# A.C.E.S.

***A**ir-breathing **C**old **E**ngine **S**tart*

## Test Readiness Review

Alex Bertman, Jake Harrell, Tristan Isaacs, Alex Johnson, Matthew McKernan, T.R. Mitchell, Nicholas Moore, James Nguyen, Matthew Robak, Lucas Sorensen, Nicholas Taylor

# Outline

- Overview
- Schedule
- Testing
- Budget

# Overview

Overview | Schedule | Testing | Budget

# Project Description

**Design, build, and test a system to facilitate starting a JetCat P90-SXi jet engine at a temperature of -50°F by:**

- Controlling the temperature and mass flow rate of the fuel into the engine
- Ensuring that the engine electronics are within their operating temperature range
- Ensuring that the heating system has sufficient power to heat the fuel delivery system and engine electronics

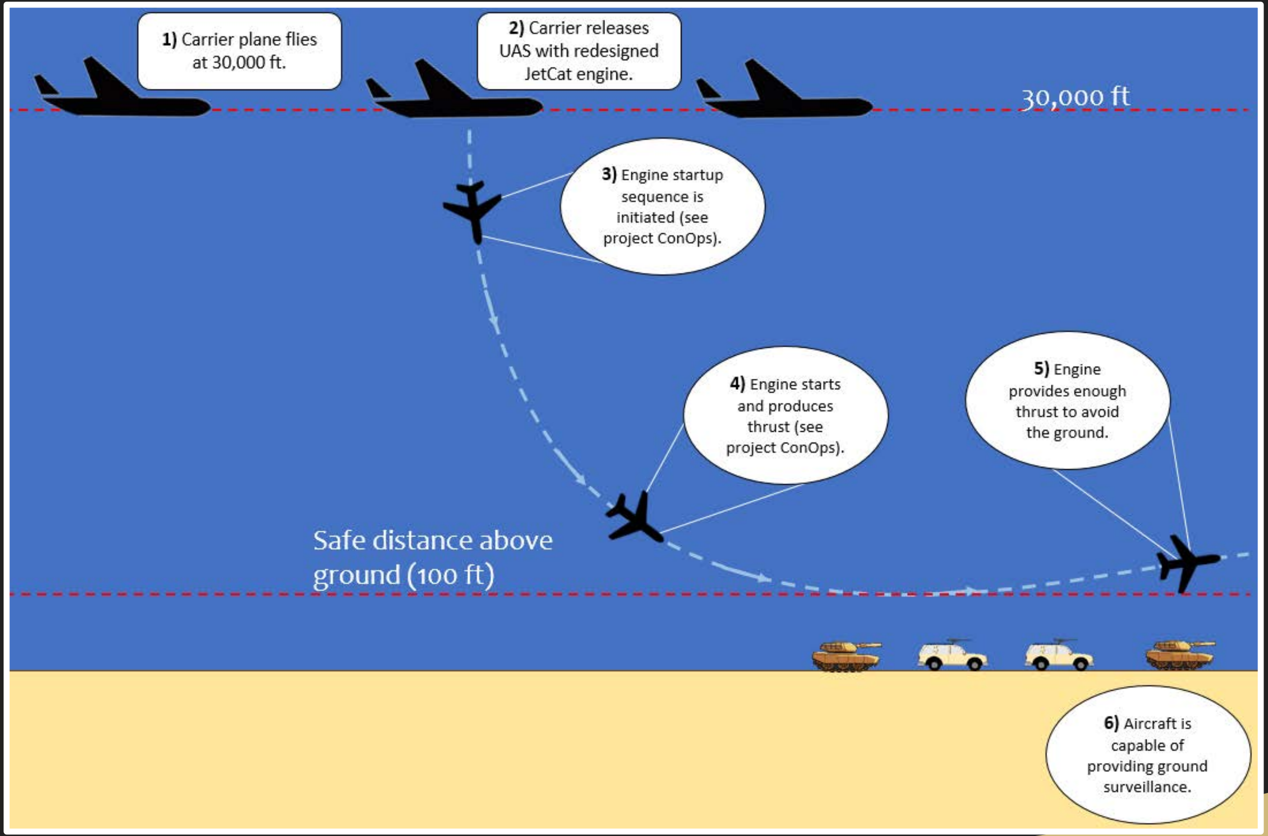
**Motivation:**

- Air Force Research Lab (AFRL) conference
- Proof of concept for high-altitude (cold-temperature) restart for jet-powered UAS

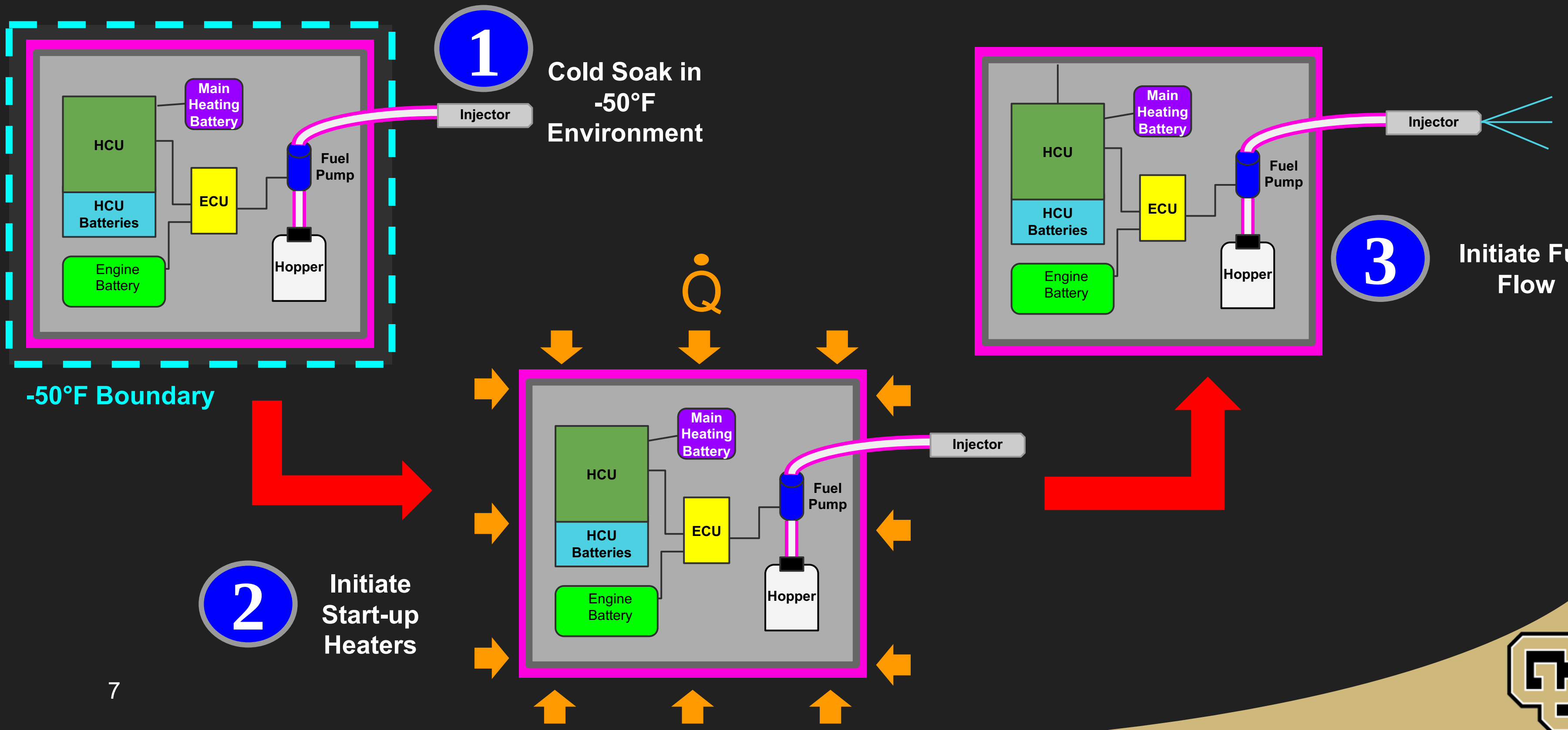
# Course Project Objectives

| | Fuel Delivery System (FDS) | Electronics Heating | Startup Time | AFRL Conference |
|---|---|---|---|---|
| **Level 1** | System will control mass flow rate & temperature of fuel when placed in an environment cold-soaked to -30°F. | The electronics will be heated to 60°F after being placed in an environment cold-soaked to -30°F. | The fuel delivery and electronics heating systems objectives will be completed in less than 3 hours. | |
| **Level 2** | System will control mass flow rate & temperature of fuel when placed in an environment cold-soaked to -40°F. | The electronics will be heated to 60°F after being placed in an environment cold-soaked to -40°F. | The fuel delivery and electronics heating systems objectives will be completed in less than 1.5 hours. | |
| **Level 3** | System will control mass flow rate & temperature of fuel when placed in an environment cold-soaked to -50°F. | The electronics will be heated to 60°F after being placed in an environment cold-soaked to -50°F. | The fuel delivery and electronics heating systems objectives will be completed in less than 8 m 42 s | |
| **Level 4** | | | | Entire system will be integrated with engine and successfully start within 3 hours. |

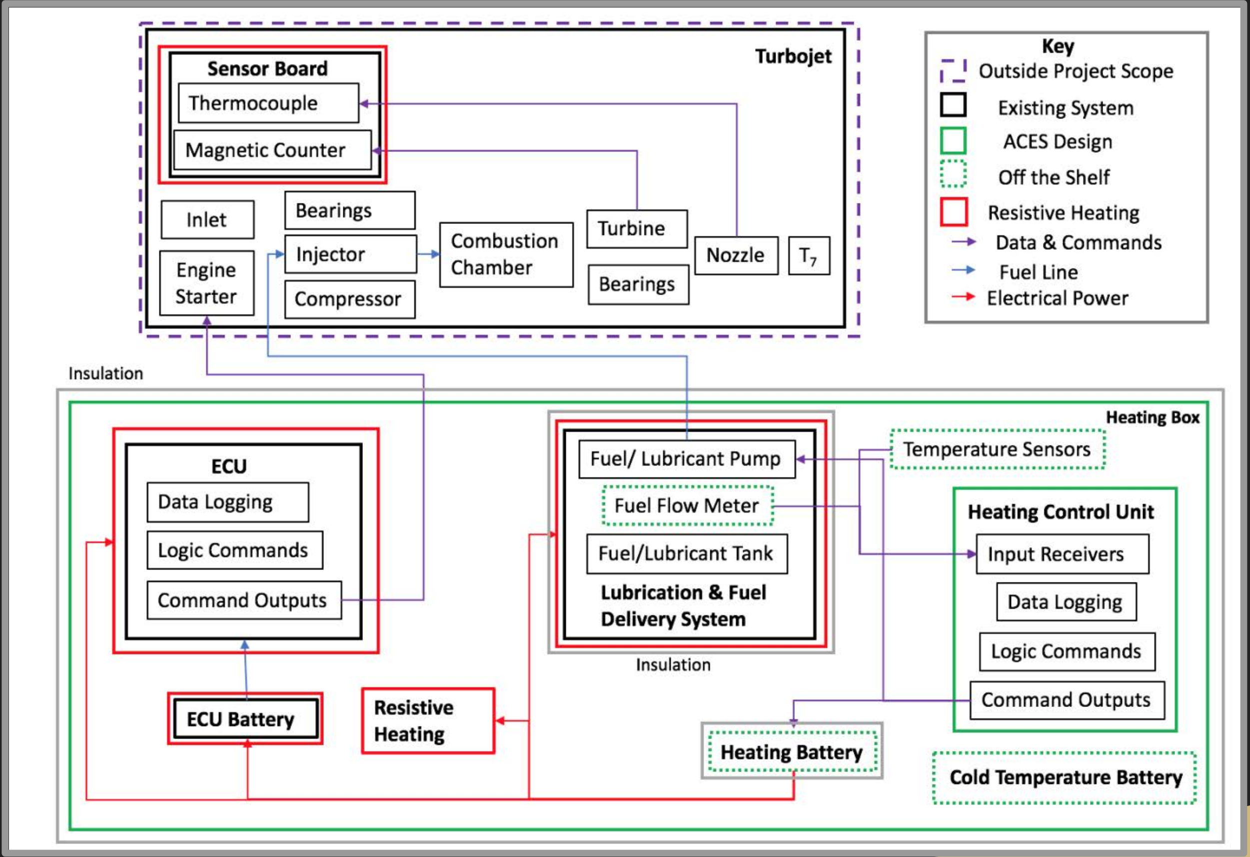
# Mission CONOPS



# Project Conops

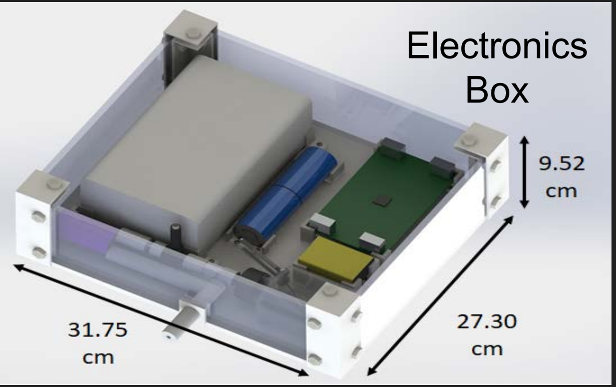


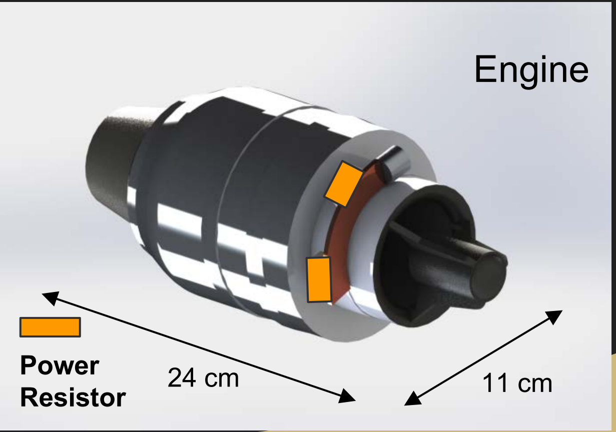
# Functional Block Diagram



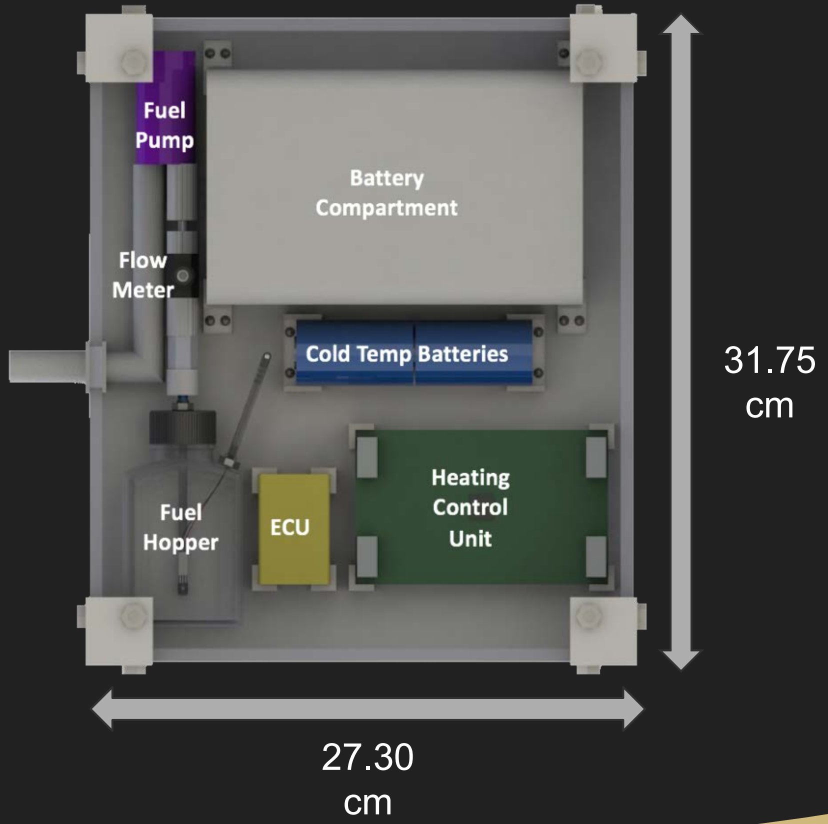
# Baseline Design

- **Initial Energy:** Cryogel insulated battery
- **Fuel Delivery System:** Resistive heating wire wrapped around fuel delivery components insulated in Cryogel
- **Electronics Heating:** Resistive heating within manufactured plastic box, ESB heated by power resistors in engine cowling
- **Heating Control Unit (HCU):** Microcontroller powered by cold temperature batteries, controls temperatures and fuel flow rate
- **Updates Since MSR:** Complications arose when testing the method of sewing insulation. Now securing aerogel around essential components by wrapping with thread.



# Baseline Design



# Critical Project ELements

**CPE 1:** Temperature of main heater battery must be > 30°F and < 122°F

**CPE 2:** ECU, ESB, and engine battery temperatures must be > 60°F while < 122°F for the battery and < 150°F for the ECU and ESB

**CPE 3:** Temperature of fuel in fuel delivery system must be > 60°F and < 115°F

**CPE 4:** A Heating Control Unit (HCU) must control the mass flow rate of fuel and heating systems

# Functional Requirements

- ***FR 1.0) ENERGY:*** An initial energy source shall provide adequate power for the fuel delivery system heating and electronics heating.

- ***FR 2.1) FDS:*** The Fuel Delivery System shall provide a specified fuel flow rate from 0 to 4.8 g/s ± 0.13 g/s to the engine.

- ***FR 2.2) FDS:*** The Fuel Delivery System shall provide fuel at a specified temperature from 60 to 110°F ± 3.6°F to the engine.

