



**Cook Engineering
Design Center**
at Dartmouth

Final Report

*Submitted in partial fulfillment of the requirements for
Engineering Design Methodology and Project Completion*

Safe Charging Locker for E-Bike Batteries

March 12, 2025

Project Team 20-720

Grace Connolly, Gannon Forsberg, Nathan McAllister, Avery Moorhead

Faculty Advisor

Vicki May



**DARTMOUTH
ENGINEERING**

Executive Summary

Significance: As electric bikes have taken off as an environmentally friendly form of transportation, the inherent safety risks have commensurately become apparent, as eighteen people died in e-bike fires in New York City alone in 2023. There are currently no regulations on e-bike batteries at the national level in the United States, resulting in a proliferation of aftermarket and unregulated batteries that have been a significant factor in many of the reported fatalities. The risk of e-bike fires can act as a deterrent to both new buyers and governments that hope to support eco-friendly transit. Currently, most safety measures are integrated into the battery systems themselves, leaving universities and municipalities with limited options to ensure safe e-bike charging outside of attempting to mandate certification.

Objectives: The objective of our project is to create a device that can detect the early increases in temperature that occur before a lithium ion battery fire starts, and initiate an immediate shutoff. The technical objectives met to achieve this goal were to (1) identify and test the ideal sensor technology for this project, in this case a thermal infrared camera, (2) design a shutoff switch, as was done using a relay, and (3) create a housing that will allow for this device to function as a consumer product, in this case completed with a flammables locker and custom mounts for electronic components.

Innovation: Currently, e-bike fire safety features are primarily focused on batteries, with certified batteries offering the most advanced safety features but often being more expensive. While some cities such as New York have banned uncertified batteries and provide free certified batteries to certain groups, such measures are reactive instead of proactive. There are no current solutions that work to reduce fire risk on the charging end. Developing a safety feature on the charging side would enable universities and other bodies serving e-bike users to mitigate the risk of fires from all charging bikes, as communities cannot completely control the types of e-bike batteries that users bring to charge. In addition, it would allow for continued usefulness of a battery after thermal runaway is successfully averted.

Approach: Our first step was to identify a safe way to test our device's functionality, without starting any actual fires. Afterwards, the students with electrical expertise worked to design a shutoff switch that acts on receiving a signal from the thermal infrared camera we purchased. Meanwhile the student with mechanical expertise designed the housing to allow for the product to be used with actual e-bike chargers, and ensure the necessary protection of the electrical components of the project. We designed and tested our prototype in consultation with our advisor as well as safety and electrical experts at Thayer.

Impact: Our product has the potential to drastically reduce the risk of e-bike fires that occur during charging, acting as a stopgap to fill the current gulf in regulation that exists around e-bikes. Further, this project can raise awareness about the inherent dangers of uncertified lithium-ion batteries, and help to deter the purchase of bikes containing such batteries, as well as underline the importance of universities recognizing and responding to these dangers with necessary regulation. This, in turn, allows college students to safely charge their e-bikes, and encourages further adoption.

Table of Contents

Executive Summary	2
Overview	4
Problem Statement.....	4
Non-Confidential Abstract.....	4
Societal Context.....	5
Objectives and Deliverables.....	6
Methodology of Approach	6
Target Buyer Demographic.....	6
Sensor Selection, Alternatives Matrix and FMEA.....	7
Design Requirements, Process, and Ideation.....	9
Testing and Validation Ideation.....	12
Deliverables	13
In transitioning from ideation to prototyping, specific design, and assembly, the project accomplished two deliverables:	13
Mechanical Design.....	13
Electrical Design.....	14
Software Design.....	15
Functionality Testing.....	16
User Testing.....	17
Societal and Economic Analysis	19
Societal Context.....	19
Economic Analysis.....	20
Recommendations for Future Work	24
Extensive Analysis of Thermal Runaway Options.....	24
Prototype/Design improvements.....	24
Testing.....	24
Technical Testing.....	24
User Testing.....	25
Designing a bigger locker.....	25
Conducting a more thorough economic analysis.....	25
FYREE project.....	25
Reference Endnotes	26
Appendix	28
Appendix 1: Debugging Code.....	28
Appendix 2: Raspberry Pi Code.....	29
Appendix 3: Bill of Materials and Cost Analysis.....	32
Appendix 4: Updated Safety Plan Sections 3 and 4.....	33
Appendix 5: Electrical Schematic.....	36

Overview

Problem Statement

Due to the lack of e-bike batteries above the local level in the United States, there has been a proliferation of cheap after-market batteries, which are responsible for a disproportionate number of fire incidents. There is a need to design a technology that is built into a charger that can detect e-bike fires and cut power as currently safety technologies are only integrated into batteries. We plan to use existing thermal infrared sensor technology to detect the early signs of a possible fire, and create a corresponding shutoff mechanism. We plan for our prototype to serve as a valuable safety mechanism in university housing, and serve as a stopgap measure in the likely lengthy period before e-bike batteries are tightly regulated.

Non-Confidential Abstract

As the e-Bike market continues to grow without effective standardization, fatal battery fires (especially among cheaper alternative products) have become increasingly common. Dartmouth College (and many universities nationally) prohibit unsupervised indoor charging of e-Bikes without offering suitable alternative charging solutions. Enter the Fire-Safe e-Bike Charging Locker, which provides a safe charging location for e-Bike batteries. Targeting academic institutions and shared housing communities as buyers, the locker provides peace of mind and reduced insurance rates due to decreased safety risks.

The locker prevents these fires through use of a thermal infrared camera, which detects abnormal increases in battery temperature before they reach dangerous levels, and initiates a battery shutoff. Currently, market solutions exist only to detect and extinguish fires, resulting in destruction of the battery. Our product allows for potential continued use of the battery, and a complete prevention of lithium-ion battery fires which can spread dangerously out of control.



Figure 1: Fully assembled locker prototype

Societal Context

The value of our proposed project lies in its ability to counteract the dangers presented by e-bike fires. Currently, electrical safety measures consist of Battery Monitoring Systems (BMS) and other measures within the battery itself. Thus, there are no measures to protect university infrastructure or other users from the dangers prevented by substandard lithium ion batteries. We envision our project being used at private and public sites, where colleges, and shared housing communities, can confidently provide safe charging stations for e-bike users.

Beyond just safety concerns, the implementation of the design could work to raise awareness about the dangers of lithium ion batteries that necessitate the technology, for both potential e-bike users as well as governments and regulators. It can also be used to show that charging stations can broadly be safely installed, and alleviate the concerns of cities and towns who are yet to install such infrastructure. Electric bikes are a powerful new technology with the potential to greatly drive down fossil fuel use, and this project could allow for the further development and proliferation of these devices.

E-bike battery fires are relatively common; approximately 1/15,000 to 1/30,000 e-bike batteries will have a fire.¹ While it is difficult to quantify the exact number of e-bike fires in the U.S., in New York City, in 2023, there were 18 deaths and 150 injuries from e-bike battery fires. In London, U.K., there is, on average, an e-bike fire every other day.² There are numerous examples of these fires causing catastrophic damage; in New York City, a single e-bike battery fire resulted in a five alarm fire that destroyed a grocery store and required more than 200 firefighters to extinguish.³ In London, a house fire, which led to the rescue of two people and destroyed most of the home, was caused by an e-bike battery.⁴

Unlike electric vehicles, the e-bike industry is largely unregulated resulting in the use of low-quality, unsafe batteries. While expensive, high quality e-bikes voluntarily use certified batteries, many cheaper e-bikes use uncertified batteries. These unregulated, uncertified batteries are significantly more likely to be set on fire and pose a safety risk.⁵ While there are no federal regulations surrounding e-bike batteries, Underwriters Laboratories Solutions (UL) have published e-bike battery standards. Specifically, UL 2849 provides fire safety certification for e-bikes by examining their “electrical drive train system, battery system and charger system combinations.”⁶ A number of groups have spoken out against uncertified batteries and have recommended the UL certification. For example, the National Fire Protection Association (NFPA), has recommended using only e-bikes and chargers that are certified by a nationally recognized testing laboratory such as UL.⁷ In 2022, the National Bicycle Dealers Association (NBDA) advised all retailers to encourage their suppliers to certify their e-bikes to UL 2849⁸. When announcing this recommendation Heather Mason, the president of the NBDA stated that “The bicycle industry needs to take immediate action. After extensive consultations with experts in the field, e-bike and e-scooter lithium-ion battery safety is a large and immediate subject that we need to act on now.” New York City officials have also been outspoken about the dangers of e-bike batteries. In September 2023⁹, the City banned the sale and rental of e-bikes and other

micro-mobility products that have not been certified, citing the dangers of uncertified batteries. On October 23rd, 2024, New York City announced a \$2 Million City investment, allowing city delivery workers to trade in their uncertified e-bike for a UL certified e-bike and two UL-certified batteries. The goal of the program is to reduce e-bike fire risks by reducing the number of uncertified batteries used in the City.¹⁰

Objectives and Deliverables

As we prepared to begin work on the safe charging locker this term, we identified multiple design-independent requirements: (1) Must detect abnormal battery conditions and stop charging (2) Must secure battery while charging, and (3) Must be user-friendly. These requirements served to inform our work throughout the term and ensure that we stuck to our original goals. Ultimately, we were able to meet all three of these requirements in our project design.

We additionally identified our two main deliverables, which we committed to producing by the end of the term. These were (1) developed a functional charging locker prototype that detects temperature increases of $\geq 5^{\circ}\text{C}$ per minute and automatically shuts off power to the battery for safety, and (2) conducted community testing to gather feedback and inform future improvements. As expanded upon in Deliverables below, we were successfully able to complete both of these deliverables.

Methodology of Approach

Target Buyer Demographic

Before beginning work on the prototype, we wanted to first determine our target buyer demographic, so that we could design our charging locker with their needs in mind. We considered five possibilities:

- Landlords, for use in shared housing (apartments, co-ops, etc)
- Academic institutions, for use in dorms and campus buildings
- Municipalities, for use in public buildings and infrastructure
- College students, for personal use
- General public, for personal use

We ruled out several of these options right off the bat. Any consumers in the general public would buy our product because they are concerned about battery safety; however, safety-minded consumers would likely buy an e-bike with a safe, certified battery in the first place.

Municipalities struggle to find funding to invest in e-bike infrastructure, making our project a risky business venture. College students, who tend to buy inexpensive e-bikes with unregulated batteries, would benefit from our charging lockers, but would not be willing to spend the money to purchase them.

