Cook Engineering Design Center at Dartmouth

Final Report

Submitted in partial fulfillment of the requirements for

Engineering Design Methodology and Project Initiation

Pulse Electrothermal De-icing Air Source Heat Pumps for More Efficient Residential Renewable Energy Systems

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Sponsored by

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Project 06-709

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Relevant Acronyms and Units

AHU – Air Handling Unit

ASHP — Air Source Heat Pump

ASHRAE—American Society of Heating, Refrigerating, and Air-Conditioning Engineers

AVR - Automatic Voltage Regulator

AWG — American Wire Gauge

BTU — British Thermal Unit

CoP — Coefficient of Performance

CRREL — Cold Regions Research and Engineering Laboratory

ENGS — Engineering Sciences

EPA — Environmental Protection Agency

FTC — Federal Trade Commission

GFCI — Ground Fault Circuit Interrupter

GSHP — Ground Source Heat Pump

HDD — Heating Degree Days

HGBP — Hot Gas Bypass

HSPF — Heating Seasonal Performance Factor

HVAC — Heating, Ventilation and Cooling

IPC — Institute of Printed Circuits

MCU — Microcontroller Unit

OAT — Outdoor Ambient Temperature

ODU — Outdoor Unit

PETD — Pulse Electrothermal-De-icing

PSU — Power Supply Unit

RCD — Reverse Cycle Defrost

TPI — Teeth per Inch

Wh — Watt-Hours

Non-Confidential Abstract

Air source heat pumps (ASHPs) are increasingly being adopted as energy-efficient alternatives to traditional oil and gas furnaces for heating and cooling homes. However, in colder climates, these systems often face significant challenges due to frequent icing on the outdoor condenser fins during winter months. This icing condition drastically hinders performance by reducing efficiency, leading to higher energy consumption and increased operational costs. In the most common conventional defrosting method, the reversing valve sends refrigerant from the indoor space to the outdoor unit to melt the ice, effectively cooling the room. This defrosting process is both energy intensive and intermittently disruptive to heating functionality. To address this fundamental issue, the integration of the patented pulse electrothermal de-icing (PETD) technology into ASHP systems is explored. In this potential novel application, PETD technology efficiently removes ice and frost buildup through a series of high power pulses sent directly to the condenser fin system. This project analyzes the feasibility of advanced PETD and ASHP integration, with the potential for improved efficiency and lengthened operational lifespan for the ASHP unit, by reducing the mechanical stress caused by ice buildup. This advanced deicing solution demonstrates the potential for novel improvements to the reliability and performance of ASHPs, making them a more viable option for residential heating in regions with harsh winter conditions. The results ultimately highlight the need for further research into the potential of PETD and ASHP integration in overcoming environmental challenges and advancing efficient HVAC systems in our uncertain energy future.

Executive Summary

Air source heat pumps (ASHPs) play a crucial role in reducing carbon emissions from residential heating. Heat pumps can cut household carbon emissions by 36 to 64 percent, or a staggering 2.5 to 4.4 metric tons of CO_2 per household per year, as compared to conventional furnaces and boilers. For context, 2.5 tons of CO_2 is equivalent to not driving for half a year, and 4.4 metric tons of CO_2 approaches the emissions from a roundtrip flight from New York City to Tokyo [5]. In the face of global geopolitics jeopardizing incumbent heating technologies, efficient heating systems like ASHPs provide a means for people to heat their homes reliably and comfortably. Currently, one of the greatest barriers to adoption of ASHPs is their performance in cold climates. In freezing conditions, ice and frost buildup on the outdoor unit and significantly reduce efficiency, necessitating a reversing cycle to melt the ice and defrost the unit [16]. On the coldest days, less efficient auxiliary heating is needed to supplement the heating losses.

To address inefficiencies of ASHPs under icing conditions in cold climates, our team studied the integration of the highly efficient pulse electrothermal de-icing technology (PETD) into next-generation cold climate ASHPs. Through this potential novel application of the PETD technology [12], invented, developed, and tested at the Thayer School of Engineering, we can theoretically directly target frost accumulation on the heat exchanger. Using short, high-power electric pulses to rapidly break down ice with minimal disruption to the heating process, PETD integration has shown the potential to cut defrosting energy requirements by up to 20% which could remove the need for supplemental heating systems entirely, improving efficiency.

In order to assess the effectiveness of our integrated PETD, ASHP solution, our team has conducted a comparative analysis of energy consumption of a fluid loop prototype and a standard ASHP operating with the reversing cycle defrost (RCD) system. This evaluation provides critical insights into the potential benefits of this new approach to ASHPs. The findings will serve as a foundation for potentially scaling the technology to full ASHP systems, optimizing their design for improved performance, and advancing their adoption in cold-climate applications where efficiency and reliability are held paramount.

Overview

Problem Statement and Significance

Air source heat pumps are a critical technology in residential heating decarbonization. As fossil fuel-based heating systems become less viable and more expensive, a more effective approach to de-icing has the potential to expand the reach of affordable, reliable, and renewable heating solutions for cold climate homeowners. The widespread adoption of ASHPs promises to expedite the global transition towards sustainable and reliable energy systems, particularly in the face of threats to traditional gas and oil access. ASHPs can operate in heating or cooling mode, however, for the purposes of this project, we only focus on the heating mode. ASHP heating operates by extracting heat energy from outdoor air and transferring that energy indoors. This process is made possible by a compressor that circulates refrigerant and ensures that refrigerant is colder than the ambient air when in the outside coil, and hotter than the ambient air when in the inside coil [14]. However, at sub-freezing temperatures and relatively high humidity conditions, ice and frost can accumulate on the outdoor evaporator coils, drastically reducing efficiency. In the most common de-icing method, the reverse cycle defrost (RCD), a reversing valve reverses the flow of refrigerant to draw heat from indoors to melt the ice. This conventional method of deicing does not require a lot of additional electrical energy input, but it interrupts heating and cools the indoor space instead of continually heating it [15]. Further, ice accumulation may accelerate wear or damage over the course of an ASHP's life. The idea: integrate high efficiency pulse electrothermal de-icing technology (PETD) into ASHPs in order to optimize de-icing performance and improve overall efficiency. Our team's analysis aimed to evaluate the merit of this integration and its potential to influence the adoption of cold climate ASHPs worldwide, ideally leading to a transformation in the decarbonization of energy systems across the globe. See the image below for full details on how an ASHP functions.

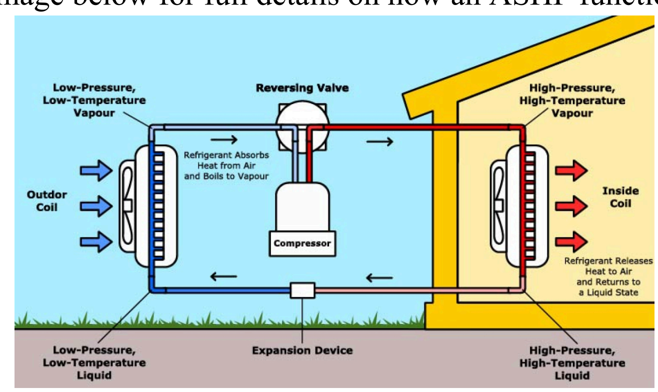


Figure 1: Diagram of an Air Source Heat Pump from the US Department of Energy that shows how in the colder months, cold air is brought in from the outside, and circulates through the compressor with refrigerant, to then pump warm air into the home. The reversing valve that controls how frequently the defrost cycle takes place is detailed as well.

Introduction to PETD

Pulse electrothermal de-icing technology uses high power, short pulses, to more efficiently melt ice. The patent includes an array of different applications of the tech. Depending on how it's used, PETD can remove ice, prevent ice formation, and both increase and decrease ice-surface adhesion. The technology was developed by Petrenko and his team — including our sponsor, John Chen — who worked in the Thayer Ice Lab in 2011 [18]. The technology is based on their research into ice theory which concluded that ice's stickiness is due to its charged surface, which induces an opposite charge on the surface to which it adheres. This creates tendril-like connections, which explain ice's strong adhesion to a variety of surfaces. PETD functions by melting the interfacial ice layer with the electric pulses, creating a thin film of water, and causing the ice to fall with the help of gravity. It's important to note that this technology is typically only implemented on surfaces that are flat and smooth. ASHP condenser coils are an unusual and novelty application because they do not have this expected surface type. PETD technology, per its patent, can directly be applied to de-ice airplanes, power lines, windshields, ships, cars, trucks, offshore wind structures, roads, bridges, ski lifts, roofs, freezers, and more. Our project, again, aimed to potentially add ASHPs to that list by evaluating the merit of integrating PETD into the coils. Figure 2 demonstrates our testing set up with an actual ASHP coil fluid loop.

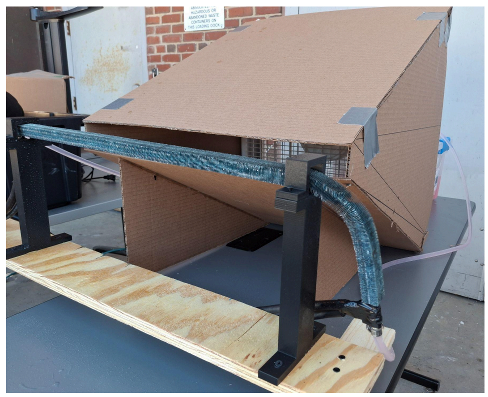


Figure 2: Image of coil testing set up on an ASHP coil with PETD integration (as a peak on what is to come with our PETD and ASHP integration)

Sponsor Goals

Our project sponsor's long-term goal is to develop the integration of ASHPs and PETD technology for eventual widespread, global adoption. His vision for our group was to make headway on this long-term goal by fabricating prototypes, running rigorous experiments, collecting data, and analyzing efficiency discrepancies between control and experimental test results. Our team has now reported back all data recovered during our research process and delivered all research materials, prototypes, and test apparati back to our sponsor. Our team ultimately did not reach full ASHP and PETD integration for deicing capabilities, given safety and resource constraints. However, we have been able to successfully provide crucial insights and data that can inform our sponsor's future work and potential improvements in PETD and ASHP integration.

Project Specifications

In the beginning during ENGS 89 our team identified key project specifications based on communication with our sponsor and understanding his goals, and our advising team. We updated the specifications matrix seen below to visualize these goals given all data learned throughout ENGS 89 as we began implementing our testing procedures in ENGS 90.

Specifications	Justification	Metrics of Success
Efficient	Current market leading cold weather ASHPs are inefficient at sub-freezing ambient temperatures	Coefficient of Performance (CoP) and energy consumption (kWh) of defrost
Safe	Exposure to natural elements, animals, and homeowners or home residents	Acceptably low exposed voltage, isolated high voltage
Durable	Replacements are costly, and areas may have limited access to maintenance and repair	Thermal, environmental and corrosion testing
Affordable	Encourage homeowners in cold climates to install new ASHPs	Production and installation cost estimation
Legal	Compliance with electrical and refrigerant laws	Local Laws and EPA Regulations
Quiet	Comfortable audible sound level	Decibels (Db) and Location

Table 1: Specifications Matrix

These specifications address key performance and operational priorities, ensuring the system meets the diverse needs of users while complying with industry standards. Efficiency is a primary concern, as current market-leading cold-weather ASHPs struggle with performance at freezing temperatures. This is measured through the Coefficient of Performance (CoP) and the energy consumption of the defrost cycle. Safety considerations address exposure risks to elements, animals, and homeowners by maintaining acceptably low exposed voltage and isolating high-voltage components. Durability is essential to minimize costly replacements and ensure reliability in areas with limited access to maintenance and repair. This can only be evaluated through longer term testing. Affordability is another key factor, encouraging homeowners in cold climates to adopt ASHP technology, with a goal to keep production and installation costs as low as feasibly possible. Compliance with legal regulations, including local electrical and refrigerant laws, ensures adherence to EPA standards. Finally, noise levels are considered to maintain a comfortable and acceptable sound profile, measured in decibels (dB) based on location. These specifications collectively ensure that the system meets user needs while maintaining efficiency, safety, durability, affordability, legal compliance, and comfort.

