# De-Icing for More Efficient Renewable Energy

Madeleine Carr, Abby Hughes, Thea Kunzle, Justin Sapun

Team 06-709 - ENGS 90 - 25W

# Team Roles

**Madeleine Carr**
Project Manager
Treasurer

**Abby Hughes**
Advising Team POC
Control Testing Lead

**Thea Kunzle**
Electrical Lead

**Justin Sapun**
Controls Lead
Mechanical Lead

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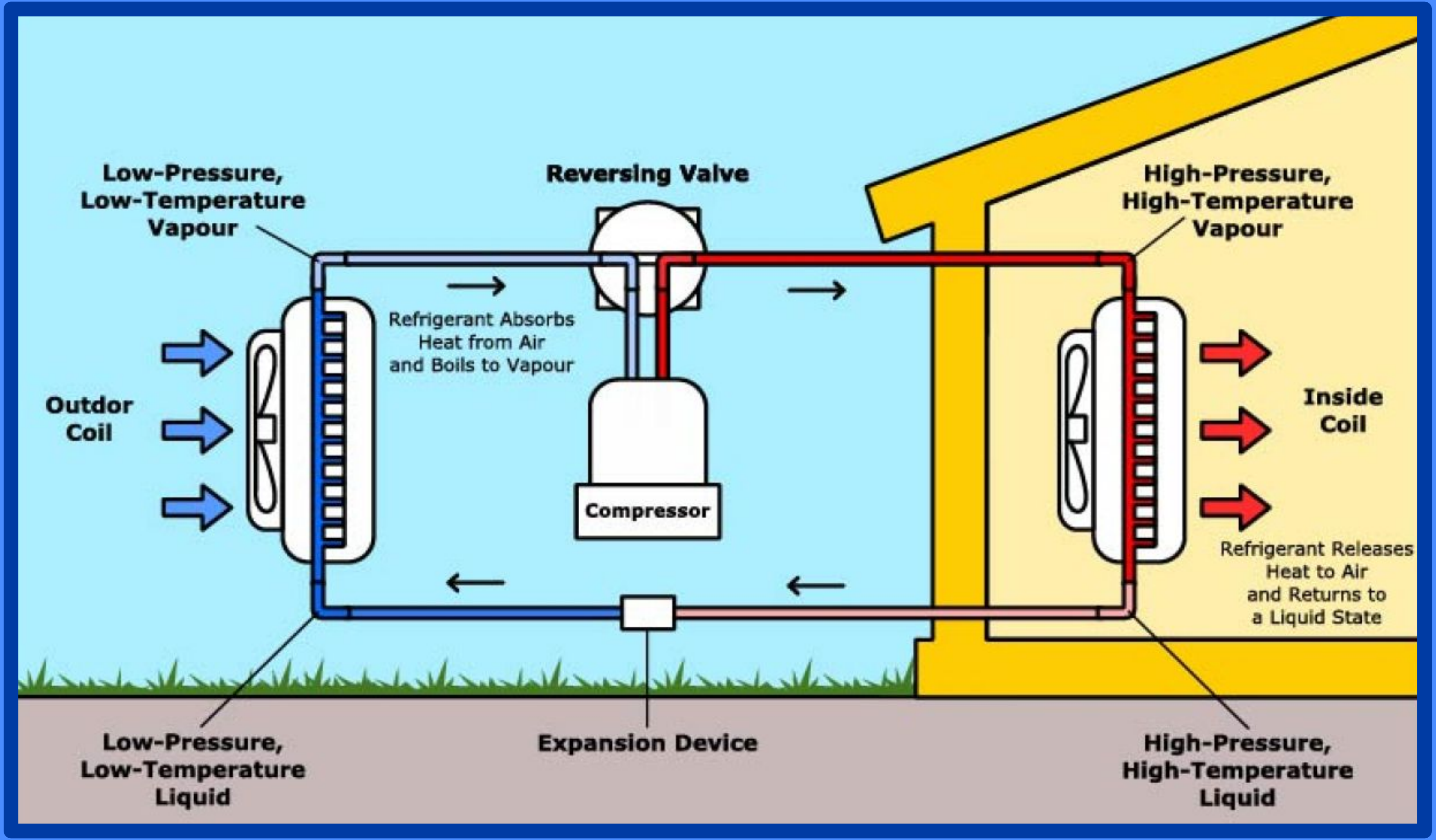
# Overview


Low-Pressure, Low-Temperature Vapour
Reversing Valve
High-Pressure, High-Temperature Vapour
Refrigerant Absorbs Heat from Air and Boils to Vapour
Outdor Coil
Compressor
Inside Coil
Refrigerant Releases Heat to Air and Returns to a Liquid State
Low-Pressure, Low-Temperature Liquid
Expansion Device
High-Pressure, High-Temperature Liquid

To promote wider adoption of cold climate **air-source heat pumps**, we integrated **high-power pulse** technology to enhance the **overall efficiency** of ASHPs.

# Pulse Electric Thermo Deicing (PETD)

An array of patented methods that use **high-power electric pulses** to **remove** ice, **prevent** ice formation, and either increase or decrease **ice-surface friction**.

**Patent Inventors**

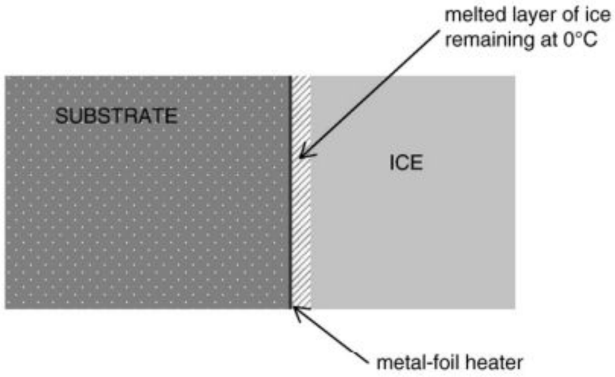
- Victor F. **Petrenko**: Dartmouth Engineering Professor
- Fedor V. Petrenko: Developed analytics for Dartmouth's Energy Initiative
- Cheng Chen: Dartmouth Alum, Former Ice Lab Researcher
- John **Chen** (Owner): Project Advisor, Former Ice Lab Researcher

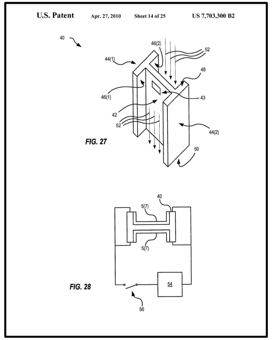
# Ice Theory and PETD

Ice's stickiness is due to its charged surface, which induces an opposite charge on the surface it adheres to.

PETD melts the interfacial ice layer, creating a thin film of water, and causing the ice to fall with the help of gravity.

Many applications: Deicing airplanes, power lines, windshields, ships, cars, trucks, offshore wind structures, roads, bridges, ski lifts, roofs, freezers, and more.



| Specifications | Justification | Quantification |
|---|---|---|
| Efficient | Current market leading cold weather ASHPs are inefficient at below freezing temperatures | Coefficient of Performance (CoP) and energy (kW) of defrost cycle |
| Safe | Exposure to elements, animals, and homeowners | 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 |

# Sponsor Goals

Our sponsor's long term goal is to **develop the integration of ASHP and PETD** technology for widespread, **global adoption**.

His vision for our group is to make that possible through a **prototype iteration, experimental procedure, data collection, and analysis.**

# Testing Approach

- **Testing Plan**
  - **Control Testing**
    - ASHP Monitoring
    - Velocity Profile
  - **Prototype Testing**
    - Electrical Prototyping
    - Fluid Prototyping

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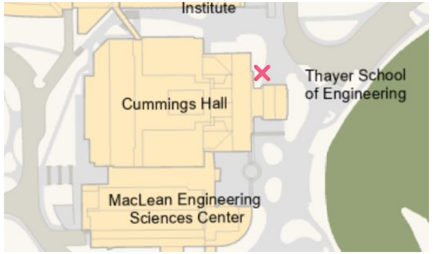
# Methodology Approach: Control Testing

# ASHP Installation




(Thank you Dave, John, and Raina!)

## Indoor Unit

**Mitsubishi Hyper Heat**
**Model ASUG09LZBS**

## Outdoor Unit

**Mitsubishi Hyper Heat**
**Model AOUG09LZAH1**

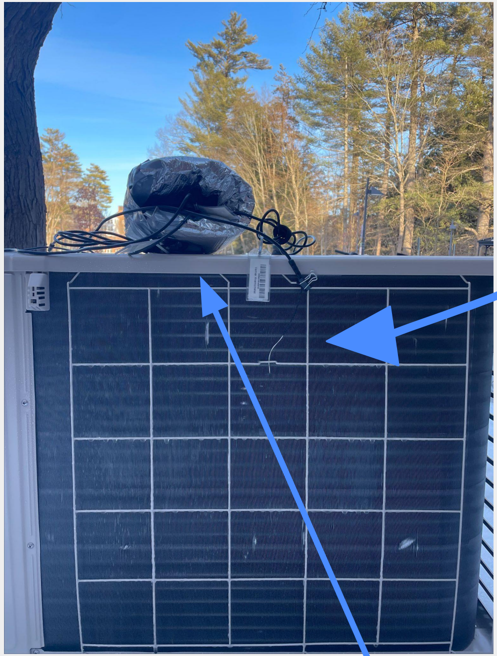
# Data Collection

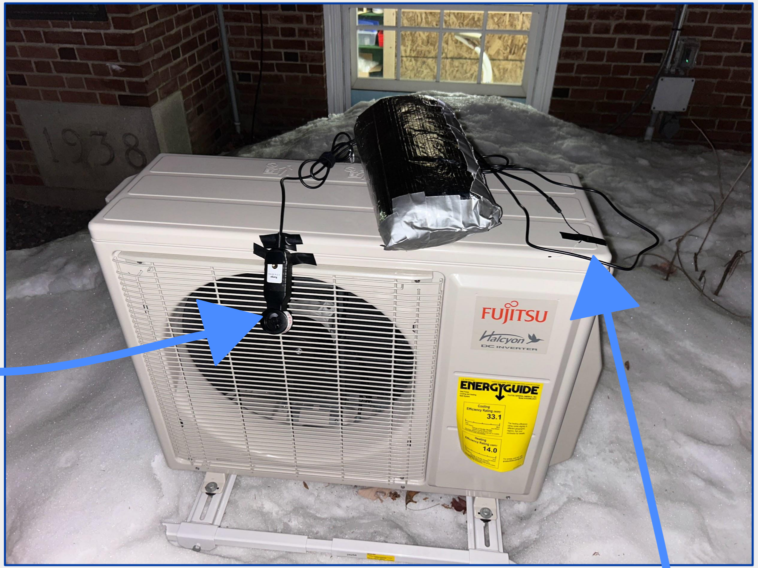
| Sensor | Desired Parameter |
|---|---|
| **Impeller Anemometer (2x)** | Inlet and Outlet Airflow on Outdoor and Indoor Units |
| **Exposed Thermistor (4x)** | Direct Inlet and Outlet Temperature on Indoor and Outdoor Units<br><br>Indoor and Outdoor Ambient Temperature (75 cm away) |
| **Relative Humidity Sensor (1x)** | Humidity at the outdoor unit inlet |
| **Eyedro Home Energy Monitor** | Monitors the kW that the ASHP pulls |