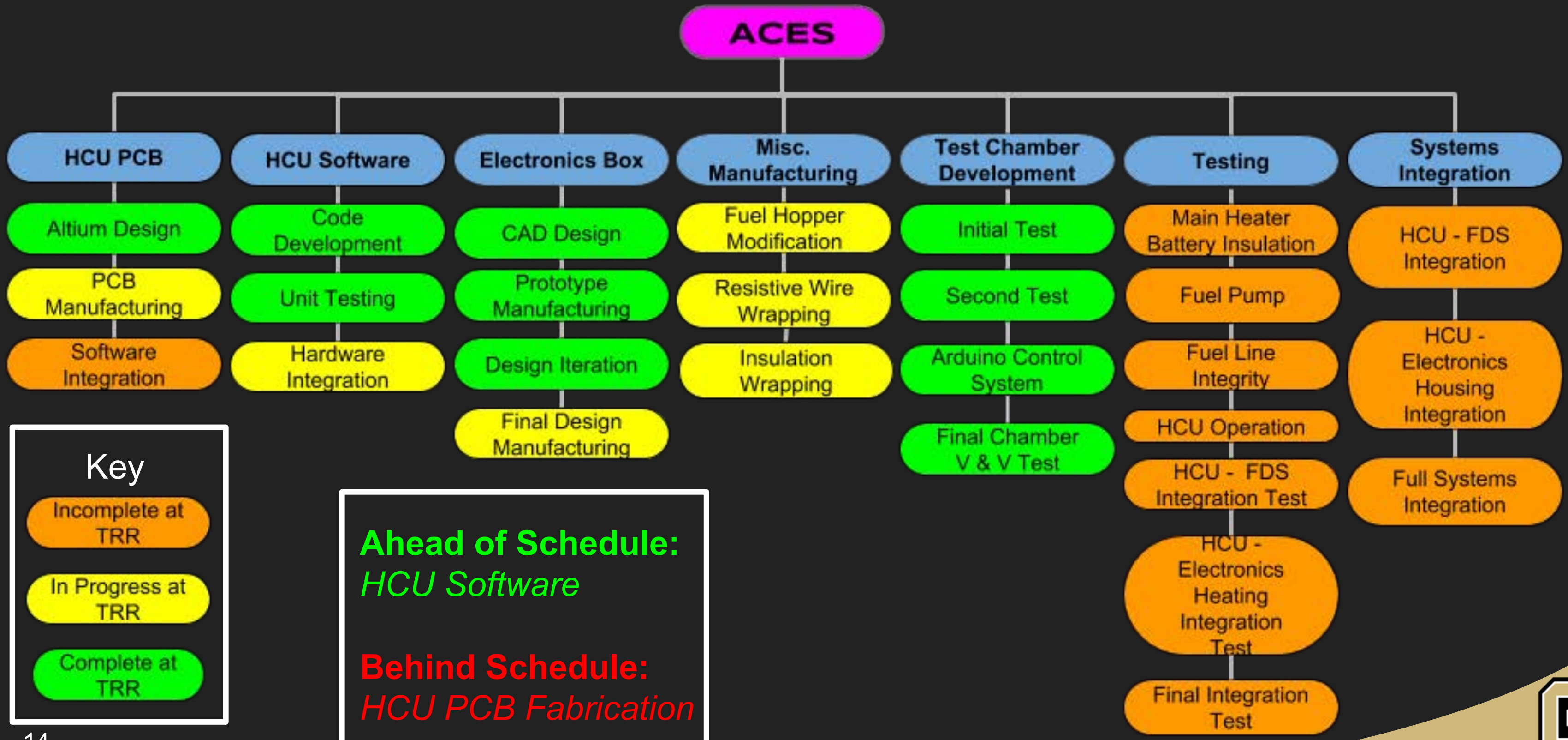
- ***FR 3.0) Electronics Heating:*** The electronics (ECU, ESB, batteries) shall be heated to within their operating temperature range of 60°F to 122°F.

- ***FR 4.1) HCU:*** The Heating Control Unit (HCU) shall monitor and regulate the temperature of the electronic components and fuel delivery heating systems.

- ***FR 4.2) HCU:*** The Heating Control Unit (HCU) shall monitor and regulate the mass flow rate of the fuel delivery heating system.

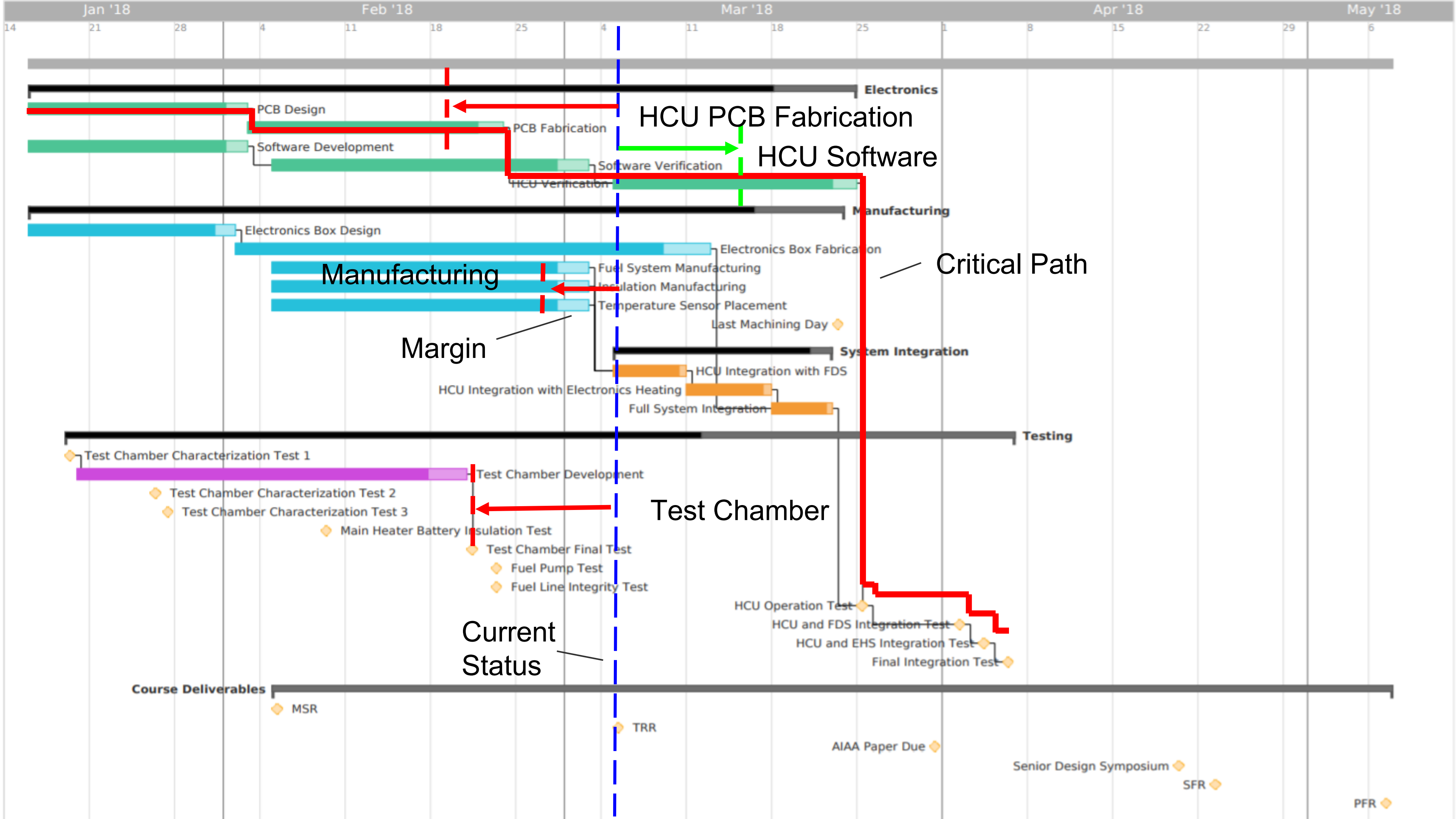
# Schedule

# Status Summary

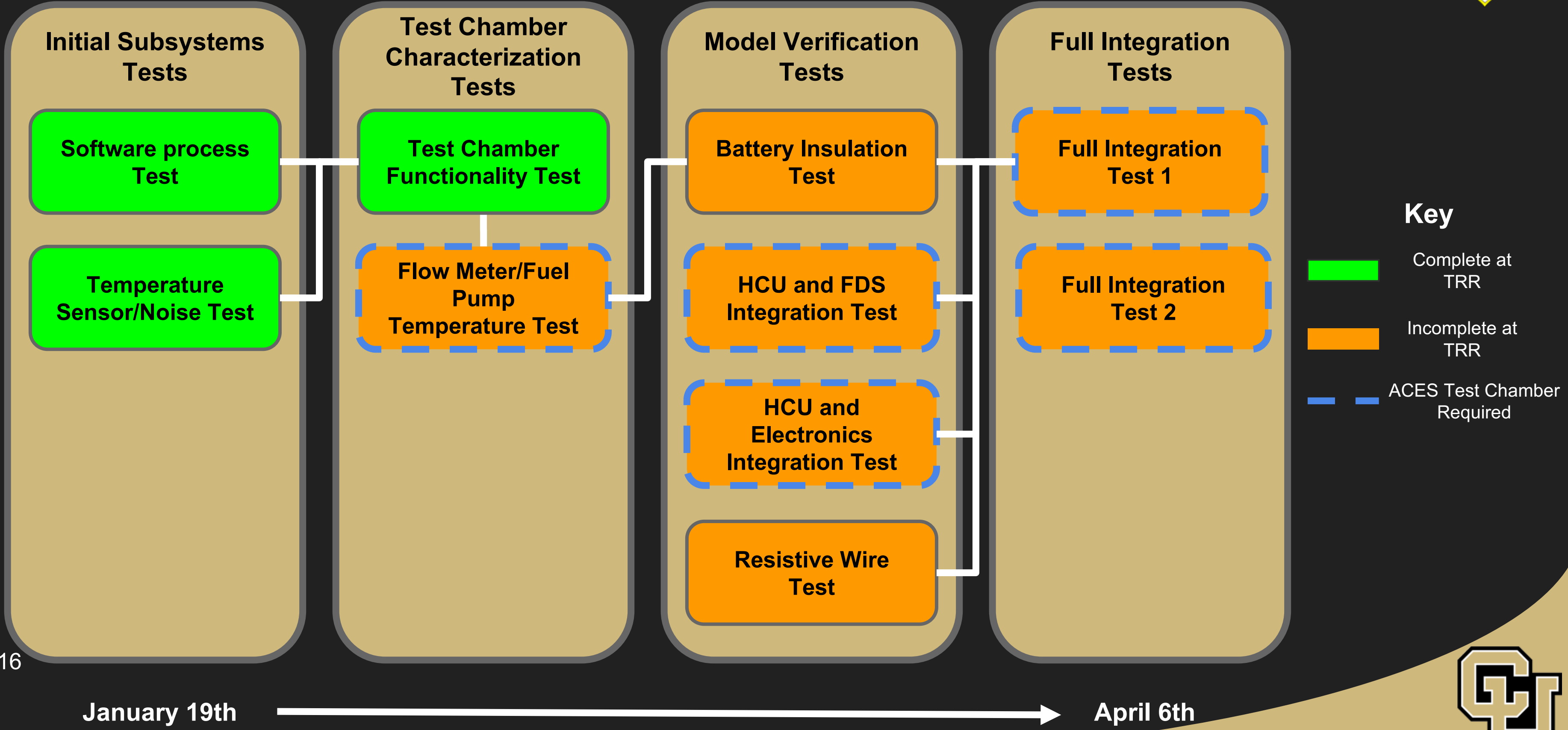



**Ahead of Schedule:**
*HCU Software*

**Behind Schedule:**
*HCU PCB Fabrication*

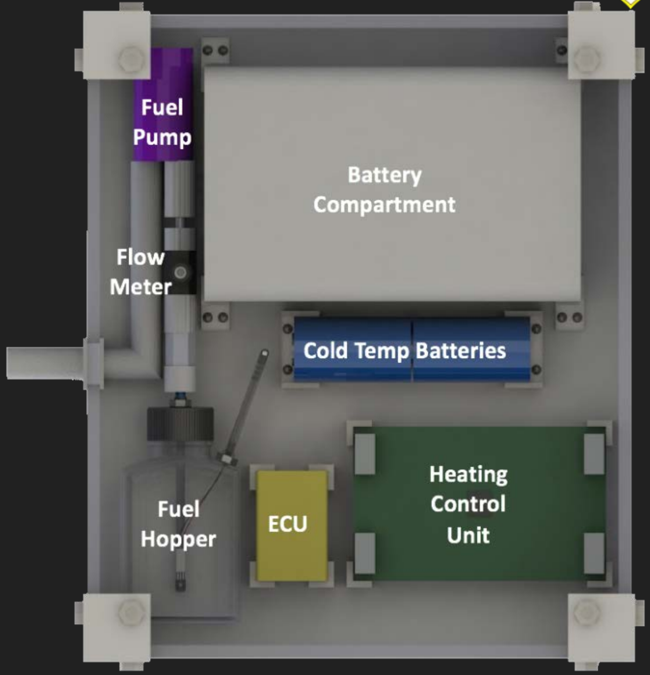

Jan '18
Feb '18
Mar '18
Apr '18
May '18
Electronics
PCB Design
PCB Fabrication
Software Development
Software Verification
HCU Verification
HCU PCB Fabrication
HCU Software
Manufacturing
Electronics Box Design
Electronics Box Fabrication
Fuel System Manufacturing
Insulation Manufacturing
Temperature Sensor Placement
Last Machining Day
Manufacturing
Margin
Critical Path
System Integration
HCU Integration with FDS
HCU Integration with Electronics Heating
Full System Integration
Testing
Test Chamber Characterization Test 1
Test Chamber Development
Test Chamber Characterization Test 2
Test Chamber Characterization Test 3
Main Heater Battery Insulation Test
Test Chamber Final Test
Fuel Pump Test
Fuel Line Integrity Test
Test Chamber
HCU Operation Test
HCU and FDS Integration Test
HCU and EHS Integration Test
Final Integration Test
Current Status
Course Deliverables
MSR
TRR
AIAA Paper Due
Senior Design Symposium
SFR
PFR

# Planned Tests Summary



# Testing

Initial Subsystems
Test Chamber
Model Verification
Full Integration

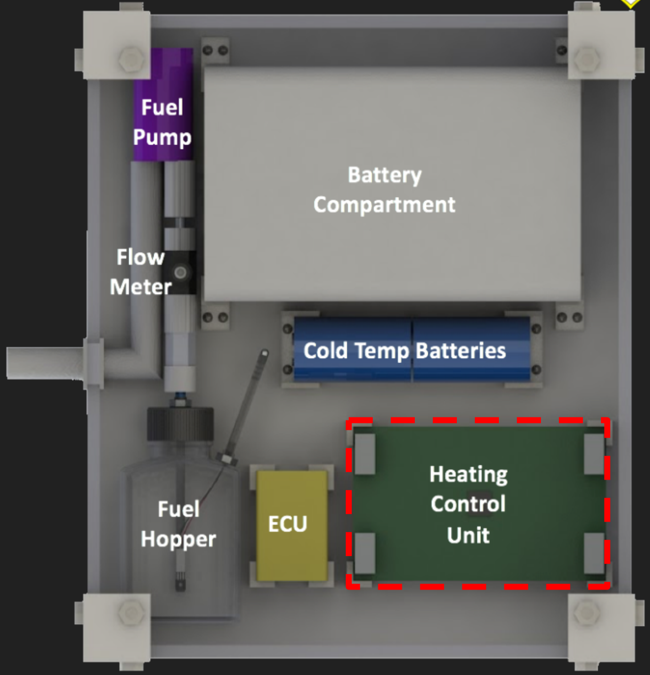



Overview | Schedule | Testing | Budget

# Initial Subsystems

Software Flow

Temp Sensor/Noise




Overview | Schedule | Testing | Budget

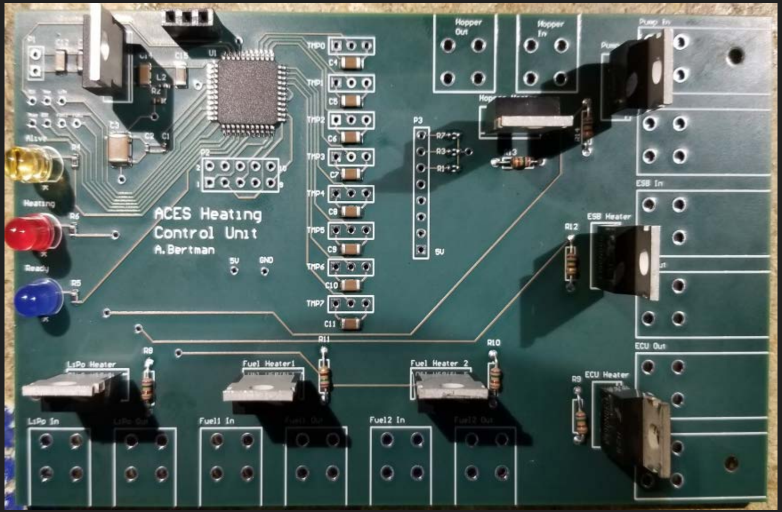
# HCU Software Testing

1. **Software Process Test**

1. **Temperature Sensor/Noise Test**

1. **Flow Meter/Fuel Pump Temperature Test**

7.5 cm




12.7 cm

Status of HCU (3/2/2018)

# Software Process Test

**Purpose:**

- Test HCU's ability to meet **FR 4.1 and 4.2**
- Ensure HCU can transition between the 3 modes of operation:
    - Warming
    - Pumping (and still warming)
    - Warming (fuel exhausted)

**Plan:**

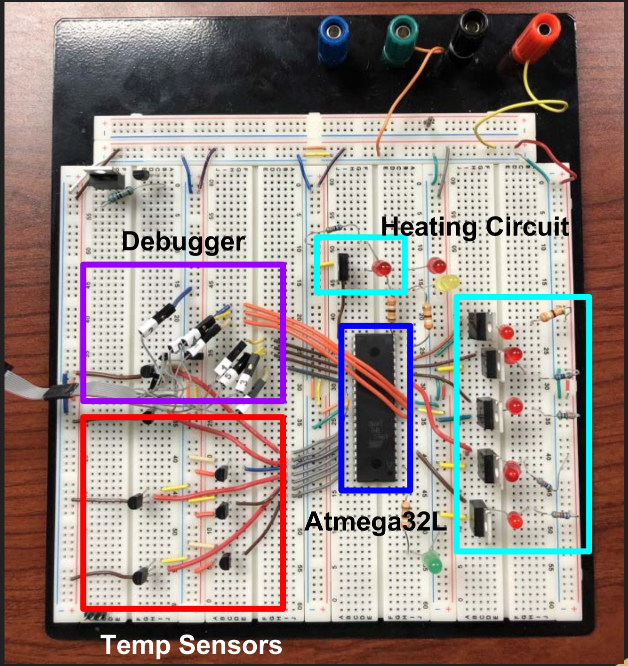
- Verify software functionality by stepping through code

**Expectation:**

- Code behaves as designed (detailed in flowchart)

**Status:**

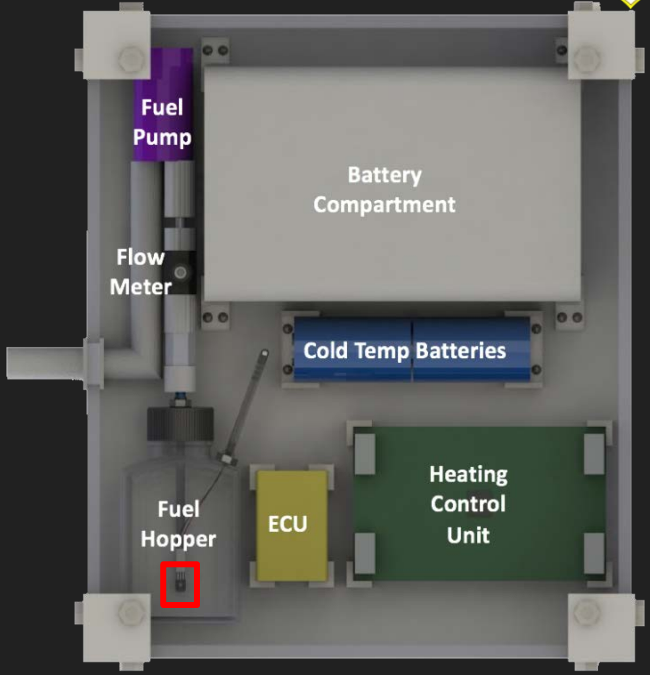
- **Completed on 2/8/2018 with no experienced bugs**