Methodology of Approach

Our team adopted a parallel design strategy to tackle this project, which was divided into two key components: control testing and prototype testing. The control testing approach focused on monitoring ASHP performance in normal operation and deicing operation, as well as velocity profiling. The prototype development and testing approach involved both electrical and fluid system design and testing. Our team's "divide and conquer" approach not only streamlined our workflow, but also enabled us to achieve dual outcomes in parallel efficiently. This approach proved highly effective for productivity and research outcomes. See the diagram below for a visual representation of how we split the work.

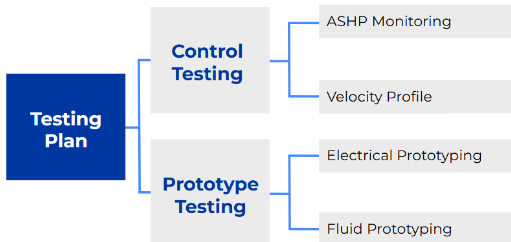


Figure 3: Testing plan visualization of project breakdown

Control Testing

The first step in initiating control testing was selecting a location for ASHP installation. Given current construction and constraints on undergraduate work in the Dartmouth Ice Lab, our team was offered the testing space of the back of the Fluids Lab, C003A. Ensuring access to this space required consultation with Associate Director of Facilities Dave McDevitt and Engineering Lab Instructor Raina White, of the Fluid Mechanics department. The next step was locating and securing equipment to perform the control testing on. This involved the installation of an ASHP unit at Thayer. Sponsor John Chen generously provided the Mitsubishi Fujitsu Hyper Heat 220V for the team's use in ENGS 90. The indoor air-handling unit (AHU) model number is ASUG09LZBS and the outdoor unit (ODU) model number is AOUG09LZAH1.

In terms of installation, our group has emphasized the importance of installing under the jurisdiction of Thayer-affiliated HVAC Certified Technicians. Only these designated parties were able to work with refrigerants in this project. This was an important agreement for environmental safety and EPA compliance. In order to ensure adequate installation in the back storage room of the Fluids Lab, we had to configure a mounting system for the indoor unit to stand, involving proper weighting and a series of 4x8 plywood and 2x4 boards. This work was largely supported by Thayer's Associate Director of Facilities Dave McDevitt and Director of Facilities Planning and Operations Jonathan Stark, who also installed the Eyedro Home Energy Monitor we would be using for extracting the essential energy consumption measurement that led us to our final assessment of ASHP reverse cycle deicing efficiency.

Following installation, we were able to begin honing our monitoring set up. In our final data collection setup, we used two impeller anemometers to measure inlet and outlet airflow on outdoor and indoor units, four exposed thermistors to measure direct inlet and outlet temperature on indoor and outdoor units as well as indoor and outdoor ambient temperature (75 cm away from the inlet in both cases), and one relative humidity sensor to measure the humidity at the outdoor unit inlet. We used a LabQuest and a LabQuest2 [11] to collect data, and used the LoggerPro application to visualize the data in post. Additionally we made use of an Eyedro Home unit installed on the spider box to measure the kW that the ASHP unit pulled during operation. We based the scrutiny of our testing set up on advice from various advisors including our sponsor John Chen, Alexa Freitas from Trane Technologies and Cheng Chen - an industry specialist and former ice lab researcher. We also compared our testing set up to that of a similar testing operation done by the National Renewable Energy Laboratory of the U.S. Department of Energy [5]. In this study they provide a consistent methodology for performance measurement of

ASHPs when installed in a building [5]. This allows us to ensure our testing set up meets the rigor of standard ASHP monitoring.

Velocity Profile

In addition to monitoring the ASHP (discussed in the following section), we developed a detailed velocity profile for the outlet of the indoor unit to comprehensively analyze the airflow distribution across it. This allowed us to precisely determine the cubic feet per minute (CFM) of the unit, a critical metric for evaluating system performance. The decision to create this velocity profile was driven by recommendations from several advisors, who emphasized the significance of CFM in understanding the overall operation of the AHU and allowing a single point flow anemometer to be used as the sole measurement point on the outlet. By undertaking this approach, we ensured the reliability and precision of our measurements, ultimately enhancing the overall accuracy of our performance assessments for the control test.

To understand the velocity profile, we began by creating a rectangular ductwork to encapsulate the entire outlet of the indoor unit. This ductwork helps create a more uniform velocity profile by minimizing turbulence, and eddies because there are no corners between the length of the outlet and the end of the duct. This provides smooth transitions, and ensures that air is distributed evenly across the width of the duct. While it may not create a perfectly uniform velocity profile (due to factors such as friction at the walls), our well-designed ductwork significantly improves the uniformity of airflow. It should also be noted that as air moves through a straight duct, the velocity near the walls slows down due to friction, while the center remains faster, but over a sufficient length, the velocity profile can become more fully developed, which is more predictable and easy to understand.

After building our duct work we took seven velocity measurements five inches apart across the bottom of the duct (25 in down from the outlet). See Figure 4 for details.

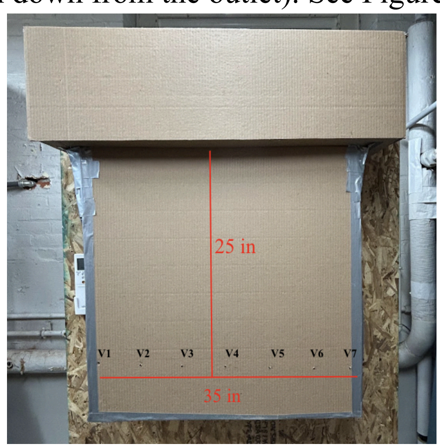


Figure 4: Velocity Profile duct work created with an internal volume of 7.07 ft³, air sealed with several layers of hot glue, super glue and duct time on all connection points of the various sections of cardboard

We took these velocities with the Kanomax Anemomaster 6036 [10], a professional HVAC level anemometer and allowed us to get down to two decimal places which is rigorous enough for our testing needs at this stage (SOURCE: Kanomax). We then took these seven velocity measurements and averaged them out and got an average velocity across the outlet of 0.1614 m/s (see appendix for the velocity at each of the 7 points). This then leads us to calculate the CFM of the outlet. We took the product of the known volume of the duct work and the average velocity to get a CFM of 224.61. This value aligns with the expected values for our

Mitsubishi Hyper Heat pump model, based on a heating mode range of 206 to 542, given by the submittal sheet (recreated in Table 2). Therefore, we know we can verify we are operating at a typical airflow rate most likely in the range of low to quiet mode.

<table>
<tr><th colspan="5">Fujitsu Inverter Driven Heat Pump</th></tr>
<tr><th colspan="5">9,000 BTU Single Zone High SEER Wall Mounted System</th></tr>
<tr><th colspan="5">Fan Data</th></tr>
<tr><td rowspan="8">Indoor Unit Airflow Rate</td><td rowspan="4">Cooling</td><td>High</td><td rowspan="10">CFM [m³/h]</td><td>542 (920)</td></tr>
<tr><td>Medium</td><td>406 (690)</td></tr>
<tr><td>Low</td><td>312 (530)</td></tr>
<tr><td>Quiet</td><td>206 (350)</td></tr>
<tr><td rowspan="4">Heating</td><td>High</td><td>542 (920)</td></tr>
<tr><td>Medium</td><td>406 (690)</td></tr>
<tr><td>Low</td><td>312 (530)</td></tr>
<tr><td>Quiet</td><td>206 (350)</td></tr>
<tr><td rowspan="2">Outdoor Unit Airflow Rate</td><td colspan="2">Cooling</td><td>1089 (1850)</td></tr>
<tr><td colspan="2">Heating</td><td>1089 (1,850)</td></tr>
</table>

Table 2: 09LZASH1 Submittal Sheet CFM Values

ASHP Operation Monitoring

After ASHP installation we ran into a few different challenges before landing on our final testing set-up. One of the first challenges was the fact that C003A was a very hot room to begin with. We discussed this barrier to operation with Associate Director of Facilities Dave McDevitt, and were granted permission to open the window in the room during testing. This solution allowed for the room to cool down, and the heat pump to operate effectively to warm the room up. In a perfect testing setup, we would have climate controlled conditions in which the room was at the same cold starting temperature for all testing. Based on our research into heat pump testing, this initial ambient temperature should be around 60°F [4], however given that we had a lack of control and only could use whatever was the outdoor ambient temperature on a given day this specification was largely uncontrolled during our testing. In our limited scope, we focused on keeping a consistent set point of 75 °F. We based this consistent set point on advice from ice lab research advisor Chen Cheng who discussed with us the ways in which industry standard ASHP monitoring tests are conducted. Another challenge we came across was the LabQuests were only rated to operate down to freezing (32°F) [11] and many of the days we tested were below this temperature which led to the outdoor LabQuest freezing and malfunctioning. To combat this issue we purchased a roll of premium duct insulation, with an R value of 6.0, and fashioned a sleeve for the LabQuest to be inside of on the ODU while we conducted our testing. This allowed for the LabQuest to operate longer tests, in colder temperatures, and ensure consistent data collection with no electronic breakdowns.

After iterating through a few different set up methods we landed on our standard control testing set up as seen in the images below (Figures 5-7). We included a thermistor on the fins directly, an ambient temperature 75 cm away and an inlet fan speed anemometer on the ODU. On the AHU we had a similar setup with a single point anemometer and a thermistor directly at the outlet, as well as a thermistor 75 cm away from the outlet for ambient temperature. This setup allowed us to gather all the necessary data to understand the operation of the ASHP on cold days.

Figure 5: (Left) Coil side of the ODU showing the temperature sensor directly on the fins of the unit, also on top is the insulated packaging we designed for the LabQuest2 to keep it from malfunctioning in the cold weather
Figure 6: (Right) Front side of the ODU with anemometer on front fan, and the ambient temperature sensor 75 cm away from the outlet

Figure 7: The indoor set up of the AHU featuring the ambient temperature sensor 75 cm away, the outlet anemometer and outlet temperature directly at the outlet fan of the unit, additionally showing the LabQuest used to store and log the data

A crucial challenge we faced was determining how to force a defrost cycle to run. We learned from industry expert Alexa Freitas from Trane Technologies that this Mitsubishi unit has the ability to run what is known as a partial defrost cycle. In standard operation, 100% of the hot gas is directed towards the air handling unit (AHU) to keep the space warmed, as the outdoor unit (ODU) is not under de-icing conditions. In a full, reverse defrost cycle, 100% of the hot gas is directed to the ODU to focus on de-icing the outdoor coil. In preparation for the reverse defrost, the system purposely heats up the zone a degree or two above the set point. Once the process starts, the AHU ceases operation until the reverse defrost cycle is complete, effectively cooling down the space. In a partial defrost, or hot gas defrost, 50% of the hot gas is directed to the AHU for continued operation but the other 50% of hot gas travels to ODU. This dual action allows the AHU to continue keeping the space warm, albeit under decreased fan speed and output, while the OCU de-ices. From this testing we were able to monitor the ASHP in standard operation, full defrost cycles, and partial defrost.