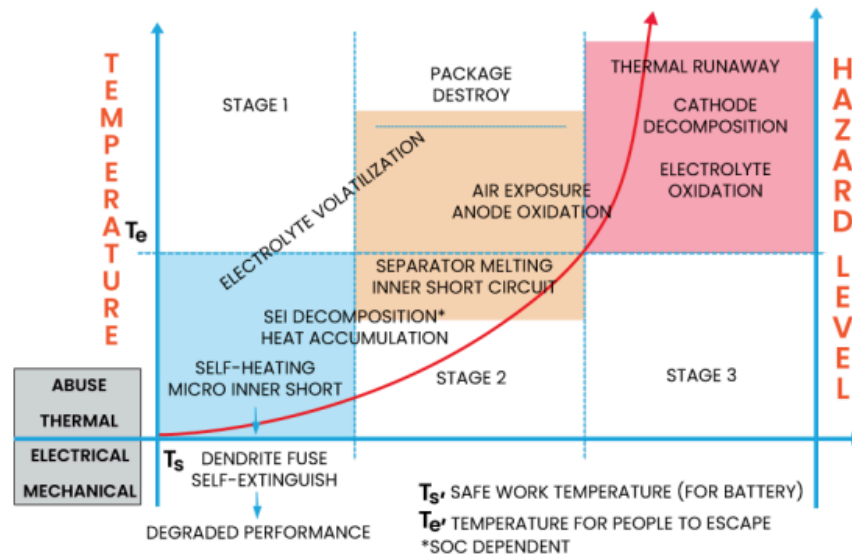
Academic institutions have a great incentive to purchase our product. They need to protect student safety and college property from e-bike battery fires. They can't effectively police e-bikes on campus to ensure that they use safe, certified batteries. They also have enough money to purchase our product. Landlords have a similar incentive to protect their property and the property of their tenants, and a similar lack of control over what type of e-bikes their tenants choose to buy.

We elected to pursue a target buyer demographic of academic institutions over landlords for ease of access. We could talk with college officials about their thoughts on the project and develop a robust idea of their design needs and incentives for adopting our charging lockers. We could also easily conduct user testing with college students. Additionally, e-bikes are experiencing a surge of popularity on college campuses as an alternate mode of transportation to cars.

Sensor Selection, Alternatives Matrix and FMEA

E-bike fires are caused by thermal runaway. Thermal runaway is when...

“a lithium-ion cell generates heat at a rate several times higher than the rate at which heat dissipates from the cell. The cell reaches thermal runaway when its temperature rises uncontrollably at a rate greater than 20° centigrade per minute with maximum temperatures reaching greater than 300°C accompanied by gas and/or electrolyte venting, smoke or fire or a combination of all” - UL Research Institutes.¹¹



 Stages of Thermal Runaway in Lithium Batteries

Figure 2: Graph of Stages of Thermal Runaway in Lithium Batteries¹²

E-bike fires typically begin with a localized thermal event in a given battery cell such as a short circuit or failure—this typically occurs during charging. This leads to thermal runaway, which then spreads to other battery cells causing significant fire or an explosion. With our

design-independent requirements in mind, we considered numerous possible solutions for detecting abnormal battery conditions, which are summarized in Table 2 below. We decided to pursue thermal sensing because it was (1) technically feasible within a term, (2) strongly supported by our literature on thermal runaway, and (3) user-friendly. We decided to house our sensing system within a fireproof locker in order to meet our requirement of securing the battery when charging, preventing theft and vandalism.

During our literature review at the beginning of the term, we learned that while normal charging leads to a battery temperature increase of 0.2° C per minute, dangerous temperature increases begin at 10° C per minute, leading to full thermal runaway at 20° C per minute as described above.¹³ This gave us a large intermediate range before the increase reaches unsafe levels where we would be able to sense abnormal temperature increases. We decided to benchmark 5° C per minute as our shutoff threshold, as this is well below the threshold for dangerous charging.

To differentiate between heat sensors, we spoke to Professor Charles Sullivan and Raina White. Both stated that a thermal camera would be better than a surface mount sensor, as the surface mount sensor would only be able to sense temperature increases at the point it was applied, rather than throughout the battery. However, Professor Sullivan warned us to stay away from complex image processing beyond the scope of our project, so we decided to use a thermal infrared sensor which connects to a Raspberry Pi.

We additionally decided to pursue a locker for institutional applications, specifically for universities, rather than municipal applications, as few municipalities are expanding e-bike infrastructure due to safety concerns, while many consumers continue to purchase e-bikes. This was modified slightly when we decided to market to universities, which are dealing with the increasing popularity of e-bikes on campuses.

	DECISION MATRIX						Weighted Score
	Technical Feasibility (1-10)	Notes	Market Size (1-10)	Notes	Novelty (1-10)	Notes	
<i>Weights</i>	<i>1</i>		<i>1</i>		<i>0.5</i>		
Locker (Institutional Applications)	9	Fire-safe locker with an outlet, sensor, and shutoff switch	6	Could appeal to landlords, university administration and e-bike owners who own less fireproof bikes, but would be advertising to those who already chose a cheaper, less safe option	3	Inclusion of shutoff switch is the only primarily new component, but will also be cheaper than market due to reduced fireproofing required	16.5
In-Line Device (AC Side)	3	Literature is unclear on connection between temperature and impedance or AC current. More investigation needs to be done. If a correlation is detected, would be a clean solution	9	Would be simple, small, and accessible.	7	Using AC voltage current as a measure of thermal runaway has not been used in a e-bike fire detection device	15.5
In-Line Device (DC Side)	7	Technically feasible and plenty of literature to suggest that the technology could work.	2	Given that there are dozens of different charger connectors, this device would require a specialized adapter for each individual e-bike. This makes it inaccessible to the majority of e-bike users. This device would only be feasible for	7	Using DC voltage plateau as a measure of thermal runaway has not been used in a e-bike fire detection device	12.5
Locker (Municipal Applications)	9	Fire-safe locker with an outlet, sensor, and shutoff switch	3	Few municipalities are investing in e-bike infrastructure	3	Inclusion of shutoff switch is the only novelty	13.5
Surface-Mount Heat Sensor	5	Sensing temperature rate of change could pose some technical difficulty	8	Could see both individual and municipal customers	6	Using temperature rate of change to trigger a shutoff has not been done before	16

Table 2: Decision Matrix for Sensor and Design

We also conducted a Failure Mode and Effects Analysis on potential sensor and testing components, which is included below. This steered us further away from considering using AC current in the battery to detect thermal runaway. Because the literature was inconclusive on whether AC current could be linked to precursors for thermal runaway, pursuing this solution would have required significant testing. We spoke to Bob Barry and Tad Truex about how this testing could be conducted and what we would need to do to electrically simulate a battery entering thermal runaway (testing with a real battery was deemed too dangerous). They expressed skepticism at the scope and possibility of the project. If, after weeks of testing, we discovered that there was no link between AC current and thermal runaway, we would not have enough time to pivot and pursue another solution space, resulting in an incomplete project. The FMEA is included below in table 3.

ID	System / Item / Process Step	Function	Potential Failure Mode	Effects of Failure	Severity	Causes	Occurrence
#	Name, ID number, etc.	Primary function	How could the system / item / process potentially fail?	Consequential impact on other systems, departments, etc.		All contributing factors	
1	IR Sensor	Temperature sensing	Computational intensity	Slow processing, more expensive components	4	Complexing of sensor output	4
2	Thermocouple	Temperature sensing	Breaking from user interaction	System unusable	10	User interaction	3
3	Hot Plate	Thermal Runaway Simulation	Temperature/ Temperature rate Inaccuracy	System may not work in real-world conditions	7	Hot plate quality & controllability	3
4	Microcontroller	Temp rate detection through serial data stream	Development difficulty	Incomplete project	10		2
5	In-line electrical detection (AC)	Overall viability	Unable to complete within timeframe	Incomplete project	10	Lack of literature, too many complex tests to verify behavior, difficulty simulating V & I of battery during thermal runaway	9

Table 3: FMEA for Potential Sensor and Testing Components

Design Requirements, Process, and Ideation

Once our design of a charging locker with thermal sensing was determined, we crafted a set of design requirements, aimed at ultimately fulfilling our design-independent requirements to meet our solution:

Requirement	Specification
Charging Versatility	Locker should work for >99% of removable e-bike batteries
Safety -Thermal Runaway	Locker should effectively detect thermal runaway in >99% of cases and stop charging

Safety - Fire Suppression	Locker should suppress fire in >99% of cases
Cost Effectiveness	\$500 or less to purchase
Security	Negligible chance of battery theft
Environmental Impact	Minimal or positive impact on the surrounding environment

Table 4: Design Requirements for Safe Charging Locker

Throughout the mechanical design process, user experience was front-of-mind. Users of the locker should be able to quickly and easily open the locker, plug in their battery, turn on the power, close the locker, and be able to move along with other tasks, as shown in Figure 3:

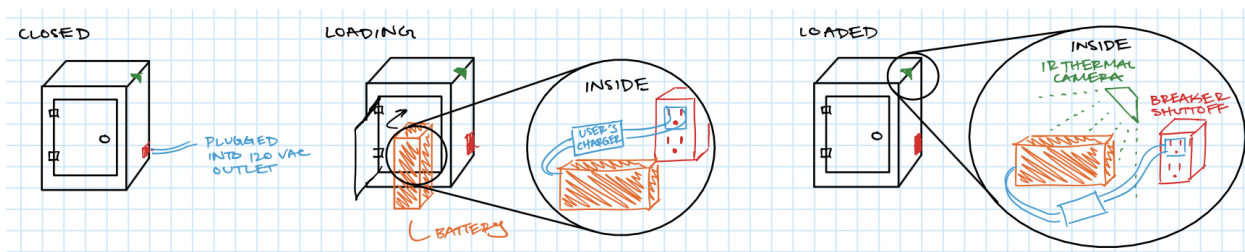


Figure 3: Initial design ideation sketch, displaying UI/UX

One component was selected from the beginning of the project, out of necessity: a Raspberry Pi 4B functioned as the hub around which all of the electrical and mechanical systems were built. The Pi's versatility and computing power allowed unconstrained forward movement towards more difficult design choices later in the project. Additionally, two indicator lights (white for power, red for shutoff) were selected purely for functionality. Three components of the locker assembly required more thoughtful consideration: the container, the sensor, and the relay. An alternatives matrix was constructed for each (Table 5), and the following options were selected:

Container: Due to a compressed timeline for this project, a traditional (yellow) flammables cabinet was selected as the container to assemble electronic components within. Flammables cabinets are not completely fireproof; they are designed to meet Occupational Safety and Health Administration (OSHA) specifications (a ten-minute fire test)¹⁴. Planning for the worst case in the prototyping phase, the cabinet adds redundancy to the design in the case of component failures. With more time, a custom design may have been feasible, and would help bring down the cost of production.

Sensor: Inside the locker, a number of thermal sensors were considered. A small 24 x 32 pixel IR camera (MLX90640) was selected due to its form factor and ease-of-use: mounted in the upper corner of the locker, users do not have to interact with it, and perhaps will not even notice its presence. The IR sensor was chosen over a surface mount sensor, which users would have to set up for each charge, adding complexity to the user experience.

Relay: For switching power off to the battery, a four-outlet controllable relay module was selected. This decision was again made with a compressed timeline in mind, and was made easy by the selected relay module's clean look and functionality. The module was chosen over an arduino relay shield (which would have required an arduino in addition to the existing Raspberry Pi), and over designing something with the same functionality in-house, which would have been time intensive, less reliable, and required working with 120VAC, which is against college policy.

