauge and temperature rating. [27]

3.5.3 - Technology Comparison and Selection

The following table summarizes and compares key parameters between wire conductors and insulation types:

Table 7: Conductor Technology Comparison

	Bare Copper	Tinned Copper	Aluminum
IASC Conductivity	100%	100%	62%
Typical Operating Temperature	150 C	150 C	90 C
Relative Corrosion Resistance	Medium	High	Low without external compound
Relative Solderability	Medium	High	Low
Relative Cost	Low	Low	Lowest

Table 8: Insulation Technology Comparison

	PVC	XLPE	PTFE	Silicone
Material Type	Thermoplastic	Thermoset	Thermoplastic	Thermoset
Typical Dielectric Strength	~15kV/mm	~20kV/mm	~50kV/mm	~20kV/mm
Relative Flexibility	Low to Medium	Medium	High	High
Typical Temperature Ranges	-55 to 105 C	-40 to 130 C	-70 to 260 C	-65 to 150 C
Relative Cost	Low	Medium	High	Medium

In terms of conductor material, all of the specified conductors are low cost, so pure performance becomes the deciding factor. Tinned copper retains all of the benefits of bare copper plus includes additional corrosion resistance and makes any potential soldering easier. As a result, tinned copper was selected as the conductor material.

In terms of insulation, there needs to be a balance between dielectric strength and cost. Additionally, the wire itself should be fairly flexible in order to make potential chassis wiring and routing easier. For the majority of the wire market when it comes to 1200V or higher ratings, XLPE or Silicone Rubber is utilized because they strike a balance between these requirements. For this project, silicone rubber insulation was selected due to its better flexibility and temperature performance for roughly the same cost as XLPE.

3.6 - Wire Selection

In terms of wire options from different manufacturers, once the conductor, insulation, and wire gauge are all selected, their properties are all essentially identical. The only difference is the rated voltage, but all three options are above 1200V needed for this project. So, the selection will essentially come down purely to cost.

Table 9: Comparison of Wire Options

	CNC Tech Wire	Rowe Lead Wire	McMaster-Carr Wire
Insulation	Silicone Rubber	Silicone Rubber	Silicone Rubber
Conductor	Tinned Copper	Tinned Copper	Tinned Copper
Gauge	14 AWG	14 AWG	14 AWG
Rated Voltage	3kV	5kV	10kV
Rated Temperature	150 C	150 C	150 C
Estimated Ampacity	~ 9 A	~ 9 A	~ 9 A
Cost Per Foot	$0.30	$0.82	$5.64
Minimum Required Feet to Purchase	500	25	1

When considering cost for wire, an important factor besides the cost per foot is the minimum amount of feet required to be purchased at once from the manufacturer. Since this project is not expected to utilize large wire lengths, the Rowe Lead Wire ends up being the most economical choice for the application. As a result, it was selected as the wire for this project.

3.7 - Voltage Sensing Technology

Voltage sensing/measurement is what allows a microcontroller or other computing chip to control a system. Some microcontrollers have voltage measurement capabilities built in, but some may not or might be lacking in terms of sampling rate, accuracy, or voltage range. To account for this, one can select dedicated voltage measurement ICs or systems that help translate the analog signal into a readable signal by the MCU. In this section we review and contrast a variety of voltage sensing and supporting technologies to determine what would be the best fit for our system.

Our system needs high speed, low-latency, and accurate voltage measuring capability to operate effectively. The capacitor discharge tool switches between discharge resistor stages and sends logic outputs depending on the active voltage reading. One of our stretch goals is to also track the voltage discharge curve and plot it after the cycle is complete. To achieve these levels of operation, we need our voltage measurement system to meet a few criteria. It must be able to read the voltage level of our capacitor, ranging from 1200-0 V with an accuracy of ± 5 %. It needs to be sampled at a rate of at least 25 Hz. It needs to be compatible with voltage isolation procedures to adhere to safety principles for this project.

3.7.1 - Input Scaling and Networks

The capacitor/input voltage we are trying to measure is very high, ranging from 1200-0 V. This is beyond the range supported by typical voltage measurement ICs. We can use scaling networks on the input to be able to reduce the voltage down and measure it with traditional voltage measurement ICs.

For DC or very slow time varying signals, we can use a simple resistor voltage divider with the input to our voltage measurement IC connected across the lower value resistor. It is important to note the tradeoff between high versus low value resistors for this. Low value resistors will draw excess current and give off excess heat, while high value resistors can be noisy and throw off a voltage measurement [28]. Also, when attaching a voltage measurement IC to the lower resistor in a network, the input impedance/resistance of the IC can throw off the voltage divider ratio. The effect is minimal if the input impedance of the measurement IC is much larger than the lower resistor. If the IC does not have a high input impedance, a voltage follower circuit can be used to copy the voltage seen by the lower resistor to the measurement IC without loading that portion of the circuit [29].

For AC or fast-moving transient portions of a circuit, a capacitor voltage divider network can be used at the input of a measurement IC. Sometimes capacitor and resistor divider networks are used together to divide both the AC and DC portions of signals together for measurement. Similar concerns show up here. The specific frequency or transient speed you can measure will be determined by the size of your capacitors.

Special resistors are needed for our resistor voltage divider network. Inside this voltage divider chain, the individual voltages across the resistors may be very high. Some resistor technologies are prone to varying resistances based on applied voltage. This is characterized by the VCR (voltage coefficient of resistance) of the specific resistors [30]. The resistors should also have a matching TCR (temperature coefficient of resistance). This means that their resistance changes the same given the same temperature change [31]. Resistors can also come in pre-packaged network ICs, which are thermally bonded to help keep their resistance ratio stable. However, these packages are often not rated for HV.

In addition to the voltage divider, we can add additional input-side components to our measurement ICs to increase performance. Often, TVS (transient voltage suppression) diodes are added to the input lines to prevent high voltage transients or spikes from damaging or overloading a measurement IC [32]. These can clamp the input lines both above and below certain set voltages.

Some voltage measurement ICs use internal resistor and capacitor divider networks. These are constantly switching and cause a dynamic complex input impedance to be seen. To account for this, one can use a voltage follower circuit or series resistor and parallel capacitor at the input.

3.7.2 - Comparators

Comparators are logic level devices that compare an analog input to a reference and then output high or low depending on if the analog input is above or below the reference. You can combine two comparators together to make a window comparator, a device that can check if an input is within a set voltage range. Comparators are very fast and reliable. However, they are not useful for measuring voltages. They are useful for determining if voltages are above, below, or within a certain range.

Comparators can be fixed with a given voltage reference and specific values of resistors, but there are a variety of techniques that can be used to make a variable voltage comparator. The voltage reference pin can be the output from a DAC. You can also use digital potentiometers to adjust the resistor ratio values.

While comparators are not useful for voltage measurements, they can serve as a backup or safety measurement. A system can implement both an ADC and a comparator for voltage measurements. When trying to determine if the system is in a safe condition, the ADC and comparator’s voltage can be read. If both don’t show safe, the system can show warning. This could make for a good, easy to integrate solution to having a backup for safe voltage measurement.

3.7.3 - Voltage to Frequency and Voltage to Time Converters

There are a variety of voltage measurement tools that read an analog voltage level and output a frequency/time varied digital signal. There are three main kinds of conversion. The first is outputting a single pulse train with frequency of the pulses proportional to the voltage input. The second is outputting an extended/longer period pulse proportional to the voltage input. The third is adjusting the duty cycle of a fixed frequency output proportional to the voltage input. [33]

The benefit of these converters are their isolation requirements and their cost/compatibility with existing hardware. These converters only use a single digital line output. That means only a single optocoupler is needed for each voltage measurement to be properly isolated from the LV portion of the board. These types of ICs are also often cheaper/simpler than full ADC ICs. The conversion of the digital pulses into a voltage reading can be done by most microcontrollers.

3.7.4 - ADC Architectures

A standard way of measuring voltage level is by using an ADC IC. These take in an analog level and convert the output to a bitstream or digitally encoded piece of data. There are many kinds of ADC IC architectures, each having their own benefits and drawbacks.

The most basic ADC architecture is the successive approximation register (SAR) ADC. It uses a resistor or capacitor divider internally and a binary search against a reference voltage to get the voltage input equivalent. They usually have low latency. They can have a complicated input impedance due to the sample and hold nature and the capacitive divider, so the data sheet needs to be consulted for input circuitry. These usually have resolutions on the order of 12-18 bits and are in the kilosamples per second range.

Another common ADC architecture is the delta-sigma converter. This oversamples the voltage input. It then uses a low pass filter to cancel out the noise and a decimator to convert into a readable digital output. It then takes this average and outputs it as a digital signal into your controller. These converters have average sampling rate and high resolution. However, the decimation filter introduces a latency in the signal measurement.

The integrating ADC switches an integrating op amp between the voltage input and a known positive and/or negative reference voltage. The run-up time and the run-down time of the integrator are proportional to the input voltage. A comparator device detects the zero-crossing line of the integrating op amp, and a timer measures the run-down time. These times together allow you to find the voltage input. This architecture has good absolute accuracy, but they do have low sampling rates.

Pipeline ADCs have very high sampling rates at the expense of resolution. These perform the analog to digital conversion in stages. Each stage uses a tiny DAC to generate an amount to subtract from the input [34]. The difference is passed onto the next stage where this process repeats until the sum of the DACs equals the input voltage. These ADCs have a longer latency between the input and the measurement. They are also more complicated. Their benefit is in their very high sampling rate.

3.7.5 - Voltage Sensing Technology Comparison and Selection

Knowing the above, we compared the comparators, voltage-to-frequency/time, SAR ADC, and delta-sigma ADC technologies together to determine if there was a best fit for our situation Below is a table comparing the technologies.

Table 10: Voltage Sensing Technology Comparison

Technology	Resolution	Sampling Rate	Latency	Setup Overhead	Cost
Comparator	N/A (or very low)	N/A (very fast)	Very low	Low (op amp setup)	Low
Voltage-to-frequency/time	10-14 bits	10-1000 sps	Low-medium	Medium (IC + MCU timer + filter)	Medium
SAR ADC	10-16 bits	1-1000 ksps	Low	Low (single IC /in MCU)	Very Low
Delta-Sigma ADC	16-24 bits	1-100 ksps	Medium-high	Low-Medium (internal clock vs MCU conversion)	Low

Based on the comparison we selected the Delta-Sigma ADC. This choice best matches our latency, sampling rate, and accuracy requirements while also keeping the design simple and the board power low. The Delta-Sigma ADC can also oversample and we can use code to average the oversampling to stabilize the voltage level and get a more accurate reading.

3.8 - Voltage Sensing Component Selection

To handle the conversion of an analog voltage level into a digital signal that our microcontroller can process and act on, we need an appropriately specified analog-to-digital converter component. The key requirements that will help guide this decision is the resolution requirement, the sampling rate, and the cost/complexity of integrating the component into our system.

The capacitors we will be discharging are rated for 1200V. To have room for safety and accuracy at high voltage, we will be designing our system to be able to read up to 1500V. After our scaling system and isolation barrier, we end up with a voltage range of 0 to 3.3V that corresponds to an input range of -1500 to 1500V. To determine the minimum step size or distinguishable voltage level of our system, we take our total input voltage range, 3000V, and divide it by the number of levels of our ADC, 2^n. This means that for a 12-bit ADC and our 3000V range, we have a 732mV step size. However, we can often assume that there is roughly 3 bits of LSB noise on our ADCs. This means that a 12-bit ADC has a conservative resolution of 9 bits. This can also be resolved by oversampling. [35]

The capacitor is to be discharged within 30 seconds. The faster we discharge it, the faster the energy is dissipated, the hotter our components would get, and the more dangerous our system would be. To solve this, we aim to be within the 30 second timeline, but not much faster. The active voltage level serves as an indication of charge in the capacitor and determines when to switch to the various resistor discharge stages. Based on this fact, we do not need to sample very fast. A sampling rate in the range of 25 to 50Hz suits our design. As mentioned in the previous paragraph, oversampling can help counter the effects of noise on the ADC measurement. The approximate rule states that every 4x increase in sampling rate, you gain an extra bit of effective resolution. If we assume 3 bits of noise, this means we need to sample at 4^3 = 64x our necessary sampling frequency. For sampling frequencies of 25 to 50Hz, this means sampling at rates of 1600 to 3200Hz. [36]

Regarding the cost and implementation complexity, this corresponds to the analog and digital setup of the component. ADC ICs may require or benefit from having external voltage references, but this involves needing to select an external voltage reference, setting up the necessary supporting circuitry, and doing low noise PCB layout around the reference and ADC. Discrete ADCs may also use different communication protocols. I2C may be easier to integrate as opposed to a higher frequency or more wire SPI layout or setup. On the digital side of things, you have the complexity of communicating over whatever digital communication protocol your discrete ADC uses or interacting with an integrated ADC and potentially setting up manual oversampling for either case.

3.8.1 - AD7606C-16BSTZ

The ADC7606 is a 16-bit DAS (data acquisition system). The data acquisition system naming convention just refers to how the chip has a more complicated front end. It integrates input buffers, programmable amplifiers, and an anti-aliasing filter on the front end as well as having its built in ADCs. It runs off a single 5 V supply and has a max throughput of 1 MSPS while all eight channels are active. It accepts a wide range of inputs in 5 V, 10 V, and 12.5 V modes of bipolar and unipolar types (bipolar just means -12.5 V to 12.5 V and unipolar is only 0 to 12.5 V). It uses an internal 2.5 V precision reference for its measurements. It also has capability for bipolar differential measurements. It uses SPI to communicate with your microcontroller or system. It comes in a 64 pin LQFP package. It has nice features but is overkill for our project, adding complexity in terms of physical construction (soldering) and software setup of the channels.

3.8.2 - MCP3008-I/P

The MCP3008 is a low power 10-bit ADC with multiplexed input channels which can be configured as single ended inputs or pseudo-differential pairs. The reason for the "pseudo-differential" pair is because while this chip can do a differential measurement, the negative input needs to stay very close to 0V (+/- 100 mV). It uses a single 2.7 to 5.5 V supply, working with both common 3.3 V and 5 V supplies. It supports sampling rates up to 200 ksps. The IC has an external voltage reference pin meant for an external reference. This can be tied to the supply line or any reference with a voltage less than the Vdd supply pin. The IC is available in both 16 pin PDIP and SOIC packages. It uses SPI to communicate with the microcontroller. This is a simpler external IC, but requires an external reference, only has 10 bits of resolution, and adds complexity without extra performance.

3.8.3 - ADC128S102CIMT/NOPB

The ADC128S102 is an eight channel 12-bit ADC that supports sampling rates from 500 ksps to 1 MSPS. It has an internal track-and-hold. This is a system that captures an analog voltage level and holds it while the analog to digital conversion process takes place, resulting in lower noise and better conversions. The chip has separate digital and analog supply pins. The analog supply pin also acts as the reference. However, the very low power draw makes it such that a precision reference can be connected directly to the analog supply pin. The IC communicates over SPI. It comes in a 16 pin TSSOP package. It does offer more resolution than the MCP3008 and is less complicated than the ADC7606, but still requires an external reference, extra board design, and SPI integration.

3.8.4 - ESP32 Built in ADC

The ESP32 has two integrated 12-bit SAR ADCs. These can be driven by the RTC controller or main digital controller. The RTC controller is used for low power modes, and not what we will be using for our purposes. The ESP32 supports accuracy of up to 2 MSPS when using the main controller. It also should be noted it has some differential and integral non-linearity. To account for these, we can apply oversampling and look-up-table calibrations. Because of the ADCs integration into the MCU, it makes it the easiest by far in terms of setup, integration, and physical usage in our project, however the accuracy (being only 12 bit and highly nonlinear) is lacking.

3.8.5 - ADS1120IPWR

The ADS1120 is a 16-bit, delta-sigma ADC with four input channels. These input channels can be configured as 4 individual or 2 differential inputs. It supports conversion rates up to 2 ksps. It also includes an internal voltage reference, so an external one is not needed. It has internal amplifier gain it can apply from 1 to 128 V/V. The data is output over SPI operating on a 3.3V or 5V logic level based on the input. The high bit count and ability to measure a differential voltage directly make it able to integrate directly with our isolation IC, not requiring any extra circuitry.

3.8.6 - Summary and Selection

Overall, the ADCs compared each have their own tradeoffs between performance and integration complexity. The ADC7606 had very high performance, but also many unnecessary features and package complexity, making integration difficult. The ESP32 internal ADC would be by far the easiest to integrate, but it was lacking in accuracy and precision. After evaluating our choices, we decided to select the ADS1120. It's 16-bit resolution calculate to give us plenty of headroom, even accounting for noise in the measurement. Its sampling rate allows us to oversample for a cleaner result. It has low integration complexity featuring a built in voltage reference and differential measurement capability. It also integrates over SPI into our existing communication bus.

Table 11: Voltage Sensing Component Comparison

Device	Resolution	Sampling Rate	Integration Complexity
ADC7606	16-bit	1 MSPS	High
MCP3008	10-bit	200 ksps	Medium
ADC128S102	12-bit	500 ksps – 1 MSPS	Medium
ESP32 Internal ADC	12-bit	2 MSPS	Very Low
ADS1120IPWR	16-bit	2 ksps	Medium

3.9 - Temperature Sensing Technology

Temperature sensing is what allows our microcontroller to read the current state and control the system. Some microcontrollers do have temperature sensing built in that can measure the temperature of the individual IC or PCB. This only measures local temperatures to the MCU. To measure the temperature of a remote system or location, we can select a remote temperature sensor that communicates the information to our MCU. In this section, we will be going over various types of remote temperature sensing technologies, how they work, and which one would work best for our application.

Our system needs low-latency and accurate temperature measurement capability to operate effectively. The capacitor discharge tool switches on/off resistor stages, dissipating the energy stored in the capacitor as heat in the resistors. The resistors are power resistors meant for high energy throughput. They were also sized such that the peak wattage in them stays below their continuous wattage rating. These aluminum cased resistors will sit on top of an aluminum plate, thermally bonded to the plate, to add thermal mass and dissipate extra heat. One of our goals in this project is to discharge the capacitor safely. If there is a situation where a discharge event creates a very high temperature, this can melt/deform plastics and melt the insulation on wires creating shorts in the system. This could lead to rapid discharges and unsafe situations for the operators of the tool. To ensure that the system stays below a certain temperature, we need to first read the temperature and then if the temperature increases too much, open the contactors to stop the flow of current. To be able to do this effectively, we need to be able to read the temperature within the range of 0-150 degrees Celsius with a +/- 5% accuracy tolerance. The poling rate should be as fast as possible to ensure that the system can be shut off as quickly as possible. However, the thermal resistance of the plate and the resistors housing and the connection to the thermal probe means that our temperature measurement may lag or change slowly with the current discharge state.

RTDs (Resistance Temperature Detectors) are precision resistors that have a positive temperature coefficient (their resistance increases as temperature increases). RTDs are made of components with repeatable temperature and resistance profiles. The RTD element is fed a known current value. The voltage across the RTD is then measured. Ohms law is then used to find the resistance of the probe, and from that the temperature is calculated. Lead wire resistance can be a source of error in the RTD probe measurement. To account for this, RTD probes can be found in 3 wire and 4 wire packages. These additional wires feed the excitation current through one pair and use the other wire(s) to read the voltage, this way the resistance of the wires is ignored. An important thing to note with RTDs is that you are feeding a known current through a resistor. There will be some self-heating, which can throw off very cold or sensitive measurements. Their main benefits lie in their accuracy and linearity. The only downsides would be their cost and additional circuitry needed to give the excitation current and read the voltage. [37]

The NTC (Negative Temperature Coefficient) thermistor is a semiconductor device whose resistance decreases as temperature increases. These sensors are also given an excitation. Their voltage is measured in an external voltage division circuit. The NTCs are highly nonlinear. There is no fixed change in resistance based on a fixed change in temperature. Instead, the voltage across the NTC is taken into software and compared against a curve or lookup table to find the appropriate temperature. They are simpler to implement hardware wise, but require special programming to be able to decode the temperatures. They also offer smaller temperature sensing ranges than the other options. [38]

The thermocouple is a joint of two different metals. This junction will have a voltage across it based on the current temperature. There are various types and classes of thermocouple. The thermocouple is very robust, usually used in hard applications with rough environments and high temperatures. Thermocouples are also nonlinear. These devices rely on polynomial functions or lookup tables to determine their temperatures based on the measured voltages.

The analog ICs are built in units that take in a voltage level and usually have a BJT with variable gain based on temperature. These units will have 3 wires, one for input, one for sense, and one for ground. These usually have good linearity, but not a very high temperature measurement range.

The digital ICs use the same sensing technology as analog ICs, but they also have integrated ADCs and linearization/calibration tables internally that help the output be more accurate. These can have 3 wires for power, ground, and data or 2 wires if they have parasitic power based on the data signal. These are simpler to use than the analog sensors but can cost more. They also have a more limited temperature measurement range.

The last temperature measurement technique is the infrared non-contact type. This is the technology behind IR sensors and guns that record temperatures of objects without direct contact.

They rely on reading the emissive radiation of a source and then calculating the temperature of the object. These usually have a higher temperature measurement range, but can have various effects based on the material they are measuring. Shiny objects such as metals reflect infrared and cannot be measured reliably unless you paint it or cover portions of the surface. [39]

3.9.1 - Temperature Sensing Technology Comparison and Selection

We can now summarize the technologies listed and explained above in a table. The table compares the key figures of merit of a temperature sensor: sensing range, accuracy, linearity, cost, and integration effort on our end. As we said before, the sensor needs to be able to support the range of temperatures we expect on the discharge heatsink. It also needs to be accurate. The linearity is the change in how much a sensor's output changes based on how much its input changes. A linear temperature sensor may always output an additional 10mV for every 5 degrees C it reads. A nonlinear sensor might only output 5mV for a 5 degrees C change when it reaches 150 C. Linearity makes processing a temperature sensor's information easier. Cost is also a prohibiting factor. While we are not absolutely maximizing cost, picking technologies/components for quality instead, we still try to pick the most reasonable option. The integration effort summarizes how complex it would be to use the specific sensor.

Table 12: Temperature Sensing Technology Comparison

Technology	Sensing Range	Accuracy	Linearity	Cost	Integration Effort
RTD	-50 to 250 C	+/- 0.3 to 0.8 C	High	High	Medium
NTC	-40 to 125 C	+/- 0.5 to 2 C	Nonlinear	Low	Low
Thermocouple	0 to 800 C	+/- 1.1 to 2.2 C	Nonlinear	Medium	High
Analog IC	-40 to 125C	+/- 0.5 to 2 C	Medium	Low	Very Low
Digital IC	-40 to 125C	+/- 0.5 C	Medium	Low	Low
IR non-contact	-70 to 350 C	+/- 0.5 C	Nonlinear	High	High

Based on the above table, the RTD wins out in terms of range, accuracy, and linearity, with its drawbacks coming from the cost and integration effort. The RTD also is unique compared to the analog/digital ICs in that it provides pre-made thermal probes, some of which come with holes for easier mounting. One of these was suggested by our sponsor as an item that would work with our systems temperature range, was well priced, and would easily mount to our discharge plate. The RTD costs could be much higher, but because our probe and digital converter were not extremely expensive, we decided to use the RTD sensor for our device.

3.10 - Temperature Sensing Component Selection

For monitoring the thermal state of our discharge resistors and heatsink plate, we selected platinum resistance temperature detectors (RTDs) and their respective RTD to digital converter ICs. Compared to other temperature sensing technologies, RTDs offer a very linear relationship and long term stability.

3.10.1 - RTD Probe Introduction

To meet our systems requirements, there are a few things we need to consider as we look at various RTD probes. One thing we need to look at is the temperature range the probe is rated for. We want to make sure our system is kept under 120 degrees Celsius. To account for that, we need a probe rated for at least 120 degrees C. RTD probes also follow accuracy and tolerance classes with type A being the best and type B falling below that [40]. For our case either is fine, the temperature measurement is a rough measurement and any RTD will be accurate enough. There is also the base resistance of the probes, which is either 100 or 1000 ohm. The 1000 ohm RTDs are more sensitive and more power efficient. The 1000 ohm RTDs also have less self-heating. There are also various wiring configurations. The minimum is 2 wire, but 3 and 4 wire variants help cancel out the effects of reading the wire's resistance. This is less critical for our application where we are using the 1000 ohm RTDs and where accuracy isn't as important. The last important factor is the mounting mechanism. Often times RTDs come with very large bulky probes or very thin capsule probes, both of would prove hard to mount to our heatsink plate. Some RTDs come with ring terminals which make mounting easier.

3.10.2 - TT4-PT1000B-T125-M5-500

The TT4-PT1000B is a platinum 1000 ohm RTD probe rated at class B. It has a built in metal encasement in the probe with a ring terminal for easy mounting. The probe is rated for an operating temperature of -20 to 125 C, which would work for our application. This is a two wire probe with leads less than a foot long. This probe is also relatively inexpensive, coming in at just $7.

3.10.3 - HEL-705-U-1-12-00

The HEL-705-U-1-12-00 is a thin-film platinum 1000 ohm RTD. It is a class B probe. The probe has a ceramic shell with two wires of one foot each. It supports a wider operating range of -70 to 260 C. This probe offers higher temperature range compatibility, but does not provide a way to easily or effectively mount it to our discharge plate. The probe also is expensive, coming in at $40.

3.10.4 - Adafruit 3984

The Adafruit 3984 is another 1000 ohm RTD. This one is mounted in a stainless steel capsule and is attached to a three wire 1m cable. It also has a temperature measurement range of -50 to 280 C. This probe also costs $15. While this probe may seem like a great choice given it's 3 wire configuration for less noise, cheap price point, and excellent temperature range, the mounting makes it fall behind. Having to add in an additional mounting system to the heatsink plate would prove difficult and result in decreased thermal performance and measurement capability.

3.10.5 - RTD Probe Summary and Selection

All three sensors are candidates for the project, each meets the technical requirements as far as being 1000 ohm RTDs with enough temperature range to measure our heatsink plate. What differentiates them is their temperature range excess, mounting, and cost. The TT4 has the lowest temperature measurement range, which still covers the operating range of our plate, and it has a ring terminal for easier mounting. It also comes in at a competitive cost in relation to the other RTD probes.

Table 13: Temperature Sensing RTD Probe Component Comparison

Device	Temperature Range	Mounting	Cost
TT4-PT1000B-T125-M5-500	-20 to 125 C	Ring terminal	$7
HEL-705-U-1-12-00	-70 to 260 C	None / ceramic capsule	$40
Adafruit 3984	-50 to 280 C	None / stainless capsule	$15

3.10.6 - RTD to Digital Converter Introduction

To make use of the platinum 1000 ohm RTD probes we selected, we need some way to interface with them and read the voltage to get the temperature. These probes rely on an excitation current and then the voltage across them is read as the resistance changes with temperature. This is a complicated front end to design with discrete component. Instead, you can find ICs that have internal current sources and voltage measurement tools that can feed the excitation current, read the voltage, convert that to a temperature value, and communicate that over a digital communication protocol. [41]

We know what probe we are using, but when selecting an RTD to digital converter we need to know how many wires our probe is. In our case it’s two wires. You also need the type of probe, for us it’s a 1000 ohm probe. You also need to look at the digital communication interface and the built in features/accuracy/linearity.

3.10.7 - MAX31865AAP+

The max31865 is a dedicated RTD to digital converter that is optimized for 100 and 1000 ohm RTDs. It has an internal ADC and RTD bias generator as well as a reference resistor interface. This has compatibility for use for two, three, and four wire RTD probes. The chip runs on a single 3.3V supply and uses SPI to communicate with the microcontroller. It comes in 20 pin SSOP and TQFN packages. For our project, it fits all the requirements and is very well recommended online for RTD applications.

3.10.8 - LTC2983HLX#PBF

The LTC2983 is a multi-sensor digital temperature measurement system. It supports two, three, and four wire RTDs as well as thermocouples, thermistors, diodes, etc. It has reconfigurable analog inputs and various internal ADCs and amplifiers. It operates on a single 2.85-5.25V supply and communicates over SPI. It is highly reconfigurable and capable of integration with multiple and multiple kinds of sensors. It comes in a 48 pin LQFP package. It is very capable but also overkill for our design requirements. It would require a lot of configuration and make the integration difficult in the high-density pin package. It is also costly coming in at $51.

3.10.9 - ADS1248IPWR

The ADS1248 is a more traditional analog to digital converter with a programmable gain amplifier. It also includes programmable excitation current sources. This IC is made as a general converter for analog sensors with high customization. It would require extra setup, but it could be configured to work with two, three, and four wire RTD probes. It has low internal drift and has eight channels. It would require more analog front end and configuration in software, but it is usable as a measurement device.

3.10.10 - RTD to Digital Converter Summary and Selection

All three devices can support high-accuracy RTD measurements and would technically work in our system. The differences lie in the software configuration effort and the BOM cost. The LTC2983 has the high compatibility, but it requires additional setup, large pin count, and high cost. The ADS1248 has the highest compatibility for usage even in other types of sensors, but requires a lot of configuration and external circuitry to setup with our RTD probe. The MAX31865 provides the simplest and easiest integration while still being capable.

Table 14: Temperature Sensing RTD to Digital Converter Component Comparison

Device	Type & Channels	Integration Complexity
MAX31865AAP+	Dedicated RTC-digital converter, 1 channel	Very Low
LTC2983HLX	Multi temp sensor system, 20 inputs	Medium
ADS1248IPWR	General sensor system, 8 channels	High

3.11 - Isolation Technology

Isolation is an important part of our project. Our system discharges a high voltage capacitor (max expected value of 1200V with an absolute maximum of 1500V). This voltage level is very dangerous and can kill or severely injure instantly. It is important that we keep areas that users/operators are expected to touch and can come into contact with at a safe voltage level. To be able to ensure this, we use isolation technology. This technology allows us to transfer power or communicate data between high voltage and low voltage/safe portions of our PCB and system. In this section, we will be going over the various kinds of isolation technology and strategy that will allow our system to remain safe and operational.

When selecting isolation technology, there's a few things we need to understand about our system. The first is that it should not be an unlimited power supply. The systems are disconnected from the mains lines and the capacitors have a finite amount of energy stored in them. There's also whether we need to withstand or isolate a constant high voltage level or if we will be seeing short term (less than 1 minute) voltage spikes up to the max level. The main guidelines that relate to our PCB design and selection will be the creepage and clearance. These relate to the distance along a material that high voltage can travel and the air gap that high voltage can travel respectively. Our system is designed to discharge 1650uF capacitors that are rated for usage at 1200V. Based on conversations with the sponsor, the capacitors should rarely be at/around the 1200V level, most discharges should start at a lower level. We also have a max voltage of 1500V, as that is what the capacitor's max voltage rating is. When comparing isolation technology there are a variety of ways you can group it, whether that be by the underlying technology, the specific device's operation technique, or by the device's purpose. [42]

The first kind of isolation transfers analog signals between the high voltage and low voltage sides. These can "copy" voltages and currents also carrying the data from analog sensors such as temperature sensors. [43] There are a few different types of analog isolation devices including but not limited to the isolation amplifier, isolated sigma-delta modulator, and linear optocoupler. The isolation amplifier modulates the HV side voltage level across the isolation barrier to the low voltage side where it is demodulated and re-created. The delta-sigma modulator has an internal ADC and DAC that transfers the digital signal across the isolation barrier. The linear optocoupler uses an LED and photodetector to sink currents. This is the most inaccurate version of the analog isolation devices. It also often requires additional power on the HV side.

The next technology is for digital communications. To do this we have logical optocouplers, magnetic isolators, and capacitive isolators. It is important to note that certain digital communications protocols, beyond requiring certain numbers of pins may also require certain pins to be pulled high/low by both sides of the line. For this reason, special digital isolators are needed that can perform this function. The optocouplers again are the weakest in this category, requiring the most power to activate and not having the highest communication rate capability. It should be noted that many digital isolators require an external source on the HV side in order for them to transfer data properly. This adds additional components and failure points. [44]

Another technology used in isolation is how you transfer power between the low voltage and high voltage sides. These are often in the form of DC/DC isolated converters. [45] Some isolated DC/DC converters copy over the same voltage, but some also act as regulators taking a low voltage input level and converting that into an isolated separate voltage level on the high voltage side. These components are necessary if there are any electronics that need power on the high voltage side. These converters modulate DC voltage into high frequency AC that they then transfer over to the HV side through transformer windings. [46]

3.11.1 - Isolation Technology Comparison and Selection

Summarizing the above, we looked at a few different kinds of technology used in isolation. Our analog isolators form the simplest base requiring the fewest components and having the simplest operation. The digital isolators are usually paired with isolated power converters and are more complicated needing to support high frequency signals that can be pulled high or low. The isolated power converters are used in conjunction with our signal isolators as well as to power the rest of our components.

Table 15: Isolation Technology Comparison

Technology	Use	Accuracy	Simplicity	Integration Effort
Analog Isolator	Copying analog signals	High	High	Low
Digital Isolator	Digital communications protocols	Very High	Low	High
Isolated Power Converter	Transferring power between high and low voltage sides	High	Medium	Medium

3.12 - Isolation Component Selection

For our voltage sensing path, we need to have an isolation point between the HV capacitor and our low voltage side. Though our capacitor will go through a voltage divider so the output voltage should be low, we need isolation for safety. In the event something is shorted and HV reaches a pin that would otherwise touch the low voltage side, the operator could be hurt. To get around this, we selected a specific isolated analog-to-analog converter or isolation amplifier. Because we are measuring a very slow change in voltage (a discharge over 30 seconds), we do not need very high bandwidths. We just need a strong isolation barrier and accurate voltage representation across the barrier.

Some of the important specifications we will look at in selecting a good isolation amplifier is the isolation rating and working voltage. These determine the max voltages that can be seen by the input terminals and remain isolated from the low voltage side. For our case, we need at least 1500V to have appropriate margin of safety. The power and reference architecture of the isolation amplifier should be simplified. Amps with built in power delivery for the high voltage side and built in references are the best case as these require fewer external components and supporting circuitry.

3.12.1 - ADUM3195BRQZ

The ADUM3195 is an isolated error amplifier meant for feedback control in isolated power supplies. It has two internal op amps and voltage references. It is contained in a 16 pin QSOP package and has a 3000 Vrms isolation rating. This chip requires external power on each side. The high voltage and low voltage sides both have supply connections, ground connections, and on one side we have the op amp connections. This chip could work but it would require external circuitry for the op amp setup as well as external power delivery on the high voltage side.

3.12.2 - AMC3330QDWERQ1

The AMC3330Q1 is a precision +/- 1V reinforced isolation amplifier with an integrated DC/DC converter. This device converts a +/- 1V signal to a differential signal on the low voltage output side. It can be powered with a single 3.3V or 5V supply and uses the internal DC/DC converter and references to provide the power and reference for both the high and low voltage sides. The reinforced isolated barrier gives the unit a 6000 V peak and 4250 Vrms isolation rating. This device was made for precision voltage measurement and it shows in its stable operation and low non-linearity. The only external circuitry required for this setup is the passive resistor network for dividing the high voltage into a lower voltage for measurement.

3.12.3 - AMC1301DWVR

The AMC1301 is a precision +/- 250 mV reinforced isolation amplifier, targeted for shunt resistor current sensing applications. It takes an input voltage over a sense resistor and gives a differential output voltage. This output, similar to the AMC3330Q1 can be converted into a single ended setup with some additional circuitry. This device has isolation rated for 7070 V peak and 5000 Vrms.

However, the extremely low input voltage makes it require a very high resistor ratio relative to our input voltage. It also requires an external isolated power supply as it needs high voltage side power.

3.12.4 - Isolation Component Summary and Selection

Considering the above components pros and cons, the AMC3330Q1 is the clear winner. It offers very easy compatibility and integration. It is also purpose designed for precision voltage measurement of high voltage applications. Its internal references and DC/DC conversion make it the simplest to use all while keeping the board complexity and BOM cost low. The other isolation amplifiers require additional input circuitry as well as their own high voltage side power and reference.

Table 16: Isolation Component Comparison

Device	Input Range	Isolation Rating	Integration Complexity
ADUM3195BRQZ	Op amp input	3000 Vrms	Very High
AMC3330Q1	+/- 1V	4250 Vrms	Low
AMC1301DWVR	+/- 250mV	5000 Vrms	High

3.13 - Microcontroller Technology

When deciding what will be the brains of any embedded system, there are an abundance of considerations that must be accounted for prior to the first prototype. Some factors that influence the decision would be the clock speed required to run the software, what other components need to connect with the microcontroller, how much and what types of input and output pins will be needed, along with multiple other variables specific to each project.

3.13.1 - Clock Speed

To keep track of the latest voltage levels, the microcontroller needs to have a sufficient clock frequency to perform all required computation, including user interactions, numerical conversions, state updates and outputs to the relays and discharge indicators. Additionally, there needs to be enough overhead to comfortably run the display program that allows the user to configure the stages in the first place.

Part of the calculation for how fast the processor needs to run will also be determined by the efficiency of the software implementation. For example, a poorly designed system might split the program into time slices where sub-routines are run for a long period of time. In extreme situations, that might lead to a button press being missed from a user. On the other hand, a well-planned interrupt-based approach could respond to time-critical events as needed, while handling data sampling, state changes and communication protocols in the background.

3.13.2 - I/O & Connectivity

When selecting a processor to be used in a project, another important consideration is the type and rate of data transfer required to support the system's operation. This can include the number of buttons required, such as over a hundred on a full-size keyboard or just a handful on an alarm clock. Additionally, driving a large display directly from the main microcontroller could significantly reduce the amount of compute time available to perform the rest of the program required by a given system. Another consideration is that the package must either have enough current output to power connected devices or rely on other components to supply the power requirements of the devices it controls.

3.13.3 - Project-Specific Considerations

In this project, the microcontroller will also need to read a scaled analog voltage to determine which stage to set the relays, which requires either receiving data from an external analog to digital converter or finding a microcontroller that has one built in. At the same time, the internal clock must be fast enough to drive communication protocols with other components in the system, such as a display or sensors. Due to its isolation from the high-voltage components of the system, the microcontroller will not be directly driving the relays but rather controlling amplifiers that drive the relays, significantly reducing the current output requirements of the controller itself.

The physical package must be reasonably large enough to place by hand using equipment available in the Senior Design lab, while also having enough general purpose I/O pins to support four digital outputs (one per relay and one for the safe indication), at least three buttons for directional navigation and control, along with at least one analog input of sufficient resolution to determine if the scaled voltage is under the ten volt safe threshold and at least two groups of pins able to run communication protocols such as SPI, I^2C and UART.

3.13.4 - Microcontroller Technology Comparison

Below is a table of comparisons between three major manufacturers of processors that we have considered for the project, considering factors listed above along with other factors that will affect the development of software on each platform.

Table 17: Microcontroller Brand Comparisons

	Arduino	**ESP32**	**STM32**
Team's Overall Familiarity	Medium	Low	Medium
Third-Party Library Availability	High	Medium	Low
Quality of Documentation	Medium	High	Low
Feature Sets	Low	Medium	High
Power Consumption	Medium	High	Low
Processor Speeds	Medium	High	Medium
I/O Options	Low	Medium	High

Given the hardware accelerated features such as ADC oversampling, direct memory access, and a full hardware abstraction layer, we initially planning to select a microcontroller from the options provided by ST Microelectronics. However, we were strongly advised by Dr. Weeks to change our selection due to technical difficulties experienced by other Senior Design teams using STM chips in addition to Dr. Weeks' knowledge and experience with ESP-based projects.

3.14 - Microcontroller Selection

Of the variety of microprocessor options available from ST, our use case was able to fit into their Mainstream MCU category, which includes the STM32 C, F and G families. The family of microcontrollers that matched our requirements was the STM32G4, which had a high feature density and clock rate while keeping power consumption low. We found a microcontroller and development board pair, the STM32G431RB, which had the required I/O and hardware to support our use case, and selected the STM32G431RBT6 because it had the largest pin spacing and would therefore be the easiest package to solder of the product line. However, with the help of Dr. Weeks, we were able to find an equivalent ESP32 board to meet our requirements.

Table 18: Microcontroller Chip Selection

	STM32G431RBT6 (Initial Selection)	**ESP32 WROOM-32D** (Updated Selection)	**ESP32 C3FH4AZ**
Support from Dr. Weeks	No	Yes	No
GPIO Pins	86	32	16
CPU Frequency	170 MHz	240 MHz	160 MHz
ADC Resolution	12 bits + 4 oversampled	12 bits	12 bits
ISA	ARM	Xtensa (RISC-V)	RISC-V
RAM	32 kB	520 kB	400 kB
Flash Storage	128 kB	4 MB	4 MB

We changed the selection of the microprocessor for our system to the ESP32 WROOM-32D because of the larger package size and higher number of available GPIO pins compared to other microcontrollers options from Espressif. Additionally, Dr. Weeks' familiarity with the WROOM-32D and the availability of replacement processor units directly from Dr. Weeks were considerations that influenced our decision to switch. However, this change brought some drawbacks, specifically with the reduction in overall pins to interact with other devices such as indicator LEDs or directional button inputs [47].

3.15 - Display Technology

When designing a computing device that needs to be observed and controlled by a human user, one of the important design considerations is how the device's data should be presented and how the user can manipulate the device's state. An example would be how most computers use a video display to show information, while taking a combination of keyboard and mouse inputs. However, a digital clock does not have the same level of complexity and usually has somewhere between 3 and 5 buttons to control its current time and alarms. For embedded devices and other systems driven by microcontrollers, there are a few common ways a user can interact with the system that each have unique constraints, strengths and weaknesses. Below is a comparison of different display and control technologies considered for this project.

3.15.1 - Segmented LED Displays

One of the first digital display technologies was the segmented LED display. Common variants include the 7 and 14-segment displays, which are used commonly in clocks, kitchen appliances and simple calculators. Segmented displays excel in devices that prominently display a small amount of simple data or in applications with extremely low power requirements, in addition to being very inexpensive compared to other display technologies. However, the practicality of this display technology is limited by the number of general-purpose output pins on the microcontroller, as each segment requires its own output pin and can quickly outnumber the I/O capabilities of a smaller chip.

3.15.2 - Dot Matrix Displays

The modern alternative to segmented displays, the Dot Matrix display, operates by displaying data as a grid of pixels rather than a fixed set of segments. This type of display encompasses a wide range of technologies, which range from the OLED displays seen on modern phones to the 16-character 2-line LCDs that are used in the EEL3946 Junior Design project here at UCF. Dot Matrix displays almost always come with a separate processor to drive the display, which is controlled using a protocol such as SPI or UART by the main microprocessor of the system, thereby overcoming the I/O limitations posed by segmented display technologies, at the cost of a slightly reduced response time. These displays can display text or graphics, with options for both black-and-white and color in a wide range of sizes, visibility angles and lighting conditions, and some even include touchscreen input capabilities. Additionally, there are many open-source libraries available designed to support modern user interface paradigms on low power processors and microcontrollers.

3.15.3 - Display Technology Comparison

Below is a table to compare the previously discussed display technology using a few metrics that inform our decision for how our project will communicate information to the user.

Table 19: Display Technology Comparisons

	E-Ink	**Dot Matrix**	**Segmented LED**

Visibility	Variable, Low to High	Variable, Low to Medium	High
Detail	Medium	High	Low
Information Density	Medium	High	Low
Versatility	Medium	High	Low
Simplicity	Low	Low	High
GPIO Required	Medium to High	Low to Medium	High

Given that this project needs to present the user with a variety of changing information during the various discharge stages, it would not be feasible to implement the user interface on a segmented LEDs, so we chose to use a dot matrix display, and specifically an LCD display because of their widespread availability and integration with embedded systems. However, there will be dedicated indicator LEDs that activate when the system is powered on, when each stage is active, and when the system has finished discharging the capacitors.

3.16 - Display Component Selection

While researching display options available, we were advised to investigate displays that used communication protocols to communicate with a dedicated coprocessor, as that would allow the main microcontroller to not store or compute the graphics itself, which in turn would allow for more responsive operations and faster sampling rates for our connected sensors. When searching for a display matching these characteristics, we found the NHD-5.0-800480FT-CTXL-T by Newhaven Display, which is a 5" LCD panel with a FT812 graphics coprocessor. It has a 20-pin header on the back, which would allow us to mount it directly to our main PCB and control the display using SPI.

Table 20: Display Component Comparisons

	NHD-5.0-800480FT	**KD50G21-40NT-A1**	**GDEY042T81**
Screen Size	5"	5"	4.2"
Resolution	800x400	800x400	400x300
Built-in Coprocessor	FTDI FT812Q	None	STM32
Color Space	sRGB	sRGB	B/W
Connection	SPI	24-bit Parallel	SPI
Touchscreen?	Yes	No	No

3.17 - User Input Technology

3.17.1 - Touchscreen Displays

With the improvements in display technology, many embedded devices have shifted from the push-button and dial interface in favor of a touchscreen. This allows the user to interact with the device using the same interface the device uses to communicate with the user. Touchscreens grant much more intuitive experiences for navigation and control, with the drawbacks of a higher cost for an equivalent non-touchscreen display and requiring more system resources during runtime for handling interactions. Another consideration specific to this project is that the device is intended to be used in laboratory conditions with high voltage operations. As such, the user should have PPE equipped, which may include handwear that would prevent the user's touch from being detected.

3.17.2 - Push Buttons

The simplest way of controlling the system would be a set of three or five buttons, with two or four respectively for directional navigation and one for selection. The benefits of this control technology include simplicity for both the design implementation and user experience. These types of buttons would also be operatable even if the user wears personal protective equipment and provide both mechanical and sometime audible feedback that the push button has been actuated.

3.17.3 - Safety Buttons

When working with high voltage, heavy machinery or any other equipment that could potentially cause harm to someone, there are often emergency shutoff buttons, or E-stop buttons. These differ from typical push buttons in two major ways, both of which are critical for ensuring safety when working. First, the housing and actuation of E-stop buttons are intentionally designed to be easily pressed, mechanically lock into its depressed state, and difficult to reset by accident.

Common examples include large, mushroom-shaped keycaps so the E-stop button can be pressed from any direction, red coloring with warning icons or labels, or a mechanism requiring the button head to be twisted to reset after a locking linear depression. Second, the button is normally closed allowing current to flow through to the rest of the system. This allows the E-stop button to physically disconnect the rest of the system from power in the event of an emergency shutoff. As such, these buttons are typically mounted in an easily accessible panel and are expected to handle much higher voltage and current loads compared to the rest of the user interface.

3.17.4 - Input Technology Comparison

Below is a comparison of several factors that could affect the development and usability of each of the discussed user input methods.

Table 21: Input Comparisons

	Touchscreen	**Push Buttons**	**Safety Buttons**

Ease of Use	Variable, Medium to High	High	Low
Ease of Implementation	Low	High	High
Intuitiveness	High	Medium	Variable, Low to Medium
Accessibility	Medium	High	Low
Haptic Feedback	Low	Medium	High

While the selected display is capable of touch input, we decided to use a set of push buttons arranged in a directional navigation style to allow the user to move through software menus and control the system without needing to use a touchscreen or stylus.

3.18 - User Input Component Selection

For user input, we decided to use the Cherry MX Blue switches. This decision was formed by the accessibility of the user, who may use personal protective equipment while connecting the capacitor bank to the discharge tool, so they can use the system without having to remove gloves or delay the process to interact with the tool. The Cherry MX Blue push buttons were identified for their clicky mechanism, which is used on both mechanical keyboards and some industrial equipment to give the user both tactile and audible feedback of the button actuation, which could be useful in the situation where the user's sense of touch is impeded by a glove or other PPE.

Table 22: Push Button Selection

	GPTS203211B	**EAO 84-5231.2B20**	**Cherry MX Blue**
Action	Momentary Push	Locking Push / Twist Reset	Momentary Push
Tactile Feedback	Minimal	Strong	Medium
Auditory Feedback	Minimal	Medium	Strong
Ease of Actuation	Medium	Difficult	Easy

3.19 - External Power Technology

3.19.1 - Power table

A power table like the one below provided a look at the overall power distribution system and enabled the team to account for power required for certain specific components. It was important to keep in mind that the set amount of specific regulators varied depending on design so the team decided to use more of a general estimate. Dividing up the voltages also allowed for estimations on how many 3.3- and 5-volt regulators would be roughly required. The values in general used were not totally accurate, but detailed estimations based on the specifications sheets of the respective components and their usage within the system. In addition, the estimations were more on the high end, naturally for in case more wattage is required, than on the low end of the overall range.

Table 23: Power Table

Component	Maximum Current Required	Voltage Required	Quantity	Maximum Power Consumption
Isolation Amplifier	48 mA	5V	1	240 mW
Dual Operational Amplifier	15 mA	5V	2	150 mW
ADC	10 mA	3.3V	1	33 mW
Relays	85 mA	24V	3	6.12 W
Transistor	20 mA	3.3 V	3	199 mW
RTD to Digital	3.5 mA	3.3V	1	11.5 mW
MCU	50 mA	3.3V	1	165 mW
Display	100 mA	3.3V	1	330 mW
LED’s	20 mA	3.3V	4	26.4 mW
Current limiting resistors for buttons	40 mA	3.3 V	3	396 mW
3.3- and 5-volt regulators	3 A(for both)	3.3 V/5V	2(1 of each)	5V- 0.191 mW 3.3V- 0.342 mW
Display driver	590 mA	3.3V	1	1,947 mW

Total Current Consumption (3.3 V)	1013 mA			
Total Current Consumption(5 V)	78 mA			
Total Power Consumption	-	-	-	11.56 W

External Power supplies were an extremely important aspect of the design. A power supply unit (PSU) provided the initial electrical energy that was further regulated into energy suitable for use. [48] The main function of a power supply is to convert electrical energy, which tends to be in the form of high voltage alternating current (AC), into lower voltage direct current that is safer for further testing. [49] [48]

In the case of this circuit, the power supply was essential in order to provide the DC current that was further adjusted by the regulators to propel the microcontroller and other components of the design. If the PSU wasn't in the design, then there would be no safe launchpad from which the relays, alarms and even LEDs could have received a suitable level of voltage for their respective compatibilities. In a sense, the power supply functioned as the first point of energy into the system, from which the regulator acted as the controller and adjustor of said energy. The below listed research studied a small variety of power supplies in the market that gained an adequate perspective of their advantages and disadvantages, of which a suitable selection was made based on the scope of the project. [50]

3.19.2 - Battery Powered Options

Battery power was a fundamentally crucial consideration for the design of the project. Batteries could have provided a stable and powerful source of energy, allowing for the operation of the system even if no AC power were to be available. Furthermore, the choice of exact battery type was critical as well, as the correlation between type of battery and energy density, safety and longevity is high. [51] Battery systems also related to power management, as they functioned as the initial boost of energy that could be further rectified and adjusted by other components in the circuit.

For this specific discharge circuit, battery power would not be the only component required, as other supporting elements were needed. Firstly, a charging circuit would have been useful, with the first stage being an AC to DC adapter converting initial voltage into a usable DC level. Next, a charging system would have been used in order to provide a consistent level of current during charging up to when the battery reached its maximum nominal voltage, in which the system would then have provided a constant level of that voltage. [51] In addition, throughout the process, protections against excessive voltage and potential thermal monitoring would have been necessary to ensure added safety within the design. Once a stabilized output from the battery was reached, the voltage from that stage would be sent to the regulator stage, allowing for the microcontroller and other low voltage components to have received adequate and consistent levels of voltage. [51]

3.19.2.1 Lithium-Ion Batteries

Lithium-Ion batteries are among the most widely used batteries for energy storage. For the cathode side, either lithium iron phosphate or lithium cobalt oxide would have been used. While the two shared similar levels of rechargeability and cycle life, they differed slightly in terms of overall nominal voltage. Lithium cobalt oxide typically had a nominal voltage range of 3.6-3.8 volts per cell, while lithium iron phosphate had a slightly smaller range of 3.2-3.4 volts per cell. [52] [53] These voltage levels made both these sub types of batteries suitable options for our circuit, as steady energy delivery and no self-discharging were crucial features required in order to ensure efficiency. [52]

Within the two options, lithium cobalt hds a slightly higher energy density, around 150-250 Wh/kg compared to 90-160 Wm/kg. [52] [53] Lithium cobalt also tended to perform better in more chilly conditions compared to lithium iron phosphate, which mayhave been relevant depending on the heat dissipation in other parts of the circuit. However, lithium cobalt also came with serious ramifications. Cobalt was comfortably less abundant than phosphate, which could have raised the cost of using lithium cobalt oxide as a battery type. [53] Working better in colder conditions meant that the thermal resistance of the material was comparatively weaker. In contrast, lithium iron phosphate, while not as powerful, was cheaper, safer, more abundant and had a significantly longer shelf and cycle life than cobalt. [52] [53] Based on this information, it follows that lithium iron phosphate would have been the overall better option. The lower cost, extended battery life and the stability compared to cobalt outweighed the slightly better energy density and efficiency that cobalt provided. [52] [53]

3.19.2.2 Nickel Metal Hydroxide

Nickel Metal Hydroxide batteries were first considered as a suitable substitute for comparatively older nickel cadmium due to their higher nominal voltage and lessened impact on the environment. The nominal voltage range for this battery material tended to range from 1.1-1.4 volts, and like lithium, these batteries were rechargeable, making them beneficial for longer use, and were relatively cheaper, as compared to lithium. [54]

However, nickel metal hydroxide batteries had the lowest nominal voltage of all the options considered, rendering it suitable for medium voltage applications at best. While nickel metal batteries were rechargeable, the potential for self-discharge was higher, in other words, the ability to lose charge if left unused for a significant time period. [54] In addition, heat could also have built up significantly during the charging process, and nickel batteries tended to weigh a lot more than lithium or even alkaline batteries. Both limitations could have led to additional measures being required if nickel batteries were to have been a suitable option within the circuit. Overall, nickel metal hydroxide batteries would have offered a safer and cheaper alternative to other options for more moderate voltage levels and longevity. [54]

3.19.2.3 Alkaline

Alkaline batteries remain one of the popular options for consumers looking for a cheap and moderately effective battery type for power. A zinc anode along with a potassium hydroxide electrolyte was used. [55] The nominal voltage for an alkaline cell ranged from 1.4-1.7 volts, higher than nickel metal hydroxide. [56] Moreover, the abundance of alkaline ensured that the cost will always be significantly lower than it would be for the other types of batteries on the market.

The shelf life of alkaline is excellent and able to last around 5 to 10 years without need of a replacement. [56] Alkaline batteries were ideal for low power applications that provide a simple and stable tool of energy at a very minuscule cost.

Regardless of these benefits, alkaline batteries could carry a variety of disadvantages. It could be very difficult to recharge an alkaline battery, meaning that it is single use and very inefficient. [55] Furthermore, when faced with heavier loads, the performance of the battery faced a sharp decline, not ideal for a high voltage scale like our design ended up expecting to bear. Hence, while alkaline batteries were inexpensive and suitable for low voltage power applications, implementing this type of battery within the scope of a high voltage and consistent supply would have been a challenge

3.19.2.4 Lead Acid

Lead Acid Batteries were one of the oldest rechargeable battery options available. Lead dioxide was used at the positive electrode side, while sulfuric acid lay at the electrolyte side. [57] The nominal voltage for lead acid ranged from 1.9-2.2 volts, so it was higher than alkaline and nickel metal hydroxide. [58] The abundance of lead was common, which rendered the production cost for the battery type fairly minimal. In addition, the self-discharge rate was a lot slower compared to other compositions, which allowed for the charge to be held for longer periods without usage. The main drawback to using lead acid as a battery type came with the environmental impact, due to the toxic lead content and sulfuric acid use that has long terms ramifications for the environment. Furthermore, the energy density for lead acid was the lowest out of all other battery types considered, along with a relatively short cycle and shelf life. These drawbacks made it complicated to implement the use of this battery type within the scope of the circuit, as aspects needed to be running at maximum efficiency.

3.19.3 - AC DC Power options

It was noted that both battery power and AC DC power would have required an AC-DC adapter in the design of the circuit. The difference in this case would be that the adapter would have taken wall power in and power the circuit directly. This was slightly in contrast to battery power which would have taken the power from the adapter and powered the circuit. Both methods came with distinct advantages and disadvantages that were further illustrated.

3.19.3.1 Direct Wall Mount/External PSU

Wall mounted AC DC power adapters, or external power supplies, are a very common and cost effective to provide power to low and medium voltage devices or circuits. These adapters took in AC power from the outlet, rectify and smooth the resulting wave signal into a recognizable but still higher voltage DC input. A switching transistor then takes that resulting input and cuts the DC input, which was further decreased by a transformer into a safer range of voltage. The waveform was then rectified and filtered further in order to obtain a final low voltage and safe DC output for regulated circuits. [59] In addition, protection measures against initial inrush current were abundant, along with shutdown measures in the case of a short or overcurrent. [59]

The plus side of AC to DC external adapter connected directly lay in the high availability, as well as the built in safety measures, which in turn made the cost of the product extremely affordable in the scope of the project. [60] Also, a wide range of power levels, from 1-100 watts, were available, scaled to a decent variety of output voltages. Because the adapters were globally standardized in terms of production, it was also very simple to replace if required. However, the limitations of the product included, mainly, slightly lower efficiency when compared with battery power. Batteries would have provided scalable energy storage to provide further input and could have kept running even if wall power went out, while direct connection using an adapter would have been dependent on a stable, nonfluctuating wall power source. An AC to DC adapter, overall, could also have been considered as essentially an external PSU, as the AC to DC conversion takes place outside the location of the circuit, where the other components are located. The AC input, transformer and other processes such as rectification were all contained within the wall brick. Our PCB gets the final low voltage DC output via connection to a barrel jack or connector, so in essence, the wall brick could also have been thought of as an external Power Supply Unit.