This nuance involving the partial defrost cycle was an outcome of troubleshooting our testing set-up, conversing with Cheng Chen of the Thayer Ice Lab, and Alexa Freitas, of Trane Technologies. Alexa provided us with a diagram, which we recreated below (Figure 8), following our conversation regarding the partial defrost, or hot gas defrost cycle, which was a helpful visualization of the process as we developed our understanding of it.

Single Module	Reverse Defrost		Hot Gas Defrost	No Defrost	
Multiple Modules	Reverse Defrost	Hot Gas Defrost			
	23°F	34-36°F		41°F	Ambient WB

Figure 8: N-Generation Defrost (Source: Alexa Freitas, Trane Technologies). Our model is a single module so this reveals that the most common reverse defrost is from 20-40 °F

In order to ensure adequate data collection for each mode of operation, it was necessary to come to an understanding on the sequence of operations for each mode, and the requirements that must be met for the control system to signal mode initiation. For standard heating mode, or no defrost, the system waits for a minimum of ten seconds before energizing the compressor. Depending on the outside ambient temperature (OAT), it will then modulate the compressor speed between 20~22 Hz, or 20~48 Hz for the first three minutes of operation; and between 20~48 Hz, or 20~70 Hz for the next seven minutes of operation. We have observed that given an OAT was regularly below freezing during our testing, the compressor speed was regularly on the higher end of the provided range. After approximately ten minutes of operation, the compressor speed will modulate between 20~125 Hz based on demand, and stop when there is no longer a call for heating [17]. See Figure 9 for details.

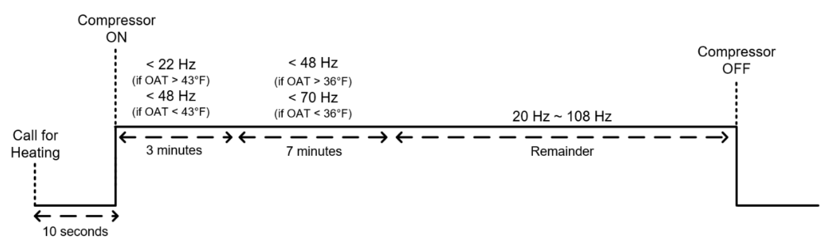


Figure 9: Mitsubishi Heat Pump Heating Standard Mode Overview

For standard ASHP operation we collected data over the course of multiple tests ranging from one to three hours in length. Below are some examples of standard operation data we collected during the testing periods.

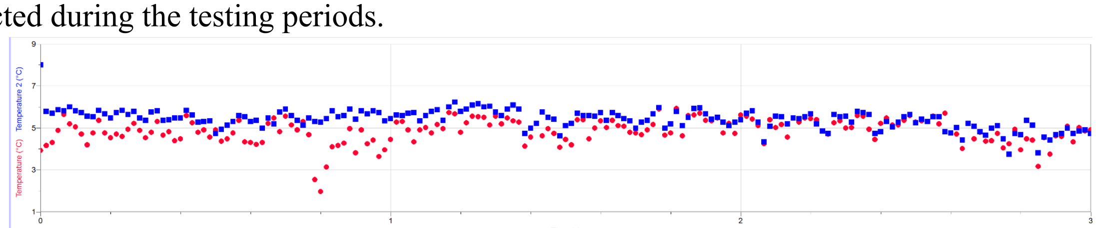


Figure 10: Outdoor Unit (ODU) operation over a 3-hour testing period, the red line (T1) is the temperature at the inlet, directly on the fins in ℃, while the blue line (T2) is the ambient temperature outdoors at 75 cm away from the inlet in ℃

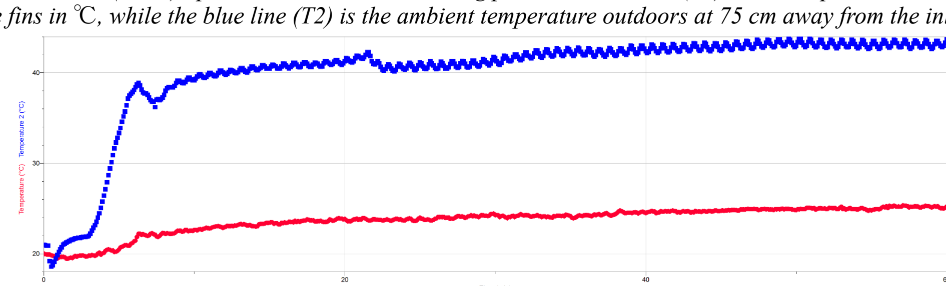


Figure 11: Indoor Unit (AHU) operation over the same 3-hour testing period as in Figure 10, the red line (T1) is the ambient temperature outdoors at 75 cm away from the outlet in ℃ , while the blue line (T2) is the temperature directly at the outlet in ℃

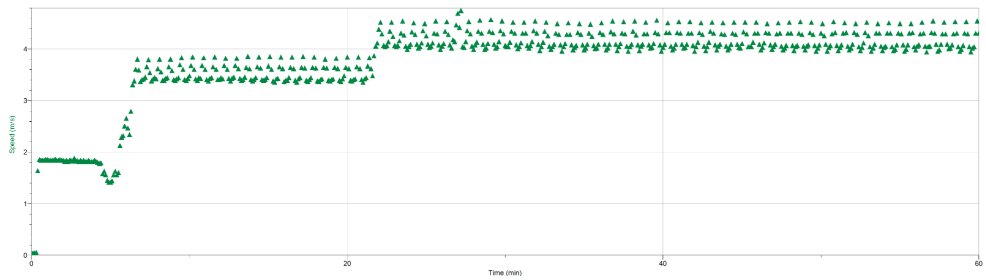


Figure 12: Indoor Unit (AHU) operation over the same 3-hour testing period as in Figure 10 and Figure 11, the green line is the fan speed directly from the outlet in m/s

From the above graphs we can see that in standard operation the ODU fin and ambient temperature (Figure 10) rarely divulge from one another, and are fairly consistent. This consistent parallel between the two leads to no defrost, partial or full) during this three hour period. Additionally, the AHU is able to easily and efficiently ramp up to the set temperature (Figure 11, blue line), and the only reason that the ambient temperature (red line) never quite gets up to the outlet temperature is because the window in C003A is open which forced the heat pump to work continually by keeping the ambient temperature cool. Finally, in the bottom graph (Figure 12) there is a direct correlation between the temperature of the air being blown and the fan speed, such that the hotter the air being blown the harder (faster) the fan is going, which makes intuitive sense. All this is what was expected for standard operation of the ASHP.

The Mitsubishi defrost mode will kick in whenever frost is detected on the ODU heat exchanger, and will return to standard heating mode after 15 minutes of defrost operation, or all defrost conditions have been met. These conditions include when the temperature of the liquid pipe at the ODU is less than or equal to the balance point of 28℉ for seven minutes for light frost, and less than or equal to 23℉ for 3 minutes for heavy frost [21]. Otherwise, if the compressor has been operating for at least 20 minutes, the defrost operation will initiate, the controller command cannot cancel this operation, and indoor unit function settings are locked until the defrost is complete.

We struggled for a few weeks to get the ASHP to run a full defrost cycle. We tried various methods including misting with a spray bottle, placing snow on the coil and a mixture of the two. Ultimately, a winter storm provided the ideal icing conditions for a defrost cycle. The image below shows the natural build up of frost and ice.

Figure 13: Ice and frost build up on the outdoor ASHP coils after a winter snow storm

After carefully monitoring the ASHP over several testing periods we were able to actively see a full defrost cycle occur. This occurred after the ASHP had been running for three consecutive hours with an OAT of 30℉, with the AHU set to run at 75℉. For the duration of the defrost cycle the AHU closed the fan and emitted no warm air into the room. The entire full defrost cycle took 9:05:04 minutes, and used a total of 0.0748 kWh of power (see Figure 14 below for the total power usage over the duration of the defrost).

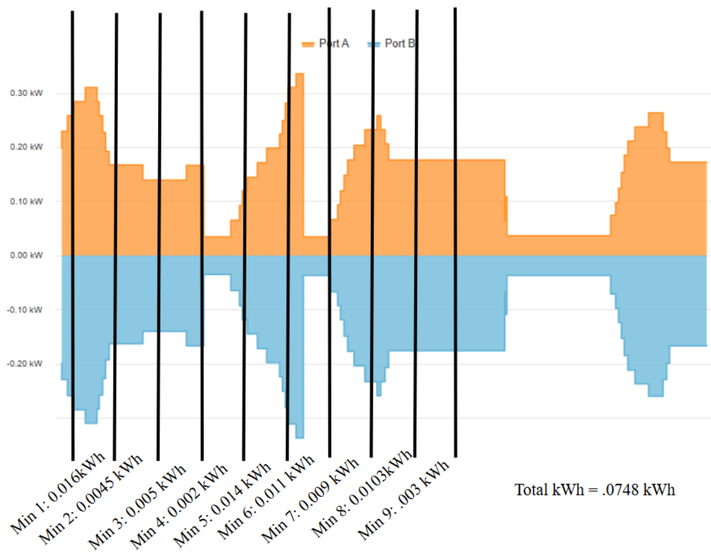


Figure 14: Eyedro Home from the full defrost cycle, showing the breakup of the kWh usage over the 9:05:04 minutes according to the Eyedro Home user interface

In addition to the full defrost as discussed above we were able to use our sensors to pick up on partial defrost cycles that occurred but were not directly announced by the indicator light on the AHU. Seen below are some example graphs of a partial defrost cycle occurring and the temperature fluctuations that come with that.

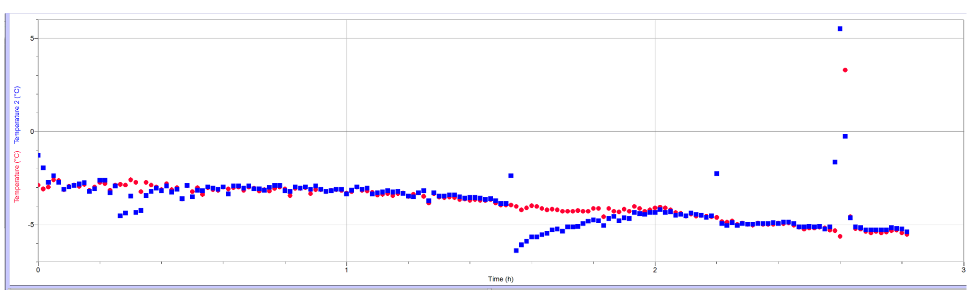


Figure 15: Outdoor Unit (ODU) operation over a 3-hour testing period, the red line (T1) is the ambient temperature outdoors at 75 cm away from the inlet in ℃, while the blue line (T2) is the temperature at the inlet, directly on the fins in ℃, the time from 1 hour 36 minutes to 1 hour 40 minutes represent the time where the fin temperature dropped low enough below the ambient to necessitate a partial defrost cycle

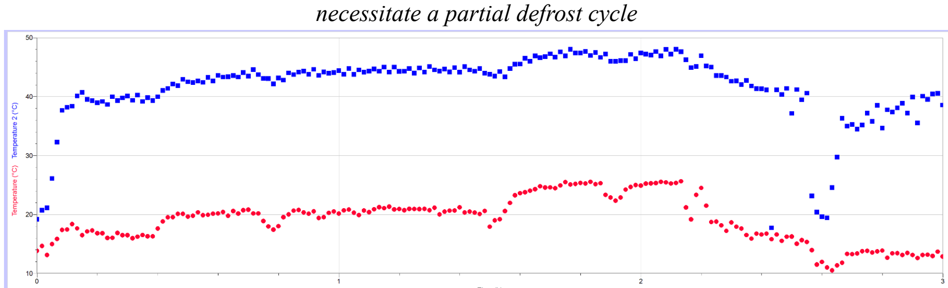


Figure 16: Indoor Unit (AHU) operation over the same 3-hour testing period as in Figure 15, the red line (T1) is the ambient temperature outdoors at 75 cm away from the outlet in ℃ , while the blue line (T2) is the temperature directly at the outlet in ℃, the same time from 1 hour 36 minutes to 1 hour 40 minutes that reveals when the fin temperature dropped low enough below the ambient to necessitate a partial defrost cycle show only a mild dip in AHU output temperature that is immediately overcorrected

As seen in the graphs above (Figures 15 and 16) we were able to accurately identify these partial defrost cycles using the thermistors on the ODU and the outlet thermistor on the AHU. This partial defrost cycle only took around four minutes and used about 0.0367 kWh. This data for the partial defrost makes sense given that it is about half of what is seen for the full defrost cycle.