CONTAINER					
Option	Engineering Dev Lift (1-10)	Development Cost (1-10)	Production Cost (1-10)	Elegance	TOTAL
<i>Weight</i>	2	1	2	2	
Traditional Flammables Cabinet	9	9	3	4	41
Vented Steel Box	7	7	3	5	37
In-House Design	2	3	7	7	35
SENSOR					
Option	Engineering Dev Lift (1-10)	Development Cost (1-10)	Production Cost (1-10)	Elegance	TOTAL
<i>Weight</i>	2	1	2	2	
MLX90640 IR Sensor	8	8	4	6	44
Long Wave IR Sensor	7	7	3	4	35
Surface-Mount Sensor	9	9	5	2	41
RELAY					
Option	Engineering Dev Lift (1-10)	Development Cost (1-10)	Production Cost (1-10)	Elegance	TOTAL
<i>Weight</i>	2	1	2	2	
Four Outlet Power Relay Module	9	9	3	5	43
Arduino Relay Shield	7	9	2	3	33
In-House Design	2	3	5	9	35

Table 5: Component alternative matrices

Testing and Validation Ideation

To validate the technical components of the design, each piece of the system was tested separately before fully assembled.

Validation Step: Read IR camera temperature data
Success Criteria: Display data in matrix form to the terminal

Validation Step: Read temperature change over time
Success Criteria: Using a hot plate as a heat source, print a warning when rate of heat increase exceeds 5 degrees C per minute

Validation Step: Control relay with Raspberry Pi
Success Criteria: Confirm charging stops

Validation Step: Relay triggered by temperature change over time
Success Criteria: Using a hot plate as a heat source, check to see that the relay cut power off when temperature threshold increases

Validation Step: Fully functional assembly
Success Criteria: Using a hot plate as a heat source, confirm charging stops and LED indicators reflect status

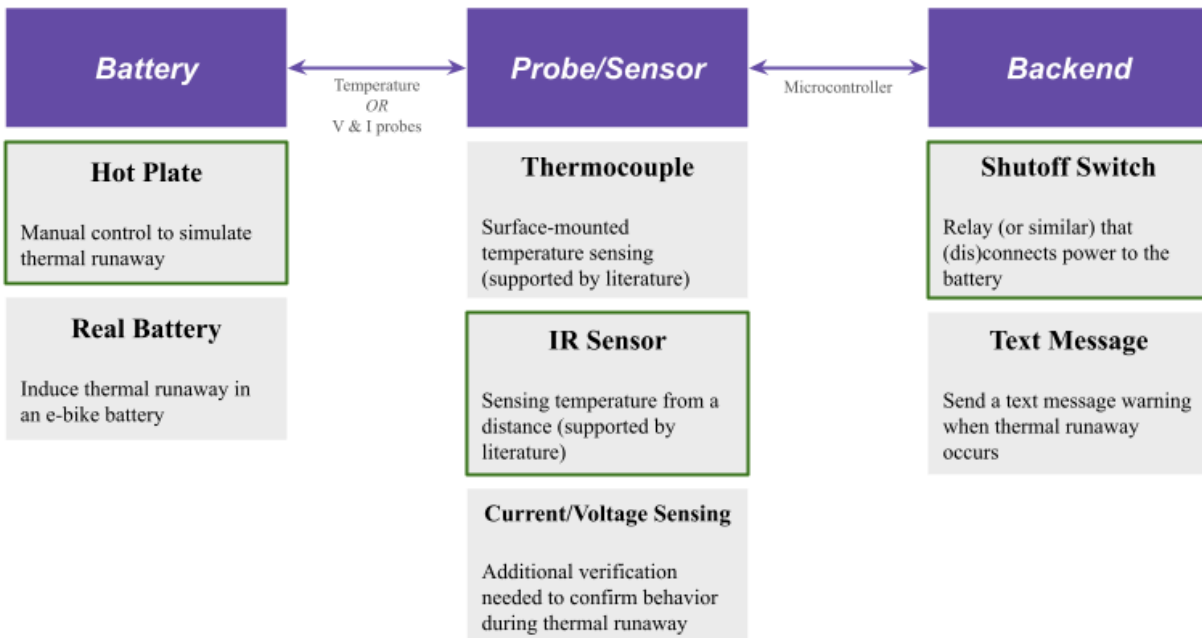


Figure 4: System Diagram of Test Setup

Deliverables

In transitioning from ideation to prototyping, specific design, and assembly, the project accomplished two deliverables:

Charging Locker Prototype: Comprising mechanical, electrical, and software systems, the prototype is a user-friendly solution for safely charging e-bike batteries.

User Testing: After assembling the prototype, user testing was conducted to confirm the usability, aesthetics, functionality, and economic viability of the product.

Mechanical Design

After making decisions about components based on weighted matrices, all components ultimately had to be neatly packaged in order to create a functional prototype. Flammables cabinets are double-walled, which added a small amount of complexity to the design: in order to route power to the relay module, a large hole was drilled and a tube was welded in to preserve the double-walled construction (Figure 5). In addition to the power cable hole, an additional hole was drilled to route the LED indicator lights through, at the back corner of the cabinet.

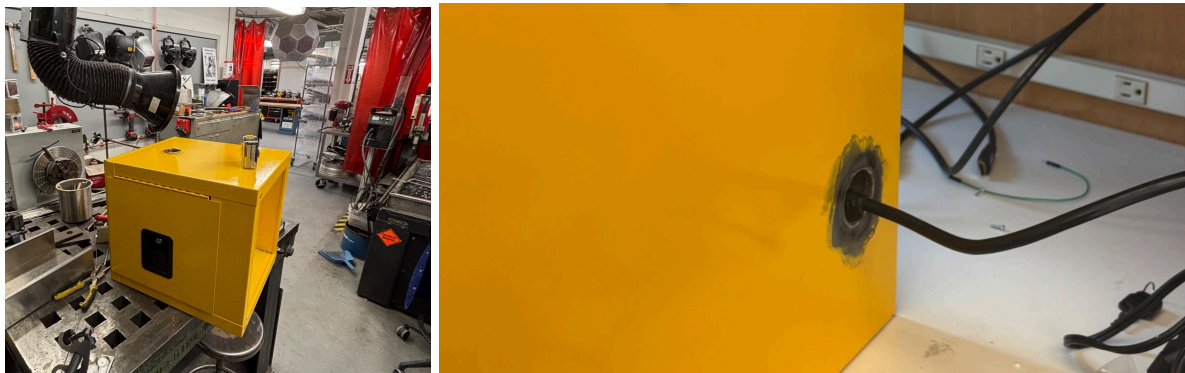


Figure 5: Welding process & final product

Multiple iterations of a 3D-printed housing were designed to mount the thermal camera in the top corner of the locker. The two-piece housing uses M2 screws to secure the camera, and mounts to the inside of the locker with #8 self-tapping sheet metal screws (Figure 6).

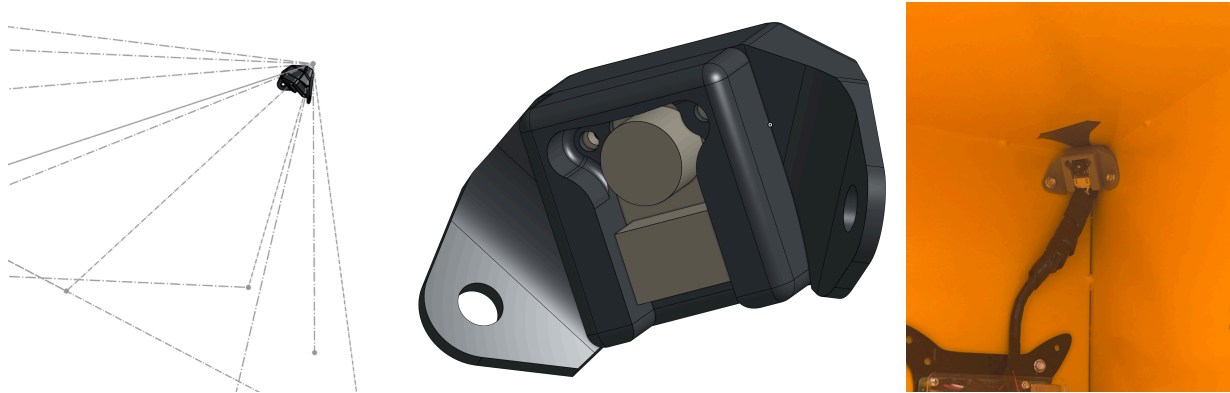


Figure 6: Thermal camera FOV sketch & housing

The same self-tapping sheet metal screws also secure the relay module and the Raspberry Pi (in a VESA mount) to the inside of the locker.

Electrical Design

The electrical design includes five main components: the Raspberry Pi 4B, the MLX90640 temperature sensor, the power relay, and two LEDs. The figure below shows the wiring of the device. See the appendix 5 for an additional electrical schematic.

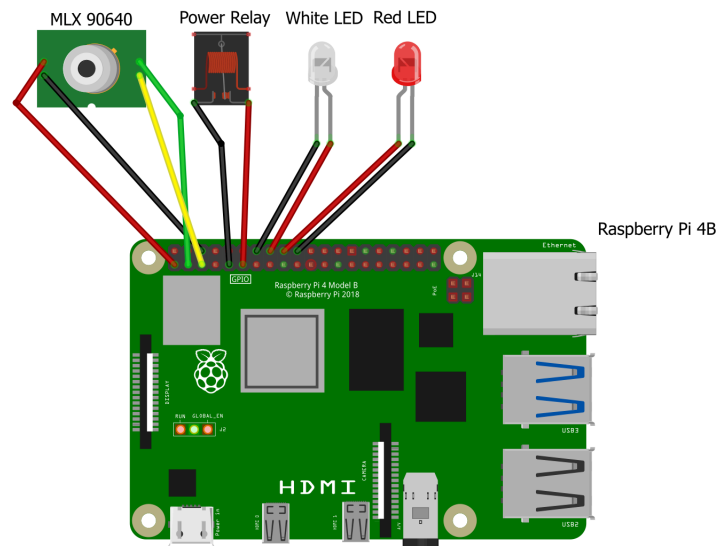


Figure 7: device electrical components

The MLX90640 sensor is a wide-angle 24x32 temperature sensor that records the temperature of the battery when it is charging. The information for the sensor is sent to the Raspberry Pi 4B, via the I2C protocol, which then calculates whether the battery has reached an unsafe temperature. If unsafe temperatures have been detected, then the Raspberry Pi sends a control signal to the relay, and the power to the battery is shut off. There are also two LEDs. The white LED is on whenever the raspberry pi is on. The red LED is on whenever unsafe temperatures are detected and power to the battery has been switched off.