# Initial Subsystems

Software Flow

Temp Sensor/Noise




Overview | Schedule | Testing | Budget

# Temperature Sensor/Noise Test

**Purpose:**

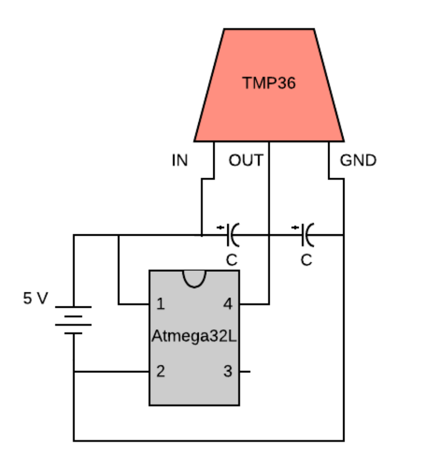
- Ensure the temperature sensor output are within allowable error (± 3.6°F)
- **Verify FR 2.2 and 3.0**

**Plan:**

- Use the oscilloscope to measure the range of output voltage swings for a constant temperature, convert this to a temperature
- Distance from Temperature Sensor to ADC initially set to ~2 ft, noise recorded on oscilloscope

**Expectation:**

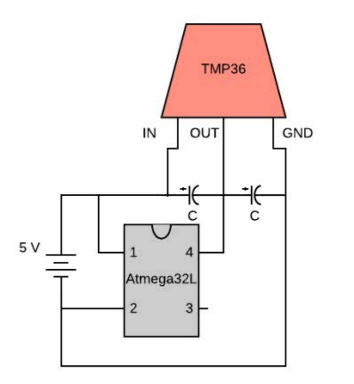
- Based on the data sheet for the TMP36 Sensors, a temperature error of ± 3.6°F
- Distance will have minimal effect on temperature error due to noise

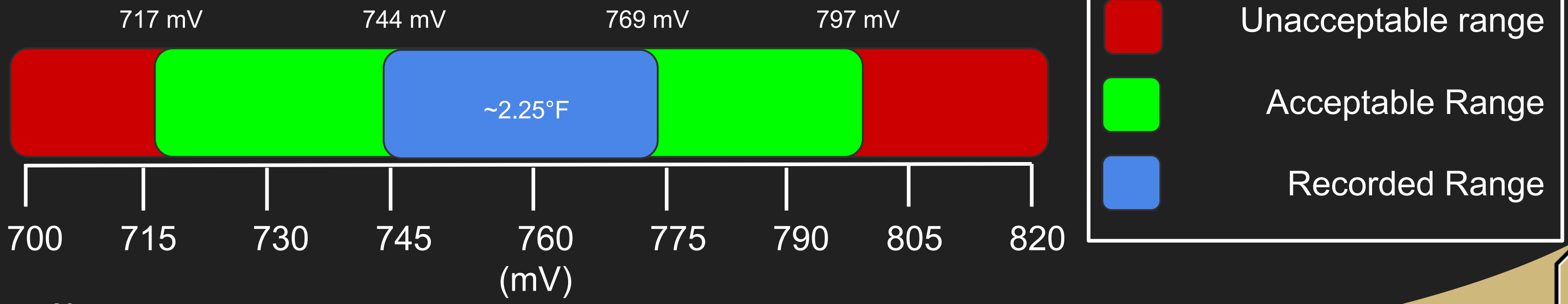


# Temperature Sensor/Noise Test

**Status:**

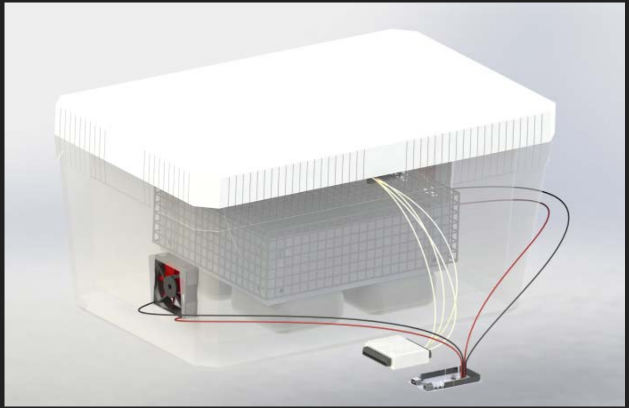
- **Completed on 2/28/2018**
- Noise generation minimized with introduction of Two 47 µF, 16V capacitors
- **Satisfies temp bounds for FR 2.2 and 3**



# Testing

Initial Subsystems
Test Chamber
Model Verification
Full Integration

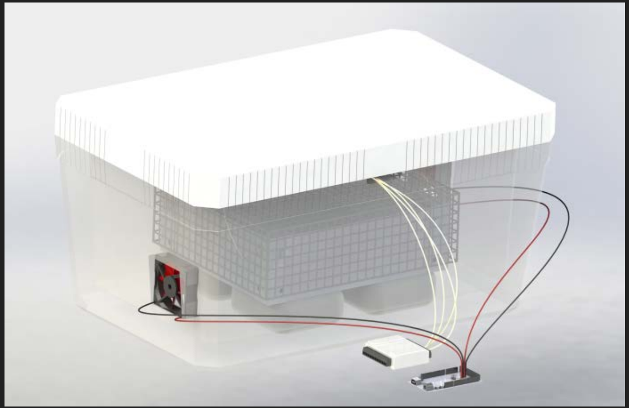


Overview | Schedule | Testing | Budget

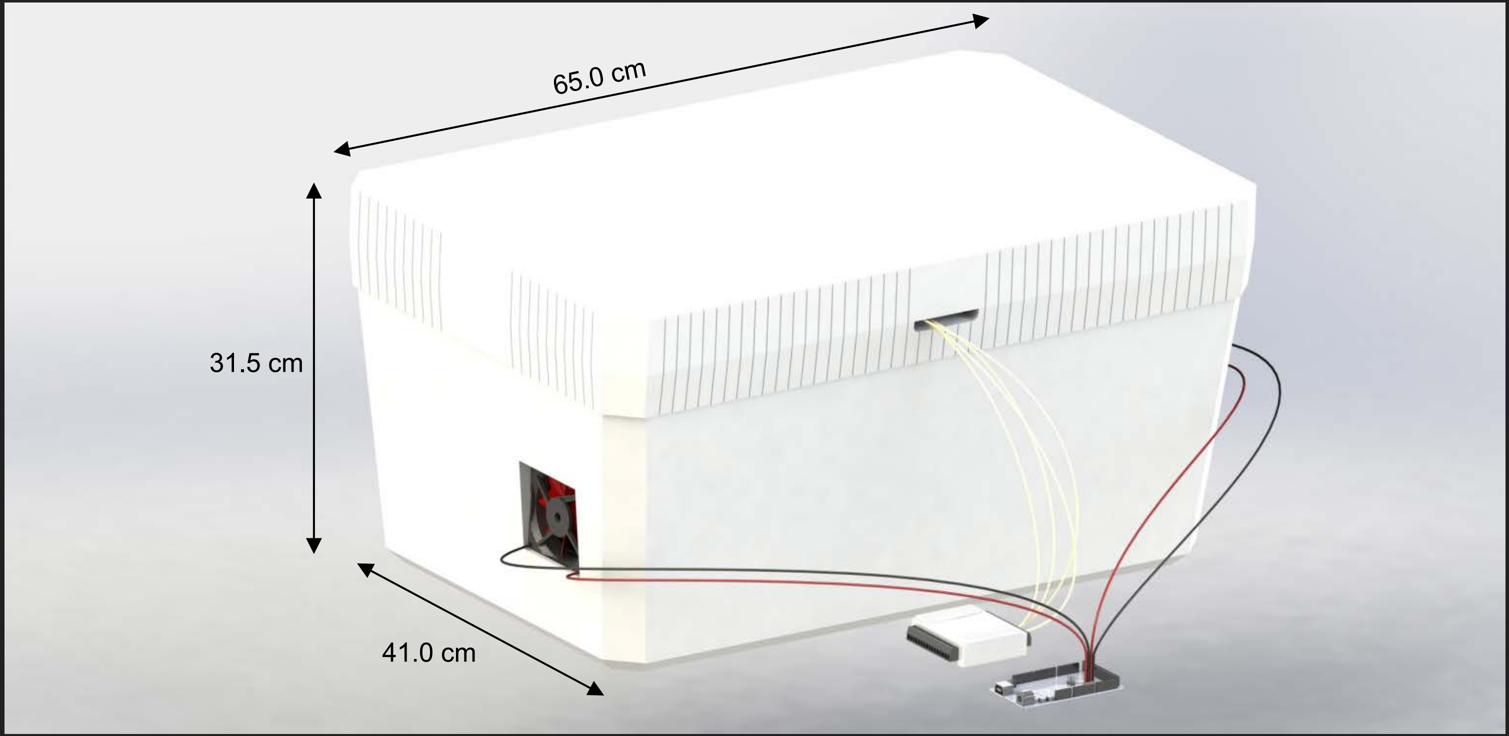
# Test Chamber

## Functionality Test

Flow Meter/Pump



# Test Chamber

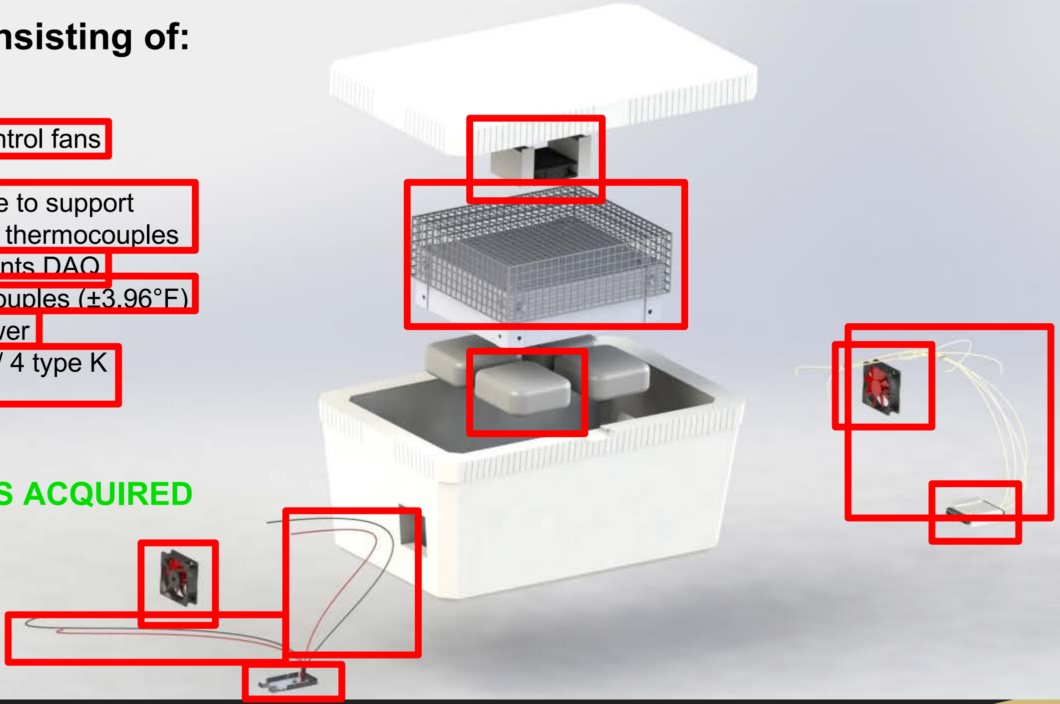


# Test Chamber Components

**Foam cooler consisting of:**

1. Dry ice blocks
2. 2 temperature control fans
3. 1 circulation fan
4. Chicken wire cage to support additional ice and thermocouples
5. National Instruments DAQ
6. 4 type K thermocouples (±3.96°F)
7. Wiring for fan power
8. Arduino MEGA w/ 4 type K thermocouples

**ALL COMPONENTS ACQUIRED**



# Test Chamber Functionality Test

**Purpose:**

- Confirm the test chamber can maintain desired cold soak environment ±5°F for 1 hour
- **Necessary for validating ALL functional requirements**

**Plan:**

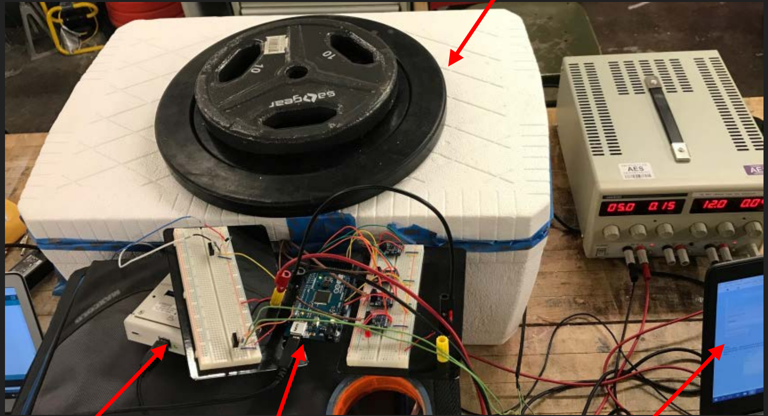
- Use DAQ + thermocouples to verify the operation of the Arduino control system at -50°F

**Expectations:**

- The Arduino will be able to control the temperature such that it will remain within the acceptable bounds

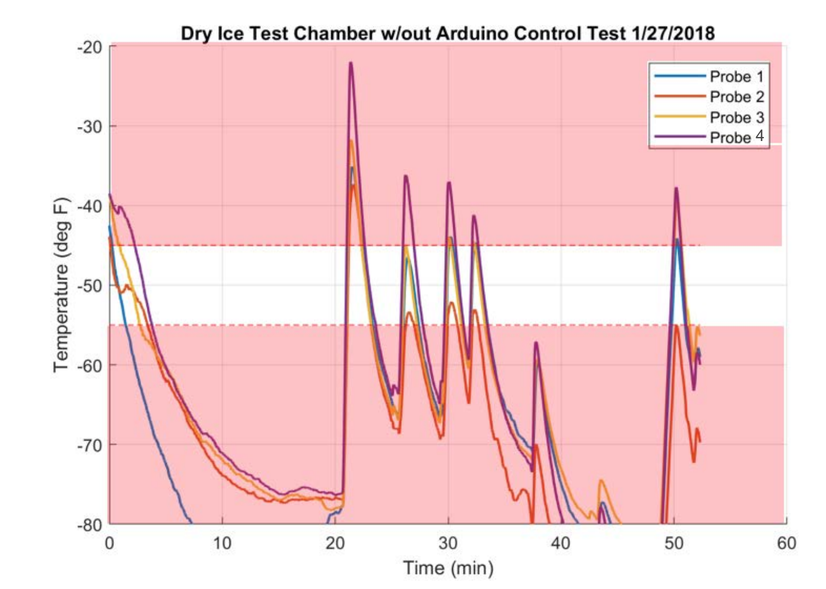
**Status:**

- **Completed on 2/27/2018**
- Further tests planned for fine tuning control law

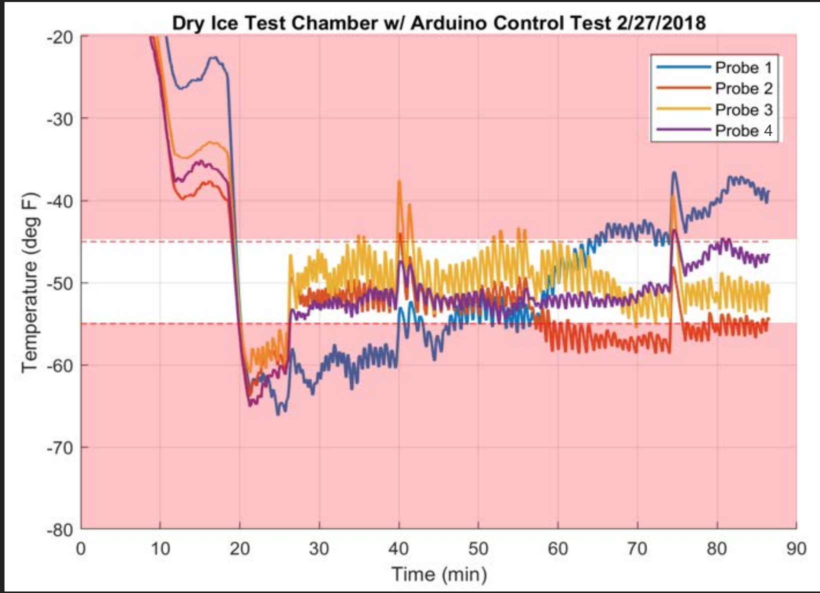


# Test Chamber Functionality Results

**WITHOUT Arduino Control:**




**WITH Arduino Control:**



# Test Chamber Functionality Results

**Test Chamber Concerns:**

- Diverging thermocouples
- Probes 1 and 2 show standard deviation outside acceptable range (±5°F)

**Potential Causes:**

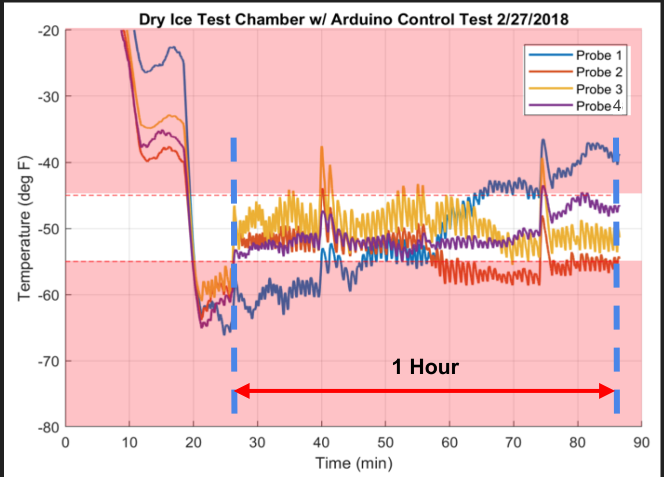
- Chamber geometry
- Inaccurate thermocouples

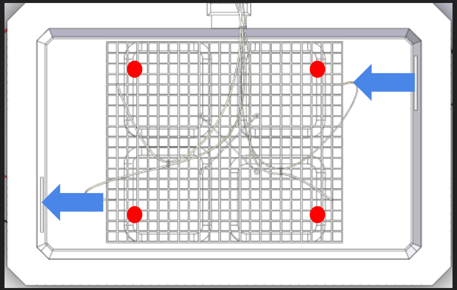
**Potential Fixes:**

- Change airflow characteristics
- More powerful circulation fan
- Replace thermocouples