Our control testing provided valuable insights into the performance of a highly efficient cold climate ASHP during winter in a cold region. By monitoring the system across different conditions, we gathered detailed data on its behavior in all three operating modes: standard operation, partial defrost, and full frost. Tracking these modes allowed us to analyze how the ASHP responds to varying levels of frost buildup and defrost cycles, which are critical to maintaining efficiency and reliability in extreme temperatures. The collected data enabled us to perform in-depth calculations under real-world conditions. These calculations formed the basis for comparative analysis against expected performance benchmarks, helping us assess the ASHP’s overall effectiveness. The results of this analysis are particularly important to our sponsor, as they provide key performance metrics that inform potential improvements for future testing operations. For a detailed breakdown of our findings and final data analysis, refer to the section on deliverables.

Prototype Design

Our prototyping had many stages, only some of which were ultimately included in our final testing. Ensuring safety throughout the term, in accordance with our agreed upon team safety plan and work guidelines, was essential. The first goal was to design a power regulating unit that could adequately handle all operations and isolate high voltage from low voltage, in order to avoid human contact with that system. Ultimately, given the scope of the term, our team opted for a standard variac that allowed us to easily adjust both voltage and time for the power applied to our coil prototypes. In tandem with the electrical design, our team created a fluid loop and cooling system to ensure our prototype would reliably frost and build up ice. All of these iterations and designs will be discussed in the following sections.

Transformer Characterization

Figure 17: Transformer with quick slide connectors attached to all six primary leads to allow for easy and quick changes in secondary voltage outputs

In order to thoroughly characterize the transformer that was provided by our sponsor, we measured the inductances and resistances of each set of leads, primary and secondary, as well real world voltage transfer from each of the 15 combinations of primary leads — as can be seen with yellow slide connectors — to the secondary side. Much of the safety concern with electrical isolation was because this transformer was not professionally built or tested, and did not come with a datasheet. Ideally, we would have been able to conduct a HiPot test in order to see the resilience of the electrical insulation inside the transformer as well. However, since this was not possible due to time and expense restraints, we proceeded with extreme caution, starting at a much lower voltage than we knew this transformer was designed to withstand. We also added an insulated variac in order to have a proven layer of isolation and a ground safety line, as will be further detailed in the design safety section. Finally, we soldered new wires and attached the yellow slide connectors for easy, safe, and quick changes in primary side inputs. Thoroughly evaluating this transformer was a vital step in order to be able to test at the power we needed while maintaining a safe working environment for our team.

Power Supply Design

After disassembling the Thayer Ice Lab provided power supply from the initial PETD tests, we were immediately concerned with the non-isolated AC-to-DC converter. There was no separation between the high-voltage (HV) and low-voltage (LV) sections. In consultation with Professor Sullivan, we decided to create our own, safer PSU. According to modern standards for switching AC with triacs—a type of semiconductor switch—the safest approach is to use a microcontroller to control the triac via an optocoupler. This setup ensures complete isolation between HV and LV. This isolation is crucial for preventing surges and ensuring the continued safe operation.

After creating a mockup of the control circuit, the next step was selecting components. Starting with the triac, we chose the Q6025LH5TP due to its 25A, 600V rating and isolated tab which allows for safe heatsink mounting. RC snubber circuits are typically used with inductive loads like ours, but the datasheet for this alternistor triac indicates that one is not required. We initially planned for the PSU to handle a ~4kW load at 16A and 220V AC, so a heatsink was necessary. For the optocoupler, which transfers electrical signals between isolated circuits using light, we selected the MOC3062: this industry-standard component offers high isolation, and zero-cross switching. The ATmega328P was chosen as the MCU since our team had the most experience programming AVR devices. A DC fan was included in the design to provide ventilation across the heatsink. The final schematic is shown below.

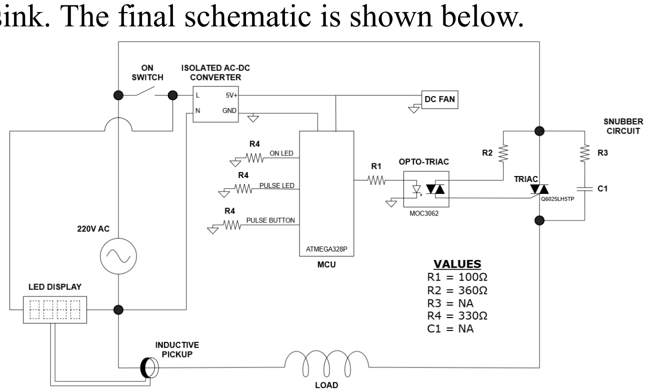


Figure 18: Using values from the datasheets, we calculated estimates for R1, R2, R4, and max thermal resistance Rth. To understand how the values were calculated, see the attached work in the appendix which uses values from component datasheets

The next step was to test the circuit to verify its operation and begin designing a PCB. Upon receiving the parts, we tested the circuit on a breadboard using a sine wave with a 10V peak voltage. The test was successful, as shown in the oscilloscope capture below.

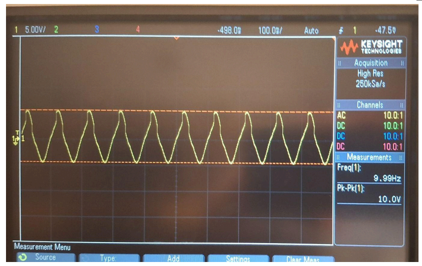


Figure 19: Triac output of 10V peak sine wave. Due to the inherent nature of a triac's operation, the sine wave can become slightly distorted which has no significant impact on the load

With the circuit verified, we moved on to designing the PCB for manufacturing. This stage involved revisions to ensure compliance with strict safety standards. To avoid dealing with high current traces up to 16A, the triac was removed from the board and mounted directly onto the heatsink. Another key concern was high-voltage clearance. According to IPC (Institute of Printed Circuits) guidelines, 240V AC mains require 2.3mm clearance and 3.2mm creepage. The final design exceeded these requirements. The board layout designated the left side for low voltage (LV) and the right side for high voltage (HV). The board housed the isolated converter and a 2A fuse. The final design is shown below.

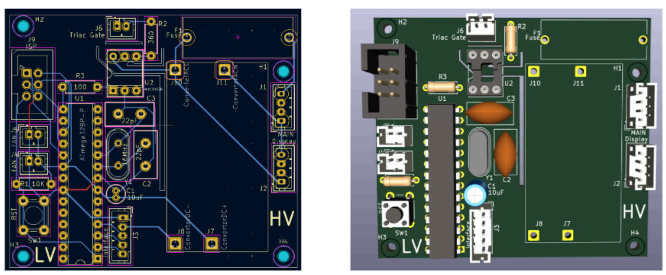


Figure 20: A final design of the PCB for the PSU, containing a barebones atmega328p on the left, an isp programmer, an optocoupler dip holder, location for a fuse (top right), location for the isolated converter (middle right), and several JST connectors. A Link to the KICAD files can be found in the appendix.

The final element of the PSU design was housing the electronics. We aimed to create something robust, portable, and compact. A SolidWorks thermal study of the heatsink and triac operation was done to ensure no overheating. The model can be seen below.

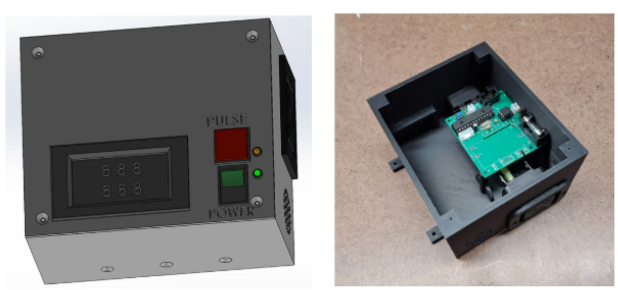


Figure 21: The first housing design for the PSU on the left, and the initial stages of assembling the housing, PCB, and other components on the right. A Link to all CAD files and demonstration videos can be found in the appendix

Although the PSU was nearly complete, concerns remained about its readiness. To assess the feasibility of producing our own, we consulted several faculty advisors who suggested we use an isolated variac — an adjustable transformer used to gradually introduce power with variable voltage. Initially skeptical due to its 130V AC limit — we originally planned to use 220V AC — we adapted by testing smaller copper pipe iterations. This shift led us to set aside the custom PSU in favor of the variac's flexibility, isolation, and availability.

Design Safety Considerations

Our team made two big safety additions in our electrical design to get around the unknowns of our transformer. These were in addition to the integrated ground fault circuit interrupter on the outlet we used. The first — the choice to use a variac — had two main drivers: the ability to easily and safely pick voltage and switch power on and off and the proven isolation of the coil. The transformer provided to us by our sponsor was one designed, built, and used by a previous Dartmouth professor and his team, so we had faith that it would work, but we were not confident it would hold up to modern safety standards. The biggest concern with this was the possibility of electrical breakdown between the primary and secondary leads of the transformer. If this breakdown were to occur, whichever voltage put on the primary side — ie up to 208 V — would be exposed to the coil and thus to the operators. Implementing the variac provided a layer of proven isolation that, especially for initial testing, fully protected any users from high voltage.

The second big safety decision — to include a grounding safety route from the open coil circuit to the mains ground — added an additional layer to protect in case of transformer breakdown and someone touching the open coil. While this was somewhat redundant when running the variac output at 25-30V, it was a vital safety backup when we moved to testing higher voltages on the primary side of the transformer. This lead meant that if there was a short across our transformer, the current would divert through that cable to ground, rather than through any person who might accidentally touch the coil. It is important to note, though, that we did not rely on this, we tracked both voltage and current during data collection to alert us of any safety risk, we physically isolated our transformer, and we did not touch the coil during testing.

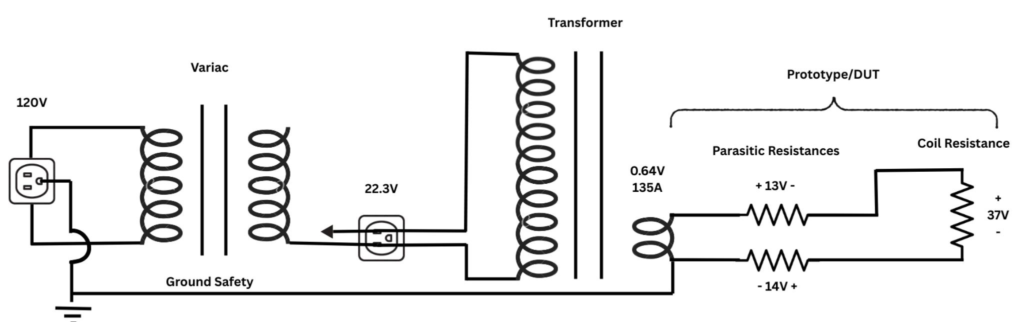


Figure 22: Full electrical circuit design of our testing setup. This includes the variac, our transformer, a ground safety line, and our actual device under test (DUT) modeled with 3 resistors. Values displayed here are the ones we used in our initial, single length test. These values vary with different tests.