3.19.3.2 Internal PSU

An internal PSU could convert AC power directly into regulated DC voltage within the PSU. Like a wall mounted adapter, AC input is filtered and rectified, then cut and stepped down by a transistor and transformer respectively. [61] The waveform is then further measured and stabilized by using feedback loops to compare to a set reference voltage. [61] This design, due to being within the PSU, may have came with increased measures and isolation barriers, which would have been a major advantage. It should be noted that the main difference between these two devices lay in the fact that the mount to adapter to regulator design converted AC to DC outside the main circuit, while an internal closed frame PSU converted AC to DC within the main capacitor discharge circuit. By that, it was meant that the internal PSU would have been directly connected to microcontrollers or a ground plane, or screw terminals may have been used to solder it directly onto the PCB or chaisse otherwise. An example of a product that may have struck an adequate balance and would have been a good comparison of an internal PSU would be an AC to DC enclosed converter. That is to say, an AC to DC converter with the box enclosed. Another advantage of using an AC to DC converter would come with the earth ground concept. A protective earth grounding wire allowed for general safety when dealing with the circuit, and an AC to DC converter box took care of the problem with built in protection and circuit measures to connect directly with isolation and ease taken into account, Within our project specifically, the concept of an earth groundwas more essential due to the amount of connections and the need to meet industry standard, as NextEra wanted our team to comply with more industry conventional design.

The main advantage of using an Internal PSU came with its compactness and versatility, which allowed for multiple input and output rails. [61] In addition, the power production for the internal PSU had more potential than the wall mount adapter , and the internal PSU was better in terms of cooling due to the fact that heat could spread across a larger space and dissipate. However, this all came with added complexity of integration within the circuit, which could have led to increased costs. The PSU would have needed to be built from the ground up, and safety certifications would have had to be obtained for industry use. [62] There would also have needed to be even more protection and shielding required for the function of the Internal PSU due to its integration within the design.

3.19.3.3 Internal PSU and Wall Mount Adapter

As explained earlier, the primary difference between the two options lay in the location, as the wall mount adapter's conversion and function lay outside the device, while the internal PSU would need to be integrated within the device. Conversely, this would have resulted in some fundamental shifts in design being required for the prototype. All in all, the plug to adapter to regulator connection would have been considered a safer and simple option while the internal PSU would have been the more varied, but more integrable option. A comparison between the two devices is shown below

Table 24: Wall Mount vs Internal PSU

AC to DC Power Type:	Wall mount (external PSU)	Internal PSU
Safety	Fully enclosed and insulated with no exposure to AC power.	Parts were also enclosed and insulated, but further isolation is given
Regulatory burden	Adapter already certified	Most aspects were already certified
Heat management	Heat stayed internal and outside the device	Heat was inside the enclosure but in open air so would dissipate easier.
Replaceability	Very easily replaceable	Not as easily replaceable, but less likely to have to buy again.
Flexibility	Only one set fixed DC voltage	Could have provided multiple options/rails(5, 12, 24 V)
Cost	Lower cost, and no money for enclosure or protection measures	Slightly higher cost due to extra money for additional protection design

Based on the research and comparison between the two products, the two products were very evenly matched so it ultimately came down to which product was best suited to our design. In this case, the use of the earth ground and Next Era's desire for that design system meant that the AC to DC converter was most preferrable to use with our design scope. However, this did not mean the internal PSU was the best option entirely, for that, the effectiveness of using an internal PSU needed to be compared to the effectiveness of using battery power.

3.19.3.4 Wall Mount to Adapter and Direct Battery Power

Ultimately, in terms of providing the initial power to the capacitor discharge circuit, both battery power and AC to DC power(on its own) were viable and very similar, at the core, options that could feasibly be used. The best options from both sides, the lithium ion phosphate battery type and the internal PSU needed to be compared through a variety of metrics, but it was also important to consider the implications of using batteries through the necessity of a BMS(Battery Management System), the nucleus behind ensuring the use of batteries is safe, efficient and for a high of a time period as possible. In case of excess voltage, current or temperature, a BMS would have ensured that battery cells could return to equilibrium at a safe output and were balanced in terms of performance. [63] However, this would also have allowed for additional expenses that would have needed to be specified for in the Bill of Materials.

Table 25: Battery power vs AC to DC adapter

Feature	Lithium Iron phosphate batteries	AC to DC converter(Internal PSU)
Power Source	Stored energy from rechargeable cells which would require	All power directly from AC mains (wide voltage range)

Safety	Required BMS to prevent overcharging and overheating	Protection was integrated within the box but further isolation and protection measures was required
Charging	A charging circuit and a BMS would have been otherwise required to maintain the circuit.	No real maintenance or charging circuit required.
Lifetime	Well beyond 5 years [64]	Can run for a very long time (almost unlimited)
Cost	Cost would have been higher as BMS and batteries would be needed	A one-time cost would have been relatively cheap due to the abundance of AC to DC converters on the market
Output Stability	Voltage decreased as the battery discharges which renders the use of a BMS.	Consistent DC output with regulation and a small voltage drop
Environmental Impact	Lithium would have been needed to be mined, which could have caused damage to non-degradable areas.	No replacement issues for the most part.
Integration	Direct AC input into charging required more shielding and more internal design work within circuits.	There would have been some integration required, but not to the extent that the battery power would need in comparison..
Power Capacity	Time required for recharge with efficiency limited by nominal voltage of battery	Wide range of wattage with no breakage for lack of runtime required.

Based on the research and comparison completed, the AC to DC converter box seemed like the ideal option, due to the flexibility and simplicity of the design with a relative low cost to efficiency ratio that allowed for more flexibility in other parts of the product if needed. Using battery power would have been a viable option, but the combination of increased protection measures, along with the increasingly complex way of implementing the battery itself with the battery management system included, dissuaded the team from pursuing the option. In addition, both the Senior Design instructors and the NextEra team would have placed a variety of resurrectionary measures on battery type and use.

It should be noted that both battery power and AC DC power would have required an AC-DC converter in the design of the circuit. The difference in this case would be that the converter took wall power in and powered the circuit directly. This is slightly in contrast to battery power which would have taken the power from the converter and powered the circuit. Both of these methods come with distinct advantages and disadvantages that will be further illustrated.

3.20 - External Power Component Selection

Having researched various different external power technologies and having concluded that the most well suited design for our project would be an internal PSU, aka a AC to DC box converter that was attached within the chaisse, the following options were listed as the most suitable for the current scope. These options were more general and depended on certain specifications since it should have been compatible with other parts of the circuit, including the DC voltage rating, current limitations and other protection measures.

3.20.1 - MPE-100C

The MPE-100C was an AC to DC converter that was designed to take in external AC power and convert it to DC voltage that could be used effectively. Within the MPE series of AC to DC converters, a variety of options were offered, but this 24 volt option specifically was of most relevance, since it matched the required voltage input to the regulator in our design scope. With a wide input voltage of 85 VAC to 264 VAC, this device could have supported a wide range of input AC values. [65] A power range of around 100 watts provided significant margin for the team, as the power specifications ran at around 10 watts. The maximum output was listed at 4.5 amps which met and exceeded the current requirements for the prototype. [65] With an efficiency close to 90%, this ensured that excess energy would not have been wasted and any overheating issues were unlikely within this aspect of the design. [65] Finally, built in protection measures, along with production by a known supplier of solid repute, such as MicroPower Direct, made the MPE-100C a very tempting option for selection.

Despite this, there were still some potential disadvantages of using this converter. The output current of 4.5 amps was suitable for the scope of the project, but higher current range could potentially have been better in case of a higher load. [65] The device only consumed around 30 watts at absolutely worst case, so a 100 watt converter was far beyond what is needed and could have resulted in decreased efficiency over time. Given that this converter was an enclosed box, proper mounting and wiring inside and outside the enclosure was essential and would have required further attention and added further complexity in comparison to a wall brick. The AC input cord and other objects such as the fuse would also have needed to be purchased as separate components and would have required further effort for purchase. Overall, while the MPE-100C was a decent option with lots of wattage, the relatively low current or a slightly smaller wattage may have been better for long term efficiency.

3.20.2 - RWS50B-24 TDK

The RWS50B-24 TDK AC to DC converter was another solid option that offered decent wattage and current for further consideration. Within the RWS series of AC to DC converters, an even bigger variety of options than the MPE series wass offered. Within the 24 volt versions specifically, the RWS50B stood out due to the relatively low power offered in comparison, at around 50 watts. [66] This low power needed offered a potentially higher efficiency considering the amount of power that was needed for the design. However, if higher power were required, given the low margin of error between the power estimated in the power table, it would have been very tough to adjust other components and aspects accordingly. With an efficiency of around 86%-87% that ensured that limited energy was not wasted, the RWS50B became an option of serious repute.

The major limitation of using RWS50B came with the decreased current which was not up to standard with the rest of the design. The maximum current was around 2.2 amps, which was not b enough to power the rest of the circuit. [66] The concept of the grounding, which was one of the main incentives to using an AC to DC converter, was not fully solved as the pins were not organized in an exact manner and connection so the chaise could have been increasingly complicated as a result. In conclusion, while the RWS50B offered a more balanced low power option of an AC to DC converter, the limited current also meant it would have been a major disadvantage to ultimately use the product.

3.20.3 - Mean Well RPS-200

The RPS-200 AC to DC converter was another of the many converters that was available within the Mean Well family. With a wide input ranging from 80 to 264 VAC, this converter did support decently sized AC inputs on both ends of the spectrum. [67] The current was also favorable, with a maximum current rating of 8.3 amps, giving the team ample safe distance for extra current if the device needed it during design and implementation. [67] A massive amount of power was offered at around 200 watts, which was also well above spectrum, but most AC to DC power converters just came with a lot of wattage in general, in contrast to AC to DC adapters. [67] Another reason for the relatively higher wattage offered was due to the lack of availability compared to AC to DC adapters, so the options on the market could not really afford to be low power. The efficiency for the product was very high, around 94%, which ensured that even if the power load being drawn is reatively low compared to its capacity, the efficiency of the circuit would not be affected that much. [67] In addition, the device also contained protections against short circuits and over heating within its enclosure, and the enclosure could fit decently within the circuit design to its compactness, at around 103.4 mm by 62 mm by 40 mm. [67]

However, there were some negative implications to using this specific converter. Since the unit was designed for internal installations, the need for proper grounding and chassis mounting was even more essential, and would have required even more focus and proper further research as opposed to using even the MPE 100C-24 for example. If proper earth grounding was not implemented, further safety or EMI issues may have arosed. Since the power supply unit needed to be enclosed and permanent, it would have been less replaceable in case the power or current draw was be sufficient.

3.20.4 - NUOWEIDE

The NUOWEIDE power supply converter was a AC to DC converter that contained idealistic specifications for our project, at a maximum of 25 amps, which was significantly more than required but also provided a high margin for error in case of overheating. An AC voltage range of 110 to 220 VAC provided a wide variety of voltage range to be safe. [68] However, the biggest advantage of this specific product was the labeling of specific aspects, such as positive and negative voltage(V+ and V-) and furthermore, the ease of connection from plug straight to a chaise without needing to solder further. In addition, the device came in with a heating and cooling fan, ensuring the temperature was always at an acceptable level, which with the amount of voltage being inputted into the system, was never a certainty. Given the product was also available on Amazon, the reviews were seen and looked extremely favorable, of course taking into account the potential biases that may occur, and all of these considerations made the NUWOEIDE an extremely promising power supply unit to use. The efficiency of the device was explicitly listed as a percentage, and the device was over 80% efficiency, so industry certified. [68] Of course, there were some disadvantages to take into account. In addition to the above-mentioned potential over specing of current and voltage, there was some doubt when it comes to the potential current load as the specs sheet claimed that the current load was dependent on the voltage or general input yet overall due to the labeling and ease of application, the NUOWIEDE 24 volt power supply was still a great option for further use.

3.20.5 - PMT-24V100W2BA

The PMT-24V AC to DC converter would be the last option that the team considered for the AC to DC power supply unit. The specifications were in order, with around 4.5 amps of current at maximum and 90 to 264 VAC of AC input voltage. [69] The size was also relatively compact, at 129 by 97 by 30 mm, and the design of the device dictated that the method of connection would have been more along the lines of soldering wires together and mounting wires onto the chaise than a direct connection like the DROK 24 volt would be. [69] However, the relative lack of current security, along with no real overcurrent protections or temperature precautions made this option not as secure in comparison to what has already been compared.

3.20.6 - External Power Converter Comparison and Selection

Table 26: External Power Converter Table

Adapter	MPE100C	RWS50B-24 TDK	Mean Well RPS-200	NUOWEIDE	PMT-24V100W2BA
Wattage	100 W	50 W	200 W	600 W	100 W
Current capability	0-4.5A	0-2.2A	0-5.9A	0-25A	0-4.5A
Voltage capability	85-264 VAC	100-240 VAC	80-264 VAC	110-220 VAC	90-260 VAC
Efficiency	90%	87%	94%	90%	90%
Price	$52.74	$37.17	$46.00	$29.99	$23.93

After constructing the converter comparison table, as the actual function of the converter within the scope of the project was relatively simple, the team talked it out and decided what converter would be best suited for the design. The power table, even if not accounting for the regulators, was still less than 30 watts, meaning that 60 watts or more was than enough for the discharge system. The efficiencies and current limits were well above what was required for the system, so the decision was made based on what converter would make earth grounding the easiest, so based on the direct connection to the chaise, as well as simple labeling, and giving that the prices are within 10-20 dollars of another, it was decided the NUOWEIDE converter would be the best option.

3.21 - Voltage Regulator Technology

Voltage regulators were a fundamentally critical element of the project. Regulators were the nucleus of external power to the rest of the circuit, and provided an stable and consistent output voltage during both ideal and non-ideal conditions and input loads. [70] Regulators were able to accomplish this through the use of a feedback loop that compared the current output to a set reference output. [71] When a discrepancy between the two values was noted, the system adjusted by either increasing or decreasing the duty cycle to ensure a steady output supply. Regulators could be used to either step down, decreasing a direct current (DC) voltage from its initial input, or to step up, increasing DC voltage from its initial output, in accordance to the specifications of the device. [70]

For this discharge current in particular, a regulator was necessary in order to ensure the microcontroller ran as effectively as possible. [72] The external power supply could not be used directly, since any deviations in power would have led to errors in when alarms would have gone off or even have led to a failure in the system. In addition, regulators enabled relays to receive power without being exposed to an extreme amount of direct voltage, as the voltage would have been scaled down to a usable and safe level before coming in contact with relays and other low voltage parts of the circuit. [72] Conversely, given our design was meant to be effective for high level of voltage, regulators acted as a shield between the potentially hazardous high voltage side and the safer control side with small voltage levels. [73] To ensure efficient performance, a variety of regulator types were researched to identify what would best be suited to the discharge circuit.

3.21.1 - Linear Regulators

Linear regulators are one of the most established and experienced methods for providing steady DC voltage to electrical systems. [70] The essence of linear regulators is based on constant monitoring of the output voltage and a feedback loop to compare set voltage to a reference. [74] An error amplifier, often in tandem located with an operational amplifier, connected to a transistor in series with the load. This transistor acted as a extra resistor in terms of passing voltage through the circuit. If the output voltage was lower than the reference voltage, the transistor would have enabled more current to pass through and increased the output voltage as a corresponding result. If the output voltage was too high to allow for effective efficiency, the transistor would have allowed for less current to pass through, which would have in turn decreased the output voltage. [70] [75] However, this extra energy that resulted due to the voltage difference between input and output dissipated as heat, which noticeably decreased the effectiveness of this product, despite its simplicity. [75]

As a result, the efficiency of this device was highly dependent on the numerical difference between the output and input voltage at any given time. [75] The smaller the difference between the output and input voltages, the more effective the regulator was at that given point. In contrast, a larger difference between the two voltages resulted in a big drop and a big loss in power, and therefore heat. Hence, linear regulators tended to be preferred when there was a small to moderate difference in adjustments between voltages. [70] An immense advantage of a small voltage difference within the use of a linear regulator would have been the lack of noise compared to switching regulators, both at the input and output side. [76] This would have resulted in a decreased power loss, since the Power lost was calculated by $P_{loss} = (V_{in} - V_{out}) \times I_{load}$ [75]. Therefore, regulators with high voltage drops will and needed to be designed with adequate protection for heat dissipation in mind, which could have affected other elements of the discharge circuit. [76]

Within linear regulators, another subtype to consider would have been the shunt regulator. The shunt regulator operateed in a different manner compared to other regulators, with a Zener diode often placed in parallel with the load. [74] A resistor was then placed in series with the initial input voltage, and depending on the load current, the Zener diode either drew in current for the output voltage or shunted the current through the regulator to be released as heat. [74] For low current uses, the shunt regulator could be extremely useful, but as current increased, as the flow was always going to be there regardless of necessity, the Zener diode just dissipated more heat accordingly, which severely damaged the effectiveness of the circuit, and series regulators were used in more complex and varied designs. [70] [74] Overall, due to the effectiveness to cost ratio, and the simplicity of design, linear regulators could have provided a suitable option for further consideration within the tool.

3.21.2 - Buck Converters

Buck converters are an extremely popular DC-DC converter, in which an initial DC voltage is otherwise converted into a lower DC output voltage. [77] In layman terms, the buck converter is called a step-down converter as voltage is slowly decreased downwards. The major components of a buck converter included a switch, an inductor, a diode, and a capacitor to ensure effective energy storage and transfer. [77] [78] When the switch turned on in the circuit, current came into the inductor, which proceeded to store energy within its magnetic field, and the inductive current continued to supply the load current. This resulted in a ripple effect due to the peak and trough current reaction of the inductor. This extra current was taken in by the capacitor, which used the current to generate inner charge, which provided an increase in the output voltage. The capacitor would then even and steady out the final output into a steady increased voltage. Similarly, once the switch turned off, the reverse process occurs in which less current was seen by the capacitor, allowing for the capacitor to discharge and release energy, which resulted in a lower output voltage that was further evened out into a smaller stable voltage. The inner workings that enabled the switch to be aware of turning on and off, and the resulting adjustments that the components make, was due to the controller and the duty cycle. The output voltage was equal to D, or the duty cycle, which was equivalent to the time period the switch is on for, times the input voltage. The duty cycle iwas always a fraction of the time period the switch is on, hence why the output voltage was always lower than the input voltage: $V_{out} = D \times V_{in}$ [79]

A feedback line to the controller compared the current output voltage to a set reference voltage. Accordingly, if the output voltage was too high, the duty cycle would have decreased in order to turn the switch on for less time to decrease the output voltage, and if too low, the duty cycle would have otherwise increased in order to turn the switch on for a certain period of time to increase the output voltage. [78] This period switching process enabled buck converters to regulate a consistent output voltage throughout various lows and highs and different types of input conditions. [77] [78]

Buck converters offered a variety of significant advantages to linear regulators. The effectiveness was significantly higher as the power loss was not released outwards as heat, but instead thrown back into the circuit in accordance to the drop or raise in duty cycle. Efficiencies ranged from around 85%-90%, [80] and in a system that was designed to minimize heat abundance within the circuit, this was a very good level. The response level to potential load differences was very fast compared to linear regulators, along with potential built-in measures and protections within components on the current market. As opposed to linear regulators that only worked for a certain rigid level of input voltage due to the required difference in input and output voltage being minimal, buck converters worked for a wide variety of input voltages. However, potential drawbacks of buck converters included the increased cost compared to linear regulators due to a broader scope in design. The output ripple that resulted required careful filtering that would have been an additional hazard in the design. The complexity as a whole, as opposed to other options, posed a problem to the consideration of this technology considering the limited time available for completion of the device, yet overall buck converters had to be considered as a serious option due to the increased efficiency and flexibility that was provided for powering both low level voltages, along with high level voltages for the long term scope of the project.

3.21.3 - Boost Converters

Boost converters are another type of switching regulator, in which an initial DC voltage is converted into a higher DC output voltage, which would otherwise have been known as a step up converter, as the voltage was increasing. [81] The parts included in the device were the same as the buck converter, yet the inductor was placed before the switch and diode as compared to after in the buck converter. When the switch was on, the inductor took in current and stored energy within its own magnetic field. However, the diode being reverse biased proceeded to block the current flow, resulting in the capacitor discharging in order to maintain the output voltage stability, resulting in a lower output voltage compared to the initial voltage. [82] Similarly, when the switch was off, the inductor released energy and the input voltage was added to the inductor's voltage. The diode was then forward biased, which allowed for a higher level of current to be received by the capacitor and load. The capacitor then charged up and this resulted in an increased output voltage compared to the input. It should be noted that in both cases, the capacitor also would have smoothed out the rough current taken in by the inductor. [81]

About the duty cycle, the basic logic was similar between both types of converters. A feedback loop was used to compare the current voltage to a reference voltage. If the output voltage was too high or too low, the duty cycle, or fraction of time for the switch being on, which would have never exceeded 1, would increase or decrease accordingly. The difference lay in the equation for the output voltage for the converters. For the boost converter, the voltage output can be calculated through this equation.
$V_{out} = \frac{V_{in}}{1-D}$ where V_{out} is the output voltage, V_{in} is the input voltage, and D is the fraction input for the duty cycle. [81] [83]

As the value of D increases, the difference between the input and output voltage gets smaller. As a result, the output voltage increased and increased beyond the value of the input voltage, but with the cost of increased ripple noise and component capabilities, so to an extent. [81] Looking at both converters, the correlation between output voltage behavior and duty cycle changes was the same, with the key difference being that the input voltage for a buck converter was always greater than the output, and the input voltage for a boost converter was always less than the output.
The advantages of boost converters over other types of regulators were various, mainly regarding increased efficiency. Like buck converters, boost converters had an ability to operate over a wide variety of input voltages. This made boost converters an ideal option for industries where a tool with adaptability was essential, such as renewable technology. [82] However, boost converters were rigid to a degree, being only step down, and the increased ripple effect was still present in the output, which would have required further filtering in order to maintain performance levels. [83]

Building on the idea of step up or step converters, there was a device that could have operated on either basis if needs be, called a buck-boost converter. The functional process would have been the same as for a buck or boost converter, but the added adaptability provided a fail-safe in case things went wrong. At a low duty cycle value, the device worked as a buck regulator would, and at a high duty cycle value, the device worked as a boost converter. Flexibility was very valuable when the input voltage frequently could have fallen above and below the preferred output voltage. However, this type of converter would have been very costly and very complex to design. [83]

3.21.4 - Flyback Converter

Flyback converters are an older more isolated class of DC-DC regulators that could either step up or step down depending on what is required within the circuit. [84]At the essence, flyback converters worked like buck and boost converters, yet a transformer was used in order to generate the momentum for current and energy. [84] When the switch was on, current flowed through the primary side of the transformer, which then stored that energy. However, the diode was reverse biased which prevented current from reaching the load. Similarly, the capacitor discharged as a result, and the output voltage dropped and maintained stability. When the switch was off, the capacitor then charged up, which resulted in a rise in output voltage and the smoothing out of the rough output current from the inductor. [85]

For designs that required electrical isolation, flyback converters were ideal as the protection measures were increased and the transformer based design allowed for isolation without a specific isolation stage of production. [86] In addition, flyback converters were also designed to be adjustable for a wide variety of input voltages and the input noise ripple was extremely minimal compared to boost or buck converters. [86] [85] These advantages combined to make flyback converters an ideal option for smaller scale voltage designs, as the cost was also affordable and on the level of linear regulators. [85]

Despite these benefits, flyback converters also came with some serious drawbacks as well. While the input noise ripple was manageable, the output noise ripple was still significant, requiring further filtering. [85] The efficiency of the device was also overall lower than linear and other switching regulators, and this was further emphasized as the power scope went up. This was due to increased strain on the transformer and transistor as usage increases. [84] [85] [86] While the separation and isolation the flyback converter provided between the high voltage and low voltage sides of the application was a major benefit, the lack of efficiency was noted when comparing to similar options.

3.21.5 - Regulator Comparison and Selection

Table 27: Regulator type selection table

Feature	Linear regulator	Buck Converter	Boost Converter	Flyback Converter
Voltage type	Steps down voltage and dissipates any extra energy as heat	Step down voltage by using an inductor to obtain control.	Step up voltage by using an inductor and switches control.	Step ups and steps down by switching transformers and

				isolating other components.
Effciency	Low (30-60) and drops lower under significant voltage strain. [87] [88]	High (80-90) for majority of loads [89]	High (80-90) for majority of loads. [89]	Moderate (70-80) but can drop depending on load and transformer stability. [90]
Cost	Low cost initially but decreased efficiency	Moderate but widely available and accessible designs reduce overall cost. [89]	Moderate but similar to buck converters, widely available and accessible designs reduce the overall cost. [89]	High due to requirement of transformers and other additional components.
Complexity	Very simple with few components	Moderate, requirement of inductor, switch and diode.	Moderate requirement of inductor, switch and diode.	High due to transformers and extra isolation being required
Power	Very limited with high power applications with extra heat dissipated.	Able to deal with high power loads with relative ease.	Able to deal with high power loads with relative simplicity	Average ability to deal with high power due to transformer limitations.

Based on the research and the comparison shown above, it was clear that buck or boost converters were the most ideal option to pursue. Unlike linear regulators, which dissipate a large percentage of power to heat, buck and boost regulators had a high level of efficiency while staying relatively compact and maintaining low thermal waste. However, the design required voltage to be decreased to be suitable to work with other components, which rendered the use of a boost converter ineffective, and the ability to step up and step down, which flyback converters have, was not very useful for this specific product. In addition, flyback converters could have created further design issues to account for the use of a transformer, and overall, buck converters were clearly the best option to pursue further.

3.22 - Regulator Component Selection

After establishing that a buck converter was most suitable for the scope of the project design, components were researched for established regulators in the market, suitable for step down voltages for various standardized input and output volt values. After intense further research, it was decided that these below options would be most suitable for discussion and to choose a final option.

It should have been noted that while purchasing the regulator was one aspect, other aspects of the circuit were needed to be bought as well. In the case of LM 2576 and 2596 and 2575 an input and output capacitor, as well as a diode and an inductor, were necessary, and this cost also furthered the overall budget for the project, along with the regulator purchase. The values of these components were in the micro henry or micro farad range and were not too much of an issue in terms of integration. However, in the case of LM 2678, due to its unique design with the DMOS output switch, more capacitors in parallel, both on the input and the output side, were required, which made the adaptability of that design something to be considered before choosing that option. In contrast, for the TPS regulators, more parts were required, and this was a factor to be considered when building the PCB for the added difficult soldering those parts and additional circuit requirements may have also factored in.

3.22.1 - LM 2576

The LM 2576 is a step-down buck converter that provided, at a maximum, 3 amps of load current with a variety of suitable output voltages that are compatible with the hardware and software within our system. [91] These output voltages ranged from 3.3 volts to 15 volts, along with an option for adjustable unspecified output voltage if needs be. [91] The input voltage ranged from 4 to around 40 volts as well, allowing for adjustable input that leads to further ease in adaptation. [91] In addition, the device also contained current limits, ranging from 4.2 to 6.9 amps in current, along with thermal shutdown protection, as well as external shutdown protection with 50 micro amps of standby current in case. [91] Efficiency for the device rised as the output voltage rised, ranging from 75% efficiency for 3.3 volts to 88% efficiency for 15 volts. [91] However, in comparison to other regulators on the market, the switching frequency was relatively small, 52 kilohertz, which required larger sized components and rendered the size of the PCB board to be larger. [91] A great advantage to the LM 2576 was in its cost, as major electronic sellers currently had the price at 3-4 dollars. The cheap cost and wide availability, along with a simple design and implementation, means the LM 2576 was a great option to consider for use within this project.

3.22.2 - LM 2596

The LM 2596, like the 2576, is a step down buck converter that could have provided up to 3 amps of load current with the same provided output voltages that would have potentially be adaptable and suited to our power design. [92] The output voltages and input voltages were relatively similar, if not the same as LM 2576, but the switching frequency was notably higher, at around 152 kilohertz, which does lead to ultimately a higher comparative efficiency at each voltage point, ranging from 73% at 3 volts, to 90% at 15 volts. [92] The same thermal protection and isolation measures located in LM 2576 were also in place, with standby current also in place, and slightly higher than LM 2576, at 80 micro amps. [92] A higher switching frequency may have led to smaller components and easier placement on the PCB board, which could have made further design a lot simpler. In addition, the LM 2596 was relatively costly, costing around 3-4 dollars, and the more complex design integration, in spite of the smaller circuitry parts, would have made using this regulator a slight challenge, but the improved efficiency, along with the increased versatility to support other subsystems of the PCB board, still made the LM 2596 a viable option to be considered. [92]

3.22.3 - LM 2678

The LM 2678 was comparatively unique, but ultimately still a step down buck regulator that contained a DMOS output switch, a difference to the other buck regulators mentioned. The current load provided up to 5 amps and efficiency was overall higher for each output voltage value, ranging from 82% for 3.3 volts to 92% for 12 volts. [93] The switching frequency was a lot higher than both LM 2576 or LM 2596, at 260 kilohertz, which contributed to the overall increased efficiency. [93] However, it also could have led to extreme output ripple noise, which could have led to complications later on. The thermal shutdown and current limit protections were in order, but the input voltage was slightly more limited, with 8 to 40 volts being the overall range. [93] The LM 2678 was also older compared to the other regulators, which may have led to less efficiency in terms of integration with other parts of the circuit, and also would have been a little more costly in comparison to the other options available. [93]

3.22.4 - LM 2575

LM 2575 was a switching regulator designed to provide a simple and efficient solution for low to moderate power applications. With a maximum load current of 1 amp, and a default switching frequency of 52 kilohertz, the efficiency would have been slightly less than the 85%-90% max efficiency seen in other regulators, yet in terms of simple power handling and extremely cheap availability, LM 2575 would have seemed to be a very good option. [94] However, despite the standard thermal protections and isolation measures, along with the standby current, the load current max was far too small to be used in most modern applications, and the switching frequency, being the same as LM 2575, was also relatively miniscule, and would have represented a real challenge in terms of board size and placement if used. Most newer models could have offered increased frequency, load current and provided similar levels of stability, if not more, when connected to other parts of a circuit design, or more specifically, to the microcontroller. [94]

3.22.5 - TPS 5430

The TPS brand of regulators were also funded by Texas Instruments, with the TPS standing for “TI Power Supply “and contained a couple of key differences in comparison to the LM family. The current specs were very similar, with a maximum of 3 amps being offered for the current input. The TPS 5430 offered a wide voltage range from 5.5 volts to 36 volts, which was roughly similar to the LM family, yet due to circuit design, one could have chosen the output voltage they wanted to emit. [95] This was in contrast to the LM regulators which offered 3.3-, 5- and 12-volt output step down voltages, with a small option for an adjustable voltage. The circuit design of this specific TPS step down regulator contained two resistors through a voltage divider, and a way to manipulate an output voltage through the following equation.

$V_{out} = V_{ref} * (1+R1/R2)$ in which R1was the upper resistor and R2 was the lower resistor. The voltage reference, Vref, was merely the reference voltage that is used for control of feedback. [95]

Based on this equation, the resistor values could have been selected in a manner to easily obtain most desired voltages. In addition, the TPS 5430 had a significantly higher switching frequency, around 500 kilohertz, which in effect contributed to its superior efficiency. [95] While there was no set efficiency, as it tended to lower depending on the variance between the difference between input voltage and final set voltage after step down. For example, going from 24 volts to 3.3 volts may have resulted in a lower efficiency than going from 24 volts to 16 volts. Overall, the efficiency was still higher than the LMs on average, given the step down voltage ratios. The TPS also contained all the standard thermal and current protections located in the LM regulators as well to offer safety in case of potential shutdown. However, the main disadvantage of using the TPS regulator could have come with actually building the regulator. Ultimately, building the PCB of the regulator would have been the main focus, and the more parts and phases of the circuit required, the harder it would have been to ensure a safe and functional PCB. The TPS design contained an extra couple of capacitors and resistors that may have been no issue to breadboard, but could have provided significant strain when actually soldering and building the PCB, and it would have be an essential question to consider the tradeoff ratio between the slightly higher efficiency that the TPS 5430 offers versus the long term issues that may come with designing and building the regulator. [95]

3.22.6 - Regulator Component Comparison and Selection

Table 28: Buck Regulators Comparison Table

Category	LM 2576	LM 2575	LM 2596	LM 2678	TPS 5430
Maximum Output Current	3 A	1 A	3 A	5 A	3-4 A
Input voltage range	4-40 V	4.75-40 V	4.5-40V	8-40V	5.5-36V
Output voltage range	1.25-37V [91]	1.25-37V [94]	1.25-37V [92]	1.25-37V [93]	1.22-32V [95]
Switching Frequency	52 kHz	52 kHz	150 kHz	260 kHz	500 kHz
General Efficiency	75-88%	75-88%	73-90%	82-92%	95%(maximum)
Safety Features	UVLO, thermal shutdown	UVLO thermal shutdown, 3 A switch	UVLO, thermal	UVLO, thermal	UVLO, thermal, stop-start
Additional components	1 inductor + 2 capacitors+ 1 diode	Same as LM 2575	Same as LM 2576	Same as LM 2678	Same as LM 2678 plus additional capacitors and additional resistors
Approximate per unit cost(from DigiKey)	$3.86	$3.98	$5.37	$6.99	$5.10
Thermal performance	Relatively cooler as long as the current	Ran relatively warm till max current	Similar thermal behavior to the LM 2596	Required large copper sink	Required some sort of power pad for extra heat.

	did not exceed 1 amp.				
Main disadvantages	Only could have delivered/take in 1 amp at maximum.	Larger inductor and a lower frequency meant more clunky parts in general.	A higher EMI was noticed	Lower range of input voltage, meaning the overall buffer/margin of error was less.	Layout of extra components and overall PCB design would have been much more difficult than the other regulators

Based on the table and prior research, the team came up with an option that was able to balance suitable performance with reasonable economic and long term reliability. For the LM 2575, the maximum 1 amp limit was seen as a major drawback that the team felt resulted in potential risk for certain components that might draw close to that total current, and we did not want to use close to the maximum current in any case. The TPS5430, while technically the most efficient, would have required a much larger soldering and overall PCB effort with a high chance of failure, so the team decided not to consider that regulator as an option. Efficiency wise, there was, when looking at the big picture, a very miniscule difference between 88 percent and 92 percent so the thought then came to the increasingly large switching frequencies for the cases of the LM 2596 and LM 2678 respectively. This could have been a potential hindrance as the duty cycle switches would have been off for longer periods and a higher input voltage might have been required, making the startup process increasingly difficult. For this reason, it was ultimately decided to go with the LM 2576 regulator as it was most suitable at combining overall efficiency with higher reliability.

3.23 - Communication Technology

3.23.1 - Universal Asynchronous Receiver/Transmitter

The Universal Asynchronous Receiver/Transmitter protocol, abbreviated to UART, is one of the three main communication protocols used in embedded systems. It is the oldest, and the only asynchronous communication protocol of the three considered for this project. It is commonly used for communication between embedded and general-purpose computers to facilitate debugging or transferring small amounts of data.

3.23.2 - Inter Integrated Circuit

Another commonly used embedded communication protocol is Inter Integrated Circuit, or I^2C. It is a bus-based communication protocol that implements the master-slave paradigm. However, I^2C stands out because it allows for multiple devices to act as both the master and slave, at the cost of drastically slower communication times as more devices are added to the I^2C bus.

3.23.3 - Serial Peripheral Interface

Like I^2C, the Serial Peripheral Interface (SPI) is a synchronous communication protocol using the idea of one device issuing commands to another device. However, a major difference is that SPI is designed such that there is a main chip that is responsible for selecting which target it wants to send and/or receive data from. This difference allows SPI to reach speeds far higher than I^2C, but all connected devices must be controlled by the main microcontroller.

3.23.4 - Communication Protocol Comparison

Below is a table to provide comparison of the three main communication protocols used in embedded systems, which consider ease of implementation, each protocol's availability given our part selections, and ability to transfer data.

Table 29: Communication Protocol Comparisons

	UART	**I^2C**	**SPI**
Ease of Implementation	High	Low	Medium
Used in Selected Parts	Some	Some	All
Data Rate	Low	Medium	High

3.24 - Communication Protocol Selection

Due to SPI's availability in our selected hardware, along with its high data rate, well-documented implementation, and its ability to connect multiple devices on the same bus if needed, we decided to implement SPI as our primary communication protocol between chips in our system.

3.25 - Programming Language Technology

3.25.1 - C (or C++)

The C family of languages has been synonymous with manual memory manipulation and management since the early 1970s, which lends itself to the field of embedded programming. It has been the go-to language for microcontrollers due to the language's high speed and easy conversion to machine code. Later, the C++ language built upon the foundation of C to provide additional features including the object-oriented paradigm while retaining the benefits of C.

3.25.2 - Python

A more recent development has been the programming language, Python. Unlike C, Python code is not compiled, rather it is interpreted line by line. Combined with its modern and looser syntax, this allows Python to be an easier language for some people to pick up compared to other languages including C. However, Python's interpreted nature comes at a significant cost of both processing speed and the hardware requirements to run it. For example, MicroPython is a variant specifically designed for use on microcontrollers and embedded devices but requires "256k of code space and 16k of RAM" [96].

3.25.3 - Programming Language Comparison

Below is a table to compare the familiarity, execution speed, level of abstraction and manufacturer support for each discussed programming language.

Table 30: Programming Language Comparisons

	C / C++	**MicroPython**
Familiarity	High	Medium
Speed	High	Low
Abstraction	Medium	High
Support on Selected MCU	High	Variable, Low to Medium

3.26 - Programming Language Selection

Given the team's higher familiarity with the language, it being more commonly used in industry projects compared to MicroPython, and intended support from the manufacturer, the code for this project will be written in a combination of C and C++.

3.27 - Integrated Development Environment

3.27.1 - Espressif IDE

The Espressif IDE is the first-party solution for developing code to run on ESP32 microcontrollers. It is based on the Eclipse development environment and uses a CMake toolchain for programming C and C++ code to the microcontroller. Source code for the IDE is provided by an Apache 2.0 license, along with a variety of open-source components such as header files and networking libraries under their individual licenses.

3.27.2 - Arduino IDE

A popular open-source alternative to the Espressif IDE is the Arduino IDE, which is officially supported by Espressif for development of ESP32 boards. While it does not have as many ESP32-specific features, it more than makes up for it with the sheer variety of libraries made for Arduino boards that have been made compatible with ESP32 by Espressif and others. Additionally, the Arduino platform has IDEs available for both C and Python-based microcontroller programs.

3.27.3 - JetBrains CLion

CLion is the integrated development environment for the C family of languages developed by JetBrains. Like most other JetBrains' products, it requires a license to use, but JetBrains offers educational licenses for students and university projects. It includes many built-in features not offered by many other IDEs, and has plugins from both JetBrains, microcontroller manufacturers and third parties to support development of software and debugging tools for embedded projects.

3.27.4 - Visual Studio

Visual Studio is the family of multi-purpose IDEs owned by Microsoft. There are multiple variants, including versions with free licenses for individuals, students and open-source projects. It offers a variety of plugins to work in different languages and build targets, including some for embedded development.

3.27.5 - IDE Comparison

Table 31: Integrated Development Environment Comparisons

	Espressif IDE	**Arduino IDE**	**JetBrains' CLion**	**Microsoft's Visual Studio**
Familiarity	Low	Medium	High	Medium
License	Apache 2.0	CC-BY-SA-4.0	Student	Student
MCU Flashing	Native	First Party Plugin	First Party Plugin	Third Party Plugin
Feature Set	Medium	Low	High	Medium
Library Availability	Low	High	Low	Medium

3.28 - Integrated Development Environment Selection

For a combination of reasons including its open-source license, extensive support from libraries of third parties such as the manufacturer of our chosen display, and previous experience using the software, our team has decided to use the Arduino IDE as the integrated development environment for the software side of this project.

Chapter 4: Standards and Design Constraints

4.1 - Applicable Standards

4.1.1 - IPC-2221/2222: Standard on PCB Design

IPC originally stood for the “Institute of Printed Circuits”. It was founded in 1957 as a trade association. It now is recognized as the Global Electronics Association. They created standards that cover data transfer, base materials, board qualifications, soldering of components, and more. One standard they are in charge of is IPC-2221, the “Generic Standard on Printed Board Design” [97]. This covers the general requirements of PCBs and component mounting. It is broken up into a few subcategories of PCB and device type: IPC-2222 through IPC-2227. These cover the following items/types of boards: rigid, flex, PC card, MCM-L, HDI, and Embedded Passive Devices respectively. The following discussion will be limited to the the section on rigid PCBs (IPC-2222), as that is what is relevant to us and our project.

One of the first aspects of the IPC-2222 standard is defining “performance” classes for the products. These define the complexity, functionality, and quality/testing frequency of the end-product boards. These classes (1, 2, 3) are as follows: General Electronic Products, Dedicated Service Electronics Products, and High Reliability Electronic Products. Boards are divided between these categories based on what kind of service and reliability is needed. Boards that are used in critical safety roles in say the medical, automotive, or aeronautic industries would be class 3. Their failure would mean risk of injury to people. The next class, class 2, would be for automotive, but non-safety electronics and industrial or business equipment where long-term reliability and performance are required, but it’s not safety critical if the component fails. The last, class 1, is products where function is the only requirement. These would be items like electronic toys, hand calculators, and the like. These still need to function and follow a standard, but it is not critical how long they last or for safety.

As part of being a standard on PCBs, the IPC talks about minimum spacings for electrical traces and openings. Table 6-1 in the IPC-2222 standard discusses various minimum spacings between electrical conductors based on whether they are coated, uncoated, what kind of coating, what kind of conductor, and what the voltage difference between the two conductors is. This section is relevant to us because it helps to tell us what the minimum spacings will be for our high voltage side of our PCB. While the table tops out at over 500 volts, it does list a specific formula to use. This formula involves taking the voltage over 500 and multiplying it by 0.0025mm and adding that to the current distance to come up with the new clearance distance value. Another important note they mention is that you should not rely on the solder mask to maintain isolation/resistance. You should make your traces in accordance with the open conductor spacing and having them coated will act as a supplement.

The standards do mention materials and minimum widths and thicknesses in section 6.2 and table 6.4 of the standard. A trace’s conductivity relates to its current temperature and its cross section. The larger a trace’s cross section, the more conductive it becomes. The lower temperature a trace is, the more conductive it is. Traces that are carrying high current on PCBs need to have thick traces. The thickness of the copper traces are called the weights. A “heavier” copper relates to a larger thickness trace. When designing your PCB and ordering it, you can select different weights of copper to adjust how thick the copper layers are on your board. If you need a certain width of trace and more current carrying capacity, you can select a heavier copper pour to increase the conductivity. You can also route traces in parallel to increase the effective total cross section. Another thing this section calls out is to account for the variance in thickness due to the process. Often times you base your values on the minimum final thickness (the minimum thickness that your trace can be after all processing is completed).

Getting more into the layout/placement of traces, there are plenty of rules or guidelines to follow. The standard introduces the idea of "necking down" or "beefing-up" traces, where traces need to temporarily have their widths decreased or increased. These should be avoided, and the traces should be made a standard width wherever possible. If possible, all traces should run in a vertical, horizontal, or 45 degree orientation. This makes the documentation/layout for the PCBs easier and makes the computer programs to drill/create the traces simpler. It stated that 90 degree bends should be avoided also for electrical characteristic reasons. It is also mentioned that there may be special rules for higher speed communications like SPI. You need to account for the line impedance and length/locations of branches relative to each other. When routing traces through pads or holes in the PCB, the traces should be equally spaced in the center between the holes and lands. Locations that will be subject to solder by hand need relief. If the hole is connected to a large ground plane, then the ground plane will suck heat away from the hole and the solder iron will need to stay to pump heat to make the joint. Instead, of a direct connection, an empty ring is made around the holes and thin traces connect the hole outwards. This increases thermal resistance so the join can be heated up quick enough to solder then leave. This helps reduce cooking certain portions of the board with soldering irons.

Concerning the vias and lands and holes, the items that make up internal and external connections on the PCB, there are various standards. Holes have a minimum thickness for the area between the hole and the edge of the copper fill around it. This minimum thickness is referred to as the minimum annular ring. The thickness of the land that makes up the portion the hole is centered in comes from an equation involving the maximum diameter of the finished hole, minimum annual ring requirement, and standard fabrication allowance (the variation in process). For vias, the connections between layers on a PCB, there are requirements for minimum spacing depending on PCB layer thickness and the class of board. Small holes will require electrical or laser drilling, while larger holes may use traditional drill bits. Holes should be sized in accordance with standard drill bit sizes if possible and larger. Otherwise, custom milling will be necessary.

The solder mask is the top layer of the PCB coating, usually made of polymer that covers the copper traces. Included in the solder mask is how the vias in the PCB are covered. Some vias are left exposed, but if an application requires insulation for electrical or corrosion-resistance reasons, a covering can be applied to the via openings. If the solder mask is used for electrical resistance and characteristics, your design should specify the minimum thickness. This way you can ensure that your design will be correct after manufacturing. Some boards that require extra insulation can have conformal coatings. The thickness and materials of these coatings vary.

The standard also mentions power delivery schemes to help reduce noise in AC systems. To do this, it recommends using a multilayer board and having ground planes underneath of high frequency traces. The ground planes here act as mirrors and copy the AC signal creating an image signal. Also recommended is adequate decoupling capacitors connected at the power/grounds of the device to help reduce AC effects. It is common in ICs to see decoupling capacitors recommended to be placed directly at the ICs to stabilize the voltage. The various digital signals are also broken up into four classes: noncritical signals, semi-critical signals, critical signals, and super-critical signals

4.1.2 - IEC-60664: Standard on Insulation Coordination

IEC-60664 is one of the main industry standards that engineers utilize to prevent hazardous conditions such as electrical shock, arcing, and insulation failure within a device. This prevention is achieved by adhering to the recommended creepage distances, clearance distances, and insulation performance presented within the standard. IEC-60664 applies to general electrical equipment, including PCBs, with nominal voltages up to 1000V AC or 1500V DC. With the system in this senior design project needing to be designed for a peak voltage of 1200V DC, the standard clearly applies. As a result, an adequate understanding of creepage, clearance, and insulation is required.

Creepage and clearance distances are relatively simple concepts that can play a large role in the safety of an electrical device at higher voltages. Creepage is defined as the shortest distance along the surface of an insulating material between two conductors. Clearance is defined as the shortest distance in air between two conductors. Although they are similar concepts, the actual values for creepage and clearance have no physical relationship to each other. This will be further evident when the process of finding adequate distances for a particular application is covered. It is also worth noting that for most applications, the creepage distance will be a higher value than the clearance distance, but awareness of both is still critical in design.

In order to find the adequate creepage distance for an application, three factors need to be known: The working voltage of the system, the pollution degree of the environment, and the material group of the insulator. The working voltage of the system is defined by the standard as the Root Mean Squared (RMS) value of the AC or DC voltage across the insulation. The pollution degree of the environment and material group of the insulator are more complex factors that warrant further discussion. Starting with pollution degrees, the main idea that this factor tries to communicate is that certain environmental conditions can make conductive paths along a surface easier to develop. Dust particles, condensation, and different types of debris can all build up over time on the surface of an electronic device and make potential arcing easier. IEC-60664 categorizes different types of environments under four distinct pollution degrees labeled degree 1 through 4. Pollution degree 1 is the most ideal of the four and assumes that only dry, nonconductive pollution occurs. By contrast, pollution degree 4 is the worst case and assumes that conductive dust and wet conditions such as rain are present. Finally, the material of an insulator is based on the Comparative Tracking Index (CTI), which is a voltage value derived from standardized testing done on an insulator to measure its resistance to dielectric breakdown along its surface. Based on the CTI, materials are categorized into four groups: group 1, 2, 3a, and 3b. Group 1 is the strongest of the four and is reserved for materials with a CTI of greater than 600V. The CTI thresholds then progressively decrease down the list of groups, with group 3b being the worst. CTI values are typically known for a given material, however if unknown then the worst-case material group can be assumed under the standard.

Finding adequate clearance distances also depends on three factors: the transient overvoltage seen in the system, the pollution degree of the environment, and altitude at which the system operates. Since pollution degrees were already discussed with creepage distances, they will not be reiterated here. Concerning transient overvoltages, IEC-60664 defines these as an increased voltage level that can be oscillatory or no oscillatory, but typically lasting only a few milliseconds. Transient events of this nature are considered more in clearance measurements because arcing or flash events in the air can happen in an instant. Electrical tracking, which is what creepage distances seek to prevent, by contrast is a process that takes longer to develop. In addition to transient overvoltage, altitude is also taken into consideration in regard to clearance distances. This is because of the dielectric strength of air decreases at higher altitudes due to the breakdown voltage being a function of air pressure. IEC-60664 takes this phenomenon into account for clearance calculations by providing correction values to be used for altitudes above 2000 meters.

With a better understanding of IEC-60664, it becomes much simpler to analyze and estimate creepage and clearance distances required for this senior design project. Beginning with clearance, the main factors to account for will be transient overvoltages and the pollution degree of the environment. Since NextEra Energy has specified that this product will be used in a laboratory environment within the state of Florida, the altitude that this product will operate at will not exceed 2000m. Therefore, utilizing the altitude correction factors for clearance calculations is not required. The specified laboratory environment also implies that a very ideal pollution degree of 1 can be assumed. Lastly, while transient overvoltage for the system may be difficult to know precisely, a conservative estimate of 2kV can be made, which is significantly higher than the nominal voltage of 1.2kV for the system. With all the major factors defined, clearance tables defined by IEC-60664 can be used to find a recommended clearance for this system of about 1.2 millimeters. The two other factors needed to define the creepage distance will be the working voltage of the system and the material group of whatever insulator will be considered. Despite the voltage in the discharge interfacing portions of the system decreasing over time from a peak of 1200V, it is safer to assume 1200V as the fixed working voltage for those components in this analysis. Additionally, it is also safe to assume a material group of 3b as a worse case for the creepage distance. Together these factors determine a creepage distance of 4.2 millimeters which, as expected, is larger than the required clearance distance. Overall, the calculated distances for this application are fairly reasonable and is incorporated into the final design for proper operation and safety.

4.1.3 - IEC-60063: Preferred Number Series for Resistors and Capacitors

IEC-60063 standardizes values for resistors, capacitors, and other electronic components. In general, the standardization of these components helps to ease manufacturing burdens and simplifies how component values should be stocked. Rather than having to constantly create custom component values, manufacturers can depend on designers utilizing preset standardized values. Over time this lowers manufacturing costs and makes components cheaper.

In terms of how the values are determined, IEC-60063 incorporates what is known as various E-series sets of component values based on various tolerances. These include E3, E6, E12, E24, E48, E96, and E192. The numbers associated with each series designate the number of equal logarithmic steps or values are available for each decade. For example, a decade of resistances could include values between 1Ω and 10Ω. Within this defined range, the E12 series will only specify 12 unique resistance values between 1Ω and 10Ω while the E96 series would specify 96 unique values. Additionally, because the E96 series fits more values within the same decade, the tolerance between each value must be much tighter than the E12 series. In fact, the typical tolerance for E12 series resistors is 10%, while the tolerance for E96 series resistors is 1%. Lastly, the fixed spacing between the values in a series can be found via the following formula: $10^{\frac{1}{m}}$, where m is the number associated with a particular series (3, 6, 12, etc.)

In terms of this project, this standard is important to be aware of when underdoing design. When designing it can be possible to specify component values that may not be standard and readily available on the market. Additionally, tolerancing can have effects that must be accounted for within a circuit. This is especially important for the discharge stages and other circuitry that can be very sensitive to or dependent on component values.

4.1.4 - Serial Peripheral Interface

While the Serial Peripheral Interface (SPI) is not defined by one of the major standards organizations, its ubiquity with synchronous inter-device communication has made SPI the go-to communication protocol for systems that require full-duplex interaction between two or more devices. Originally introduced by Motorola as a feature on a line of microprocessors, SPI follows the Master-Slave paradigm which has one main "master" device selecting and sending data either directly to a single "slave" device or a bus of receiving devices distinguished by the main device's chip selection, and uses four wires: one for a shared clock, two for simultaneous bidirectional communication, and a dedicated per-device active-low chip select signal [98].

Each time a SPI slave device receives a clock and is selected, it uses bit shifting to write a single bit to the master device, and writes the input provided by the master to the newly vacated bit. One downside of this protocol is that both the master and slave devices need to send their respective LSB or MSB, otherwise the data must be converted by each device after reading. Alternatively, projects that implement multiple devices using SPI but do not want to use the master device to waste time reading from one device and immediately writing to another can implement a "daisy-chain" network, where the output of each device is connected to the input of the next device until the data is sent to the device where it originated. Then, when the master sends the chip select signal, all devices in the chain will shift the data by a bit, allowing multiple devices to read data from multiple other devices while the full system still being controlled by a master device.

4.2 - Design Constraints

To ensure that the team developed a realistic prototype in accordance to the set standards, it was essential for some constraints to also be developed in order to allow for a narrower scope, which allowed the team to have increased clarity on certain elements of the design. This included the overall space of the design, with a separate area for the chassis board for discharge. as well as the method for providing wattage to the overall circuit.

4.2.1 - Power Constraints

The power of the overall circuit needed to be manageable for both the team, and NextEra in the future if they want to expand on the prototype, to work with suitably without compromising safety and efficiency. A majority of the power went towards powering the relays and ensuring the relays were always working properly. Regarding the power system, some form of adapter was used, be it an external power adapter or a AC/DC converter, and provided a steady supply of voltage to be supplied into a switching regulator, such as the LM2576, and its numerous versions that allow for different voltage outputs. Certain components required 5 volts, and certain components required 3.3 volts, and many different components required varying degrees of power, such as the sensors and op amps, as well as the software-based components such as the microcontroller unit and the light emitting diodes. If power was not suitably managed, the system could have potentially experienced voltage inconsistencies, excess heat, and overall instability and inefficiency, which could have severely damaged the long-term functionality of the prototype.

The system contained a couple of parts that required much of the overall power provided, mainly the three relays being implemented in the sensing system. A relay, at its simplest essence, is a long and thing wire coiled up to work like an electromagnet, which with current creates an electromagnetic field which thus latches and unlatches accordingly. Because the wire was so long, there was considerably increased resistance compared to a wire of normal length, and thus more voltage was required in order to ensure a high current and ensure the device latches and unlatches at the correct times. Therefore, a constant and frequent source of power was required in order to guarantee that this process flows and would not be interrupted.

Ensuring that the regulation of power was stable and efficient was essential to allow for the steady operation of the overall capacitor discharge system. Being efficient with the use of steady power supply into the initial circuit and requiring proper voltage regulation and resource management is general enabled a system that provided stability, efficiency and long term reliability without worrying about system breakdown.

4.2.2 - Space Constraints

In a capacitor discharge system integrated onto a chassis board with supporting components such as regulators and relays, design space became a factor of major importance. Each subsystem required cautious placement in order to minimize tangling and interference, and design of short current paths for high current pathways, as well as making sure heat protection is adequate. The majority of the footprint was compromised of the large storage capacitors, and thus their layout will, in turn, dictate the amount of space required for the other components. Then, within the level of space that the other components such as the regulators and sensors will have, they needed to be positioned in a manner to allow for efficient protection and isolation between the low voltage and high voltage sides of the circuit.

Given the outline of the circuit design, space constraints were made more important by the need to find a balance between electrical performance with workability and accessibility. Furthermore, the inclusion of so many components required that PCB construction might be more difficult, and more layered PCB design was required. Overall, effective use of the horizontal space and efficient positing of both the high and low voltage zones provided assurance of reliability and longevity.

4.3 - General Constraints

While the design of the prototype contained practical limits in terms of the power consumption and the size of the PCB board and chaise, more general, non-engineering constraints needed to be considered as well. Money and time had always been objects of consideration for every senior design project, but the complexity of needing to produce high voltage calculations and a low voltage design that should have, with a couple of minor changes and step ups in terms of component values, be able to be applicable at higher voltages as well. The location of the use of the product also needed to be considered, as the safety measures varied depending on whether the location is lab based or in a more public setting where higher prioritization needed to be placed on exposure to others.

4.3.1 - Time

Our capacitor discharge project was subject to the constraints imposed by the Senior Design schedule, which was divided into Senior Design 1, which focused more on research and initial development, and Senior Design 2, which focused more on PCB construction and finalization. Both courses came with their own sets of deadlines and deliverables which combined to ensure that timing is tight and the margin of error in every department of the design process was extremely slim.

Senior Design 1 emphasized completing scheduled based tasks, such as planning of the project, designation of team roles, and documentation of project based progress and deadlines. The bulk of the focus for that course focused on research of component parts and design framework. In order to maintain this, certain deadlines had been set, including the submission of the Midterm Milestones document by October 31st 2025, and completion of the demonstration of the capability of the project, which included showing certain components have been ordered and worked to a functional capability. These deadlines were absolutely fundamental in ensuring the groundwork for our project was established and that all required research and planning and processing was completed before we moved on to other focal points of actual implementation and PCB design.

The team also had some additional challenges, both internal and external, to deal with that served as additional roadblocks in order to complete the required deliverables. With only one computer engineer on hand, it meant that at least one other member of the team was required to step up, and all three electrical members had limited outside experience dealing with C++ and microcontroller applications and coding beyond undergraduate class labs and lessons. The knowledge gap these members had put increased pressure on the sole computer engineering student, who did not have much reliance or fallback options if things went incorrect during the software process. At best, extra time was needed at times in order for an electrical member to be caught up to speed on what he needed to do in order to best help the computer engineering student, and at worst, it could have led to potential failure based on one scope part of the system and execution of said part. Thankfully, that was not the case. Moreover, the team was dealing with a new potential hardware system for the schematic, known as Atriun. It is a application, while decently popular and familiar to the sponsor of the project, NextEra, the team lacked overall experience in this department which created problems when designing our PCB board and time was required in order to master certain uses of the design. Eventually, with the grace of our sponsors, the thought of using Atrium as an application was discarded in order to use KiCad, as it allowed for increased familiarity and ease for PCB design and assistance.