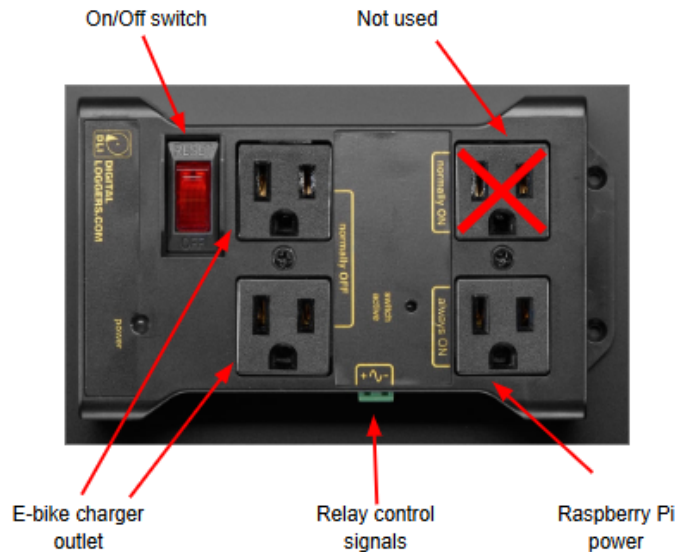


Figure 8: Power Relay Overview

We used the Adafruit Controllable Four Outlet Power Relay Module. As seen in the figure above, the Raspberry Pi was plugged into the “always on” outlet so that regardless of whether the relay was on or off, the Raspberry continued to sense temperature. The user could plug their battery into either of the “normally off” outlets; we specifically chose the “normally off” outlets so that batteries could only be charged when the camera was monitoring the temperature. The “normally on” outlet was not used in our device. There was also an on/off switch on the relay box which was used to turn the device on and off.

Software Design

Overall, the software was designed incrementally, starting with smaller functionality and then working up to create a finished design. The first software design step was to ensure the functionality of the MLX90640 sensor. Code was first written to print serial temperature values for each pixel. Next, the code was designed to measure the change in temperature between pixels at designed sampling rates; if a temperature increase of greater than 5°C was observed over the span of one minute over several pixels, then the code printed a message to the screen indicating thermal runaway (see [appendix](#)). We tested this code by activating a hot plate in every corner of the charging locker, to ensure that the entire locker was within the field of view of the thermal sensor.

After this portion of the code worked, the relay was implemented. First to ensure basic functionality, the relay was implemented to turn power on/off with a keypress; then, the code was integrated with the temperature detection code. Similarly, the LED indicators were tested separately to ensure that they worked and then were integrated into the code. Next, the code was set to run on Raspberry Pi startup to ensure that the code constantly ran without any required interventions from the user.

Overall, if the code senses a greater than 5°C temperature change, and if this temperature change is detected over multiple pixels, then power to the e-bike battery is stopped.

Functionality Testing

Before our group started the design and testing process, we first spoke to Jonathan Stark, Director of Facilities Planning & Operations at Thayer, and David McDevitt, the Associate Director of Facilities. Both informed our team that we could not test non-UL certified batteries Thayer, particularly if dangerous heating was our goal. Thus, with their approval, the team decided to use a hot plate for testing, due to the low chance of fire. We also created a safety plan which we followed to ensure safe testing and our knowledge of how to deal with potential fire risks. A more detailed review of our safety plan can be found in the appendix.

Later in the term, our group scheduled a meeting with Jeffrey Murphy, a Fire Protection Professional Engineer. This meeting proved highly encouraging, as the points he brought up concerning ventilation of the box, hazards while testing, and the testing of UL-certified batteries had all been discussed and addressed in our project already. He stated that he found our project to be well-thought out and to have real potential for positive change. The only feature he suggested was, if this product was going to be developed for market it would require stress testing with actual unsafe batteries to ensure performance, which as discussed above was not possible this term.

For our final test, we wanted to ensure that (1) that the code could run continuously for long periods of time and that (2) the ambient heat generated by normal battery charging would not trigger our temperature sensor. To conduct our test, we borrowed a safe, certified e-bike battery from Omer and Bob's in Lebanon. We left the battery charging in the locker, with the code running, overnight. We measured the temperature inside the locker throughout the night. The results are displayed below in Figure 9. The battery began at room temperature and slowly increased to 30°C while it was charging; once fully charged, the battery returned to room temperature. This test confirmed that our chosen temperature threshold of 5°C/minute was sufficient to avoid misfires during normal charging conditions; the battery we tested never increased faster than 0.15°C/minute.

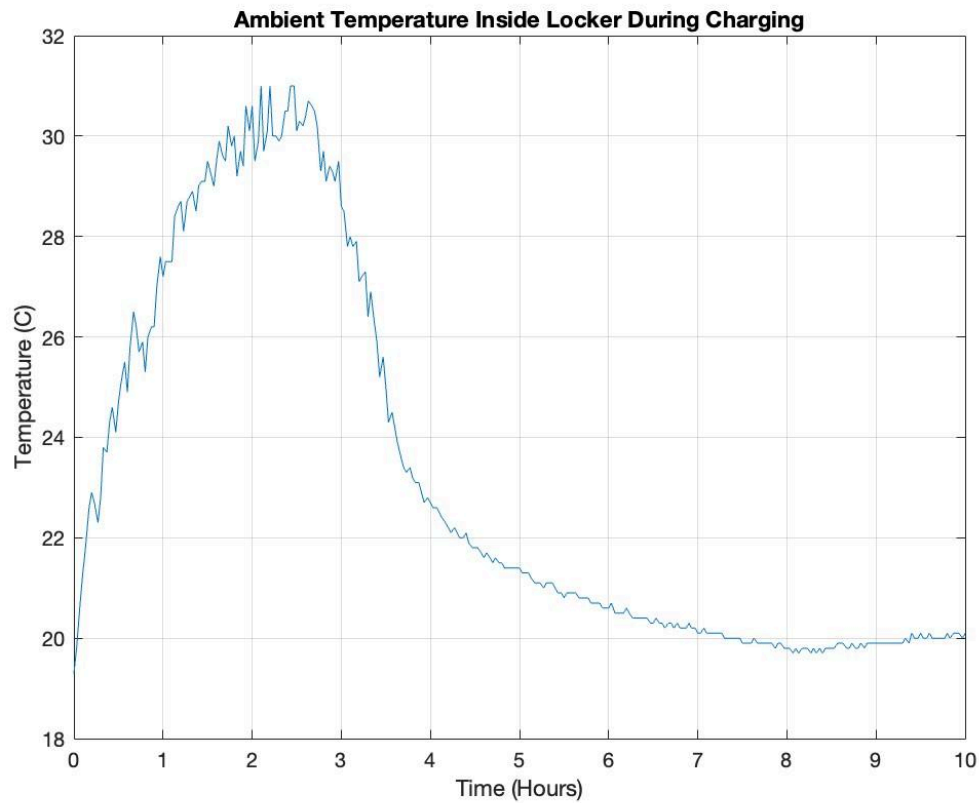


Fig. 9: Ambient Temperature Inside Locker During Normal Charging

User Testing

Once we completed our prototype, we conducted user testing with our peers. We conducted qualitative user testing, observing how college students interacted with our charging locker. After they finished, we asked for feedback, which led us to tangible design improvements and ideas for future improvements. For example, many users forgot to power on the box with the on/off switch inside, and expressed confusion at the indicator lights on the top of the box. We responded to this by printing labels and received positive user feedback once it was installed. Finally, we issued a survey to collect quantitative data, some of which is summarized below in Figure 10.

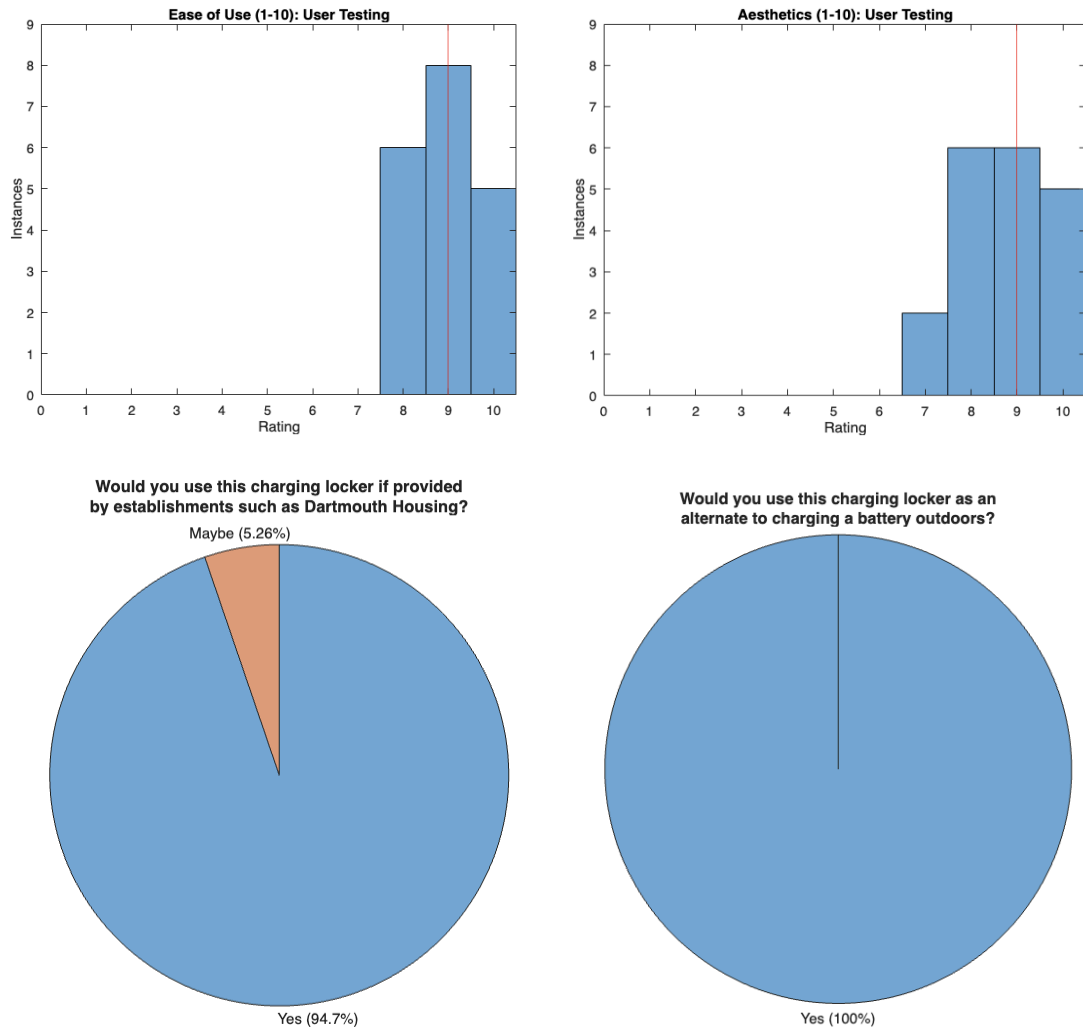


Fig. 10: Visualizations of Quantitative Survey Responses

With a sample size of 19, median ratings on a scale from 1-10 for both Ease of Use and Aesthetics were 9. Additionally, 100% of respondents said they would use the charging locker as an alternative to charging a battery outdoors, and all but one indicated that they would use the locker if provided by establishments like Dartmouth Housing.

In addition to the quantitative metrics, qualitative feedback was also collected. The most common recommendation for improvement was the addition of a light inside the locker for increased visibility when plugging in a battery. Additionally, the on/off switch inside the locker was missed by some users, and a few recommended moving the switch to the outside of the locker for ease of access and visibility. Overall, though, users responded positively to the design and found the locker intuitive and easy to use.

Societal and Economic Analysis

Societal Context

Our project exists within the context of numerous political, environmental, and socio-cultural systems, which each have a large impact on our project beyond the scope of just the engineering and design portions of the project. Each of these three systems must be considered in turn as we work toward the completion of our safety device.