**Average Temperature Readings**

| Probe | Temperature (°F) |
|---|---|
| 1 | -49.56 +/- 7.40 |
| 2 | -53.82 +/- 2.74 |
| 3 | -49.36 +/- 2.82 |
| 4 | -50.72 +/- 2.49 |

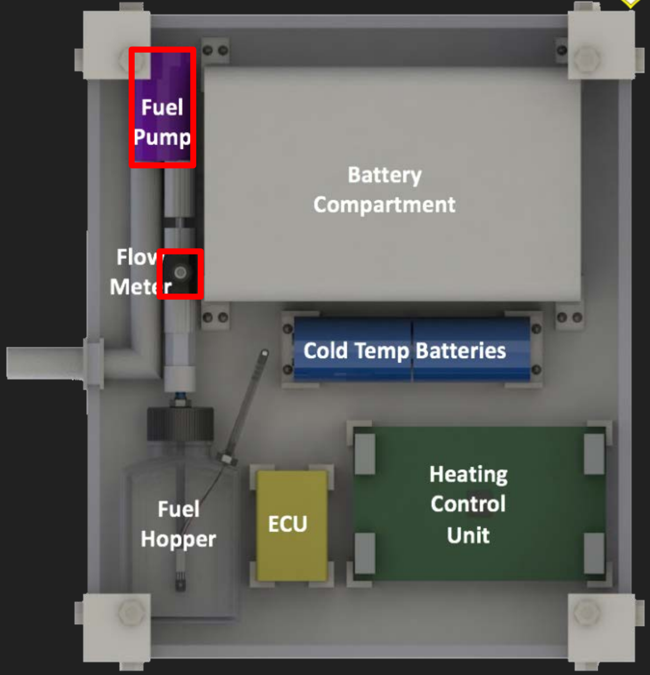


Thermocouple Locations

Direction of Airflow

# Test Chamber




Functionality Test

Flow Meter/Pump

# Flow Meter/Pump Temperature Test

**Purpose:**

- **Determine a relationship between K-Factor and temperature**
- **Allowing subsequent verification of FR 2.1**

**Plan:**

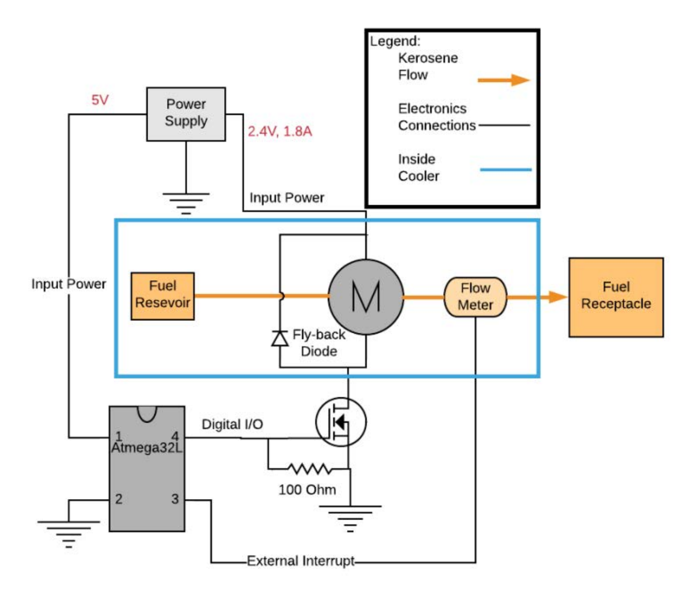
- Pump kerosene into container and record output mass
- Calculate mass flow and K-Factor
- Perform test again to ensure validity of K-Factor
- Fit curve to data

**Expectation:**

- Constant K factor in accordance with datasheet
  - K factor is the conversion between pulses and liters

**Status:**

- **Scheduled for 3/8/2018**



# Flow Meter Calibration

**Status:**

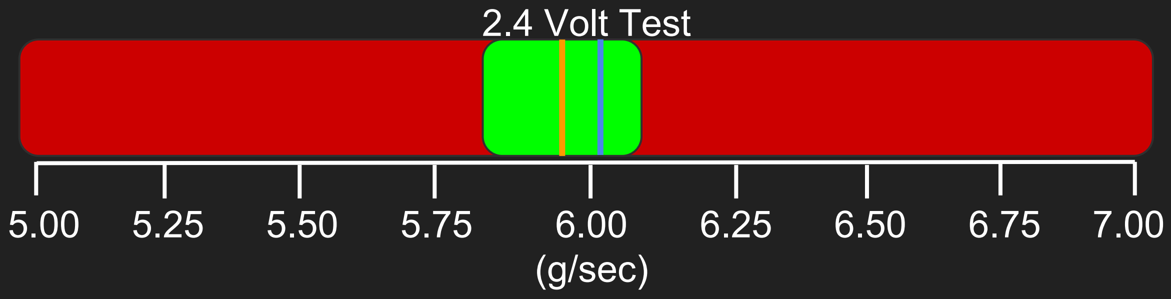
- **Completed Feb 25, 2018**
- K-Factor determined to be **91,387**, Datasheet claims 110,000

Unacceptable range

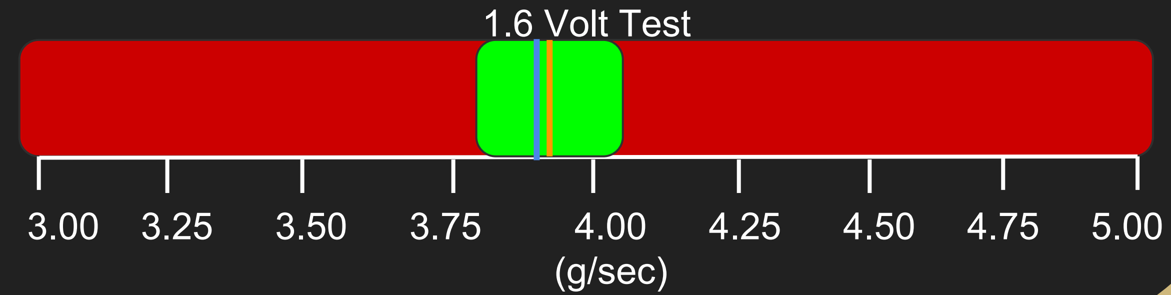
Acceptable Range

Code Produced Average

Experimental Average




Code Average: 6.006 g/sec  Experimental Average: 5.945 g/sec




Code Average: 3.883 g/sec  Experimental Average: 3.922 g/sec

# Testing

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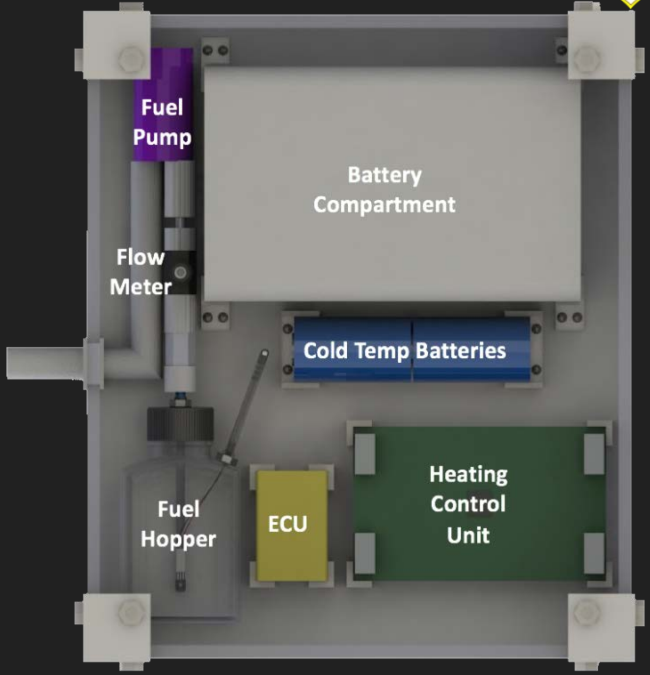


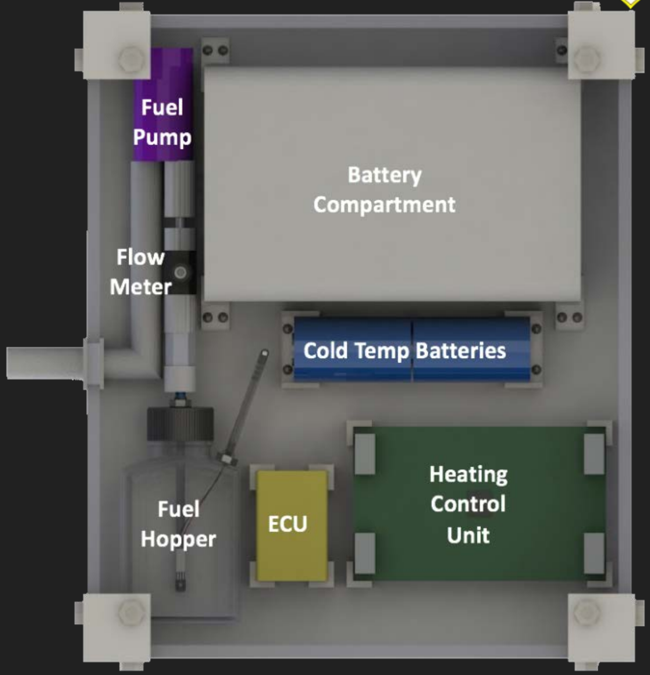
# Model Verification

Resistive Heating

Battery Insulation

HCU FDS Integration

HCU Electronics Int.




Overview | Schedule | Testing | Budget

# Resistive Heating Tests

**Purpose:**

- Validate the functionality of heating for the batteries, fuel hopper, ECU, fuel lines, and ESB.
- **Validate FR 3.0**

**Plan:**

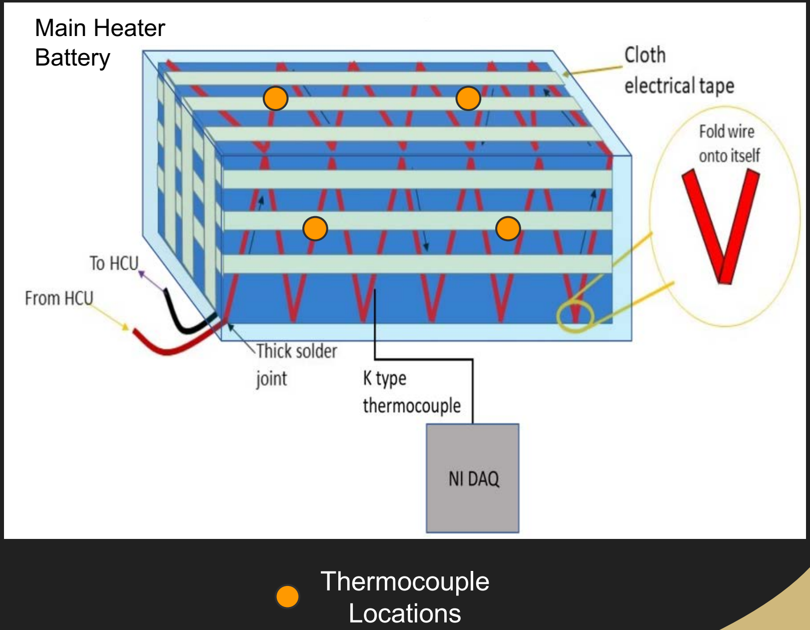
- Using the calculated lengths of wire wrapped around each component as well as power resistors for the ESB and fuel hopper
- Using the 22.2 V input voltage seen from the main heater battery using the HCU to control the heater's output
- Record thermocouple surface measurements

**Expectation:**

- Reach temperatures specified by the SolidWorks models

**Status:**

- Wire still needs to be wrapped around each component
- **Scheduled for 3/9/2018**

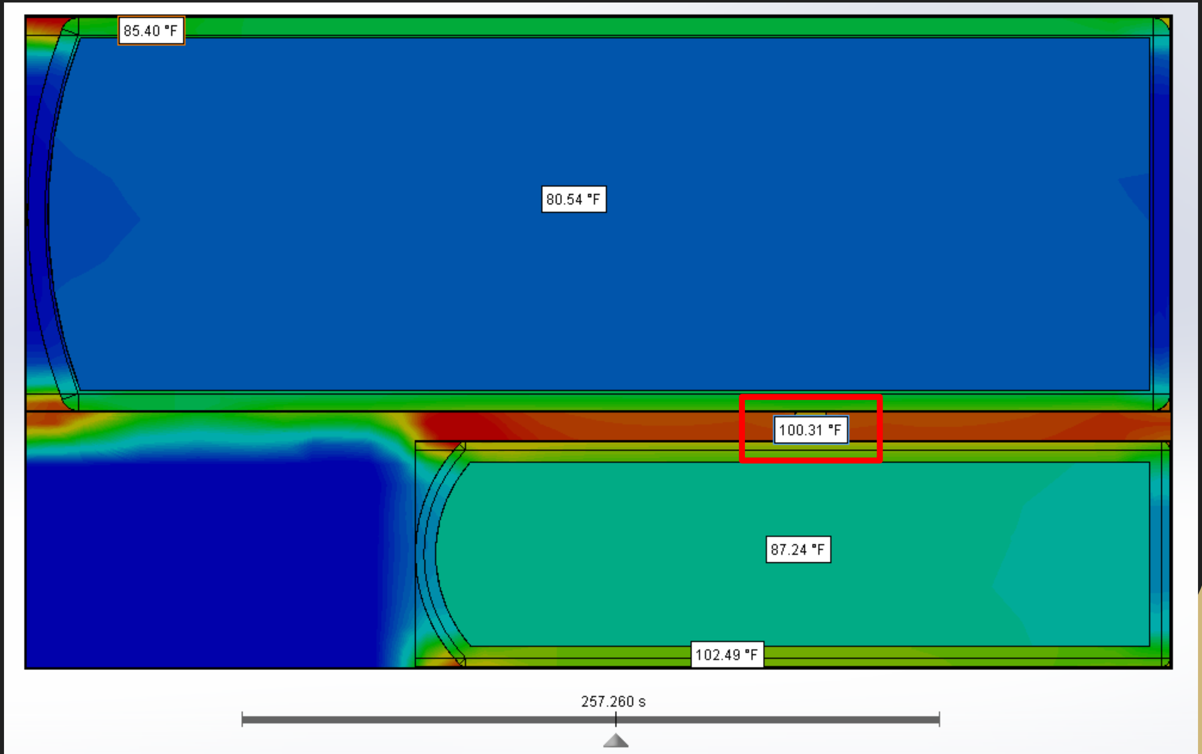


# Expected Component Temperatures

Surface Temperatures After 4.25 minutes of Resistive Heating:

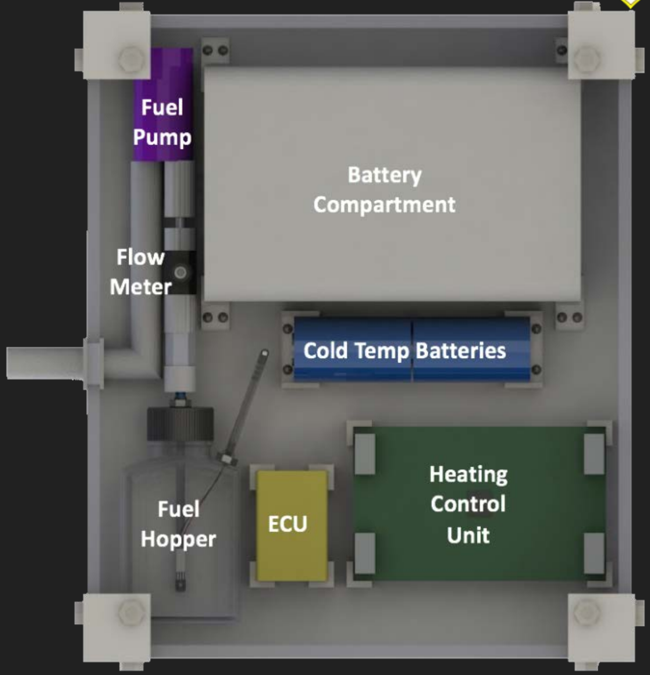
- **Batteries: 100.31°F**

For tests, measurements within +/- 3.6°F of the above values are acceptable. Additional models for all other components are given in the backup slides.



# Model Verification

Resistive Heating
Battery Insulation
HCU FDS Integration
HCU Electronics Int.