# Outdoor Unit (ODU)

Outlet Temperature on Outdoor Condenser Fins

Inlet Airflow on Outdoor Fan







LabQuest 2 in Insulating Sleeve

Ambient Temperature (75 cm from Inlet)

# Indoor Unit (AHU)

Anemomaster

Ambient temperature
(75 cm from outlet)

LabQuest


Outlet airflow and
temperature


Using a single point flow from the impeller anemometer is sufficient and accurate because we can account for the **velocity profile**

# Velocity Profile

# Velocity Profile Justification

- Recommendations from advising team
  - Alexa Freitas (Trane Technologies)
  - Cheng Chen (Thayer Ice Lab Researcher)
  - Raina White (Thayer Systems and Fluids)

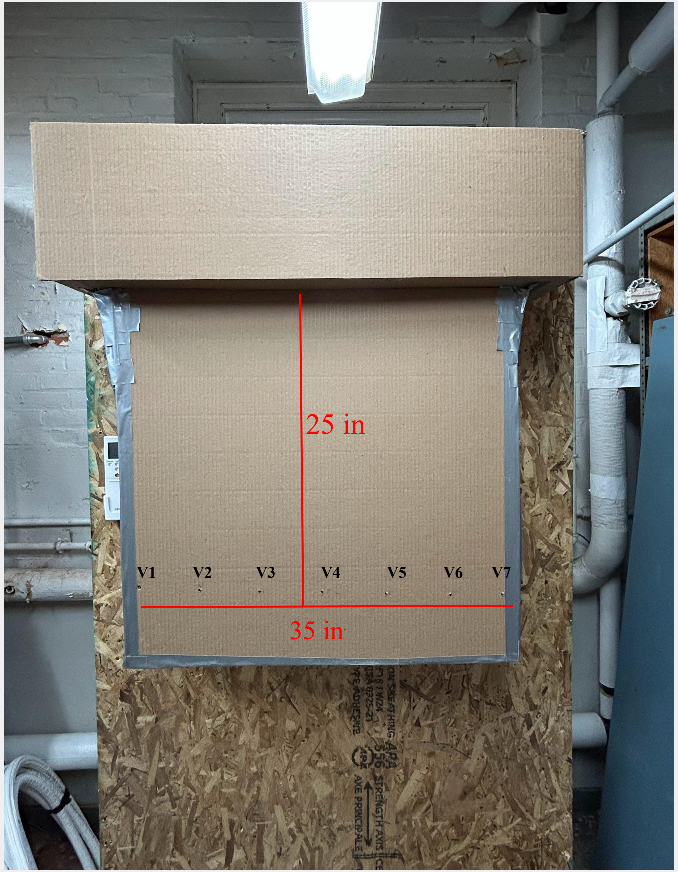
1. Achieve uniform flow across outlet
2. Calculate velocity profile
3. Calculate CFM
4. Calculate COP

Anemomaster 6036 Professional HVAC Anemometer (Thank you Raina!)


$$CoP = \frac{Q_{out}}{Q_{in}} = \frac{CFM \cdot \Delta T \cdot 1.08}{(kWh_{ODU} + kWh_{AHU}) \cdot 3413}$$

# 1. Build Ductwork for Velocity Profile

# 2. Calculate Velocity Profile




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

**$V_{avg}$ = 0.1614 m/s**

## 3. Calculate CFM

# Ductwork Volume =
# 30 x 37 x 11 = 11210 $in^3$ = 7.07 $ft^3$

CFM (cubic feet per minute) = **224.61**

Higher CFM generally means
better performance and versatility

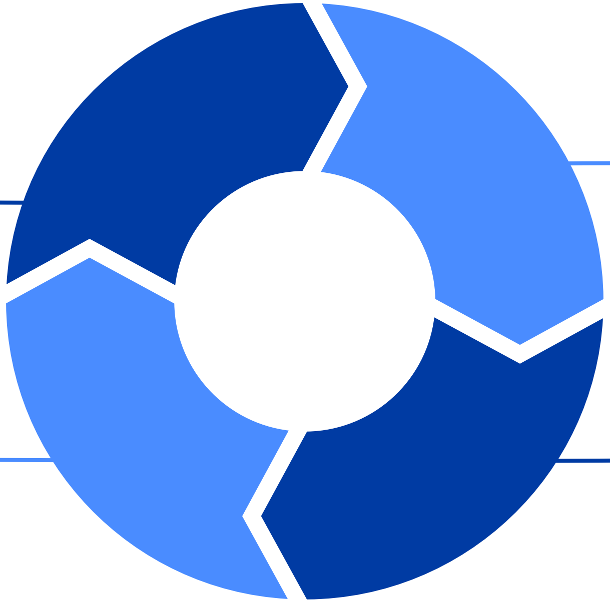
## 4. Calculate COP

# ASHP Monitoring

# Goal: Gather Data on ASHP Operations

- **ASHP Operational Data**
  - **Standard Operation**
    - 1-hour tests
    - 3-hour tests
  - **Forced Defrost Cycle**
    - 1-hour tests
    - 3-hour tests
    - Specific defrost cycle data

# Challenges Faced



Lack of Climate Control and Seasonal Variability

Triggering Standard and Defrost Operation

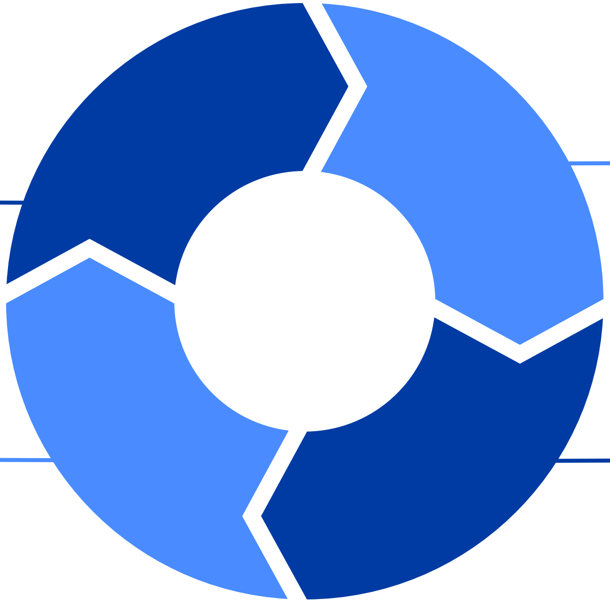
Data Collection in Cold Weather Conditions

Understanding the Partial Defrost Cycle

# Solutions

Testing at **20-40 ℉** ambient for optimal ice buildup conditions

Built **insulating package** for outdoor LabQuest to ensure continued data collection at sub-freezing temperatures

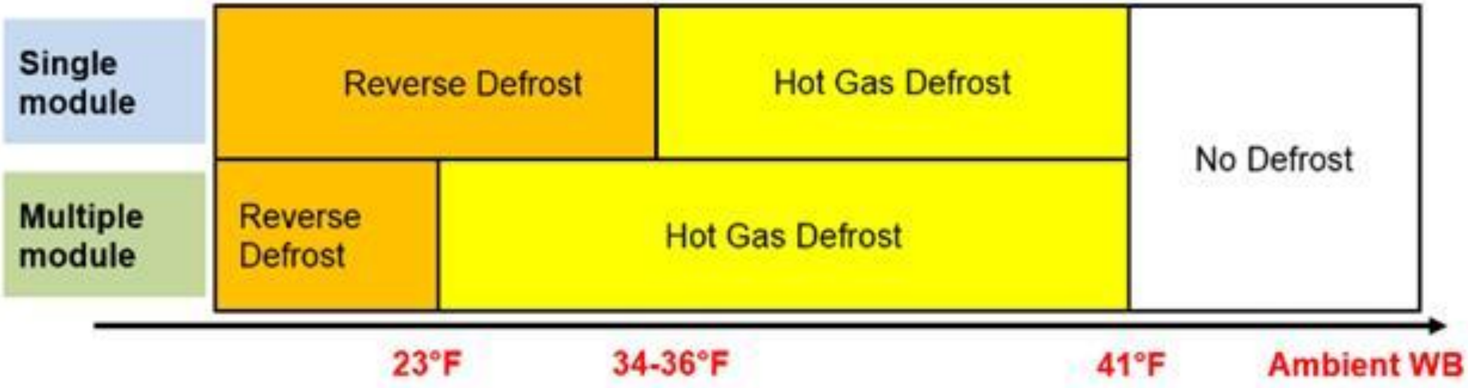


Using spray bottle to **simulate misting and frosting conditions** and opening C003A window during testing