Beginning with political systems, a major drive behind this project is the current lack of political intervention when it comes to e-bike safety. Underwriters Laboratories (UL) is currently one of several companies approved by the OSHA to perform safety testing, and is most widely known for setting the standards for electrical products. While UL has certification criteria for e-bikes, this certification has not been used toward widespread regulation of e-bike batteries, of which there is currently none in the United States. This lack of regulation, as has been thoroughly addressed elsewhere in this proposal, has had serious ramifications for public perceptions around safety and accessibility of e-bikes. The lack of battery safety wards away numerous potential customers, as does a lack of e-bike-specific infrastructure.

In addition, electric vehicles in general often become topics of political discourse, with electric bikes being seen as representing a more green, eco-friendly alternative to cars and other gas-powered transportation. This can, as is the case with many other new technologies, artificially turn e-bikes into a politicized topic instead of allowing them to be recognized as a new tool to allow for lower-impact transportation.

On a similar note, e-bikes are a large part of the environmental system. E-bikes have the potential to greatly benefit the environment through both far lower emissions produced in their use and manufacturing compared to conventional motor vehicles, and as they reduce demand for car-centric infrastructure. Both conventional and electric vehicles produce a staggering amount of emissions in just their manufacturing, while e-bikes produce far less due to their far smaller size. In addition, e-bikes do not emit toxic tire particles in the same manner as cars, which can enter and poison local bodies of water. Finally, the relatively small size of e-bikes also means that they are far more efficient in terms of energy consumption per mile than all cars or similar vehicles.

Car-centric infrastructure has a negative impact on both the natural environment and on the people living nearby. It leads to massive increases in air pollution and emissions, and motor vehicles are responsible for tens of thousands of deaths in the United States alone every year. In addition, car-centric infrastructure makes it far more difficult for residents to exercise and socialize, and presents a massive financial burden, in that cars are very expensive to buy and maintain, and rapidly depreciate. E-bikes allow for users to commute, complete errands, and exercise, all with a far smaller footprint and cost compared to cars. Their potential to reduce many regions in the United States's reliance on car-centric infrastructure alone can prove to be a great boon for the environment.

However, there are environmental drawbacks to e-bikes. For one, in areas where electricity is provided by fossil fuels, all of the electricity used by the battery will contribute to emissions. In addition, lithium-ion batteries must be safely disposed of at industrial waste centers, as their “ignitability and reactivity characteristics” cause them to be classified as hazardous waste by the Environmental Protection Agency (EPA). E-bike fires, as discussed extensively elsewhere, additionally can be a great hazard to the environment, as lithium-ion battery fires are notoriously dangerous and difficult to extinguish. Our project aims to partially counteract these net-negatives through its prevention of e-bike fires, meaning that it will not only make e-bikes safer, but more environmentally friendly.

Finally, e-bikes are part of a socio-cultural system, as is our team’s device. There is a wide gap between the cost of safe, UL-certified e-bikes and unregulated e-bikes. Often, bike shops will not even service the unregulated bikes due to their safety concerns, meaning that these bikes can easily end up in the landfill. Even though e-bikes can act as an equalizer in providing transportation for those who cannot afford cars, a socio-economic gap persists.

We hope that our design can play a positive role in helping to mitigate many of the negative aspects of e-bikes within the frameworks of the three systems above. By increasing both the visibility of potential dangers of e-bikes through the implementation of a safety measure at charging stations, and eliminating much of the risk of e-bike charging, we hope to improve how electric bikes are used and viewed by many.

There are a few possible unintended consequences of our project. The first is that we could be unintentionally supporting or promoting uncertified e-bike batteries. Given that our device makes uncertified batteries safer, it could be perceived that our device is encouraging the use of these batteries. Of course, we do not want users to use uncertified batteries, but it could be perceived in this way.

Another possible unintended consequence is that our device could place an added burden on e-bike users. It may be less convenient for users to place their device in our charger versus simply charging their device in their room. Additionally it is possible that some college/apartment complexes could pass the cost of the device off to the consumer through rent increases or required payment per use of the product.

Economic Analysis

Considering our chosen target buyer demographic of universities, we conducted an economic analysis of our product. This economic analysis consisted of a bill of materials, a market analysis, and a business growth plan. We intended to demonstrate that our product is desirable for consumers and can support a viable, profit-earning business.

Building our first prototype of our safe charging locker over the course of ENGS 90 cost a total of \$342. We analyzed our bill of materials to determine where we could reasonably cut costs. Next, we found sources to assist in estimating the cost of each part at-scale. We determined that our at-scale manufacturing cost for each locker would be about \$141. The bill of materials and cost calculations are included in the appendix.

A market analysis for our product demonstrates plenty of space to find our niche. The closest competitor to our product is a fireproof box. There are currently no products on the market designed specifically for e-bike batteries, which are capable of detecting precursors to thermal runaway and responding by shutting off power. There are fire-detecting lockers equipped with automatic fire extinguishers, but these are not specifically designed for e-bike batteries, do not shut off power to the battery, and activate once the battery has already caught on fire. Considering the extremely high energy density of lithium ion batteries, it is important to prevent any fires before it starts to minimize damage. Considering all these advantages, our safe charging locker is the most desirable option for universities in our target market.

There are multiple incentives for universities to buy our product. The first is student safety. There are 3000 fires on college campuses in the US annually, and since 2000 there have been 94 deaths. These numbers have been declining over the past two decades since statistics have been counted, largely in part to legislation that mandates the installation of sprinklers.¹⁵ However, lithium ion battery fires cannot be suppressed by water (although water can minimize the spread of the fire beyond the immediate vicinity of the battery). Because of this, in order to ensure safety, colleges need a specific solution that prevents lithium ion battery fires. While protecting students has plenty of value in itself, safety has been proven to be a top factor for incoming students deciding where to attend college.¹⁶ A safer university will receive more applications and can charge more tuition, providing an indirect financial incentive.

Another incentive is insurance savings. Currently, the price of insurance for colleges is soaring and is difficult for them to manage.¹⁷ We spoke to a family friend with more than twenty years of experience in the insurance business on why our product made sense from an insurance standpoint. He estimated that insurance companies would charge 1-2% less for insurance with our lockers. While this amount seems small, for universities that are paying enormous sums of money, this could amount to huge savings. For example, the University of Georgia pays \$3.6 million each month to insure its buildings.¹⁸ 1.5% of this value is \$54,000. We will demonstrate below, in our business plan, that this value is higher than a college would pay for our product. Another insurance incentive that Dan mentioned was the removal of exclusions regarding fires started by lithium ion batteries from the college's insurance policy.

A final incentive is reducing damages. Fires on college campuses in the US cause \$9.4 million in direct property damage annually,¹⁹ before considering substantial indirect costs, such as potential lawsuits. There was even a lithium battery fire outside of Dartmouth's Dining Hall this previous fall. Universities are always looking for ways to reduce their damages and their liability, and our safe charging locker provides them with an attractive option. We spoke to Jon Stark, Dartmouth's Head of Facilities, who confirmed that the main financial incentive for Dartmouth is in risk avoidance. He pointed to the recent fire in Geisel's Vail building as an example, reporting that "the lab fire itself caused maybe a few hundred dollars' worth of damage, but between the sprinkler system deploying in the room and the fire department unleashing a huge amount of water onto the small fire it caused hundreds of thousands of dollars in water damage." With just one fire prevented by our safe charging lockers, a university would prevent tremendous financial damages, and break even on their investment.

With our target audience of universities in mind, we created a five-year business plan demonstrating how our product could reasonably grow into a thriving business. To price our product, we used three methodologies - adding a 50% profit margin to our bill of materials, analyzing willingness to pay data from our quantitative user testing, and speaking with Jon Stark, Dartmouth's Head of Facilities. Our BOM and willingness to pay data indicated that we should price our product around \$300 - however, Jon Stark's price estimate was much higher, and considering that our target buyer demographic is universities, we decided to increase our final price to \$500. With our price in hand, our growth plan was as follows:

Year	Market
1	Dartmouth
2	UVM, UNH, and Middlebury
3	New England Universities - 50% Market Penetration
4	National Universities - 5% Market Penetration
5	National Universities - 25% Market Penetration

Table 7: Selected Markets in Business Growth Plan

We estimated other variable costs for our product in each of these markets, consisting of manufacturing labor, distribution, and warranties/returns. We also estimated yearly fixed costs, consisting of facility rent, sales, and insurance and legal fees. We calculated the market size as 1 safe charging locker for every 5 e-bike using students living in university housing in each market. Our results are as follows:

Market Size Calculations						
Year	Number of students	Percent of students living in college housing	Number of students living in college housing	Portion of students with e-bikes	Ratio of e-bikes to charging lockers	Market Size
1			4050	1/30	1/5	27
2	31000	2/3		1/30	1/5	138
3	0.5 * 800k	2/3		1/40	1/5	1160
4	0.05 * 18M	1/3		1/40	1/5	1440
5	0.25 * 18M	1/3		1/40	1/5	7200

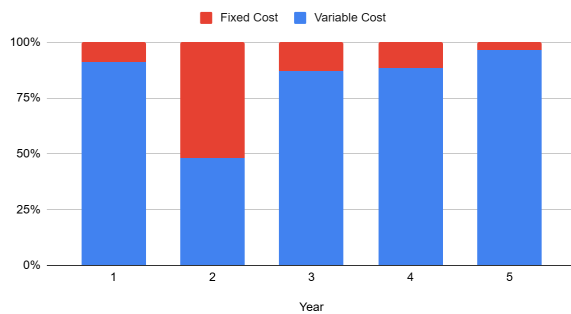
Table 8: Market Size Calculations in Business Growth Plan

Costs					
Year	Cost of Materials/Unit	Other Variable Costs/Unit	Total Variable Cost	Total Fixed Cost	Total Cost
1	\$141	\$52.50	\$5,225	\$504	\$5,729
2	\$141	\$102.50	\$33,603	\$36,504	\$70,107
3	\$141	\$90	\$267,960	\$40,104	\$308,064
4	\$141	\$90	\$332,640	\$44,004	\$376,644
5	\$141	\$90	\$1,663,200	\$59,004	\$1,722,204

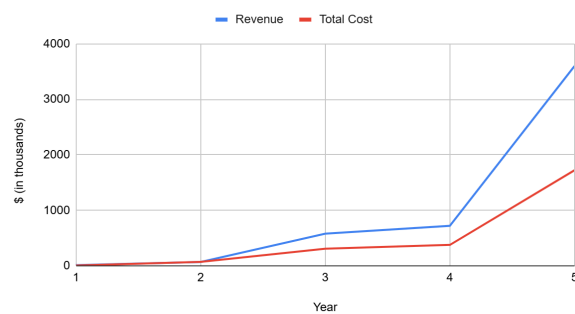
Revenue and Profit					
Year	Market Size	Price/Locker	Revenue	Total Profit	Profit/Unit
1	27	\$500	\$13,500	\$7,772	\$288
2	138	\$500	\$69,000	-\$1,107	-\$8
3	1160	\$500	\$580,000	\$271,936	\$234
4	1440	\$500	\$720,000	\$343,356	\$238
5	7200	\$500	\$3,600,000	\$1,877,796	\$261