Moreover, the team was also enrolled in other classes, with the projects and exams that class entailed and maintained a level of priority to other commitments. One of our team members, Kealan, maintained a four-class schedule, along with work in the semiconductor lab as well as a position as the workshop chair for the Institute of Electrical Engineers(IEEE), while another one of the members of the team, Will, in addition to a four class schedule, also worked at another job on the weekends. Balancing the workloads and commitments of the other members can and did lead to difficulties when scheduling consistent meetings with both other team members and the sponsor of our project. This led to certain team members not being on the same page as other, and other forms of general communication was often needed to take over, such as calls on online platforms such as Discord or Zoom.

Another aspect of the project where time was a serious constraint regarded the ordering of parts and the testing phase of the PCB. It was very important that parts were ordered relatively early because certain elements, such as the chips for the regulators, needed to be breadboarded properly into a circuit to ensure the adequate voltage was being delivered, and if discrepancies were noted, new parts needed to be then ordered even more urgently to replace them. During actual PCB construction, it was almost a given that the initial design would not work and modifications had to be made, so time needed to be allotted, as had been done in Chapter 10, for errors to be made and corrections to be implemented accordingly. The team also needed to be in constant communication when ordering parts, since certain models of components sometimes did not meet the required standards that other components require, and for that reason, it was essential that every team member ws staying on top of their specific sub system and coming together to discuss errors and correct errors both in part ordering and actual manufacturing.
Overall, to meet these deadlines and submit the required deliverables, the team needed to maintain and follow a tight schedule, be in constant communication in terms of what was required and needed to be quick to address and solve any issues that may and will arise, given the lack of overall experience in this project experience and setting. Furthermore, consistent and efficient time management was very important among team members in order to ensure successful completion of the Senior Design course and project.

4.3.2 - Economic

The economic constraints of the prototype primarily revolved around the costs and budget of the overall design, both in terms of our economic contribution and what NextEra provided. Being that this project was sponsored, the overall current budget listed in Chapter 10 was decently accurate, but the difference lay in terms of costs that we payed from out of our pocket and what certain aspects NextEra covered. Parts that were required more urgently and with less time available, as well as certain cheaper components, were covered from the team, while more costly components, most of the discharge system, for example, that could afford to be purchased later than other components, were more likely to be covered by Next Era. While the support of a sponsor provided us with a buffer of sort, they also stated a general budget that they did not want us to exceed, so some degree of limitation is in place regardless.

The team recognized that with the limitations of budget, certain aspects of the design were not as enhanced as we would have liked. There was a tradeoff that needed to be made in terms of designing a product that was cost effective or a higher efficient performance. A balance between the efficiency and productivity of the product while maintaining a certain level of economic efficiency in terms of spending was essential. This especially applied when considering the protection and distinction between the high voltage elements and the low voltage elements where separation of the two was crucial to not only ensuring safety but also allowing for an effective transition.

Other aspects to consider economically included the designation of potential backup funding. With an initial budget already looking around 1500 dollars, something that needed to be factored in was potential backup expenses in case parts didn't work the first time, or in case the initial designs failed. While this provided buffer of sorts in case certain things went wrong, it also further narrowed our time and economic scope considering this backup budget was likely money that ended up coming out of pocket and not from the sponsor. A factor that also had to be considered was unexpected delays in terms of shipping and increased demand for certain components, which did lead to us spending extra money in order to ship the part relatively quickly. It was important that these small, yet potentially significant factors were factored into the overall budget and then we maintained a level of smartness and caution when planning and managing our financial pool and prevented needless spending.

Overall, the economic constraints provided significant barriers that caused the team to fully consider factors that could have been fairly detrimental if market research was not done adequately efficiently. The use of a budget limited us in terms of looking for products that were cost effective rather than simply the best available products on the market to accomplish the design goals. By allocating some extra money for backup in the case of component or design failures, we ended up affording a degree of flexibility and significant decreased the financial stress both we, and our sponsor, were under. Furthermore, by discussing and carefully planning our budget, focusing on the purchase of the most crucial components first, and making educated and researched decisions about things to prioritize when making financial decisions in the project, we were able to complete and design our prototype without compromising both effectiveness and the project scope.

4.3.3 - Manufacturability

A key constraint to consider lies in the manufacturability with the design and potential further implementation of the prototype. The sponsor, NextEra, told us that the prototype we were designing was meant to be used in a research lab setting, with adequate potential protection available for anyone who will use the product in the future. Our prototype was aimed at being used as a testing, more experimental base for both low and high voltage applications. If the prototype works to a suitable level of efficiency, the sponsor aimes to use the calculations and design to replicate future versions for lab use. Thus, it was essential that the design could be manufactured effectively since it was a process that needs to be repeated by other parties.

One of the main manufacturability issues came with PCB design and implementation. The design included a separation between high voltage and low voltage elements. Developing a printed circuit board, or a PCB, for this system required high levels of accuracy, obtaining specific components that fit the size and were relatively simple to solder. It should be noted that a high level company like NextEra obviously had more resources to solder and to design and make PCB's so we could be a bit more flexible in terms of the actual building, yet it was still essential that the layout was proper and there were no issues with component selection and fitting. Any error, even an extremely small one, on the PCB board could have led to disastrous consequences in large scale and long term manufacturing.

Durability and long term use was also one of the main manufacturability concerns of the system. The capacitor discharge needed to function reliabilly over very long stretches of time, and needd to be able to be resistant to changes in temperature and ripple effects from electrical current noise. This was especially important due to the lack of temperature sensors, so the users would not be immediately sure of a drastic change in temperature until a visual or sense based indication, such as touching and feeling the heat within the components. In a lab setting, the enclosure and protection, as well as the isolation measures, needed to meet certain industry requirements in order to maintain effective performance in the future. Our prototype was primarily focused on efficiency and functionality for both high and low levels of voltage, yet in a professional lab setting, a manufacturable version of the capacitor discharge needed to pass further tests and obtain electrical safety certifications, especially on the protection parts.

In order to address and fully solve these potential issues, the selection of proper fitting components, optimization of the PCB layout, and maintaining a balance between cost and efficiency was be essential. Our final design was merely designed for functionality, but in order to make it ideal for larger scale manufacturing, these constraints needed to be addressed properly within the design choices and selection we ultimately made, and furthermore, needed to be adaptable and flexible in case they were changed, within the project process or within the long term manufacturing process that NextEra ultimately took.

4.3.4 - Scalability

Scalability was perhaps a crucial aspect of this project more than any other specific idea due to the distinction of the project scope between low and high voltage requirements. While the general understanding was that a low voltage prototype that should theoretically also work at high voltages, with calculations provided, was thought to be suitable, the team decided to make a high voltage version as well, given that the calculations were already being made. While this made the system a more usable and realistic application for industry use, it also resulted in increased difficulty in terms of getting the system to function and increased costs in now having to cover more components than originally planned.

Thus, having increased the workload of the original system significantly, it was essential to develop a way to incorporate the elements of a higher voltage application, which would likely be just larger values of components for the low-scale application, while not compromising the protection and effectiveness of the original system and still achieving the baseline goals and objectives. This meant that further costs and space in the budget needed to be outlined for HV(high voltage) parts along with a separation measure between low and high voltage, as the team wanted to make sure the LV(low voltage) didn't affect the HV and vice versa. This required further space on the board and increased the overall footprint of the PCB design. With these potential roadblocks in mind, the team needed to make sure that the HV and LV sides did not interfere and that the space and capacity of other components, such as the discharge overall and the microcontroller, had the capacity to handle HV application.

4.3.5 - Health and Safety

The safety of both the team and the users of the product was something that needed to be taken into account both before and after construction of the prototype. Dealing with such high levels of voltage, and specifically discharging said levels, could have been extremely hazardous, both for the team and for any long term scaling of the product that NextEra may have wanted to contribute. For these specific reason, it was outlined that the team would not be allowed to test the prototype at high levels of voltage, with the inference being that if the system worked at low levels of voltage, then with the right component values the system should also work at high levels as well, which was a fair assumption. Thus, it was essential that the product was tested only in lab settings, even with low levels of voltage, an aspect also outlined by NextEra for its future long term use of the product.

Electrical safety was the primary aspect of the design that needed to be properly considered. Since we ended up using AC power from a wall outlet, all wiring and power components needed to be adequately protected, with potential copper covering on the regulator chips in order to prevent overheating. In addition, further precautionary measures potentially were needed to be taken in order to prevent typical electrical safety concerns such as short circuits or other electrical failures.

Chapter 5: Comparison of ChatGPT with other Similar Platforms

Over time, large language models have rapidly developed and gained increased popularity among the public, industry, and academia. By utilizing unique training algorithms along with a massive amount of training data, AI chatbots can now rapidly retrieve and summarize information, brainstorm creative ideas, debug code, and edit writing. Due to their increased popularity and capability, there is a new focus among many industries to investigate ways in which large language models can help streamline work and increase productivity. Similarly, throughout this senior design project AI tools were utilized to assist in general research and design considerations to increase understanding and productivity. Whether this was achieved, however, depended heavily on the case of use. Some of these cases were analyzed below along with general limitations of AI chatbots. The cases were divided among the specific subsystem of the project that they were used for.

5.1 - AI Chatbots and Their Limitations

Before discussing specific case studies, it was necessary to provide context on existing AI chatbots and general limitations across their models. These limitations impacted how the team utilized AI and provides a background for analyzing the AI's response.

5.1.1 - ChatGPT

Many AI chatbots exist, but undoubtedly the most popular of them all is ChatGPT which was developed by OpenAI, a private company focused on AI research and development. The current free model of ChatGPT available to users is GPT5 which was released in August 2025. [99] GPT5 is marketed as having reduced instances of hallucinations (instances where the AI provides false or misleading information as fact), while also increasing performance in writing, coding, and health queries. [99] Despite these performance improvements, OpenAI still listed some limitations of the tool. For starters, despite reducing instances of hallucinations, they can still exist, and it is important to be able fact check the responses that the model provides. [99] The prompts provided also had a huge impact on the quality of the model's answer. Even small changes in the prompt phrasing changed the potential response. While ChatGPT was, and still is able to ask for clarifying questions to provide a better response, it was crucial to write an initial prompt that is clear, specific, and concise to guarantee the best potential outcome.

5.1.2 - Google Gemini

Google Gemini is the main AI tool which was developed by Google DeepMind and provides a variety of functions including the ability to converse and understand text, as well as being able to adequately respond to audio and visual images, and be able to provide coding advice and application. [100] The current version of Google Gemini is Gemini 2.5, which was released around June 2025. [100] The latest version of Google Gemini is marketed as having improved efficiency in all departments, which include image generation and audio instruction. [100] In addition, the latest version of Google Gemini also includes some experimental and innovative measures such as enhanced reasoning, which aims to use parallel thinking and learning through repetition in order to allow the AI to think of numerous possibilities before generating a well-rounded response. Furthermore, Gemini seamlessly integrates with other Google apps such as Google Maps, Docs, and Drive. Despite these innovations and noticeable overall improvements in the design, Google

Gemini still has some notable limitations. Like ChatGPT, hallucinations are still present, and for that reason it is essential to check responses and weblinks sent to make sure they exist and the information seen from weblinks are valid. The model also heavily depends on the user's knowledge of said subject when asking for information, as a less detailed question will lead to an increasingly vague reply. It is essential to always be clear and very detailed when writing prompts within Gemini as even with the tool's built in feature to ask for clarity, it is very easy to be steered in the wrong direction and lose crucial understanding. Google Gemini also struggles with more higher scale operations, such as massive data loads, which leads to a slower and less accurate response in comparison to other platforms.

5.1.3 - Copilot

Microsoft Copilot is the primary AI tool developed by Microsoft for Microsoft technologies, particularly Microsoft Word, PowerPoint, Excel and Teams. It provides significant major assistance when it comes to coding applications, integrating well with Visual Studio Code and providing coding suggestions and blocks of code. [101] It should be noted that while ChatGPT is capable of the same function, Copilot focuses more in depth on coding as a whole and can provide more detailed responses in comparison. [101] Furthermore, the application is integrated into all the products mentioned. [101] In addition, the software can offer many of the same benefits as ChatGPT and Gemini such as image generation and audio understanding. In addition, Copilot also offers very integrated methods to collaborate with others, such as document collaboration and offering scheduling conveniences for timings within Microsoft Teams. Potential limitations within the scope of Copilot include the quality of said AI-generated code that needs to be fact checked and rechecked repeatedly before implementation. [101] This also leads towards copyright limitations as code is taken from other aspects of the Internet and can lead to potential plagiarism implications. [101] Another limitation within the tool includes cybersecurity and suggesting elements of code that contain security issues. Extra precautions would need to be put in place to use the tool further, given all the concerns. [101]

5.1.4 - General Pros and Cons/Comparison

Large Language Models(LLM) come with a variety of benefits and downsides when put into use. Idea generation and new insights are a highly valued benefit of using LLM's as the tool offers different perspectives on a topic, along with inquiring in depth about what specific knowledge a user is requiring, which allows for increasingly detailed inquiries and responses to further knowledge down to specific ideals. [102] Scalability is also a great benefit to using LLM's as the tools are adapted to manage and view a variety of applications and databases before providing analysis. [102] That way, an inquiry can be effectively researched by the LLM before delivering a response, as opposed to searching countless sources on open source engines such as Google or Bing. Improved communication is another significant upside to using LLM's both in the context of translating languages, as in verbal languages, allowing for people with different linguistic abilities to benefit massively with communication with other cultures [102]. Another aspect of improved communication that LLM's assist with regard writing, specifically generating outlines and paragraph structure. Furthermore, writing assistance also comes with suggestions of focal points and fixing grammatical errors.

At the same time, these AI tools also come with a variety of downsides when put in application. Often when writing, the user will ask for a source for the information being generated, and while a source will come in, the source is often a weblink to an expired page that can no longer be accessed, which puts the user at risk of plagiarism. [103] Inaccuracy is also a major issue within these tools as they operate based on pattern recognition from large datasets, but true critical thinking and self-contextual applicability is lacking within the models, which results in lack of accuracy when posed with increasingly more specific inquiries. [103] Bias and misinformation is another negative implication as LLM's are typically trained on massive datasets that may contain biases and inaccuracies. [103] Thus, it is essential to fact check, both personally, and from others, information given from LLM's, in addition for developers of AI in the future to finetune and adjust future versions of the tool to be less susceptible to biases. Finally, with the advent of AI as a whole, it is a common danger for students to become overly reliant on AI which could have severe ramifications on the critical thinking and problem-solving skills, as well as decreasing levels of creativity and uniqueness within the report and writing style.

5.2 - Case Studies Within the Discharge System

For the discharge system, AI was used as part of the research process to provide a starting point for understanding what technologies existed for various component types. Within Appendix E, case study 1 highlights an example prompt [1a] of AI being specifically for general resistor research along with the responses from each of the three LLMs discussed. Of the three, the response from ChatGPT [1b] is the most detailed, offering the most amount of content while also summarizing that content effectively in the form of various tables. Copilot [1c] also followed a similar structure, highlighting the same resistor technologies and summarizing effectively through tables. The detail of the content, however, was much less. Of the three, Gemini [1d] was the most unique. In its output it offered a feature to create a specific research plan for the topic and approve of the AI's strategy for conducting said research. It then took multiple minutes for the AI to follow that research plan before providing an output. The ability to have more customizability over how AI conducts research is an exciting feature. In reality, however, the output only provided 40+ sources of information, rather than summarizing the information. This defeated the goal of using the AI in the first place. There are some options to have the AI build certain features off the sources of information (flashcards, webpages, etc.), but having to take the extra steps to better organize and understand the information is a weakness.

Another important thing worth noting when utilizing AI for research in this manner is the availability/nicheness of the topic itself. Resistors are a very old and common component with over a century of maturity. As a result, there are a plethora of quality resources, articles, and webpages that AI can pull from to produce a informative and helpful output. If technology research was done on a topic that is more cutting edge, then its possible AI has less to pull from in terms of sources. Fortunately, the technology utilized in the discharge is very standard (resistors, relays, wire), so AI can be a great source for expediting research.

In order to provide a more open ended prompt to the different AI applications, a prompt was fed for the AI to explain what their process would be for calculating the temperature rise in an TE HSC100 power resistor over the course of a 30 second discharge cycle. The datasheet for the resistors was also attached. The exact prompt can be found within Appendix E under case study 2. Without getting into specifics about the exact theory pertaining to the prompt itself, it seemed as though ChatGPT (2b) gave the most thoughtful answer. Rather than trying to provide one very specific answer, it outlined multiple assumptions it was making and provided a range of answers based on different cases. Copilot (2c) also was able to do this, but to a lesser extent than ChatGPT. It outlined key assumptions and uncertainties and clearly explained its thought behind the theory, but an attempt to provide a single answer was still made. This shows that ChatGPT can more effectively understand nuance, estimation, potential grey areas. The Gemini response (2d) also unique under this prompt. Of all the LLMs, it was the only one that made an attempt to read from the graphs included in the datasheet. ChatGPT and Copilot did pull written information from the datasheet, and acknowledged the existence of the provided graphical data, but they did not source as having used them to develop their answer. This made the response from Gemini more practical in the sense that it did not get overly cluttered by assumptions and calculations. It simply read straight from the document. The answer it provided was also fairly within the range of the other AI models.

This second case study provides insight into how AI should be used to approach engineering design and calculations. Firstly, the assumptions that AI applications have to be clearly understood in order to provide context to the answer. None of the AIs in case study 2 provided the same answers, but their approaches and assumptions differed. Engineers need to be able to understand the differences and even be able to specify their own assumptions to the AI for better results. Additionally, the outputs for these cases are estimates, and no AI response at the moment will ever be able to provide concrete answers for more complex design considerations. But even then, having a resource that can provide estimates and act as another backcheck of an engineers work is a valuable tool as long as its limitations are understood.

5.3 - Case Studies Within the Sensing System

There was AI usage regarding the sensing system and components. It was used to help find different technologies to compare, understand data sheets, and figuring out what components to select. AI and generative LLMs are very powerful tools, especially those trained well and with access to the internet/searches. In this section I compare a few of the main tools (Grok 4 Expert, Claude Sonnet 4.5, Gemini 2.5 Pro) against each other. The first prompt I gave was a question asking the LLM to list all of the possible voltage sensing systems/components/categories that could possibly read the voltage level of the capacitor and translate that into the MCU. Reading through the prompts each model had their pros and cons. Each model talked about the different kinds of technologies as well as listed some example components. I liked the response that Gemini gave the best. It listed off the various kinds of architectures and ways to solve the problem, then under each category, it gave a few more specific examples of how to apply specific ICs to solve that problem in that category. Claude gave a shorter outline filled with many more specific examples of ICs that could be used. The list was very complete, covering more technologies than the other LLMs, and while I understand the different technologies, it would have been nice for it to re-explain how each technology works along with their strengths and weaknesses. Grok did a good job at this, it listed off many of the kinds of technology as well as a specific example for each and a summary of how it works with strengths and weaknesses. However, Grok did not summarize this or provide a separate comparison between or recommendation of a specific technology/component to use like the other LLMs did. There were also follow-up prompts/questions provided by both Gemini and Claude, asking about creating a block diagram or schematic. This would have worked fine, unless the schematic/diagram was a image generation, these LLMs are not great at schematic generation. Grok's app had follow up prompts, but nothing in the message it sent.

In the same chats of each LLM app, I made another prompt asking about the temperature sensing technologies and components that would be able to work with my systems parameters and translate the temperature of the discharge heatsink/plate into our MCU. The responses to the prompts were similar to the responses seen in the previous cases. Claude listed out multiple different kinds of technologies, but with either very brief or non-existent explanations of each. It did cover many different kinds of sensors as well as specific model numbers for all the sensors. The table provided at the end was filled with each technology and one to three examples or subsets of each technology. The comparing values section included the accuracy, cost, range, mounting ease, and more. It then gave detailed recommendations. The recommendations it gave were a best overall, best for highest accuracy, best digital only solution, and more. It provided me with the options to choose the best based on what I valued or needed most from the temperature sensor. Grok's response to this prompt was pretty good. It gave multiple different kinds of technologies as categories then gave subcategories within those of more specific kinds of technology. It listed pros, cons, examples, and explanations throughout the response text. In the comparison table it listed off all the values we would care about (accuracy, temperature range, pros, cons, etc.) Gemini's response was good, but not as detailed or with as many options presented as the other two. It did do a good job of explaining how each type of temperature sensor works, where its pros and drawbacks come from, and why or why not it would be a good fit for my application. That may have been partially why it did not include as many examples or types of technologies. Some are just unpractical for our specific needs regarding temperature range, accuracy, packaging, and power. It did not list as much information, but it was good information. Questions were again asked by Gemini and Claude directly, but only indirectly with Grok.

The third prompt asked about specifics of isolation technologies, strategies, and components. It also asked if there were any gaps in understanding or principle in my idea of the design so far. Gemini did a good job at summarizing what I asked. It explained what items would need to be grounded and which items would need to be isolated. It then went on to explain how to isolate those items, what kind of features the isolators for these systems would need, specifications and such. After that, Gemini went into depth about the different kinds of isolators, what each are good at, and how they work. It summarized all of this information into a table comparing the technologies of isolators, what their best use cases would be, their pros, their cons, etc. Grok provided a similar response. It covered IEC and UL standards for PCB and electric isolation. It mentioned all the items that should be isolated/grounded. It mentioned how to handle isolated power on the HV side and control/signal paths between items that cross the LV-HV boundary. It also summarized this in a table, comparing the different types of isolators. Claude was an interesting case on this. The response from the prompt by Claude was much longer than any of the others. I had to tell it to continue multiple times to get the rest of the information. It started by listing many areas that would need protection/isolation. It then went into explaining the different kinds of isolation technology and components. For each kind of isolation technology, it listed the subcategories and multiple examples within each subcategory. It then had a short summary listing the advantages and disadvantages at the end of each subcategory. It also did a similar thing for grounding and other safety strategies such as interlocks or case open warning systems, double isolation, overcurrent protection, etc. It then started to make many tables comparing isolation technology for various situations. It then went into recommending specifics (technologies and components) for my situation and use case.

As said before, generative AI and LLMs are very powerful tools that have many applications. We see companies using AI to analyze weather data and forecast the weather better than any reporter has been able to. We see it being used to predict finance markets and when to best perform maintenance on equipment. Many companies are also integrating their own LLMs trained on private company data to better help the people who work there communicate and get tasks done in accordance with company standards, practices, quality, etc. LLMs are valuable tools. They are trained on massive amounts of data and have that data retained perfectly in their memory. Before, if you had a question, you would have to try to think about how you could get your question to be solved. Now, you can just ask your question directly. It speeds up the question-answer process, leading to information being learned in those who use it. However, it is not without its drawbacks. Some argue that it decreases brain functionality or capability. Some argue that half of learning comes from having to struggle to find the material or the background/side material you learn on your way to answering a deeper question. One issue we may have in senior design in particular is thinking that an answer given by an LLM is correct because it uses technical jargon or is long, but it may still be missing key information or be factually incorrect. These errors are called hallucinations. They are especially dangerous in LLMs, because the LLMs will say them with full confidence, but still be incorrect. Often, confidence is associated with correctness, but it can be a detriment in this case.

5.4 - Case Studies Within the Power System

For the power system, AI was used as a component of the research process to provide a starting point for what regulators were available for a capacitor discharge project. Case study 3 and 4 within Appendix E showed the responses given by ChatGPT, Gemini and Copilot in exactness, as well as the elaborated prompt in detail. On an overall basis, the level of detail ChatGPT gave in terms of design considerations was vastly superior to the other two tools. All three tools recommended roughly the same types of regulators, such as linear regulators, switching (including buck and boost) regulators, yet GPT further provided recommendations for type of regulator based on the function of the project. For example, if the capacitor voltage was numerically higher than the load voltage, then ChatGPT recommended a buck converter, which was the case during our project. Google Gemini merely listed a brief description of each type of regulator, while Copilot listed out a brief list of advantages and disadvantages for each type of regulator, including more uncommon cases such as shunt regulators. ChatGPT had all the above listed already, in addition to use cases, marking it clearly more detailed in comparison to its competition. Furthermore, both ChatGPT and Copilot also asked follow up questions to the inquiry, such as whether I would have needed assistance choosing components or a comparison table to be made of the trade offs of each type of regulator. The latter inquiry asked by ChatGPT was clearly the more detailed response, demonstrating that in this specific inquiry, it was clearly the most well equipped to handle further questions.

Elaborating on the inquiry, it was asked whether ChatGPT could come up with the mentioned table, along with different types of buck converters equipped for both 3.3 volts and 5 volts at a minimum. In response to this, a variety of types were suggested, such as non-synchronous and synchronous buck, along with more specific types from Texas Instruments. However, since my inquiry was more general, the lack of detail was clear. On a more general note, all 3 applications provided a decent start on a more knowledge-based inquiry, where AI applications can also, in the future, provide in depth information based on massive searches and data sets.

The next inquiry that was in mind was more creativity based, which can be verified in Appendix E, Case Study 4, mainly on what additional features could be added to the power subsystem besides the requirements such as the regulators and AC-DC adapter? From all three AI applications, I received roughly similar answers, mainly the use of bleeding resistors, temperature and current sensing, isolation and protection materials along with power switching with a MOSFET. However, all of these features were already be located within other aspects of the design, and it was there where the lack of creativity and context that AI is limited by acts as a determent. While ChatGPT was able to provide the most information and different types of components for further use, it felt like it just gave me a list of every possible component to use in general, rather than something specifically needed for a power subsystem. ChatGPT listed out UART as a example of a communication/telemetry feature, which clearly dealt more with software than power. Similarly, Copilot provided status indicators such as LED's or displays as a component for a power subsystem, again an aspect of a system that had more to do with the software side in terms of programming lights to turn on or off. With further context, AI could obviously have been more specific, such as if I had provided the design for the other subsystems with the microcontroller and user interface. Ultimately, the responses received showed that given context and clarity regarding a question or inquiry, all 3 platforms were able to provide competent responses yet ChatGPT provided more options and general information as opposed to Copilot or Gemini. Yet when questions will get more general in the future, as users often asking questions will not have true clarity on a topic hence why the question is being asked, AI responses will probably get extremely general and rely on user clarity and detail for further instruction, a major note to take into consideration when using AI software in the future.

5.5 - Case Studies Within the Computing System

One of the areas of interest surrounding the emerging technology of large language models is their ability to assist with software development by augmenting the writing code phase of a project. Over the past few years, there have been several notable plugins developed to insert these tools into integrated development environments, such as Google's Gemini into Android Studio or Microsoft's Copilot into GitHub. In past projects where the use of these generative transformers and subsequent documentation of the experience of using the tools was required, I have struggled with the phenomenon of LLMs forgetting the context of a conversation or "hallucinating" a non-existent function. More case studies for the computing system will be added for the process of implementing our project's software design in an embedded environment.

On the other hand, a strong point of LLMs is the summarization of well-documented topics, where they are less prone, but not entirely immune, to generating mistakes due to the high volume of data surrounding the subject during the model's training. For example, when searching Google and prompting Microsoft's Copilot for common application of the Serial Peripheral Interface, both models highlighted the use of SPI in memory, industrial devices and audio interfaces. Gemini highlighted the connectivity applications of SPI, while Copilot included a section to explain why SPI has risen to be an unofficial standard of the embedded world.

Chapter 6: Hardware Design

6.1 - Discharge System and High Voltage Calculations

Since the scope of this project involves designing a discharge tool for high voltage applications but only testing the device at low voltage, theoretical calculations and simulations become especially important. As a result, the following section will focus on the theory behind a controlled capacitor discharge and the calculations and simulations used to determine the discharge time, power draw, working voltage, and thermal performance.

6.1.1 - Capacitor Discharge Energy and Voltage Setpoints

The energy stored in the electric field of a capacitor can be expressed as a function of its capacitance and the voltage across it. This is shown in the following equation:

$$E = \frac{1}{2}CV^2$$

Based on the requested specifications from NextEra, the discharge system is designed to operate on capacitor banks with a capacitance of 1650μF and a rated voltage of 1200 V. This yields a stored energy of 1188 J. In order to design an effective discharge system, the distribution of dissipated energy across the three discharge stages needs to be considered. The energy absorbed by a stage is determined by the change in capacitor voltage it experiences before the subsequent stage activates. As a result, the voltage setpoints for each stage become the main way of controlling their energy dissipation.

The first stage of the discharge process should be designed to handle the bulk of the capacitor energy. This then provides flexibility for the other stages to handle less energy, but at a much faster rate to meet the less than 30 seconds discharge requirement. Within the current design, stage 2 of the discharge can begin anywhere between 800 to 600 V. This means that stage 1 will absorb anywhere between 55% and 75% of the capacitor's initial energy. Stage 3 of the discharge can begin anywhere between 400 to 200 V. So, stage 2 will absorb anywhere between 14% and 42% of the capacitor's initial energy, and stage 3 will absorb anywhere between 3% and 11% of the capacitor's initial energy.

Table 32: Bounds for Voltage Setpoints

Stage	Start Voltage (V)
1	1200
2	800 to 600
3	400 to 200

As stated before, stage 1 will see the majority of the energy in the system in addition to the highest voltage level. This means that the equivalent resistance of that stage will need to be higher in order to handle the start of the discharge. As will be discussed soon, this higher resistance will create a slower rate of discharge initially. However, since the second and third stage see less energy and voltage, their equivalent resistance can be much lower and create a faster discharge rate that makes up for the slow speed of the first stage.

6.1.2 - Discharge Time and Stage Resistance

The voltage decay of a discharging capacitor can be expressed as an exponential decay function as seen below:

$$V = V_o e^{-\frac{t}{RC}}$$

In this equation, the discharge is related to the initial and final voltage being analyzed along with the RC time constant, which is a product of the capacitor's capacitance and the equivalent resistance that it sees in the system. With the voltage setpoints established for each stage, it is possible to impose a max discharge time on the stages as a starting point for finding adequate resistance values. Initially, it was assumed that the max time for each stage would be 10 seconds. Below are the initial calculations under that assumption:

$$R1_{Eq} = \frac{-10}{0.001650 \ln(600/1200)} \approx 8743.6\Omega$$
$$R2_{Eq} = \frac{-10}{0.001650 \ln(200/800)} \approx 4371.8\Omega$$
$$R3_{Eq} = \frac{-10}{0.001650 \ln(10/400)} \approx 1642.9\Omega$$

To be closer to standard E-series resistance values, and to accommodate the availability of certain resistances in chassis mount resistors on the market, the following choices were made for each stage's individual resistance values: $R1 = 10k\Omega$, $R2 = 4.7k\Omega$, $R3 = 1.8k\Omega$. It is worth noting, however, that these selected values are not the equivalent resistance of each stage. In fact, the equivalent resistance will be lower since stages are added in parallel to each other over the discharge cycle. After taking this parallel effect into account, the following are the true equivalent resistances: $R1_{Eq} = 10k\Omega$, $R2_{Eq} = 3.2k\Omega$, $R3_{Eq} = 1.2k\Omega$. As seen, with the exception of the first stage, the equivalent resistances are under the initial values obtained from the max time assumption. The first stage taking longer than 10 seconds is acceptable since it needs to dissipate the most energy and the other stages will be faster to make up for it. Below is the initial LTSPICE circuit with simulation results for the maximum and minimum discharge time, followed by a table summarizing various discharge time for each stage at different edge cases of voltage setpoints:

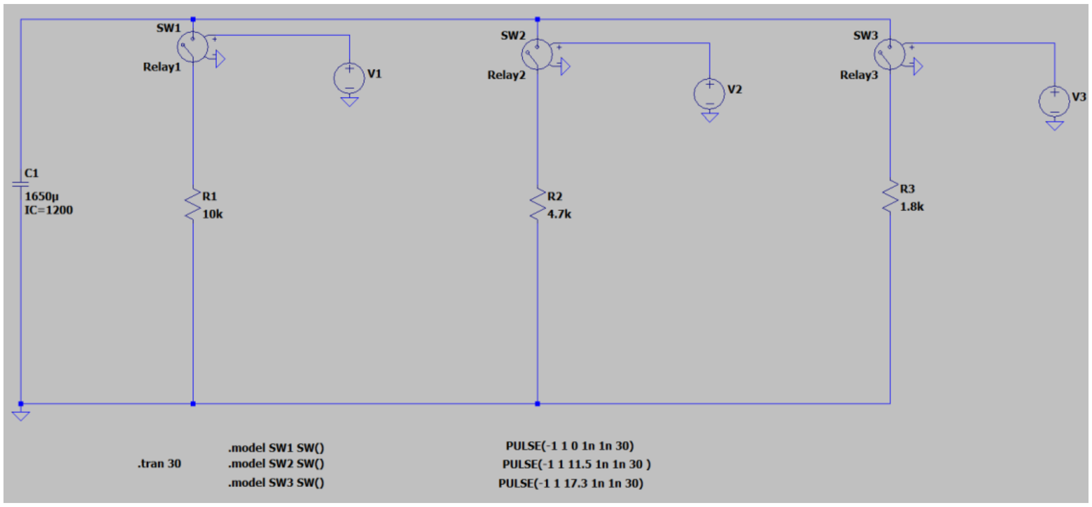


Figure 4: LTSPICE Model with Equivalent Stage Resistances

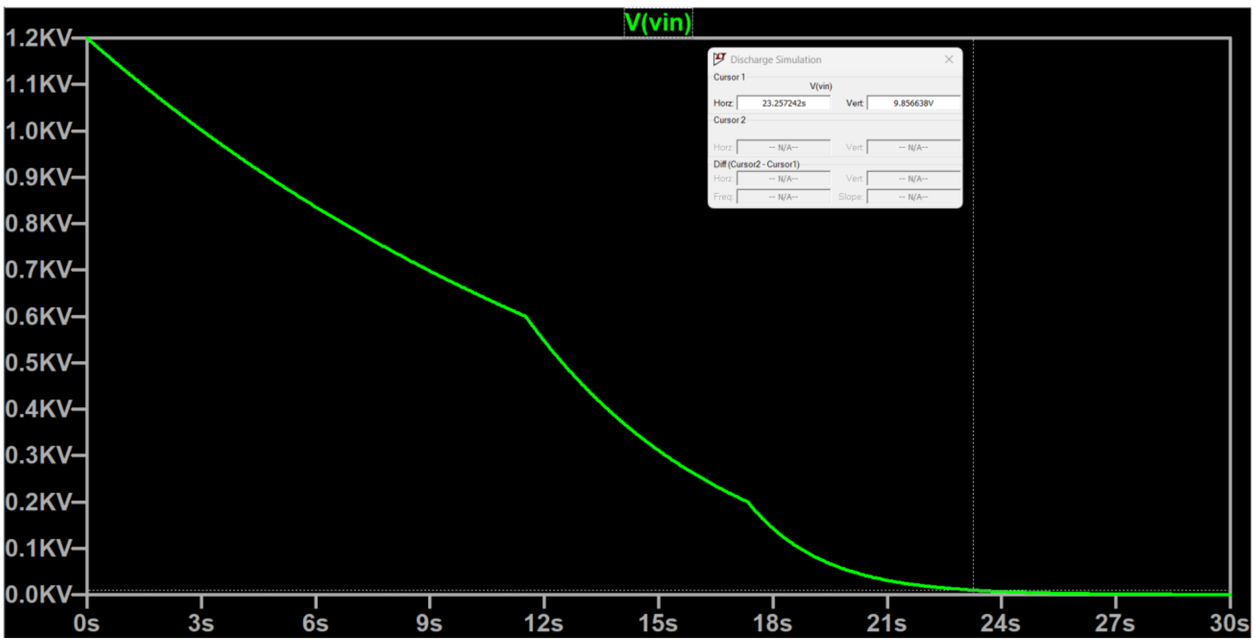


Figure 5: Max Discharge Time Simulation

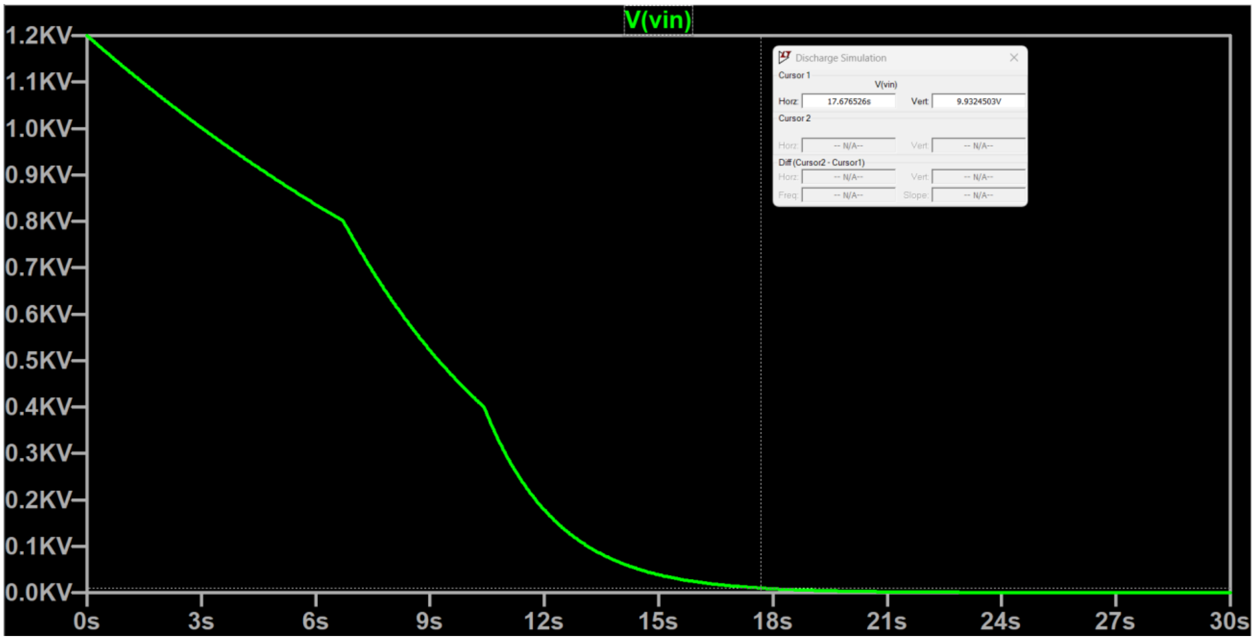


Figure 6: Minimum Discharge Time Simulation

Table 33: Discharge Time for Voltage Setpoint Possibilities

	Voltage Range (V)	Time (secs)
Stage 1	1200 to 800	6.7
	1200 to 600	11.5
Stage 2	800 to 400	3.7
	800 to 200	7.4
	600 to 400	2.2
	600 to 200	5.8
Stage 3	400 to 10	7.1
	200 to 10	5.7

So, based on the simulations, the maximum time that this discharge design should take to reach a safe voltage level (<10 V) would be around 23 seconds. This provides an adequate amount of margin for the small effects of increased external resistance from items such as wires and the relays and overall switching/processing time for each stage to activate. The minimum time would be around 17.5 seconds. Based on the voltage setpoint ranges, this provides around 5.5 seconds of possible adjustment to the discharge time based on user input, which is suitable to the sponsor.

6.1.3 - Voltage, Power, and Current Ratings

Arguably more important than the discharge time is the ability of the resistors to handle the applied voltage and pulse of power from the capacitor. When comparing the power and voltage handling, it became clear that the working voltage of the resistors will be much more limiting to the design than their power capabilities. As a result, the working voltage calculations will be discussed first, followed by the power calculations, and concluded by the calculations of the maximum expected current in the system.

To calculate the maximum working voltage of a resistor, some important information from the datasheet is required. The datasheet for TE Connectivity's HSC100 series of chassis mount, wire wound power resistors can be found in appendix C. Within it, the maximum working voltage, assuming the power rating is not exceeded, is listed at 1900V. This is much higher than the max voltage seen by the system which is 1200V. Taking the power rating into account, however, allows for the calculation of a maximum working voltage that is derived from ohms law. This is shown in the formula below:

$$V_{max} = \sqrt{P_{max}R}$$

The actual working voltage of a resistor will be the lower value between the 1900 V provided in the datasheet, and the value provided by the formula. To make use of this formula, the max power of the resistor must be known. According to the datasheet, the HSC100 resistors are rated for 100 W. This, however, assumes very ideal thermal management of the resistors on a standard heatsink. Although it is planned within the design for these power resistors to be mounted onto an aluminum plate which will provide some heatsinking, it is more conservative to utilize the resistor power rating in the absence of a heatsink, which is 50 W. This way, the discharge design will not fully depend upon a perfect heatsink design. Under this assumption, the following working voltages were calculated for resistance values utilized in the final design and series combinations of resistors were used to ensure that the voltage for each resistor did not exceed the calculated working voltage:

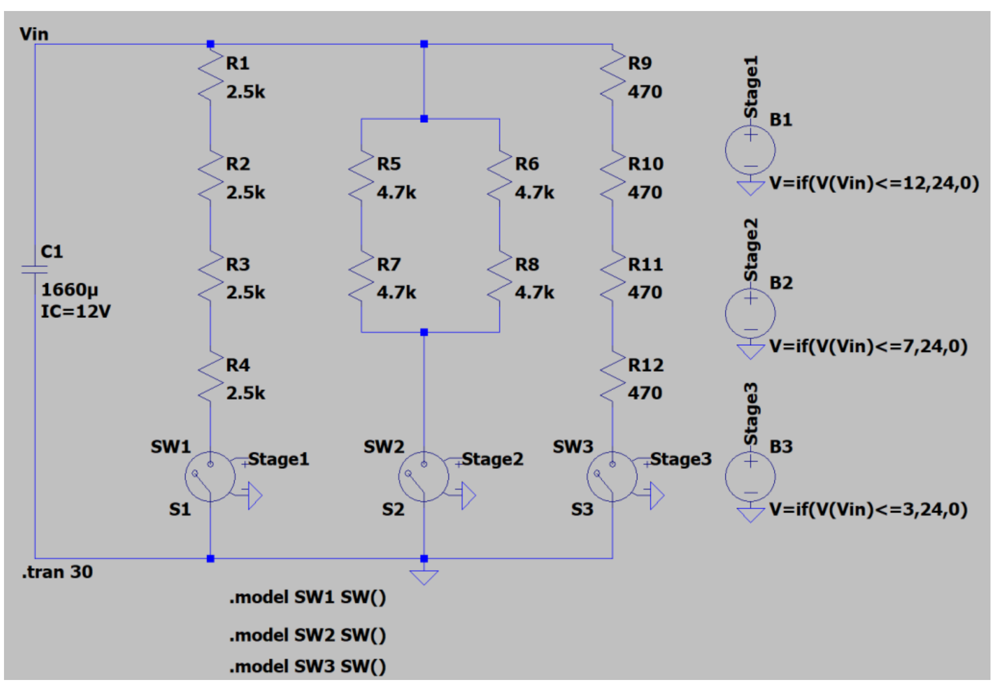


Figure 7: Final LTSPICE Model for Discharge Stages

Table 34: Voltage Margins per Discharge Resistor

Resistance (Ω)	Calculated Max Working Voltage (V)	Max Voltage Seen in Design (V)	Margin (%)
470	153.29	100	34.64
2500	353.55	300	15.01
4700	484.76	400	17.36

Both the peak power and average power that each of the resistors see in the system was also analyzed. This was done by isolating each stage of the design and applying the maximum initial voltage that a stage would see. The stage was then left connected for the maximum amount of time it is expected to operate in the discharge system. For example, when analyzing the first stage, the initial condition of the capacitor in the simulation was set to 1200V and only the first stage was connected to the capacitor for 30 seconds. For the second stage, the initial voltage would change to 800V, and the stage would be left connected for about 23 seconds. For the final stage, the initial voltage was set to 400V, and the stage would be left connected for about 19 seconds. Below is a table summarizing the results for all three stages:

Table 35: Peak and Average Power per Resistor

Resistance (Ω)	Initial Voltage During Test (V)	Test Runtime (secs)	Peak Power (W)	Average Power (W)
2500	1200	30	36	9.64
4700	800	23	34	5.73
470	400	19	21.2	1.73

Lastly, the maximum current in the entire system was analyzed by setting the stages to activate at their highest voltage setpoint and simulating the current through the capacitor throughout the discharge process. Since all the stages are in parallel, and the stage resistance progressively decreases, and the current waveform will have three distinct spikes over the discharge time. The largest of these spikes helped inform decisions on suitable wire gauge and relay selections for the project. The largest spike seen coming from the capacitor peaks at around 335mA. For good margin in the design, a wire gauge that can support at least double this current would be ideal. As shown in previous research, most wire options with high voltage insulation will offer minimum wire gauges of around 22 AWG. The current carrying capacity of this wire gauge, or wire gauges with lower numbers than this (ex: 14 AWG) should be more than sufficient to handle the expected current in the system. The simulation results can be seen below:

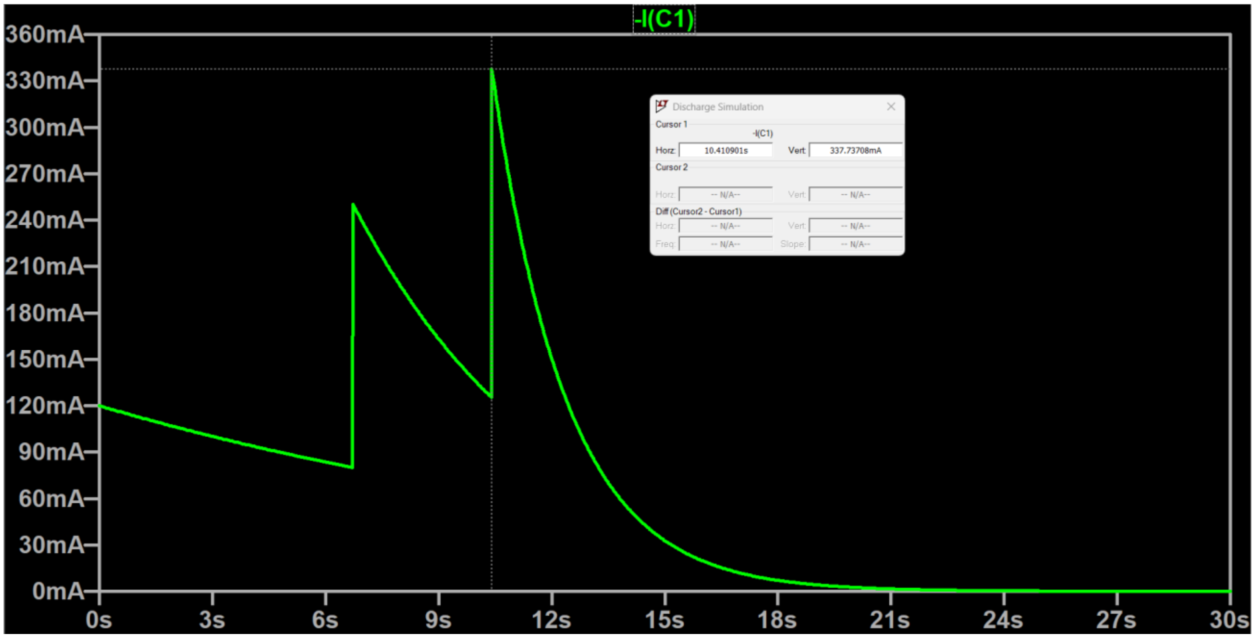


Figure 8: Capacitor Current Profile during Discharge

6.1.4 - Effect of Component Tolerances and Switching Speeds

Since the designed discharge time is extremely dependent on the resistor and capacitor values because of the RC time constant, it is worth analyzing the effect that component tolerances will have on the discharge time. All the discharge resistors have a ±5% tolerance on their values. Additionally, NextEra has specified that the tolerance on the capacitor banks that they utilize is ±10%. To simulate a worst-case discharge time, the capacitor value was increased by 10% and all resistor values were increased by 5%. This creates the highest, and subsequently slowest, possible RC time constant. The simulation on LTSPICE was run in the same manner in which the original discharge time simulations were run, and the results can be seen below.

Table 36: Discharge Times Accounting for Component Tolerances

	Voltage Range (V)	Time (secs)
Stage 1	1200 to 800	7.87
	1200 to 600	13.55
Stage 2	800 to 400	4.37
	800 to 200	8.67
	600 to 400	2.53
	600 to 200	6.88
Stage 3	400 to 10	8.56
	200 to 10	7.02

Under the specified conditions, the maximum discharge time rises to 27.45 seconds. As a worst-case figure, its also worth accounting for the max operating time of each relay, which is 25 milliseconds. With three relays in the system, this adds 75 milliseconds to the overall discharge time. The digital components that control and drive the relays also have switching speeds associated with them, but when compared to operating time of the relays, they are fairly negligible. Thie brings the final max discharge time to be 27.525 seconds.

6.1.5 - Thermals and Mechanical Design

When it comes to predicting the thermal performance of the discharge resistors and the aluminum heatsink, the following calculations will act more as estimates as opposed to an in-depth analysis and simulation. Starting off with the potential temperature rise in the heatsink, the highest of the previously calculated average power for the discharge resistors can be used as a starting point for knowing how much energy the aluminum heatsink will absorb. With this it can be assumed that each of the 12 resistors in the discharge design will dissipate an average power of 10W over the course of 30 seconds. So the total energy across all of the resistors can be found via the formula below:

$$Q = P \cdot t = 120 \cdot 30 = 3600 \text{ J}$$

Its worth noting at this point that 3600 J of energy is much higher than the 1180 J of energy that was calculated to be stored in the capacitor at 1200V. This means that the initial assumption for this calculation will yield a very worst case scenario result. Assuming that all of this energy gets absorbed by the aluminum plate, then the temperature rise in the plate will be dependent on the plate's mass and its specific heat capacity. For the discharge design, the aluminum chassis shall be a 1 foot by 2 foot plate of 6061 aluminum with a thickness of 0.25 inches. For comparison, the standard heatsink size recommended by the resistor's data sheet is about 1 foot by 1 foot and 0.12 inches thick. After converting this sizing to metric units, the total volume of the selected plate will end up being 0.001179 cubic meters. With the density of 6061 aluminum being 2700 kilograms per cubic meter, the total mass of the plate is roughly 3.18 kilograms. Lastly, with the specific heat of 6061 aluminum being known to be about 900 Joules per kilogram degree Celsius, the following formula can be used to calculate the temperature rise:

$$\Delta T = \frac{Q}{mC} = \frac{3600}{(3.18)(900)} = 1.26 \text{ °C}$$

So, at worst, the aluminum plate over the course of a 30 second discharge would only experience a little more than a 1 degree increase above ambient temperature. This is perfectly tolerable, however its worth noting once again that this assumes all the dissipated energy is going straight into the aluminum plate. In practicality, some of the energy will dissipate through the air, but a good portion will also dissipate through the body of the resistors. As a result, it is worth also looking at a worse case estimate of the temperature rise in the resistor bodies as well based on information presented in their datasheet (datasheet #9 in Appendix C). The first graph of importance is titled, "Surface Temperature Rise," and shows the relation between temperature rise of the resistor and the power that it dissipates. For the HSC100 series of resistors, assuming the highest average power of 10W, there should only be an increase of around 10 °C per resistor. Considering that the power dissipation will end up being over the course 30 second pulse, the temperature rise calculated would also seem to be a worst-case scenario. With this in mind, it is also worth looking at the graph titled, "Derating Curve," which shows how the power handling capabilities of the HSC100 resistors decreases with increased heatsink temperature rise. Based on this graph, the resistors can reach a temperature of up to 100 °C before there is a loss of performance. This temperature is not expected to be met in the current design. As a result, derating is not necessary.

With the thermal considerations analyzed, the discharge design consisting of 12 HSC100 power resistors, three P115 contactors, and a 1ft by 2ft, 0.25in thick aluminum can be finalized. At 1200V in free air, the clearance distance for components is about 1 millimeter. The terminals of both the resistors and the contactors include the necessary insulation / insulating walls to cover the creepage distances at this voltage. The following 3D model shows a potential layout for the components when mounted on the chassis. Wire connections between the resistors and contactors are not shown.

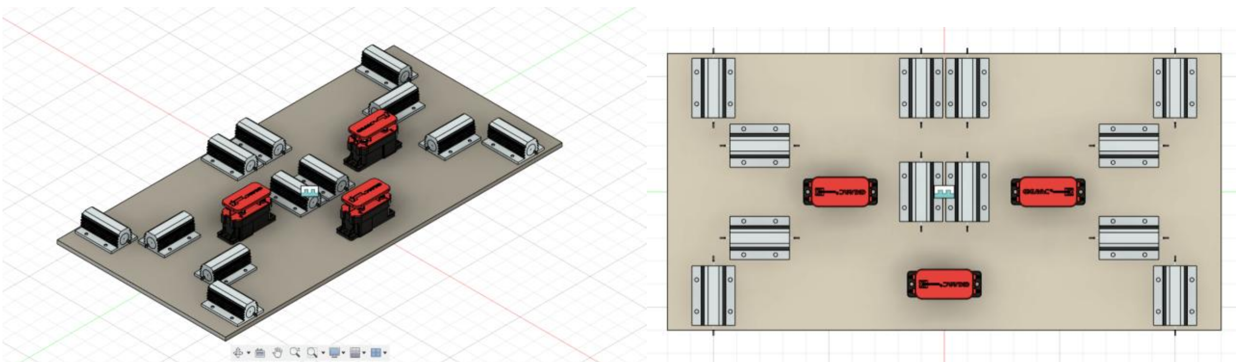


Figure 9: Isometric View and Top View of Discharge Chassis

6.1.6 - Test Bank Circuit

While not entirely within the scope of the project, a method of simulating the 1650uF capacitor at a low voltage for testing and validation purposes is required. As a result, a simple capacitor bank circuit was developed. The circuit includes three capacitors in parallel to create an equivalent capacitance of 1660uF, which is slightly higher than the expected 1650uF of the real capacitor bank, but acceptable for testing purposes. Screw terminals are included on both sides of the circuit. The left side allows for a power supply connection to charge the bank at 12 V, and the left side allows for connection to the discharge system. The included switch allows for disconnection of the charging side in order to isolate the charged capacitors for discharging. Its worth noting that with a 1000 ohm limiting resistor, the expected peak charging current at 12 V is only 12mA. The resistor itself is rated for 1W, and the capacitors are rated for 50V, which is more than enough for this application. The extra margin included allows for potentially higher voltage testing, say at 24V, if time allows for it.

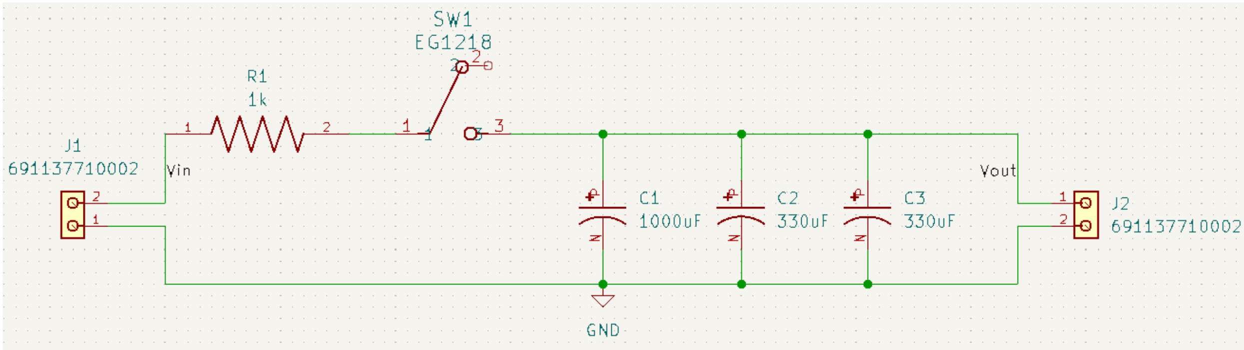


Figure 10: Test Bank Circuit

6.2 - Voltage Sensing and Isolation

One of the main goals of this project is that it is safe in its functionality. Part of the systems functionality depends on reading the voltage. This meant we had to incorporate some kind of analog-to-digital converter to read the voltage level of the capacitor into the MCU. While we are doing that we need to maintain safety in the system by isolating the high voltage side of the board from the low voltage side of the board. To do this, we selected an analog isolation amplifier that copies an analog signal and recreates it as a differential signal all the while keeping the two sides isolated.

That specific IC, the AMC3330QDWERQ1, only needs power from the low voltage side. It has an internal switching supply that transforms the DC on the low voltage side into DC on the high voltage side. Because this IC has a high internal switching frequency it is susceptible to noise and other radiative effects. The datasheet calls for a specific set and size of capacitors and ferrite beads to help minimize it. Sometimes capacitors are used in parallel on the same pin in order to properly counter different frequencies of signal. The data sheet also recommends a specific layout or organization of the capacitors. You want to get them as close to the IC as possible, so it specs out 0603 components and shows you where to connect them on the PCB.

Our analog isolation amplifier requires a bias current over the resistor it is measuring of 100 micro amps. Based on our estimated max volage of 1500V and that bias current, we got our total resistance needing to be around 15M ohm. This 15M ohm value was split between the top and the bottom to form the divider. It was then split again between resistors so that the voltage across each resistor is a manageable amount. Shown below is the high voltage portion of the schematic that shows the voltage divider, and some of the capacitors and ferrite beads used to help control noise on the IC.