Tracking partial defrost on **Eyedro Home** and fin **temperature** sensor

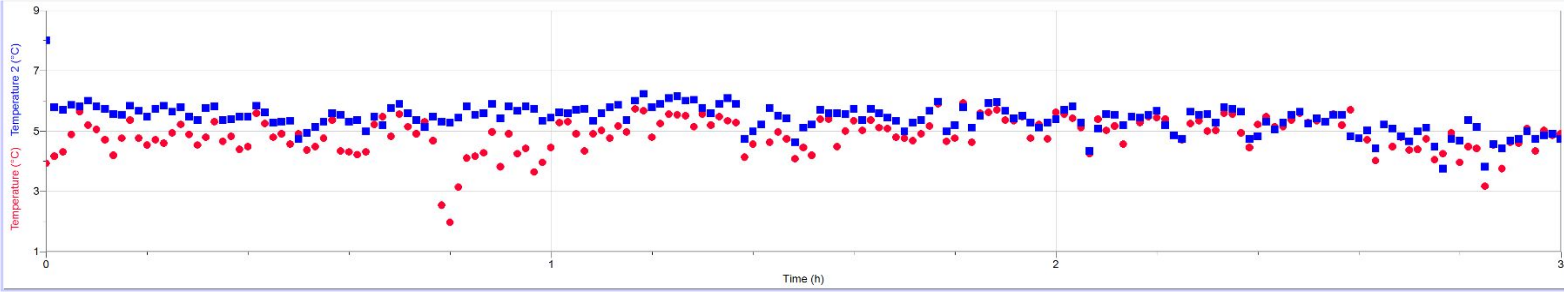
# Full and Partial Defrost

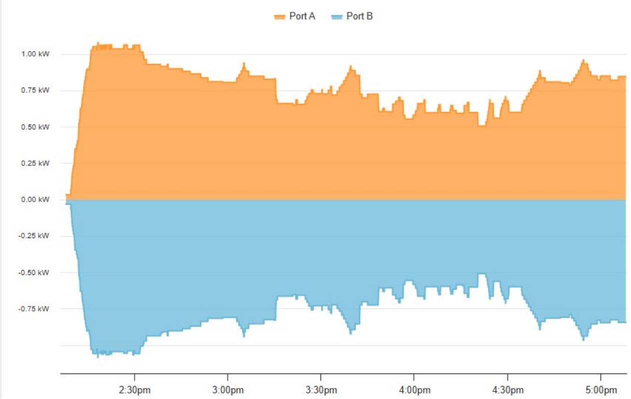
- Full: **100%** of hot gas directed to ODU to defrost condenser fins
- Partial: **~50%** of hot gas directed to ODU, **~50%** used to heat AHU



# Standard Operation Data

## Outdoor Unit (3-Hour Test)



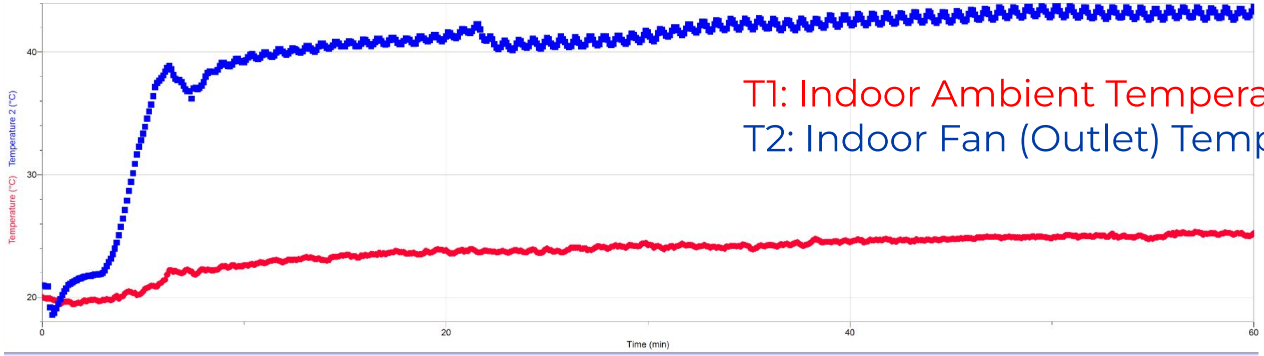




T1: Outdoor Fin (inlet) Temperature
T2: Outdoor Ambient Temperature

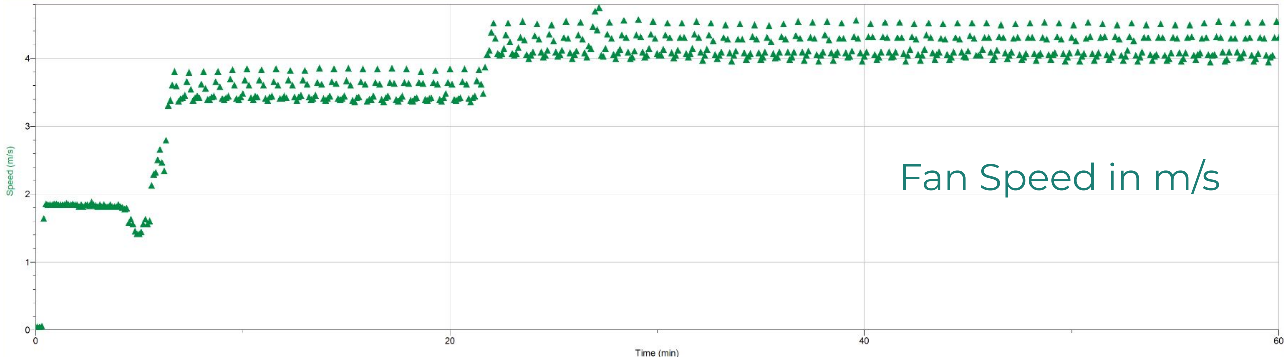
Port 1: Power Usage in kW
Port 2: Power Usage in kW