Table 9: Economic Data in Business Growth Plan

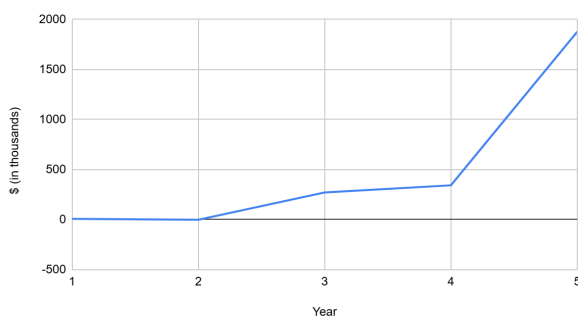
Proportion of Fixed Cost to Variable Cost



Revenue and Total Cost



Profit



Profit per Unit

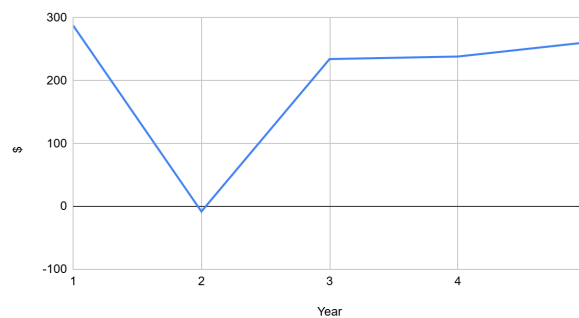


Figure 11: Visualizations of Economic Data in Business Growth Plan

This business growth plan demonstrates that the financials of our product can support a healthy profit margin. Backend calculations for our business plan are included in the appendix.

Recommendations for Future Work

We have several recommendations for future work. These are specifically: improving our prototype/design, conducting more thorough testing, designing a bigger locker, conducting a more thorough economic analysis, and designing a FYREE project.

Extensive Analysis of Thermal Runaway Options

While we spent the first three weeks of the term evaluating different options to detect precursors to thermal runaway, we did not have time to extensively evaluate every option. For example, it could be possible to detect the precursors to thermal runaway through current changes on the AC side of a charger, but given that there is not extensive literature on this topic, we chose to investigate temperature instead. With more time, all possible precursors to thermal runaway could be effectively evaluated to ensure that we create the best possible solution. Alternative options could be significantly cheaper, which could increase the overall profitability of the device.

Prototype/Design improvements

Given that our project was conducted over only one term, we only had the ability to create a prototype. We were unable to optimize parts and components to create the best possible design. For example, instead of designing and building a locker that would be the optimal size for our project, we purchased one. In our final design, we would redesign our project to include optimal components. For example, we would design and build our own locker; this would allow the price of the design to be significantly cheaper as well as better suit our needs. The redesigned locker would include a specifically designed housing for the Raspberry Pi and the LEDs. The wires between the Raspberry Pi and the thermal camera would also be hidden inside the box instead of our prototype, increasing durability and visual appeal. The redesigned locker would better meet the needs of users and also decrease the cost of parts; currently, the fire-proof box was the most expensive component of our project, but by creating our own box, we could significantly decrease cost. Another possible improvement would be to use a cheaper Raspberry Pi (e.g. a Raspberry Pi Zero) as our project uses very little computing power. This would allow us to save \$20-30 per product.

Testing

An important future step is to conduct more thorough testing. First, uncertified batteries should be tested. Per the request of Thayer safety officials we were unable to use uncertified batteries or similar dangerous conditions of thermal runaway. To ensure that the design works effectively, it is imperative that the device is extensively tested with uncertified batteries.

Technical Testing

The reliability of the device must be evaluated. Given that we only created a prototype through this class, we did not evaluate the reliability of the device and determine which components are most likely to fail. To do this, we must extensively test the device over several weeks to make

sure that it continues to operate. A few possible areas of concern are the longevity of the relay, thermal camera and door hinges; all of these areas must be explored to ensure that the device remains functional and safe with extended use. The thermal camera is likely to be the area of greatest concern given that the first MLX90640 sensor we purchased was faulty; the sensor we purchased is relatively inexpensive and therefore may not be extremely reliable. We should test a number of different MLX90640 sensors over a long period of time to ensure that they are reliable. If the sensors are not reliable, we should investigate whether there are alternative sensor options available that better suit our needs.

User Testing

We must also more extensively user test the device. We only had the opportunity to test the device with Dartmouth community members; therefore, it is important that in the next phase of testing, a number of different groups of people test the device to ensure that it works well. In addition, it is imperative that we set up long term testing options. For example, we could pilot the device in a Dartmouth building or apartment building for a few months to effectively gather user feedback.

Designing a bigger locker

Our initial prototype focused on removable e-bike batteries, but there are other types of micro mobility vehicles that could benefit from our device; for example, there are a large number of electric scooters on Dartmouth's campus. Generally, electric scooter batteries are non-removable so they cannot currently use our device. A possible improvement would be to design a larger locker that could fit an entire electric scooter.

Conducting a more thorough economic analysis

We had to make a number of assumptions for our economic analysis including the price of parts, willingness to pay and expansion rates. For a next step, we could spend time better understanding our target market by speaking with customers, such as colleges across the country to better understand their willingness to pay for the product, and if they are willing to pay, how much.

FYREE project

We believe that our project could be continued through the work of a FYREE project. One possible project idea could be to create a more refined design of our current work. For example, students could work to create a more finalized housing/locker for the product. Another possible project could be to better evaluate the economic feasibility of the project; students could work to ask different colleges and apartment complex owners about their need for the project and their willingness to pay. We have included all of our documentation and code in this report; a FYREE project could use this information to start their project.

Reference Endnotes

1. Chub, Anastasiia. "E-Bike Battery Fire Statistics 2024." Whizz, 14 Oct. 2024, getwhizz.com/blog/battery/e-bike-battery-fire-statistics-and-safety-advice/.
2. "#ChargeSafe: E-Bike and E-Scooters are London's Fastest-Growing Fire Trend." *London Fire Brigade*, www.london-fire.gov.uk/safety/lithium-batteries/the-dangers-of-electric-scooter-and-electric-bicycle-batteries/. Accessed 21 Nov. 2024.
3. Botelho, Jessica A. "Fires Caused by Lithium Batteries 'have Increased Dramatically' in New York, Mayor Says." *The National Desk*, 23 Mar. 2023, thenationaldesk.com/news/americas-news-now/fires-caused-by-lithium-batteries-have-increased-dramatically-in-new-york-mayor-says-lithium-ion-faulty-e-bike-batteries-blaze-flames-safety-precautions-death-lethal-bronx-commercial-building-supermarket-laundry-mat.
4. Stott, Seb. "E-Bike Battery Fires - Should You Be Worried? ." *Pinkbike*, 29 Mar. 2024, www.pinkbike.com/news/e-bike-battery-fires-should-you-be-worried.html.
5. "Mayor Adams Takes New Actions To Prevent Deadly Lithium-Ion Battery Fires, Promote Safe E-Bike Charging And Usage." *The Official Website of the City of New York*, 22 July 2024, www.nyc.gov/office-of-the-mayor/news/574-24/mayor-adams-takes-new-actions-prevent-deadly-lithium-ion-battery-fires-promote-safe-e-bike#/0.
6. "E-Bikes Certification: Evaluating and Testing to UL 2849." *UL Solutions*, www.ul.com/services/e-bikes-certificationevaluating-and-testing-ul-2849. Accessed 21 Nov. 2024.
7. "NFPA Fact Sheet: E-Bike and E-Scooter Safety." *NFPA*, www.nfpa.org/en/forms/E-Bike-Fire-Safety. Accessed 21 Nov. 2024.
8. "E-Bikes Certification: Evaluating and Testing to UL 2849." *UL Solutions*, www.ul.com/services/e-bikes-certificationevaluating-and-testing-ul-2849. Accessed 21 Nov. 2024.
9. Smith, Greg B. "Megastores and Small E-Bike Shops Blow Off City Ban on Unsafe Batteries." *THE CITY - NYC News*, 15 May 2024, www.thecity.nyc/2024/05/16/ebike-shops-flout-ban-batteries-fire/#:~:text=Since%20September%2C%20the%20City%20of,fires%20triggered%20by%20exploding%20devices.
10. "Mayor Adams Announces Finalized E-Bike Trade-In Program to Keep New Yorkers Safe." *The Official Website of the City of New York*, 23 Oct. 2024, www.nyc.gov/office-of-the-mayor/news/783-24/mayor-adams-finalized-e-bike-trade-in-program-keep-new-yorkers-safe-lithium-ion#/0.
11. "E-Bikes Certification: Evaluating and Testing to UL 2849." *UL Solutions*, www.ul.com/services/e-bikes-certificationevaluating-and-testing-ul-2849. Accessed 21 Nov. 2024.
12. "Stages of the Thermal Runaway Process in Lithium Batteries." *Manage Risks and Maximize ROI for Your PV and Energy Storage Projects, Sinovoltaics (Hong Kong Office)*, 29 Mar. 2023, sinovoltaics.com/energy-storage/batteries/stages-of-the-thermal-runaway-process-in-lithium-batteries/.
13. "Stages of the Thermal Runaway Process in Lithium Batteries." *Manage Risks and*

- Maximize ROI for Your PV and Energy Storage Projects, Sinovoltaics (Hong Kong Office), 29 Mar. 2023,
sinovoltaics.com/energy-storage/batteries/stages-of-the-thermal-runaway-process-in-lithium-batteries/.
14. Thornton, Nathan. "Flammable Cabinets 101: Regulations & Recommendations." *IQ Labs*, 8 May 2024,
iq-laboratory.com/flammable-cabinets-101/#:~:text=Flammable%20cabinets%20are%20constructed%20to,in%20a%20flammable%20storage%20cabinet.
 15. Murphy, Jan. "College Fire Tragedy Sparks Law Facilitating Sprinkler Installation: How'd That Work Out." *Pennlive*, 24 Aug. 2016,
www.pennlive.com/politics/2016/08/college_fire_tragedy_sparks_la.html.
 16. SEM Works. *SEM Works Report: Campus Safety*, Jan. 2008,
www.semworks.net/papers/sem-works-report-campus-safety.html.
 17. Kafka, Alexander C. "The Cost of Insuring Colleges Continues to Rise. And Covid's Not the Reason." *The Chronicle of Higher Education*, 3 Mar. 2021,
www.chronicle.com/article/the-cost-of-insuring-colleges-continues-to-rise-and-covids-not-the-reason?bc_nonce=l2dxeor3mpaz9ibabavu&cid=reg_wall_signup.
 18. Habersham, Raisa. "Univ. Insurance Costs \$3.6 Million per Month." *The Red & Black*, 27 Sept. 2013,
www.redandblack.com/news/univ-insurance-costs-3-6-million-per-month/article_161c4973-d43f-5f4a-93ed-96caff35a926.html.
 19. "Safety Facts About Campus Fires." *Environmental Health & Safety*,
ehs.ucr.edu/image/training-safety-hot-facts-about-campus-fires. Accessed 10 Mar. 2025.