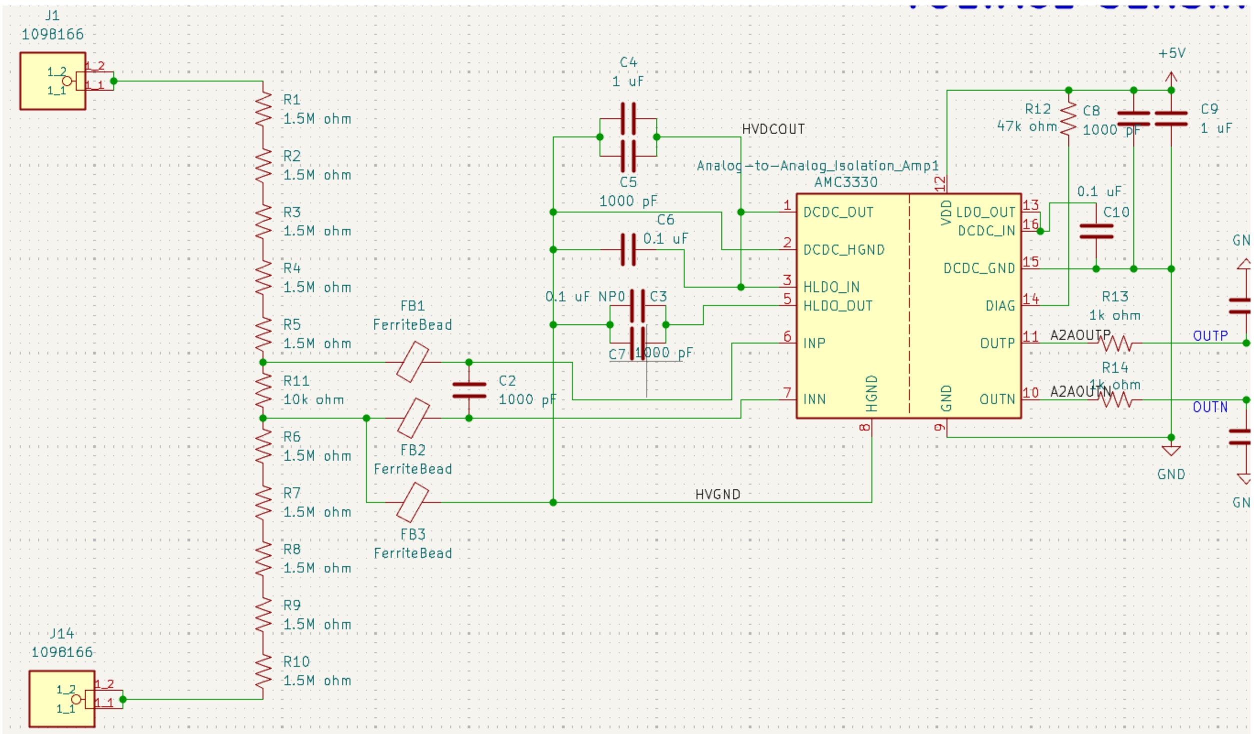


Figure 11 HV Portion of Schematic

Depending on the polarity or orientation of the connections, our input voltage range is +/- 1500V. This correlates to a +/- 1V signal between the INP and INN pins on the AMC3330 isolation amplifier. The isolation amplifier outputs a differential signal between pins OUTP and OUTN correlating to the +/- 1V input.

Table 37 AMC3330 Input and Output Voltage Relationship

VIN	VOUTP	VOUTN	Diff (P-N)
-1.00	0.44	2.44	-2.00
-0.50	0.94	1.94	-1.00
0.00	1.44	1.44	0.00
+0.50	1.94	0.94	+1.00
+1.00	2.44	0.44	+2.00

As seen on the low voltage side of the isolation amplifier, there is a differential output centered around 1.44 with a +/- 1V swing. This differential output is routed directly to the Ain0 and Ain1 pins of the ADS1120 ADC. Series 1k ohm resistors and parallel 10nF capacitors are used to form low pass filters on the lines, providing slight anti-aliasing and limiting high frequency noise. Since the differential output spans +/-2V, the ADS1120's internal reference value of +/- 2.048V is sufficient and an external reference is not needed. The ADC is continuously converting the data, sampling faster than necessary to allow for software oversampling. AVDD and DVDD are both supplied from the 3.3V rail with decoupling caps. The SPI interface including clock, MISO, MOSI, chip select, and data ready interrupt pin are connected back to the ESP32. A series 47 ohm resistor is used to help reduce overshoot/ringing. Test points are included on the VOUTP and VOUTN lines for troubleshooting.

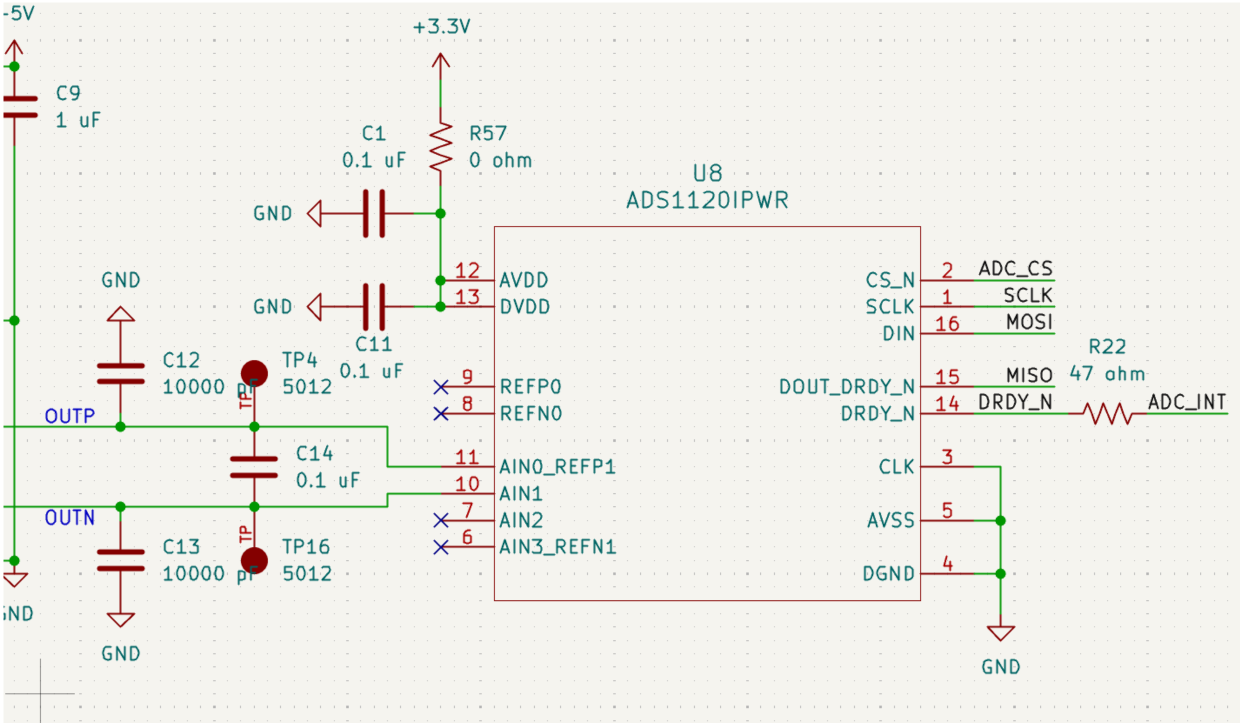


Figure 12 ADC Portion of Schematic

6.3 - Relay Driving and Isolation

Our relays/contactors are made to withstand 1500V. Contactors are internally and intrinsically isolated. There is a magnetic field that is used to pull a piece of metal shut to complete a connection. This separation and “connection” by the magnetic field makes the contactor isolated. The control pins of the contactors we selected run on 24V. The nominal hold current is 0.085A. This means to control the contactor and activate the resistor bank, we need to supply 0.085A of current to the contactor. The MCU pins do not operate at 24V or are able to sink enough current to activate the relays. To achieve proper relay activation, we use nmos mosfets, controlled by the MCU GPIO pins to sink enough current for the relays. These mosfets have a resistor to limit current to the gate. They also have a pull down resistor to make sure they remain off unless the MCU is pulling the pin high. Below is a schematic showing the three different stage control relays and their connections.

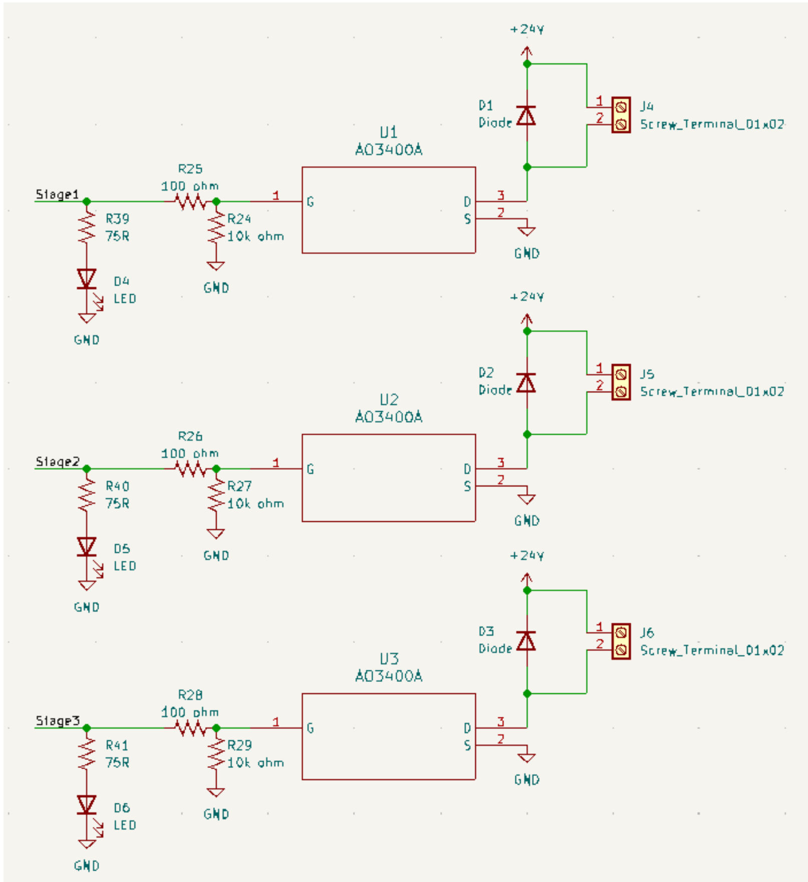


Figure 13: Relay Driving Schematic

6.4 - Temperature Sensing

Our temperature sensing comes from a combination of an RTD thermal probe and an RTD-to-Digital decoder IC made by analog devices. The RTD converter IC has a few different settings or variations you can choose from. Depending on the resistance of probe you select, you change the bias resistor value. For instance, the datasheet recommends using a 4.7k ohm resistor value for RTDs of 1000 ohms, and a 470 ohm resistor for RTDs of 100 ohms. Along with this, you wire the connects differently depending on what kind of connection you are using, and how many wires it has. In a 2 wire RTD, you have to connect the FORCE+ and FORCE- pins directly to the RTDIN+ and RTDIN- ports. There are also plenty of places for decoupling and smoothing capacitors for stability. One important note about this IC is that it uses SPI for communications. SPI is a very fast protocol. Because of this, on select lines I choose pull up resistors to help the lines maintain signal integrity. I also added in line resistors of just 100 ohms to help prevent reflections when you get fast incoming signals. The pins to connect to the MCU are also labeled in the net list.

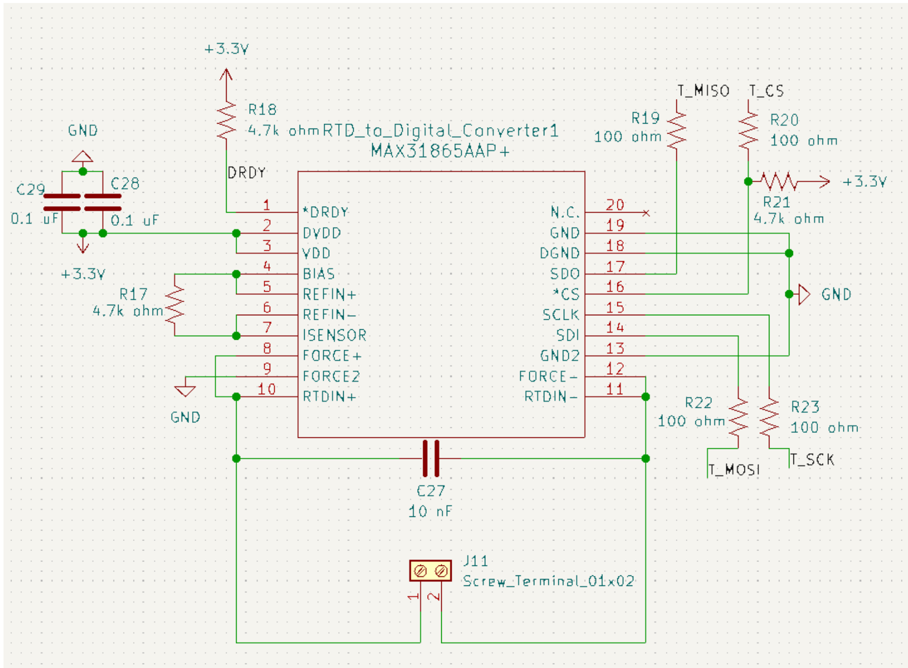


Figure 14: RTD to Digital Converter Schematic

6.5 - Display and User Inputs

The graphics display utilized in this design includes its own integrated circuit driver which communicates with the system's MCU via SPI. These SPI connections, along with power connections and the display interrupt are routed to a 20-pin box header with 2.54mm pin pitch on the display itself. For integration into the control PCB, a similar header will need to be incorporated so that the two systems can be connected together via an appropriate ribbon cable. The schematics below show the header connection on the display (right) and the header connection on the control PCB (Left)

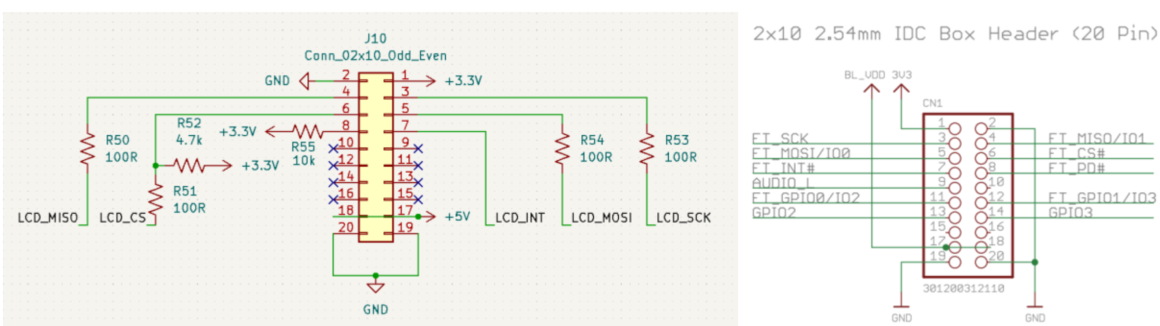


Figure 15: Board and Display Header Comparison

From these two schematics, it is worth discussing what was left unconnected from the display. Firstly, the display includes a potential audio connection on pin 9 which will not be used since this project does not have audio functionality within its scope. Additionally, the integrated driver IC for the display includes additional GPIO that can be used for quad SPI. This will not be used in this project and is thus left unconnected. Finally, Pin 8 is an active low power down function that can be connected to the MCU in order turn off the screen despite power still running in the system. Since there is no intention of turning the display off while the system is powered on, this pin is pulled high to ensure the display remains active.

The other form of information output to the user aside from the display comes in the form of LEDs that indicate the current stage of discharge, when the safe voltage level in the discharge cycle is achieved, and general power indication. The stage LEDs specifically are electrically tied to the relay driving circuits shown previously. The safe and power LEDs, in contrast, are run on their own dedicated GPIO from the MCU. Since the forward voltage for the colors used for these LEDs (green and blue respectively) are specified to be in the range 3.0V to 3.2V, a MOSFET was used to drive them off of 5V as opposed to the 3.3V pin output. This allows for a more flexible selection of the current limiting resistor while also limiting the amount of current being pulled from the GPIO pins. All of these LEDs, however, are present on a separate I/O board better user visibility.

Lastly, for user input, three cherry blue keyboard switch buttons were connected to GPIO. These buttons will represent up, down, and select when it comes to menu navigation on the display. Like the LEDs, the buttons are included on the separate I/O board. This board will connect back to the control PCB via 20-pin box headers and a ribbon cable.

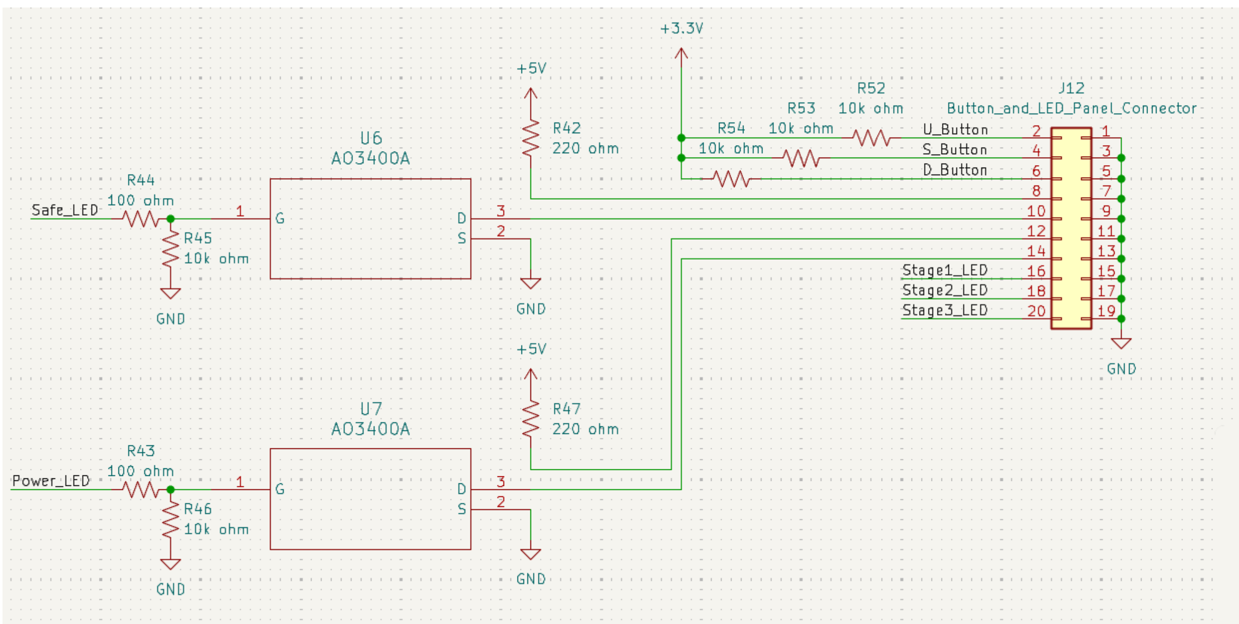


Figure 16: Control PCB Header and Button/LED connections

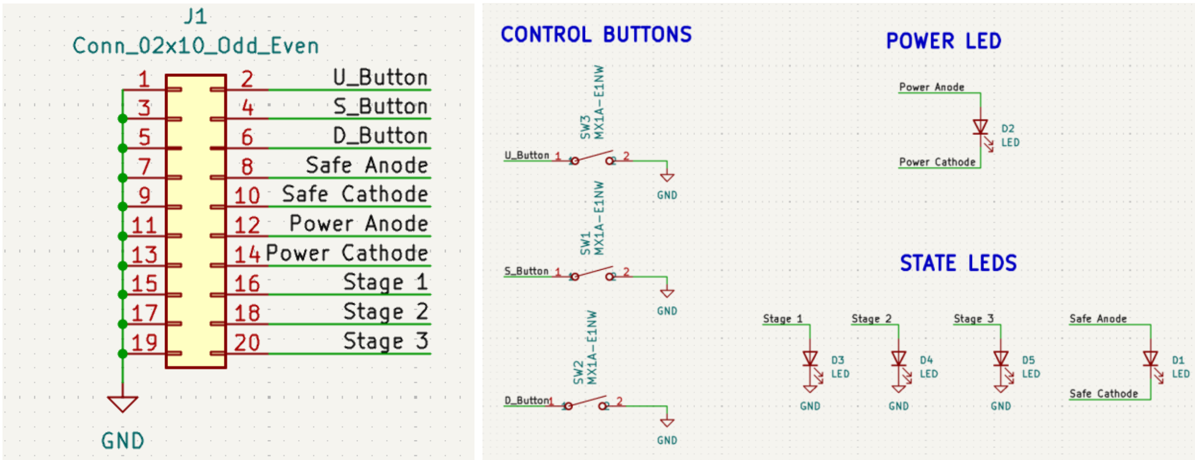


Figure 17: I/O Board Header and Button/LED Connections

6.6 - MCU

6.6.1 - Flashing Programs

Integrating the ESP32-WROOM MCU into the design required multiple connections and external circuitry. Before diving into the MCU itself, it is worth first discussing the circuitry needed to run an external program on it. To flash code, the ESP32 needs to enter its UART Download mode which is achieved by holding GPIO0 low while the chip's enable pin is reset (brought from low to high). While in the download state, the ESP32 will ignore whatever firmware it already has, communicate to an external device via UART, and accept new firmware from that device into its memory. The first step in achieving this entire process is having a way for an external device, like a PC, to communicate with the ESP32 via UART. This was achieved by integrating a USB type B connector alongside a USB to UART converter IC, specifically the CP2102N, so that an external device can plug in and communicate with the MCU. In addition to the standard IC connections specified by the CP2102N datasheet, ESD protection diodes were added on the USB pins to protect the IC from any voltage spikes that may occur from an electrostatic discharge event when plugging in the USB connector. For potential troubleshooting purposes, zero-ohm resistors were also added to the transmit and receive UART lines going to the MCU.

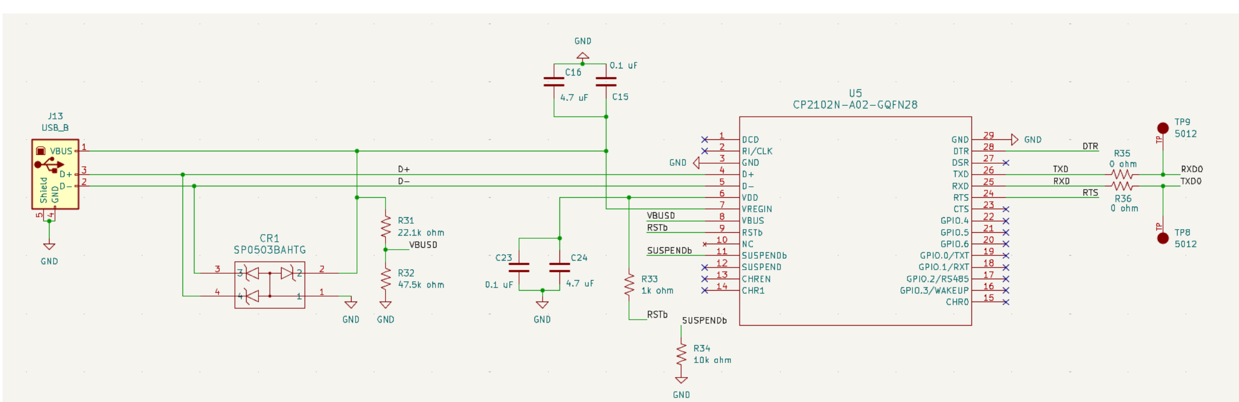


Figure 18: USB to UART Converter Schematic

With the UART connection established, circuitry was then needed to manipulate the GPIO IO0 and Enable pins for entering download mode. Two methods were included in the design to achieve this. The first, and simplest, was the use of push buttons to manipulate the pins. The first button is a boot button which ties GPIO0 low when pressed while the second button acts as a reset button and ties the Enable pin low when pressed. As a result, to enter the download mode for code flashing, one would need to hold down the boot button, tap the reset button, and release the boot button. In order to prevent issues from button bouncing during this process, 0.1uF capacitors were added in parallel. Overall, this circuit provides a reliable and manual way for a user to enter download mode.

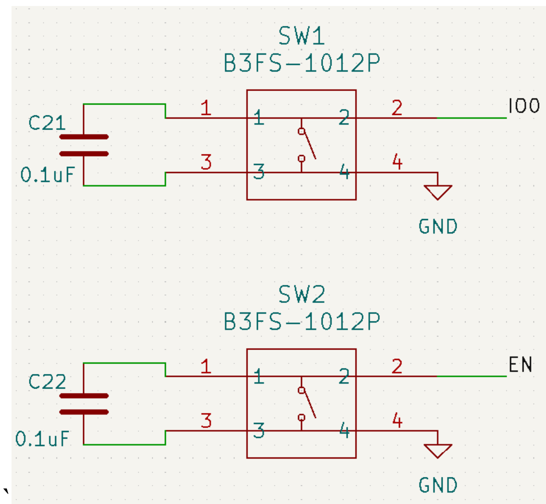


Figure 19: Manual Boot and Reset Button Schematics

To provide a more automatic way to enter the download mode and flash code, hardware flow control signals available on the USB to UART converter can be used change the states of the GPIO0 and Enable pins the moment that a program is ready to be transmitted over UART. The specific control signals involved are Data Terminal Ready (DTR) and Request to Send (RTS) which are both active low signals. When code is ready to transmit, the DTR terminal will be held low, and RTS will be pulsed low and then high again. BJTs are used to implement logic that causes GPIO0 to follow the output DTR and Enable to follow the value outputted by RTS. So, when DTR gets held low, GPIO0 will also be held low. The pulsing of RTS from low to high will cause the Enable pin to be reset from low to high. This fulfills the same conditions as the manual buttons to enter bootloader mode right when the code is ready to transmit. If the auto program circuit ever shows any timing issues, or if manual operation is simply preferred, zero-ohm resistors have been added to its output for troubleshooting and easy disconnection. Below is the truth table for these conditions, followed by the auto program circuit.

Table 38: Auto Program Circuit Truth Table

Auto Programming Truth Table				
RTS	DTR	GPIO0 (BOOT)	Enable (RESET)	Function
0	0	0	0	Download mode will be entered on Enable's next positive edge
0	1	1	0	Normal Reset operation
1	0	0	1	GPIO0 ready to enter download mode
1	1	1	1	Normal operation

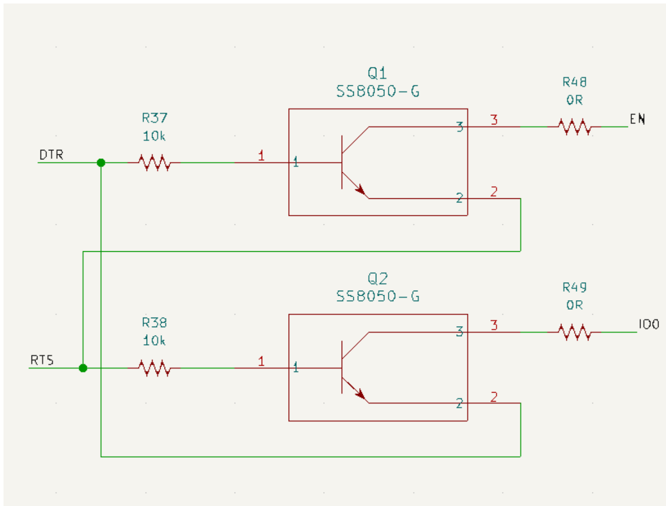


Figure 20: Auto Program Circuit Schematic

6.6.2 - MCU Connections

Compared to the programming circuitry, the actual connections to the MCU itself are fairly straightforward. Most of the GPIO is versatile and configurable in programming, however some are reserved as input only. To efficiently use these pins, the user selection buttons will be tied to them. Additionally, one of the input only pins will be configured as an ADC input, and the output of the voltage sensing system will be tied to it. The next major uses of the GPIO come from driving the three relay stages, driving the safe indication and power LEDs, and SPI connections from both the display and temperature sensing system. Relay and LED driving can be done from any GPIO pin, and the ESP32 allows for configurable SPI pins as well, so the GPIO selection isn't too crucial except for one important note. Certain GPIO pins are also strapping pins that can affect boot behavior during reset if used improperly. This includes GPIO2, 4, 5, 12 and 15. As a result, these GPIO were avoided where possible in order to not cause issues when the MCU needs to reset and enter download mode for program flashing. The only other crucial connections that do not include the already mentioned programming circuits are specific bypass capacitors on the 3.3V supply pin and the enable pin to help with voltage stability.

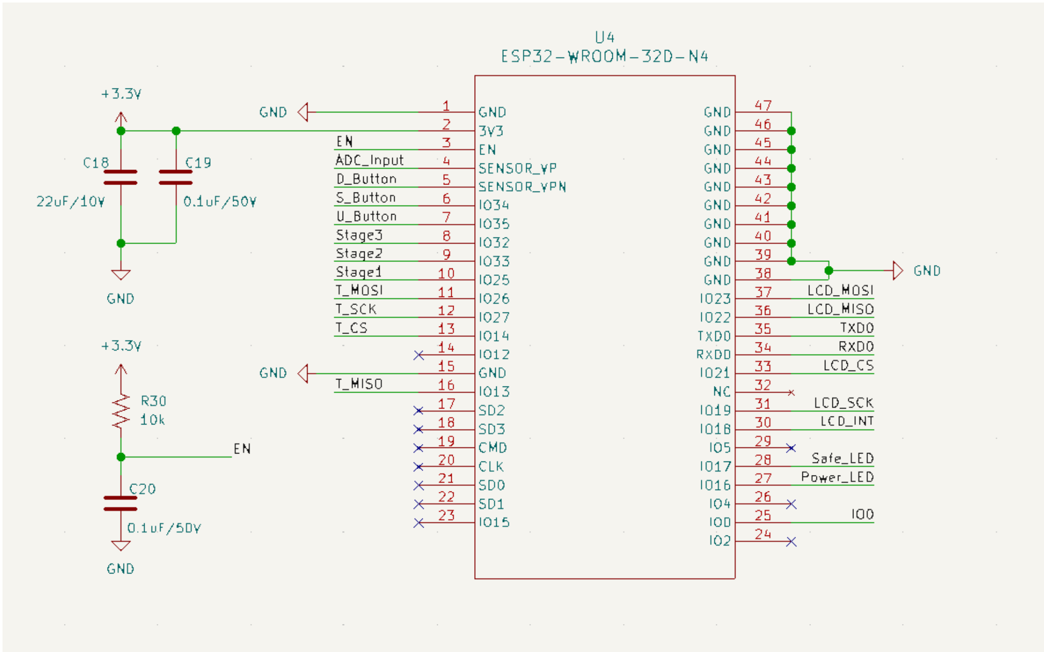


Figure 21: MCU Schematic

6.7 - External Power and Regulators

The power delivery system was best optimized to deliver power to all the major components in their respective subsystems. The system started with a 24-volt external power supply that was converted from a 120V AC wall connection. This voltage was then fed into different 3.3 volt and 5-volt regulator for various design components. The 3.3-volt regulator fed voltage into many of the software-based parts, such as the microcontroller, LED's and driver, along with the transistor. In contrast, the 5-volt regulator mainly provided drive for the sensing-based components, such as the isolation and operational amplifiers. Both the regulators were supported by suitable input and output capacitors, along with a functional diode and inductor placed according to the data sheet standards. Overall, this power structure with two efficient regulators provided an effective level of power to all the major components of the capacitor discharge system.

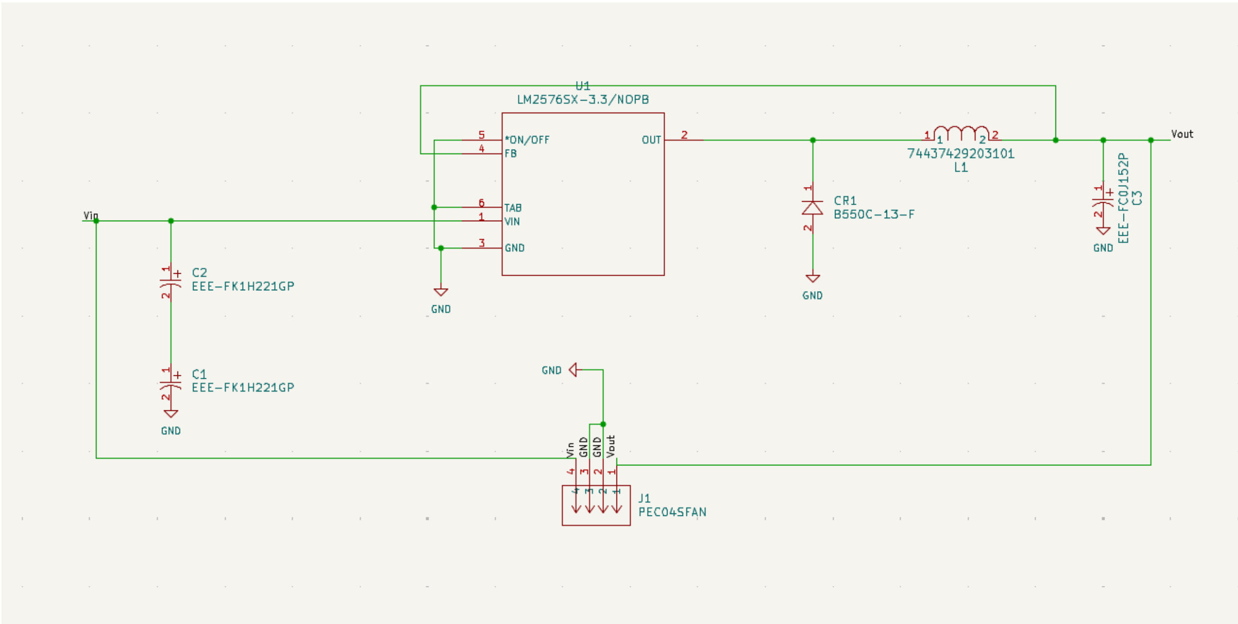


Figure 22: Schematic of the LM 2576 3.3-volt regulator

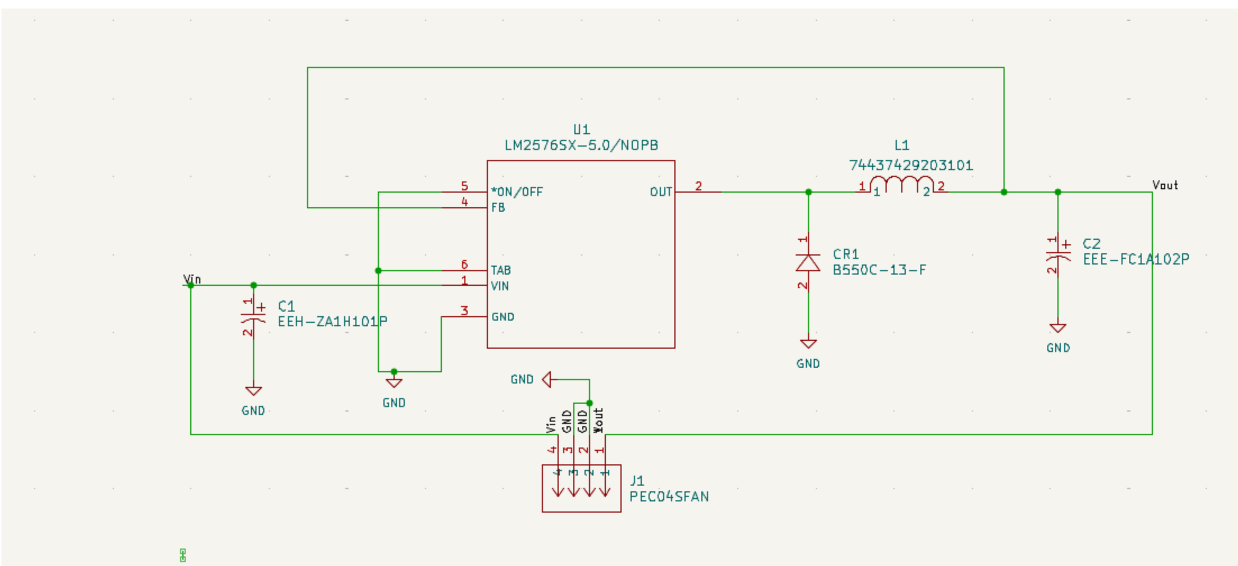


Figure 23: Schematic of the LM 2576 5-volt regulator

Chapter 7: Software Design

For this project, the software will be running on a primary microcontroller which will receive inputs from the scaled-down voltage difference across the discharge network, the temperature of the heatsink attached to the resistors, and the user of the device. In turn, it will accordingly set the outputs of the relays to control the rate of discharge, along with controlling LEDs and a display to communicate information about its state to the user.

Like many other embedded systems, this project's software needs both perform background tasks such as sending data over synchronous communication protocols (i.e. SPI) or polling data from input sources. However, it also needs to be responsive to inputs from the user and changes detected by its built-in ADC. On general-purpose computing systems this balance is maintained by the operating system, but most embedded hardware lacks the resource overhead to store such a program. A common solution is to implement a real-time operating system (RTOS) which are specifically designed to adhere to strict timing of background tasks while also supporting customizable interrupt handling for inconsistent but important events such as user input. The ESP32 microcontroller we selected for this project is built around a dual-core Xtensa microprocessor and is built around the Thread and Handler paradigm, which splits the program into threads that are "used to execute application software" with a single handler which is responsible for managing the priority of up to two-hundred and forty interrupts and any exceptions that occur during runtime [104]. As such, the software can be implemented as a state machine while also remaining responsive to input from the user.

7.1 - User Interface

This project's user interface consists of a display, three buttons, and a variety of colored indicator LEDs to facilitate communication with the user. The primary method the system will use to communicate with the user shall be on the LCD using a graphical user interface, with the indicator LEDs intended to provide information about whether the device is powered, which stages are currently active, and whether the discharge sequence has brought the capacitors below the safe voltage threshold. To allow simple, intuitive and responsive controls, the system will use a primary selector button with two secondary inputs representing the up and down directions.

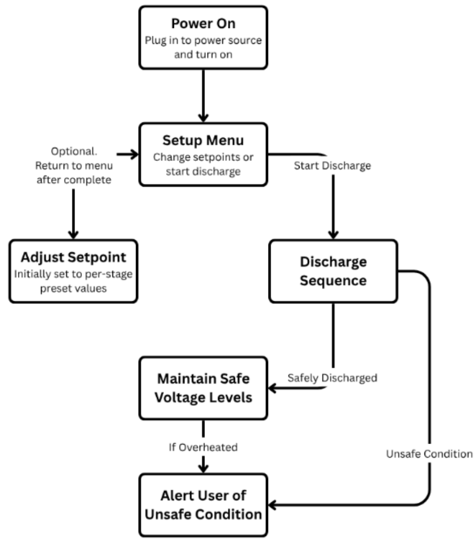


Figure 24: User Use Case Diagram

7.1.1 - Configuration Menu

When the user is in the configuration menu, the program should display four options on the menu: reset the voltage setpoints to their predefined default values; adjust the voltage threshold setpoint where the second discharge stage will activate; adjust the voltage threshold setpoint where the third discharge stage will activate; and start the discharge sequence with the current values as the setpoints. Because the first stage will activate at the start of the discharge sequence, and the project requirements specified $10V$ as the safety threshold, there are no setpoints to define at the start of the first stage nor the end of the third stage. Below is a figure to approximate the configuration menu's appearance on the LCD when implemented, with the Reset to Defaults option selected and the threshold stages one and two modified to start at a custom voltage.

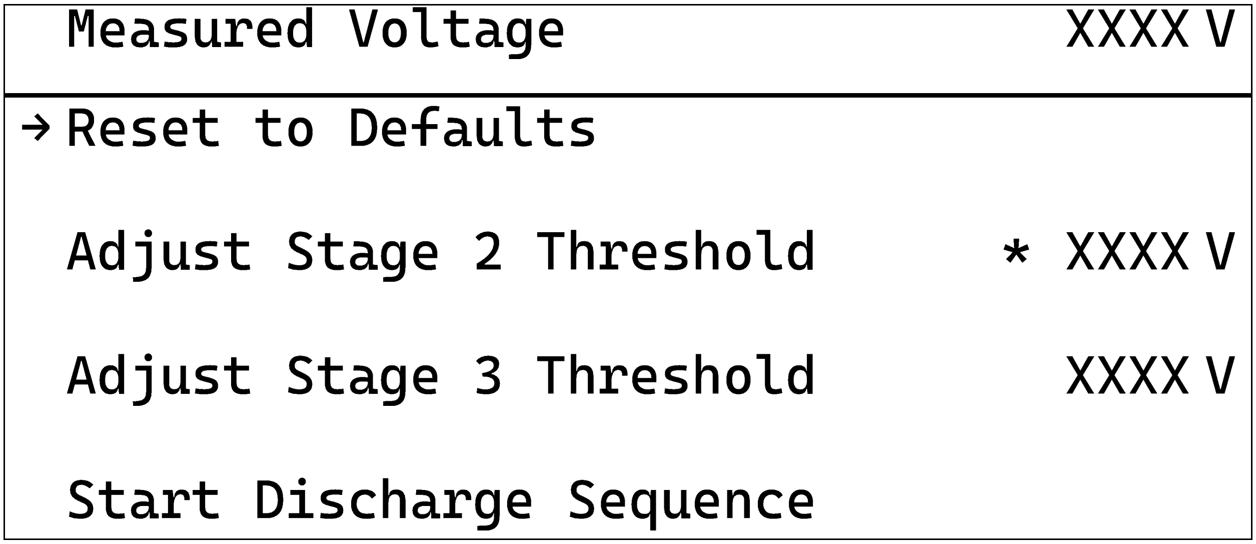


Figure 25: Wireframe Diagram of Configuration Menu

7.1.2 - Setpoint Adjustment

When the selected menu option is one of the voltage threshold setpoints, the cursor will be moved from the left margin and split into two arrows, or a hyphen to indicate if the value cannot be adjusted further in the given direction.

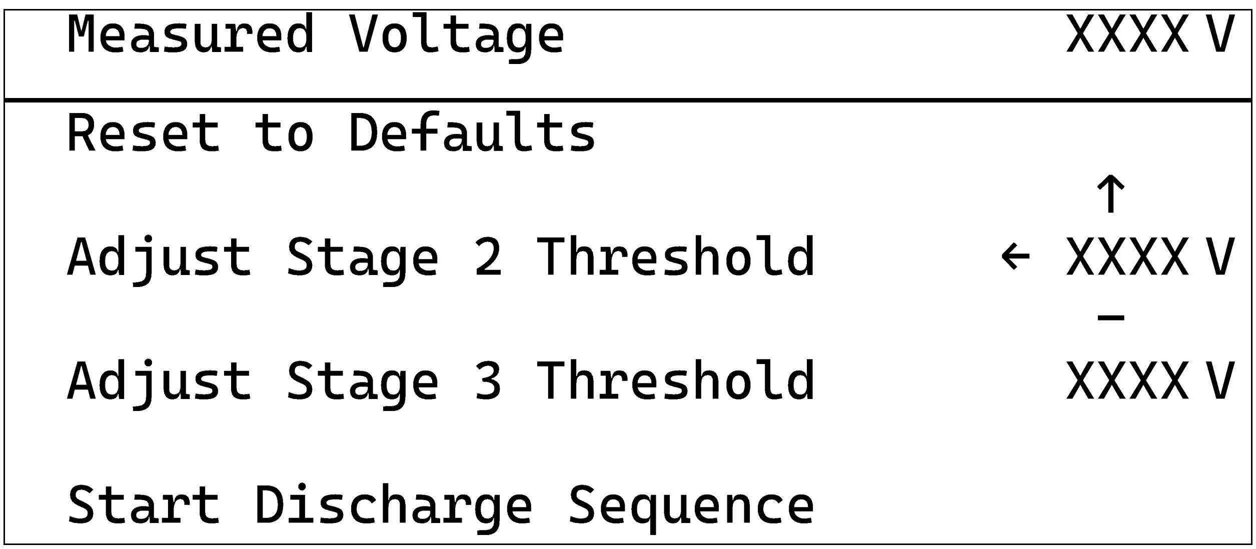


Figure 26: Wireframe Diagram of Setpoint Adjustment

7.1.3 - Discharge Sequence

The discharge sequence will have a single screen that displays important information to the user, such as the current stage, voltage difference across the discharge network, time elapsed since the start of the discharge sequence, real-time temperature of the heatsink for the resistor network, and a graph of the capacitor bank over time. Additionally, the user can use the select button to cancel the discharge in case they need to stop the sequence. Below is a wireframe mockup of the contents displayed during the discharge sequence.

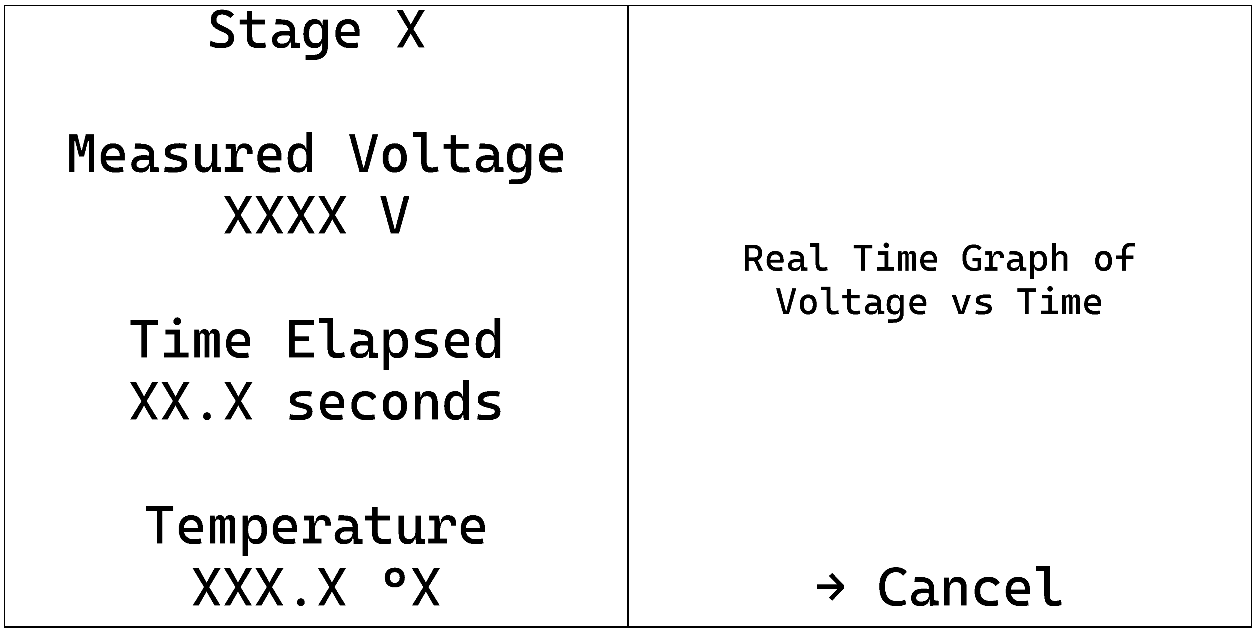


Figure 27: Wireframe Diagram of Discharge Sequence UI

7.1.4 - Completion Screens

The discharge sequence can automatically enter the two following screens, the first when the discharge sequence is completed safely and the remaining voltage does not exceed $10V$ across the discharge network. This screen is very similar to the interface for the discharge sequence but instead will indicate to the user that the discharge sequence has been completed. It will keep the graph of voltage over time, but it will no longer be real time, instead it will be generated from the data collected during the discharge phase. Readouts of the measured voltage and heatsink temperature will still be updated in real time, but the time elapsed will also be stopped once the voltage is under the safety threshold.

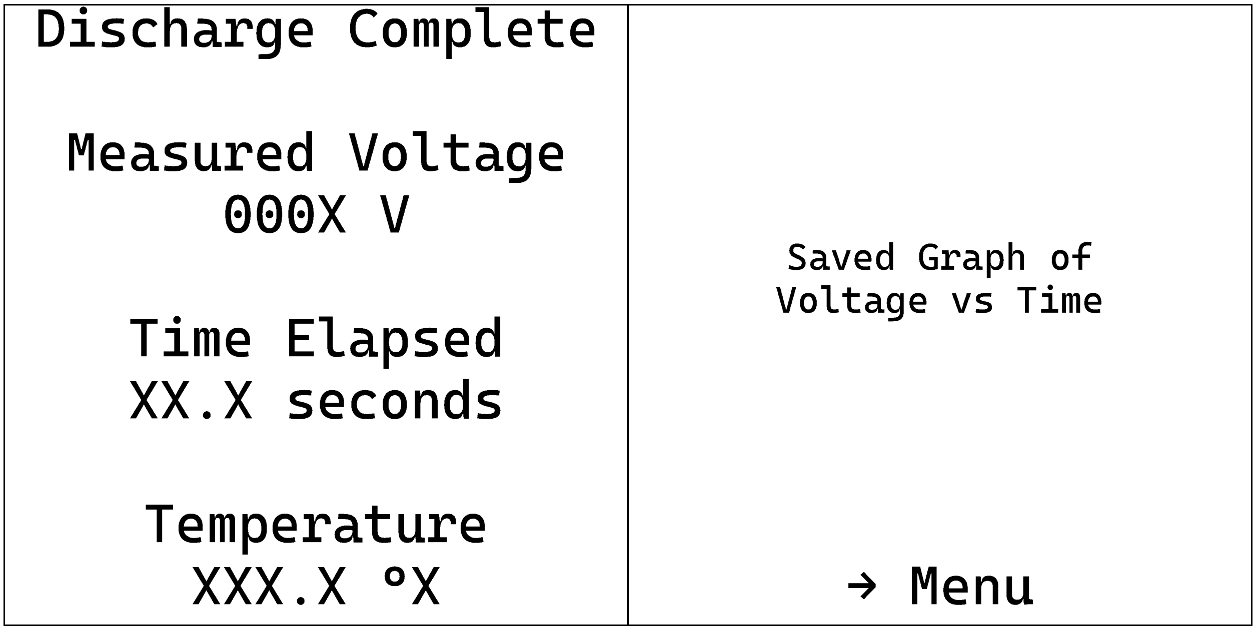


Figure 28: Wireframe Diagram of Safe Condition Screen

The other automatic end of the discharge phase occurs when the microcontroller detects an unsafe condition, such as the voltage not decreasing after relays have been signaled to close, an unexpectedly rapid drop of the voltage, or the heatsink temperature exceeding safe values. This screen will display a short list of possible causes along with a lookup code for further information. The user can then use the select button to dismiss the warning and return to the configuration phase.

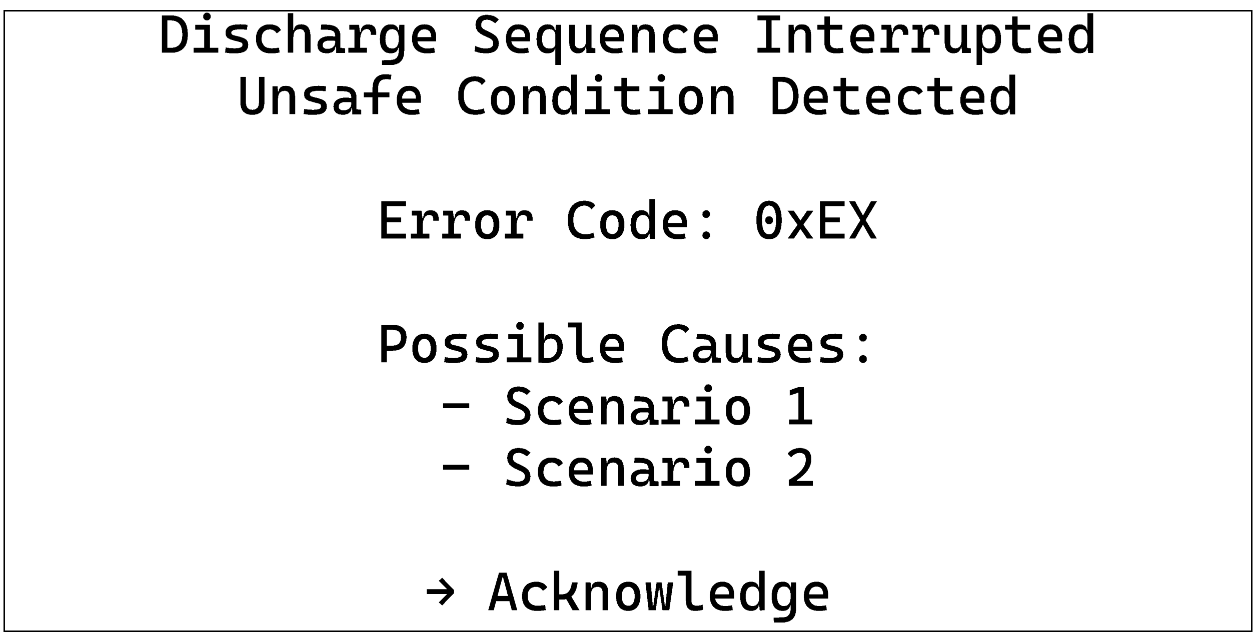


Figure 29: Wireframe Diagram of Unsafe Condition Screen

7.1.5 - Indicator LEDs

Each of the five indicator LEDs will have a unique color that represents the status of the current state of the system. For the sake of simplicity, none of the indicator LEDs should have blinking patterns, instead they will represent a true or false condition of their respective values. Per project requirements, three of the LEDs indicate which of the discharge stages are active, while a fourth will be activated when the system has been safely discharged. Additionally, there will be a fifth LED to indicate the system is powered and properly configured. As such, the fifth LED should be connected to a general-purpose output pin rather than at the voltage source of the microcontroller. This will ensure that the LED will not be turned on until the system has completed its I/O configuration.

Table 39: Indicator LED Definitions

Description	**Color**	**Active Condition**
1st Stage	Red	The relay connected to the 1st discharge subnetwork is active.
2nd Stage	Yellow	The relay connected to the 2nd discharge subnetwork is active.
3rd Stage	Yellow	The relay connected to the 3rd discharge subnetwork is active.
Complete	Green	Safe completion with $10V$ or less across the discharge circuit.
Power	Blue	Device is powered on and microcontroller is running the program.

7.2 - State Flow

From a high-level overview, there are three main states which the program will need to cycle through; the configuration phase, where the user connects the device to the bank of capacitors and tweaks the voltage threshold setpoints if necessary; the discharge phase, where the device will go through the configured sequence of discharge stage activations, activating each by comparing the observed value of the scaled-down voltage against the setpoints provided; and finally the completion phase, which holds all relays in the discharge network closed, to ensure the connected capacitors remain at a safe voltage, until the device is either powered off or reset to the configuration phase.

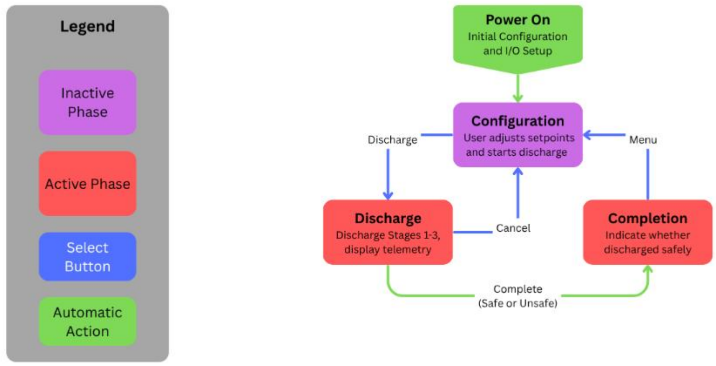


Figure 30: Overview of Software Phases

Each of the three main phases have their own subroutines, such as the three distinct discharge stages defined by the project requirements that comprise the discharge phase. Some of these states are progressed through automatically, including the discharge stages, while others must receive user input to enter the stage, like when adjusting a voltage threshold setpoint or when switching between the configuration phase and first discharge stage.

7.2.1 - Power On

Once the microcontroller is powered on, the program will start by configuring the internal clocks, general-purpose I/O pull-up and pull-down resistors, mapping relevant pins as input versus output, and other relevant actions to ensure the system is able to take input from and communicate with the user. After the initial setup is complete, the system will enter the Configuration Phase with the default voltage thresholds as the initial values.

7.2.2 - Configuration Phase

While in the configuration phase, the program will display the user with a menu presenting the stored voltage thresholds for each discharge stage, along with the option to adjust the values (within a safe limit) to change the profile of the sequence. Additionally, the user will have the option to reset any changes made to the default values. Finally, when the user is ready, they can start the discharge sequence. Even though the user can adjust the setpoints, it is not required for them to do so before starting the discharge, as the program should be initialized with default values. None of the relays should be active during the configuration phase, and the program will ensure the corresponding output pins are off when in any state within the configuration phase.

Figure 31: Configuration State Diagram

7.2.3 - Discharge Phase

Once the user selects the option to start the discharge sequence, the system will enter the discharge phase. This will start by closing the relay connected to the first phase of the discharge network, corresponding to the highest equivalent resistance. After which, the program will remain in the first discharge stage until the measured voltage is below the voltage threshold for the second stage to start. Then, the microcontroller will activate the second relay in the discharge network while holding the first relay to enter the second discharge stage.

Like with the first stage, the sampled voltage will be compared to the threshold setpoint, which will be activated when it drops below the value provided by the user. While the first two relays continue to hold their discharge subnetworks closed, the third relay will then be activated to start the third and final stage of the discharge sequence. Finally, when the measurement indicates the remaining charge in the capacitors is less than ten volts, the discharge sequence is considered complete and will continue into the safe state of the completion phase of the program.

At any point during the discharge stage, if the microcontroller determines that there is an unsafe condition within the discharge network, it will turn off all the relays and enter the unsafe state of the completion phase to prevent damage to the system or harm to the user. A few examples of detected conditions that would cause the system to stop the discharge would include: if the measured voltage is less than ten volts when the discharge sequence is activated, which could indicate that the capacitor is not fully connected or the analog-analog converter may be damaged; or if the measured voltage remains constant while the discharge stage is active, which could indicate that the relay or another connection within the subnetwork is damaged; or a sudden drop in voltage, which could indicate the connectors for the capacitor were disconnected, or a possible ground fault occurring.

During the discharge phase, the program will use both the display and several indicator LEDs to display the current discharge stage to the user. The indicator LEDs will be tied to the signals for their corresponding relay and will light up to indicate that the discharge stage has been activated. At the same time, readings from the voltage and temperature sensors will be displayed along with other helpful information on the display so the user can have more information that just which stages are activated at any given time. Additionally, the user can use the select button to cancel the discharge at any of the three stages.