Fluid Loop

Another significant portion of the prototype test was to figure out how we could get an evaporator coil cold enough to freeze water vapor in the air. Our first idea was to use Dartmouth's Ice Research Laboratory, an internationally recognized facility. Inconveniently, the location was inaccessible due to construction requiring us to search for alternatives. There was the prospect of partnering with CRREL in Hanover to test both portions of this project, but due to time and budget constraints, we were unable to fulfill this possibility. We were left to determine how to make the coil cold enough without fancy lab equipment. A preliminary thought was to use a fluid loop, like the refrigerant in an ASHP, but with less pressure. If we could keep the fluid temperature below freezing, it could keep the coil in a cold state to freeze the water vapor in the air. Now, there's a couple things to consider, like how can we keep the fluid cold enough, and where is the water vapor coming from. Well for starters, we considered liquid nitrogen but decided against it to reduce safety considerations. Instead, we planned to use ice and salt to keep the fluid below freezing. We initially used automotive antifreeze but later switched to 50/50 RV antifreeze to not require special disposing. A simple submersible pump would push the antifreeze through a silicone tube to the coil, through the coil, and then back to the bucket via another silicone tube. The fluid loop diagram can be seen below.

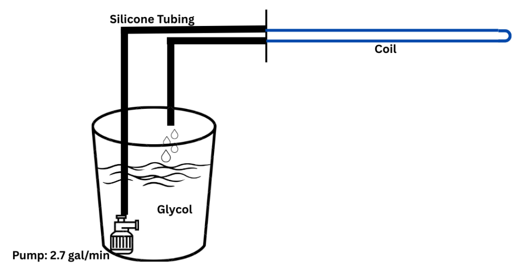


Figure 23: Fluid loop diagram. A simple submersible pump pushes the glycol, salt, ice mixture clockwise out of the container, through silicone tubing, through the coil DUT, and back through a return tube to the same container.

We conducted an initiatory test to prove we could frost the coil with the fluid loop. We used a spray bottle to introduce water vapor into the air, and waited a couple minutes. While this did not immediately freeze the coil, the simple addition of a fan was enough to cause water to freeze on the coil. Once this initial test was completed, we built a box fan tunnel to direct the fan's aireflow directly onto the coil. The full setup can be seen below. Following this, the team moved onto full prototype testing. During several tests, our mixture froze inside the copper pipe. This was most likely attributable to the mixture being too diluted or the switch we made from automotive antifreeze to non-toxic RV antifreeze. In order to combat this, we tried to keep the ice quantity to a minimum to control temperature and minimize end state dilution. Unfortunately, this was less consistent in cooling the coil and we became more reliant on the ambient temperature. The fluid loop with the fan tunnel did, however, provide adequate cooling ability to generate testable icing conditions in temperatures as high as 35ºF.

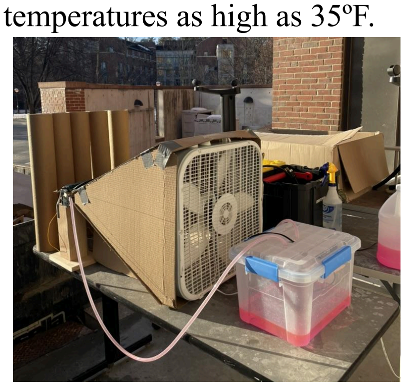


Figure 24: The full prototype testing setup in operation outside. The fluid loop is pumping RV antifreeze through the coil, while the fan is blowing onto the coil on the left. The transformer is inside the bin to maintain some degree of safety. The cardboard tubes were put in place to provide shade.

Implementations of Coil Prototype

The next step was the construction of the evaporator coil and electrical connections as detailed in Figure 22. We decided to keep the coil itself small and simple due to our time constraints. During October 2024, we tried 3 different methods of cutting the fins on the evaporator coil, ultimately deciding to use a bandsaw at low gear, with a blade speed of 3500 RPM and 10 TPI, as the most efficient way to make these cuts. We also found that aviation snips were the best tool to cut the stainless steel at the end of the coil. With this method, we were able to make several different prototype iterations.

We started our prototype planning by using one copper pipe stretching 0.762m. We estimated from previous research that the power density needed to deice each length of copper would be in the ballpark of $50W/m^2$. We also decided to start with a safe working voltage, under 35V, per Thayer guidelines, across the primary side of the transformer in case of electrical breakdown. We also used several smaller gauge wires, as opposed to one large gauge wire, to connect the secondary side of the transformer to the pipe for easy assembly and transport. Working backwards from power density and assuming around 1mΩ parasitic resistance per cable, we needed 135A through the secondary side of the transformer. By putting 22.3V out of the variac, we could generate 0.64V across the secondary leads, 0.37V across the coil itself, and the 50W. The details of each physical prototype, particular design and construction decisions, and the data from these will be detailed in the deliverables section of this report.

Deliverables

Control Test

The main deliverable of our control testing was determining the energy consumption of the Hyper Heat ASHP under standard heating mode and defrost mode and extracting a plausible efficiency metric for PETD and ASHP integration. The measurement of kWh used for the reverse cycle defrost can be directly compared to the kWh required to deice using PETD. This comparison will be evaluated in the combined analysis.

However, in order to determine the efficacy of our integrated PETD and ASHP solution, we needed to quantify efficiency of electricity input transferred to heating (or cooling) with CoP. In order to calculate CoP for ASHPs in heating mode, the useful heating output from the condenser (Q) is compared to the equivalent electric power input supplied to the compressor (W). The higher the CoP, the more efficient the system.

In terms of understanding the CoP we ran into a roadblock in the fact that the rated CoP on the submittal sheet for our unit states that the CoP is 18.2 (Table 3 recreated below for reference). This value of 18.2 seems far too high considering literature agrees that a standard ASHP unit has a CoP of 2-4, with cold climates ASHPs reaching 5 or 6 for their efforts in greater efficiency in those colder regions [20].

Electrical Specifications				
Voltage/Frequency/Phase				208/230V / 1Ø / 60Hz
Voltage Range				187-253V~60Hz
Current	Cooling	Rated	A	2.5
	Heating	Rated	A	3.3
Maximum Operating Current		Cooling	A	9.4
		Heating	A	11.9
Starting Current			A	3.3
MCA				14.4
Maximum Circuit Breaker				15
Input Power	Cooling	Rated	kW	0.5
		Min.-Max.	kW	0.11-0.85
	Heating	Rated	kW	0.66
		Min.-Max.	kW	0.17-1.93
Power Factor	Cooling		%	87
	Heating		%	87

Table 3: Electrical Specifications for the Mitsubishi Hyper Heat

We expected CoP to be between 3-6 for this Mitsubishi Hyper Heat Unit based on all previous research into ASHPs and conversations with industry experts. Due to this our first goal was to settle the discrepancy and understand this value. This led us to the calculations below.

$$\frac{12000\,\frac{BTU}{hW}}{\frac{0.66\,kW}{1000\,W}} = 18.2$$

Equation 1: We determined that the 18.2 CoP is from Fujitsu testers taking the given rated BTU/hW and dividing the rated input converted from kW to W, so the CoP appears to be in units of BTU/h, though unlabeled on the submittal sheet we read

$$\frac{12000\,\frac{BTU}{Wh}}{\frac{3.412\,\frac{BTU}{kWh}}{0.66\,kW * 1000\,W}} = 5.33$$

Equation 2: We decided to recalculate CoP given the information from the datasheet, this time using the conversion factor of 3.412 BTU/kWh to ensure the CoP was a unitless value, and got a new CoP for the unit of 5.33

This new calculated value of CoP from the submittal sheet makes more sense from our researched understanding and consultation with our advising team. We additionally wanted to calculate our own standard operation CoP to see how our testing set up and real world conditions lined up with the submittal sheet. From our Eyedro Home energy monitor, we estimate that a 3-hour running cycle on a 20℉ day uses about 0.85 kW of power, which is within the standard range for this unit. Using the same formula as before with the rated 12,000 BTU/Wh because we were unable to measure that we calculated a new CoP that we consider to be a rough estimate of what we are calling the "cold weather CoP" of 4.14.

$$\frac{12000\,\frac{BTU}{Wh}}{\frac{3.412\,\frac{BTU}{kWh}}{0.85\,kW * 1000\,W}} = 4.14$$

Equation 3: Our calculation of the "cold weather CoP" which makes sense that it is lower since ASHP are less efficient in cold climates

This calculation gives us an estimation and understanding of the cold weather CoP for this ASHP unit. For defrost cycle-specific data, we tested multiple methods to calculate the defrost-specific CoP. However, we later identified flaws in each approach. Ultimately, we chose to focus on kWh usage during the defrost cycle. This decision was driven by the complexity of tracking flow patterns in the ASHP mini-split unit, as its variable-speed operation makes precise calculations challenging. More details on power comparison between ASHPs and PETD prototype in next two sections.

Prototype

The second half of this project's deliverables regard the physical test apparati, which make up what we call our prototypes. In more specificity: we needed to collect and analyze data as well as to fabricate the physical products. The main goal was to determine the energy needed to de-ice a full size coil with PETD. We also implemented different designs to explore which fabrication method and implementation was most efficient. The design of these was touched upon in the methodology section, but the specific measurements and iterative design process will be described here. Additionally, our data is included in the appendix, but we will only reference relevant numbers in this section.

Single Length: Cables

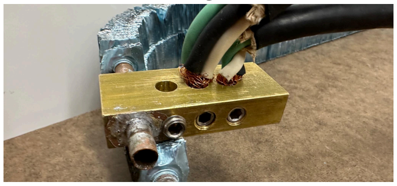
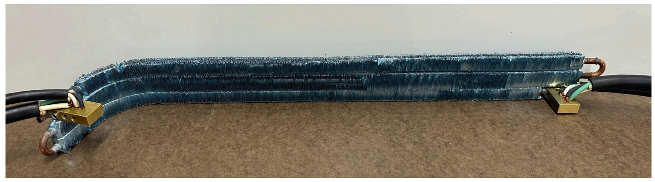
Our first design used six 12 AWG wires soldered directly to the test piece and mechanically clamped to the transformer. Due to the delicacy of the copper tube and the unconventional nature of this solder job, construction of one testing prototype took over 6 hours. We also created a custom stand out of plywood and 3D printed holders. Using these wires at an ambient temperature of 35ºF or less should allow around 295A assuming max cable temp of 200ºF. The electrical connection between the pipe and the wire is shown in Figure 25.


Figures 25 and 26: Single length prototype with six 12 AWG wires soldered directly to the copper pipe, mechanical clamping to the secondary side of the transformer not pictured

This prototype took 6:00 minutes at 64.8 W to fully de-ice. This translates to a total power usage of 3.6 kW and total energy usage of 363 Wh to de-ice a full coil, which is much higher than the 75 Wh we had hoped for (calculations 4 and 5). This was likely due to the high parasitic resistance of 1.4 mΩ per set of cables accounting for just over half of our power dissipation. With these levels of parasitic resistance, a full size coil could take as little as 182 Wh to fully de-ice, using around 1.8 kW of power. At 30V, for example, this would require 60A, and therefore would also only require half of the wires we used in this experiment.