# Standard Operation Data

## Indoor Unit (3-Hour Test)

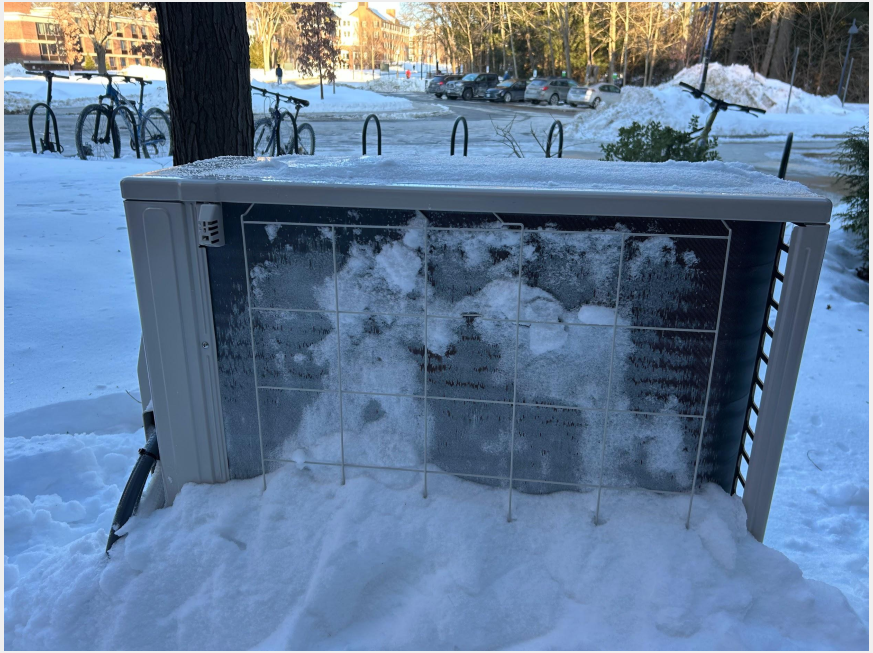



T1: Indoor Ambient Temperature
T2: Indoor Fan (Outlet) Temperature

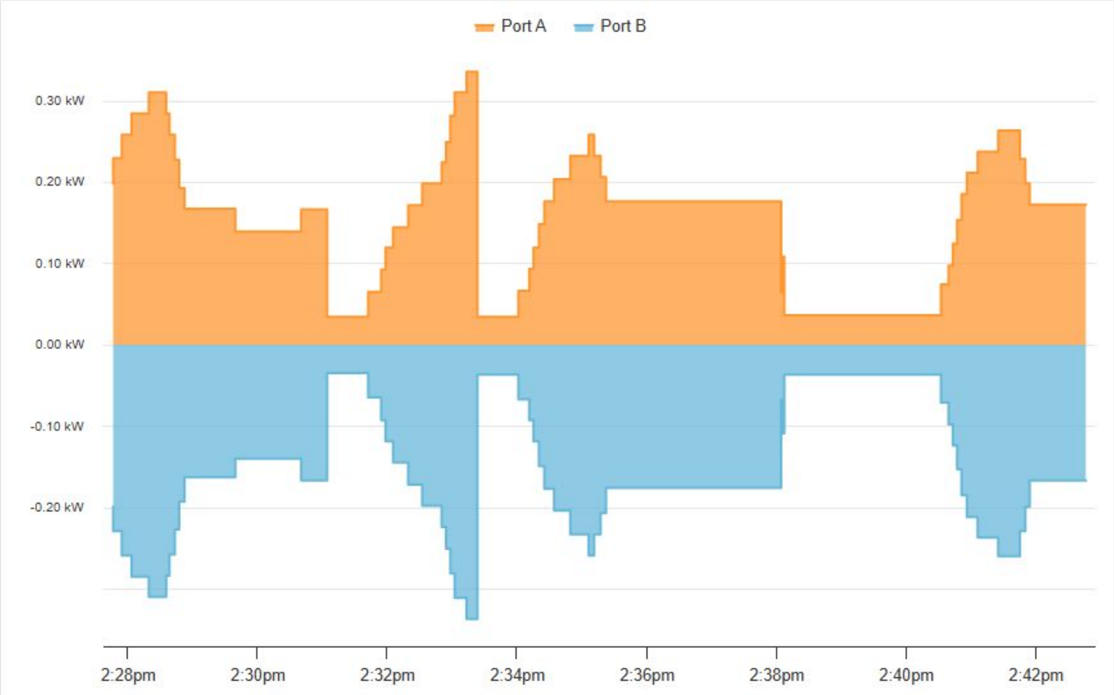



Fan Speed in m/s

# Forced Defrost Cycles



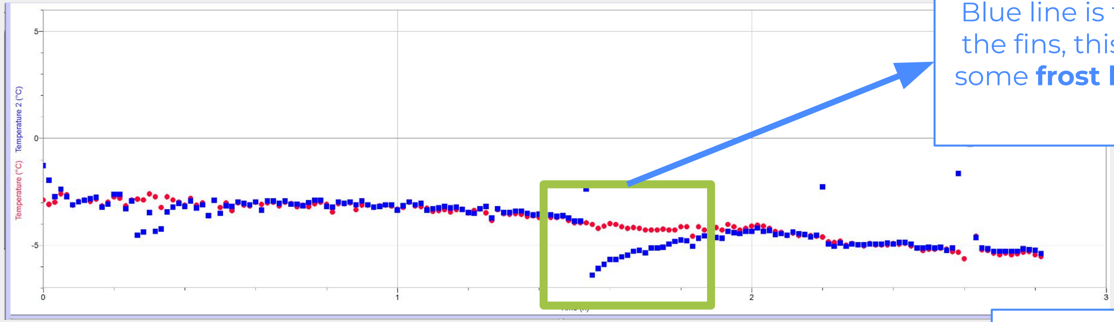
# Full Defrost Cycle



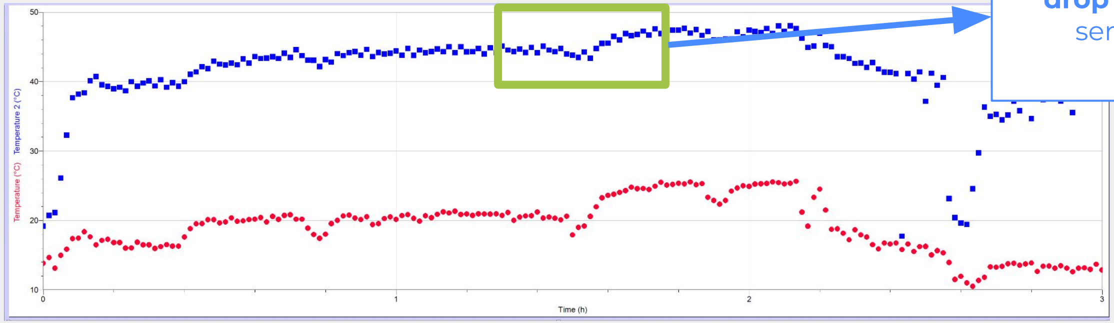

**Time: 9:05:04 mins**

**Power Consumption: ~4.68 kW**

# Partial Defrost Cycle




Blue line is the temperature sensor on the fins, this temperature drop reveals some **frost building up** on and cooling down the fins




Only yields a **small temperature drop** on the inlet temperature sensor that is rapidly over corrected

Only took **~4:40 mins**
and used **~2 kW** power

# 03
# Methodology Approach: Prototype Testing

# Parallel Design

## Power Supply

- Need ability to safely control 120/220V AC input to the coil
- Learn high power electronics

## Icing Methods

- Need method of cooling coil so that it would freeze water vapor in the air

## PETD Implementation

- Shifting focus to smaller scale testing
- Transformer specifications
- Increasing power capability

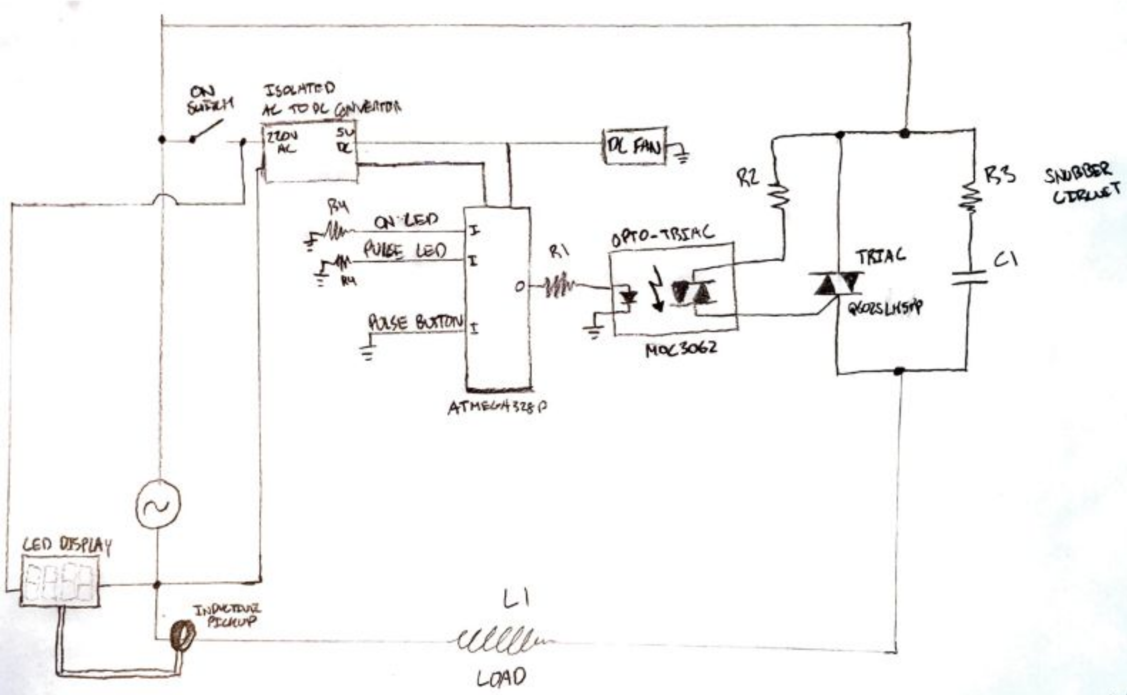
# Power Supply

# Power Supply - Schematic

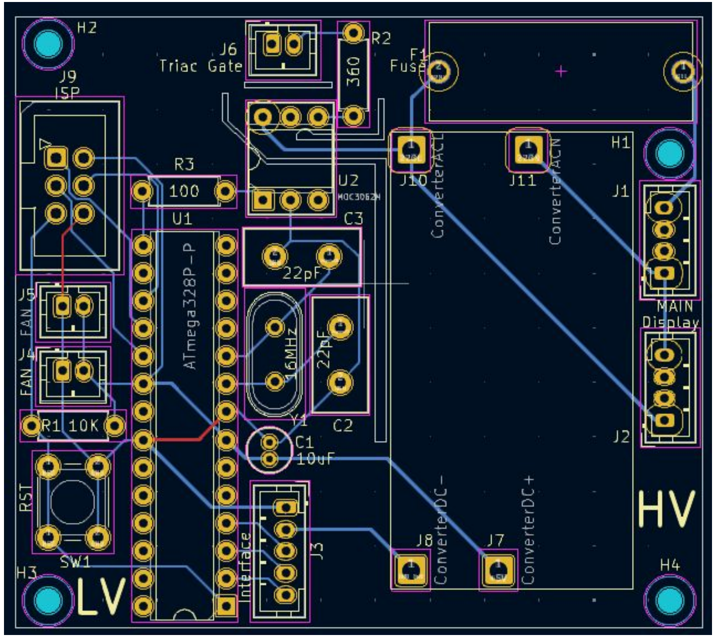
**Basic Idea:** Create a control system that toggles AC input

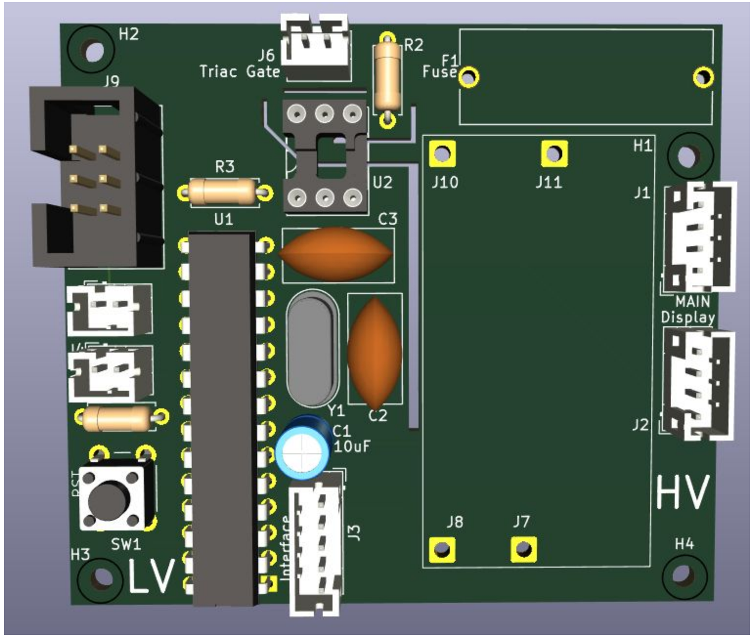
**Design:** Use a microcontroller (atmega328p) to operate an optocoupler (transfers electrical signals between isolated circuits) which will drive a triac (semiconductor switch). The output of the triac will go straight to the load, and allow for steady dI/dt.