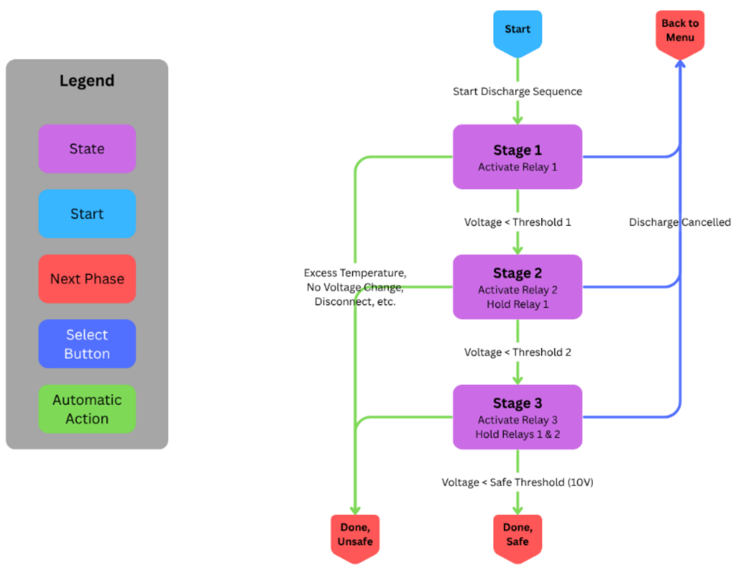


Figure 32: Discharge State Diagram

7.2.4 - Completion Phase

As mentioned in the discussion on the discharge phase, the completion phase has two distinct states: safe and unsafe. The safe state will indicate to the user that the discharge sequence has been safely completed and that the remaining charge in the capacitors is less than ten volts between the terminals. During the safe state, all relays should be held closed to ensure the capacitors will be fully discharged while the device is connected. When the user presses the select button, the relays will be reset, and the program will return to the configuration phase so the device can be used to discharge another bank of capacitors.

On the other hand, the unsafe state will stop powering all relays that were previously activated to ensure all subnetworks in the discharge circuit remain open until the issue is resolved. While the program is in this state, it will display a prominent warning on the display and require the user to acknowledge the cause of the unsafe state before returning to the configuration phase.

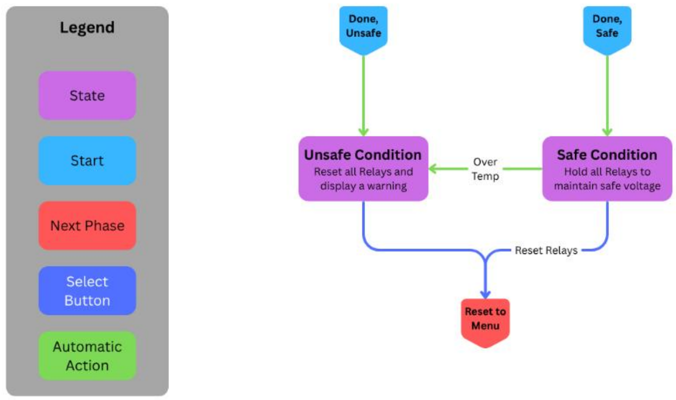


Figure 33: Completion State Diagram

7.3 - Classes & Data Structures

7.3.1 - State

An instance of the State class represents one of the possible states the program can be in, as discussed in the previous section. These phases can be split into one of three categories, which are separately represented by the enumerated Phase class. Depending on its phase, each state has different states that it can switch to when it receives a variety of signals, including user input, automatic state advancement, or failsafe events triggering when an unsafe condition occurs. These are stored as references within each State instance, each paired with a callback to run when the state is updated.

The current state of the program is controlled by a reference to the current state of the program, which is initially set as the Reset to Defaults menu option, but can be updated using one of the various go functions of the State class. For the Configuration Phase, these options include goNext, goAbove and goBelow, which are controlled by the select, up and down buttons respectively. During the Discharge Phase, the goNext callback is still tied to the select button, which allows the user to cancel the discharge sequence. At the same time, the goContinue callback is only accessible by the program itself, when it determines that the voltage across the resistor network has dropped below the set threshold. Finally, during any Discharge Stage or the Safe Completion State, the goUnsafe callback can be used by the program to indicate an unsafe condition to the user and update the state to the Unsafe Completion State. Because no State will have more than three possible States to advance to, the same variable can be repurposed depending on the instance's phase.

Data Type	Name	Properties
`const char*`	`name`	`private`
`unsigned char`	`id`	`private`
`Phase`	`phase`	`private`
`Action`	`next`	`private`
`Action`	`above`	`private`
`Action`	`below`	`private`

Return Type	Name	Properties
`State`	`(const char*, Phase, Action, Action, Action)`	
`unsigned char`	`getId()`	`const`
`const char*`	`getName()`	`const`
`Phase`	`getPhase()`	`const`
`void`	`goNext()`	`const`
`void`	`goAbove()`	
`void`	`goBelow()`	
`void`	`goContinue()`	
`void`	`goUnsafe()`	`const`
`void`	`log()`	`const`

Figure 34: State Class Diagram

See *Figure* 57 in Appendix D for definition in C++.

7.3.1.1 Variables

Every State is given the following properties upon initialization:

- A name to be used in debugging.
- An index identifier to be used in debugging.
- The Phase which the State belongs to.
- A reference to the State to advance to when the user presses the select button.

Depending on the Phase, a State will have its remaining two Actions set as the state and callback combination when the user navigates up and down if the State is in the Configuration Phase, or the next applicable Discharge Stage or Completion State in the sequence combined with the unsafe State for the other Phases.

7.3.1.2 Constructors

The State class has only one constructor, which has three required parameters and two optional parameters. The name, phase and primary action are required to create a State, but the remaining two actions are not necessary for every State. Additionally, a static counter is incremented each time a new State is created, using its value to set the State’s unique identifier.

7.3.1.3 Methods

All instances of the State class will have access to the following methods:

- Get the unique identifier of the State instance.
- Get the debug name of the State instance.

- Get the Phase which the State belongs to.
- Advance to the next State when the user presses the select button.

When the State is in the Configuration menu, two additional methods will be available:
- Navigate upwards or increment the selected threshold.
- Navigate downwards or decrement the selected threshold.

All other States besides the Unsafe Completion State will have another method to perform the following action:
- Update the current State to the Unsafe Completion State.

Finally, if the State is in the Discharge Phase, it will have a function that advances to the next State in the discharge sequence.

If a method that is unavailable for the current State is invoked, the program will print a message over Serial indicating the reason why but perform no further actions to alter the current State.

7.3.2 - Threshold

The Threshold class represents the voltage setpoint where a discharge stage should be activated. Each threshold should have a minimum and maximum value that the user can set the voltage and should not be able to exceed its limits in either direction. Additionally, because this class represents a discrete voltage value, it should be comparable to other integers using C++'s ability to overload operator and casting functions.

Data Type	**Name**	**Properties**
`int`	`value`	`private`
`int`	`min`	`private`
`int`	`max`	`private`
Return Type	**Name**	**Properties**
`Threshold`	`(const int, const int)`	`constructor`
`int`	`minimum()`	`const`
`int`	`maximum()`	`const`
`operator`	`int()`	`const`
`void`	`reset()`	
`Threshold&`	`operator=(const int)`	

Figure 35: Threshold Class Diagram

To represent the three Discharge Stages, there will be three instances of the Threshold class. The first Threshold will not change, as the first Stage should always start at or above 1200 volts, and therefore should be a const instance, preventing its value from being modified. The second stage will have a Threshold with a minimum of 600 volts and a maximum of 800 volts, giving it an initial value of 700 volts. The third stage also has its own Threshold with between 200 and 400 volts, with a preset value of 300 volts.

See *Figure* 58 in Appendix D for definition in C++.

7.3.2.1 Variables

Each Threshold instance will contain 3 variables:

- The current value which the threshold is set to.
- The minimum value which the threshold cannot be assigned below.
- The maximum value which the threshold cannot be assigned above.

These values are expected to be discrete values that do not exceed 1200 volts, so each of these variables should be represented using a standard 16-bit integer.

7.3.2.2 Constructors

The Threshold class should have a single constructor, which takes two integer values representing the minimum and maximum values. The current value will be initialized as the average of the two.

7.3.2.3 Methods

All instances of the Threshold class have the following methods:

- Get the minimum value the threshold can be set as.
- Get the maximum value the threshold can be set as.
- Cast instance as the integer representation of its current value.

Additionally, modifiable instances of the Threshold class will have the following modifier functions:

- Set the current value of the threshold.
  - If the provided value is out of the threshold's range, the value should instead be set to the closest allowed value instead.
- Reset the value of the threshold back to its initial preset value.

7.4 - Background Tasks

While changes in the program's state will be controlled using interrupts generated by user input or built-in timers, there are a few subroutines that need to be handled on regular intervals to ensure the program receives the latest data from its sensors and communicates that data back to the user. These background tasks will include measuring the scaled voltage to determine the remaining voltage across the capacitor, communicating with other devices using SPI, and the proper handling of any interruptions or exceptions that occur during the program's runtime.

7.4.1 - Voltage Reading

To determine the capacitor bank's voltage at any given time, the microcontroller needs to continuously sample the scaled analog input provided by the sensing circuitry. This is often performed using timer-generated interrupt-based polling. While this is a viable option in many scenarios including this project, there are a few analog integration features provided by the microcontroller that simplify this process.

One of these features is that the ADC operates on a different clock signal than the microcontroller's system clock, allowing the sampling rate to be independent of the microcontroller. Another useful feature provided by the family of microcontrollers is the ability to write ADC measurements directly to a specified address using the hardware abstraction layer. This removes the requirement of a dedicated timer and interrupts in favor of having the latest measurement already stored in a volatile global variable, with only the slight cost of a larger initial setup phase.

7.4.1.1 Oversampling

To improve the effective resolution of the built-in ADC, an oversampling technique can be applied through a software implementation of the digital signal processing technique. The original microcontroller selection had built-in support for hardware-based oversampling, but an equivalent feature is not available on the ESP32.

Instead, each measurement from the ADC can be added to a long 32-bit integer used to store the sum of each recorded sample. Once there have been 2^n samples summed into the long integer, the entire sample can be shifted right by n bits, which has the effect of averaging all the results without executing a division operation, which can take many more processor cycles on embedded hardware compared to general purpose computing hardware.

In our case, if we collect 256 samples at the $200\ ksps$ of the ESP32 microcontroller, we will collect approximately 750 over-samples per second at an effective resolution of 20 bits. Assuming that the least significant 3 bits from every sample are noise, we could shift the total right by 4 bits, which also truncates directly into an unsigned 16-bit integer that can provide a higher resolution but slightly slower frequency for our voltage measurements.

7.4.2 - Communication

Many embedded systems utilize communication protocols to connect multiple devices responsible for specialized duties, such as the RTD for temperature sensing and display for user interaction in this project. While there are many common protocols for varying devices and applications, the two submodules managed by the microcontroller will both communicate using SPI, which requires synchronization between devices.

The SPI protocol allows for both bus and daisy chain configurations in systems that rely on a large number of devices to be interconnected, but because the microcontroller we selected has an abundance of SPI-capable GPIO pins, it is not necessary for the RTD and display to share a connection as there are enough pins for each device to receive their own dedicated connection.

7.4.2.1 Display Controller by SPI

The selected display is equipped with its own microcontroller that can handle a vast majority of the graphics-related computation, allowing the main microcontroller to preserve its resources for other tasks that may require a large amount of processing power or quick responses. While the traditional option of writing a frame buffer is still available, a major consideration during the component selection for the display was its ability to receive a library of commands over SPI [105].

When the program's state is changed, program should command the display to present the user with the relevant information discussed in the User Interface section. This would include issuing a command to reset the contents on screen, followed by state-specific commands to present the user with data or control options. When the program is in the discharge phase the display should provide a secondary indicator of which stage is active. Additionally, the screen should have other helpful information such as the voltage measurement, time elapsed since the start of the discharge sequence, a graph of voltage over time, etc. Finally, during the completion phase, the display should indicate whether the capacitors were discharged to a safe voltage or alert the user of the cause if there is an unsafe condition.

To ensure the display updates on a regular interval, one of the microcontroller's internal timers should be dedicated to generating an interruption that will run a subroutine to update the display with the latest measured data. However, because the refresh rate is very low compared to the microcontroller's main clock, nor does it require a high level of precision, it can be configured to run on a low-speed, low precision capacitor oscillator. Another method that can improve the display's response time is triggering the display interrupt after each state change to ensure the information provided to the user is up to date.

7.4.2.2 RTD Polling by SPI

For the program to receive the latest temperature data from the discharge network heatsink, another timer needs to be dedicated to polling the RTD using SPI.

7.4.3 - Push Button Interrupts

Interruption-based user input handling is one of the most common ways to balance responsiveness with low resource overheads, especially in embedded systems. As such, the program running on the microcontroller will be implemented to use two separate handlers for when the user interacts with the push buttons to control the system. The select button will have its own dedicated interrupt handler, as it will be the primary method for the user to initiate a state change. The secondary interrupt handler is for both directional inputs, as having both the up and down button pressed at the same time should be ignored.

When any button is pressed, the program will add a short duration $(\sim 50ms)$ a dedicated timer linked to the built-in crystal oscillator. This first timer will indicate the button is in its debounce period, where measuring the push button input will yield inconsistent results. Once this timer expires, it will generate another interrupt to handle the input. If the button pressed is the select button, the program will always advance to its next user input state. However, if the input is one of the directional buttons, the program will first check that it is in the configuration phase.

When in the configuration menu, the selected menu item or voltage threshold will be updated to the next allowed value in the input direction. For example, pressing up while a threshold was selected would increase the saved threshold value to the next increment or set it to the maximum allowed value, whichever is lesser. After the update is processed, a longer timer $(\sim 500ms)$ will be scheduled, and if the button is still depressed when it expires, the program will register the action as a button hold, and in the previous example, would start increasing the value by larger increments, limited to the maximum allowed value. If the current state is not in the configuration phase, the directional input will be ignored.

Chapter 8: System Fabrication and Prototype Construction

8.1 - Discharge Plate Mechanical Design and Fabrication

All of the discharge resistors and high voltage contactors require a chassis mounting scheme. The recommended material to mount the discharge resistors based on their data sheet is aluminum. This is due to the material's structural integrity, machinability, and thermal properties. As a result. 6061 aluminum was used as the main mounting material. Based on the engineering specifications for the systems area, a 1foot by 2 foot, ¼ inch, aluminum plate was purchased for use as the systems main discharge plate.

With the components and plate material known, 3D STEP Files of the plate, resistors, and contactors were imported into the 3D modeling software SolidWorks. Within the SolidWorks part and assembly environments, an accurate sketch of all of the mounting holes was created on the discharge plate itself. Then, with the mounting holes represented in the model, the 3D components for the resistors and contactors were assembled virtually. Finally, once all of the spacing for the components was confirmed, a drawing file was made of the discharge plate. This file was sent to the UCF Machine Shop, along with the original 3D CAD file of the discharge plate for manufacturing via a CNC router with appropriately sized tool heads. The majority of the mounting holes on the discharge plate are standard M4 through holes, however there are also 4 imperial ¼-20 through holes as well.

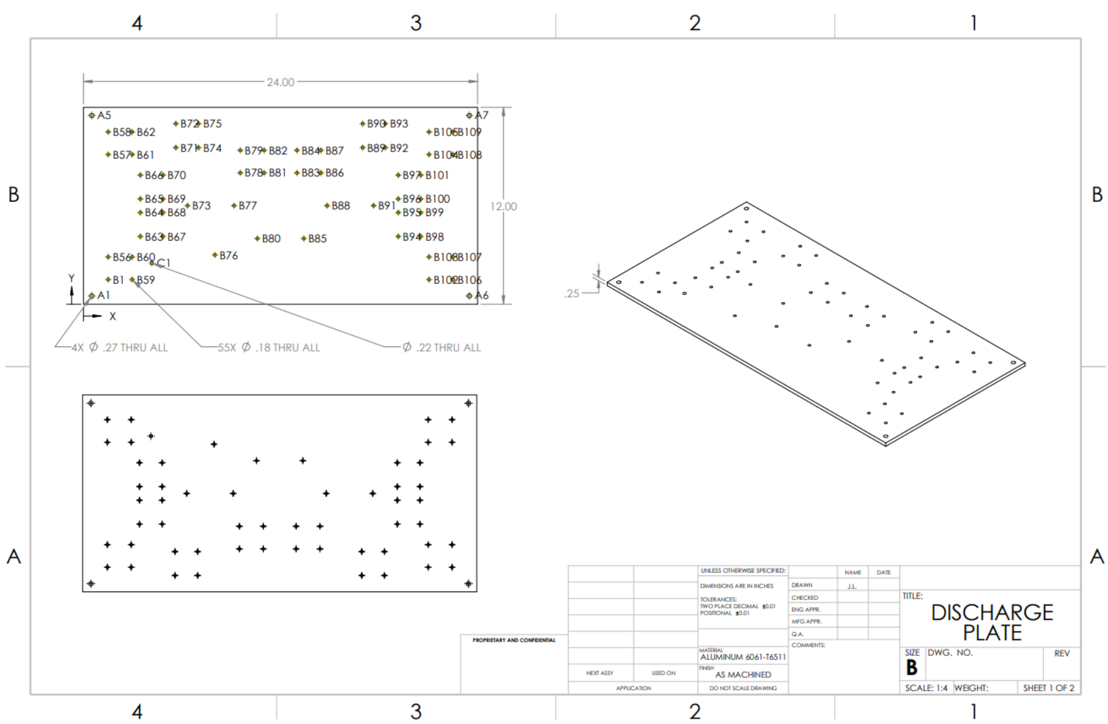


Figure 36: Drawing of Custom Discharge Plate (Hole Table Not Shown)

8.2 - Top Panel Mechanical Design and Fabrication

A separate mounting space was also needed for low voltage electronics as well. This is especially true considering that the user needs to interact with some of the electronics. For this, acrylic was employed since it is a robust, machinable material that also acts as a good insulator. The main components that needed to be mounted onto this panel included: mounting holes and a cutout for the display, mounting holes and a cutout for the I/O PCB, mounting holes for the control PCB, mounting holes and a cutout for the power switch/wall outlet connection, and mounting holes for the power supply.

Similar to the discharge plate design, a CAD file of all the components and PCBs were obtained, along with the file for a 1ft by 2ft, ¼ inch thick, sheet of acrylic. The components were spaced out over the acrylic and sketches were made to size and dimensions the holes and cutouts needed on the panel. Once everything was properly dimensioned, a drawing file was made of the top panel and provided to the UCF machine shop along with the 3D CAD file. The machine shop then manufactured the panel via their CNC router to the appropriate dimensions.

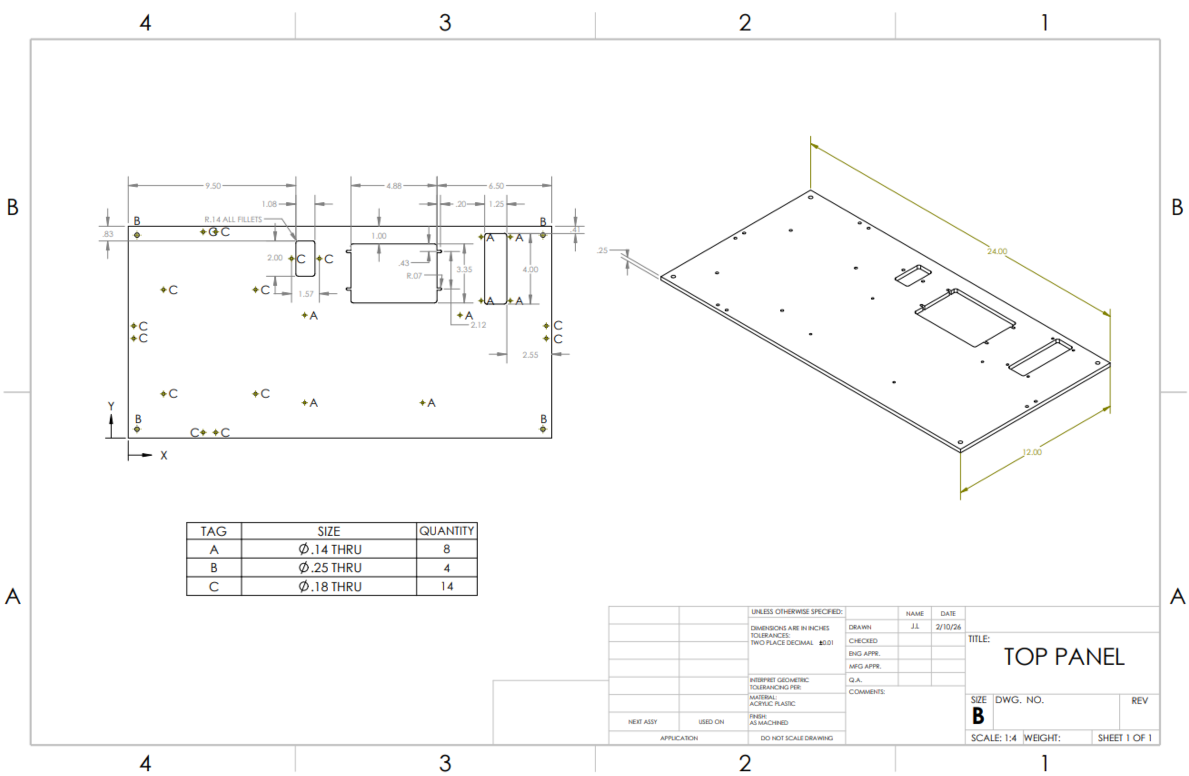


Figure 37: Drawing of the Top Panel

8.3 - Enclosure and Wiring

To connect the top panel with the discharge plate, six inch standoffs were used. These standoffs also allowed for the inclusion of rubber feet on the bottom of the discharge plate. Since the connection between the discharge plate and the top panel created a large gap between the two, hinges were included on the top panel to implement acrylic side panels onto the system. This ensures that users are not able to touch non-insulated high voltage components.

For wiring, 14AWG, 5kV rated, tinned copper wire was hand soldered to the discharge resistors to created the necessary series and parallel connections for the discharge stages. High insulating heat shrink tubing was used to cover all exposed solder connections. Ring terminals were also used to connect the contactors into the system along with the RTD. With so many connections, wire management did become a concern. As a result, soldered connection were kept as short as possible. Additionally, zip ties were used to organize related wire pairs together (ex: keep high voltage + and – connections together).

8.4 - PCB Designs and Layouts

8.4.1 - Regulators

For the regulators, the team decided it was easiest to separate the regulators into two separate daughter boards to ensure that any issues could be identified and isolated in a more effective manner. Any replacements in components were therefore done individually, which was often necessary during PCB construction. One of the inductors was seen as too bulky for ideal PCB organization, and it was decided that an inductor with slightly less current but more symmetry should be, and was used instead. The new inductor was still slightly over spaced yet by placing the inductor and diode close to the pin connectors for the sake of less noise and overall increased efficiency, along with placing the capacitors connecting to the voltage input and output on the other side of the LM 2576 chip, allowed for a more even board that should be user friendly. 3D printed support spacers, however, were still included as a precaution for supporting the weight of the regulator on the 4 pin connector.

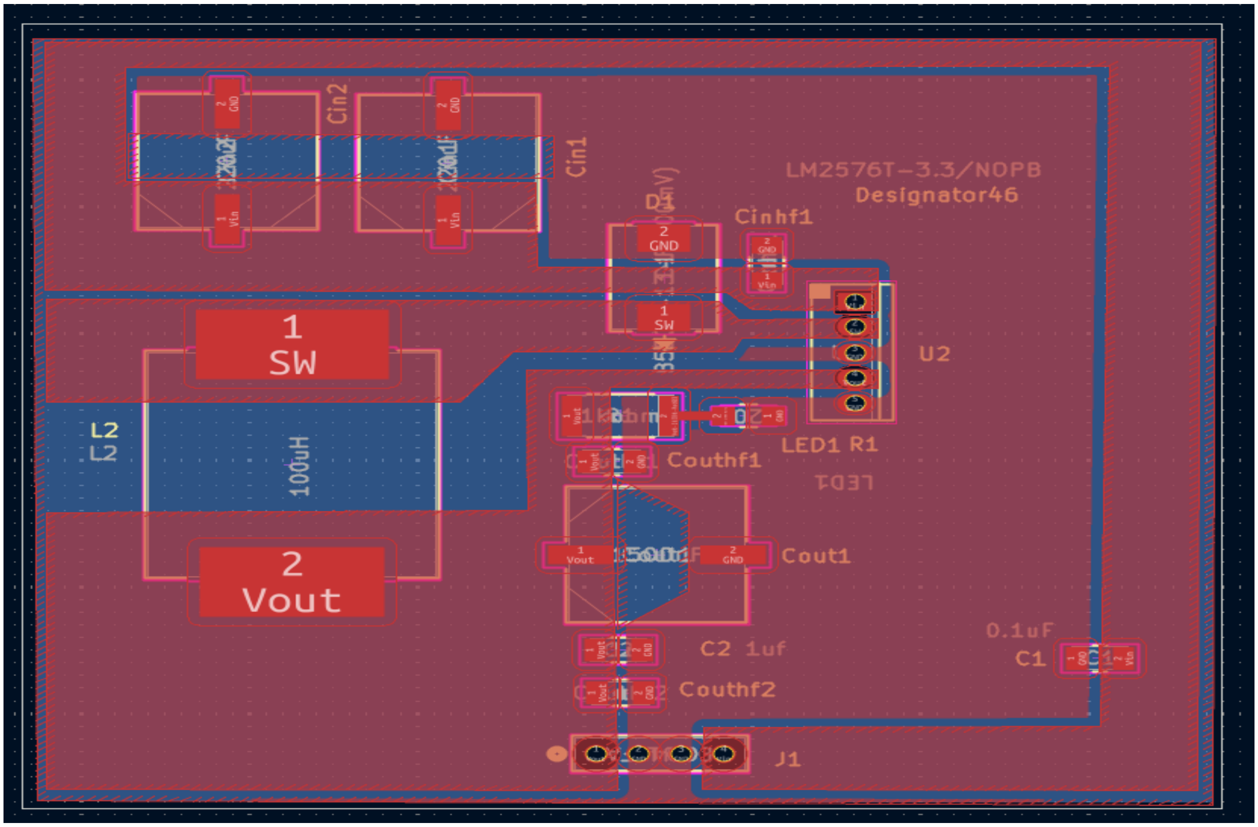


Figure 38: LM 2576 3.3V Regulator Board

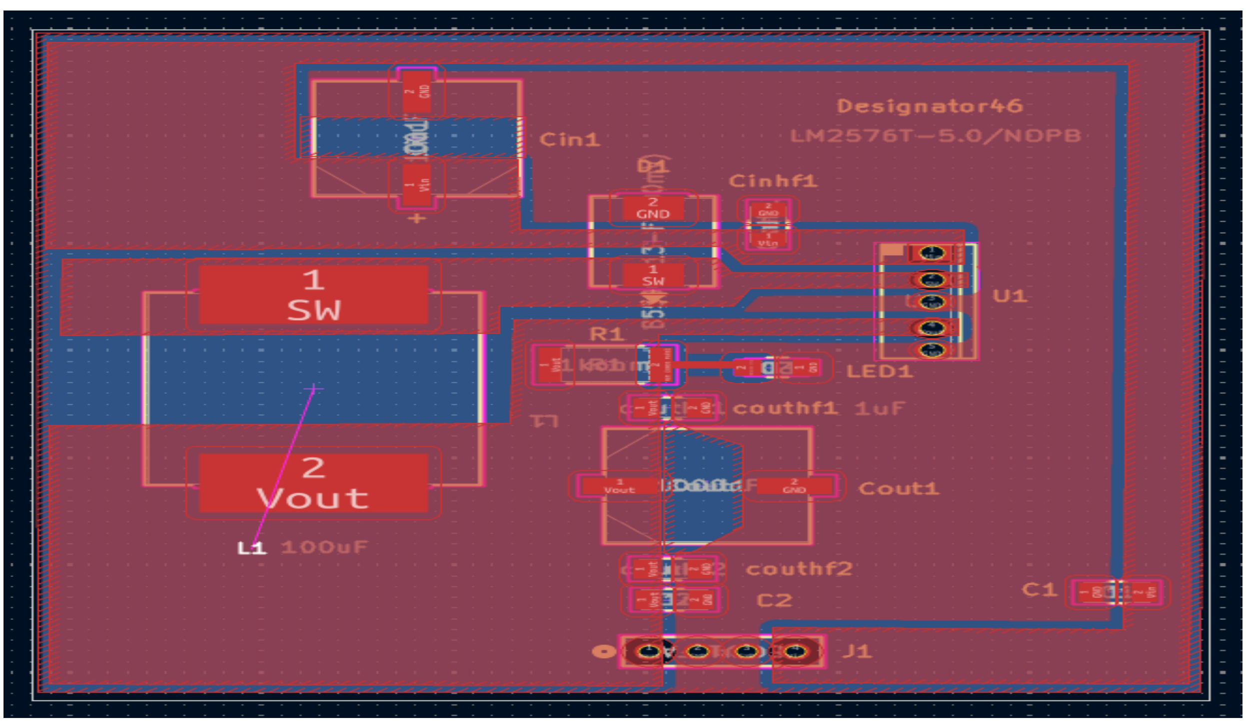


Figure 39: LM 2576 5V regulator board

8.4.2 - Test Bank

To be able to accurately test the discharge system, a dedicated PCB to hold components necessary for connecting a charged capacitor into the discharge circuit was needed. Due to the simplicity of the circuit, the PCB design was also simple. All the components with the exception of the charging resistor are through-hole components. This makes soldering them to the PCB simpler. Additionally, all the components are placed on the front layer of the PCB with a ground pour applied in the surrounding space. Since the PCB has such few components, the bottom layer was also made into a ground plane and is stitched to the front layers ground via by way of the through-hole components. This should be sufficient stitching considering the PCBs size is only about 3 inches by 2 inches. In terms of traces, the maximum current ever expected in the PCB would be 24 mA. Based on the IPC standard, the minimum trace width should be 0.005mm (about 0.0002 inches). This minimum is incredibly small and would make any potential rework impossible. As a result, the trace width was set to be 0.05 inches instead. The below images show the front layer of the PCB in both the layout view and the 3D render view.

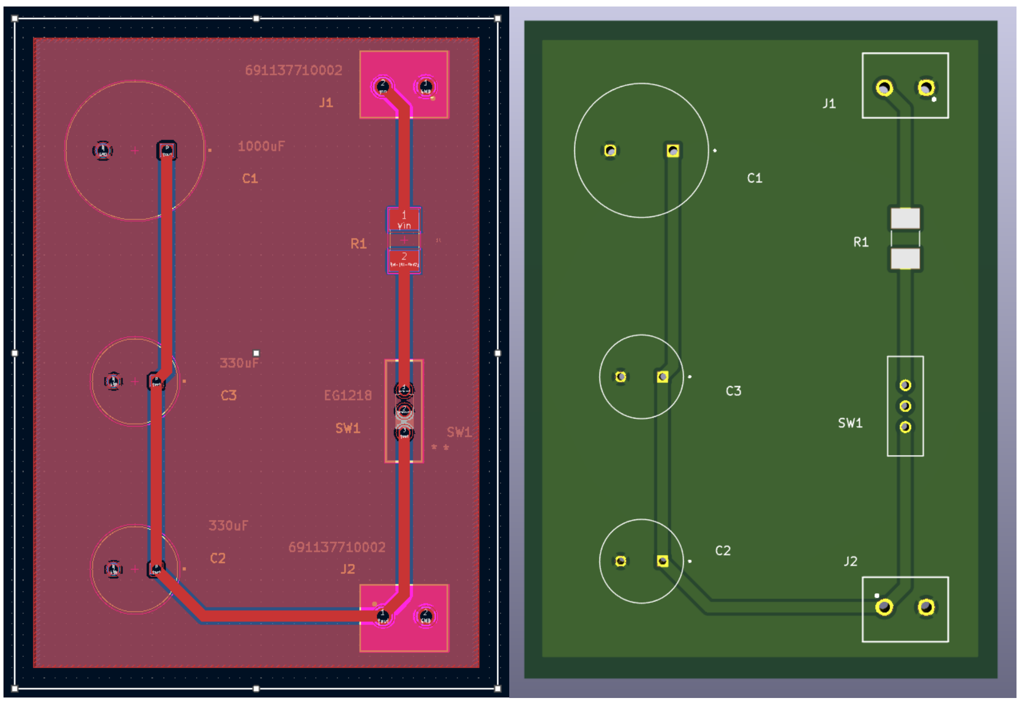


Figure 40: Front Layer View of Test Bank PCB

8.4.3 - I/O Board

The I/O Board utilizes through-hole technology for the three buttons and the 20-pin header. The five indication LEDs on the board are all SMD. In terms of the boards layout, the only major constraint was the dimensions of the board, since this directly impacted spacing of components mounted on the top panel of the enclosure. As a result, the board was made as small as possible, while still leaving room for a logical flow and structure to both the button layouts and the LED layouts. Labeling was used on the silkscreen layer to indicate which button performed what action and which LED corresponded to which discharge stage.

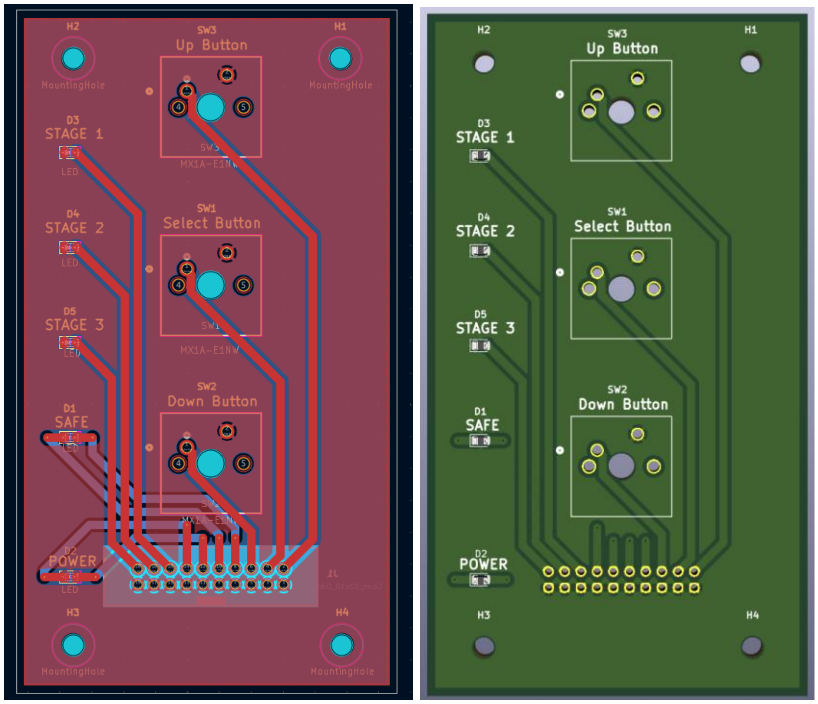


Figure 41: Layout of I/O Board

8.4.4 - Control PCB

The low voltage and control elements of our system (ESP32 MCU, RTD-to-Digital Converter, display, relay drivers, etc) will all be on a single PCB designed in KiCad. Our current specification is a standard 2 layer 1 oz copper board at standard thicknesses. To keep the layout properly isolated, There are distinct and separate low voltage and high voltage sections of the PCB. These sections will not have their internal ground planes connected or touching. The high voltage section will have a separate design with spacing between internal layers/wiring and external/exposed traces of the low voltage side. The spacing here is dictated by our creepage and clearance calculations from earlier. Under our isolation amplifier IC, which acts as the bridge between these two regions, a slot was milled out to increase the effective creepage distances and amplify the isolation. The connectors used to connect 1200V into the board are also specialized for that voltage and are similarly spaced out to the required creepage distance.

On the low voltage side, the traces for the shared SPI bus were kept as short and as uniform as possible. Adequate spacing was reserved for the regulator daughter boards. Screw terminal connections for the RTD, relays, and power input were routed to the same side of the PCB for ease of access. The USB type B connection was subsequently routed to the opposite end of the board. This was to prevent any potential interference from other circuitry from affecting the higher speed USB data bus. Additionally, as a differential connection, the USB data bus was routed as a differential pair. Finally, test points were included throughout the PCB to make troubleshooting with an oscilloscope easier, especially at power inputs, SPI lines, USB lines, and UART lines.

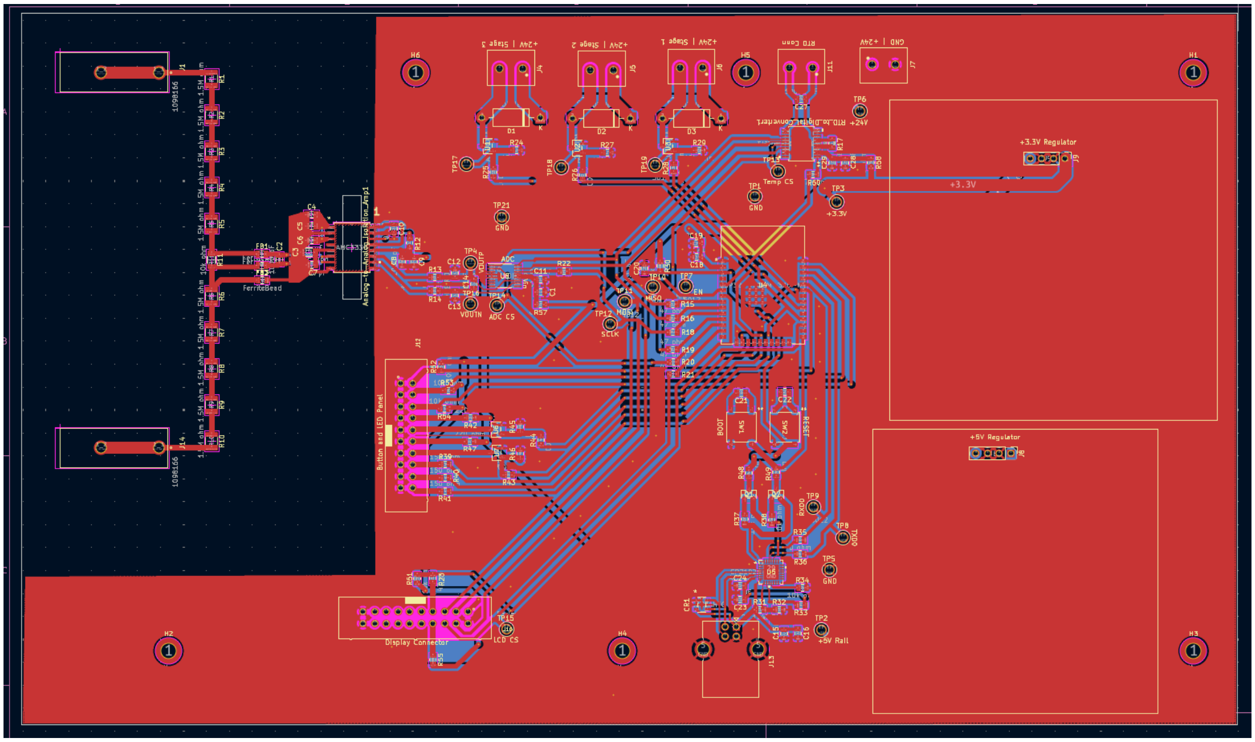


Figure 42: Layout of the Control PCB

8.5 - PCB Manufacturing and Assembly

Manufacturing of the PCBs was done through JLCPCB. Standard 2-layer settings were used for the boards. In addition to the boards themselves being ordered, solder stencils were also included in the order. While the PCBs use a mix of SMD and through-hole technologies, the majority of the components were SMD. Therefore, solder stencils made the assembly process much easier, since a unform amount of solder paste could be applied to each of the SMD pads. Once solder paste was applied, components were carefully placed on their appropriate pad, utilizing the silkscreen layer labels and KICAD schematics as a reference guide. With all the components in place, a heat gun was used to apply the necessary amount of heat to cause the solder paste to melt, flow, and create a solid electrical connection. Then, the SMD components were inspected with an electronic microscope to ensure no bridges or short circuits were present. This process was especially important for higher density chips, such as the ESP32 and CP2102N. Finally, once all the SMD components were in order, through-hole soldering was conducted with a standard solder pen. This included the screw terminals, USB connector, high voltage connector, 20-pin box headers, etc.

Once the PCBs were assembled, continuity checks were conducted with a digital multimeter to ensure that all the connections were behaving as intended. Regulators were tested with an electronic load to confirm functionality before integrating with the control PCB.

Chapter 9: System Testing and Evaluation

9.1 - Senior Design Testing Objectives

Senior Design 1 focuses on the schematic design and component level testing of the device. Senior Design 2 focuses on PCB and full system-level testing. Due to the safety concerns, the scope of the project was to officially test at low voltage and have appropriate documentation and research showing how the design could be modified or adjusted to operate safely and effectively at high voltage/standard operation. To do this, the team is, wherever possible, designed the system as though it will operate at high voltage, and completed the high voltage application research throughout the design process. As our components, and eventually our system, were tested, the team ensured that the components selected acted as expected and that they were integrated smoothly to accomplish the desired functions as expected. An external, lower voltage, but equivalent capacitance capacitor bank was used to simulate a real discharge at 12V. This was also used in the team's final presentation and showcase evaluation.

9.2 - Individual Component and System Testing (Senior Design 1)

9.2.1 - Power Supply Testing

In order to test our power supply properly, there were several considerations that were taken. Firstly, the power aspect of the design was divided into two parts, the initial power to the regulators, and the regulators effectiveness in relaying the required current and voltage to the other components of the circuit. The aim was also to minimize the amount of power loss and maximize efficiency across both regulators. For most of our components such as the MCU and driver display, a consistent voltage level of either 3.3 volts or 5 volts was required. Therefore, we used the LM 2576 regulator, a buck converter that combines decent efficiency with ease and simplicity when it comes to PCB construction. In order to test whether the PCB of the regulator would supply the power needed, the team purchased an LM 2576 development board and adjusted the voltage to the expected 3.3- or 5-volt standard and observed the resulting output. It was also important to clarify the impact of noise and EMI which was combated through the correct placement of the inductor and diode close to the ground pins. In addition, ultimately, a heat sink over the through hole chip was also used to basically null the effect.

The results of the adjustment to 3.3 and 5 volts on the development board of the LM 2576 were relatively positive, with minimal discrepancies with the voltage drop. For the 5 volt, which needed to have at least 0.2-0.3 amps, the voltage at different currents was compared and the resulting efficiency at 0.6 amps, with a given input current of 0.168 amps at around 0.6 amps(as an example) and a constant input voltage of 24 volts at each point, the overall efficiency was shown to be around 90 percent, which is accurate with the datasheet and the expected result from the research of the Senior Design supervisors, given their experience with the LM 2576 regulator. It should be noted that the input current for each point changed in accordance to around a 70-75% efficiency in total, so this was a bonus.

For the 3.3-volt regulator, the process was similar apart from increasing the load current from a maximum of 0.6 amps to a maximum of around 1.2 amps, as the maximum rampage that the 3.3-volt regulator required was around an amp. The input voltage was kept at 24 volts, and the input current changed accordingly. At the maximum value of testing, so theoretically the lowest the efficiency could possibly be, at 1.2 amps, the output voltage was around 3.1 volts, with the current input being around 0.231 amps, for an efficiency of around 87%. This lined up with the team's expectation and standard considering the constraints of the system and the realization that even testing 1.2 amps was a bit of a stretch and the current ended up being lower in practicality, resulting in increased efficiency overall. For the initial power supply, the use of the converter immediately was not necessary as a basic power supply in the Senior Design Lab provided the necessary input voltage for testing of a lot of the components such as the regulators and MCU.

9.2.2 - Dual to Single Ended Conversion Stage and Isolation Amplifier Testing

An important part of our initial voltage measurement system was the conversion of the differential output to a single ended output on the scale of 0V to 3.3V for measurement by our ADC. Our isolation amplifier has a positive and negative output supply pin. These pins range from 0.44V to 2.44V. The difference between these pins from -2V to 2V feeds the positive and negative input pins of an op amp in a summing configuration. This op amp maps this difference to the output range of 0V to 3.3V. Another critical part of this setup was a constant 1.65V reference, the halfway point between 0V and 3.3V, attached to our op amp. In the initial circuit this came from a precision reference IC connected to an op amp for current supply.

The entire setup consisting of the dual op amp, buffer amp/summing amp, and the voltage reference was tested by using ICs, IC to DIP conversion boards, breadboards, and laboratory equipment. Two channels of a function generator were set to be sine waves and connected to the input positive and input negative terminal of the op amp. The op amp and precision reference were supplied with a 5V DC source. The output and input waveforms to the op amp were recorded and shown to be correct. On the oscilloscope you can see how the yellow and blue input waveforms result in an orange waveform on the scale of 0V to 3.3V.

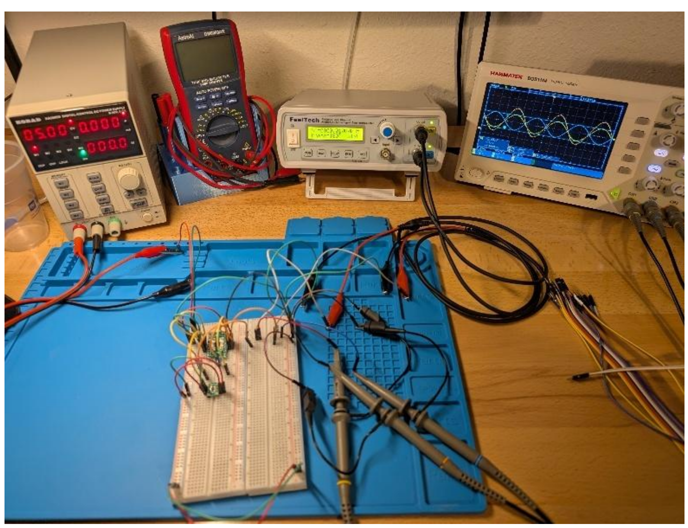


Figure 43: Dual to Single Ended Conversion Stage Testing

The isolation amplifier was tested in a similar manner to the dual to single ended conversion stage. The amplifier was powered with a DC source and an input waveform of -1V to 1V was applied to the high voltage input terminals. The voltage at the positive and negative output terminals was tested and showed the input waveform as well as the two differential waveforms appropriately.

9.2.3 - Relay Driving Circuit Testing

To control the contactors, MOSFETs were used to allow higher currents to flow through them when the signal was given by our microcontroller. The NMOS MOSFETS are active high, so they allow current to flow when powered. This is preferred as it means in an unpowered state, the normally open contactors will be off. There is also pull down circuitry to keep the contactors off until our microcontroller explicitly turns them on. To test this, we connected our contactors and our MOSFETS in the appropriate configuration and tested seeing if setting the ESP32 pins high and low would cause the contactor to open/close. It worked as expected. Setting the ESP32 control pin high caused the MOSFET to conduct current and made the relay short as seen by the low resistance reading on the multimeter.

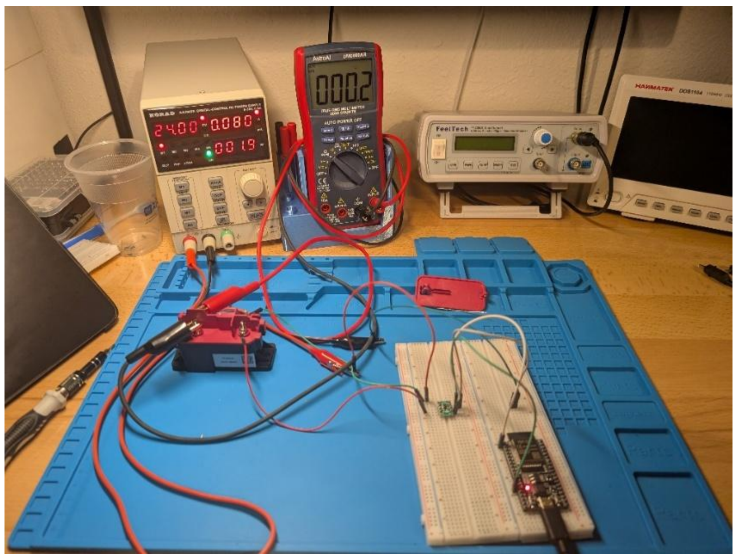


Figure 44: Contactor Driving Testing

9.2.4 - RTD Testing

The RTD to digital converter is a digital component requiring power as well as embedded code configuration within our ESP32. The MAX31865 RTD-to-Digital converter IC has publicly available libraries, headers, and documentation compatible with the ESP32. That header and library was used in the code setup along with a standard program that configures the ESP32 pins to read SPI data, poll the RTD converter, then print the data to the serial monitor on the computer. The test setup shows the computer reading the RTD temperature every half a second. It closely matches the temperature of the room as shown by another thermometer.

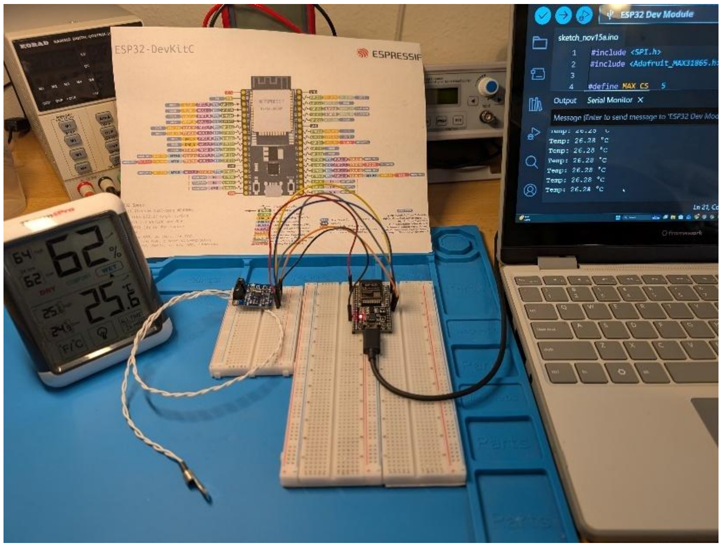


Figure 45: RTD Digital Converter and Programming Testing

9.2.5 - TFT Display Testing

The 5 inch TFT display is another device that requires setup with our ESP32. The display has a built in graphics engine that takes SPI commands and directly controls the screen. Graphics libraries can be used, and the commands can be communicated over SPI between the ESP32 and the display graphics engine. Once the standard SPI connections, power connections, and control pins are connected to the display, the display can be programmed. This, however, requires the installation of the appropriate header files. Testing this display required downloading SD card, display graphics engine, and graphics library header files. After this, the screen can be used with the normal commands in the library documentation.

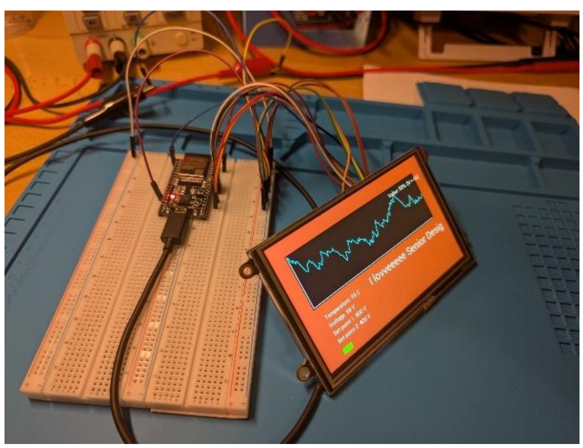


Figure 46: TFT Display and ESP32 Programming Testing

The screen was tested at the same time as the RTD-to-Digital converter. Issues, however, did arise from trying to run both devices via the same SPI Bus. Each item worked individually on the bus, but when connected the header function calls from each device to control the SPI lines, were interfering with the other. This had to troubleshooted within the code by the team later in order to have a functional SPI Bus for Senior Design 2.

9.3 - Software Simulations

For the software side of the system testing and evaluation, we first developed the State and Threshold classes to be used in the program. Next, we set up the main loop of the Arduino project to read for user input over Serial, and taking different actions depending on which option was selected. If the user enters 0 or something that cannot be parsed into an integer, it is ignored, and the loop continues. If the parsed input is greater than six or below zero, the input is invalid, and the testing program displays the menu option to the user again.

When the user inputs a 2, the program performs the action it would if the user had pressed the select button. Depending on the State, this can perform various actions, including resetting the setpoints to their default values, selecting or saving a voltage threshold, starting or stopping the discharge sequence, or acknowledging unsafe conditions. If the user enters a 1 or a 3, it is treated as if the user is pressing the down or up buttons respectively. During the menu phase, this either moves the cursor to the adjacent menu option or adjusts the selected voltage setpoint. When outside of the Configuration Phase, these buttons have no effect.

When the current State has an automated next State (i.e. all Discharge Stages), the input 4 would trigger the advancement that would be handled by the program. This would either advance the next stage of the discharge sequence or put the system into its Safe Completion State. To simulate an unsafe condition, the test program allows the user to enter a 5 at any time. This will update the current State to the Unsafe Completion State, which can only be exited from direct user interaction.

To learn more information about the current State, the user can also enter option 6 which will print the name and unique identifier of the current State along with the potential next States it can advance to. Using this tool, we were able to experimentally verify that each trigger in every State resulted in the expected update to the current state, if applicable. For example, attempting to increment a voltage threshold after it has already been set to its maximum value will not increase the setpoint, and pressing the up or down button during the Discharge Phase will have no effect on the system.

9.4 - Final System Testing and Validation (Senior Design 2)

9.4.1 - Changes From Senior Design 1

It is worth noting that various components and subsystems were added and/or removed during design changes between Senior Design 1 and 2. Most notably, hardware relating to differential to single ended conversion for the signal chain of the isolation amplifiers output to the ESP32's internal ADC was removed. This was due to the use of a dedicated external ADC which could accept differential input directly in lieu of the ESP32's internal ADC. Another example includes changes to the programming circuit that acts as the bridge between the ESP32 and an external programming device such as a laptop. In light of these changes, the following testing information and data is conducted on the final designed system and is the most up to date information pertaining to system level testing.

9.4.2 - Regulator Testing

The final designed 3.3V and 5V regulator boards were connected to a 24V input off of a benchtop power supply and their outputs were tied to an electronic load in continuous current mode. The current setting on the load was varied from zero amps to 1.5 amps to test the regulation and efficiency of both regulators. Overall, the voltage regulation across the load range was as designed and the efficiency for both regulators hovers around 80%.