Appendix

Appendix 1: Debugging Code

The first image is of the changes in temperature of every pixel. The second is of when successive temperature increases are detected

```
Temperature Changes (C):
-0.2c, -0.4c, -0.7c, 0.0c, -0.3c, 0.3c, -0.1c, -0.1c, -0.1c, -0.1c, -0.1c, 0.1c, -0.2c, 0.2c, -0.1c, 0.0c, 0.0c, -0.2c, 0.0c, 0.1c, 0.1c, -0.3c, -0.4c, 0.3c, -0.1c, -0.3c, 0.2c, 0.0c, -0.3c, 0.0c, 0.0c, -0.7c,
0.0c, -0.2c, 0.2c, -0.3c, -0.2c, 0.0c, 0.1c, 0.0c, -0.3c, -0.3c, 0.1c, 0.0c, -0.1c, 0.0c, 0.0c, -0.1c, 0.0c, 0.0c, 0.0c, -0.1c, -0.1c, 0.1c, -0.2c, -0.2c, -0.3c, 0.2c, 0.0c, 0.0c, -0.2c, -0.2c, -0.4c,
0.2c, 0.2c, -0.2c, -0.2c, -0.4c, 0.0c, 0.0c, 0.0c, 0.1c, -0.1c, -0.3c, 0.0c, -0.1c, 0.1c, 0.0c, 0.1c, -0.1c, 0.0c, 0.0c, -0.2c, 0.0c, -0.2c, -0.1c, -0.1c, 0.0c, 0.1c, 0.0c, -0.1c, 0.1c, 0.2c, -0.4c, 0.2c,
-0.2c, 0.0c, -0.3c, -0.1c, -0.1c, -0.1c, -0.1c, -0.2c, 0.0c, 0.0c, -0.3c, 0.0c, -0.2c, 0.1c, -0.1c, 0.0c, -0.1c, -0.2c, -0.2c, 0.0c, -0.1c, -0.2c, 0.0c, -0.1c, -0.2c, 0.0c, -0.1c, 0.1c, 0.0c, -0.3c, 0.3c, -0.3c, -0.2c, 0.2c, 0.0c,
-0.2c, 0.2c, 0.0c, 0.0c, 0.0c, 0.0c, 0.0c, -0.1c, -0.1c, 0.0c, -0.1c, -0.2c, -0.2c, -0.1c, -0.2c, -0.1c, -0.1c, -0.1c, -0.2c, -0.2c, -0.3c, 0.2c, 0.0c, 0.0c, -0.5c, -0.3c, 0.1c, -0.3c, 0.0c, -0.2c, -0.2c,
0.2c, -0.2c, -0.1c, 0.0c, 0.0c, 0.1c, 0.0c, -0.2c, 0.0c, 0.0c, -0.1c, 0.2c, -0.1c, -0.1c, 0.0c, -0.1c, -0.1c, 0.1c, -0.1c, 0.1c, -0.1c, -0.1c, -0.1c, -0.1c, -0.1c, -0.1c, -0.1c, 0.1c, 0.1c, 0.1c, 0.1c, -0.2c, 0.2c,
0.2c, 0.0c, 0.0c, -0.3c, 0.0c, -0.2c, 0.2c, 0.4c, 0.0c, -0.1c, 0.1c, -0.2c, 0.0c, 0.0c, -0.2c, -0.1c, -0.2c, -0.1c, 0.0c, -0.1c, -0.2c, -0.3c, 0.1c, 0.1c, -0.2c, -0.1c, 0.0c, -0.1c, -0.3c, -0.3c, -0.2c, 0.0c,
-0.1c, 0.0c, -0.1c, 0.1c, -0.1c, -0.1c, -0.1c, 0.2c, 0.0c, -0.2c, 0.0c, 0.0c, 0.0c, 0.0c, -0.1c, 0.0c, -0.1c, 0.0c, -0.1c, 0.1c, 0.0c, -0.1c, 0.1c, 0.0c, -0.1c, 0.1c, 0.0c, -0.1c, -0.4c, 0.0c, 0.1c, 0.0c, -0.1c, -0.2c,
0.0c, -0.3c, 0.1c, -0.1c, 0.0c, 0.1c, 0.0c, -0.2c, -0.1c, -0.1c, 0.0c, 0.1c, 0.0c, 0.1c, 0.0c, -0.1c, 0.1c, 0.1c, -0.2c, -0.1c, 0.1c, 0.1c, -0.2c, -0.1c, 0.1c, 0.0c, -0.4c, 0.0c, 0.1c, -0.1c, -0.3c,
0.2c, 0.2c, -0.1c, 0.1c, -0.1c, -0.1c, 0.1c, 0.0c, 0.0c, -0.1c, 0.1c, 0.0c, 0.0c, -0.3c, -0.1c, -0.1c, -0.3c, -0.2c, -0.1c, -0.1c, 0.0c, -0.1c, -0.1c, 0.3c, -0.1c, 0.0c, 0.0c, 0.2c, 0.5c, -0.1c, -0.3c, 0.5c,
0.0c, 0.0c, 0.0c, 0.0c, 0.0c, -0.1c, -0.1c, 0.1c, -0.2c, 0.1c, 0.1c, 0.1c, -0.2c, 0.2c, 0.0c, -0.1c, -0.2c, 0.1c, -0.2c, -0.1c, 0.0c, 0.0c, -0.2c, 0.0c, 0.0c, -0.2c, 0.0c, 0.0c, 0.1c, 0.3c, 0.2c, 0.2c,
-0.3c, 0.0c, -0.1c, 0.4c, 0.0c, -0.1c, 0.1c, 0.0c, -0.1c, 0.0c, 0.0c, -0.1c, -0.1c, 0.0c, 0.0c, 0.1c, 0.1c, -0.1c, -0.1c, -0.2c, -0.1c, -0.1c, -0.1c, -0.1c, -0.2c, -0.1c, 0.1c, -0.1c, 0.3c, -0.1c, -0.4c, -0.2c,
0.0c, -0.3c, 0.1c, -0.1c, 0.0c, 0.1c, 0.0c, -0.2c, -0.1c, -0.1c, 0.0c, 0.1c, 0.0c, 0.1c, 0.0c, -0.1c, 0.1c, 0.1c, -0.2c, -0.1c, 0.1c, 0.1c, -0.2c, -0.1c, 0.1c, 0.0c, -0.4c, 0.0c, 0.1c, -0.1c, -0.3c,
0.2c, 0.2c, -0.1c, 0.1c, -0.1c, -0.1c, 0.1c, 0.0c, 0.0c, -0.1c, 0.1c, 0.0c, 0.0c, -0.3c, -0.1c, -0.1c, -0.3c, -0.2c, -0.1c, -0.1c, 0.0c, -0.1c, -0.1c, 0.3c, -0.1c, 0.0c, 0.0c, 0.2c, 0.5c, -0.1c, -0.3c, 0.5c,
0.2c, 0.0c, 0.0c, 0.0c, 0.0c, 0.0c, -0.2c, -0.1c, -0.2c, -0.1c, -0.1c, -0.2c, -0.2c, -0.3c, 0.2c, -0.2c, -0.1c, -0.1c, -0.2c, -0.1c, 0.0c, 0.0c, -0.2c, 0.0c, 0.0c, -0.2c, 0.0c, 0.0c, 0.1c, 0.3c, 0.2c, 0.2c,
-0.2c, 0.2c, 0.0c, 0.2c, -0.4c, -0.1c, 0.2c, 0.0c, -0.1c, -0.1c, 0.2c, -0.1c, -0.1c, -0.2c, -0.1c, 0.0c, 0.0c, 0.0c, -0.1c, 0.0c, -0.1c, 0.0c, -0.2c, 0.0c, -0.2c, 0.0c, -0.2c, 0.0c, -0.1c, -0.3c, 0.0c,
0.0c, -0.3c, -0.3c, -0.1c, -0.3c, -0.4c, -0.1c, 0.1c, -0.1c, -0.1c, -0.2c, 0.0c, 0.0c, 0.0c, -0.1c, 0.0c, -0.1c, 0.0c, -0.1c, 0.0c, -0.2c, 0.0c, -0.1c, -0.1c, -0.2c, 0.0c, 0.3c, -0.3c, 0.0c, 0.0c, 0.2c,
0.0c, 0.0c, 0.2c, -0.4c, 0.0c, 0.0c, -0.4c, -0.2c, 0.0c, 0.3c, 0.0c, -0.3c, 0.2c, -0.3c, 0.3c, 0.0c, 0.0c, -0.1c, 0.1c, -0.1c, -0.3c, -0.3c, -0.3c, 0.0c, 0.2c, 0.0c,
0.2c, 0.0c, 0.0c, -0.2c, -0.1c, 0.2c, -0.1c, -0.1c, -0.1c, -0.1c, 0.1c, 0.0c, -0.1c, 0.1c, 0.0c, -0.1c, -0.2c, -0.1c, 0.0c, 0.0c, -0.1c, 0.1c, -0.2c, -0.4c, -0.1c, -0.3c, 0.2c, 0.2c, 0.0c, 0.0c, -0.2c,
-0.2c, 0.0c, 0.0c, -0.3c, -0.4c, -0.3c, -0.1c, 0.4c, -0.4c, -0.1c, -0.1c, -0.2c, -0.1c, 0.0c, 0.1c, -0.1c, -0.1c, 0.1c, -0.1c, -0.1c, -0.1c, -0.1c, -0.2c, 0.0c, -0.1c, 0.0c, 0.0c, -0.3c, 0.0c, 0.0c, 0.0c, -0.2c,
-0.2c, 0.4c, 0.2c, 0.0c, 0.0c, -0.2c, 0.2c, -0.1c, 0.0c, -0.1c, -0.4c, -0.1c, 0.1c, 0.1c, 0.1c, -0.4c, -0.4c, -0.2c, -0.1c, 0.0c, 0.3c, 0.3c, 0.3c, 0.0c, 0.0c, -0.2c, 0.0c, 0.0c,
0.3c, 0.0c, 0.2c, 0.0c, -0.2c, -0.2c, 0.0c, -0.3c, -0.1c, -0.1c, 0.0c, 0.1c, -0.1c, -0.1c, -0.2c, 0.0c, -0.1c, -0.1c, 0.1c, 0.1c, -0.1c, -0.1c, 0.1c, -0.1c, 0.0c, 0.3c, 0.2c, 0.5c, -0.2c, 0.2c, 0.0c, 0.0c,
Biggest Temp Change: 0.5c at position (12, 28)
Relay Deactivated due to potential thermal runaway!
```

```
Consecutive Temp Increase at Pixel (21, 31)!
Consecutive Temp Increase at Pixel (23, 16)!
Consecutive Temp Increase at Pixel (22, 25)!
Consecutive Temp Increase at Pixel (21, 16)!
Consecutive Temp Increase at Pixel (21, 26)!
Consecutive Temp Increase at Pixel (23, 18)!
Consecutive Temp Increase at Pixel (22, 27)!
Consecutive Temp Increase at Pixel (23, 20)!
Consecutive Temp Increase at Pixel (22, 29)!
Consecutive Temp Increase at Pixel (22, 14)!
Consecutive Temp Increase at Pixel (23, 22)!
Warning: Multiple pixels detected with consecutive increases! Possible thermal runaway!
Relay Deactivated due to potential thermal runaway!
```