**Safety:** Certified isolated AC to DC converter, optocoupler, isolated LV and HV, 2A fuse, heatsink, waterproof housing



# Power Supply - PCB

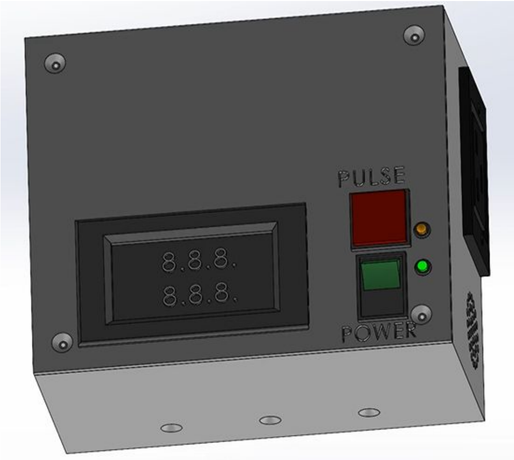


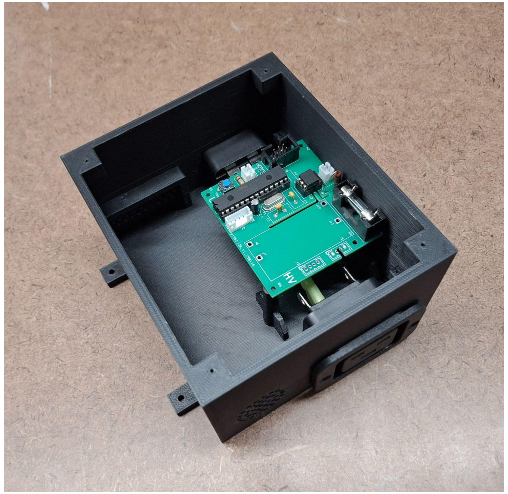

* This design follows IPC clearance and creepage guidelines for 240 AC mains.

# Power Supply - Housing

Custom Design




Assembly

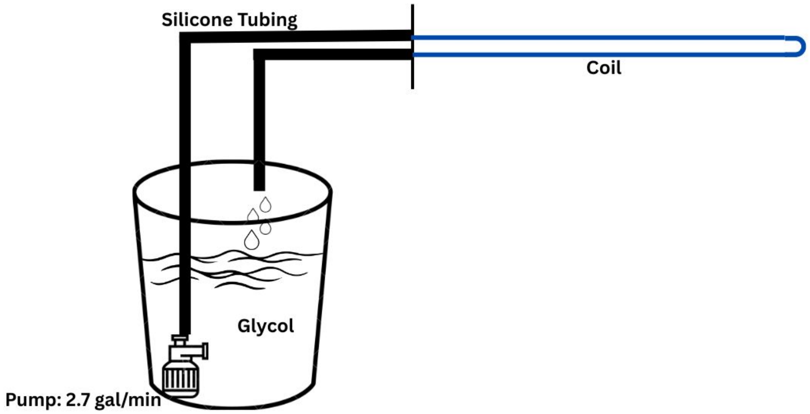


# Power Supply - Isolated Variac

- Proven electrical isolation from mains supply to coil
- Manual switch — safety
- Simple voltage adjustments

# Icing Methods

# Icing Methods - Fluid Loop



# Icing Methods - Fluid Loop Testing

Conducted a preliminary test to verify the possibility of freezing water vapor using this method. Ambient temperature was 30F.

**Test #1:** Antifreeze, ice, salt, coil, tubing, hose clamps, pump, and a misting bottle

- The coil itself was cold to the touch, but no ice was forming

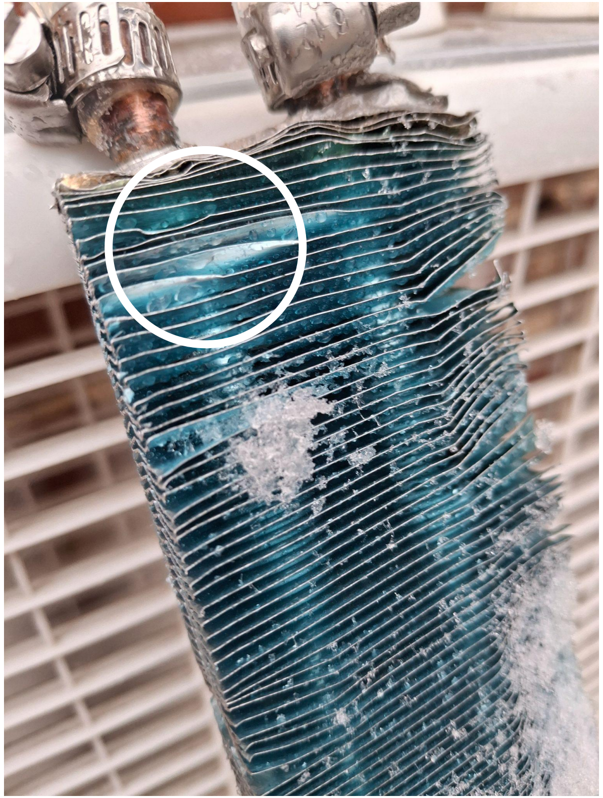
**Test #2:** Added a box fan to the setup

- Results! Water droplets began freezing

**Test #3:** Placed snow on coil

- Snow remained in position

# Icing Methods - Fluid Loop Testing



# Icing Methods - Fan Tunnel

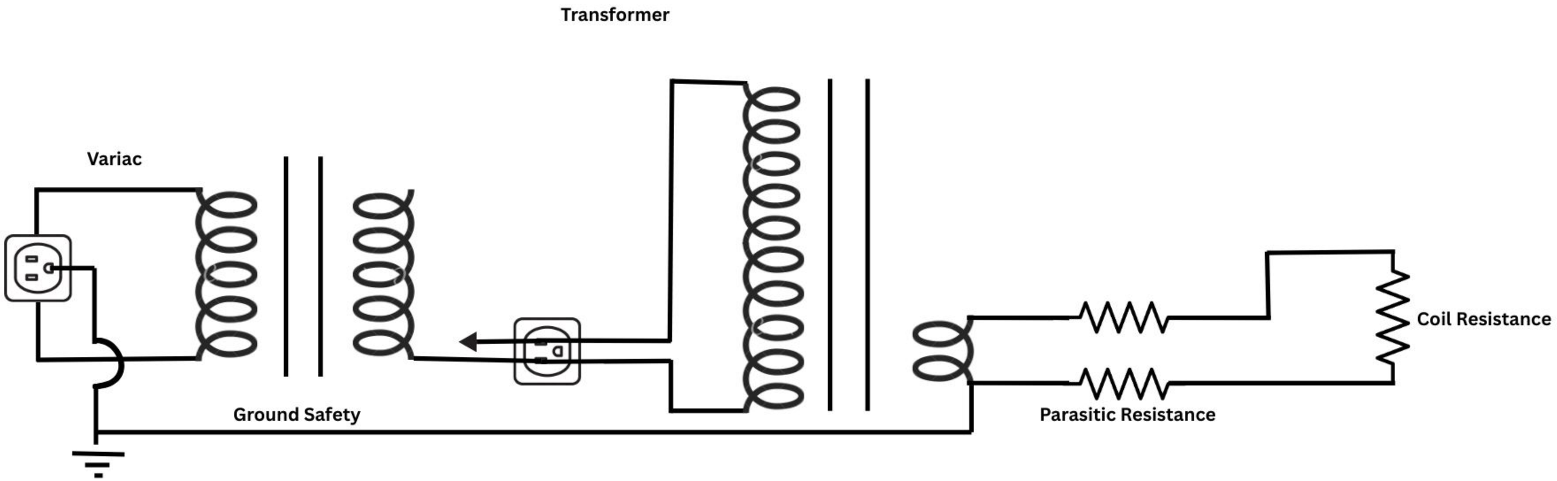
After our initial fluid loop test, we wanted to focus the airflow onto the coil to further **improve our icing capabilities**

# PETD Integration

# Transformer Characterization

- Measuring inductance, resistance, real voltage transfer
    - Done with Bob Barry and Professor Sullivan
- Safety: electrical isolation not fully trusted
- Also concluded which leads to use

# Electrical Design



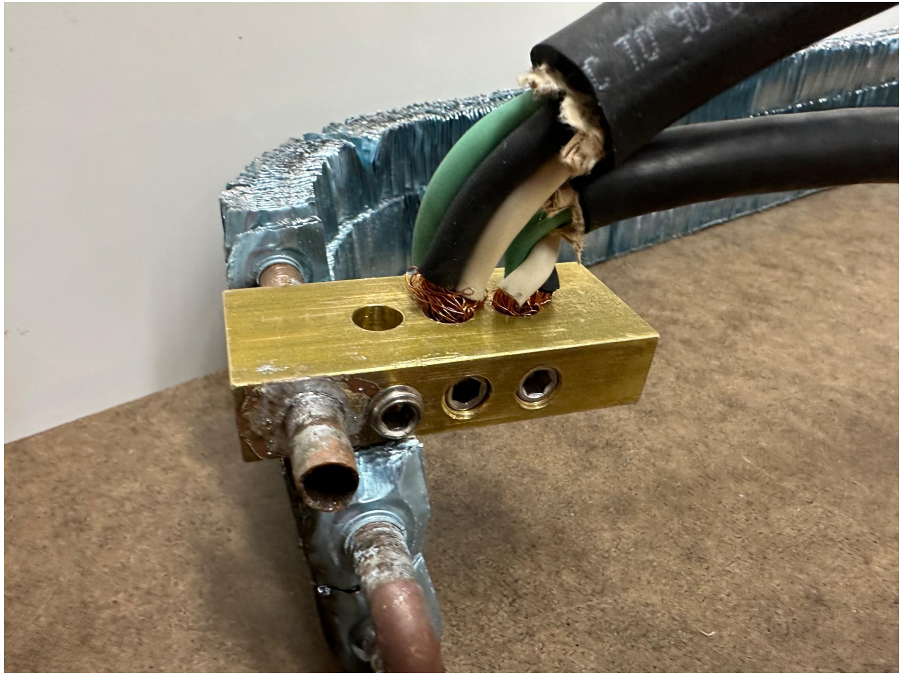
# Design Iterations

# Cables + Solder

- Soldered 6 stranded 12 gauge wire to pipe
- Mechanically connected wires to transformer
- Limited to 120 A