Overview | Schedule | Testing | Budget

# Battery Insulation Test

**Purpose:**

- Confirm that, with insulation applied, the LiPo battery outputs its nominal voltage of 22.2 +/- 2.97 V after being cold soaked for 1 hour
- Verify the accuracy of the thermodynamic models
- **Verify FR 1.0**

**Plan:**

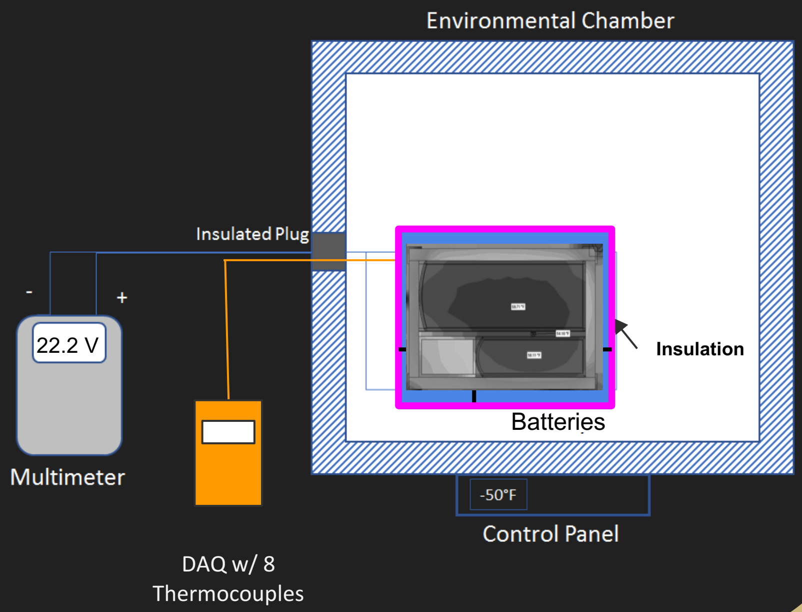
- Cold soak main heater and ECU battery with insulation for 1 hour at -50°F in chamber
- Record battery surface temperature

**Expectations:**

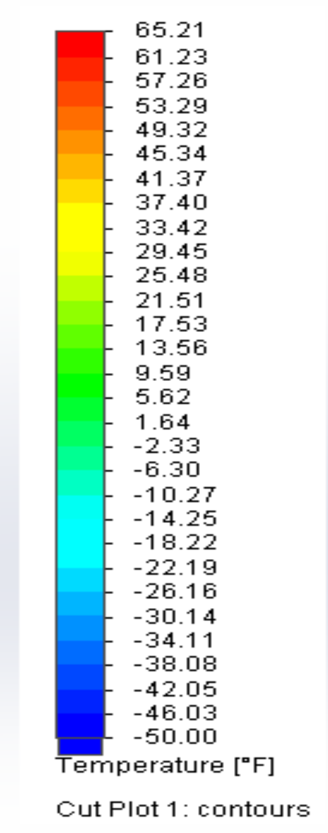
- Temperature readings that validate model

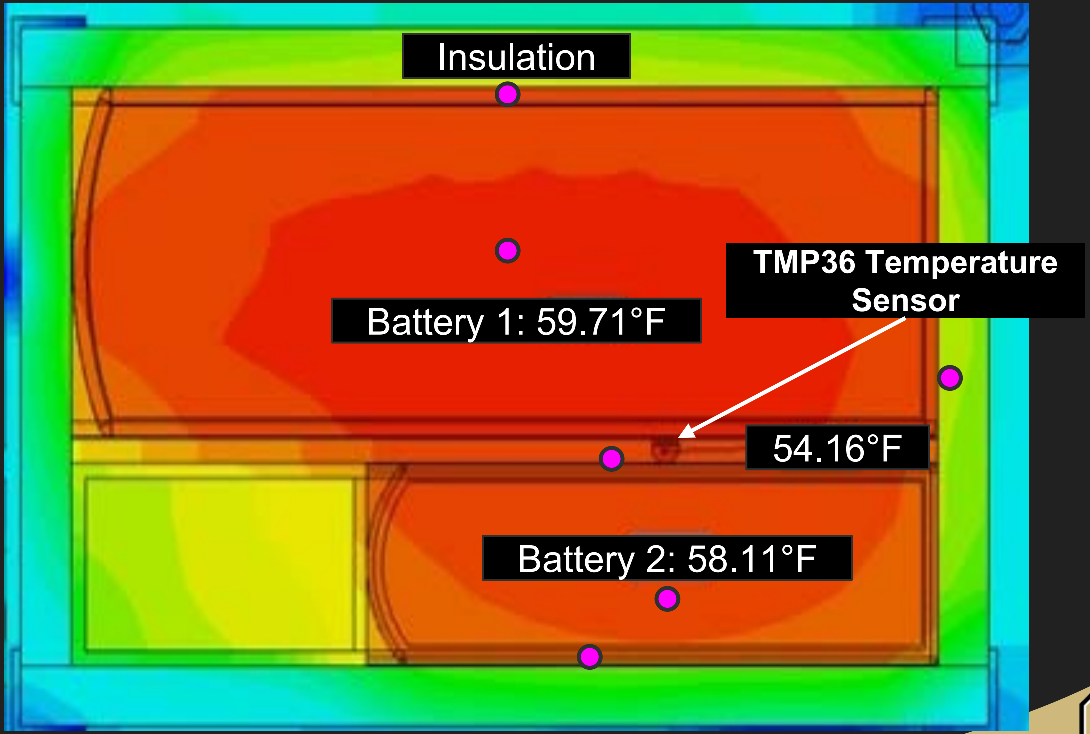
**Status:**

- **Awaiting availability of an environmental chamber**



# Battery Insulation Test Model




Surface Thermocouple Location

# Partial Integration Test (FDS)

**Purpose:**

- **Partial verification of FR 4.1:**
  - Regarding FDS heating
- **Verification of FR 4.2**

**Plan:**

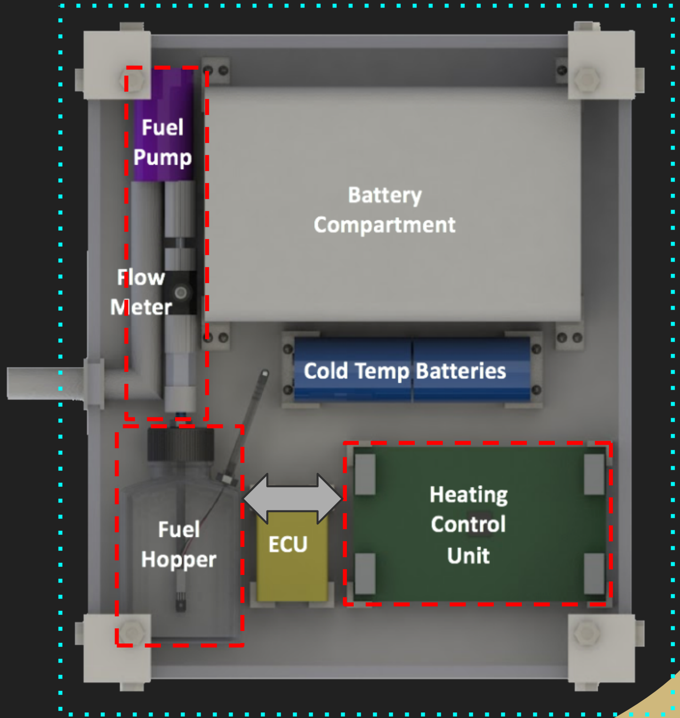
- Cold-soak electronics heating box at -50°F for one hour, then run FDS portion of HCU.
- After fuel fully heated, HCU commands fuel pump to pump fuel at the desired flow rate into a container (not the engine)
- DAQ informed by thermocouple monitoring fuel temperature and flow meter monitoring fuel flow rate
  - Ensuring that each rate is within the desired range

**Expectation:**

- Fuel should flow into container at desired flow rate and temperature
  - Acceptable temperatures: 60°F to 115°F
  - Acceptable flow rates: 4.8±0.13 g/s

**Status:**

- **Scheduled for 4/2/2018**




Test Chamber

# Partial Integration Test (Electronics)

**Purpose:**

- **Partial verification of FR 4.1**
  - Concerning Electronics heating

**Plan:**

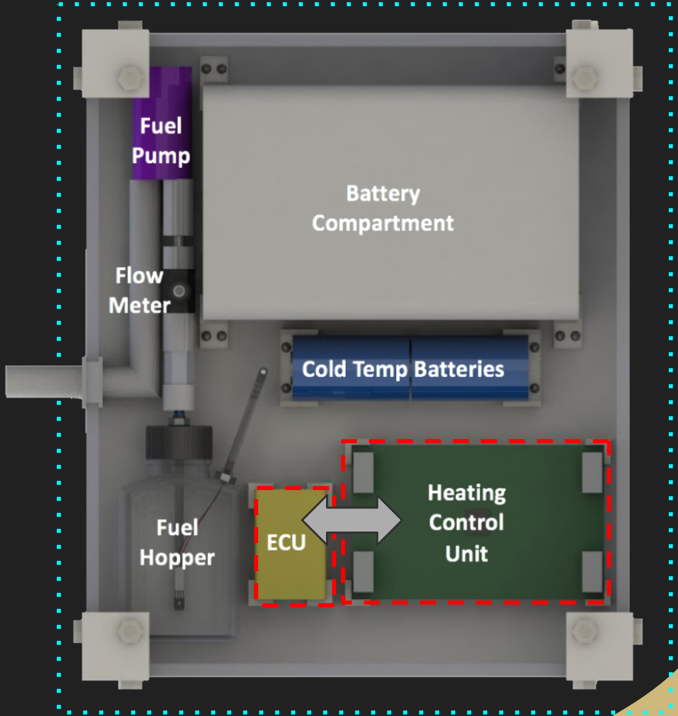
- Place electronics heating box inside -50°F test chamber for one hour, then run electronics heating portion of HCU
- DAQ informed by thermocouples monitoring the temperature of electronic components
- **Electronic components reach their desired temperature**

**Expectation:**

- Engine electronics will be heated to and then remain within their operational temperature range.
  - Engine battery: 60°F to 122°F
  - ESB/ECU: 60°F to 150°F

**Status:**

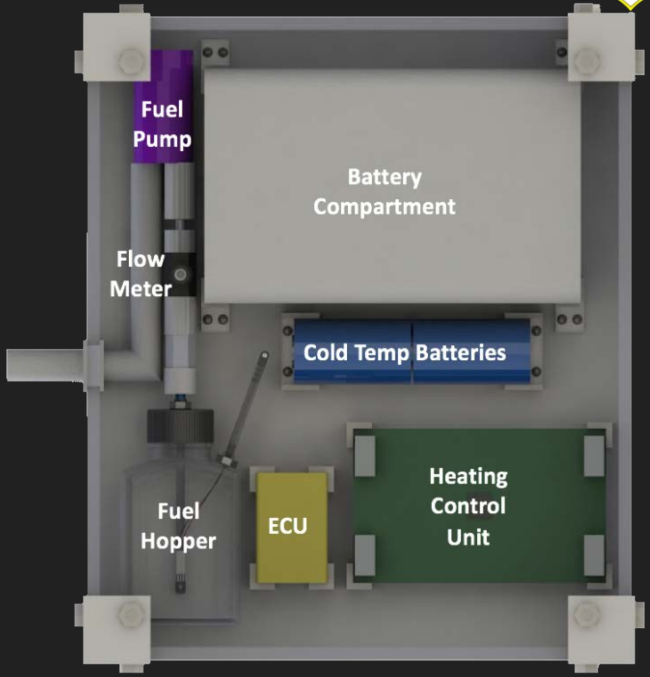
- **Scheduled for 4/4/2018**



Test Chamber

# Testing

Initial Subsystems
Test Chamber
Model Verification
Full Integration



# Full Integration Test

**Purpose:**

- Need to verify that the project's subsystems function and interact as expected at -50°F as a complete setup
- **Simultaneously verify all Functional Requirements**

**Plan:**

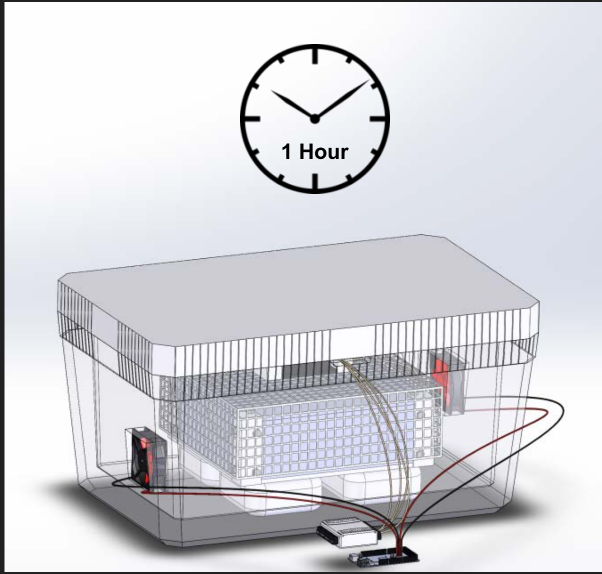
- Full electronics box placed in  -50°F test chamber for an hour.
- System initialized, heating begins.
- Monitor electronics with DAQ-connected thermocouples
- Once fuel flow begins, measure fuel flow using in-line flow meter. Fuel will flow into a container (not the engine)

**Expectation:**

- System will successfully maintain electronics at operational temperature and supply fuel at desired flow rate and temperature.

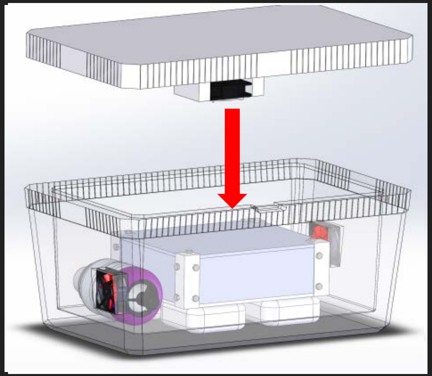
**Status:**

- **Scheduled for 4/6/2018**



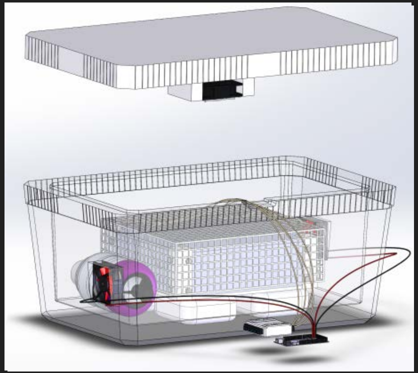
# Full Integration Test Plan Summary

**1**



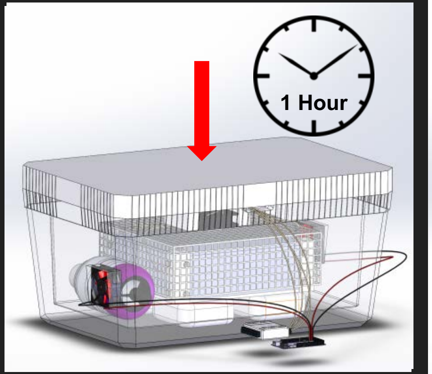
*Place the electronics box and engine in test chamber with 10 lbs of dry ice*

**2**



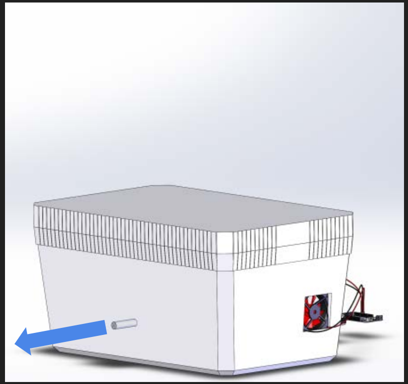
*Insert the support cage over electronics box and attach thermocouples for DAQ and Arduino controller*

**3**



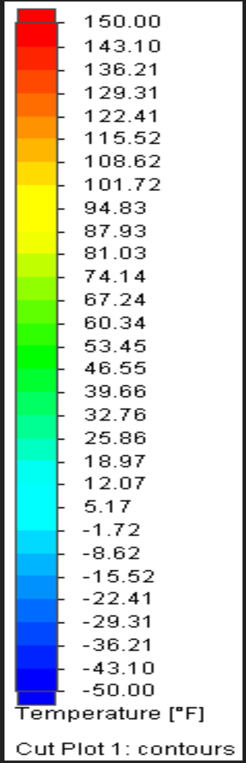

*Close the cooler and cold soak for 1 hour at -50±5°F*

**4**

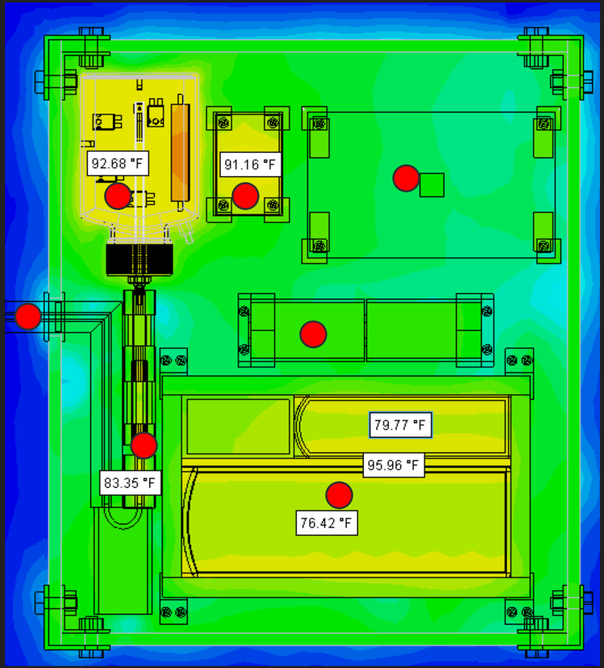


*Initiate heating procedure and monitor for fuel flow out of electronics box at 4.8±0.13 g/s*