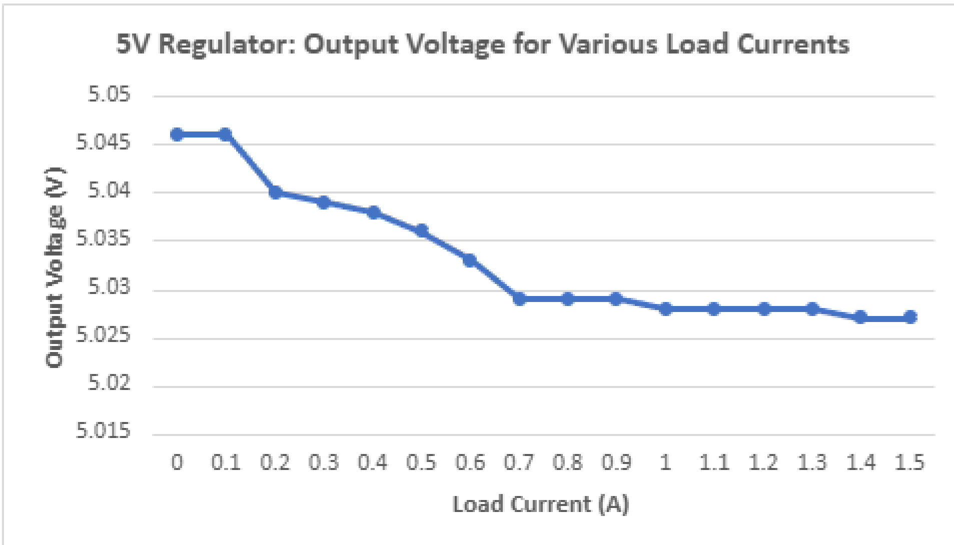


Figure 47: Output Voltage Under Various Loads for the 5V Regulator

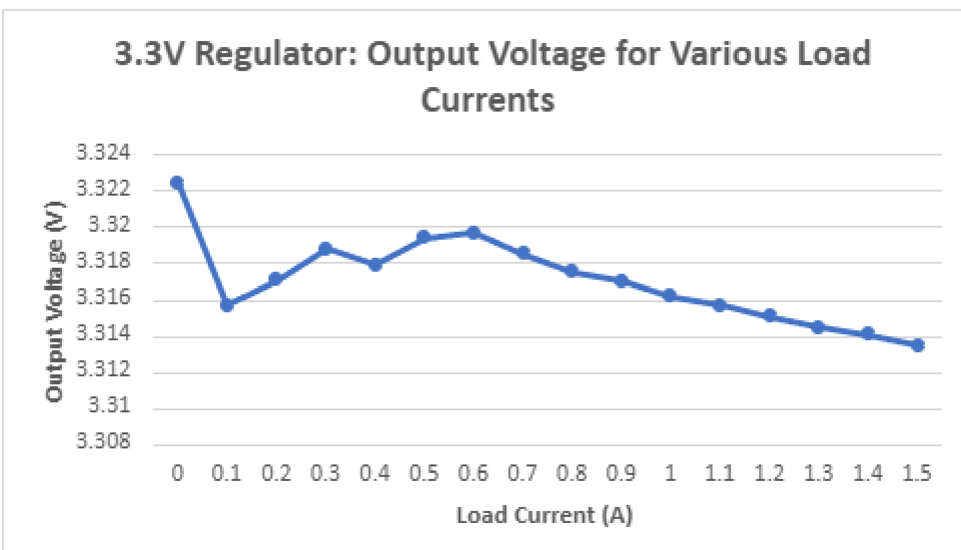


Figure 48: Output Voltage Under Various Loads for the 3.3V Regulator

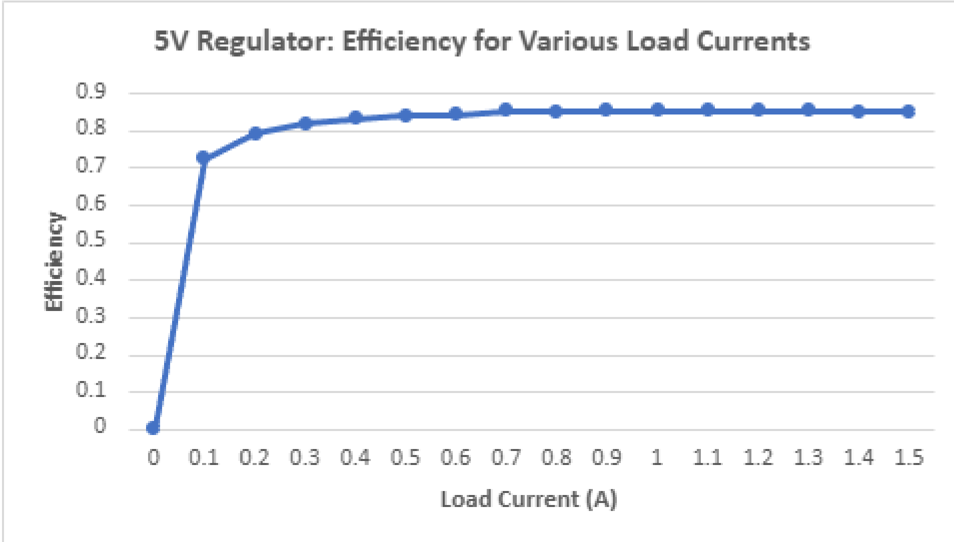


Figure 49: Efficiency Graph of the 5V Regulator

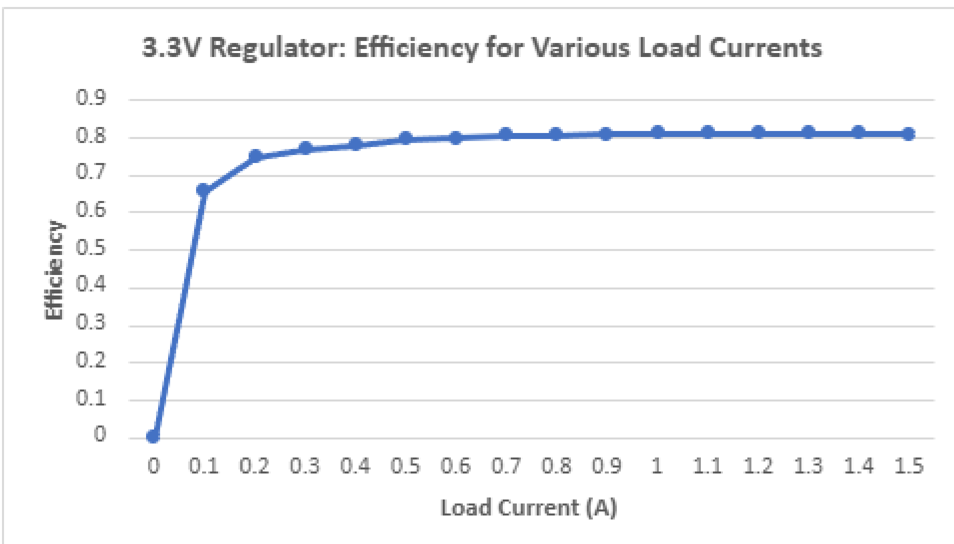


Figure 50: Efficiency Graph of the 3.3V Regulator

Additionally, at no load conditions, the input voltage for both regulators was varied from 24V to zero volts in order to find the dropout voltage of the regulator. For both regulators, the dropout voltage was found to be around 5V.

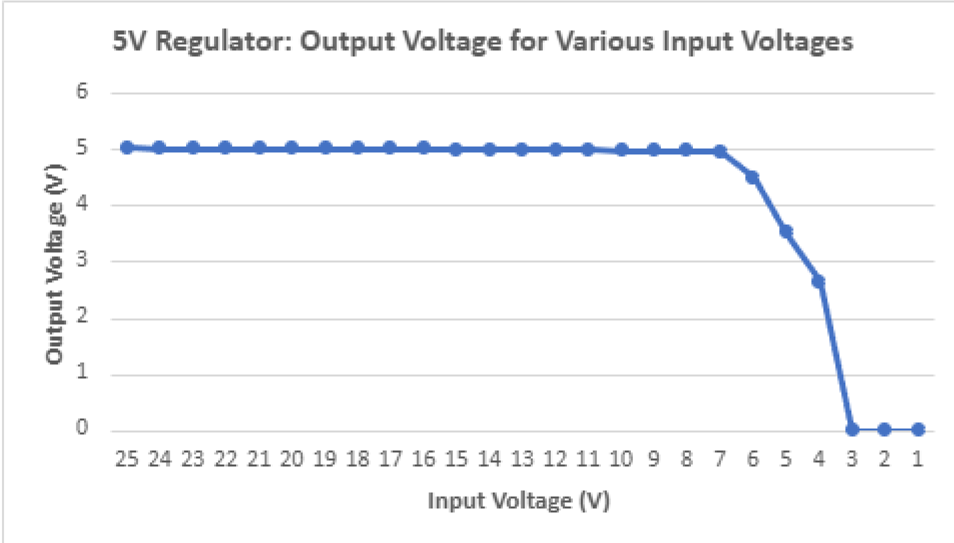


Figure 51: Voltage Regulation Graph for the 5V Regulator

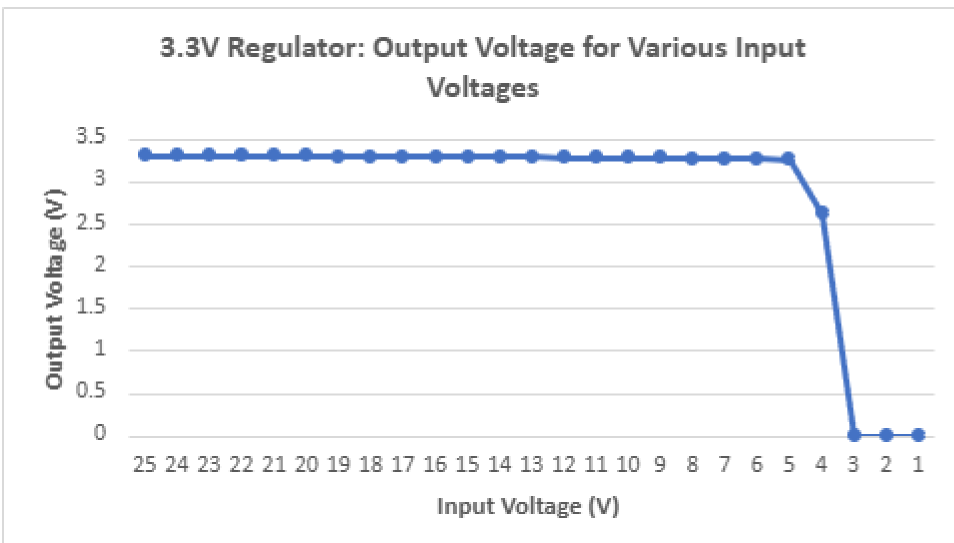


Figure 52: Voltage Regulation Graph for the 3.3V Regulator

9.4.3 - Voltage Measurement Testing

To ensure that our system is displaying proper voltage readings from the capacitor bank, a benchtop power supply was connected directly to the discharge tool’s input terminals. While the system was on and measuring voltage, the voltage of the power supply was varied. The value shown on the system’s display was then compared with the power supply setting in order to find the measurement error of the tool. It is also worth noting that the discharge tool measure’s the absolute value of the input voltage, so negative voltages still show as positive on the display.

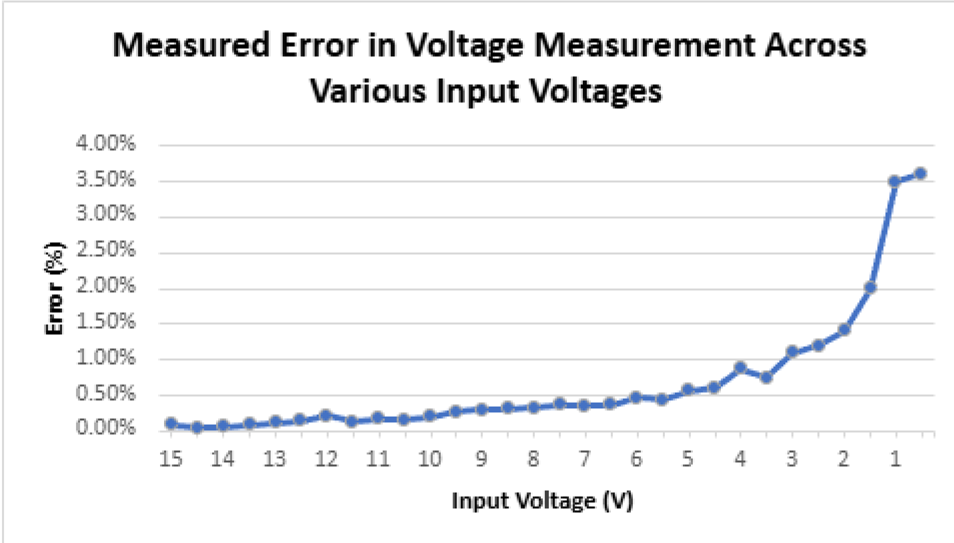


Figure 53: Voltage Measurement Error for Various Input Voltages

Overall, the average measurement error of the system was found to be 0.87%, with the highest error seen being 3.6%. Error increases more at lower voltages, which is expected to do a lower signal to noise ratio, but it is never higher than our engineering specification of 5% error.

9.4.4 - Discharge Time Testing

Testing the discharge time of the system was straightforward since it only required the system to be run under normal operation. As the system ran, an external timer was utilized as a reference to ensure that the displayed time was accurate. Lastly, the initial voltage of the capacitor bank was varied, along with certain setpoints, to test a variety of discharge scenarios.

Figure 54: Discharge Time Test Setup

Test Conditions: Stage 2 Setpoint = 8V, Stage 3 Setpoint = 4V, Safe Voltage Setpoint = 0.1								
Starting Voltage (V)	LTSPICE Discharge Time (sec)	Trial 1 Time (sec)	Trial 2 Time (sec)	Trial 3 Time (sec)	Trial 4 Time (sec)	Trial 5 Time (sec)	Average Time (sec)	Error (%)
12	17.67	19.29	19.11	19.23	19.23	19.04	19.18	8.55%
9	12.89	14.37	14.17	14.17	14.17	14.37	14.25	10.55%
6	9.42	10.75	10.74	10.94	10.77	10.74	10.788	14.52%
3	6.71	7.92	7.89	7.9	7.94	7.95	7.92	18.03%

Test Conditions: Stage 2 Setpoint = 6V, Stage 3 Setpoint = 2V, Safe Voltage Setpoint = 0.1								
Starting Voltage (V)	LTSPICE Discharge Time (sec)	Trial 1 Time (sec)	Trial 2 Time (sec)	Trial 3 Time (sec)	Trial 4 Time (sec)	Trial 5 Time (sec)	Average Time (sec)	Error (%)
12	23.25	24.53	24.71	24.71	24.54	24.52	24.602	5.82%
9	18.48	19.63	19.84	19.89	19.68	19.66	19.74	6.82%
6	11.72	13.17	12.95	13.16	12.82	13.15	13.05	11.35%
3	8.04	9.31	9.32	9.13	9.32	9.3	9.276	15.37%

Test Conditions: Stage 2 Setpoint = 7V, Stage 3 Setpoint = 3V, Safe Voltage Setpoint = 0.1								
Starting Voltage (V)	LTSPICE Discharge Time (sec)	Trial 1 Time (sec)	Trial 2 Time (sec)	Trial 3 Time (sec)	Trial 4 Time (sec)	Trial 5 Time (sec)	Average Time (sec)	Error (%)
12	20.16	21.46	21.46	21.67	21.53	21.52	21.528	6.79%
9	15.35	16.6	16.8	16.4	16.46	16.61	16.574	7.97%
6	10.38	11.75	11.74	11.56	11.59	11.54	11.636	12.10%
3	6.71	7.93	7.93	7.89	7.97	7.9	7.924	18.09%

Table 40: Discharge Time Testing Results

Across all tested scenarios, the discharge time was always under 30 seconds. When compared to discharge times in the initial design's LTSPICE simulation, the real discharge time was always higher than the theoretical. This is expected since external factors such as component tolerances, parasitic resistances, and processing delays are not reflected in the simulation.

9.4.5 - Temperature Measurement Testing

Testing that the systems temperature measuring functionality was within specification was harder than other subsystems. The most accurate test setup found by the team consisted of heating up the RTD probe with a heatgun to high temperatures (>120 degrees Fahrenheit), removing the heat source, and then scanning the temperature of the probe as it gradually cools down with an infrared thermometer gun. The temperature displayed on the infrared thermometer was then compared with that shown on the system's display.

After multiple trials, the highest temperature measured was 190 degrees Fahrenheit and the average error seen between measurements was 4.5%. The highest error seen was 8.08%, so the system is always within the 10% error of the team's engineering specification.

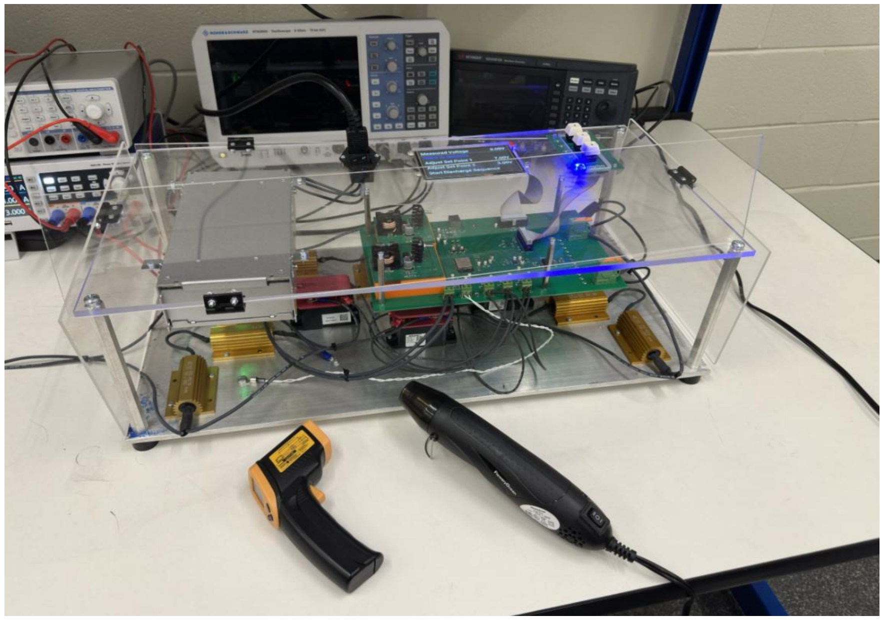


Figure 55: Temperature Measurement Test Setup

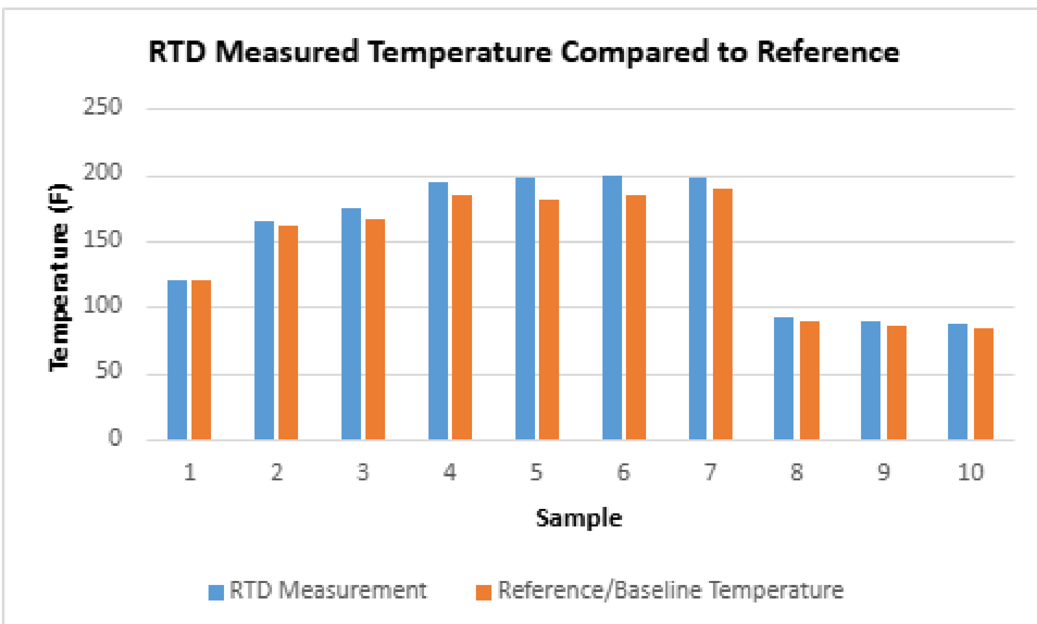


Figure 56: System Temperature Compared to Infrared Thermometer Temperature

Chapter 10: Administrative Content

10.1 - Project Milestones

These milestones were meant to keep the group on track and enable adequate preparation for the numerous tasks that need to be completed in both Senior Design 1 and 2. These included tasks related to documentation, design, manufacturing, and testing.

Table 41: Senior Design 1 Project Documentation Milestones

Start Date	End Date	Item
8/18/25	8/22/25	Project idea and group formation
8/25/25	9/5/25	Divide and Conquer Document
9/8/25	9/12/25	Divide and conquer revisions
9/15/25	10/31/25	80-page milestone
10/20/25	11/7/25	Overall revision of report
10/20/25	11/18/25	120-page milestone (these two items can be done simultaneously)

Table 42: Senior Design 1 Project Design Milestones

Start Date	End Date	Item
9/15/2025	10/1/2025	Research and System definition
10/3/25	10/19/25	Individual System design and component selection
10/20/25	10/31/25	Schematic Development and Component Ordering
11/1/25	11/17/25	Breadboard experimentation and PCB Design
11/17/25	11/25/25	Finalization of PCB design/demo video

Table 43: Senior Design 2 Project Milestones

Start Date	End Date	Item
12/2/25	12/17/25	PCB ordering
01/13/26	02/01/26	PCB prototype design
01/13/26	02/01/26	Integrate and complete software code
02/01/26	02/15/26	PCB assembly/System testing
02/15/26	03/01/26	Buffer for solutions (If things go wrong, a period to account for assembly of things or to reorder parts is essential)
03/01/26	03/20/26	PCB assembly part 2 and testing of prototype
03/23/26	04/14/26	Working prototype
01/13/26	04/20/26	Final Documentation (secondary activity throughout semester)
01/13/26	04/20/26	Calculations for high voltage design, along with comparisons between high level voltage and low level, and high- level voltage BOM

10.2 - Work Distribution

To meet the specified project milestones under the limited amount of time present within the senior design course, an effective distribution of major design tasks was required. As the features and functionalities of the project evolved, particular subsystems also grew and became clearer. These subsystems eventually became the main way in which work was divided between team members. To avoid team members from becoming too isolated, however, a primary and secondary person was assigned to each subsystem. This provided a form of assistance and collaboration in the design process. Additionally, the entire team met twice a week to update each other on progress, struggles, and potential concerns/conflicts with the design process. This provided a second form of collaboration between team members.

Table 44: Work Distribution Table

Subsystem	Primary	Secondary	Responsibilities
Sensing and Isolation	Kealan Frost	Will Serface	Sensor research and selections
			Sensor circuit designs
			Sensor, MCU, and relay integration
			Isolation from high voltage
Discharge	Javier Lopez-Marrero	Kealan Frost	High power resistor research and selection
			Relay research and selection
			Discharge network design
			Relay and MCU integration
Computing	Will Serface	Zeeshan Asif	MCU research and selection
			Display and I/O research and selection
			Embedded Programming
Power	Zeeshan Asif	Javier Lopez-Marrero	External power research and selection
			Regulator designs
			Capacitor charging circuit design

The only items not covered in the above distribution are the PCB design and general device testing. Since both of these items brought every subsystem together, the team worked as one to complete these tasks together. GitHub integration with KiCAD, allowed the team to have version control methods in place with all of the PCB designs. This allowed multiple team members to work on the same project files at different times, while also always being aware of what changes were made in the past. Additionally, group lab sessions were frequently held to adequately test and troubleshoot the system.

10.3 - Project Budget and Bill of Materials

This project was sponsored by NextEra Energy. A fixed budget was not established as part of NextEra's initial project proposal. As a result, the team presented an initial budget to NextEra after some of the preliminary design estimates were conducted. This initial budget included a target unit cost, which is the cost of just the components and manufacturing of the system, a unit cost that included the cost of taxes and shipping, and an overall project cost that included additional headroom for things like experimentation and components breaking.

Table 45: Initial Budget

Category	Items	Price
Controller & UI	microcontroller, display, buttons, lights	$55
Device Power Supply	DC power brick, regulators, connectors	$72
Sensing & Isolation	digital isolators, isolation transformer, temp sensing, voltage divider, adc	$180
Discharge Stage	power resistors, contactors, wire, connectors, aluminum plate	$800
PCB & Assembly	main pcb, accessory components, enclosure, assembly consumables	$630
Total		$1,737
Total after tax		$1,850
Total after tax + 30% headroom (unexpected items, unsure selections, etc.)		$2,405

After the project had nearly reached completion, and with a more accurate BOM developed, the real costs of the project were discovered. Overall, the project remained under budget in every category, which indicates that our solution was fairly cost effective considering various design changes took place.

Table 46: Up to Date Budget

Type	Cost
Discharge Chassis	$804.99
Main PCB	$198.40
Test Bank	$7.28
Power Supply	$95.72
Regulators	$36.22

Manufacturing	$580.00
Total Unit Cost	$1722.61
Total After Tax	$1843.1927
With Headroom Used	$2359.98

Below is the overall BOM for the design requested by NextEra. Please note that purchase links are not included within the copy present in this report.

Table 47: Final System BOM

System	**Item**	**Vendor**	**Unit Cost**	**Quantity**	**Total Cost**
Discharge Chassis	1/4in 1ft x 2ft 6061 Aluminum	McMaster-Carr	$58.10	1	$58.10
Discharge Chassis	1/4in 1ft x 2ft Plexi Glass	McMaster-Carr	$35.68	1	$35.68
Discharge Chassis	1/8in 0.5ft x 1ft Plexi Glass	McMaster-Carr	$6.95	2	$13.90
Discharge Chassis	1/8in 4in x 24in Plexi Glass	McMaster-Carr	$5.62	2	$11.24
Discharge Chassis	Hinges	Digikey	$3.92	4	$15.68
Discharge Chassis	2500 Ohm, 100W, Power Resistor	Digikey	$17.84	4	$71.36
Discharge Chassis	4700 Ohm, 100W, Power Resistor	Digikey	$17.84	4	$71.36
Discharge Chassis	470 Ohm, 100W, Power Resistor	Digikey	$17.84	4	$71.36
Discharge Chassis	P115CDA Contactor	Digikey	$105.10	3	$315.30
Discharge Chassis	PT1000 RTD	Digikey	$8.09	1	$8.09
Discharge Chassis	14 AWG, M4 Ring Terminal	Digikey	$0.61	8	$4.88
Discharge Chassis	14 AWG, M3 Ring Terminal	Digikey	$0.61	6	$3.66
Discharge Chassis	6 inch standoffs	McMaster-Carr	$7.49	4	$29.96
Discharge Chassis	3 inch standoffs	McMaster-Carr	$3.49	4	$13.96

Discharge Chassis	1/4-20 5/8inch length screws	McMaster-Carr	$7.40	1	$7.40
Discharge Chassis	M5 10mm length screws	McMaster-Carr	$8.12	1	$8.12
Discharge Chassis	M3 Screws	McMaster-Carr	$5.79	1	$5.79
Discharge Chassis	M3 Nuts	McMaster-Carr	$2.81	1	$2.81
Discharge Chassis	1/4-20 Nuts	McMaster-Carr	$6.32	1	$6.32
Discharge Chassis	M5 Nuts	McMaster-Carr	$3.56	1	$3.56
Discharge Chassis	Heat Shrink	Digikey	$1.54	2	$3.08
Discharge Chassis	5kV 14 AWG Wire (25ft)	Grainger	$22.00	1	$43.38
Main PCBs	2 Wire Screw Terminal	Digikey	$0.36	5	$1.80
Main PCBs	NMOSFET	Digikey	$0.46	5	$2.30
Main PCBs	Flyback diodes	Digikey	$0.56	3	$1.68
Main PCBs	MAX3186 RTD to Digital Converter	Digikey	$7.84	1	$7.84
Main PCBs	AMC3330 Isolation Amplifier	Digikey	$6.95	1	$6.95
Main PCBs	ADS1120 ADC	Digikey	$7.06	1	$7.06
Main PCBs	NHD 5.0 LCD Display Module	Digikey	$93.21	1	$93.21
Main PCBs	ESP32	Digikey	$4.84	1	$4.84
Main PCBs	USB Type B recepticle	Digikey	$1.27	1	$1.27
Main PCBs	CP2102N USB to UART	Digikey	$4.32	1	$4.32
Main PCBs	SP050 ESD Diodes	Digikey	$0.60	1	$0.60
Main PCBs	BJT	Digikey	$0.24	2	$0.48
Main PCBs	Push Button	Digikey	$0.42	2	$0.84
Main PCBs	2.54mm 4 pin header	Digikey	$0.40	2	$0.80
Main PCBs	2.54mm 2x10 IDC pin header	Digikey	$0.41	2	$0.82
Main PCBs	2x10pin 2.54mm pitch IDC cable	Digikey	$1.22	2	$2.44
Main PCBs	High Voltage Wire Connectors	Digikey	$2.57	2	$5.14
Main PCBs	Test Points	Digikey	$0.21	25	$5.25
Main PCBs	100nF NPO Capacitor	Digikey	$0.45	1	$0.45
Main PCBs	100nF X7R Capacitor	Digikey	$0.08	13	$1.04

Main PCBs	1uF X7R Capacitor	Digikey	$0.08	2	$0.16
Main PCBs	10nF X7R Capacitor	Digikey	$0.08	3	$0.24
Main PCBs	22uF Capacitor	Digikey	$0.19	1	$0.19
Main PCBs	4.7uF Capacitor	Digikey	$0.52	2	$1.04
Main PCBs	Ferrite Bead	Digikey	$0.21	3	$0.63
Main PCBs	1.5Mohm Resistors	Digikey	$1.98	10	$19.80
Main PCBs	1.1Mohm Resistors	Digikey	$0.10	1	$0.10
Main PCBs	10kohm resistor	Digikey	$0.81	15	$12.15
Main PCBs	47kohm Resistor	Digikey	$0.10	1	$0.10
Main PCBs	4.7kohm Resistor	Digikey	$0.10	1	$0.10
Main PCBs	47ohm Resistor	Digikey	$0.10	9	$0.90
Main PCBs	100ohm Resistor	Digikey	$0.10	7	$0.70
Main PCBs	0 ohm Resistor	Digikey	$0.10	6	$0.60
Main PCBs	47.5k Resistor	Digikey	$0.10	1	$0.10
Main PCBs	22.1k Resistor	Digikey	$0.10	1	$0.10
Main PCBs	2k Resistor	Digikey	$0.10	1	$0.10
Main PCBs	75ohm Resistor	Digikey	$0.10	3	$0.30
Main PCBs	1k Resistor	Digikey	$0.10	3	$0.30
Main PCBs	150 ohm resistor	Digikey	$0.10	3	$0.30
Main PCBs	220 ohm resistor	Digikey	$0.10	2	$0.20
I/O PCB	LED Kit	Digikey	$7.00	1	$7.00
I/O PCB	Cherry Buttons	Digikey	$1.25	3	$3.75
I/O PCB	2.54mm 2x10 IDC pin header	Digikey	$0.41	1	$0.41
Test Bank PCB	1k Resistor	Digikey	$0.76	1	$0.76
Test Bank PCB	330uF 50V Capacitor	Digikey	$1.43	2	$2.86
Test Bank PCB	1000uF 50V Capacitor	Digikey	$2.22	1	$2.22
Test Bank PCB	Switch	Digikey	$0.72	1	$0.72
Test Bank PCB	2 Wire Screw Terminal	Digikey	$0.36	2	$0.72
Power Supply	AC to DC Power Supply	Amazon	$34.99	1	$34.99
Power Supply	Male to female AC power cord	Digikey	$11.01	1	$11.01
Power Supply	C14 Socket with switch	Digikey	$5.06	1	$5.06
Power Supply	14 AWG Wire (25ft)	Grainger	$43.38	1	$43.38
Power Supply	Quick Connectors	Digikey	$0.32	4	$1.28

Regulators	LM2576 3.3V Regulator	Digikey	$3.86	1	$3.86
Regulators	LM2576 5V Regulator	Digikey	$3.86	1	$3.86
Regulators	Schottkey Diode	Digikey	$0.65	2	$1.30
Regulators	1000uF capacitor	Digikey	$0.96	1	$0.96
Regulators	100uF capacitor	Digikey	$1.92	1	$1.92
Regulators	1500uF capacitor	Digikey	$1.02	1	$1.02
Regulators	1uF Capacitor	Digikey	$0.21	5	$1.05
Regulators	0.1 uF Capacitor	Digikey	$0.23	5	$1.15
Regulators	220uF capacitor	Digikey	$1.12	2	$2.24
Regulators	100uH inductor	Digikey	$8.49	2	$16.98
Regulators	1kohm Resistor	Digikey	$0.71	2	$1.42
Regulators	LED	Digikey	$0.23	2	$0.46
Manufacturing	UCF Machining Cost Estimate	UCF	$200.00	1	$380.00
Manufacturing	PCB Ordering Cost Estimate	JLCPCB	$500.00	1	$200.00
				Total	**$1,722.61**

Chapter 11: Conclusion

Through the help and guidance provided by the University of Central Florida and NextEra Energy, this senior design team was able to develop a system design for safe and quick discharge of high voltage capacitors. Research was conducted in both familiar and unfamiliar technologies, and knowledge gained throughout the team's various degree paths was applied to create a foundation for system design. In confronting various complexities of the project, new technical skills were developed in high voltage isolation design, PCB design, and overall system integration. Various interpersonal skills were also developed as it related to building a team and providing satisfactory results for the sponsor.

This report serves as a record of the team's design process which includes but is not limited to: selecting reasonable components, applying relevant theories, identifying applicable standards, confronting specific limitations, and developing administrative plans/procedures. While some testing has been conducted on various aspects of the system, further execution and validation of the design will continue over the subsequent months within the second portion of the senior design course. This includes overall PCB manufacturing and testing, alongside the manufacturing of the overall system chassis.

Appendix A: References

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Appendix B: Copyright Permissions

Within the documentation for this senior design project, no copyrighted materials, such as graphics or logos, were utilized. Datasheet information referenced within the body of this report can be viewed in their original, publicly available, online sources through the links provided in Appendix C: Data Sheets.

Appendix C: Data Sheets

1. MAX31865 RTD to Digital Converter:
2. AMC3330 Isolation Amplifier
3. TLV2313 Dual Operational Amplifier
4. REF2033-Q1 Voltage Reference
5. AO3400A N-Channel MOSFET
6. ESP32-WROOM MCU
7. CP2102N USB to UART Converter
8. NHD-5.0-800480FT-CTXL-T Graphic Display
9. TE HS Series Power Resistors
10. P115 Contactor
11. LM2576 Voltage Regulator

Appendix D: Software Code

Figure 57: State Header File (state.h)

```
#include "threshold.h"

// The Program Phase a State belongs to.
enum class Phase : unsigned char {
  // Menu to either set or reset voltage thresholds and start discharge.
  CONFIG,
  // Program is actively discharging the capacitor bank.
  DISCHARGE,
  // Either safely discharged (<10V) or the program encountered an unsafe condition.
  COMPLETION
};

// A possible State of the program.
class State;

// Pair of references to a state and the callback to run before switching.
typedef struct state_callback_p {
  State* state;
  void (*callback)() = {};
} Action;

class State {
  // Name of this State
  const char *name;
  // A unique identifier for the State. Used for debugging.
  unsigned char id;
  // The Phase of the program the State is a part of.
  Phase phase;
  // The State to advance to from its corresponding event callback.
  Action next, above, below;
public:
  // Initialize a State in the given Phase by specifying its next State, other applicable States and
callbacks.
  State(const char *, Phase, Action, Action = { nullptr }, Action = { nullptr });
  // Provides the debug identifier of the State.
  unsigned char getId() const;
  // Provides the debug name of the State.
  const char *getName() const;
  // Provides the Phase of the given State.
  Phase getPhase() const;
  // Provides the next State when the user presses select.
  void goNext() const;
  // Provides the next State when the user navigates up.
  void goAbove();
  // Provides the next State when the user navigates down.
  void goBelow();
  // Provides the next State when the program auto-advances.
  void goContinue();
  // Provides the next State when the program detects an unsafe condition.
  void goUnsafe() const;
  // Outputs a String representation of the State over Serial.
  void log() const;
};
```

```
namespace menu {
  const Phase phase = Phase::CONFIG;
  extern State resetToDefaults;
  extern State hoverThreshold1;
  extern State adjustSetPoint1;
  extern State hoverThreshold2;
  extern State adjustSetPoint2;
  extern State startDcSequence;
};

namespace discharge {
  const Phase phase = Phase::DISCHARGE;
  extern State stage1;
  extern State stage2;
  extern State stage3;
}

namespace complete {
  const Phase phase = Phase::COMPLETION;
  extern State safely;
  extern State unsafely;
}

// The current State of the program.
extern State *current;
```

Figure 58: Threshold Header File (threshold.h)

```
// Represents the configurable Voltage Threshold of a Discharge Stage Setpoint
class Threshold {
  // Configured voltage.
  int value;
  // Limits of what voltage values can be configured.
  int min, max;
public:
  // Initialize a Threshold as the average of its minimum and maximum limits.
  Threshold(const int, const int);
  // Get the Threshold's maximum allowed value.
  int minimum() const;
  // Get the Threshold's minimum allowed value.
  int maximum() const;
  // Set Threshold to its preset value.
  void reset();
  // Implicitly cast the Threshold's current value as an integer.
  operator int() const;
  // Adjust the Threshold's setpoint to the nearest voltage within its limits.
  Threshold& operator=(const int);
};

namespace threshold {
  // Voltage Threshold to start Stage 1. Always 1500V.
  extern const Threshold setpoint0;
  // Voltage Threshold to start Stage 2. Between 600 to 800 volts.
  extern Threshold setpoint1;
  // Voltage Threshold to start Stage 3. Between 200 to 400 volts.
  extern Threshold setpoint2;
}
```

Appendix E: AI/LLM Prompts and Responses

[1a] **Case Study 1 Prompt:** "Give me a description of various resistor technologies, how they are made, how common performance specifications for them compare, and their common use cases. Also list the sources you used for this research"

[1b] Case Study 1 ChatGPT Copied Output:
1. Introduction
Resistors are passive components that limit or regulate electrical current. Their performance depends heavily on the material and manufacturing technology used. This document summarizes major resistor technologies, their construction, performance characteristics, and common applications.

---

2. Resistor Technologies Summary

Type	Construction	Typical Specs / Performance	Common Uses
Carbon Composition	Mix of carbon and ceramic binder pressed into a rod; leads attached.	Tolerance ±5–20%; TCR ≈ 2000–5000 ppm/°C; high noise; poor stability.	Low-cost general circuits, surge-resistant applications.
Carbon Film	Carbon film on ceramic substrate; spiral-trimmed for value.	±1–5%; TCR ≈ 200–500 ppm/°C; moderate noise.	General electronics, moderate precision needs.
Thick Film (SMD)	Resistive paste printed on ceramic and fired.	±1–5%; TCR ≈ 50–300 ppm/°C; moderate drift, higher noise than thin film.	Standard SMD chip resistors in consumer devices.
Metal Film	Thin metallic film (NiCr, etc.) sputtered onto ceramic, laser-trimmed.	±0.1–1%; TCR ≈ 5–50 ppm/°C; low noise; stable.	Precision analog, audio, instrumentation.
Metal-Oxide Film	Metal-oxide (e.g. SnO_2) film on ceramic; spiral-trimmed.	±1–2%; TCR ≈ 50–200 ppm/°C; better heat/surge handling than metal film.	Industrial, high-temp, power circuits.
Wire-Wound	Resistive wire wound on ceramic core; often coated or heat-sunk.	±0.1–1%; TCR depends on alloy (10–50 ppm/°C); very high power; low noise; may be inductive.	Power resistors, current shunts, precision standards.
Metal Foil / Bulk Alloy	Metal foil bonded to substrate and laser-trimmed.	±0.005–0.01%; TCR < 2 ppm/°C; extremely low noise; best long-term stability.	Precision instrumentation, calibration, metrology.

---

3. Key Specification Comparison

Spec	Definition	Typical Range (Across Technologies)
Tolerance	Deviation from nominal resistance.	±20% (carbon comp) → ±0.001% (foil).

Spec	Definition	Typical Range (Across Technologies)
TCR	Change in resistance per °C (ppm/°C).	5000 ppm (carbon comp) → < 1 ppm (foil).
Noise	Excess noise beyond thermal noise.	High (carbon) → very low (metal/foil).
Stability / Drift	Change over time/load.	Poor (carbon) → excellent (foil/wire-wound).
Power Rating	Continuous dissipation capability.	< 0.25 W (SMD film) → > 100 W (wire-wound).
Surge Handling	Short-term overload tolerance.	Best: wire-wound, metal-oxide; Worst: thin/thick-film.
Parasitics	Inductance/capacitance at HF.	Worst: wire-wound; Best: foil/film.

---

4. Technology Comparison Summary

Technology	Precision	Temp Stability	Noise	Power	Cost	Frequency Suitability
Carbon Composition	Low	Poor	High	Medium	Low	Low
Carbon Film	Medium	Fair	Medium	Medium	Low	Fair
Thick Film	Medium	Fair	Medium	Low	Very Low	Moderate
Metal Film	High	Good	Low	Medium	Medium	High
Metal-Oxide Film	Medium	Good	Medium	High	Medium	Moderate
Wire-Wound	High	Very Good	Very Low	Very High	High	Low (inductive)
Metal Foil	Very High	Excellent	Very Low	Medium	Very High	Excellent

---

5. Manufacturing Overview

- Carbon Composition: Carbon and binder mixed, molded, and baked.
- Film Types: Thin or thick resistive layer deposited on ceramic, then laser-trimmed.
- Metal-Oxide Film: Similar to metal film but with oxide materials, giving better heat resistance.
- Wire-Wound: Resistive alloy wire wound on a core, sometimes bifilar for low inductance.
- Foil / Bulk Alloy: Foil bonded to a substrate and trimmed; used for metrology-grade stability.

---

6. Application Guidelines

Application	Recommended Technology
Consumer Electronics	Thick Film / Carbon Film
Audio / Analog Circuits	Metal Film
Precision Measurement	Metal Foil / Bulk Alloy
Power / Load Resistors	Wire-Wound
High-Temperature Environments	Metal-Oxide Film

Application	Recommended Technology
High-Frequency Circuits	Thin / Metal Film, Foil (low inductance)

---

7. Typical Performance Examples

Example	Tolerance	TCR (ppm/°C)	Power (W)
Standard Metal Film	±1%	±25	0.25
Precision Thin Film	±0.01%	±5	0.125
Carbon Composition	±10%	±2000	0.5
Wire-Wound Power	±1%	±20	50
Foil Precision	±0.005%	±0.2	0.1

---

8. Trade-Off Overview

When choosing resistor types:

- Precision & Stability: Foil or metal film.
- Power: Wire-wound or metal-oxide.
- Cost & Compactness: Thick film.
- High Temperature or Harsh Use: Metal-oxide or wire-wound.
- Low Noise / High Frequency: Thin film or foil.

---

9. References

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[1b] Case Study 1 Copliot Copied Output:
Resistor technologies vary widely in construction, performance, and application. Here's a breakdown of the most common types, how they're made, how they compare, and where they're used.

🛠️ Common Resistor Technologies & How They're Made

Type	Construction	Manufacturing Notes
Carbon Composition	Mix of carbon powder and binder molded into a cylinder	Oldest type; simple and cheap but noisy and unstable
Carbon Film	Carbon layer deposited on ceramic rod	Laser-trimmed for resistance; better stability than composition
Metal Film	Thin metal layer (e.g., nickel-chromium) on ceramic substrate	Precision trimming allows tight tolerance and low noise
Metal Oxide Film	Tin oxide film on ceramic	Higher temperature and voltage tolerance than metal film
Thick Film	Screen-printed resistive paste (often ruthenium oxide) on ceramic	Common in surface-mount devices (SMD); cost-effective for mass production
Thin Film	Vacuum-deposited metal film on ceramic	High precision, low TCR (temperature coefficient of resistance), stable over time
Wirewound	Resistive wire (e.g., nichrome) wound around a ceramic or fiberglass core	High power handling; inductive unless specially designed
Foil (Bulk Metal)	Etched metal foil bonded to a substrate	Ultra-precise, extremely low TCR and noise; expensive

📊 Performance Comparison

Type	Tolerance	TCR (ppm/°C)	Noise	Power Rating	Stability
Carbon Composition	±5–20%	±1000+	High	Moderate	Poor
Carbon Film	±2–5%	±200–500	Moderate	Low–Moderate	Fair
Metal Film	±0.1–1%	±25–100	Low	Low–Moderate	Good
Metal Oxide Film	±1–5%	±300–500	Moderate	Moderate	Good
Thick Film	±1–5%	±100–300	Moderate	Low–Moderate	Fair
Thin Film	±0.01–1%	±5–50	Very Low	Low	Excellent
Wirewound	±0.1–5%	±5–50	Very Low	High	Excellent
Foil (Bulk Metal)	±0.005–0.1%	±0.2–2	Extremely Low	Low–Moderate	Exceptional

⚙️ Common Use Cases

- Carbon Composition: Vintage electronics, surge protection (due to energy absorption)
- Carbon Film: General-purpose consumer electronics
- Metal Film: Precision analog circuits, audio equipment, instrumentation
- Metal Oxide Film: Power supplies, automotive, high-temp environments
- Thick Film: Mass-produced SMD circuits, consumer electronics
- Thin Film: High-precision applications, medical devices, aerospace
- Wirewound: Power resistors, motor drives, high-current applications

- Foil: Metrology, high-end instrumentation, aerospace, military

📚 Sources

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4. SEI Electronics – Nichrome vs. Tantalum Nitride Comparison
5. Altera Price – In-Depth Analysis of Resistor Technologies

If you're designing a circuit or selecting components, I can help you choose the right resistor type based on your specific needs—just let me know your constraints or application!

[1c] Case Study 1 Gemini Copied Output:

I've put together a research plan. If you need to update it in any way, let me know.

Resistor Technologies: A Comprehensive Overview

Research Websites

(1) Systematically define and describe the major fixed resistor technologies, including Carbon Composition, Carbon Film, Metal Film (Thin Film), Thick Film (SMD/Chip), and Wirewound resistors.
(2) Investigate the general manufacturing processes for Carbon Composition, Carbon Film, and Metal Film resistors, focusing on the differences in how the resistive element is created and trimmed.
(3) Investigate the manufacturing processes for Wirewound resistors and Surface Mount Device...

More

Analyze Results

Create Report

Ready in a few mins

Edit plan   Start research

Resistor Technologies: A Comprehensive Overview   Create   ×

Researched 45 websites

In researching your report, Gemini searches the web and browses content from relevant websites on your behalf.

- **circuitmasterclass.com** Carbon Film Resistor – Detailed Explanation - Circuit Masterclass
- **vishay.com** Manufacturing Process for Fixed Film Resistors - Vishay
- **circuitmasterclass.com** Metal Film Resistor – Construction and Applications - Circuit Masterclass
- **xy-resistor.com** Film Resistor : Construction, Working, Types and Its Applications
- **electronics-tutorials.ws**
- **vpgfoilresistors.com** Reading Between the Lines in Resistor Datasheets-FAAG-63517
- **newark.com** Locked in resistance: Exploring the world of fixed value resistors - Newark Electronics
- **circuitschools.com** FIXED RESISTOR: Guide to Identification, Types & Applications - Circuit Schools
- **blikai.com** Wirewound Resistor: An In-Depth Overview - Blikai
- **madpcb.com** Thick Film Resistor(s): Surface Mounting Device (SMD) | MADPCB
- **en.wikipedia.org** Thick-film technology - Wikipedia
- **susumu.co.jp** 2.Manufacturing methods and characteristics of thin film resistors | Susumu Deutschland GmbH
- **korvustech.com** Thin Film Resistors | A Deep Dive - Korvus Technology

[2a] **Case Study 2 Prompt:** "Explain to me the process you would go through, along with relevant scientific theory, for estimating the temperature rise in a TE HSC100 series resistor (datasheet attached) if it dissipated an average power of 10W over 30 seconds."

[2b] Case Study 2 ChatGPT Copied Output:

- 1) Physical and Conceptual Model

Step 1: Lumped Thermal Model (RC Analogy)

The resistor and its aluminum housing (and any heatsink it's mounted to) can be modeled as a single thermal capacitance, denoted *Cth* (in joules per kelvin), connected to ambient air through a thermal resistance *Rth* (in kelvins per watt).

- The thermal capacitance *Cth* equals the mass *m* of the body multiplied by the specific heat capacity *cp*.
  (That is, Cth = m × cp.)
- The thermal resistance *Rth* describes how easily heat escapes to ambient air.

This simple "RC" model is valid when the temperature is fairly uniform through the resistor body or when we only need an average body temperature.

Step 2: Governing Transient Equation

When constant power *P* is dissipated for a time *t*, the temperature rise above ambient, written as delta-T(t), is given by:

delta-T(t) = P × Rth × [1 - exp(-t / tau)],

where *tau* (the thermal time constant) equals Rth × Cth.

The temperature rise will eventually reach the steady-state value delta-Tss = P × Rth once enough time has passed.

Step 3: Why This Model Works for a 30-Second Event

A 30-second pulse is usually short compared to the thermal time constant of a metal-housed resistor and its heatsink. Therefore, the resistor temperature typically does not reach steady state, and transient heating dominates.

- 2) Data Needed and Where to Get It

You need the following inputs:

- **Thermal resistance (Rth)**: found or inferred from the TE datasheet for the HSC100. If not directly listed, it can be estimated as Rth = (Allowed temperature rise) / (Rated power).
- **Thermal capacitance (Cth)**: estimated as the product of the mass of the resistor (or housing) and the specific heat capacity of aluminum, which is about 900 joules per kilogram per kelvin.
- **Mounting details**: whether the resistor is attached to a standard heatsink, and whether thermal compound or insulation is used. These factors strongly affect Rth.
- **Ambient temperature**: usually assumed to be around 25 degrees Celsius unless otherwise specified.

The datasheet includes pulse overload and surface temperature rise curves that allow a more precise inference of thermal performance.

- 3) Step-by-Step Estimation Procedure

1. Identify whether the resistor is used with a heatsink or free in air.

2. Obtain or estimate the steady-state thermal resistance Rth from the datasheet or by measurement.
3. Estimate the thermal capacitance using the formula Cth = m × cp, where m is the mass of the resistor or housing.
4. Compute the thermal time constant tau = Rth × Cth.
5. Compute the temperature rise after 30 seconds using the formula delta-T = P × Rth × [1 - exp(-30 / tau)].
6. Compare your results to the datasheet's overload and pulse graphs to ensure consistency.
7. Validate through measurement if needed.

- 4) Worked Example with Assumed Values

We will calculate temperature rise for a 10-watt average dissipation over 30 seconds using several reasonable assumptions.

- Common Assumptions
- Power = 10 watts
- Specific heat capacity of aluminum = 900 joules per kilogram per kelvin
- Ambient temperature = 25 degrees Celsius

We will consider two different masses and two different thermal resistances to show the sensitivity of the results.

Case A: Good heatsink and large mass

- Thermal resistance Rth = 1 kelvin per watt
- Mass m = 0.20 kilograms
- Thermal capacitance Cth = 0.20 × 900 = 180 joules per kelvin
- Thermal time constant tau = 1 × 180 = 180 seconds
- Steady-state temperature rise delta-Tss = 10 × 1 = 10 degrees Celsius
- Transient rise after 30 seconds = 10 × (1 - exp(-30 / 180)) ≈ 1.5 degrees Celsius

Case B: No heatsink but large mass

- Rth = 5 kelvins per watt
- Cth = 180 joules per kelvin
- tau = 5 × 180 = 900 seconds
- delta-Tss = 10 × 5 = 50 degrees Celsius
- delta-T at 30 seconds = 50 × (1 - exp(-30 / 900)) ≈ 1.6 degrees Celsius

Case C: No heatsink and small effective mass

- Rth = 5 kelvins per watt
- Mass = 0.02 kilograms
- Cth = 0.02 × 900 = 18 joules per kelvin
- tau = 5 × 18 = 90 seconds
- delta-Tss = 10 × 5 = 50 degrees Celsius
- delta-T at 30 seconds = 50 × (1 - exp(-30 / 90)) ≈ 14.2 degrees Celsius

Case D: With heatsink and small effective mass

- Rth = 1 kelvin per watt
- Mass = 0.02 kilograms
- Cth = 18 joules per kelvin
- tau = 1 × 18 = 18 seconds
- delta-Tss = 10 × 1 = 10 degrees Celsius
- delta-T at 30 seconds = 10 × (1 - exp(-30 / 18)) ≈ 8.1 degrees Celsius

---

- 5) Interpretation of Results

For a 10-watt, 30-second pulse, the temperature rise depends strongly on both the thermal mass and thermal resistance:

- If the resistor is well-heatsinked and massive, the temperature rise is only about 1 to 2 degrees Celsius.
- If the resistor is poorly cooled or has little effective thermal mass, the temperature rise may be around 8 to 15 degrees Celsius.
- If the same 10 watts were applied indefinitely, the steady-state rise would approach P × Rth (for example, 50 degrees Celsius with Rth = 5 kelvins per watt).

- 6) Practical Recommendations
- Use the datasheet's "Pulse and Overload" curves to verify that a 10-watt, 30-second load falls within safe limits.
- Measure the real resistor temperature during a test run to confirm your assumptions for Rth and Cth.
- Improve thermal contact with a flat mounting surface, proper torque, and thermal compound.
- Always ensure that the resistor surface temperature remains below its rated limit, even during transient pulses.

- 7) Summary

To estimate the temperature rise for a TE HSC100 resistor dissipating 10 watts for 30 seconds:

1. Obtain Rth and Cth.
2. Compute tau = Rth × Cth.
3. Compute delta-T = P × Rth × [1 - exp(-t / tau)].
4. Check results against datasheet pulse ratings.

In practical terms, for 10 watts over 30 seconds, the temperature rise will typically be a few degrees Celsius for well-mounted resistors or up to about 15 degrees Celsius for less ideal cooling.

[2c] Case Study 2 Copilot Copied Output:
Overview of process

1. Gather required datasheet parameters and geometric data for the HSC100.
2. Build a thermal model treating the resistor housing and heatsink as a lumped thermal mass coupled to ambient through a thermal resistance.
3. Compute steady-state temperature rise as DeltaTss = P * Rth.
4. Estimate the thermal capacitance Cth of the aluminium assembly.
5. Compute the thermal time constant tau = Rth * Cth and the transient temperature rise after t = 30 s using the first-order lumped-capacitance response.
6. Report result and list assumptions and uncertainty sources.

Datasheet parameters and constants used

- Standard heatsink area for HSC100: 99,500 mm2 which is 0.0995 m2.
- Housing thickness used for mass estimate: 3 mm which is 0.003 m.
- Dissipated power: 10 W for duration 30 s.
- Aluminium density rho = 2700 kg/m3.
- Aluminium specific heat c = 900 J/(kg·K).
- Natural convection heat transfer coefficient h assumed = 5 W/(m2·K).
- Contact/interface thermal resistance assumed Rth_contact = 0.2 K/W.

Step 1 — Estimate thermal resistance Rth

- Convective thermal resistance Rth_conv = 1 / (h * A).
- With h = 5 and A = 0.0995, Rth_conv = 1 / (5 * 0.0995) = 2.01005 K/W (approx 2.01 K/W).
- Add contact resistance Rth_contact = 0.2 K/W.
- Total thermal resistance Rth_total = Rth_conv + Rth_contact = 2.01 + 0.2 = 2.21 K/W (rounded 2.2 K/W).

Step 2 — Steady-state temperature rise

- DeltaTss = P * Rth_total.
- With P = 10 W and Rth_total = 2.21 K/W, DeltaTss = 10 * 2.21 = 22.1 °C (approx 22 °C above ambient).

Step 3 — Estimate thermal capacitance Cth

- Heatsink volume V = area * thickness = 0.0995 m2 * 0.003 m = 0.0002985 m3.
- Mass m = rho * V = 2700 kg/m3 * 0.0002985 m3 = 0.80595 kg (approx 0.806 kg).
- Thermal capacitance Cth = m * c = 0.80595 kg * 900 J/(kg·K) = 725.355 J/K (approx 725 J/K).

Step 4 — Thermal time constant tau and transient rise at 30 seconds

- Time constant tau = Rth_total * Cth = 2.21 K/W * 725.355 J/K = 1603.0 s (approx 1600 s).
- First-order transient response DeltaT(t) = DeltaTss * (1 - exp(-t / tau)).
- For t = 30 s, exponent = -30 / 1603.0 = -0.01872; exp(exponent) = 0.98145.
- Fractional rise = 1 - 0.98145 = 0.01855.
- DeltaT(30 s) = 22.1 °C * 0.01855 = 0.410 °C (approx 0.41 °C above ambient).

Final numeric summary

- Steady-state temperature rise at 10 W: 22.1 °C above ambient (rounded 22 °C).
- Temperature rise after 30 seconds of continuous 10 W dissipation: 0.41 °C above ambient (rounded 0.4 °C).

Key assumptions and uncertainty sources

- Convection coefficient h assumed 5 W/(m2·K); real h depends on orientation, proximity of other components, and airflow. Forced convection reduces Rth significantly.
- Contact/interface resistance assumed 0.2 K/W; poor mounting or missing thermal compound increases Rth.
- Lumped-capacitance model assumes uniform temperature within the aluminium mass; in reality the resistor element and leads can be hotter than the housing surface.
- Mass estimate used heatsink area and a uniform thickness of 3 mm; actual effective thermal mass may be larger if internal components or additional mounting hardware contribute.
- Datasheet experimental derating and surface-temperature graphs can provide more accurate Rth and transient behavior if read directly or requested from TE.

Practical recommendation

- Use these numbers for quick screening calculations.
- For design-critical work, measure temperature on the actual mounted HSC100 under intended ambient and airflow or obtain TE’s application-specific thermal data for the chosen mounting and environment.

[2d] Case Study 2 Gemini Copied Output:

🌡️ Estimating Temperature Rise for the $\mathrm{HSC100}$ Resistor

To estimate the temperature rise in a $\mathrm{TE\ HSC100}$ series resistor that dissipates an average power of **ten watts** ($10\ \mathrm{W}$) over a duration of **thirty seconds** ($30\ \mathrm{s}$), the process involves analyzing the event's safety using a transient check, and then estimating the temperature rise using the steady-state thermal graph provided in the datasheet.

1. Scientific Theory: Thermal Analysis

The dissipation of power over a short period like **thirty seconds** is a **transient thermal event**. However, because the applied power (**ten watts**) is a small fraction of the resistor's continuous rating, the final temperature rise will be close to the **steady-state** (continuous) rise for that power level.

- **Transient Analysis (Safety Check):** This is governed by the resistor's **thermal capacitance** (its ability to store heat) and is visualized in the **Power Overload** graph.
- **Steady-State Analysis (Temperature Estimation):** This is governed by the **thermal resistance** between the resistor's element and the heatsink, and is visualized in the **Surface Temperature Rise** graph.

---

2. Step-by-Step Estimation Process

Step A: Transient Power Check (Safety and Context)

First, determine how the **ten watts** compares to the component's maximum rated continuous power.

- **Rated Power (with standard heatsink):** The $\mathrm{HSC100}$ is rated for **one hundred watts** ($100\ \mathrm{W}$).
- **Multiples of Rated Power:**

$$\text{Multiples} = \frac{\text{Actual Power}}{\text{Rated Power}} = \frac{\text{ten watts}}{\text{one hundred watts}} = \text{zero point one}$$

- **Using the Power Overload Graph (Page Three, Bottom Left):**
  - The graph plots overloads (multiples of **five** to **thirty** times the rated power) against duration.
  - Since the actual power is only **zero point one** times the rated power, it is significantly **below** the minimum overload condition shown. The resistor is safely operating at only **one-tenth** of its maximum capacity, making a 30 s duration a very benign event.

Step B: Steady-State Temperature Estimation

Since the power is low and the duration is relatively long, the temperature rise will closely follow the continuous power curve.

- **Using the Surface Temperature Rise Graph (Page Three, Bottom Right):**
  1. Locate **ten watts** on the x-axis (*Power Dissipation (Watts)*).
  2. Trace a vertical line up to the curve corresponding to the $\mathrm{HSC100}$ resistor.
  3. Trace a horizontal line from this intersection point to the y-axis (*Surface Temp. Rise* ($^\circ\mathrm{C}$)).
  4. The intersection point for $\mathrm{HSC100}$ at $\mathrm{ten\ watts}$ is very low, visually falling between zero and twenty degrees Celsius.

---

3. Conclusion

The estimated **surface temperature rise** for the $\mathrm{HSC100}$ resistor dissipating **ten watts** for **thirty seconds** on a standard heatsink is very low, approximately **five degrees Celsius ($5^\circ\mathrm{C}$) to ten degrees Celsius ($10^\circ\mathrm{C}$)**.