Appendix 2: Raspberry Pi Code

```
import time
import board
import busio
import numpy as np
import adafruit_mlx90640

from gpiozero import OutputDevice
from pynput import keyboard

# Define GPIO pin for the relay and LEDs
RELAY_PIN = 17
relay = OutputDevice(RELAY_PIN, active_high=True, initial_value=False)
RED_LED_PIN = 23 #Red LED on indicates thermal runaway
WHITE_LED_PIN = 24 #White LED on indicates power to the device
red_led = OutputDevice(RED_LED_PIN, active_high=True, initial_value=False)
white_led = OutputDevice(WHITE_LED_PIN, active_high=True, initial_value=False)

#LED and relay initial conditions
white_led.on()
relay.on()

# Set up I2C interface
i2c = busio.I2C(board.SCL, board.SDA, frequency=800000)

# Initialize MLX90640 sensor
mlx = adafruit_mlx90640.MLX90640(i2c)

# Print the serial number to confirm sensor is connected
print("MLX addr detected on I2C", [hex(i) for i in mlx.serial_number])

# Set the refresh rate
mlx.refresh_rate = adafruit_mlx90640.RefreshRate.REFRESH_2_HZ

# Initialize the frame arrays
frame = [0] * 768
last_frame = [0] * 768

increase_counts = {}

# Configurable number of consecutive increases before fire detection
FIRE_DETECTION_THRESHOLD = 2

# Function to track temperature change for a specific pixel
def track_pixel_increase(h, w, current_temp, fire_pixels):
    pixel_id = (h, w)
    if pixel_id not in increase_counts:
        increase_counts[pixel_id] = {"count": 0, "last_temp": current_temp}
```

```

# Check if the temperature increased by 2.5°C or more compared to the last reading
if current_temp - increase_counts[pixel_id]["last_temp"] >= 2.5:
    increase_counts[pixel_id]["count"] += 1
else:
    increase_counts[pixel_id]["count"] = 0 # Reset count if the increase doesn't meet threshold

# Update the last recorded temperature for this pixel
increase_counts[pixel_id]["last_temp"] = current_temp

# Check if the pixel has had the configured number of consecutive increases
if increase_counts[pixel_id]["count"] >= FIRE_DETECTION_THRESHOLD:
    fire_pixels.add(pixel_id) # Track this pixel as part of a potential thermal runaway

# Function to handle keyboard inputs
def on_press(key):
    try:
        if key.char == 'a': # Press 'a' to activate relay
            relay.on()
            print("Relay Activated")
        elif key.char == 'd': # Press 'd' to deactivate relay
            relay.off()
            print("Relay Deactivated")
    except AttributeError:
        pass # Ignore special keys

# Set up keyboard listener in a separate thread
keyboard_listener = keyboard.Listener(on_press=on_press)
keyboard_listener.start()

#Wait 30 seconds for user to plug in battery and close door
#time.sleep(30)

#Set up loop condition
condition = True

# Main loop
while condition:
    try:
        mlx.getFrame(frame) # Read current frame from the sensor
    except ValueError:
        continue

# Track the biggest temperature increase
max_temp_change = float('-inf')
max_temp_change_position = (0, 0)
fire_pixels = set() # Set to track multiple fire detections

# First block: print absolute temperatures
print("Absolute Temperatures (C):")
for h in range(24):

```

```

for w in range(32):
    current_temp = frame[h * 32 + w]
    print(f"{current_temp:0.1f}C", end=" ")
    print()
print()

# Second block: print temperature changes and track the largest change
print("Temperature Changes (C):")
for h in range(24):
    for w in range(32):
        current_temp = frame[h * 32 + w]
        last_temp = last_frame[h * 32 + w]
        temp_change = current_temp - last_temp # Calculate the change in temperature

        print(f"{temp_change:0.1f}C", end=" ")

        # Track the biggest temperature change
        if temp_change > max_temp_change:
            max_temp_change = temp_change
            max_temp_change_position = (h, w)

        # Track temperature increases for each pixel
        track_pixel_increase(h, w, current_temp, fire_pixels)
    print()
print()

# Print the largest temperature change and its position
h, w = max_temp_change_position
print(f"Biggest Temp Change: {max_temp_change:0.1f}C at position ({h}, {w})")

# Print all fire detections after temperature deltas
for h, w in fire_pixels:
    print(f"Consecutive Temp Increase at Pixel ({h}, {w})!")

# Check for multiple simultaneous fire detections (thermal runaway)
if len(fire_pixels) > 1:
    print("Warning: Multiple pixels detected with consecutive increases! Possible thermal runaway!")
    relay.off() # Turn off relay as a safety measure
    red_led.on()
    print("Relay Deactivated due to potential thermal runaway!")
    #condition = False

# Update the last frame for the next iteration
last_frame[:] = frame[:]

# Delay
time.sleep(20)

```

Appendix 3: Bill of Materials and Cost Analysis

Bill of Materials			
Part	Cost in Prototype	Cost at Scale	Notes
Locker	\$149.99	\$50	At scale, we would manufacture our own locker. We estimate a price of \$50 for the sheet metal to construct the locker.
Raspberry Pi	\$45	\$20	We used 1GB Raspberry Pi 4B in prototype. We do not need all of this processing power and could use a cheaper Pi such as the Raspberry Pi Zero.
IR Sensor	\$66.50	\$59.95	MLX 90640. to cheaper prototype
Relay Module	\$39.95	\$5	At scale, we would design and build our own relay module that would fit into a compact electrical box. The most expensive part of the module, the power relay, is available in our required specifications (120VAC, 12A) on Digikey for \$1.
LEDs	\$5	\$1	At scale, LEDs are very inexpensive.
VESA Mount	\$17.95	\$4	At scale, we would construct our own VESA mount from plastic.
Tapping Screws	\$5.54	\$1	At scale, screws are very inexpensive.
Spiral Cable	\$6.99		Not used in product at scale.
Steel Reinforceme	\$5		Not used in product at scale.
Total Cost	\$341.92	\$141	
Other Variable Costs			
Manufacturing Labor		\$32.50	Years 1-2: two hours of labor per locker at \$16.25/hr Dartmouth minimum wage.
		\$20	Years 3-5: two hours of labor per locker at \$10/hr wage.
Packaging and Distribution		\$50	Estimate from Amazon of shipping a similarly sized product. Not applicable for Year 1.
Warranties and Returns		\$20	Assuming some boxes need to be fixed or replaced.
Fixed Costs (One-Time)			
Engineering and Design Costs		\$5,000	100 hours of labor at median engineering wage of \$50/hr
UL Certification		\$5,000	
Fixed Costs (Yearly)			
Facility Rent		\$36,000	Lab space rental is \$3000/month Not applicable for Year 1
Marketing and Sales		0	Year 1-2: Not applicable
		\$3,600	Year 3: \$15/hr for 20 hr/month
		\$7,500	Year 4: \$15/hr for 10 hr/week
		\$22,500	Year 5: \$15/hr for 30 hr/week
Insurance and Legal		\$504	\$42/month

Appendix 4: Updated Safety Plan Sections 3 and 4

Section 3: Hazard Acknowledgment and Assessment

3.1 Hazard Assessment (Risk assessment and mitigation at time of the test)

	Hazard	Present Y/N	Hazard Mitigation
1	Hearing Protection	N	
2	Explosives	N	
3	Confined Space	N	
4	Eye Protection	N	
5	Projectile	N	
6	Chemical Burn	N	
7	Heat Burn	Y	Since we will be using a hot plate, there is a possibility of heat burn. We will mitigate this by communicating with everyone whenever the hot plate is on, and not touching it until it is fully off and cooled down.
8	Weather	N	
9	Water	N	
10	Unstable Load	N	
11	Heavy Objects	N	
12	Fire Hazard	Y	Since we are using a hot plate elevated to relatively high levels, there is a small possibility of fire. We will mitigate this by always having at least two people working with the hot plate at a time, being aware of the fire extinguisher location in Fahey and how to use it, and being aware of exit routes from the room. We will also ensure the plate is not on for too long, and unplug it immediately if we have any safety concerns.
13	Unstable Chemical	N	
14	Oxidizer	N	
15	Corrosive Agent	N	
16	Radiation	N	
17	Containment and Storage	N	
18	Lockout Tag out of Energy	N	
19	High Voltage (>35V)	N	

If you have answered YES to any hazard then proceed to Sections 4 (Hazard abatement) and Section 5 (Signatures). If NO hazards are present then stop here because no abatements or signatures are needed, and attach to your proposal.

Section 4: Hazard Abatement

4.1 Significant or High-Risk Activities (Risk assessment and management in preparation)

4.1(a): *Raising a hot plate to a high rate of temperature increase*

- Safety Considerations

1. *What do we need to communicate with each other? How can we be aware of heat burn and fire prevention and mitigation strategies?*

- Hazard Acknowledgement

1. *Raising any material to a high temperature/rate of temperature increase carries potential risk for heat burn and fire, particularly without constant, careful supervision.*

- Measures taken to Address Hazards

1. *Ensuring that at least two people at a time are supervising testing with the hot plate.*

- *Will leave a note warning of the hot plate whether it is currently in use or not, and will always pull the plug from both the wall outlet and hot plate when the latter is not in active use.*

2. *Ensuring that all group members are fully aware of the heat and fire risks and how to both prevent and mitigate them.*

3. *Being aware of where the fire extinguisher and exit routes are.*

- *Figures of the setup and fire extinguisher are below; all are aware of the one exit from the room, and our bench is next to an open window, so one last resort could be to drop anything which is on fire into the snow, as we will only be dealing with small parts for this project.*



Fig. 1: Example setup. Will be holding the camera to the hot plate for initial testing; once the optimal angle is figured out we will design a mounting to hold it in place.

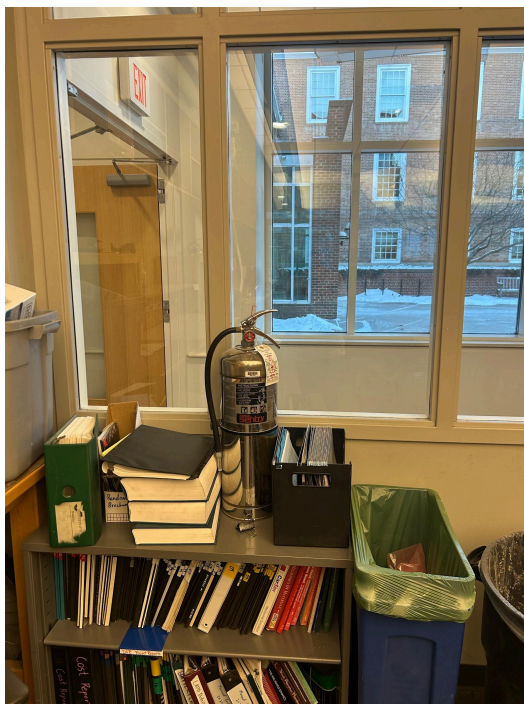


Figure 2: Location of nearest fire extinguisher in the lab

Appendix 5: Electrical Schematic