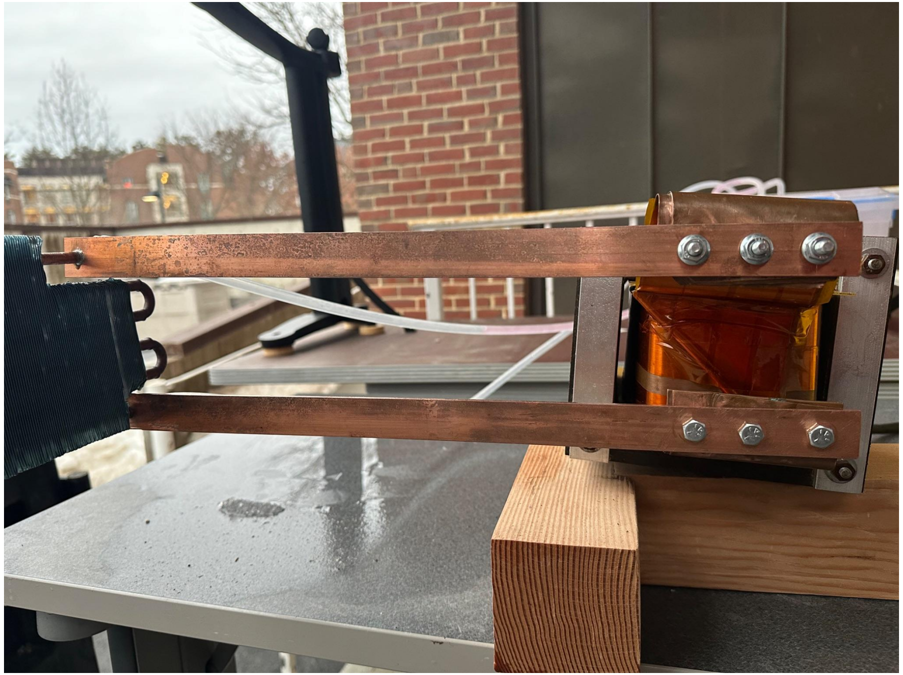
# Cables + Bronze Busbars

- Mechanically screwed wire to busbars
- Mechanically connected and soldered busbars to pipe
- Mechanically connected wires to transformer
- Limited to 150 A

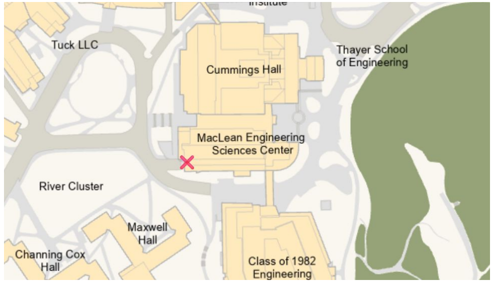


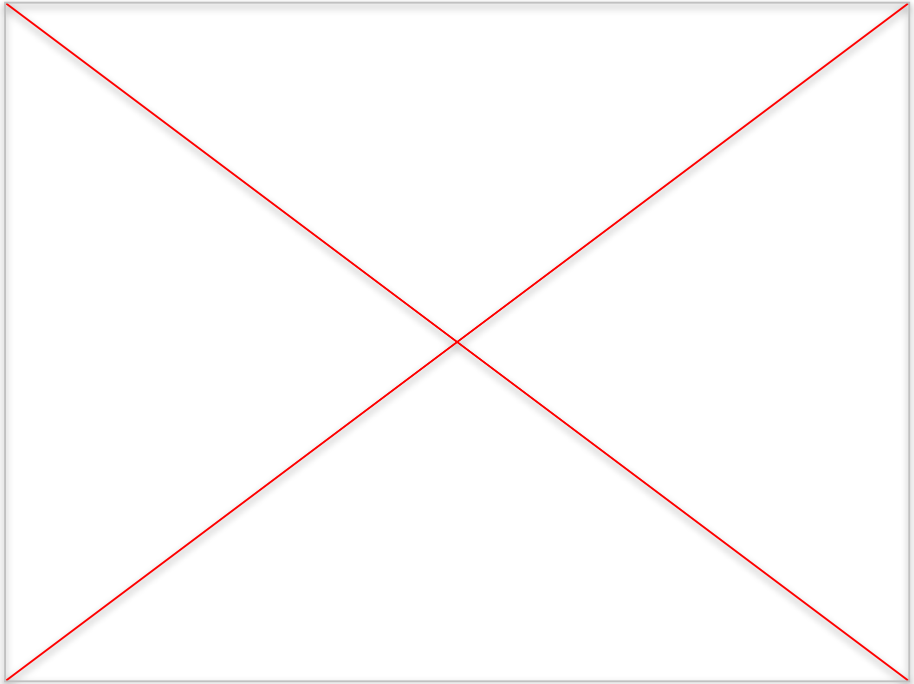
# Copper Busbars

- Mechanically connected and soldered busbars to pipe
- Mechanically bolted busbars to transformer
- High current capability



# Full Test Setup

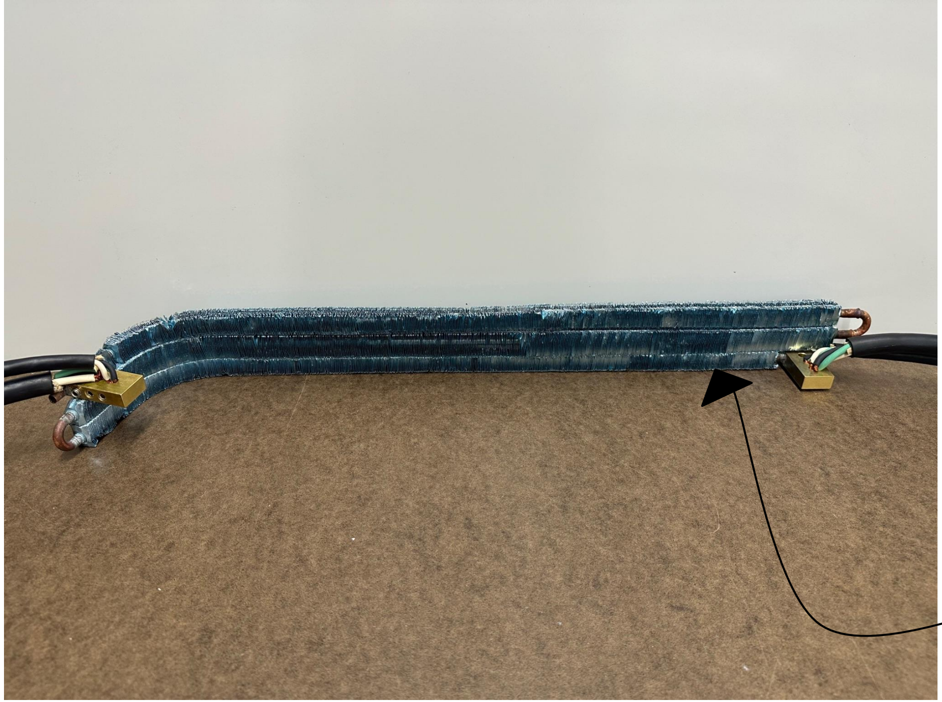


# 1 Length

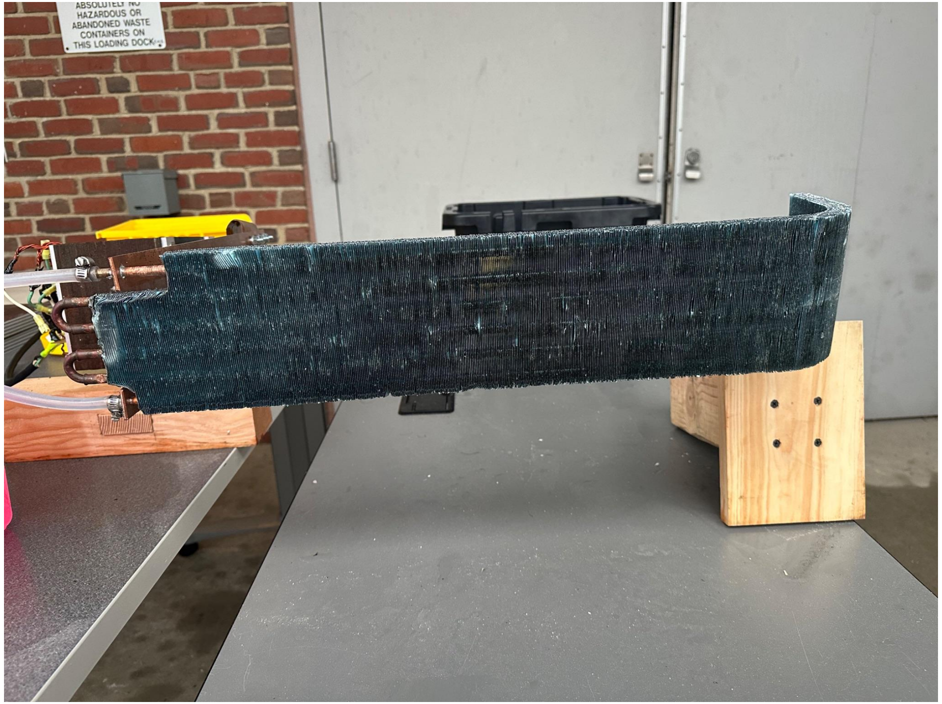
Custom built stand with 3 printed holders

# 3 Lengths



Cuts made in between pipes led to uneven deicing

# 6 Lengths




One complete coil ensures uniform deicing

* LV prevents current from traveling through aluminum fins

# Demo

# Testing Results

| 1 Length | 3 Lengths | 6 Lengths |
|---|---|---|
| 64.8 W → 3.6 kW | ~350 W → 6.5 kW | ~730 W → 6.8 kW |
| 6 minutes | 4:54 minutes | 2:28 minutes |
| 363 Wh | 535 Wh | 283 Wh |

# Takeaways

**0.432 kWh**

Average Total Power Consumption (extrapolated)

**0.342 kWh**

Average Power Consumption Under Favorable Conditions (extrapolated)