Three Lengths: Cables and Busbars

Due to the high parasitic resistance to coil resistance ratio in the single length experiment, the team decided to use a longer coil of 3 lengths. The theory of PETD says that more power for less time is more efficient, and the extra power dissipation in the cables prevented getting the voltage, and thus power, high enough without pulling too much current through the cables. The team ordered 99.9% pure busbars, but due to shipping time, we also manufactured an intermediary prototype using brass bus bars that were readily available from the machine shop. Although brass is only about 28% as conductive as copper, the bars we used had a large enough cross sectional area to have no meaningful resistance, relative to the rest of our system. We drilled holes in the brass bars for both the copper pipe to run through and for cables to be mechanically attached. We used 3 10 AWG and 3 12 AWG wires to up our current limit to 360A assuming the same conditions as above. One of the bus bars, connected to the pipe and to the wires, can be seen in Figures 27 and 28.

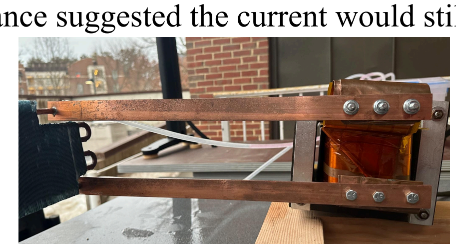



Figures 27 and 28: Three length prototype with three 12 AWG and three 10 AWG mechanically clamped into a brass bus bar that is mechanically connected to and soldered to the pipe, mechanical clamping to the secondary side of the transformer not pictured

This prototype took an average of 4:54 minutes at 355 W to fully de-ice. This translates to a total power of 6.6 kW and total energy usage of 535 Wh to de-ice a full size coil, which is unfortunately more than our initial test. While the higher power of this test apparatus, as compared to our first, did take less time, it still disagrees with PETD theory because the defrost took more energy overall. Our cables did still have 0.7 mΩ of resistance each, but this was smaller relative to this section of coil, so this does not explain the increase in energy usage. Our team is not quite sure exactly why this is the case, and we have thus detailed a further experiment to narrow down why this might be the case. The edge sections of the aluminum fins were definitively much hotter than the middle section. This is unexpected because the middle should be hotter due to electrical heating and heating from the neighboring metal which is also being heated by electric power dissipation. The fins were also unfortunately more bent in this prototype than others which may have played a role in slowing the defrost.

Six Lengths: Busbars

Because our second prototype disagreed with PETD and we were still limited to 360A, the team decided to proceed with the solid copper busbars. We fabricated two custom bus bars, as can be seen in Figure 29, to match the existing holes on our transformer and then to evenly connect to a coil section of 6 pipe lengths. Using these, we can get a current limit of around 1.5 kA, extrapolating from the current limit of an 8 gauge wire in open air and the temperature conditions above. This allowed us to mechanically bolt the busbars to the secondary side of the transformer and both mechanically hold the pipe as well as add solder to increase the electrical conductivity. Each of the busbars had a resistance of only 100 μΩ, less than a tenth of our initial test. These bars wasted minimal power in the connection between the transformer and coil and allowed as high a power as we might need for this device. Because of the uneven heating in our 3 length trial, the team also decided not to cut this coil. The low voltage and high contact resistance suggested the current would still flow through the copper, where it was designed to.




Figures 29 and 30: Six length prototype with two 99.9% pure copper bus bars mechanically clamped to the secondary side of the transformer and mechanically attached to and soldered to the copper pipe

This prototype took an average of 2:28 minutes at 737 W to fully de-ice. This translates to a total power of 6.9 kW and total energy usage of 283 Wh to de-ice a full size coil. This aligns much closer with PETD theory: more power, less time, less energy. While this is still more than electrical input in a reverse cycle defrost, it is less than the total energy supplied to the ASHP during a reverse cycle defrost. More exact comparisons will be made in the next section. This was by far the most promising test, and it indicates that this technology could work, but it is not as significant as we and our sponsor had hoped.

Final Power Consumption: Prototype vs Standard Defrost

The data collected during this project, at our current stage of data collection and analysis, points to the PETD and ASHP integration as less energy efficient than the standard reverse cycle defrost employed by cold climate ASHPs. The average electrical power usage across all of our test apparati was 432 watt-hours (Wh), while our reverse cycle defrost used only 78 Wh. This finding correlates with research that suggests an average of 67 Wh of energy provided by the compressor in a typical reverse cycle defrost [23]. Even when you account for the heat energy extracted from inside when the ASHP kicks into defrosting mode, as the PETD defrost would not extract heat from the room, the reverse cycle defrost only takes 351 Wh of energy.

There is some promise: our most efficient defrost used only 233 Wh of energy. This is less than the total energy supply for the reverse cycle defrost, but still much more than the electrical energy extracted from the main electrical supply for the defrost itself. Our initial estimates indicated we would use 67 Wh or less, meaning the theory of this implementation could potentially save energy. The problem here most likely lies in the fact that this is not the most effective implementation of PETD. The technology relies on the melting of an interstitial layer of ice and the physical removal of the bulk of the ice. Because of the closely packed fins, PETD in this implementation must melt all of the ice. As such, although the PETD theory of higher power and less time leading to less energy should still hold true, the energy at any power is higher than on a smooth surface implementation, leading to an overall less efficient application.

Societal and Economic Analysis

Stakeholder Engagement

Three key tiers of stakeholders have been identified in reference to project success. The first, and primary stakeholder is homeowners in cold climates. Understanding their needs, preferences, and challenges is crucial, as their adoption of our solutions will directly influence the project's impact. As such, our team has developed a Residential Heating Survey to gain a better understanding of the existing adoption of and potential for further ASHP technology efficiency improvements. Our team has been in consultation with stakeholders in Irving Institute’s Energy Justice Clinic, and the local Sustainable Hanover Energy Committee. The survey will be piloted in the spring following this restructuring of the Sustainable Hanover meetings. The survey will provide insights into the current heating practices of local cold climate homeowners, their interest in transitioning to alternative heating solutions, and current perceptions of cold climate ASHP technology. Looking to future work for this project, this qualitative data collection will aid in project development and support the quantitative findings our team has established in our control and prototype testing methodologies.

The second stakeholder is HVAC manufacturers and service providers, responsible for fabricating, installing, and maintaining HVAC systems that will be augmented by PETD integration, given the implementation of our project. Engaging with this group, through events such as the NH ASHRAE conference and meetings with HVAC certified technicians, including Dartmouth certified technicians, has provided valuable insights into the integral group of people supporting ASHP societal inclusion and acceptance. Engaging with Alexa Freitas at Trane Technologies provided insights on this front, industry standards, technical requirements, and potential barriers to market entry, enabling us to develop a robust and effective solution. In particular, our conversations provided insights into the operation of current Mitsubishi heat pumps, in accordance with the most stringent HVAC standards. This helped us to tailor our control testing setup, and understand the sequence of operations behind standard heating and defrosting modes.

The tertiary stakeholders are local governments, whose regulatory frameworks and policies set the operational environment for our product. Their role in shaping energy efficiency standards and incentive programs, building codes, and environmental regulations will directly impact the feasibility and scalability of our project. We have seen the Dartmouth Sustainability Office as a helpful liaison between the Dartmouth Community and local government policy understanding. We have identified a series of local community social media channels and bulletin boards across the Upper Valley in order for us to maximize our reach and ensure diverse participation in our residential energy survey. Keeping all stakeholders in mind, our design and testing approach has intended to focus on the primary tier of homeowners, supported by the secondary and tertiary stakeholders of HVAC professionals and local government entities.

Societal Implications

From an environmental standpoint, ASHPs present a sustainable alternative to conventional heating and cooling systems. By utilizing renewable energy sources, ASHPs significantly reduce carbon emissions and contribute to a cleaner, more energy-efficient future. However, as we potentially expand the use of ASHPs integrated with PETD, we are committed to ensuring that our innovations do not introduce new risks to local ecosystems. Specifically, we made sure to eliminate any potential threats such as the risk of electrocution with the high power pulses to wildlife and nearby individuals. We also ensured to prevent any refrigerant leakage into the soil, which could endanger soil health and ultimately plant life. Our goal is to enhance the environmental sustainability of ASHPs in cold climates, ensuring they remain a safe, responsible choice for homeowners seeking to reduce their carbon footprint.

At present, ASHPs are only an affordable possibility when supplemental heating isn't required. Installing an ASHP in cold climates is a significant investment that may result in variable energy savings. However, our project aims to work towards changing this barrier to adoption by improving the efficiency of ASHPs in cold climates, making them a more viable and attractive option for a range of consumer financial situations. In order to promote inclusivity and accessibility of our potential design, we considered the current state of ASHP adoption and maintenance, particularly in cold climate regions. Installation of ASHPs requires a significant installation cost and investment from homeowners upfront. By enhancing overall performance, and advocating for awareness at the local community level, we hope that ASHP and PETD integration can become a cutting-edge solution that encourages local governments to provide financial incentives, such as stipends or tax benefits, to support renewable energy technology adoption across residential income levels. This approach would not only help reduce energy costs for low and middle-income families, but also contribute to reaching broader environmental targets by increasing the adoption of sustainable heating solutions.

Locally, one example of this already starting to occur is the *Air Source Heat Pumps Tax Credit*, [1] a federal incentive designed to promote the adoption of energy-efficient technologies. This policy provides financial relief to homeowners and businesses by covering the installation costs of heat pumps from 2023 to 2032, thereby reducing the initial financial burden. Heating-dominated applications, such as cold climates, are the first pathway for eligibility. There is no longer a regional restriction on this eligibility [1]. This is an incredible opportunity for homeowners to invest in renewable energy that meets the most advanced efficiency standards, as established by the Consortium for Energy Efficiency [2]. Globally, ASHPs are becoming very popular in European countries due to the war in Ukraine interrupting their oil supply. This leads to a large demand for highly efficient ASHPs in Europe to be developed and adopted in the coming years. Our sponsor's long term goal is to appeal to this rapidly growing European market as quickly as he possibly can in order to help make their energy transition one that is as efficient in cold climates as possible. Overall the more widely adaptable ASHPs are made, homeowners worldwide can take advantage of the opportunity to have a more green source of home heating.

Economic Analysis

The integration of ASHPs and PETD could create a large cash flow eventually, but there are still several steps that need to be taken before the potential pay out. The costs for future work and manufacturing are based on the experimental conclusion that with more controlled testing conditions and further experimental iterations PETD and ASHP integration can be proven more effective. Figure 31 below shows the estimated gradient cash flow series over the next few steps of this research and integration into the real world.

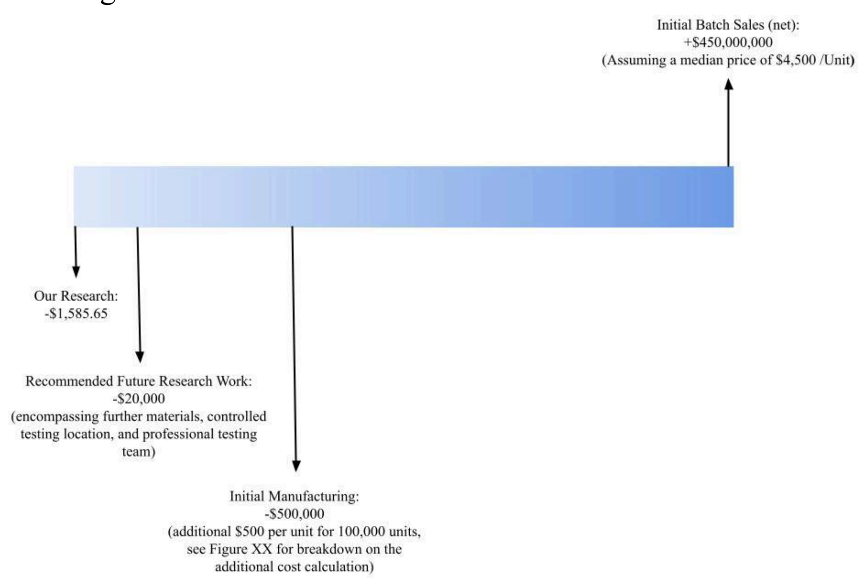


Figure 31: Estimated Gradient Cash Flow Series for the Next Steps of Integration of ASHP and PETD

The estimated additional manufacturing cost of $750 per unit comes from a spreadsheet tabulating the estimated costs of integrating ASHP and PETD. This can be seen in Table 4.