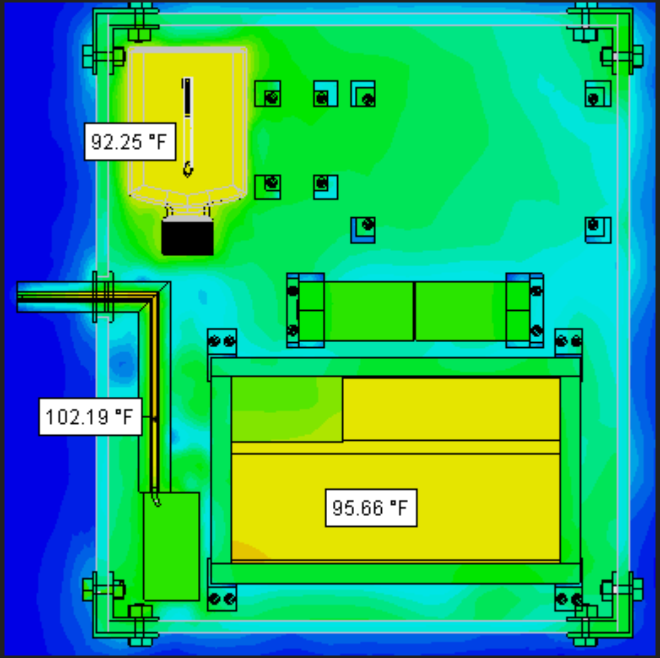
# Full Integration Test Models




**Top-Down**




**Cutaway**

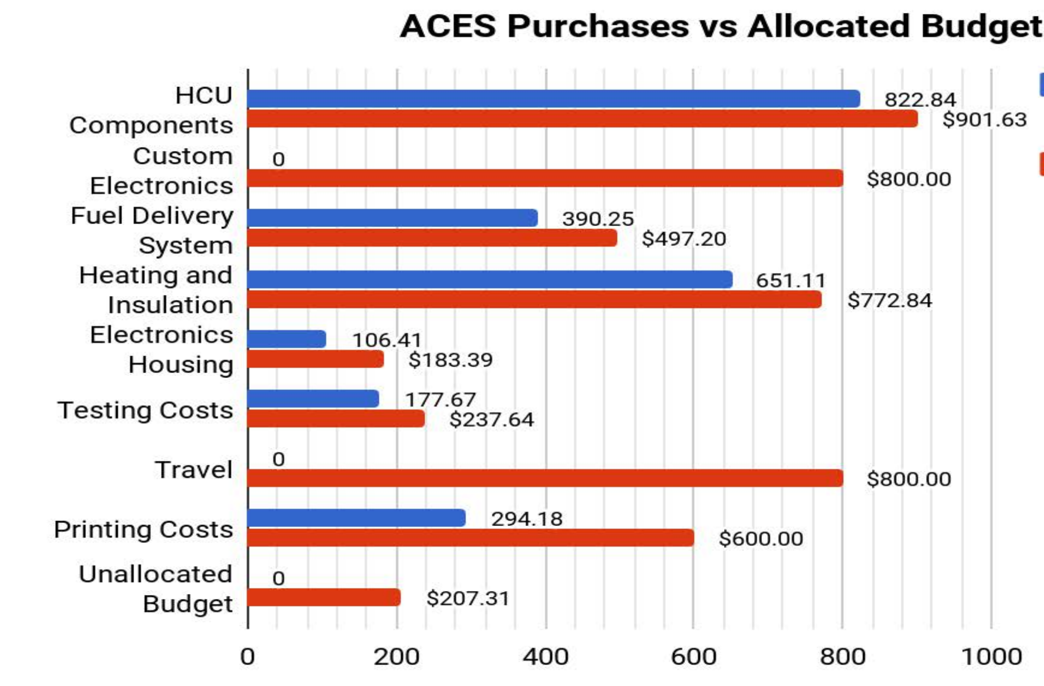



● Thermocouple location

# Budget

Overview | Schedule | Testing | Budget

# Cost Plan




Current Total Expenditures = $2442.46

Remaining Budget = $2557.54

Remaining Purchases: PCB Revisions, Custom ECU components

# Acknowledgements

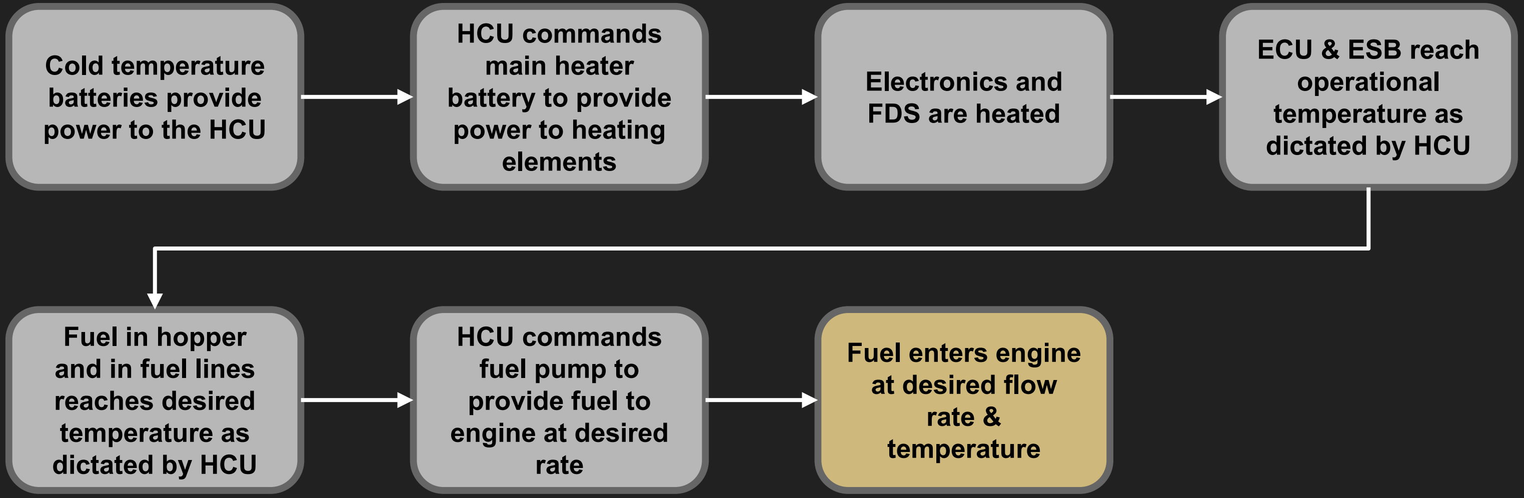
- Dr. Donna Gerren
- Matt Rhode
- Trudy Schwartz
- Bobby Hodgkinson
- Tim May
- Lee Huynh
- Tim Kiley

# Questions?

# BACKUP SLIDES

# Overview

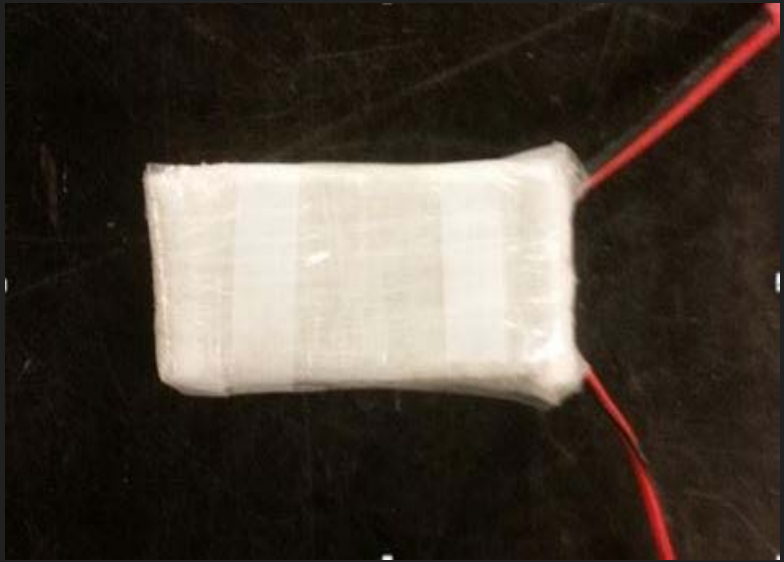
# Process Flow Diagram



# Manufacturing

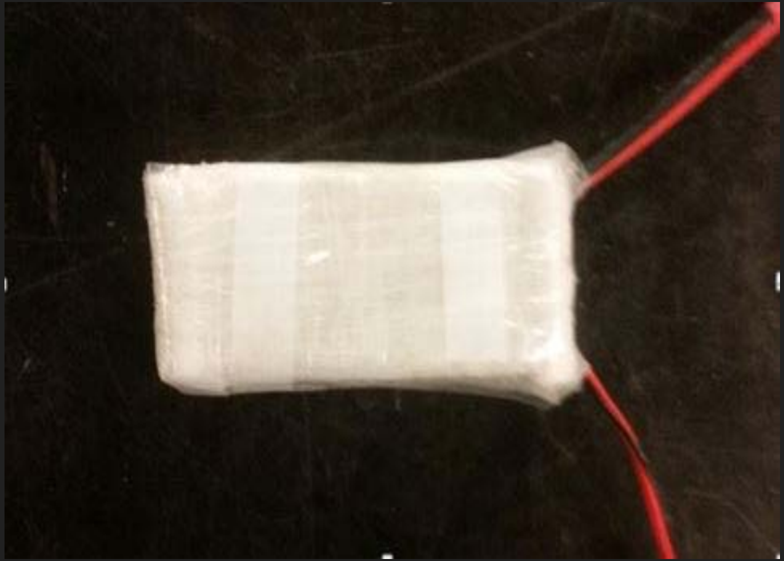
# Manufacturing Updates

- Method of securing Aerogel
  - Originally wanted to sew around necessary components
  - Issues that arose when testing this method:
    - Aerogel is incredibly strong and difficult to work with
      - Need access to both sides in order to properly sew
        - This WON'T be possible on the final side
      - Forcing several punctures into material made material less dense
        - Worried this will degrade its robust thermal properties
      - Significantly increased its manufacturing time with this method



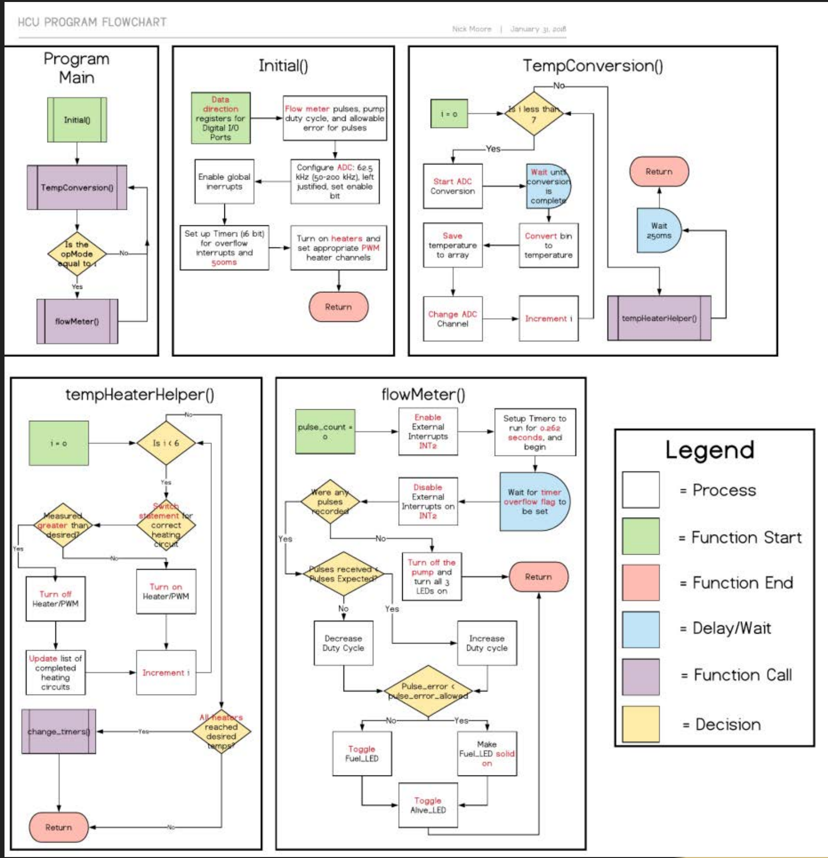
# Manufacturing Updates

- Method of securing Aerogel
  - NEW Verified Solution
    - Wrap exterior of aerogel layers with  thread
      - Secures aerogel around components without thermal gaps
        - Ensuring that sewn thread was taut everywhere proved difficult
      - Ease of manufacturing
        - Takes significantly less time to assemble
    - Saran wrap exterior of aerogel
      - Prevents dust from getting on essential electrical components
      - Makes wrapped components safer for team members to use
      - Small pieces of clear tape secures the saran wrap in place
    - Overall, the new method looks cleaner, functions better, and is easier to assemble without possible degrading the thermal properties of aerogel that are crucial to the success of the project