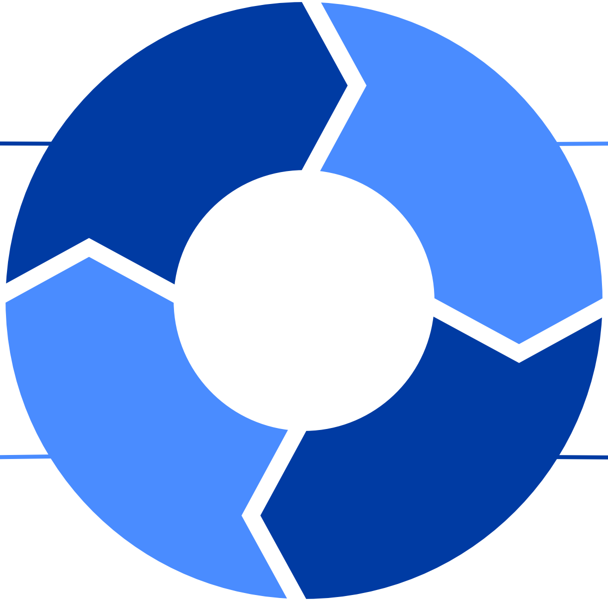
**0.613 kWh**

Average Power Consumption Under Unfavorable Conditions (extrapolated)

# Challenges Faced

**Fluid Loop:**
Glycol-salt-ice mixture freezing in coil

**Variable Conditions:**
Inconsistent ice and snow accumulation on coil



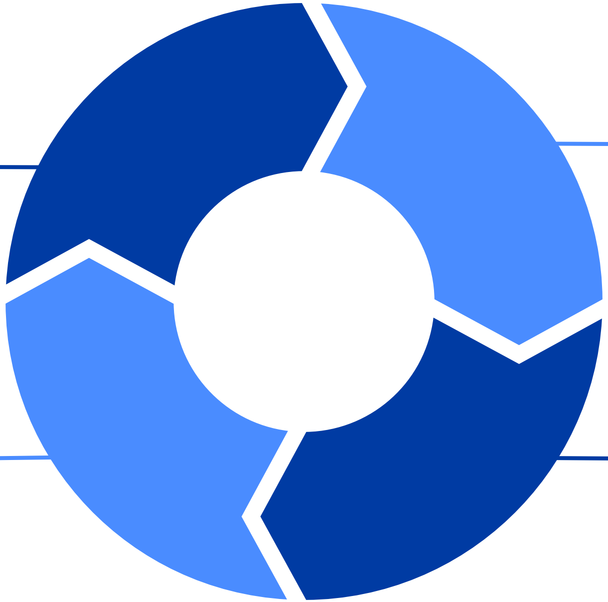
**Safety issues:**
High voltage
Transformer
Control system

**Transformer:**
lower than ideal voltage, big and heavy

# Solutions

**Fluid Loop:**
No dilution paired
with limited ice

**Variable Conditions:**
Spray bottle
Snow application
Fan tunnel



**Safety issues:**
Isolated variac
Dropped to ≤ 120 V

**Transformer:**
High current batteries
should be considered

# 04
# Deliverables: Results

# CoP Calculation

Coefficient of Performance **(CoP)** quantifies efficiency of transfer of electricity input into heating or cooling output as an **instantaneous measurement**

$$CoP = \frac{Q_{out}}{Q_{in}} = \frac{CFM \cdot \Delta T \cdot 1.08}{(kWh_{ODU} + kWh_{AHU}) \cdot 3413}$$

$$\boxed{\mathrm{CoP_{HP}} = \frac{Q_H}{W_{in}}}$$

# CoP Calculations (Defrost Specific)

$$CoP = \frac{Q_{out}}{Q_{in}} = \frac{CFM \cdot \Delta T \cdot 1.08}{(kWh_{ODU} + kWh_{AHU}) \cdot 3413}$$

CFM = 224.61

$\Delta T$ = 24 °F

$kWh_{combined}$ = .702

$$\text{CoP} = \frac{224.61 \cdot 24 \cdot 1.08}{.702 \cdot 3413}$$

**CoP = 2.43**

# CoP Comparisons

## CoP Defrost

CFM = 224.61
$\Delta T$ = 24 ℉
$kWh_{combined}$ = 0.702 kWh

$$CoP = \frac{224.61 \cdot 24 \cdot 1.08}{.702 \cdot 3413}$$

**CoP = 2.43**

## CoP Standard

CFM = 224.61
$\Delta T$ = 24 ℉
$kWh_{combined}$ = 0.150 kWh

$$CoP = \frac{224.61 \cdot 24 \cdot 1.08}{.150 \cdot 3413}$$

**CoP = 11.37**

# Final Comparison

ASHP Defrost

$4.68\ \text{kW} \cdot 0.150833\ \text{hr} =$

**0.702 kWh**

Prototype

$6.37\ \text{kW} \cdot 0.07\ \text{hr} =$

**0.432 kWh**

# 05

# Societal Impacts and Economic Analysis

# Societal Impact

## 1 Political

Advanced, high-efficiency ASHPs designed for cold climates have the potential to influence policymakers to enact more supportive regulations and incentives for renewable energy adoption.

## 2 Environmental

Implemented safety measures to eliminate the risk of electrocution to local wildlife and prevent refrigerant leaks, safeguarding soil integrity and protecting plant life

## 3 Economical

ASHPs designed for greater efficiency in cold climates deliver substantial long-term economic advantages, such as sustained energy savings, reduced operational costs, and a stronger return on investment over their lifespan

# Economic Analysis

| Components | Cost | | Ratings |
|---|---|---|---|
| Breaker | $85.00 | /unit | 300 A 48 V |
| Relay | $20.00 | /unit | 200 A 24 V |
| Transformer | $100.00 | /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 | $500.00 | /unit | |
| | | | |
| Added revenue | $230.00 | /unit | |

# Market Adoption

Our sponsor’s goal is to have convincing data to pitch to **HVAC manufacturers**.

Our project did not provide entirely conclusive results, however it justifies further data collection.

If results are more certain, this product could save energy on a global scale.

# 06
# Conclusions and Future Work

# Conclusions

- Proved significant drop in CoP during defrost cycle
  - Added potential **novel contribution** to literature on defrost cycle
- PETD uses less energy than classical defrost cycle
  - Difference is **not as substantial** as hoped
  - May not be worth the cost
- Variable conditions and inconsistent data for both control and prototype testing contribute to higher uncertainty
  - Better **controlled lab** needed to do full cost benefit analysis

# Next Steps

**Further prototype testing** → **Re-evaluate power supply** → **Improve rigor of defrost cycle testing**

- Scale up to a full size system
- Weigh coil, frost, collected frost
- Vibration to remove water

- Consider using 30V
- Still safe
- Less current requirement
- Smaller, lighter

- Use Ice Lab facility
- Control temperature, humidity, etc.
- Repeatable conditions
- HVAC/Ice Lab Researchers

# Special Thanks

Bob Barry
John Chen
Sol Diamond
Chris Magoon
Emily Monroe
Jason Stauth
Raina White
Cheng Chen
Danny DeNauw
Alexa Freitas
Dave McDevitt
John Stark
Charlie Sullivan

# Thank You

Questions?

# Appendix

# Transformer Data

| Inductance Secondary (mH) (Sullivan) | Inductance Secondary (mH) (Bob) | Primary Wires | Inductance Primary (mH) (Sullivan) | Inductance Primary (mH) (Bob) | DC Resistance Primary (Ohm) (Bob) | Turns Ratio (Sullivan) | Turns Ratio (Bob) | Turns Ratio (avg) | Vout Predicted (10V, 60 Hz, input) | Vout Real (10V, 60 Hz input) | Vout Real (10V, 100 kHz input) | Ratio (real/expected) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.046 | 0.047 | 1->2 | 28 | 30.5 | 0.12 | 0.04053217417 | 0.03925536405 | 0.03989376911 | 0.3989376911 | 0.206 | | 0.5163713648 |
| | | 1->3 | | 40.1 | | | 0.03423550533 | 0.03423550533 | 0.3423550533 | 0.197 | | 0.5754260032 |
| | | 1->4 | | 50.68 | | | 0.0304530381 | 0.0304530381 | 0.304530381 | 0.187 | | 0.6140602438 |
| | | 1->5 | | 61.04 | | | 0.02774863769 | 0.02774863769 | 0.2774863769 | 0.177 | | 0.6378691522 |
| | | 1->6 | | 75 | | | 0.02503331114 | 0.02503331114 | 0.2503331114 | 0.166 | 0.195 | 0.6631164334 |
| | | 2->3 | 0.429 | 0.43 | 0.02 | 0.3274539773 | 0.3306090222 | 0.3290314997 | 3.290314997 | 0.0453 | | 0.01376767879 |
| | | 2->4 | | 1.754 | | | 0.1636945176 | 0.1636945176 | 1.636945176 | 0.134 | | 0.08185979711 |
| | | 2->5 | | 3.731 | | | 0.1122370658 | 0.1122370658 | 1.122370658 | 0.2 | | 0.1781942521 |
| | | 2->6 | | | | | | | | 0.244 | | |
| | | 3->4 | 0.429 | 0.43 | 0.02 | 0.3274539773 | 0.3306090222 | 0.3290314997 | 3.290314997 | 0.0455 | | 0.01382846324 |
| | | 3->5 | | 1.57 | | | 0.1730211135 | 0.1730211135 | 1.730211135 | 0.124 | | 0.07166755401 |
| | | 3->6 | | | | | | | | 0.206 | | |
| | | 4->5 | 0.33 | 0.34 | 0.01 | 0.3733549777 | 0.3718000728 | 0.3725775253 | 3.725775253 | 0.0375 | | 0.01006501935 |
| | | 4->6 | | | | | | | | 0.134 | | |
| | | 5->6 | 0.529 | 0.535 | 0.03 | 0.2948839123 | 0.296395795 | 0.2956398537 | 2.956398537 | 0.055 | | 0.01860371642 |