Components	Cost		Ratings
Breaker	$85.00	/unit	300 A 48 V
Relay	$20.00	/unit	200 A 24 V
Transformer	$500.00	/unit	24 V 200 A
Controller	$15.00	/unit	
Wiring	$5.00	/unit	
Expenses	Cost		
Additional Labor	$15.00	/hour	
	$45.00	/unit	
Revenue	Amount		
Additional price	$750.00	/unit	
Added revenue	$80.00	/unit	

Table 4: Estimation of the cost to implement PETD into ASHP at the step of the manufacturer (27–31)

As seen in Table 4, the greatest barrier to making this implementation profitable for ASHP manufacturers is the prohibitive price of the transformer needed to run the high power pulses safely. These numbers are all either extracted directly from a supplier like Digikey or Grainger [30], or extrapolated based on slightly different requirements, assuming bulk production costs. Looking into alternatives like batteries should be considered. Despite added costs, on the whole, this technology could reasonably be added while increasing revenue for the manufacturing companies.

Recommendations for Future Work

Based on research and experimental prototype integration of PETD and ASHP at the scale of this capstone project, the team's recommendation does include further research and development of PETD integration. At the conclusion of two terms of literature review into heat transfer and ice theory, iteration through power supply implementations, control testing with an actual ASHP and forcing a defrost cycle, and prototyping a functioning electrical and fluid loop driven prototype, our team has invested significant time and resources into PETD and ASHP integration. To be precise, our team has invested upwards of 250 hours (12 hours minimum/week) into the capstone work, $1,585.65 from the Thayer budget, in addition to our sponsor's initial investment including new and decommissioned ASHPs. We have also consulted with many faculty, researchers, industry professionals, facilities management personnel, and potential residential end users through community outreach. This work points to the value in exploring new and innovative approaches to renewable energy technology development and implementation.

Our team's greatest recommendation for future work is continued rigorous ASHP operation testing in controlled, repeatable ambient conditions, and continued testing iterations with the developed six lengths prototype, eventually scaling up to a full condenser coil system. In light of our own time and resource constraints, our team believes that future work can produce more consistent data and accurate energy estimations and clarify how much the integration of PETD can enhance ASHP efficiency.

Next Steps: Control Testing

In order to achieve the level of rigor and precision required to meet our sponsor's end goal of pitching PETD and ASHP integration to HVAC manufacturers, or if determined, clarifying with certainty that the implementation is not worthwhile, it is crucial to establish precise control over both indoor and outdoor temperatures, as well as humidity levels. These environmental factors play a significant role in determining the rated performance and efficiency of HVAC systems, and even minor variations can lead to inconsistent or inconclusive results. By implementing stricter control over these variables, future work can ensure that the data generated for both the control testing and the prototype testing is both reliable and reproducible. These results would provide a robust foundation for validating the technology's efficacy in ASHP contexts, and would be essential for gaining the confidence of industry stakeholders and advancing the adoption of innovative HVAC solutions.

This testing work could be carried out by locations like The Emerging Technologies (ET) Program of the Building Technologies Office (BTO) [23], under the U.S. Department of Energy (DOE). This program plays a pivotal role in advancing applied research and development (R&D) for innovative technologies, systems, and models aimed at reducing building energy consumption and could be an excellent candidate for testing on the ASHP and PETD integration. An additional location for this work could be The National Institute of Standards and Technology (NIST) HVAC Equipment Division [4]. NIST is another key player in the field of HVAC efficiency and focuses on the development and evaluation of HVAC systems. NIST's research emphasizes the importance of precise testing conditions to validate the performance of HVAC equipment under various environmental scenarios. In terms of some smaller operations many colleges and universities boast robust building efficiency and HVAC solutions divisions including Berkley's Center for the Built Environment [14], CU Boulder's Larson Building Systems Laboratory [13], and University of Florida's HVAC Laboratory [19]to name a few.

Next Steps: Prototype

In terms of prototype design and further prototype iteration, there are several steps to take before moving to the testing of a full size coil. The first would be to characterize a copper tube without aluminum fins. During our testing of three lengths with cut fins, we found that the areas of fins near the ends of the tube heated very effectively, while the middle length heated slowly and ineffectively. This was not expected or easily explainable because, assuming uniform copper tubing throughout the length, power and heat dissipation would be evenly distributed. Therefore, the middle of the tube should actually heat slightly faster than the edges, as it has the combined effect of heat dissipation from electrical power and from its sections of tubing. Due to our time constraints, however, measuring the exact voltage and temperature of the copper tube without fins was not possible. Therefore, to confirm this assumption of uniform power and heat dissipation, voltage, current, and temperature measurements must be taken across the tube alone. If the assumption is proven true, the aluminum fins can be reintegrated, and analysis of the impact of heat transfer can be carried out.

The interface between the copper and aluminum also introduces a potential issue with durability of this system. Due to the differing work functions of copper and aluminum, corrosion is likely to occur over time, and this will begin to impact both thermal and electrical conductivity. This corrosion appears to be manageable in the case of classic ASHPs, though increased electrical activity on the coils may expedite this process, causing issues on both sides.

This would need to be studied over time, both for regular ASHPs and a coil with PETD implemented. Knowing the impact of PETD on the durability of the device would also be invaluable to evaluating the potential benefit of this improvement.

Finally, it would be important to evaluate the efficacy of these prototypes under different icing and weather conditions, including humidity and storms. Due to our limited testing facilities, our team was unable to test a multitude of icing conditions, and most of our trials had what we deemed worst case scenario solid ice or added snow. Using an ice lab with varying levels of humidity as well as adding wind and snow falling, as opposed to packed in, would be vital to evaluating total efficacy of this improvement. This data could also provide invaluable insights to pitching this to ASHP manufacturers.

Conclusion

We investigated the potential integration of ASHPs with PETD to assess whether this combination could improve ASHP performance in cold climates. Our hypothesis was that PETD integration can significantly enhance de-icing efficiency and mitigate performance degradation, ultimately accelerating ASHP adoption in cold weather regions. While our current results do not definitively support this approach as a standalone solution, they indicate promising areas for further exploration. Our work explored different executions of PETD implementation, and we did collect promising data for control and defrost testing. This is valuable information to inform future exploration and fabrication. Future work should focus on optimizing PETD materials, refining system design, and conducting long-term controlled tests to better evaluate performance.

We provided our sponsor, John Chen, with crucial data, prototypes, and learnings that he can take into his future work, supporting the transition to sustainable energy systems. As global momentum builds, improved, more efficient PETD integration has the potential to decarbonize residential heating, and foster a more resilient energy future for all.

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Appendix

Calculations

Calculations 1: Resistance of coils, cables, bus bars

https://docs.google.com/spreadsheets/d/1FlbUbT5w7OCbVUhrF-MaG3xhboh3grgJ1UGjbq4b3ws/edit?gid=0#gid=0

Calculations 2: PSU Component Values

$$R1 = \frac{V_{LED} - V_F@I_F}{I_F}$$

$$R1_{min} = \frac{5V - 1.4V}{40mA} = \frac{90\ \Omega}{0.95\ (5\%\ tolerance - E24)} = 95\ \Omega \ => \ 100\ \Omega\ (E24)$$

$$R1_{max} = \frac{5V - 1.2V}{10mA} = \frac{380\ \Omega}{1.05\ (5\%\ tolerance - E24)} = 362\ \Omega \ => \ 360\ \Omega\ (E24)$$

$$R2 = \frac{Vp{,}max}{min(I_{GTM}, I_{TSM})} = \frac{240\sqrt{2}\ V}{min(4, 1)\ A} = 240\sqrt{2}\ \Omega = \frac{340\ \Omega}{0.95} = 357\ \Omega \ => \ 360\ \Omega\ (E24)$$

$$R4 = \frac{5V - 1.8V}{10mA} = \frac{320\ \Omega}{0.95} = 337\ \Omega \ => \ 330\ \Omega\ (E24)$$

$$R_{th} = \frac{T_{c,\,max} - T_{air,\,max}}{P@I_{RMS}} = \frac{85\ C - 30\ C}{16\ W} = 3.44\ K/W$$

Calculations 3: Transformer characterization measurements and calculations

https://docs.google.com/spreadsheets/d/1FWj28le9oBklsOD4UgNAMkwf8oASvoQluUbBkys8pEk/edit?gid=0#gid=0

Calculations 4: Real Power and Current of Our System

$$R_{total} = R_{coil} + R_{transformer\ output} = 2.40\ m\Omega + 1.80\ m\Omega = 4.2\ m\Omega$$

$$P_{actual} = (4.36\ V)^2 / 4.2\ m\Omega = 4.53\ kW$$

$$I_{actual} = 4.53\ kW/4.36\ V = 1039\ A$$

Calculations 5: Real Energy Savings

$$E_{PETD\ cycle} = 4.53\ kW \bullet 60\ s/cycle = 272\ kJ/cycle$$

$$E_{typical\ \ cycle} = 1139.8\ kJ$$

$$Percent\ Saved = 1 - (272\ kJ/1139.8\ k\ ) * 100\% = 76\%$$

Power Supply Unit CAD Files

The KiCad files for the power supply unit can be accessed via this google drive link: https://drive.google.com/file/d/1OHZrCrathYvOS8iFvRzNwECoqCBjn7hC/view?usp=sharing.