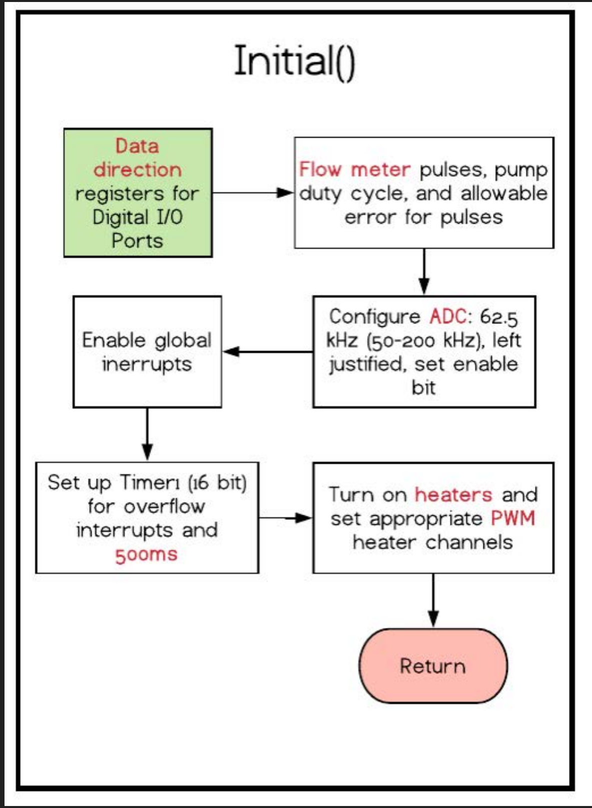


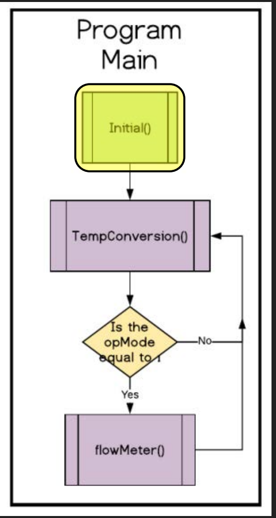
# HCU

# HCU SOFTWARE OVERVIEW

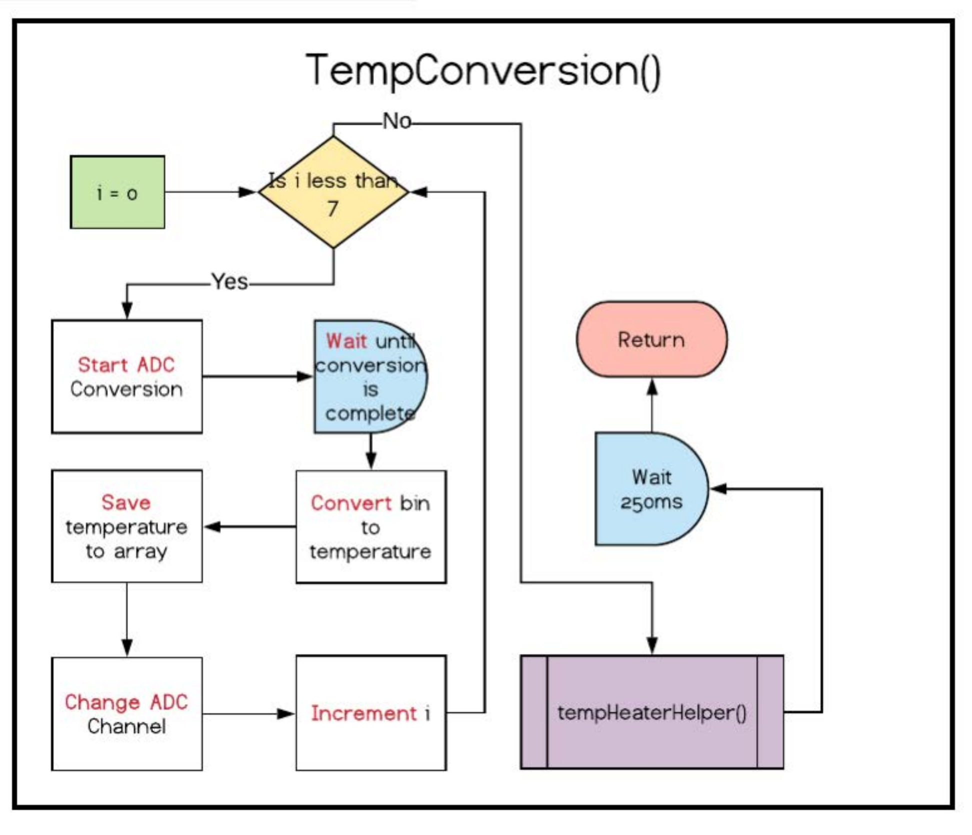


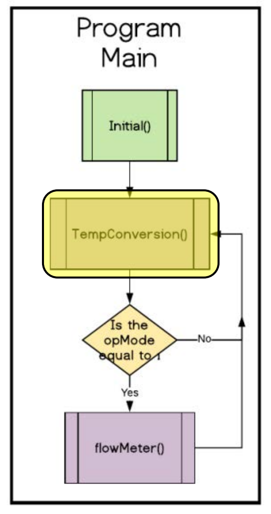
# HCU: SoftwARE

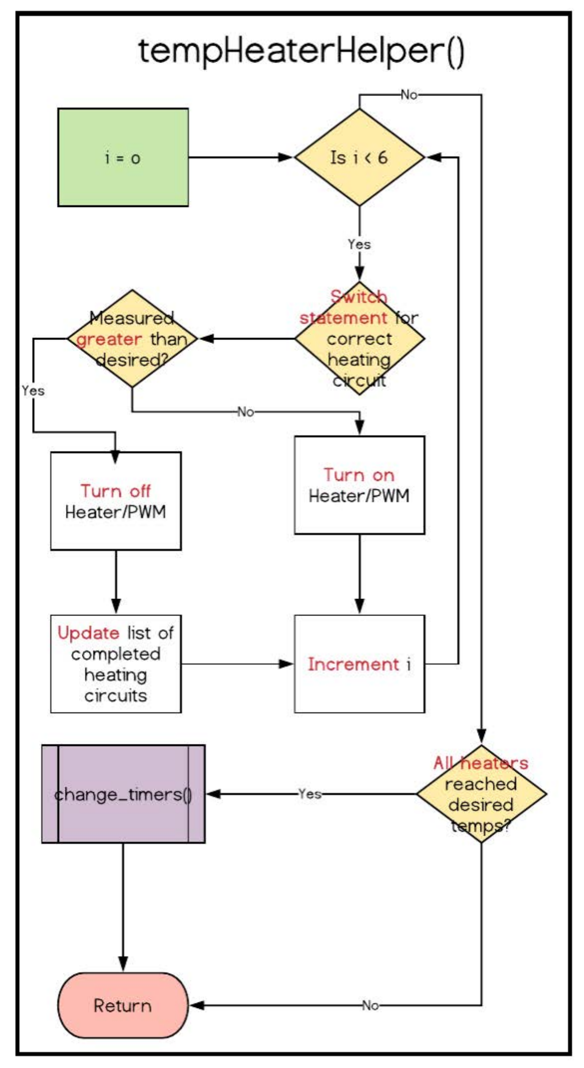


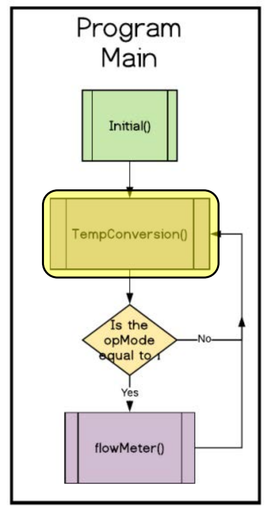



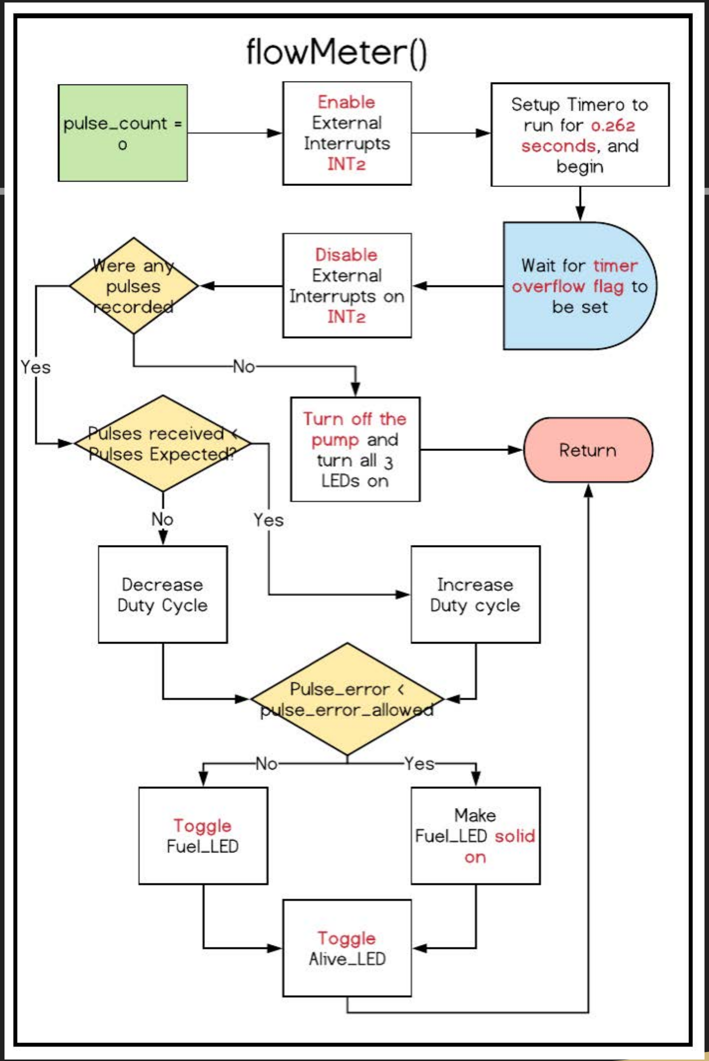
# HCU: SoftwARE

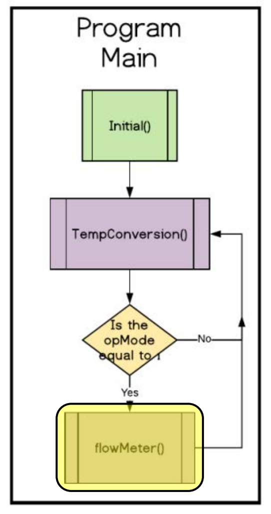


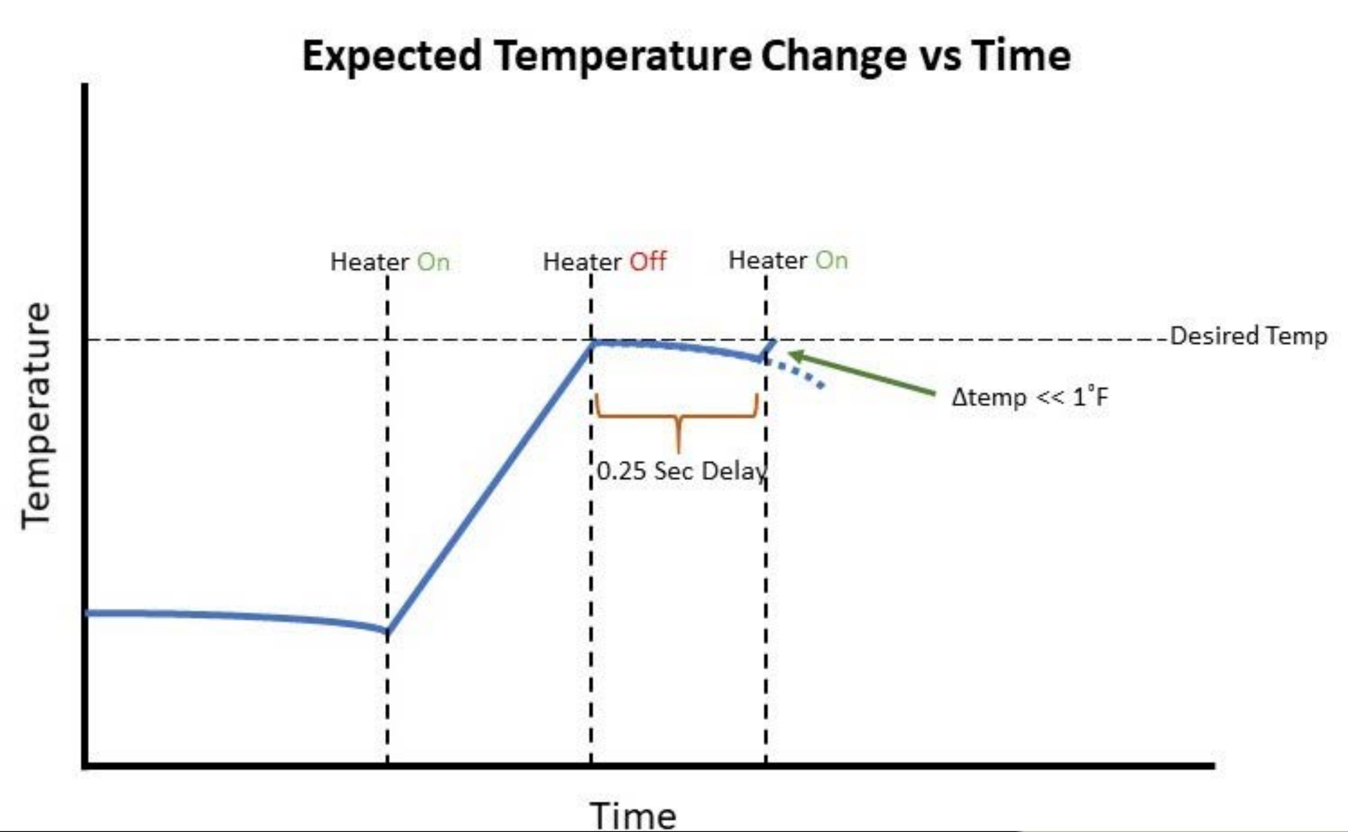

tempHeaterHelper()
i = 0
Is i < 6
No
Yes
Switch statement for correct heating circuit
Measured greater than desired?
Yes
No
Turn off Heater/PWM
Turn on Heater/PWM
Update list of completed heating circuits
Increment i
All heaters reached desired temps?
Yes
change_timers()
No
Return


Program Main
Initial()
TempConversion()
Is the opMode equal to 1
No
Yes
flowMeter()

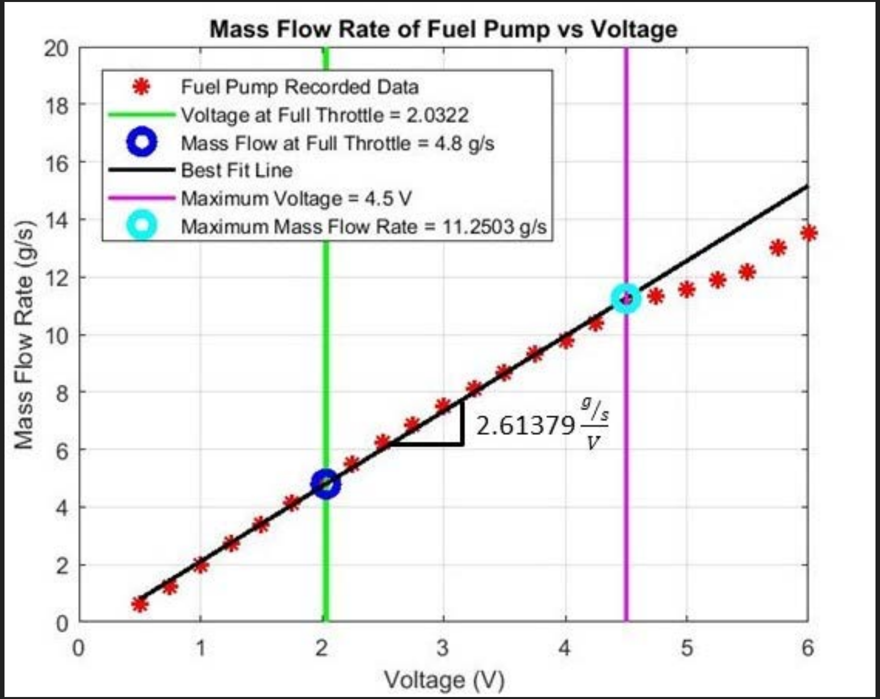

flowMeter()
pulse_count = 0
Enable External Interrupts INT2
Setup Timer0 to run for 0.262 seconds, and begin
Wait for timer overflow flag to be set
Disable External Interrupts on INT2
Were any pulses recorded
Yes
No
Turn off the pump and turn all 3 LEDs on
Return
Pulses received < Pulses Expected?
No
Yes
Decrease Duty Cycle
Increase Duty cycle
Pulse_error < pulse_error_allowed
No
Yes
Toggle Fuel_LED
Make Fuel_LED solid on
Toggle Alive_LED


Program Main
Initial()
TempConversion()
Is the opMode equal to 1
No
Yes
flowMeter()

# HCU: SoftwARE Temp Control



# HCU: Software Mass flow




$$\frac{4.8\text{ g}}{1\text{ s}}\cdot\frac{1\text{ mL}}{0.81\text{ g}}\cdot\frac{1\text{ L}}{1000\text{ mL}}\cdot\frac{110{,}000\text{ pulses}}{1\text{ L}}\cdot\frac{0.262144\text{ s}}{1\text{ period}} = 171\text{ pulses per period}$$

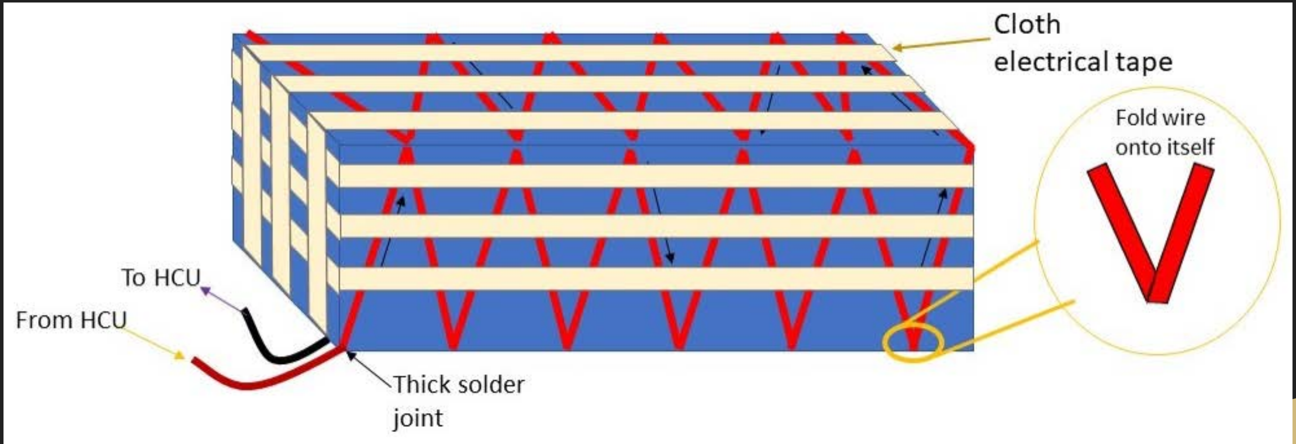
$$\frac{4.8\text{ g}}{1\text{ s}}\cdot\frac{1\text{ period}}{171\text{ pulses}} = 0.02807\text{ g/s error per pulse}$$

$$\frac{1\text{ pulse}}{}\cdot\frac{0.02807\text{ g/s}}{1\text{ pulse}}\cdot\frac{0.382587\text{ V}}{1\text{ g/s}}\cdot\frac{}{6\text{ V}}\cdot\frac{20{,}000\text{ counts}}{} = 35.797\ \Delta\text{OCR1B per pulse error}$$

# Electronics

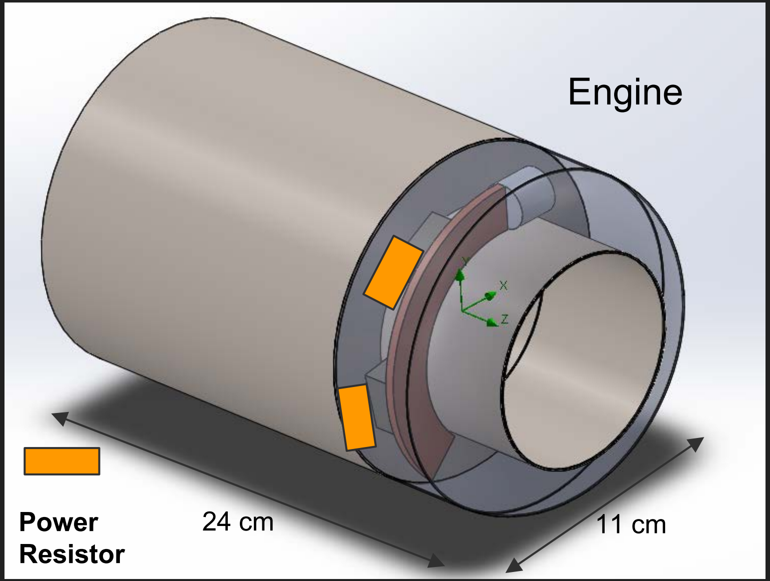
# Wire Wrapping

- Need to prevent wire wrapping from being an electromagnet.
  - Could/probably will disrupt the Lipo battery equalizing circuits and ECU
    - This configuration will produce destructive B fields.
  - Fuel lines do not have this concern so they will be wrapped in the more traditional sense.



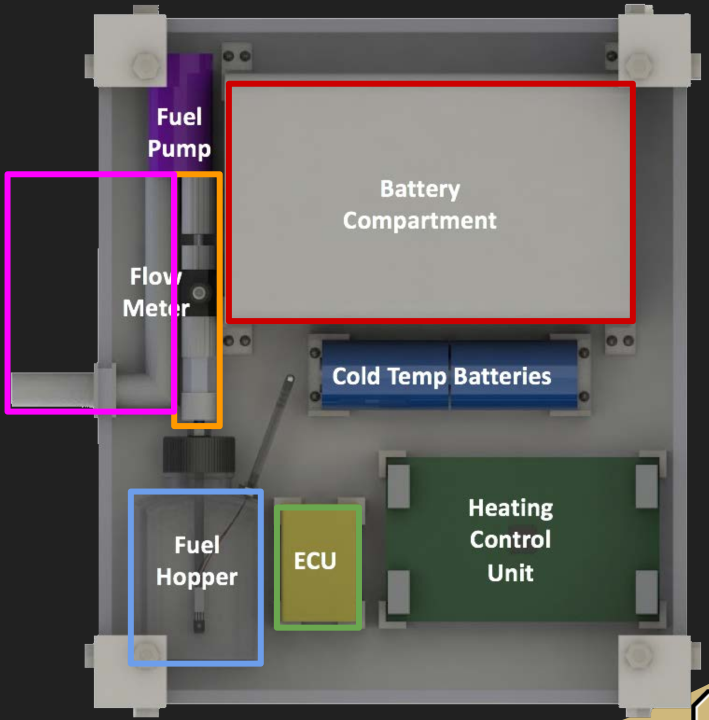
# Power Resistors for ESB

- **Vishay/Dale 12 Ohm 15W** power resistors to heat ESB (x2)
- These will be mounted to the underside of the ESB using a Cyanoacrylate
  - An example of this is super glue
  - These have temperature ranges of -67 to 482 F.



# Lengths of Resistor Wire

- 18.9 ft (0.88Ω/ft) for both Lipo batteries
- 3.9 ft (3.17 Ω/ft) for the ECU
- 13.8 ft (3.17 Ω/ft) for outside the hopper
- 0.8 ft (3.17 Ω/ft) for Fuel line section 1
- 2.4 ft (3.17 Ω/ft) for Fuel line section 2



# Flow Meter Calibration

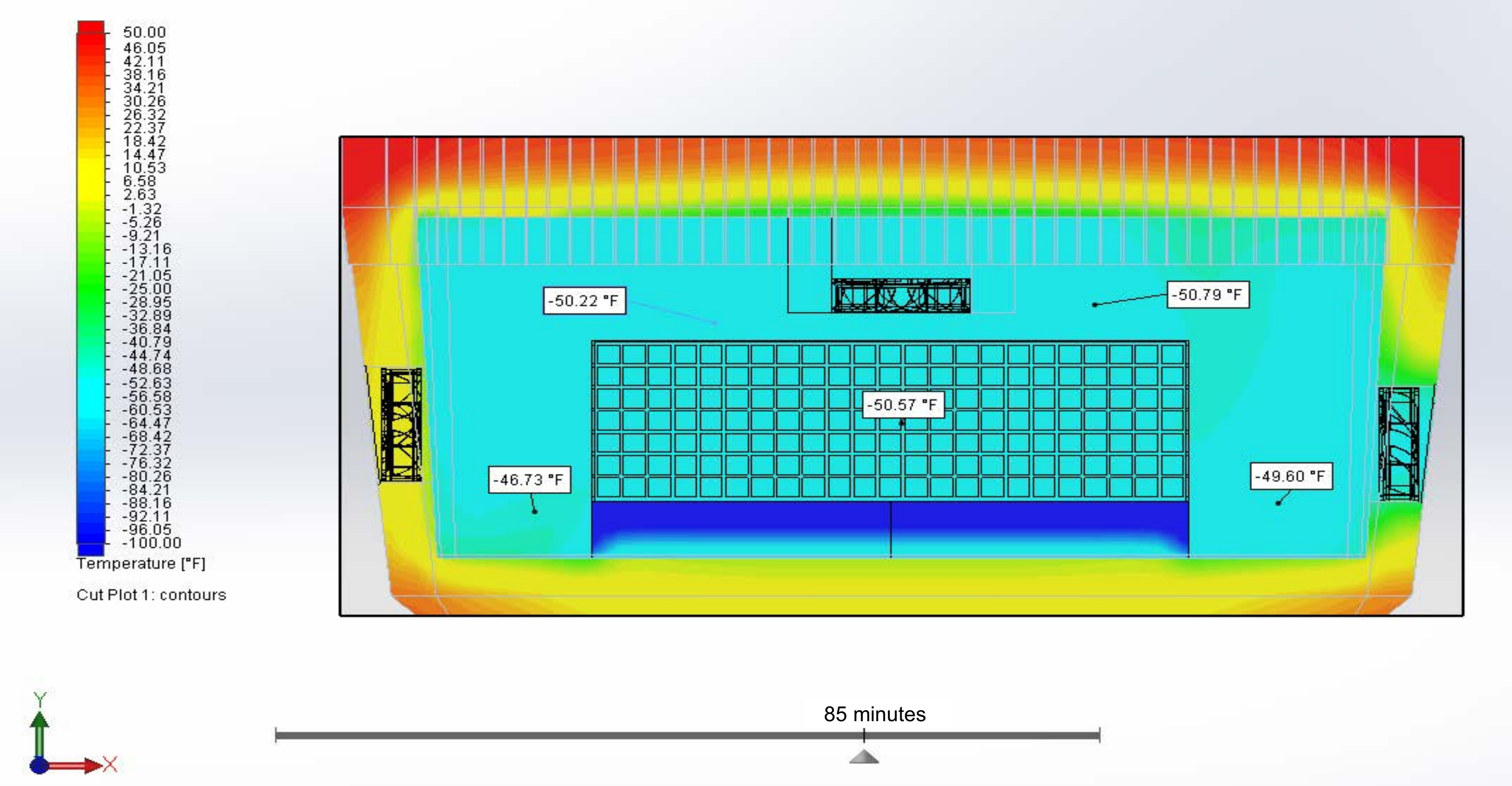
**Status:**

- **Completed Feb 25, 2018**
- K-Factor determined to be **91,387**, Datasheet claims 110,000


| 2.4 V Pump Voltage | | | | | |
|---|---|---|---|---|---|
| Trial | Code | Experiment | Trial | Code | Experiment |
| 1 | 6.048 g/s | 6.050 g/s | 2 | 6.014 g/s | 5.643 g/s |
| 3 | 5.946 g/s | 6.019 g/s | 4 | 6.014 g/s | 6.013 g/s |
| Average | 6.006 g/s | 5.931 g/s | Error | **0.075 g/s** | **-0.021 g/s** |
| **1.6 V Pump Voltage** | | | | | |
| Trial | Code | Experiment | Trial | Code | Experiment |
| 1 | 3.917 g/s | 3.931 g/s | 2 | 3.917 g/s | 3.932 g/s |
| 3 | 3.849 g/s | 3.918 g/s | 4 | 3.849 g/s | 3.905 g/s |
| Average | 3.883 g/s | 3.9215 g/s | Error | **-0.039 g/s** | |