Would you like me to find the **Standard heatsink area** for the $\mathrm{HSC100}$ resistor in square millimeters?

Sources

[3a] **Case Study 3 prompt: "**types of regulators to use in a capacitor discharge project"
[3b] Case Study 3 ChatGpt output: 1. Switching (Buck / Step-Down) Regulators
Use when: You need to charge a capacitor bank from a higher DC voltage efficiently.

- **Why:** Buck converters are ideal for efficiently stepping down voltage from, say, a 24 V DC input to a lower voltage (e.g., 12 V or 5 V) for the control circuitry or gate drivers.
- Examples:
  - **LM2576 / LM2596** (Fixed 3.3 V, 5 V, 12 V options, 3 A output)
  - **TPS5430** (5 A switching regulator from Texas Instruments)
- **Efficiency:** 80–95%, low heat.
- **Typical use:** Powering microcontrollers, trigger circuits, MOSFET gates, sensors.

⚙️ 2. Boost (Step-Up) Regulators
Use when: You need to charge capacitors to a higher voltage than your supply (e.g., from a 12 V source up to 48 V or 100 V).

- **Why:** A capacitor discharge circuit often needs a higher charge voltage for a strong pulse discharge.
- Examples:
  - **LT3750 / LT3751** – specifically designed for **capacitor charging** up to hundreds of volts.
  - **XL6009 / LM3478** – general-purpose boost converters.
- Efficiency: 85–95%.
- **Notes:** Include current limiting and feedback control to avoid capacitor overcharging.

⚙️ 3. Linear Regulators (LDOs)
Use when: You need a **clean, low-noise** power rail for sensitive analog or timing circuits.

- **Why:** In capacitor discharge systems, the control circuit may include op-amps, comparators, or microcontrollers that benefit from noise-free supply.
- Examples:
  - **LM7805 / LM7812** for basic fixed-voltage regulation.
  - **LT1763** for precision, low-noise applications.
- **Efficiency:** Lower (50–70%), but simple and stable.

⚙️ 4. Constant-Current Regulators
Use when: You want to control the charging current to the capacitor.

- **Why:** Prevents damaging surge currents that can over-stress components or power sources.
- Examples:
  - LM317 configured as a constant-current source.
  - **Dedicated LED driver ICs** like **LT3474** can also be used for constant-current charging.
- **Benefit:** Smooth, controlled charge curve to capacitor.

⚙️ 5. Specialized Capacitor-Charger ICs
Use when: The design centers around **high-voltage capacitor charging and controlled discharge** (e.g., flash, pulse, or coil-gun circuits).

- Examples:

- **LT3750 / LT3751 (Analog Devices)** – dedicated ICs for charging large capacitors to high voltage with built-in current sensing and shutdown.
- **MIC3172 / MAX1771** – compact boost controllers.

- **Advantage:** Simplified control, built-in safety, high power handling.

⚙️ Recommended Setup Example

If your project uses a **24 V DC input**, and your discharge circuit needs:

- 5 V control logic → use a Buck converter (LM2576-5.0).
- 48 V capacitor bank charge → use a Boost converter (LT3750).
- Stable reference voltage for sensing → use an LDO (LM7805 or LT1763).
- Current limit protection → add a constant-current circuit using LM317.

[3c] Case Study 3 CoPilot Output

For a capacitor discharge project, the most suitable types of voltage regulators are typically linear regulators, switching regulators, and programmable regulators—each offering distinct advantages depending on your design goals.

Here's a breakdown of the most relevant regulator types and how they fit into capacitor discharge applications:

Common Regulator Types for Capacitor Discharge Projects

1. Linear Voltage Regulators

- **Examples**: LM317, 7805, 7812
- **Best for**: Low-noise applications, simple designs
- Pros:
  - Easy to use and inexpensive
  - Provide clean, stable output
- Cons:
  - Inefficient for high current or large voltage drops (dissipate excess energy as heat)

2. Switching Voltage Regulators

- **Examples**: Buck (step-down), Boost (step-up), Buck-Boost
- **Best for**: Efficient power conversion, battery-powered or high-current systems
- Pros:
  - High efficiency (up to 90%+)
  - Can step voltage up or down
- Cons:
  - More complex design
  - Can introduce switching noise (requires good filtering)

3. Programmable Regulators

- **Examples**: Digital potentiometer-controlled regulators, microcontroller-based control
- **Best for**: Projects needing variable output voltage or controlled discharge profiles
- Pros:
  - Adjustable output
  - Can be integrated with sensors or feedback loops
- Cons:
  - Requires programming and additional circuitry

4. Induction and Step-Type Regulators

- **Used in**: Larger-scale or industrial capacitor banks (e.g., substations)

- Pros:
  - Handle high power levels
  - Suitable for reactive power compensation
- Cons:
  - Not practical for small-scale electronics projects

When choosing a regulator, consider:

- **Discharge voltage range**: Does your capacitor discharge from a high voltage that needs stepping down?
- **Load requirements**: What current does your load draw during discharge?
- **Efficiency vs simplicity**: Linear regulators are simple but waste energy; switching regulators are efficient but complex.
- **Noise sensitivity**: Audio or analog circuits may require low-noise linear regulators.

If you're working with high-speed switching or pulsed loads, capacitor selection also becomes critical. Use **low-ESR capacitors** like ceramic or film types to support fast current delivery and minimize losses.

Would you like help designing a specific regulator circuit for your project? I can walk you through component selection or simulate a discharge curve.

[3d] Case Study 3 Google Gemini Output

That's a great question, especially since a capacitor discharge can have a **wide and rapidly falling voltage**—a challenging input for a regulator!

The best type of regulator for your capacitor discharge project depends on your specific needs, primarily the **input voltage range** (from the capacitor) and the **required output voltage**.

Here are the main types of regulators and which ones are typically suited for a capacitor discharge scenario:

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1. Switching Regulators (DC-DC Converters)

These are generally the **best choice** because of their high efficiency and ability to handle a varying input voltage, especially as the capacitor discharges.[1]

Type	Function	Why it's useful for Capacitor Discharge
Buck Regulator (Step-Down)	Output voltage is always **lower** than the input.	Good if the fully charged capacitor voltage is high and you only need a lower output. The high efficiency is key.
Boost Regulator (Step-Up)	Output voltage is always **higher** than the input.	Useful if you need a higher regulated voltage than the capacitor's voltage *after* it has discharged somewhat (e.g., boosting a 2V supercapacitor up to 3.3V).
Buck-Boost Regulator	Output voltage can be **lower or higher** than the input.	**Most versatile** for capacitor discharge. It maintains a constant output voltage as the capacitor voltage drops from above to below the required output. **Highly recommended** if the capacitor voltage swings widely.

Key Advantages:

- **High Efficiency:** Often 85% to over 95%, meaning less power is wasted as heat, which is critical when drawing limited energy from a capacitor.
- **Flexibility:** Can step up, step down, or both (Buck-Boost).[2]

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2. Linear Regulators

These are simpler and quieter but less efficient, which can be a major issue when using a capacitor as your primary energy source.

Type	Function	Why it's useful for Capacitor Discharge
Low-Dropout Regulator (LDO)	Output voltage is always **lower** than the input, but it can maintain regulation even when the input voltage is *very close* to the output voltage (low "dropout" voltage).	Best linear option. It maximizes the usable energy from the capacitor because it can continue regulating until the capacitor voltage drops almost to the output voltage level.
Standard Linear Regulator (e.g., 78xx series)	Output voltage is always **lower** than the input, requiring a significant voltage difference (e.g., 2V-3V) between input and output.	**Generally not recommended.** The poor efficiency (wasted energy = $(V_{IN} - V_{OUT}) \times I_{LOAD}$) and high dropout voltage will quickly waste the capacitor's stored energy and drastically limit the usable range of the discharge.

Key Advantages:

- **Low Noise:** Excellent for noise-sensitive circuits (e.g., radio, audio).
- **Simplicity:** Fewer external components are required.

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3. Zener Diode/Shunt Regulator (Passive)

While technically a regulator, this is typically only used for very low-power, simple reference voltage circuits, and **not** for powering a load from a capacitor discharge.

- It regulates by shunting (diverting) excess current to ground. If the capacitor voltage drops, it simply stops regulating. Its inefficiency makes it unsuitable for energy-limited applications like a capacitor discharge.

💡 Recommendation and Next Steps

For most capacitor discharge projects where **efficiency and maximizing run-time** are important:

1. **Use a Buck-Boost Switching Regulator (DC-DC Converter).** This gives you the best efficiency and the ability to maintain a constant output over the capacitor's entire discharge range (high voltage to low voltage).
2. If the capacitor voltage will *always* be close to and slightly higher than the required output: An LDO (Low-Dropout Regulator) is a simple, low-noise option, but you'll still lose more energy than with a switching regulator.

To help you choose a specific part number, would you like me to find some examples of **Buck-Boost DC-DC converters** suitable for a specific set of parameters, such as a **target output voltage (e.g., 5V or 3.3V)** and **maximum current**?

[4a]- “ within the power subsystem of my capacitor discharge project, what other features should I add besides the regulator and external power”

[4b]- Case Study 4 Google Gemini Output

Safety and Discharge Control

These components are critical, especially if you are working with large or high-voltage capacitors, as they directly manage the rapid energy release.

Feature	Purpose and Why It's Needed
Bleeder Resistor	A high-value resistor connected **permanently in parallel** with the capacitor. It slowly drains the stored charge when the main power is disconnected.
High-Current Switch/Contactor	A fast-acting, high-power switch (like a **MOSFET, IGBT, or SCR**) placed between the capacitor and the load circuit.
Current Limiter / Fuse	A fuse or circuit breaker on the main power input, and potentially a fast-acting current limiter within the discharge path itself.

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2. 📊 Monitoring and Feedback

The unique challenge of a capacitor discharge is the constantly falling voltage, making monitoring essential for performance and reliability.

Feature	Purpose and Why It's Needed
Voltage Monitoring Circuit	A simple circuit (often a voltage divider) that feeds the capacitor voltage to a microcontroller (MCU).
Over-Voltage Protection (OVP)	A circuit that monitors the capacitor voltage and disconnects the charger once the voltage hits a safe maximum limit.
LED Indicators	Simple LEDs for status.

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3. 🔌 Charging and External Power Interface

You mentioned external power; these features optimize how that power is used to charge the capacitor.

Feature	Purpose and Why It's Needed
Charging Circuit/Converter	A dedicated circuit (often a **current-limited source**) to safely charge the capacitor from your external power.
Input Isolation/Reverse Polarity Protection	A diode (or a MOSFET in a smarter circuit) on the main power input.

[4c] – Case Study 4 ChatGpt Output

Essential protections & safety

- **Input fuse / circuit breaker** — slow-blow or fast depending on inrush and fault type.
- **Inrush limiter / NTC or soft-start** — protects supply and prevents contactor tripping when capacitors charge.
- **Precharge / current-limit resistor + relay/contactor** — prevents huge charging surge into the empty capacitor bank; use a relay/contact to bypass the precharge resistor after charging.
- **Bleeder (discharge) resistor** — slowly drains capacitors to safe voltage when powered off; add a mechanical shunt that shorts for fast discharge only when testing.
- **Over-voltage, over-current, over-temperature shutdown** — hardware comparator/MCU logic trips a disable signal to the charger/MOSFETs.

- **Crowbar / TVS / MOV / surge protection** — transient protection for spikes from AC mains or inductive loads.
- **Isolation & earth-grounding** — ensure chassis, measurement circuits, and operator safety are correctly grounded and isolated where needed.

Charging & energy control

- **Controlled charge algorithm** — current-limited charging (constant current then constant voltage or stop at set voltage) with monitoring.
- **Charge current sensing** — low-ohm sense resistor + differential amplifier or isolated current sensor (Hall effect) for control & protection.
- **Charge/discharge enable logic** — a clearly defined enable/arm sequence (interlocks + status LEDs) to avoid accidental firing.
- **Reverse-polarity protection** — for battery/supply connections.

Discharge control & switching

- **High-current switch/MOSFET or IGBT with gate driver** — sized for pulse current and dV/dt; include a proper gate driver, dead-time control, and gate resistors.
- **Snubbers / RC or RCD snubber networks** — clamp voltage overshoot from switching and protect the switch.
- **Current sensing in discharge path** — fast sense for monitoring and for over-current cutout.
- **Soft / staged discharge (if applicable)** — multiple stages or parallel switches to control discharge profile or share stress.

Sensing, measurement & telemetry

- **Voltage sensing on each capacitor bank** — for safety, balancing, and logging. If multiple cells, sense cell-level voltages.
- Temperature sensors (thermistors/RTDs/thermocouples) on capacitors, MOSFETs, inductors, and enclosure.
- **Accurate current measurement** — shunt + ADC or Hall sensor; ensure bandwidth covers discharge pulse.
- **Isolated ADCs or isolated measurement front-end** if measurements cross different potential domains.
- **Status indicators & meters** — voltmeter, ammeter, LEDs for armed/charged/error states.
- **Data logging / telemetry** — log charge/discharge cycles, peak currents, temps, and faults for debugging and lifetime analysis.

Balancing & longevity (for multi-cell packs)

- **Cell balancing (active or passive)** for multi-cell Li or supercap packs.
- **Battery Management System (BMS)** if using batteries — pack voltage, cell balancing, thermal, and safety cutouts.

EMI / EMC and layout

- **Input EMI filter** (common-mode choke + capacitors) and output filtering to meet emissions and prevent interference with control electronics.
- **Good PCB layout**: separate power and signal grounds, short high-current traces, wide copper, proper thermal vias and busbars for high currents.
- **Shielding and cable routing** to reduce radiated emissions and avoid noise coupling into sensors.

Thermal management & mechanical

- **Heatsinks, forced air / fan control** and thermal cutouts for MOSFETs/regulators/inductors.
- **Thermal pads / insulating hardware** and airflow channels in enclosure.
- **Robust connectors & cable gauge** sized for pulse current (use rated connectors and measure derating for pulse duty).
- **Clear labeling and safe enclosure** with interlock switches that cut main power when opened.

User interface & safe operation

- **Arm/Disarm sequence with physical confirmation** (e.g., key switch or two-button safety) to avoid accidental discharge.
- **Visible indicators** for charged state and fault conditions.
- **Enable lockout on faults** and auto-retry logic only after manual reset (for safety).
- **Emergency stop** that immediately isolates the discharge path.

Testing, calibration & diagnostics

- **Test points** for voltage, current, and gate drive waveforms.
- **Self-test routines** in firmware to check sensors, ADCs, and relays before allowing charge.
- **Built-in diagnostics & fault logging** to store the last error condition and parameter values.

Firmware & control features

- Watchdog and safe-state on MCU failure (drive gates low, open relays).
- **State machine**: clearly defined states (Power-off → Precharge → Charged/Armed → Discharge → Fault).
- **Rate limiting and interlocks** in software for repeated pulses (duty cycle control, cooldown times).
- **Remote control / comms (optional)** — serial, CAN, USB, or wireless with authentication and safe-operation rules.

Documentation & compliance

- **Schematic-level safety notes** and clearly written operating procedures.
- **BOM with derated component selections** (components rated for higher voltage/current/temperature than expected).
- **Regulatory checks** (if the device will be used publicly): basic EMC and safety rules, high-voltage handling procedures, and labeling.

[4d]- Case Study 4 CoPilot Output

Active Discharge Circuitry

- **Purpose**: Ensures capacitors safely discharge when power is removed.
- Components:
  - *Power MOSFETs*: Enable controlled discharge paths.
  - *Discharge resistors*: Premounted modules improve reliability.
  - *Gate resistors and optocouplers*: Provide isolation and control.

🔒 Protection Features

- **Overvoltage Protection**: Prevents damage from voltage spikes.
- **Reverse Polarity Protection**: Safeguards against incorrect power connections.
- **Current Limiting**: Avoids excessive current draw during charging/discharging.

📊 Monitoring and Feedback

- **Voltage and Current Sensors**: Track capacitor charge/discharge status.
- **Microcontroller Interface**: Enables real-time data logging and control.

- **Status LEDs or Display**: Visual indicators for system health and capacitor state.

🔁 Switching and Control

- **Relay or Transistor Switching**: Allows staged capacitor bank discharge.
- Programmable Logic (e.g., FPGA or MCU): Automates timing and sequencing.

🧯 Safety Enhancements

- **Bleeder Resistors**: Passive discharge when active circuitry fails.
- **Thermal Management**: Heatsinks or fans for dissipating energy safely.
- **Isolation Barriers**: Protect users and sensitive components from high voltage.

🧠 Smart Features (Optional)

- **Auto-discharge on power-off**: Prevents residual voltage hazards.
- **Self-test routines**: Verifies system integrity before operation.
- **Remote control or telemetry**: Useful for industrial or remote applications.

[5a] **Case Study 5 Prompt:** what are some common applications of the serial peripheral interface?

[5b] **Case Study 5 Gemini Output:**

Common applications of the Serial Peripheral Interface (SPI) include connecting microcontrollers to various peripherals like **sensors** (temperature, accelerometer), **memory devices** (flash, EEPROM, SD cards), and **displays** (LCD, OLED) in embedded systems, Internet of Things (IoT) devices, and wireless communication modules. It is also used for motor control, audio codecs, and for high-speed data transfer between microcontrollers and wireless modules like Wi-Fi and Bluetooth.

Embedded systems

- **Sensors:** Communicating with sensors such as temperature, pressure, light, accelerometers, and gyroscopes to gather environmental and motion data.
- **Memory:** Interfacing with flash memory, EEPROM, and other storage devices for data storage and retrieval.
- **Actuators:** Controlling devices like motors and servos in applications such as robotics and industrial automation.
- **Audio:** Connecting to audio chips, including digital-to-analog converters (DACs) and audio codecs.

Internet of Things (IoT)

- **Environmental monitoring:** Connecting to sensors for smart home and industrial applications, like tracking temperature, humidity, and air quality.
- **Connectivity:** Linking microcontrollers to wireless modules for Wi-Fi and Bluetooth communication, enabling high-speed data transfer.

Displays and other peripherals

- **Graphical displays:** Driving and communicating with OLED, LCD, and e-paper screens.
- **Data converters:** Interfacing with analog-to-digital (ADC) and digital-to-analog (DAC) converters.
- **Real-time clocks (RTCs):** Communicating with real-time clock ICs.
- **Expansion:** Connecting to devices like shift registers for I/O expansion.

[5c] Case Study 5 Copilot Output:

Serial Peripheral Interface (SPI) is commonly used in embedded systems to connect microcontrollers with peripheral devices like sensors, displays, and memory modules.
Here are some of the most frequent and practical applications of SPI:

🧠 Embedded Systems & Microcontrollers

- **Microcontroller-to-peripheral communication**: SPI is ideal for connecting microcontrollers to devices like EEPROMs, ADCs (Analog-to-Digital Converters), DACs (Digital-to-Analog Converters), and RTCs (Real-Time Clocks) GeeksForGeeks.
- **Inter-microcontroller communication**: It enables fast data exchange between multiple microcontrollers in a master-slave configuration Wikipedia.

📟 Display Interfaces

- **LCD and OLED displays**: SPI is often used to drive graphical displays in embedded devices due to its high-speed data transfer capabilities Electronics Hub.

🎧 Audio and Sensor Modules

- **Audio ICs**: Many audio chips use SPI for configuration and control.
- **Sensors**: SPI is used to interface with sensors like temperature, pressure, and motion sensors for real-time data acquisition Electronics Hub.

💾 Memory Devices

- **Flash memory and EEPROMs**: SPI is a popular protocol for accessing non-volatile memory in embedded systems, especially in bootloaders and firmware storage Electronics Hub.
- **SD and MMC cards**: SPI mode is supported by many memory cards for simple and low-cost interfacing Electronics Hub.

🧩 Industrial and Consumer Electronics

- **Industrial control systems**: SPI is used in PLCs and other automation systems for fast and reliable communication between control units and sensors.
- **Consumer electronics**: Devices like smartwatches, fitness trackers, and digital cameras often use SPI internally for component communication Spiceworks.

⚙️ Why SPI Is Preferred

- **High speed**: Faster than I²C for short-distance communication.
- **Full-duplex**: Can send and receive data simultaneously.
- **Simple hardware**: Requires fewer pins than parallel communication.

If you're working on a project involving microcontrollers or embedded systems, SPI is a go-to protocol for efficient and reliable communication. Want help choosing between SPI and I²C for a specific application?

[6] – Case Study in the Sensing System
PROMPT 1:
I am designing a PCB for a system that discharges a high capacity (1650uF) and high voltage (up to 1500V) capacitor. I need to switch the resistor stages with relays based on the current voltage of the capacitor. This means I need a system that allows my microcontroller to know what voltage the capacitor is currently at. I also need to maintain isolation and safety ensuring that the operator of the tool is never in a situation where they can come into contact with high voltage. What are all the different ICs, architectures, tools, methodologies, etc that would allow me to read the voltage

level of the capacitor while maintaining safety/isolation? Be thorough in your answer and give me every combination of technology that would work in this situation.

This is an excellent safety-critical design challenge. Here's a comprehensive breakdown of all viable approaches for measuring high voltage (up to 1500V) while maintaining isolation:

1. Isolated Voltage Divider + Isolated ADC/Amplifier

A. Voltage Divider + Isolation Amplifier

- **Resistor divider** (high voltage, high wattage resistors like Ohmite or Vishay HVR series)
- **Isolation amplifiers:**
  - **AMC1301** (Texas Instruments) - ±250V input, reinforced isolation
  - **AMC1311** (TI) - 2kV isolation
  - **ISO124** (TI) - precision isolation amplifier
  - **AD210** (Analog Devices) - 3-port isolation amp
  - **ACPL-C87x series** (Broadcom) - isolated sigma-delta modulators

B. Voltage Divider + Isolated ADC

- **AMC1035** (TI) - isolated 16-bit delta-sigma ADC
- **AMC3330** (TI) - reinforced isolated precision ADC
- **AD7400** (Analog Devices) - isolated sigma-delta modulator
- **Si8920** (Silicon Labs) - isolated ADC with digital output

C. Voltage Divider + Optocoupler + Non-isolated ADC

- Voltage divider → buffer → optocoupler (linear type like **IL300, LOC110, LOC111**) → microcontroller ADC
- Less accurate but simple and cheap

---

2. High Voltage Differential Probes + Isolation

Integrated High Voltage Sensing ICs

- **LEM CV Series** - voltage transducers with isolated output (CV 3-1000, CV 3-1500)
- **LV 25-P** (LEM) - Hall-effect based voltage transducer
- **Honeywell CSNP661** - current sensor (measure voltage via precision resistor)
- **ACS780** series (Allegro) - Hall-effect current sensors for indirect voltage measurement

---

3. Capacitive Voltage Divider + Isolation

Architecture

- High voltage capacitive divider (C1 small, C2 larger) provides inherent isolation
- Low voltage side measured with isolated ADC or isolation amplifier
- **Advantages:** No resistive power dissipation, excellent for AC or pulsed DC
- **Examples:**
  - Custom design with high voltage ceramic capacitors (TDK, Murata, AVX)
  - Commercial HV probes (Tektronix P5100A concept)

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4. Optical Isolation Methods

A. Fiber Optic Voltage Sensors

- **Photonic voltage sensors** (research/specialized products)
- Pockels effect sensors - voltage changes optical properties
- **NxtPhase** and **ABB** make commercial fiber optic voltage sensors (primarily for power grid applications)
- Most practical for industrial/utility scale, expensive

B. Optically Isolated Voltage Sensing ICs

- **HCPL-7860/HCPL-7840** (Broadcom) - isolated amplifiers with LED/photodiode
- **Si86xx/87xx** (Silicon Labs) - digital isolators with integrated DC-DC for power

---

5. Magnetic Isolation Methods

Hall Effect Voltage Transducers

- Voltage → current through precision resistor → Hall sensor measures current
- **LEM CV/DVL series** - closed-loop voltage transducers
- **Tamura L01Z** series - PCB-mount voltage transducers
- Excellent linearity and isolation (often > 6kV)

---

6. Digital Isolation + Standard ADC

Architecture

- Voltage divider to safe voltage
- Standard ADC
- **Digital isolators** for SPI/I2C:
  - **Si84xx** (Silicon Labs) - up to 5kV isolation
  - **ISO78xx** (TI) - digital isolators with integrated power
  - **ADuM1xx series** (Analog Devices) - iCoupler digital isolators
  - **ADUM7701/7702** (ADI) - isolated sigma-delta modulators

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7. Transformer-Based Isolation

AC Coupling Methods

- For pulsed/AC voltage measurement
- **Pulse transformers** or **isolation transformers**
- Rectify and measure on secondary side
- **Coilcraft**, **Wurth**, **Pulse Electronics** make suitable transformers
- Works if you can modulate/chop the DC voltage

---

8. Wireless/RF Transmission

Architecture

- High voltage side: voltage divider → ADC → RF transmitter (powered by small isolated supply)
- Low voltage side: RF receiver → microcontroller
- **Technologies:**
  - **Bluetooth Low Energy modules** (nRF52, ESP32)
  - **Sub-GHz RF** (Si4xxx, CC1xxx series)
  - **2.4GHz proprietary** (NRF24L01+)
- Provides complete galvanic isolation
- Requires isolated power for HV side circuit

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9. Isolated DC-DC Converters for Power + Any Isolation Method

Power Supply Isolation Options

- **MEA1D0509SC** (Murata) - 1kV isolation
- **R05P21503D** (Recom) - 3kV isolation
- **MGJ2 series** (Murata) - 2kV isolation
- **IA series** (XP Power) - medical grade, 4kV isolation
- **NMAxx series** (TDK-Lambda) - 1-6kV isolation

These are critical for powering any circuitry on the high voltage side.

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10. Complete Integrated Solutions

Commercial High Voltage Measurement Modules

- **LEM DVC 1000/1500** - voltage transducers
- **NK Technologies AS Series** - voltage transducers
- **Ohio Semitronics VT7 Series** - panel-mount voltage transducers
- **Flex-Core CVS** series

Recommended System Architectures by Complexity:

Simple (Good for prototyping):

1. High voltage resistive divider (1500V → 2.5V)
2. AMC1301 or AMC1311 isolation amplifier
3. Microcontroller ADC
4. Total cost: $5-15 per channel

Moderate (Better accuracy):

1. Precision HV divider network
2. Isolated ADC (AMC3330 or AD7400)
3. Digital isolator for SPI/I2C (Si8421 or ADUM1401)
4. Total cost: $15-30 per channel

Advanced (Highest isolation/safety):

1. LEM CV voltage transducer (complete module)
2. Standard ADC on safe side
3. Total cost: $50-150 per channel
4. Meets industrial safety standards out-of-box

Maximum Safety (Medical/critical):

1. Double isolation topology
2. Capacitive + magnetic isolation combined
3. Redundant measurement paths
4. Safety-rated isolated DC-DC converters
5. Total cost: $100-300 per channel

Critical Safety Considerations:

PCB Design Requirements:

- **Creepage distances:** Minimum 10mm for 1500V (per IEC 60950)
- **Clearance:** Minimum 5mm in air
- **Use isolation slots/cutouts** in PCB
- **Guard rings** around high voltage traces
- High voltage conformal coating

Standards Compliance:

- **IEC 61010** - Safety requirements for electrical equipment
- **IEC 60664-1** - Insulation coordination
- **UL 61010-1** - North American safety
- Consider **reinforced isolation** (2× basic isolation)

Component Selection:

- Use X1/Y1 safety capacitors for any HV filtering
- High voltage resistors rated for continuous operation (pulse-proof)
- Isolation ratings should exceed working voltage by 2-3×

Testing:

- **Hipot testing** to verify isolation (typically 2× working voltage + 1000V for 1 minute)
- **Partial discharge testing** for long-term reliability

My Top 3 Recommendations for Your Application:

Option 1 (Best Balance):

- Texas Instruments AMC1311B (3kV isolation, ±2V input) with precision voltage divider
- Simple, proven, cost-effective

Option 2 (Easiest Integration):

- LEM CV 3-1500 voltage transducer module
- Complete solution, excellent isolation, more expensive

Option 3 (Highest Performance):

- Analog Devices AD7400 isolated sigma-delta modulator
- ADUM1401 for isolated digital communication
- Best accuracy and noise performance

Would you like me to provide detailed schematics for any of these approaches?

PROMPT 2:
The resistors that will discharge our capacitor are aluminum cased power resistors. They will be connected to a plate of aluminum, which will act as a heat sink for the resistors. To ensure that the discharge resistors do not get too hot, we want to measure the temperature of the plate and translate that into our MCU, so we can shut off the resistors if needed. The temperature sensor does not need to be isolated itself, as it will be measuring the underside of the plate and the plate will be grounded. What are all the different temperature sensing architectures, methods, tools, methodologies, etc that are used or could be used to measure the temperature of my system. Be thorough in your answer and give me every combination of technology that would work in my situation. At the end, review the research and compare the technologies and components together creating a table to do so.

Comprehensive Temperature Sensing Solutions for Heat Sink Monitoring

1. Thermocouples

Types & Characteristics

- **Type K (Chromel-Alumel):** -200°C to +1350°C, most common, ±2.2°C accuracy
- **Type J (Iron-Constantan):** -40°C to +750°C, good for lower temps, ±2.2°C accuracy
- **Type T (Copper-Constantan):** -200°C to +350°C, best for <200°C, ±1°C accuracy
- **Type E (Chromel-Constantan):** -200°C to +900°C, highest sensitivity, ±1.7°C accuracy
- **Type N (Nicrosil-Nisil):** -200°C to +1300°C, better stability than K

Interface ICs

- **MAX31855** (Maxim) - SPI, cold junction compensation, Type K
- **MAX31856** (Maxim) - SPI, universal thermocouple, all types, best performance
- **MAX6675** (Maxim) - SPI, Type K only, simple/cheap
- **AD8494/AD8495/AD8496/AD8497** (Analog Devices) - Amplifiers for K, J, T, E types
- **LTC2983** (Analog Devices) - Universal, 20 sensor inputs, highest accuracy
- **ADS1220** (TI) - 24-bit ADC with PGA, requires external cold junction sensor
- **MCP9600** (Microchip) - I2C, thermocouple to digital converter, all types

Mounting Methods

- **Welded bead:** Spot-weld junction directly to aluminum plate (best thermal contact)
- **Compression fitting:** Spring-loaded probe against surface
- **Epoxy/thermal paste:** High-temp epoxy (Omegabond, Arctic Alumina)
- **Mechanical clamp:** Bolt-down with thermal grease

2. Resistance Temperature Detectors (RTDs)

Types

- **PT100:** 100Ω at 0°C, most common industrial standard
- **PT1000:** 1000Ω at 0°C, better for long cable runs, less self-heating
- **PT500:** 500Ω at 0°C, compromise between PT100/PT1000
- **Ni100/Ni1000:** Nickel RTDs, cheaper, -60°C to +180°C range

Accuracy Classes

- **Class AA:** ±(0.1°C + 0.0017×T)
- **Class A:** ±(0.15°C + 0.002×T)
- **Class B:** ±(0.3°C + 0.005×T)

Interface ICs

- **MAX31865** (Maxim) - SPI, dedicated RTD-to-digital, 2/3/4-wire, excellent
- **LTC2983** (Analog Devices) - Universal sensor interface, 2/3/4-wire RTD
- **AD7124** (Analog Devices) - 24-bit ADC with PGA, requires external excitation
- **ADS1220** (TI) - 24-bit ADC, integrated current sources for RTD excitation
- **PT1000** discrete measurement - Constant current source + precision ADC

Wiring Configurations

- **2-wire:** Simplest, lead resistance causes error
- **3-wire:** Compensates for lead resistance, most common
- **4-wire:** Best accuracy, completely eliminates lead resistance errors

Mounting Methods

- **Surface mount RTD sensors:** Thin-film elements with adhesive backing
- **Bolt-on probes:** M6/M8 threaded RTD elements
- **Pocket/well mount:** RTD in protective tube, bolted to surface

3. Thermistors

Types

- **NTC (Negative Temperature Coefficient):** Resistance decreases with temperature
  - **10kΩ @ 25°C** - Most common (B-value: 3950K, 3435K, 4250K)
  - **100kΩ @ 25°C** - Less self-heating, better for precision
  - Accuracy: ±0.1°C to ±1°C, range typically -50°C to +150°C
- **PTC (Positive Temperature Coefficient):** Resistance increases with temperature
  - Less common for measurement, more for protection/switching
  - Typically used as thermal fuses

NTC Thermistor Manufacturers & Series

- **Vishay NTCLE100E3** - High accuracy, ±0.5°C
- **TDK/EPCOS B57891** series - Industrial grade
- **Murata NCP15** series - Small SMD packages
- **Semitec 103AT** series - High stability
- **TE Connectivity G22K7** - Automotive grade

Interface Methods

A. Voltage Divider + ADC

- Simple resistor divider with known reference resistor
- Use microcontroller internal ADC or external ADC
- **External ADCs:**
  - **ADS1115** (TI) - 16-bit, I2C, 4-channel
  - **MCP3208** (Microchip) - 12-bit, SPI, 8-channel
  - **AD7091R** (ADI) - 12-bit, I2C/SPI

B. Dedicated Thermistor ICs

- **MAX31889** (Maxim) - I2C, integrated thermistor measurement
- **ADT7410** (Analog Devices) - Can be configured for external thermistor
- **LTC2983** (Analog Devices) - Universal, supports thermistors with Steinhart-Hart

C. Bridge Circuit + Instrumentation Amplifier

- Wheatstone bridge configuration
- **INA826/INA128** (TI) - Precision instrumentation amplifiers
- **AD8226** (ADI) - Low power instrumentation amp

Mounting Methods

- **Thermal epoxy:** Arctic Alumina, Omegabond 101
- **Kapton tape + thermal paste**
- **Mechanical clamp with thermal interface material**
- **Potted in thermal compound** (for rugged applications)
- **Direct bolt-on** (for threaded probe-style thermistors)

4. Analog IC Temperature Sensors

Voltage Output Sensors

- **LM35** (TI) - 10mV/°C, 0-100°C, ±0.5°C accuracy, 3-wire
- **LM335** (TI) - 10mV/K, Kelvin scale, -40 to +100°C
- **TMP36** (Analog Devices) - 10mV/°C, -40 to +125°C, 500mV offset
- **AD22100** (ADI) - 22.5mV/°C, -50 to +150°C
- **LM34** (TI) - 10mV/°F, Fahrenheit output

Current Output Sensors

- **AD590** (Analog Devices) - 1μA/K, 2-wire, -55 to +150°C
- **LM134/LM234/LM334** (TI) - Programmable current source, temp sensing
- **MAX1617** (Maxim) - Remote temperature sensor

Mounting for IC Sensors

- **TO-92 package:** Bolt to surface with thermal paste, insulate leads
- **TO-220 package:** Bolt directly to heat sink with mounting hole
- **SOT-23/SOIC:** Mount on small PCB, then attach PCB to heat sink
- **Thermal tape or epoxy**

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5. Digital IC Temperature Sensors

I2C/SMBus Digital Sensors

- **LM75** (TI/NXP) - I2C, ±2°C, -55 to +125°C, industry standard
- **TMP102** (TI) - I2C, ±0.5°C, -40 to +125°C, 12-bit, low power
- **TMP112** (TI) - I2C, ±0.5°C, -40 to +125°C, 13-bit
- **TMP117** (TI) - I2C, ±0.1°C, -55 to +150°C, 16-bit, **highest accuracy**
- **PCT2075** (NXP) - I2C, ±1°C, LM75 improved drop-in
- **ADT7410** (ADI) - I2C, ±0.5°C, -55 to +150°C, 16-bit
- **MCP9808** (Microchip) - I2C, ±0.25°C, -40 to +125°C, user-programmable
- **NCT75** (ON Semi) - I2C, ±1°C, LM75 compatible
- **DS18B20** (Maxim) - 1-Wire (not I2C), ±0.5°C, -55 to +125°C, parasitic power

SPI Digital Sensors

- **MAX31725** (Maxim) - SPI, ±0.5°C, -40 to +125°C
- **MAX31820** (Maxim) - SPI, ±2°C, -55 to +125°C
- **TMP125** (TI) - SPI, ±1°C, -55 to +125°C

1-Wire Protocol

- **DS18B20** (Maxim/Analog Devices) - ±0.5°C, -55 to +125°C, multiple sensors on one wire
- **DS18S20** (Maxim) - ±0.5°C, older version
- **DS1822** (Maxim) - Similar to DS18B20, cheaper
- **MAX31820** (Maxim) - Improved DS18B20

Analog Output Digital Sensors

- **MAX6613/MAX6614** (Maxim) - PWM output proportional to temperature
- Frequency output sensors (rare)

6. Infrared (IR) Temperature Sensors

Non-Contact Thermopile Sensors

- **MLX90614** (Melexis) - I2C, -40 to +125°C ambient, -70 to +380°C object, 0.5°C accuracy
- **MLX90615** (Melexis) - I2C, smaller FOV, -40 to +115°C ambient, -40 to +85°C object
- **MLX90640** (Melexis) - 32×24 thermal array, I2C, thermal imaging
- **MLX90641** (Melexis) - 16×12 thermal array, I2C
- **TMP006/TMP007** (TI) - I2C, non-contact, -40 to +125°C
- **AMG8833** (Panasonic) - 8×8 thermal array, I2C, "Grid-EYE"
- **D6T** series (Omron) - MEMS thermal sensors, 1×1 to 32×32 arrays

Mounting Considerations

- **Line of sight required** to aluminum plate surface
- **Emissivity compensation** needed (polished aluminum ~0.05, anodized ~0.8)
- Typically mounted 10-50mm from surface
- **Advantages:** No physical contact, no thermal mass added
- **Disadvantages:** Requires calibration for emissivity, affected by ambient temperature

7. Semiconductor Bandgap Temperature Sensors

Integrated Microcontroller Sensors

Most modern MCUs have internal temperature sensors:

- **STM32** series - Internal temp sensor, ±5°C typical
- **ESP32** - Internal temp sensor
- **nRF52** series - Internal temp sensor, ±4°C
- **SAMD** series - Internal temp sensor
- **PIC** series - Internal temp sensor

Note: These are typically for die temperature monitoring, not suitable for external heat sink measurement without external sensor.

8. Fiber Optic Temperature Sensors

Technologies

- **Fiber Bragg Grating (FBG)** - Wavelength shift with temperature
- **Distributed Temperature Sensing (DTS)** - Raman scattering
- **Fluorescence-based** - Decay time varies with temperature

Commercial Solutions

- **Luna/Micron Optics** - FBG interrogators
- **AP Sensing** - DTS systems
- **FISO Technologies** - Medical/industrial fiber optic sensors

Characteristics

- **Immune to EMI/RFI** - Perfect for high voltage environments
- **Very expensive** - $500-$5000+ per channel
- **Excellent for extreme environments**
- **Overkill for most applications**

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9. Thermal Switches/Bimetallic Devices

Types

- **Bimetallic thermostats** - Mechanical contact closure at set temperature
- **Thermal fuses** - One-time protection
- **Thermal switches** - Discrete on/off, not analog measurement

Examples

- **KSD301** - Snap-action thermostat, various setpoints
- **3455 Series** (Honeywell) - Bimetallic snap switches
- **7AM Series** (Texas Instruments) - Bimetallic thermostats

Characteristics

- **Not for precise measurement** - Only indicates threshold crossing
- **Cheap and reliable** ($0.50-$2)
- **Good as backup safety** in addition to analog measurement
- **Hysteresis** - Different on/off temperatures

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10. Acoustic/SAW Temperature Sensors

Surface Acoustic Wave (SAW) Sensors

- **Wireless/passive** - No power required at sensor
- **Very high temperature** capability (up to 800°C+)
- **Expensive and specialized**
- Used in turbines, engines, harsh environments

Examples

- **SENSeOR** - SAW sensor systems
- **Transense Technologies** - SAW torque and temperature

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11. Quartz Crystal Temperature Sensors

Technology

- Oscillation frequency varies with temperature
- **Very high accuracy** - ±0.01°C possible
- **Expensive and complex**
- Requires frequency counter/oscillator circuit

Examples

- Custom designs using AT-cut or SC-cut crystals
- Primarily laboratory/metrology applications

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12. Resistance-Based Heated Sensors

Technology

- Heat element to known temperature, measure power required
- Used in specialized applications (gas sensors, flow sensors)
- **Not suitable** for heat sink temperature measurement

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13. Specialty Mounting Methods & Accessories

Thermal Interface Materials

- **Thermal paste:** Arctic Silver 5, Noctua NT-H1, Thermal Grizzly
- **Thermal pads:** Bergquist Gap Pad, 3M 5580, Laird Tflex
- **Thermal epoxy:** Arctic Alumina, Omegabond 600/700, Duralco 132
- **Phase-change materials:** High-performance but expensive

Mechanical Mounting

- **Spring-loaded probes:** Constant pressure, repeatable contact
- **Bolted sensors:** M3/M4/M6 threaded, direct metal contact
- **Clip-on sensors:** For pipes/flat surfaces
- **Magnetic mount:** For ferrous metals only

Protective Enclosures

- **IP67/IP68 rated probes** - For wet/harsh environments
- **PTFE/Teflon insulation** - High temperature wire insulation
- **Stainless steel sheaths** - For RTDs in harsh environments

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14. Multi-Channel Solutions

For Monitoring Multiple Points

- **Multiplexer ICs:**
  - **ADG706/707/708** (ADI) - Analog mux for thermistors/RTDs
  - **MAX4617** (Maxim) - SPDT analog switch
  - **CD4051/CD4052/CD4067** (TI) - CMOS analog mux
- **Multi-channel sensor ICs:**
  - **LTC2983** (ADI) - 20 universal sensor inputs
  - **MAX31850** (Maxim) - Multiple 1-Wire thermocouples
  - **ADS1256** (TI) - 8-channel 24-bit ADC

15. Calibration & Reference Standards

Calibration Tools

- **Ice point references** - 0°C reference (triple point of water)
- **Dry-block calibrators** - Fluke 914x, Ametek RTC series
- **Liquid baths** - Oil/water baths for calibration
- **Reference thermometers** - Hart Scientific, Fluke precision PRTs

Calibration Standards

- **ITS-90** - International Temperature Scale
- **NIST traceable** calibration certificates
- **Industrial vs. laboratory** grade calibration

COMPREHENSIVE COMPARISON TABLE

Technology	Accuracy	Range	Cost	Interface Complexity	Response Time	Self-Heating	Mounting Ease	Bes
Type K Thermocouple	±2.2°C	-200 to +1350°C	$	Low	Fast (100ms-1s)	None	Excellent (weldable)	Hig ran
Type T Thermocouple	±1°C	-200 to +350°C	$	Low	Fast (100ms-1s)	None	Excellent (weldable)	Bes <20
PT100 RTD (Class A)	±0.15°C	-200 to +850°C	$$	Medium	Medium (1-5s)	Low (with proper current)	Good (bolt-on)	Ind sta acc
PT1000 RTD (Class A)	±0.15°C	-200 to +850°C	$$	Medium	Medium (1-5s)	Very Low	Good (bolt-on)	Lon less
10kΩ NTC Thermistor	±0.5-1°C	-50 to +150°C	$	Low	Very Fast (<1s)	Low	Excellent	Cos fast
100kΩ NTC Thermistor	±0.1-0.5°C	-50 to +150°C	$	Low	Very Fast (<1s)	Very Low	Excellent	Pre self
LM35 (Analog IC)	±0.5°C	0 to +100°C	$	Very Low	Fast (1s)	Moderate	Good (TO-92/TO-220)	Sim volt
TMP36 (Analog IC)	±1°C	-40 to +125°C	$	Very Low	Fast (1s)	Moderate	Good	Wic neg
AD590 (Current Output)	±0.5°C	-55 to +150°C	$$	Low	Fast (1s)	Low	Good	Lon (cu
TMP117 (Digital I2C)	±0.1°C	-55 to +150°C	$$	Very Low	Fast (<1s)	Low	Good (SMD on PCB)	Hig acc
TMP102 (Digital I2C)	±0.5°C	-40 to +125°C	$	Very Low	Fast (<1s)	Low	Good (SMD on PCB)	Cos digi
MCP9808 (Digital I2C)	±0.25°C	-40 to +125°C	$	Very Low	Fast (<250ms)	Low	Good (SMD on PCB)	Exc pric
LM75 (Digital I2C)	±2°C	-55 to +125°C	$	Very Low	Fast (300ms)	Low	Good (SMD on PCB)	Ind ubi
DS18B20 (1-Wire)	±0.5°C	-55 to +125°C	$	Low	Slow (750ms-1s)	Low	Excellent (TO-92/probe)	Mul one
MLX90614 (IR Non-contact)	±0.5°C	-70 to +380°C object	$$	Low	Very Fast (<100ms)	None	Fair (needs LOS)	Nor
MLX90640 (IR Array)	±1°C	-40 to +300°C object	$$$	Medium	Fast (8Hz)	None	Fair (needs LOS)	The mul
Thermal Switch (KSD301)	±5-10°C	-40 to +180°C	$	Very Low	Slow (10s+)	None	Excellent	Bac disc
Fiber Optic (FBG)	±0.1°C	-200 to +800°C	$$$$	High	Fast (<1s)	None	Poor (requires equipment)	EM ext env
LTC2983 (Universal)	Varies by sensor	Varies	$$$	Medium	Medium	Varies	Good	Mul res flex

Cost Scale:

- $ = <$2
- $$ = $2-$10
- $$$ = $10-$50
- $$$$ = >$50

Detailed Recommendations by Priority

Best Overall Choice: 10kΩ NTC Thermistor

Component: Vishay NTCLE100E3103JB0 or TDK B57891M0103K000 **Interface:** Voltage divider (10kΩ reference resistor) → ADS1115 (16-bit I2C ADC) or direct to MCU ADC

Why:

- ✅ Excellent accuracy (±0.5°C with calibration)
- ✅ Very fast response time
- ✅ Extremely low cost ($0.50-$1)
- ✅ Simple circuit
- ✅ Perfect temperature range for heat sink (0-150°C)
- ✅ Easy to mount with thermal epoxy or bolt-on
- ✅ Minimal self-heating
- ✅ Small size

Circuit:

```
3.3V ──┬── 10kΩ Reference Resistor ──┬── NTC Thermistor (10kΩ @ 25°C) ── GND
       │                              │
       └──────────────────────────────→ ADS1115 ADC Input or MCU ADC
```

Calculation: Use Steinhart-Hart equation or beta equation for temperature conversion.

Best for Highest Accuracy: PT100 RTD + MAX31865

Component: PT100 Class A RTD (Omega, Honeywell) + MAX31865 interface board

Why:

- ✅ Industrial standard
- ✅ ±0.15°C accuracy
- ✅ Excellent long-term stability
- ✅ Wide temperature range
- ✅ 3-wire or 4-wire compensates for lead resistance
- ✅ MAX31865 handles all signal conditioning
- ⚠️ More expensive ($5-15 total)
- ⚠️ Slower response time than thermistor

Best Digital Solution: TMP117

Component: TMP117 (TI) - I2C digital temperature sensor

Why:

- ✅ Highest accuracy digital sensor (±0.1°C)
- ✅ Direct I2C interface, no calibration needed
- ✅ Low self-heating
- ✅ Small SMD package
- ⚠️ Requires mounting on small PCB, then attaching PCB to heat sink
- ⚠️ More expensive than thermistor ($2-4)
- ✅ No external components needed

Best Budget Digital: DS18B20 (1-Wire)

Component: DS18B20 in TO-92 or waterproof probe package

Why:

- ✅ Very cheap ($1-2)
- ✅ Digital output, no ADC needed
- ✅ Can use multiple sensors on one wire
- ✅ Available in probe packages for easy mounting
- ✅ Simple protocol
- ⚠️ Slower conversion time (750ms)
- ⚠️ 1-Wire protocol requires bit-banging or dedicated controller

Best for Non-Contact: MLX90614

Component: MLX90614 IR temperature sensor

Why:

- ✅ No physical contact required
- ✅ Very fast response
- ✅ I2C interface
- ⚠️ Requires emissivity calibration for aluminum
- ⚠️ Needs line of sight
- ⚠️ More expensive ($5-8)
- ✅ Good for monitoring hot spots without adding thermal mass

Best Safety Backup: KSD301 Thermal Switch

Component: KSD301 normally-closed thermal switch (select temperature setpoint)

Why:

- ✅ Independent failsafe
- ✅ Extremely cheap ($0.50)
- ✅ No software required
- ✅ Direct mounting to aluminum plate
- ⚠️ Not for measurement, only threshold detection
- ✅ Can directly cut power or trigger interrupt

My Top Recommendation for Your Application

Primary Sensor: 10kΩ NTC Thermistor (Vishay NTCLE100E3103JB0) + ADS1115

Backup Safety: KSD301 Thermal Switch (90°C or 100°C setpoint)

Why This Combination:

1. **NTC thermistor** provides accurate, fast analog temperature measurement
2. **ADS1115** gives you 16-bit resolution with I2C interface (way better than MCU's internal ADC)
3. **KSD301** provides hardware-level safety cutoff independent of software
4. **Total cost:** ~$4 for complete solution
5. **Response time:** <1 second for thermistor
6. **Accuracy:** ±0.5°C with single-point calibration
7. **Simple mounting:** Thermal epoxy or bolt-on with thermal paste

Alternative if you want "plug and play": TMP117 for highest digital accuracy, or DS18B20 for lowest cost digital solution.

Would you like detailed schematics, mounting procedures, or firmware examples for any of these solutions?

PROMPT 3:

As mentioned before, this system seeks to discharge a 1500V capacitor down to a safe level. If a human were to come into contact with this, it would/could lead to death. Safety is our number one priority. To ensure our system remains safe, we have isolation or protection measures between anything the user touches and anything that the HV could interact with. This includes, but is not limited to: grounding the case, grounding the buttons/screen, digital isolators, analog isolators, and isolation transformers for power. Isolation also does not have to be just for safety. It can increase the robustness or durability of a system. Exposed semiconductor components not meant for HV on the HV side can break under a HV situation. Moving them to the LV side and ensuring that is LV can keep them safe. Knowing all of this, first list off all the various areas we need to make sure are isolated or grounded or made safe with some other method. Next, list off all the various types of isolation technology and components and explain them, compare them, and see where they would best fit to maintain safety and robustness. Be thorough in your explanation and don't miss any key areas.