# Prototype Data

| | Voltage (V) | Amperage (A) | Power Test (W) | Avg Power (W) | Power Total (W) | Time (minutes) | Avg Time (mins) | Energy (kJ) | Energy (kWh) | Avg Energy (kWh) | Temp Coil Start (ºF) | Temp Coil End (ºF) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 length | 0.4 | 162 | 64.8 | 64.8 | 3628.8 | 6 | 6 | 1306.368 | 0.36288 | 0.36288 | NA | NA |
| 3 lengths | 1.57 | 205 | 321.85 | 354.554 | 6007.866667 | 4.75 | 4.9 | 1712.242 | 0.4756227778 | 0.5352898444 | 28.5 | NA |
| | 1.6 | 206 | 329.6 | | 6152.533333 | 6.25 | | 2307.2 | 0.6408888889 | | 28.2 | 100 |
| | 1.71 | 227 | 388.17 | | 7245.84 | 3 | | 1304.2512 | 0.362292 | | 23 | 145 |
| | 1.71 | 215 | 367.65 | | 6862.8 | 5.5 | | 2264.724 | 0.62909 | | 24.8 | 145 |
| | 1.7 | 215 | 365.5 | | 6822.666667 | 5 | | 2046.8 | 0.5685555556 | | 23.8 | 185 |
| 6 lengths | 3.41 | 220 | 750.2 | 736.6833333 | 7001.866667 | 2 | 2.4721 | 840.224 | 0.2333955556 | 0.2828640995 | 33 | 91 |
| | 3.4 | 215 | 731 | | 6822.666667 | 3.333 | | 1364.39688 | 0.3789991333 | | 33 | 115 |
| | 3.39 | 215 | 728.85 | | 6802.6 | 2.0833 | | 850.3113948 | 0.2361976097 | | 33 | 110 |
| Averages | | | | | 6371.96 | 4.212922222 | | 1555.168608 | 0.4319912801 | | | |
| Good Conditions | | | | | 6251.606667 | 3.527716667 | | 1229.632246 | 0.3415645127 | | | |
| Bad Conditions | | | | | 6612.666667 | 5.583333333 | | 2206.241333 | 0.6128448148 | | | |

# Major Setbacks

## Fluid Loop

- Freezing
- Fluid velocity
- Glycol mixture

## Safety

- High voltage
- Time intensive prototyping
- Control system

## Transformer

- Lower than ideal voltage
- Big and heavy

**Intro - 2**
**Control - 5**
**Prototype - 5.5**
**Combined - 1**
**Ending - 1**

# Electrical Design

### Cables + Solder

Limited to 120 A

Simplest to fabricate, but time intensive

### Cables + Busbars

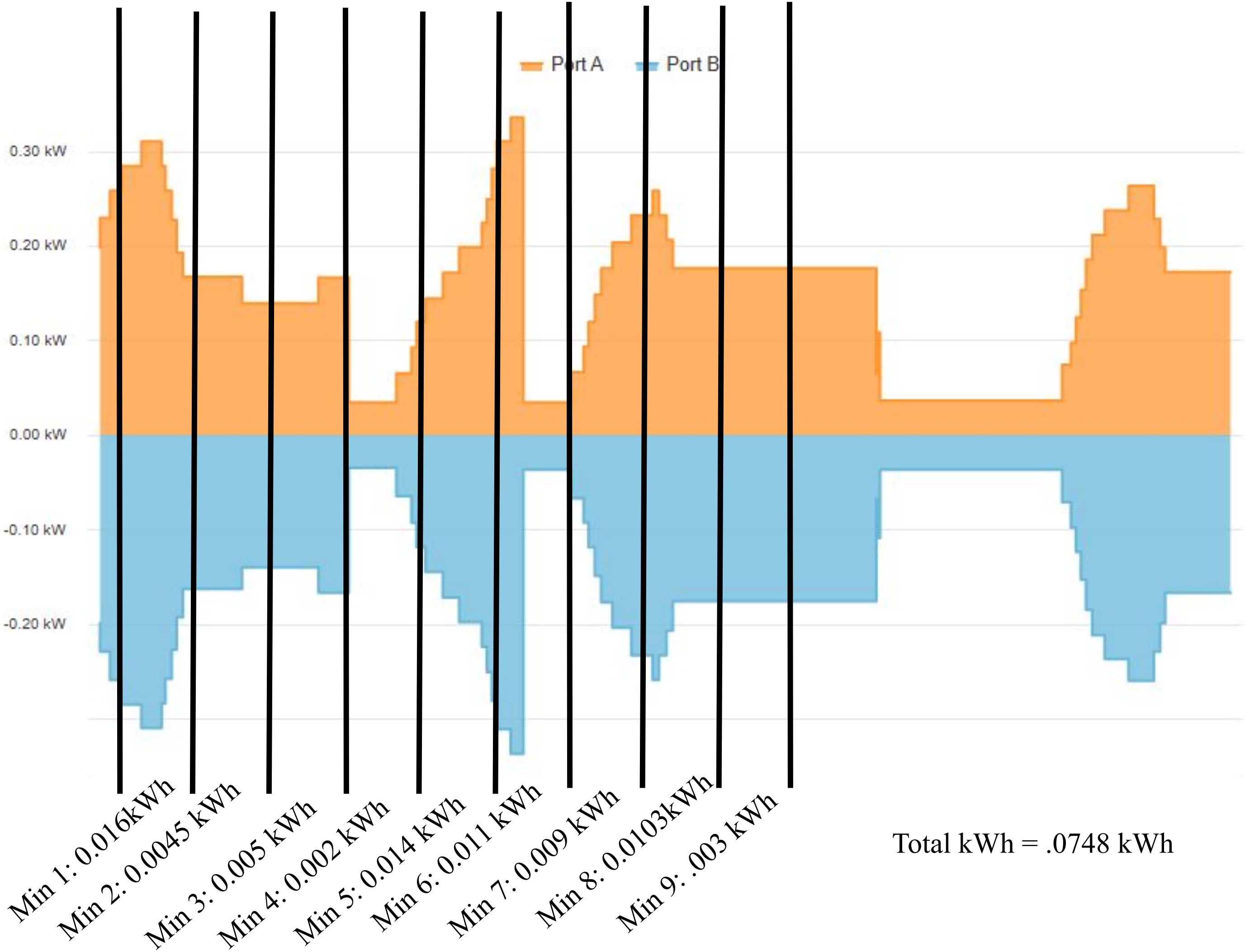
Limited to 150 A

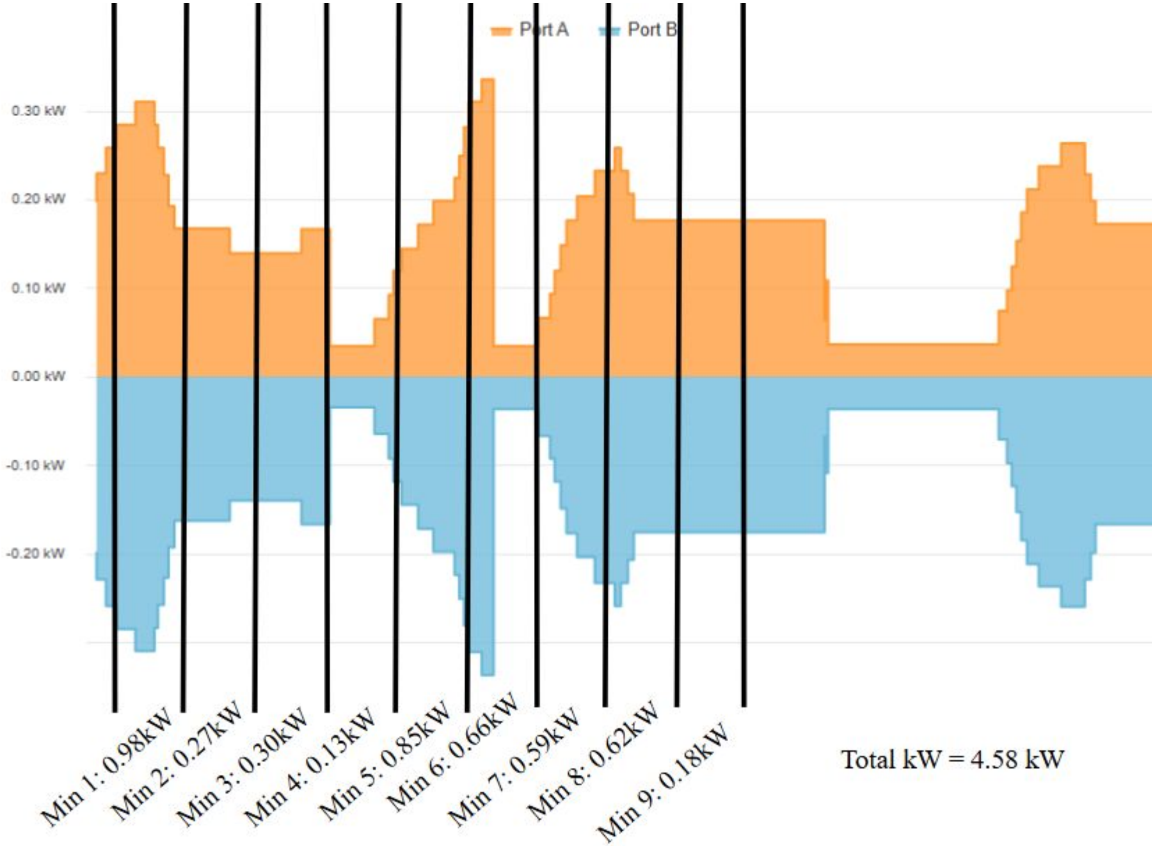
Easiest to assemble for testing

### Busbars

Very high current

Hardest to transport


Port A
Port B
0.30 kW
0.20 kW
0.10 kW
0.00 kW
-0.10 kW
-0.20 kW
Min 1: 0.016kWh
Min 2: 0.0045 kWh
Min 3: 0.005 kWh
Min 4: 0.002 kWh
Min 5: 0.014 kWh
Min 6: 0.011 kWh
Min 7: 0.009 kWh
Min 8: 0.0103kWh
Min 9: .003 kWh
Total kWh = .0748 kWh


Port A
Port B
0.30 kW
0.20 kW
0.10 kW
0.00 kW
-0.10 kW
-0.20 kW
Min 1: 0.98kW
Min 2: 0.27kW
Min 3: 0.30kW
Min 4: 0.13kW
Min 5: 0.85kW
Min 6: 0.66kW
Min 7: 0.59kW
Min 8: 0.62kW
Min 9: 0.18kW
Total kW = 4.58 kW