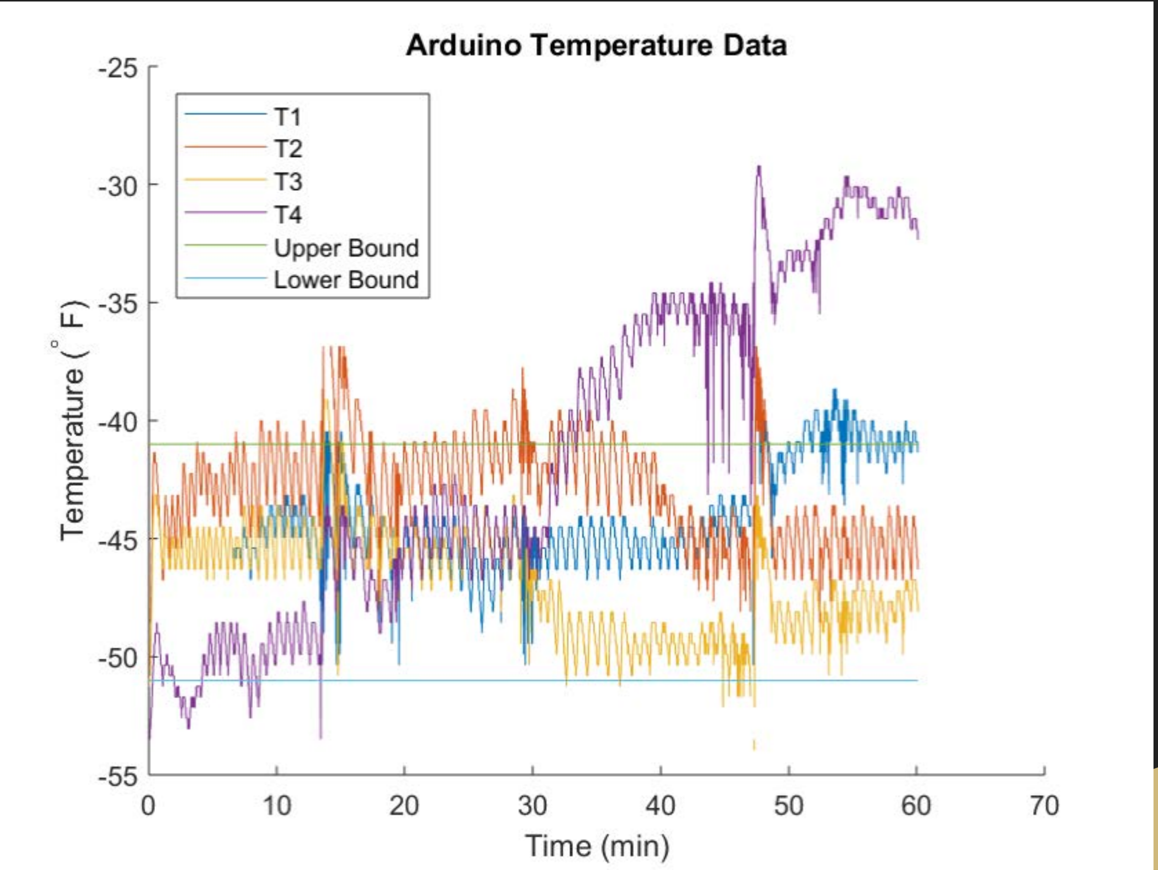
# Testing

# Test Chamber Functionality CAD



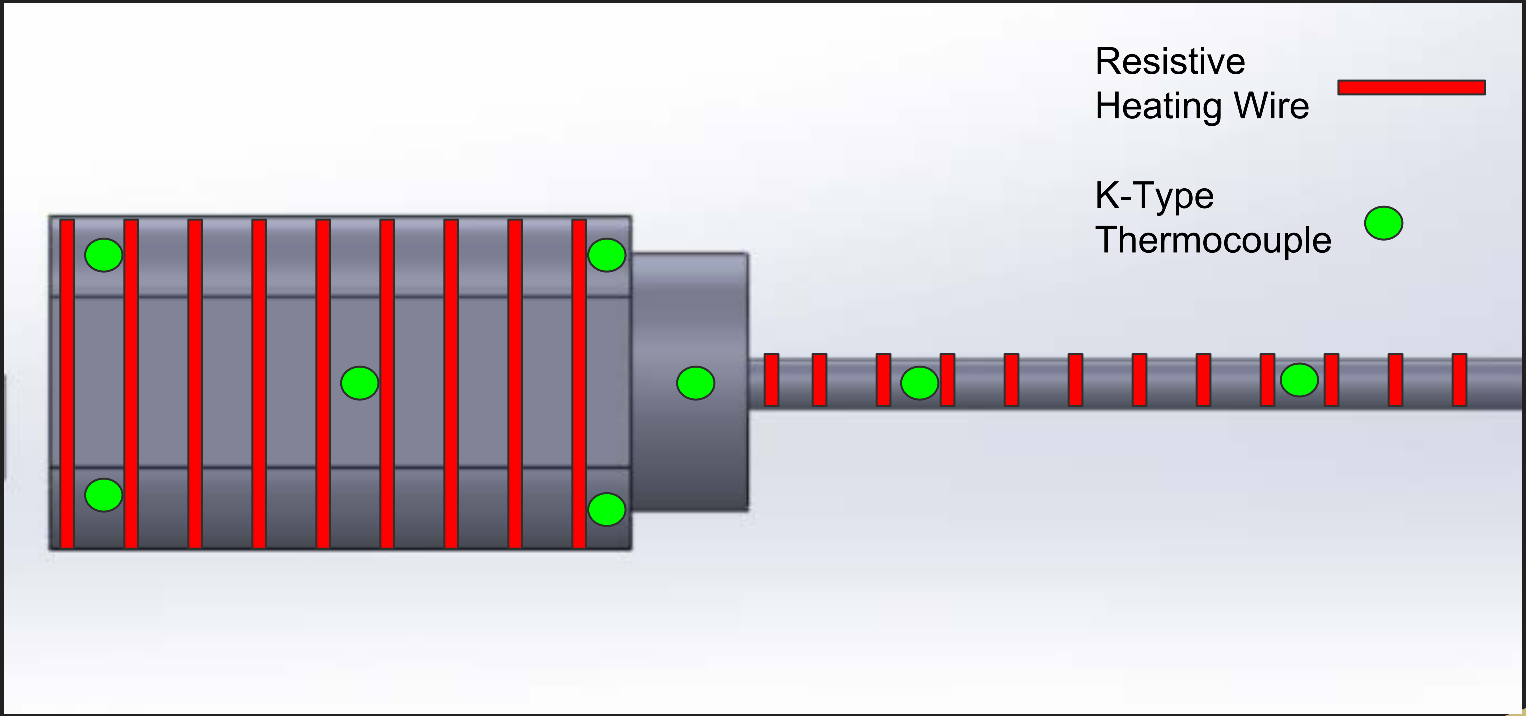
# Test Chamber Functionality Test

Temperature data from the 2/27/18 test chamber functionality test as recorded by the Arduino.

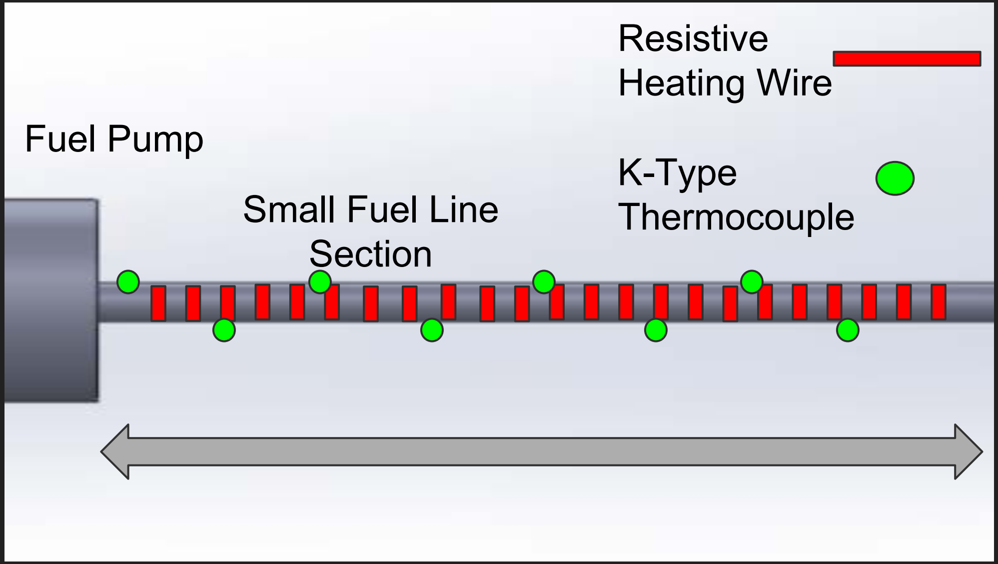


# Resistive Heater Diagrams

# Fuel Hopper/Fuel Lines Heater Diagram



# Fuel Line Heater Diagram

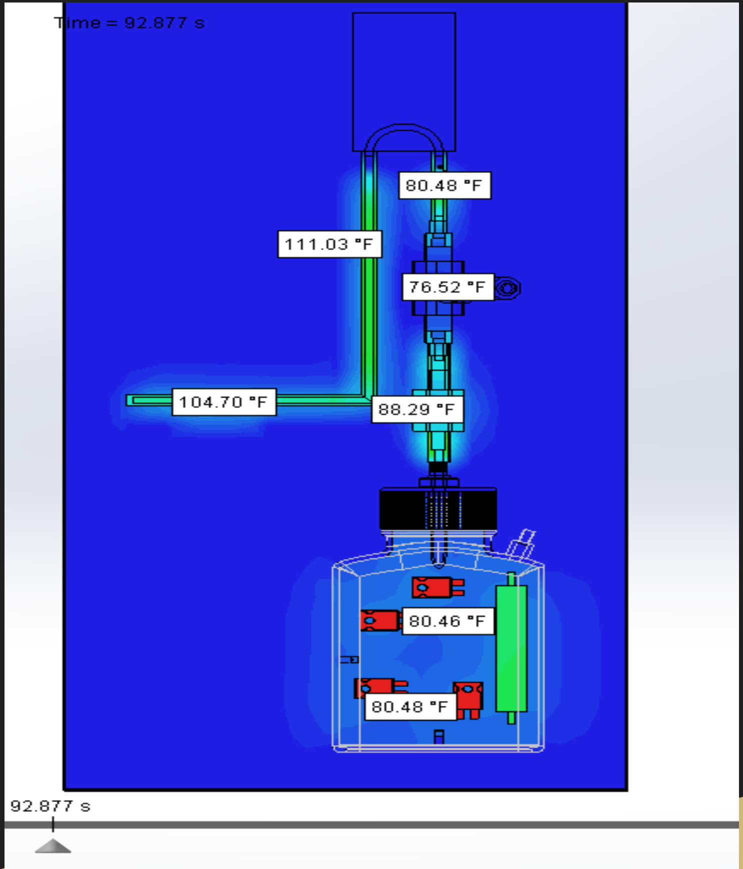


# Expected Component Temperatures

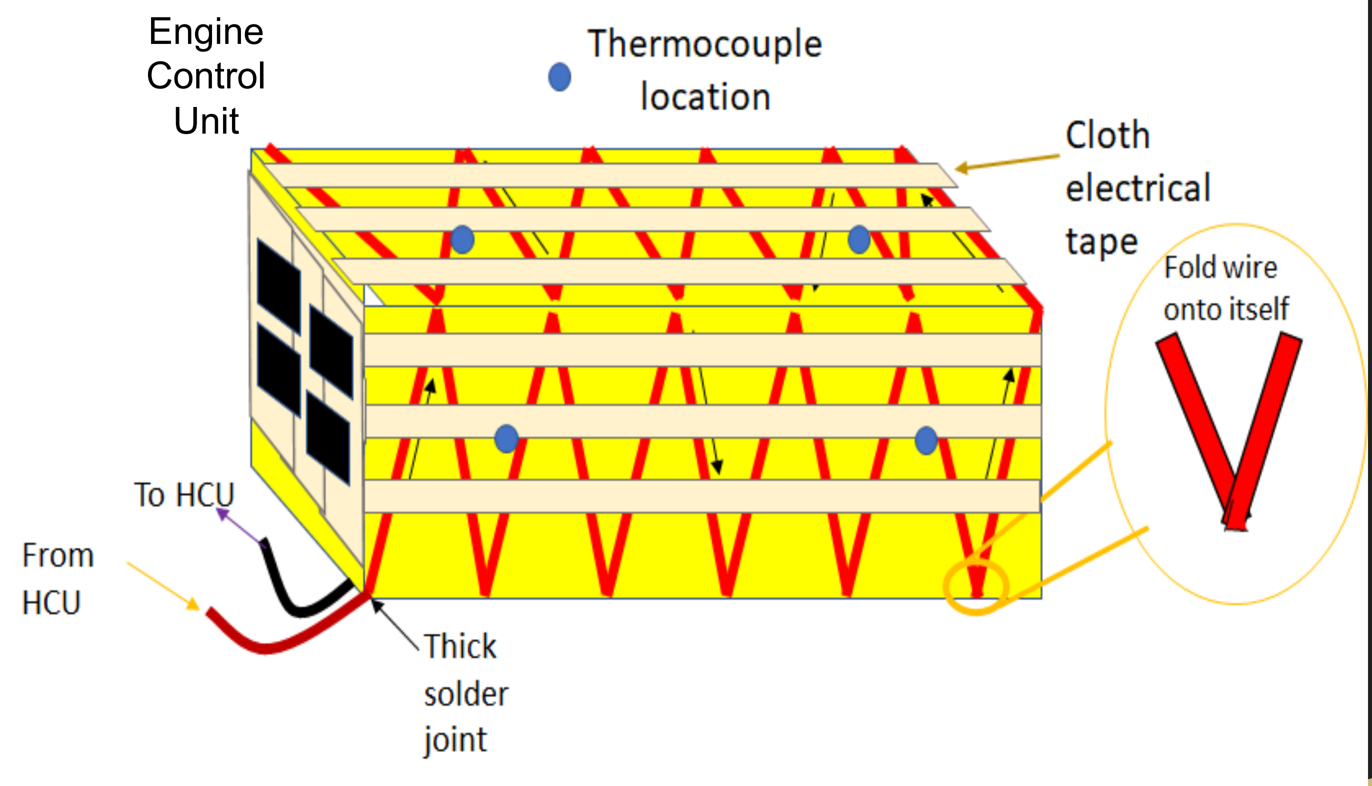
Surface Temperatures After 1.5 minutes of Resistive Heating:

- **Fuel Hopper: 80.48°F**
- **Fuel Lines: 111.03°F**

For tests, measurements within +/- 3.6°F of the above values are acceptable



# ECU Heater Diagram

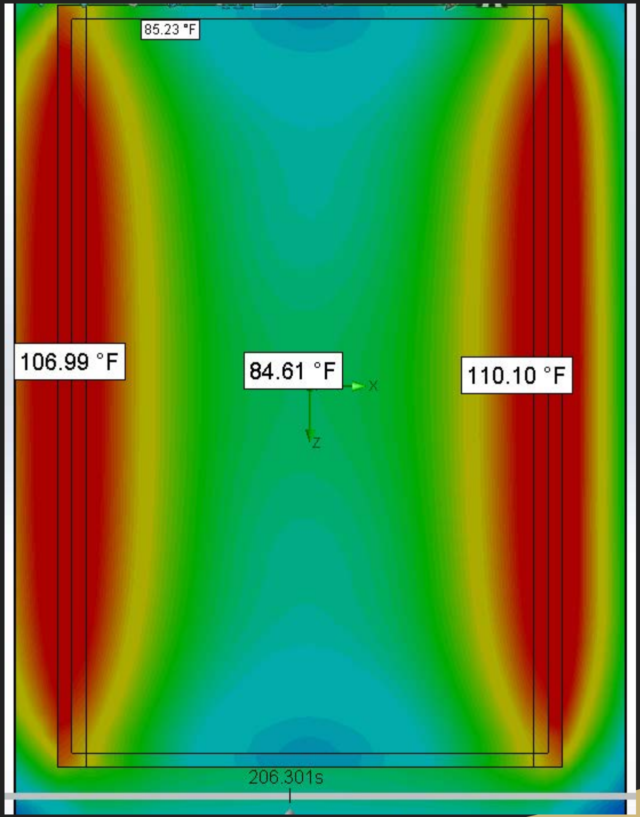


# Expected Component Temperatures

Surface Temperatures After 3.5 minutes of Resistive Heating:

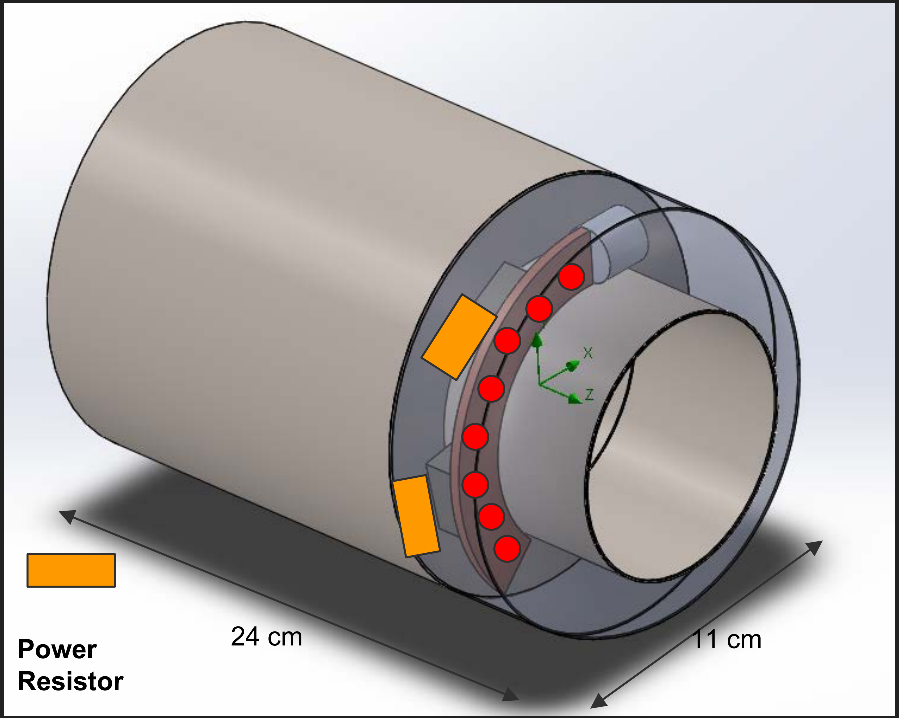
- **ECU: 110.1°F**

For tests, measurements within +/- 3.6°F of the above values are acceptable



# ESB Heater Diagram

- Thermocouple Locations



# Expected Component Temperatures

Surface Temperatures After 2.3 minutes of Resistive Heating:

- **ESB: 98.73°F**

For tests, measurements within +/- 3.6°F of the above values are acceptable