Comprehensive Safety & Isolation Analysis for 1500V Capacitor Discharge System

PART 1: CRITICAL AREAS REQUIRING ISOLATION/PROTECTION

A. User Interface & Control Elements

1. Physical Controls (Buttons, Switches, Encoders)

- **Risk:** Direct conductive path from HV side to user fingertips
- **Required Protection:**
  - Physical buttons must be on grounded LV side only
  - If HV-side switching needed, use isolated relay/SSR control
  - Metal button caps must be grounded to chassis
  - Minimum creepage distance from any HV traces to button contacts

2. Display/Screen

- **Risk:** Touchscreen or LCD with metal backing could conduct HV
- **Required Protection:**
  - Display must be on LV side with grounded metal frame
  - If OLED/LCD controller near HV, use isolated communication (I2C/SPI isolators)
  - Touchscreen metal bezel must be grounded
  - EMI shielding connected to safety ground

3. External Connectors (USB, Programming Headers)

- **Risk:** USB/UART pins directly expose HV to computer equipment and user
- **Required Protection:**
  - ALL external connectors must be on isolated LV side
  - If debugging HV side, use isolated USB or optical programming
  - USB ports must be on grounded metal chassis
  - ESD protection diodes on all exposed pins

B. Microcontroller & Digital Logic

4. MCU Power Supply

- **Risk:** HV coupling through power supply could destroy MCU and create shock hazard
- **Required Protection:**
  - Complete galvanic isolation between HV and MCU power domains
  - Isolated DC-DC converters (medical grade, >2kV isolation)
  - Separate earth grounds for HV and LV sides (single-point ground architecture)
  - Input/output filtering on isolated supply

5. MCU GPIO to HV-Side Control Signals

- **Risk:** Direct GPIO control of HV relays/switches creates path for HV to reach MCU
- **Required Protection:**
  - Digital isolators (optocouplers, magnetic isolators) on ALL control signals
  - Relay drive circuits on HV side powered by isolated supply
  - Failsafe design: Loss of isolation should open relays (fail-safe)

6. Communication Buses (SPI, I2C, UART)

- **Risk:** Sensor/peripheral ICs on HV side sharing bus with LV side
- **Required Protection:**
  - Bus isolators for any cross-domain communication
  - Separate bus controllers on each side if possible
  - Isolated power for HV-side peripherals

C. Sensing & Measurement Circuits

7. High Voltage Measurement

- **Risk:** Voltage divider directly connects 1500V to MCU ADC input
- **Required Protection:**
  - Isolation amplifiers or isolated ADCs (as discussed previously)
  - Reinforced insulation rated >3kV
  - Physical separation and creepage distance on PCB
  - TVS diodes and current limiting on measurement path

8. Temperature Sensing

- **Risk:** If heat sink/resistors float to HV potential during fault
- **Required Protection:**
  - Heat sink MUST be grounded to safety earth
  - If heat sink cannot be grounded, use isolated temperature sensors
  - Thermocouples provide inherent isolation
  - Double-check mechanical mounting doesn't create HV path

9. Current Sensing

- **Risk:** Current shunt in HV path creates measurement point at HV potential
- **Required Protection:**
  - Hall-effect current sensors (magnetic isolation)
  - Isolated shunt amplifiers
  - Current transformers (for AC or pulsed DC)

D. Power Switching & Control

10. Discharge Relay Control

- **Risk:** Relay coils controlled by MCU, but contacts switch 1500V
- **Required Protection:**
  - Optoisolators or digital isolators driving relay coils
  - Relay coil power from isolated HV-side supply
  - Snubber circuits (RC or MOV) across relay contacts
  - Use relays rated for >2× working voltage (3kV+ rating)
  - Redundant relay architecture for critical safety

11. Gate Drives for Power Semiconductors (if using MOSFETs/IGBTs)

- **Risk:** Gate driver referenced to switching node at HV potential
- **Required Protection:**
  - Isolated gate drivers (Si827x, ADUM4223, etc.)
  - Bootstrap supplies or isolated DC-DC for gate power
  - High-side and low-side isolation if using half-bridge

12. Emergency Discharge/Bleeder System

- **Risk:** If main discharge fails, capacitor remains charged indefinitely
- **Required Protection:**
  - Passive bleeder resistor network (always connected, high resistance)
  - Independent from MCU control (hardware failsafe)
  - Discharge indication (neon lamp or isolated LED)

E. Enclosure & Mechanical

13. Metal Chassis/Enclosure

- **Risk:** Capacitive coupling or insulation failure energizes case
- **Required Protection:**
  - All exposed metal connected to protective earth (PE) ground
  - Bonding straps for all panels and doors
  - Grounding stud for external connection
  - Double insulation OR grounded conductive enclosure (IEC 61010)

14. Access Panels/Doors

- **Risk:** User opens enclosure while HV present
- **Required Protection:**
  - Interlocks on all access panels (micro-switches)
  - Interlock circuit shorts HV capacitor when door opens
  - Visible discharge indicator before access allowed
  - Mechanical latching preventing opening under load

15. PCB Mounting & Spacing

- **Risk:** PCB mounted to metal standoffs creates stray capacitance/leakage
- **Required Protection:**
  - HV PCB section isolated from mounting (use plastic standoffs or air gap)
  - Keep-out zones around HV sections
  - Conformal coating on HV traces
  - Guard rings and isolation slots in PCB

F. Power Input

16. AC Mains Input

- **Risk:** Mains voltage presents shock hazard and noise coupling
- **Required Protection:**
  - Fused input with slow-blow fuses
  - MOV or TVS for transient protection
  - EMI filter (common-mode and differential-mode)
  - Earth ground connection BEFORE any electronics
  - Isolation transformer if using offline PSU topology

17. DC Power Supplies

- **Risk:** HV-side supplies could couple noise or voltage back to mains
- **Required Protection:**
  - Separate isolated supplies for HV and LV sides
  - Y-capacitors (safety rated) for EMI filtering
  - Ensure isolation rating > working voltage

G. Communication & Data

18. Wireless Communication (WiFi, BLE, etc.)

- **Risk:** Antenna could radiate HV noise or couple HV to external devices
- **Required Protection:**
  - Wireless module on LV side only
  - Antenna grounded/shielded
  - RF filtering on module power

19. Wired External Communication (RS485, CAN, Ethernet)

- **Risk:** External cable brings HV to connected equipment
- **Required Protection:**
  - Isolated transceivers (ISO1540, ADM3485, etc.)
  - Surge protection on communication lines
  - Shielded cables with shield grounded at one point

H. Operator Safety Features

20. Voltage Discharge Indication

- **Risk:** User assumes system is safe when HV still present
- **Required Protection:**
  - Visual indicator (LED or neon) showing HV status
  - Isolated LED drivers if indicator on HV side
  - Audible alarm for HV present
  - Cannot be software-controlled (hardware-based)

21. Key Switch or Lockout

- **Risk:** Unauthorized operation or accidental activation
- **Required Protection:**
  - Key switch interrupting power to control circuits
  - LOTO (Lockout/Tagout) capability
  - Software interlock with hardware override

22. Ground Fault Detection

- **Risk:** Insulation breakdown creates leakage current through operator
- **Required Protection:**
  - Ground fault detection circuit
  - Isolated current measurement (Rogowski coil, hall effect)
  - Automatic shutdown if fault detected

I. Fault Conditions & Edge Cases

23. Capacitor Failure Mode

- **Risk:** Short circuit or explosion releases energy rapidly
- **Required Protection:**
  - Current limiting resistors in series with capacitor
  - Fusing or current sensing for fault detection
  - Physical containment (blast shield)
  - PCB trace fusing for overcurrent

24. Relay Contact Welding

- **Risk:** Relay contacts weld closed, cannot turn off discharge
- **Required Protection:**
  - Relay contact arc suppression (snubbers)
  - Redundant relays in series
  - Contact voltage and current monitoring
  - Time-based failsafe (if relay on too long, open backup)

25. Software Crash/Hang

- **Risk:** Watchdog fails, MCU locks up with relays energized
- **Required Protection:**
  - Hardware watchdog timer (external IC)
  - Watchdog timer must remove power from relay coils
  - Capacitive timing circuit for maximum on-time

26. Isolation Barrier Failure

- **Risk:** Isolator component fails short, HV reaches LV side
- **Required Protection:**
  - Use reinforced or double isolation components
  - TVS diodes and current limiting on LV side of isolation
  - Redundant isolation barriers for critical paths
  - Regular high-pot testing during production

J. EMC & Noise Coupling

27. Common-Mode Noise

- **Risk:** Fast switching couples noise through parasitic capacitance
- **Required Protection:**
  - Common-mode chokes on power inputs
  - Y-capacitors (safety rated) for high-frequency bypass
  - Shielded cables and twisted pairs
  - Star grounding topology

28. Differential-Mode Noise

- **Risk:** Voltage spikes damage sensitive electronics
- **Required Protection:**
  - Snubber networks on inductive loads
  - TVS diodes at vulnerable inputs
  - Ferrite beads on signal lines

K. Environmental & Mechanical

29. **Moisture & Contamination**

- **Risk:** Conductive contamination reduces creepage distance
- **Required Protection:**
  - Conformal coating on PCBs
  - IP-rated enclosure (IP54 minimum)
  - Desiccant packs if needed
  - Keep HV section sealed from dust ingress

30. **Mechanical Stress & Vibration**

- **Risk:** Wire insulation chafes, solder joints crack
- **Required Protection:**
  - Strain relief on all wire connections
  - Lock washers on all mechanical connections
  - Cable ties and routing preventing movement
  - Potting of critical HV connections

PART 2: ISOLATION TECHNOLOGIES & COMPONENTS

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1. OPTICAL ISOLATION (Optocouplers/Optoisolators)

Technology Explanation

- Uses LED on input side, phototransistor/photodiode on output side
- Light crosses isolation barrier (no electrical connection)
- Typically 2.5kV to 5kV isolation voltage
- Available in various configurations: digital, analog, gate driver

Types & Components

A. Digital Optocouplers (Logic Level)

Standard Speed (1-10 Mbps):

- **4N25-4N35 series** - General purpose, cheap ($0.20), 2.5kV isolation
- **6N137/138** - High speed (10 Mbps), 2.5kV isolation
- **TLP181** (Toshiba) - Improved CTR, 5kV isolation
- **FOD817** (Onsemi) - Industry standard, 3.75kV isolation

High Speed (>10 Mbps):

- **HCPL-0601/0611** (Broadcom) - 10-15 Mbps, 2.5kV isolation
- **6N137** - 10 Mbps, 2.5kV isolation
- **ACPL-W345** (Broadcom) - 25 Mbps, 3.75kV isolation

Reinforced/Medical Grade:

- **ACPL-217** (Broadcom) - 5.3kV, VDE certified
- **TLP2362** (Toshiba) - 5kV, reinforced isolation
- **HCPL-0872** (Broadcom) - 5kV, dual channel

B. Analog Optocouplers (Linear)

- **IL300** (Vishay) - Dual feedback for linearity
- **LOC110/LOC111** (IXYS) - Linear isolation
- **HCNR200/201** (Broadcom) - High linearity analog isolation
- **TIL300** (TI) - Analog isolation (discontinued, use IL300)

C. Gate Driver Optocouplers

- **TLP250** (Toshiba) - MOSFET/IGBT driver, 2.5kV, 2.5A output
- **HCPL-3120** (Broadcom) - 2.5A gate driver, 3.75kV
- **FOD3184** (Onsemi) - 4A gate driver, 5kV isolation
- **ACPL-332J** (Broadcom) - 2.5A, 1200V peak voltage

Advantages

- ✅ True galvanic isolation
- ✅ Very low cost ($0.20-$2)
- ✅ Simple circuit design
- ✅ Immune to magnetic interference
- ✅ Unidirectional (no reverse coupling)

Disadvantages

- ⚠️ LED degradation over time (CTR drift)
- ⚠️ Temperature dependent
- ⚠️ Relatively slow (1-25 Mbps typical)
- ⚠️ Requires LED drive current (5-20mA)
- ⚠️ Non-linear for analog signals (except specialized types)

Best Applications in Your System

- ✅ **Relay control signals** - 4N25, FOD817
- ✅ **Emergency stop/interlock** - ACPL-217 (reinforced)
- ✅ **Gate drives** (if using MOSFETs) - TLP250, HCPL-3120
- ✅ **Status indicators** - 4N25
- ⚠️ NOT for high-speed data (use magnetic isolators)

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2. MAGNETIC ISOLATION (Transformer-Based)

Technology Explanation

- Uses transformer or coupled inductors
- Signal modulated onto carrier, coupled magnetically, then demodulated
- Typically 2.5kV to 10kV isolation
- Very fast (up to 600 Mbps)
- Bidirectional communication possible

Types & Components

A. Digital Isolators (General Purpose)

Silicon Labs (iCoupler-like):

- **Si84xx series** - 2-6 channel, up to 150 Mbps, 2.5-5kV isolation
  - Si8421 (4-channel), Si8422 (2-channel)
- **Si86xx series** - With integrated DC-DC, 2.5kV isolation
  - Si8660/Si8661 - Isolator + isolated power

Texas Instruments:

- **ISO72xx series** - 2-4 channel, up to 25 Mbps, 2.5-5kV isolation
  - ISO7221 (2-channel), ISO7241 (4-channel)
- **ISO77xx series** - High speed, up to 100 Mbps, 5kV isolation
  - ISO7741 (4-channel, 100 Mbps)

Analog Devices (iCoupler):

- **ADuM1xxx series** - 2-6 channel, up to 25 Mbps, 2.5-5kV isolation
  - ADuM1201 (2-channel), ADuM1401 (4-channel)
- **ADuM3xxx series** - With integrated isolated power
  - ADuM3151 (3-channel + isolated power)
- **ADuM6xxx series** - With isoPower (DC-DC), 5kV isolation

NVE (IsoLoop - GMR technology):

- **IL600 series** - 2.5kV isolation, ultra-low power
- Uses Giant Magneto-Resistive effect, different from transformer

B. High-Speed Data Isolators

USB Isolators:

- **ADuM4160** (Analog Devices) - USB 2.0 Full-Speed isolator
- **ISO1540** (TI) - USB 2.0 isolator
- **Si864x** (Silicon Labs) - USB isolator

SPI/I2C Isolators:

- **ISO1540/1541** (TI) - I2C isolator, bidirectional
- **Si8603** (Silicon Labs) - I2C isolator
- **ADUM1250/1251** (ADI) - I2C isolator with hot-swap
- **ISO7741** (TI) - SPI isolator (4-channel, high speed)
- **ADUM4402** (ADI) - Quad SPI isolator

CAN/RS485 Isolators:

- **ISO1050** (TI) - CAN transceiver with isolation
- **ADM3485E** (ADI) - Isolated RS485 transceiver
- **Si8662** (Silicon Labs) - Isolated CAN

C. Analog/Data Acquisition Isolators

Isolated ADCs:

- **AMC1035** (TI) - 16-bit isolated delta-sigma ADC
- **AMC3330** (TI) - Precision isolated ADC
- **AD7400** (ADI) - Isolated sigma-delta modulator
- **Si8920** (Silicon Labs) - 12-bit isolated ADC

Isolated Amplifiers:

- **AMC1301/1311** (TI) - Isolated amplifier, ±250V input
- **ISO124** (TI) - Precision isolation amplifier
- **AD215** (ADI) - Isolated amplifier
- **ACPL-C87x** (Broadcom) - Isolated sigma-delta modulators

D. Gate Driver Isolators (Magnetic)

- **Si827x series** (Silicon Labs) - Isolated gate driver, 2.5-5kV, 4A output
  - Si8271 (single output), Si8274 (dual output)
- **ADUM4223** (ADI) - Isolated half-bridge driver, 4A
- **ISO5451/5452** (TI) - Isolated half-bridge driver, 2.5kV
- **UCC21520** (TI) - Isolated dual-channel gate driver, 5.7kV

Advantages

- ✅ Very high speed (up to 600 Mbps)
- ✅ No LED degradation (long-term stable)
- ✅ Low power consumption
- ✅ Bidirectional communication possible
- ✅ Better temperature stability than optocouplers
- ✅ Small package sizes (SOIC, QFN)

Disadvantages

- ⚠️ More expensive than optocouplers ($2-$10)
- ⚠️ Susceptible to external magnetic fields
- ⚠️ Some designs require external bypass capacitors
- ⚠️ Can have higher parasitic capacitance than optical

Best Applications in Your System

- ✅ **SPI/I2C bus isolation** - ISO1540, ADuM1250
- ✅ **High-speed control signals** - ISO7241, ADuM1401
- ✅ **USB isolation** (for debugging/programming) - ADuM4160
- ✅ **Isolated voltage measurement** - AMC1301, AMC3330
- ✅ **Gate drives** (if using high-frequency switching) - Si8271, UCC21520

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3. CAPACITIVE ISOLATION

Technology Explanation

- Uses differential capacitors as isolation barrier
- Signal coupled through capacitor dielectric
- Very high speed possible (>600 Mbps)
- Lower parasitic capacitance than magnetic

Components

- **Si86xx series** (Silicon Labs) - Some use capacitive coupling
- **CAP1x** series (TI) - Capacitive touch isolators (different application)

Note: Most "capacitive isolators" are actually hybrid designs. Pure capacitive isolation is less common than magnetic for digital isolation.

Advantages

- ✅ Very high speed
- ✅ Low power
- ✅ Immune to magnetic fields
- ✅ Small package

Disadvantages

- ⚠️ More susceptible to ESD
- ⚠️ Higher common-mode transient immunity needed

Best Applications in Your System

- Similar to magnetic isolators
- Less common, usually choose magnetic or optical instead

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4. RELAY ISOLATION (Electromechanical)

Technology Explanation

- Physical air gap between coil and contacts
- True galvanic isolation (typically >5kV)
- Can switch high voltages and currents
- Inherently isolated control

Types & Components

A. Standard Electromechanical Relays

Signal Relays (Low Power):

- **G5V series** (Omron) - 1A, DPDT, 4kV isolation
- **AQV series** (Panasonic) - Solid-state relay, 5kV isolation
- **TQ2 series** (Panasonic) - 2A, DPDT, 5kV isolation

Power Relays (High Voltage):

- **G9EA** (Omron) - 30A, 250VAC, 5kV isolation
- **HF115F** (Hongfa) - 30A, 277VAC, suitable for high voltage
- **LEG series** (TE Connectivity) - Automotive grade, 5kV isolation
- **PCHN series** (TE Connectivity) - 30A power relay

High Voltage Relays (>1kV):

- **HE series** (Panasonic) - Up to 10kV, 5A
- **S2 series** (Coto) - Reed relay, 10kV, 0.5A
- **G9H series** (Omron) - 7kV isolation, 40A
- **KILOVAC/TE EV200** - 500A, 900VDC continuous, commonly used in EVs

Vacuum Relays (Ultra High Voltage):

- **Gigavac GX series** - Up to 2kV, 500A, for EV applications
- **TE Connectivity KIELV** - Vacuum contactors, >12kV

B. Solid-State Relays (SSR)

AC SSRs:

- **G3NA series** (Omron) - 5-90A, 24-480VAC
- **CPC1xxx** (IXYS) - Low current SSR
- **AQG series** (Panasonic) - PCB mount SSR

DC SSRs:

- **CPC1xxx** (IXYS) - DC switching
- **Crydom series** - DC solid-state relays
- **PhotoMOS** (Panasonic) - MOSFET-based SSR

C. Safety Relays

Force-Guided (Mechanically Linked):

- **G7SA series** (Omron) - Safety relay with force-guided contacts
- **3SK series** (Omron) - Multi-function safety relay
- **PNOZ series** (Pilz) - Industrial safety relays

Advantages

- ✅ True galvanic isolation (air gap)
- ✅ Very high isolation voltage (>5kV standard)
- ✅ Can switch high power
- ✅ Zero leakage current when open
- ✅ Simple control circuit (just coil drive)
- ✅ Visual confirmation of state (some types)

Disadvantages

- ⚠️ Mechanical wear (limited life: 10k-1M operations)
- ⚠️ Slow switching (5-20ms)
- ⚠️ Contact bounce
- ⚠️ Arcing can damage contacts
- ⚠️ Coil inrush current
- ⚠️ Audible click (noise)
- ⚠️ Larger physical size

Best Applications in Your System

- ✅ **Primary discharge path switching** - HE series, G9H series
- ✅ **Stage switching** (different resistor values) - Power relays
- ✅ **Emergency disconnect** - Force-guided safety relays
- ✅ **Interlock circuits** - Signal relays
- 🔄 Use in series with SSRs for best of both worlds

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5. TRANSFORMER ISOLATION (Power & Signal)

Technology Explanation

- Magnetic coupling between primary and secondary windings
- Physical separation provides isolation
- Used for both power and signal transmission

Types & Components

A. Isolated DC-DC Converters (Power)

Standard Industrial Grade:

- **MEA1D series** (Murata) - 1W, 1kV isolation
- **R05 series** (Recom) - 1W, 3kV isolation
- **NMA series** (TDK-Lambda) - 1-2W, 1-6kV isolation

Medical Grade (Reinforced Isolation):

- **MGJ2 series** (Murata) - 2W, 4kV isolation, medical approved
- **IA series** (XP Power) - 1-3W, 5kV isolation, medical
- **RxxP2 series** (Recom) - 1W, 6.4kV isolation, 2×MOPP

High Power:

- **IB series** (XP Power) - 15-40W, 3-5kV isolation
- **R3 series** (Recom) - 3W, 3kV isolation
- **RP series** (TDK-Lambda) - 10-30W, 1.5kV isolation

B. Isolated Gate Drive Transformers

Pulse Transformers:

- **PA2001NL** (Pulse Electronics) - Gate drive transformer
- **LPR6235 series** (Coilcraft) - Isolation transformers
- **H2019NL** (Pulse Electronics) - High-frequency isolation

Integrated Solutions:

- Already covered under magnetic gate drivers (UCC21520, etc.)

C. Isolated AC-DC Power Supplies

Flyback/Forward Converter ICs:

- **VIPER series** (STMicroelectronics) - Integrated offline converter
- **TNY series** (Power Integrations) - TinySwitch, integrated MOSFET
- **LNK series** (Power Integrations) - LinkSwitch, energy-efficient
- **UCC28700** (TI) - Constant voltage/current flyback controller

Isolated AC-DC Modules:

- **IRM series** (Mean Well) - 3-25W, medical grade available
- **RAC series** (Recom) - 1-10W, PCB mount

D. Signal Transformers

Audio/Telecom Transformers:

- **Bourns** - Audio isolation transformers
- **Pulse** - Ethernet magnetics (isolated signal coupling)

Instrument Transformers:

- Current transformers (CT) for current measurement
- Potential transformers (PT) for voltage measurement

Advantages

- ✅ True galvanic isolation
- ✅ Can transfer power and signal
- ✅ Very high isolation voltages possible (>10kV)
- ✅ No semiconductor degradation
- ✅ Proven reliability in harsh environments

Disadvantages

- ⚠️ Size and weight (for power transformers)
- ⚠️ Only works with AC or pulsed DC (DC isolation requires modulation)
- ⚠️ EMI concerns (leakage inductance)
- ⚠️ Efficiency losses
- ⚠️ Parasitic capacitance (common-mode noise coupling)

Best Applications in Your System

- ✅ **Power supply for HV-side circuits** - Murata MGJ2, Recom RxxP2
- ✅ **Gate drive power** (if using switching) - Pulse transformers
- ✅ **Current measurement** - Current transformers
- ⚠️ NOT for DC signal isolation (use optical/magnetic digital isolators)

---

6. HALL EFFECT ISOLATION

Technology Explanation

- Magnetic field sensing for current/voltage measurement
- No physical electrical connection
- Typically used for current sensing, but volt... sensing exists

Components

A. Current Sensors (Closed-Loop Hall Effect)

- **LEM HASS series** - 50-600A, ±0.5% accuracy
- **LEM HO series** - 8-25A, PCB mount
- **LEM LA series** - 25-600A, open-loop
- **ACS712/ACS723** (Allegro) - 5-30A, integrated IC
- **ACS758/ACS770/ACS772** (Allegro) - 50-200A
- **TMCS1100** (TI) - Hall-effect current sensor, isolated

B. Voltage Sensors (Hall Effect)

- **LEM CV series** - Voltage transducers (mentioned earlier)
- **LEM DVL series** - DIN-rail mount voltage sensors

C. Rogowski Coils (Alternative to Hall Effect)

- **PEM CWT series** - AC current measurement
- Flexible, wraps around conductor
- Only for AC or pulsed DC (derivative of current)

Advantages

- ✅ True galvanic isolation (magnetic coupling)
- ✅ Wide bandwidth (DC to MHz)
- ✅ No insertion loss (for current sensing)
- ✅ Excellent accuracy (0.1-1%)
- ✅ Overload protection

Disadvantages

- ⚠️ More expensive than shunt resistors
- ⚠️ Temperature drift
- ⚠️ Sensitive to external magnetic fields
- ⚠️ Offset voltage drift over time

Best Applications in Your System

- ✅ **Discharge current measurement** - LEM HASS, ACS758
- ✅ **Capacitor voltage measurement** - LEM CV series
- ⚠️ Consider cost vs. isolated amplifier + shunt resistor

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7. FIBER OPTIC ISOLATION

Technology Explanation

- Light transmitted through optical fiber
- Complete electrical isolation (dielectric medium)
- Immune to all EMI/RFI
- Can span long distances

Types & Components

A. Fiber Optic Transceivers

Simple Digital:

- **HFBR series** (Broadcom) - Versatile Link, 5-125 Mbps
- **AFBR series** (Broadcom) - Industrial fiber optics
- **IF-E96E/97E** (Industrial Fiber Optics) - RS485 over fiber

High Speed:

- **SFP/SFP+ modules** - Gigabit fiber transceivers

- **Finisar** - Industrial fiber optic modules

B. Fiber Optic Sensors

- **FBG sensors** - Fiber Bragg Grating (temperature, strain)
- **Distributed sensors** - Raman/Brillouin scattering
- Already covered in temperature sensing section

C. Fiber Optic Trigger/Sync

- **LUNA/Micron Optics** - Fiber optic timing/trigger systems
- Used in high-voltage test equipment

Advantages

- ✅ Perfect EMI/RFI immunity
- ✅ Essentially infinite isolation voltage
- ✅ Long distance capability (km+)
- ✅

KF Continue

✅ No ground loops

- ✅ Intrinsically safe (cannot create spark)
- ✅ Lightweight cabling

Disadvantages

- ⚠️ Expensive ($20-$100+ per link)
- ⚠️ Requires fiber optic infrastructure
- ⚠️ Connector alignment critical
- ⚠️ Fiber can break (fragile)
- ⚠️ Requires transmitter and receiver circuits
- ⚠️ Overkill for most PCB-level isolation

Best Applications in Your System

- 😮 **Extreme EMI environments** - If severe noise issues
- 😮 **Remote monitoring** - If control panel far from HV section
- 😮 **Research/laboratory** - If building test equipment
- ⚠️ Probably overkill for your application unless extreme requirements

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8. ISOLATION THROUGH AIR GAP (Physical Separation)

Technology Explanation

- Simple physical distance through air
- No conductive path
- Requires sufficient clearance and creepage distances

Design Parameters

IEC 60664-1 / IEC 61010-1 Standards:

Clearance (shortest distance through air):

- **Functional isolation:** 1.5mm per kV (working voltage)
- **Basic isolation:** 2.5mm minimum + 1.5mm per kV above 300V
- **Reinforced isolation:** 2× basic isolation

For 1500V DC (pollution degree 2, material group IIIb):

- **Basic isolation clearance:** ~8-10mm

- **Reinforced isolation clearance:** ~16-20mm

Creepage (shortest distance along surface):

- **Functional isolation:** 2.5mm per kV
- **Basic isolation:** 4mm minimum + 2mm per kV above 300V
- **Reinforced isolation:** 2× basic isolation

For 1500V DC:

- **Basic isolation creepage:** ~16-20mm
- **Reinforced isolation creepage:** ~32-40mm

PCB Design Techniques

A. Isolation Slots/Grooves

- Milled slots in PCB between HV and LV
- Creates air gap, increases creepage distance
- Typical: 2-3mm wide, full depth of PCB

B. Guard Rings

- Grounded copper trace surrounding HV section
- Intercepts leakage currents
- Must have proper clearance on both sides

C. Multiple Layer Separation

- Keep HV and LV on separate PCB layers
- Use inner layers for critical signals
- Outer layers for ground planes only

D. Conformal Coating

- Acrylic, silicone, urethane, or parylene
- Improves insulation, reduces pollution degree
- Can reduce required creepage distance

Materials:

- **Acrylic:** Easy to remove, good moisture resistance
- **Silicone:** High temperature, flexible
- **Urethane:** Excellent abrasion resistance
- **Parylene:** Best conformality, expensive

Advantages

- ✅ No components required (lowest cost)
- ✅ No failure modes (passive)
- ✅ No power consumption
- ✅ Infinite bandwidth
- ✅ Works for any signal type

Disadvantages

- ⚠️ Large board area required
- ⚠️ Cannot transmit signals (requires other isolation for communication)
- ⚠️ Contamination reduces effectiveness
- ⚠️ Must be maintained over product lifetir

Best Applications in Your System

- ✅ **Physical separation of HV and LV sections** - Essential
- ✅ **Between discharge terminals** - Prevent flashover
- ✅ **Around isolation components** - Backup protection
- ✅ **Mounting standoffs** - Use plastic instead of metal

---

9. DOUBLE/REINFORCED INSULATION

Technology Explanation

- Two independent layers of insulation
- If one fails, second provides protection
- Alternative to grounded metal enclosure

Types

A. Double Insulation (Class II Equipment)

- Basic insulation + supplementary insulation
- Two separate insulation systems
- Used when protective earth not available

B. Reinforced Insulation

- Single insulation system equivalent to double insulation
- Tested to higher standards
- Common in modern isolation components

C. Triple Insulation

- Exceeds reinforced insulation requirements
- Used in medical equipment (2×MOPP)
- Components: Würth WE-AGDT transformers (triple insulated)

Components with Reinforced Isolation

Isolation Amplifiers:

- **AMC1311B** (TI) - 3kV reinforced isolation
- **AMC3330** (TI) - 5kV reinforced isolation
- **ISO124U** (TI) - 1.5kV reinforced (older)

Digital Isolators:

- **ISO7741** (TI) - 5kV reinforced
- **ADuM1401** (ADI) - 5kV reinforced (VDE certified)
- **Si8642** (Silicon Labs) - 5kV reinforced

Isolated DC-DC Converters:

- **RxxP2 series** (Recom) - 6.4kV, 2×MOPP
- **MGJ2 series** (Murata) - 4kV, medical grade
- **IA series** (XP Power) - 5kV, 2×MOPP

Optocouplers:

- **ACPL-217** (Broadcom) - 5.3kV reinforced, VDE
- **TLP2362** (Toshiba) - 5kV reinforced

Advantages

- ✅ Highest safety level

- ✅ No need for protective earth on enclosure
- ✅ Meets medical/IEC 61010 requirements
- ✅ Redundant protection

Disadvantages

- ⚠️ More expensive components
- ⚠️ Still requires proper PCB design
- ⚠️ Must be certified/tested

Best Applications in Your System

- ✅ **All isolation barriers** - Use reinforced where possible
- ✅ **User-accessible areas** - Critical for safety
- ✅ **Voltage measurement** - AMC3330
- ✅ **Communication** - ISO7741, ADuM1401

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10. GROUNDING & EARTHING STRATEGIES

Technology Explanation

- Provides reference potential and fault protection
- Multiple grounding schemes possible
- Critical for safety and noise immunity

Types of Grounds

A. Protective Earth (PE)

- Safety ground, connected to earth
- All exposed metal connected to PE
- Provides fault current path
- **Green/Yellow wire in AC mains**

B. Signal Ground

- Reference for signal circuits
- May or may not connect to PE
- LV side signal ground

C. Chassis Ground

- Metal enclosure ground
- Usually connected to PE
- Provides EMI shielding

D. Floating Ground

- Not connected to earth
- Used for isolated sections
- HV side ground (floating relative to PE)

Grounding Architectures

A. Single-Point Ground (Star Ground)

- All grounds connect to single point
- Prevents ground loops
- Best for low-frequency systems

Topology:

```
         PE Earth Ground (Star Point)
                 |
         --------+--------
         |       |       |
     Chassis  LV GND  HV GND (via isolation)
```

B. Multi-Point Ground

- Multiple ground connections
- Better for high-frequency (RF ground)
- Used for EMI shielding

C. Hybrid Ground

- Single-point for low frequency
- Multi-point for high frequency
- Uses ferrite beads or RC networks

Ground Isolation Components

Common-Mode Chokes:

- **WE-CMBNC** (Würth) - Power line common-mode chokes
- **7427** (Bourns) - High current CMC
- **DLW series** (Murata) - Signal line CMC

Y-Capacitors (Safety Capacitors):

- **Class Y1:** 250VAC, up to 8kV impulse
- **Class Y2:** 250VAC, up to 5kV impulse
- **TDK/EPCOS/KEMET** - Safety-rated capacitors
- Used between line and ground for EMI filtering

CRITICAL: Must be safety-rated! Cannot use standard capacitors.

MOV/TVS for Ground Surge Protection:

- **V275LA** series (Littelfuse) - MOVs for 275VAC
- **SMCJ** series - TVS diodes for ground transients

Grounding Strategy for Your System

Recommended Architecture:

```
                     AC Mains
                        |
                     [Fuse]
                        |
                 [EMI Filter] ←— Y-caps to PE
                        |
             [Isolation Transformer or Isolated PSU]
                  |                    |
           LV Section            HV Section
           (Grounded)           (Floating)
                  |                    |
            [LV GND]──────┬──────[HV GND]
                  |         |          |
                  |    [Isolation   [Capacitor
                  |     Barrier]     Bank]
                  |         |          |
            Chassis ──────┴─── PE Earth
            (Safety)
```

Key Points:

1. **Chassis/enclosure tied to PE** - Safety ground
2. **LV ground tied to PE** - Reference for user interface
3. **HV ground floating** - Isolated from PE through isolation barriers
4. **Heat sink grounded to PE** - As you specified
5. **Single-point star ground** - All PE connections to one point
6. **Y-capacitors** - Between LV/HV grounds and PE for EMI only

Advantages

- ✅ Provides fault current path (saves lives)
- ✅ Reduces EMI emissions
- ✅ Establishes reference potential
- ✅ Required by safety standards

Disadvantages

- ⚠️ Ground loops can introduce noise
- ⚠️ Improper grounding can be dangerous
- ⚠️ Requires careful design and testing

Best Applications in Your System

- ✅ **All exposed metal** - Must be grounded
- ✅ **Heat sink** - Grounded as you specified
- ✅ **Chassis** - Connected to PE
- ✅ **LV circuit ground** - Tied to PE
- ✅ **HV circuit** - Floating, isolated from PE

---

11. INTERLOCKS & MECHANICAL SAFETY

Technology Explanation

- Physical mechanisms preventing access to HV
- Independent of software/electronics
- Required by safety standards

Types of Interlocks

A. Door/Access Panel Interlocks

Mechanical Switches:

- **D4NS** (Omron) - Safety door switch, force-guided
- **LS series** (Schmersal) - Heavy-duty safety switches
- **ZS series** (Siemens) - Coded magnetic safety switch
- **GC series** (Euchner) - Heavy-duty guard locking

Magnetic Safety Sensors:

- **PSENmag** (Pilz) - Coded magnetic sensor
- **MGB series** (Euchner) - Multi-coded magnetic guard
- **Sentry series** (Fortress) - Non-contact safety switch

RFID/Coded Sensors:

- **RE series** (Euchner) - Electronically coded
- **PSENcode** (Pilz) - Coded magnetic safety switch
- Prevents bypassing with magnets

B. Guard Locking Systems

Solenoid Locks:

- **AZM series** (Schmersal) - Safety solenoid interlock
- **STP series** (Pizzato) - Trapped key interlock
- Prevents opening until capacitor discharged

Trapped Key Systems:

- **Kirk Key** - Physical key trapped until safe
- **Castell** - Trapped key interlocks

C. Emergency Stop (E-Stop)

E-Stop Buttons:

- **A22E** (Omron) - Emergency stop pushbutton
- **3SB3** (Siemens) - Red mushroom head
- **ZB5** (Schneider) - Harmony XB5 series

Requirements:

- Red button, yellow background
- Latching (stays in until manually reset)
- Opens relay circuit (fail-safe)
- Category 0 or Category 1 stop function

D. Discharge Interlocks

Automatic Discharge on Door Open:

- Interlock switch triggers relay closure
- Connects discharge resistor across capacitor
- Visual/audible indicator shows discharge in progress
- Mechanical lock prevents door opening until complete

Short-Circuiting Bar:

- Manual shorting stick
- Must be stored in holder that blocks access
- Cannot reach HV unless tool removed

Interlock Circuit Design

Safety Relay Modules

- **G9SA** (Omron) - Dual-channel safety relay
- **PNOZ** (Pilz) - Configurable safety relay
- **3SK1** (Siemens) - Safety relay with monitoring
- Monitors interlock switches for faults
- Force-guided contacts ensure no single-point failures

Safety PLCs

- **NJ-S series** (Omron) - Safety PLC/controller
- **SIMATIC S7** (Siemens) - With safety modules
- **Micro800** (Allen-Bradley) - Safety-rated

Advantages

- ✅ Hardware-based (no software bugs)
- ✅ Required by safety standards
- ✅ Visible confirmation of state
- ✅ Prevents accidental access
- ✅ Independent backup to electronic systems

Disadvantages

- ⚠️ Adds mechanical complexity
- ⚠️ Can be bypassed by determined person (need tamper detection)
- ⚠️ Requires maintenance (mechanical wear)
- ⚠️ Additional cost

Best Applications in Your System

- ✅ **Access panel interlock** - D4NS or PSENmag
- ✅ **Emergency stop** - A22E button + G9SA safety relay
- ✅ **Discharge on open** - Relay triggered by door switch
- ✅ **Key switch for operation** - Prevent unauthorized use

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12. FUSING & OVERCURRENT PROTECTION

Technology Explanation

- Sacrificial element that opens under fault current
- Protects against short circuits and overload
- Multiple types for different applications

Types of Fuses

A. AC Mains Fuses

Slow-Blow (Time-Delay):

- **5×20mm glass** - Standard PCB fuses (250V rated)
- **T series** (Littelfuse) - Time-delay ceramic
- **3AG** - 1/4" × 1-1/4" glass fuse
- Handles inrush current of transformers/capacitors

Fast-Acting:

- **F series** (Littelfuse) - Fast-blow
- **GMC** (Bussmann) - Glass midget fuse
- For semiconductor protection

High Voltage Fuses:

- **HRC fuses** - High Rupture Capacity
- **3NE** (Siemens) - Medium voltage fuses
- For HV capacitor bank protection

B. DC Fuses

Semiconductor Fuses:

- **A50QS** (Mersen) - Ultra-fast, 700VDC
- **JJS** (Littelfuse) - 600VDC fast-acting
- Must be DC-rated (AC fuses can sustain arc in DC)

HV DC Fuses:

- **3NE8** (Siemens) - Up to 1000VDC
- **Type gG/gL** - IEC general purpose HV fuses

C. Resettable Fuses (PPTC)

Polymer PTCs:

- **miniSMDC series** (Littelfuse) - SMD resettable fuse
- **RXEF series** (TE Connectivity) - Radial resettable
- **1206L series** (Bourns) - Low resistance PPTC
- Self-resetting after fault cleared

Characteristics:

- Lower voltage rating (60V max typical)
- NOT suitable for 1500V application
- Good for low-voltage control circuits

D. Electronic Fuses (E-Fuses)

ICs:

- **TPS2595** (TI) - Adjustable current limit, 60V
- **LTC4365** (ADI) - Overvoltage/overcurrent protection
- **MAX14575** (Maxim) - Overvoltage protection switch
- Programmable trip point, faster than physical fuse

Fuse Selection Criteria

Voltage Rating:

- Must exceed working voltage
- AC voltage rating ≠ DC voltage rating
- For 1500VDC: Use ≥2000VDC rated fuse

Current Rating:

- Continuous current < 75% of fuse rating
- Account for inrush current

Breaking Capacity:

- Must interrupt available fault current
- High voltage capacitor can deliver 10kA+
- Need HRC (high rupture capacity) fuse

I^2t Rating:

- Energy the fuse can absorb
- Critical for capacitive loads

Fusing Strategy for Your System

Primary AC Input:

- Slow-blow fuse, 250VAC rated
- Size for transformer inrush
- 2-5A typical for small system

HV Capacitor Bank:

- Fast-acting HV DC fuse in series
- ≥2000VDC rating
- 1-10A rating depending on discharge current
- OR use PCB trace fusing (calculated trace width)

LV Control Circuits:

- PPTC resettable fuses on outputs
- Electronic fuses for USB/external interfaces
- Protects against shorts in wiring

Relay Coils:

- Individual fuses or current limiting
- Prevents coil failure from damaging driver

PCB Trace Fusing

Design:

- Intentional narrow trace acts as fuse
- Calculated to open at specific current
- Use online calculators (e.g., CircuitCalculator.com)

Example:

- 1oz copper, 0.5mm wide, 10mm long
- Fuses at ~10A in <1 second

Advantages:

- ✅ No component cost
- ✅ No board space
- ✅ Visual indication (burnt trace)

Disadvantages:

- ⚠️ Not replaceable
- ⚠️ Less predictable than real fuse
- ⚠️ Creates debris/smoke

Advantages

- ✅ Fast protection (μs to ms)
- ✅ Coordination with other protection
- ✅ Visual indication (blown fuse)
- ✅ Required by safety standards

Disadvantages

- ⚠️ One-time protection (must replace)
- ⚠️ Nuisance tripping if undersized
- ⚠️ Aging (resistance increases over time)
- ⚠️ Must select carefully for application

Best Applications in Your System

- ✅ **AC mains input** - Slow-blow, 250VAC
- ✅ **HV capacitor output** - Fast HV DC fuse
- ✅ **Isolated supply outputs** - Low-voltage fuses
- ✅ **USB/external interfaces** - E-fuse ICs

PART 3: COMPREHENSIVE COMPARISON TABLES

Table 1: Isolation Technologies for Control Signals

Technology	Isolation Voltage	Speed	Cost per Channel	Power Consumption	Lifetime	PCB Area	Best Use Cas
Standard Optocoupler (4N25)	2.5kV	1 Mbps	$0.20	5-20mA LED	Degrades over time	Small (DIP-4)	Simple relay control, slow signals
High-Speed Optocoupler (6N137)	2.5kV	10 Mbps	$0.50	5-15mA LED	Degrades over time	Small (DIP-8)	Fast digital signals, SPI
Reinforced Optocoupler (ACPL-217)	5.3kV	1 Mbps	$1.50	5-10mA LED	Degrades over time	Small (DIP-8)	Safety-critical signals
Gate Driver Optocoupler (TLP250)	2.5kV	High (gate drive)	$1.00	10-15mA LED	Degrades over time	Medium (DIP-8)	MOSFET/IGBT gate drive
Magnetic Digital Isolator (Si8421)	2.5-5kV	150 Mbps	$2.00	5-10mA	Stable (20+ years)	Very Small (SOIC-8)	High-speed digital, SPI/I2C
Magnetic Isolator w/ Power (Si8660)	2.5kV	25 Mbps	$5.00	50-100mA	Stable	Medium (SOIC-16)	Digital + isolat power
TI Digital Isolator (ISO7221)	5kV reinforced	25 Mbps	$2.50	3-8mA	Stable	Very Small (SOIC-8)	Industrial digit signals
ADI iCoupler (ADuM1201)	2.5kV	25 Mbps	$2.00	2-5mA	Stable	Very Small (SOIC-8)	Medical/indus digital
Relay (Standard Power)	5-10kV	10ms	$1.50	50-200mA coil	100k-1M ops	Large	Power switchi slow control
Solid-State Relay	3-5kV	1ms	$3.00	10-30mA control	100M+ ops	Medium	Fast switching wear
Fiber Optic (HFBR)	Unlimited	125 Mbps	$20.00	20-50mA	Stable	Large (connector)	Extreme EMI immunity

Table 2: Isolation Technologies for Analog Signals

Technology	Isolation Voltage	Bandwidth	Accuracy	Cost	Linearity	Best Use Case
Linear Optocoupler (IL300)	2.5kV	350 kHz	±1%	$3.00	Good with calibration	Low-frequency analog isolation
Isolated Amplifier (AMC1301)	3kV reinforced	130 kHz	±0.5%	$5.00	Excellent	±250V shunt measurement
Isolated Amplifier (AMC1311B)	3kV reinforced	250 kHz	±0.5%	$6.00	Excellent	±2V input, precision
Isolated ADC (AMC3330)	5kV reinforced	100 kHz	±0.1%	$8.00	Excellent	Precision voltage measurement
Isolated Delta-Sigma (AD7400)	2.5kV	20 kHz	±0.1%	$6.00	Excellent	High-resolution measurement
Isolation Amp (ISO124)	1.5kV	50 kHz	±0.3%	$10.00	Good	Legacy designs, precision
Hall Effect Current (ACS758)	2.1kV	120 kHz	±1%	$5.00	Good	Current sensing, 50-200A
Hall Effect Voltage (LEM CV)	5kV+	DC-25 kHz	±0.5%	$80.00	Excellent	High voltage measurement
Transformer (Current)	10kV+	DC-1 MHz	±0.5%	$15.00	Excellent	AC/pulsed current only

Table 3: Isolated Power Supplies

Component	Power	Isolation	Efficiency	Cost	Medical Grade	Best Use Case
Murata MEA1D0505SC	1W	1kV	78%	$5.00	No	Low-power isolated supply
Recom R05P21503D	1W	3kV	75%	$8.00	No	Industrial isolated supply
Murata MGJ2D051505SC	2W	4kV	82%	$15.00	Yes (2×MOPP)	Medical/safety-critical
Recom RxxP21512D	1W	6.4kV	75%	$12.00	Yes (2×MOPP)	Highest isolation, medical
XP Power IA0505S	1W	5kV	80%	$18.00	Yes (2×MOPP)	Medical equipment
TDK-Lambda NMA0515SC	1W	1kV	82%	$6.00	No	Cost-effective isolation
XP Power IB1512S	15W	3kV	85%	$35.00	No	Higher power requirements

Table 4: Isolation for Communication Buses

Bus Type	Component	Isolation	Speed	Cost	Application
SPI	ISO7741 (TI)	5kV	100 Mbps	$4.00	High-speed sensor interfaces
SPI	ADuM4402 (ADI)	2.5kV	10 Mbps	$5.00	General purpose SPI
I2C	ISO1540 (TI)	2.5kV	1 Mbps	$3.50	I2C sensor isolation
I2C	ADuM1250 (ADI)	2.5kV	1 Mbps	$4.00	I2C with hot-swap
UART/RS485	ADM3485E (ADI)	2.5kV	500 kbps	$3.00	Industrial communication
UART/RS485	ISO1050 (TI)	2.5kV	1 Mbps	$3.50	Robust RS485
CAN	ISO1050 (TI)	2.5kV	1 Mbps	$4.00	Automotive/industrial CAN
USB 2.0	ADuM4160 (ADI)	2.5kV	12 Mbps	$8.00	USB peripheral isolation
USB 2.0	ISO1540 (TI)	2.5kV	[illegible] Mbps	$7.00	USB debugging/programming

Table 5: Gate Driver Isolation (If Using Power Semiconductors)

Component	Type	Isolation	Output Current	Cost	Features
TLP250	Optocoupler	2.5kV	2.5A	$1.00	Simple, proven
HCPL-3120	Optocoupler	3.75kV	2.5A	$1.50	Higher isolation
FOD3184	Optocoupler	5kV	4A	$2.00	High current, high voltage
Si8271	Magnetic	5kV	4A	$4.00	High speed, no LED aging
ADuM4223	Magnetic	2.5kV	4A	$5.00	Half-bridge, deadtime
UCC21520	Magnetic	5.7kV	4A	$5.00	Advanced features, monitoring
ISO5451	Magnetic	5kV	4A	$6.00	Dual output, TI ecosystem

Table 6: Mechanical Safety Components

Component Type	Example	Safety Rating	Cost	Lifespan	Application
Door Interlock Switch	Omron D4NS	SIL 3, Cat 4	$30	1M operations	Access panel monitoring
Magnetic Safety Sensor	Pilz PSENmag	SIL 3, Cat 4	$80	Unlimited	Non-contact interlock
E-Stop Button	Omron A22E	Cat 0/1	$15	1M operations	Emergency shutdown
Safety Relay Module	Omron G9SA	SIL 3, Cat 4	$120	10M operations	Force-guided relay control
Guard Locking	Euchner MGB	SIL 3, Cat 4	$150	500k operations	Prevent access until safe
Trapped Key	Kirk Key	Mechanical	$200+	Unlimited	Physical key interlock

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PART 4: RECOMMENDED ISOLATION ARCHITECTURE FOR YOUR SYSTEM

Based on all the above analysis, here's a complete isolation strategy:

Critical Isolation Points & Recommended Solutions

1. High Voltage Measurement (Capacitor Voltage)

- **Primary:** AMC1311B isolated amplifier (3kV) + precision voltage divider
- **Backup:** Redundant measurement path for safety verification
- **PCB:** 20mm creepage distance, isolation slot between HV and LV

2. Temperature Measurement (Heat Sink)

- **No isolation required** - Heat sink grounded to PE as specified
- **Primary:** 10kΩ NTC thermistor + ADS1115
- **Backup:** KSD301 thermal switch (90°C) for hardware safety cutoff

3. Microcontroller Power

- **Primary:** Recom RxxP21512D (1W, 6.4kV isolation, 2×MOPP medical grade)
- **Alternative:** Murata MGJ2D051505SC (2W, 4kV, medical grade)
- **Reason:** Reinforced isolation, meets medical/industrial standards

4. Discharge Relay Control Signals

- **Primary:** ISO7241 digital isolator (TI, 5kV reinforced, 4-channel)
- **Alternative:** ADuM1401 (ADI, 5kV reinforced, 4-channel)
- **Reason:** High isolation voltage, stable over lifetime, certified
- **Relay Driver:** ULN2803 or discrete transistors on HV side

5. Emergency Stop / Interlock Circuit

- **Mechanical:** Omron D4NS door interlock switch
- **Isolation:** ACPL-217 reinforced optocoupler (5.3kV, VDE certified)
- **Safety Relay:** Omron G9SA force-guided safety relay
- **Reason:** Hardware-based, independent of MCU, SIL 3 rated

6. Discharge Current Monitoring (Optional)

- **If needed:** ACS758 Hall-effect sensor (2.1kV isolation, 50-200A)
- **Alternative:** AMC

KF Continue

1301 isolated amplifier + precision current shunt (low-side sensing)

- **Reason:** Allows monitoring of discharge current for diagnostics/safety

7. User Interface (Buttons, Display, Encoders)

- **All UI on LV side only** - No isolation needed
- **Chassis/button bezels:** Connected to PE ground
- **Display ground:** Connected to LV ground (which ties to PE)
- **Protection:** ESD diodes on all button inputs

8. External Communication (USB/Programming)

- **USB Port:** ADuM4160 USB isolator (2.5kV) between MCU and external connector
- **Alternative:** Keep USB on LV side only (no isolation if LV properly grounded)
- **UART/Debug:** ISO7221 or optical isolation for debugging HV side
- **Reason:** Protects external equipment, prevents ground loops

9. Status Indication (HV Present LED)

- **Hardware-based:** Neon indicator lamp directly across capacitor (with series resistor)
- **Alternative:** Isolated LED driver (optocoupler + LED on LV side)
- **Reason:** Must be independent of software, visible indicator

10. Power Supply Isolation Stages

- **AC Mains → LV Supply:** Standard isolated AC-DC (Mean Well, Recom)
- **LV → HV Side:** Isolated DC-DC converter (medical grade as specified above)
- **Fusing:** Slow-blow fuse on AC input, fast fuse on HV capacitor

11. PCB Physical Isolation

- **Clearance:** 20mm minimum between HV and LV copper
- **Creepage:** 25mm minimum surface distance
- **Slots:** 3mm wide routed slots perpendicular to isolation barrier
- **Guard rings:** Grounded copper ring around HV section on LV side
- **Coating:** Conformal coating (acrylic or parylene) on entire HV section
- **Layers:** Keep HV on outer layer, route critical signals on inner layers

12. Enclosure & Grounding

- **Enclosure:** Metal chassis, powder-coated or anodized aluminum
- **All metal:** Connected to PE ground via star-point grounding
- **Heat sink:** Bolted to chassis, grounded to P

- **Access panels:** Interlocked with D4NS switches
- **Ground stud:** External connection point for PE ground wire
- **EMI gaskets:** On all panel seams for EMI containment

13. Discharge Circuit Protection

- **Primary discharge:** High-voltage relay (Panasonic HE series, 7-10kV isolation)
- **Relay control:** Isolated via ISO7241 + ULN2803 driver
- **Snubber:** RC snubber across relay contacts (47Ω + 0.1μF, high voltage rated)
- **Backup discharge:** Always-connected bleeder resistor (10MΩ, 5W, high voltage)
- **Interlock discharge:** Relay triggered by door switch, dumps capacitor through 1kΩ resistor

14. Fault Detection & Protection

- **Voltage monitoring:** Continuous via AMC1311B, shutdown if out of range
- **Temperature monitoring:** NTC + KSD301 backup, shutdown if >80°C
- **Overcurrent:** Hall-effect sensor or fuse, shutdown if excessive current
- **Watchdog:** External hardware watchdog (TPS3813 or similar), resets MCU if hang
- **Ground fault:** Optional RCMU (residual current monitoring unit) for leakage detection

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Detailed System Architecture Diagram

```
┌─────────────────────────────────────────────────────────────────────────┐
│                           ISOLATED SECTIONS                             │
├──────────────────────────────────┬──────────────────────────────────────┤
│      LOW VOLTAGE SIDE            │         HIGH VOLTAGE SIDE            │
│   (Grounded to PE Earth)         │      (Floating, Isolated)            │
├──────────────────────────────────┼──────────────────────────────────────┤
│                                  │                                      │
│  ┌────────────────┐              │              ┌───────────────┐       │
│  │ AC Mains Input │              │              │  1500V        │       │
│  │  120/240VAC    │              │              │  Capacitor    │       │
│  └───────┬────────┘              │              │  1650μF       │       │
│          │                       │              └───────┬───────┘       │
│  [Fuse][EMI Filter]              │                      │               │
│          │                       │                      │               │
│  ┌───────▼────────┐              │              ┌───────▼───────┐       │
│  │  Isolated      │              │              │  HV Relay     │       │
│  │  AC-DC PSU     │              │              │  (Discharge)  │       │
│  │  5V/12V Output │              │              └───────┬───────┘       │
│  └───────┬────────┘              │                      │               │
│          │                       │              ┌───────▼───────┐       │
│  ┌───────▼────────┐              │              │  Discharge    │       │
│  │  LV Power      │   Isolated   │   Isolated   │  Resistors    │       │
│  │  Distribution  ├──────────────┼──────────────┤  (on heatsink)│       │
│  └───────┬────────┘   DC-DC      │   Power      └───────────────┘       │
│          │        (Recom/Murata)│   Supply                             │
│          │            6.4kV      │   3-5W                               │
│  ┌───────▼────────┐              │              ┌───────────────┐       │
│  │Microcontroller│              │              │  HV Relay     │       │
│  │  (STM32/etc)   │              │              │  Driver       │       │
│  │                │              │              │  Circuit      │       │
│  │  - GPIO        ├──────────────┼─────────────►│               │       │
│  │  - ADC         │  ISO7241     │  Isolated    └───────────────┘       │
│  │  - SPI/I2C     │  Digital     │  Control                             │
│  │  - UART        │  Isolators   │  Signals                             │
│  │                │  5kV         │                                      │
│  └───────┬────────┘              │                                      │
│          │                       │                                      │
│  ┌───────▼────────┐              │              ┌───────────────┐       │
│  │  User          │              │              │  Voltage      │       │
│  │  Interface     │              │              │  Divider      │       │
│  │  - Buttons     │              │              │  (1500V→2.5V) │       │
│  │  - Display     │              │              └───────┬───────┘       │
│  │  - LED         │              │                      │               │
```

```
│  │   - LED      │          │                  │                 │
│  └──────────────┘          │                  ▼                 │
│                            │           ┌──────────────┐         │
│  ┌──────────────┐          │           │ AMC1311B     │         │
│  │ External     │          │           │ Isolated     │         │
│  │ Interfaces   │          │           │ Amplifier    │         │
│  │ - USB (iso)  │◄─────────┼───────────│ 3kV          │         │
│  │ - RS485 (iso)│ ADuM4160 │ Analog    └──────────────┘         │
│  └──────────────┘ USB Iso  │ Signal                            │
│                   2.5kV    │ Isolation                         │
│  ┌──────────────┐          │                                   │
│  │ Safety       │          │           ┌──────────────┐        │
│  │ Circuits     │          │           │ Interlock    │        │
│  │ - E-Stop     │◄─────────┼───────────│ Relay        │        │
│  │ - Watchdog   │ ACPL-217 │ Hardware  └──────────────┘        │
│  │ - Door Switch│ 5.3kV    │ Safety                            │
│  └──────────────┘ Reinforced                                   │
│                            │                                   │
│  ┌──────────────┐          │           ┌──────────────┐        │
│  │ Grounded     │          │           │ Bleeder      │        │
│  │ Components   │          │           │ Resistor     │        │
│  │ - Chassis    │          │           │ 10MΩ 5W      │        │
│  │ - Heat Sink──┼──────────┼──────────►│              │        │
│  │ - Metal Parts│ PE Earth │ Always    └──────────────┘        │
│  └──────────────┘ Ground   │ Connected                         │
│                            │ (Safety)                          │
│          │                 │                                   │
│  ════════▼═════════════════▼═════════════════════════════════  │
│                  PE EARTH GROUND (Star Point)                  │
└────────────────────────────────────────────────────────────────┘

ISOLATION BARRIERS:
══════════════════   Galvanic isolation >2.5kV
- - - - - - - -    Physical/mechanical isolation
```

Specific Component BOM for Isolation

Function	Component	Manufacturer	Part Number	Spec	Qty	Cost
HV Voltage Measurement	Isolated Amplifier	Texas Instruments	AMC1311BDWVR	3kV, ±2V input	1	$6.00
HV Power Supply	Isolated DC-DC	Recom	R1212P-1W	6.4kV, 1W, 2×MOPP	1	$12.00
Control Signal Isolation	Digital Isolator	Texas Instruments	ISO7241CDWR	5kV, 4-channel	1	$4.00
E-Stop/Interlock	Reinforced Optocoupler	Broadcom	ACPL-217-50CE	5.3kV, VDE	2	$3.00
USB Isolation	USB Isolator	Analog Devices	ADuM4160BRWZ	2.5kV, USB 2.0	1	$8.00
Safety Relay	Force-Guided Relay	Omron	G9SA-321-T075 DC24	SIL 3, 4 N.O.	1	$120.00
HV Discharge Relay	High Voltage Relay	Panasonic	HE1AN-P-DC24V	7kV, 10A	2	$12.00
Door Interlock	Safety Switch	Omron	D4NS-1AF	SIL 3, Cat 4	1	$30.00
Emergency Stop	E-Stop Button	Omron	A22E-M-11	Red mushroom	1	$15.00
Thermal Cutoff	Thermal Switch	Generic	KSD301-090	90°C N.C.	1	$0.50
Relay Driver	Darlington Array	Texas Instruments	ULN2803ADR	8-channel, 500mA	1	$0.50
Watchdog Timer	Supervisor IC	Texas Instruments	TPS3813K33DBVR	Watchdog + reset	1	$1.00
TOTAL ISOLATION COMPONENTS						**~$212**

Critical Design Rules Summary

Electrical Isolation Requirements

1. **Minimum 5kV isolation voltage** for all barriers between HV and LV
2. **Reinforced isolation** (medical grade) preferred for user-accessible circuits
3. **Redundant isolation paths** for safety-critical functions
4. **Independent hardware safety** - Cannot rely on software alone

PCB Design Requirements

1. **Clearance:** ⩾20mm through air for 1500VDC
2. **Creepage:** ⩾25mm along surface for 1500VDC
3. **Isolation slots:** 3mm wide, through-board, perpendicular to isolation barrier
4. **Guard rings:** Grounded copper surrounding HV sections
5. **Conformal coating:** Mandatory on HV sections
6. **Layer stack:** HV on outer layers, critical signals on inner layers

Grounding Architecture

1. **Star-point grounding:** All grounds connect to single PE point
2. **Chassis grounded:** All exposed metal to PE
3. **Heat sink grounded:** As specified, provides safety
4. **LV ground = PE:** User-accessible circuits referenced to earth
5. **HV ground floating:** Isolated from PE through isolation barriers
6. **Y-capacitors only:** Between HV/LV grounds (safety-rated)

Mechanical Safety

1. **Interlocked access:** All doors/panels monitored
2. **Automatic discharge:** Door opening triggers capacitor discharge
3. **Visual indication:** HV present LED (hardware-based, not software)
4. **Trapped key/lockout:** Prevent unauthorized access
5. **Bleeder resistor:** Always-connected passive discharge (10MΩ)

Fault Protection

1. **Fusing:** AC input, HV output, control circuits
2. **Overcurrent:** Hardware detection with automatic shutdown
3. **Overvoltage:** Voltage monitoring with shutdown
4. **Overtemperature:** Dual sensors (analog + thermal switch)
5. **Watchdog:** External hardware watchdog resets MCU
6. **Ground fault:** Optional RCMU for leakage detection

Testing & Validation

1. **Hipot testing:** 2× working voltage + 1000V for 1 minute
   - For 1500V system: Test at 4000V minimum
2. **Insulation resistance:** >100MΩ at working voltage
3. **Partial discharge:** <10pC at 1.5× working voltage
4. **Functional safety:** Verify all interlocks and E-stop
5. **Thermal testing:** Verify temperature limits under max load
6. **EMC testing:** Emissions and immunity per IEC 61326

Standards Compliance

1. **IEC 61010-1:** Safety requirements for electrical equipment for measurement, control, and laboratory use
2. **IEC 60664-1:** Insulation coordination for low-voltage systems
3. **UL 61010-1:** North American version of IE 010-1

4. **IEC 61326:** EMC requirements for electrical equipment for measurement, control
5. **ISO 13849-1:** Safety of machinery (if applicable)

Key Recommendations Summary

Highest Priority (Critical for Safety)

1. ✅ **Use reinforced isolation everywhere possible** - AMC1311B, ISO7241, Recom RxxP2
2. ✅ **Hardware-based safety** - Thermal switch, safety relays, interlocks
3. ✅ **Proper PCB design** - 20mm clearance, 25mm creepage, isolation slots
4. ✅ **Ground chassis and heat sink** - Connect all exposed metal to PE
5. ✅ **Independent discharge path** - Bleeder resistor + interlock relay
6. ✅ **Visual HV indicator** - Neon lamp or isolated LED

High Priority (Robust Design)

1. ✅ **Redundant measurements** - Dual voltage sensing, dual temperature sensing
2. ✅ **Watchdog timer** - External hardware watchdog
3. ✅ **Status monitoring** - Relay contact voltage, current, temperature
4. ✅ **Conformal coating** - Protect HV section from contamination
5. ✅ **Proper fusing** - AC input, HV output, control circuits

Medium Priority (Enhanced Features)

1. ✅ **USB isolation** - ADuM4160 for safe debugging
2. ✅ **Ground fault detection** - Leakage current monitoring
3. ✅ **Data logging** - Store fault events for analysis
4. ✅ **Current monitoring** - Hall-effect sensor for discharge current
5. ✅ **Remote monitoring** - Isolated RS485 or wireless (optional)

Documentation & Compliance

1. ✅ **Full schematic review** - Have qualified engineer review
2. ✅ **Safety analysis** - FMEA (Failure Mode Effects Analysis)
3. ✅ **User manual** - Clear warnings, operating procedures
4. ✅ **Maintenance schedule** - Inspection intervals for relays, interlocks
5. ✅ **Certification testing** - Hipot, insulation resistance, functional safety

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Final Architecture Recommendation

For your 1500V capacitor discharge system, I recommend:

Isolation Strategy:

- **Voltage measurement:** AMC1311B (3kV reinforced isolation)
- **Power supply:** Recom RxxP21512D (6.4kV, 2×MOPP medical grade)
- **Control signals:** ISO7241 (5kV reinforced, 4-channel)
- **Emergency circuits:** ACPL-217 (5.3kV reinforced optocouplers)
- **Safety relay:** Omron G9SA (SIL 3 rated force-guided)
- **Interlocks:** Omron D4NS door switches

Why This Combination:

1. ✅ **All components exceed 2× working voltage** (>3kV isolation)
2. ✅ **Reinforced/medical grade** - Highest safety standards
3. ✅ **Industry-proven components** - Long track record
4. ✅ **Certified for safety** - VDE, UL, medical approvals
5. ✅ **Reasonable cost** - ~$200 in isolation components
6. ✅ **PCB-friendly** - Small packages, standa ↓ otprints

This architecture provides **multiple layers of protection:**

- Galvanic isolation barriers (electronic)
- Physical separation (PCB design)
- Mechanical interlocks (hardware)
- Grounded enclosure (electrical safety)
- Redundant sensing (fault detection)
- Hardware failsafes (independent of software)

The result: A system where **no single failure** can create a shock hazard to the operator, meeting or exceeding IEC 61010-1 safety requirements for high-voltage equipment.

Would you like me to provide detailed schematics for any specific isolation circuit, PCB layout guidelines, or testing procedures?