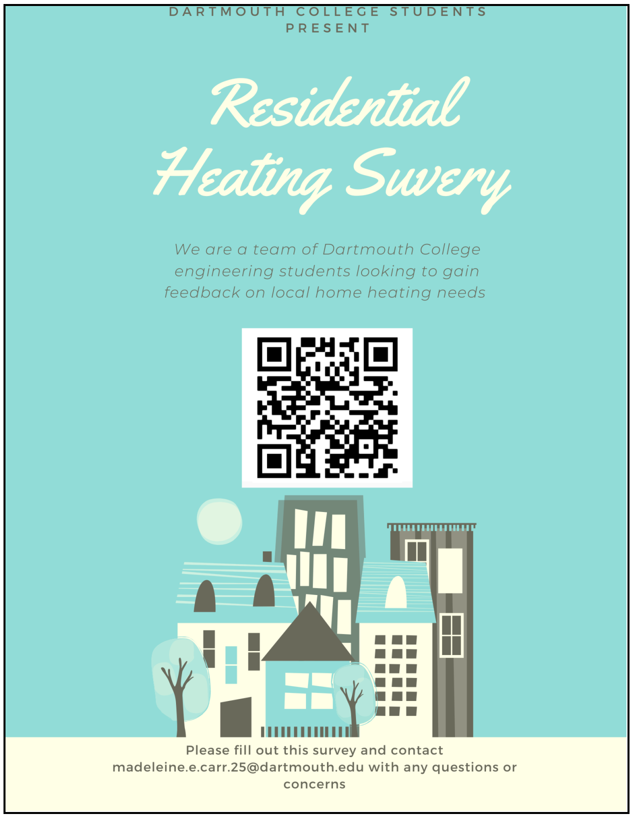
Velocity Profile Measurements

Location	Velocity
V1	0.15 m/s
V2	0.16 m/s
V3	0.18 m/s
V4	0.16 m/s
V5	0.17 m/s
V6	0.18 m/s
V7	0.15 m/s
Vavg	0.1614 m/s

Residential Heating Survey

Residential Heating Survey Outreach, Example Flyer

Residential Heating Survey



Project Safety Plan

ENGS 89/90 06-709 Project Safety Plan

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

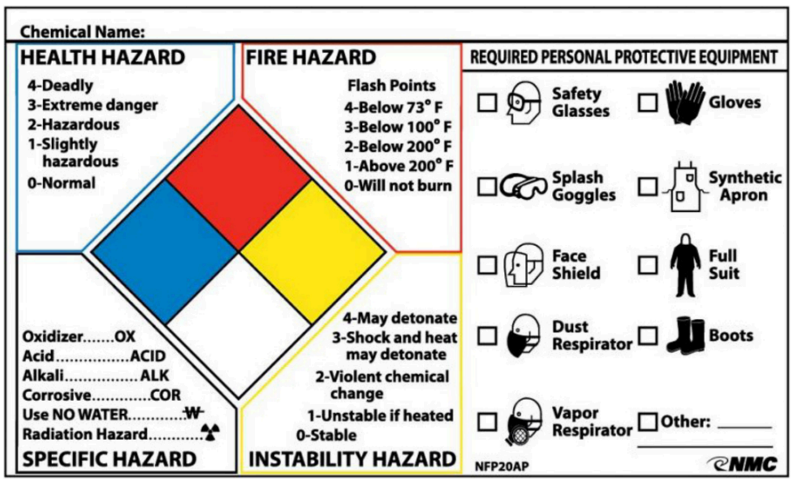
Project Safety Plan

Project Name: Pulse Electrothermal De-icing Air Source Heat Pumps for

More Efficient Residential Renewable Energy Systems

Members: Abby Hughes, Madeleine Carr, Thea Kunzle, Justin Sapun

Date: November 25, 2024



Project 6-709 Project Safety Addendum Plan

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Section 1: Scope of Work

1.1 Description

Air source heat pumps (ASHPs) are a critical technology in residential heating decarbonization. By leveraging electricity to efficiently transfer heat from the surrounding air, heat pumps are three-to-five times more energy efficient than conventional gas boilers (IEA, 2022). The widespread adoption of ASHPs will expedite the global transition to sustainable and reliable energy systems. ASHPS operate by extracting heat from outdoor air, and transferring heat indoors via a compressor circulating refrigerant. However, at freezing temperatures, ice and frost accumulate on the outdoor coils. In response, the reversing valve initiates a defrost cycle, reversing the flow of refrigerant to draw heat from indoors, further reducing operational heating efficiency.

In order to address limitations and inefficiencies of ASHPs in cold climates, our team proposes integration of highly efficient pulse electrothermal de-icing technology (PETD). Traditional thermal de-icing is incredibly energy intensive, and mechanical de-icing is often ineffective and may accelerate wear or damage to systems. However, with the application of PETD, the energy needed to effectively remove interfacial ice is significantly reduced, up to a factor of one hundred (Petrenko et al., 2011). Through this novel application, our team's solution has the potential to optimize de-icing performance, improve overall system efficiency, and increase cold climate adoption of ASHPs.

As fossil fuel-based heating systems become less viable and more expensive, a more effective approach to de-icing has the potential to expand the reach of affordable, reliable, and renewable heating solutions for cold climate homeowners. Now more than ever, advancing innovation and enhancing the efficiency of ASHPs in cold climates is essential. The team has identified three key stakeholder groups: cold climate homeowners, who would benefit from more reliable and efficient heating; HVAC producers and technicians, who stand to gain access to new market opportunities; and local governments, which could support energy-efficient policies and initiatives. This is a critical issue in the New England region, as winter inefficiencies discourage year-round residential adoption. The solution developed by our 89/90 team has the potential to significantly transform heating systems in cold climates, impacting energy systems across the globe in the fight against climate change.

1.2 Timeline

Task	W1	W2	W3	W4	W5	W6	W7	W8	W9
1. Assemble fully functional glycol evaporator									
2. Set up Prototype Testing and data collection									
3. Set up control test of cold ASHP defrost cycle									
4. Control test data collection									
5. Iteration and adjust prototype									
6. Final Data Collection and Analysis									

1.3 Location

1.3(a) Assembly Location:

15 Thayer Dr, Hanover, NH 03755

1.3(b) Testing Location:

15 Thayer Dr, Hanover, NH 03755

Section 2: Safety and Emergency Contacts

2.1 <u>Safety Manager Designation</u>

Thayer Safety Director: *Jonathan Stark*

Phone Number: *(603) 667-3399*

Email: *jonathan.h.stark@dartmouth.edu*

Project Safety Advisor: *Charles R. Sullivan*

Phone Number: *(603) 646-2851*

Email: *charles.r.sullivan@dartmouth.edu*

Project Group Safety Manager: *Abby Hughes*

Phone Number: *315-244-5753*

Email: *abigail.c.hughes.25@dartmouth.edu*

Section 3: Hazard Acknowledgment and Assessment

3.1 Hazard Assessment

	Hazard	Present Y/N	Hazard Mitigation
1	Hearing Protection	Y	Earplugs or headphones will be helpful when running the ASHP control system.
2	Explosives	N	
3	Confined Space	Y	Confined space safety measures will be taken when working with compressed refrigerants. In addition, work in any cold rooms in the Ice Lab will require precautions that no one gets locked in or gets hypothermia by being left alone in them.
4	Eye Protection	Y	Safety glasses will be necessary any time high power electrical is energized, and any power tool work is done, particularly when cutting ASHP coils. In addition, paint respirators and fume hood are necessary when cutting the aluminum fins.
5	Projectile	N	
6	Chemical Burn	N	
7	Heat Burn	Y	With high current (and resistance) there are heat concerns and potential for heat burns, even at temperatures low enough that wires aren't glowing. Sweating copper requires a blowtorch, so proper safety and care will be required.
8	Weather	Y	As we will be operating on an outdoor unit in freezing temperatures, we need to dress adequately for the weather.
9	Water	Y	We will have a fluid loop with high power, so it would be very unsafe if it leaked. Will need confirmation of pump operation before powering the circuit.
10	Unstable Load	Y	The ASHP is particularly difficult to handle, requiring organization of components and carts.
11	Heavy Objects	Y	The transformer is incredibly heavy to carry. Ensure proper carrying form and use a moving cart when necessary.
12	Fire Hazard	Y	Circuit malfunctions can cause electrical fires, only power up when approved and supervised.
13	Unstable Chemical	Y	**Only HVAC Certified Technicians will be able to work with refrigerants in this project. This is important for environmental safety and EPA compliance.**
14	Oxidizer	N	
15	Corrosive Agent	N	
16	Radiation	N	
17	Containment and Storage	Y	All items containing compressed refrigerant will be stored in predetermined safe locations.
18	Lockout Tag out of Energy	Y	Will lockout 208 V supply to PETD equipment when not ready/safe to electrify.
19	Electrical Hazards	Y	Arcing, or electrical discharge between conductors, could be of concern.

Section 4: Hazard Abatement

4.1 <u>Significant or High-Risk Activities</u>

4.1(a): *Testing PETD integration outdoors*

- <u>Safety Considerations</u>
    1. When operating in outdoor environments or areas exposed to moisture, exposure to the PETD could introduce electrical shock risks.
- <u>Hazard Acknowledgement</u>
    1. Moisture entering the power supply system
    2. High power system
    3. Compressed refrigerant
    4. Outdoor weather conditions
- <u>Measures taken to Address Hazards</u>
    1. Use a ground fault circuit interrupter (GFCI) to shut off power quickly in the event of a ground fault
    2. Buddy system, always work in pairs
    3. Only operate system following explicit permission from advisor
    4. Be aware of changing weather conditions and adjust plans accordingly.
    5. When possible, test PETD indoors in simulated cold climate conditions
    6. Familiarize ourselves with the location and operation of emergency shutoff switches, fire extinguishers, and first aid kits

4.1(b): *High power applications*

- <u>Safety Considerations</u>
    1. When operating circuits with high power there is risk of electrocution to the user if proper safety precautions are not taken
- <u>Hazard Acknowledgement</u>
    1. Electrocution risk
- <u>Measures taken to Address Hazards</u>
    1. Only operate once given explicit “power up” approval from the advisor
    2. All power-up procedures require verbal confirmation of readiness and awareness of the involved parties
    3. All personnel should be fully briefed on the equipment, procedures, and emergency shutdown mechanisms

4. All personnel must wear safety goggles when dealing with high power systems
5. All personnel must have completed Thayer Electrical Safety Training

4.1(c): *Using High Power on a water/glycol filled evaporator*

- Safety Considerations
    1. If any copper connections or tubes leak, there is potential shock risk.
- Hazard Acknowledgement
    1. Electrocution risk
- Measures taken to Address Hazards
    1. Thorough testing and assessment of the completed fluid loop with a water pump to determine if there are any leaks before adding glycol or power
    2. Be aware of closest fire extinguisher when testing this system in case of emergency
    3. Ensure the system is properly grounded before powering up, using a GFCI

4.1(d): ***Potential Refrigerant Leaks from ASHP unit***

- Safety Considerations
    1. Considerable environmental and safety hazards related to potential refrigerant leaks
    2. This environmental safety hazard has already occurred earlier in the term and requires considerable risk assessment
- Hazard Acknowledgement
    1. Unstable chemicals may leak from ASHP when setting up/carrying out testing procedures for the defrost control test
- Measures taken to Address Hazards
    1. **Only HVAC Certified technicians will be able to work on deliverables requiring working with refrigerants**
    2. Identify Dartmouth HVAC certified technician that will demonstrate the ASHP defrost cycle control test on our behalf

4.2 Safety Protocols:

1. **Consultation and Supervision:**
    - Prior to initiating any high power work, consult and seek guidance from knowledgeable Thayer faculty and staff, including but not limited to faculty advisor, Professor Charlie Sullivan.
    - Any changes to the testing setup or approach must be reviewed with Thayer personnel before implementation.

2. **"Power-Up" Approval:**
    - Explicit approval must be obtained from a supervising staff member or faculty before powering up equipment.
    - All power-up procedures require verbal confirmation of readiness and awareness of the involved parties.
3. **Buddy System Requirement:**
    - A minimum of two individuals must be present and working together at all times when handling high power and high current systems.
    - Both individuals should be fully briefed on the equipment, procedures, and emergency shutdown mechanisms.
    - Both individuals must have completed Thayer Electrical Safety Training.
4. **Personal Protective Equipment (PPE):**
    - All personnel must wear appropriate PPE, such as insulated gloves, safety goggles, and non-conductive footwear, when dealing with high power systems.
5. **Emergency Preparedness:**
    - Familiarize ourselves with the location and operation of emergency shutoff switches, fire extinguishers, first aid kits, and AEDs.
    - In case of an incident, immediately disconnect power using the emergency shutoff, and seek assistance without delay.

Section 5: Project Safety Management Plan Approval

5.1 Approval Signatures (only required if hazards are present)

Previous Contract Signed by all Group Members: Safety Agreement

Name	Signature	Date
Johnathan Stark (Thayer Safety Director)	Jonathan Stark	11/25/24
Charlie Sullivan (Project Safety Advisor)	Digitally signed by Charles R. Sullivan Date: 2024.11.25 20:40:38 -05'00'	11/25/24
Abby Hughes (Project Group Safety Manager)		11/25/24