A.C.E.S.

Air-breathing Cold Engine Start

Spring Final Review

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OUTLINE

- Project Purpose and Objectives
- Design Description
- Test Overview & Results
- Systems Engineering
- Project Management

Project Purpose and Objectives

Project Purpose → Design Description → Test Overview & Results → Systems Engineering → Project Management

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

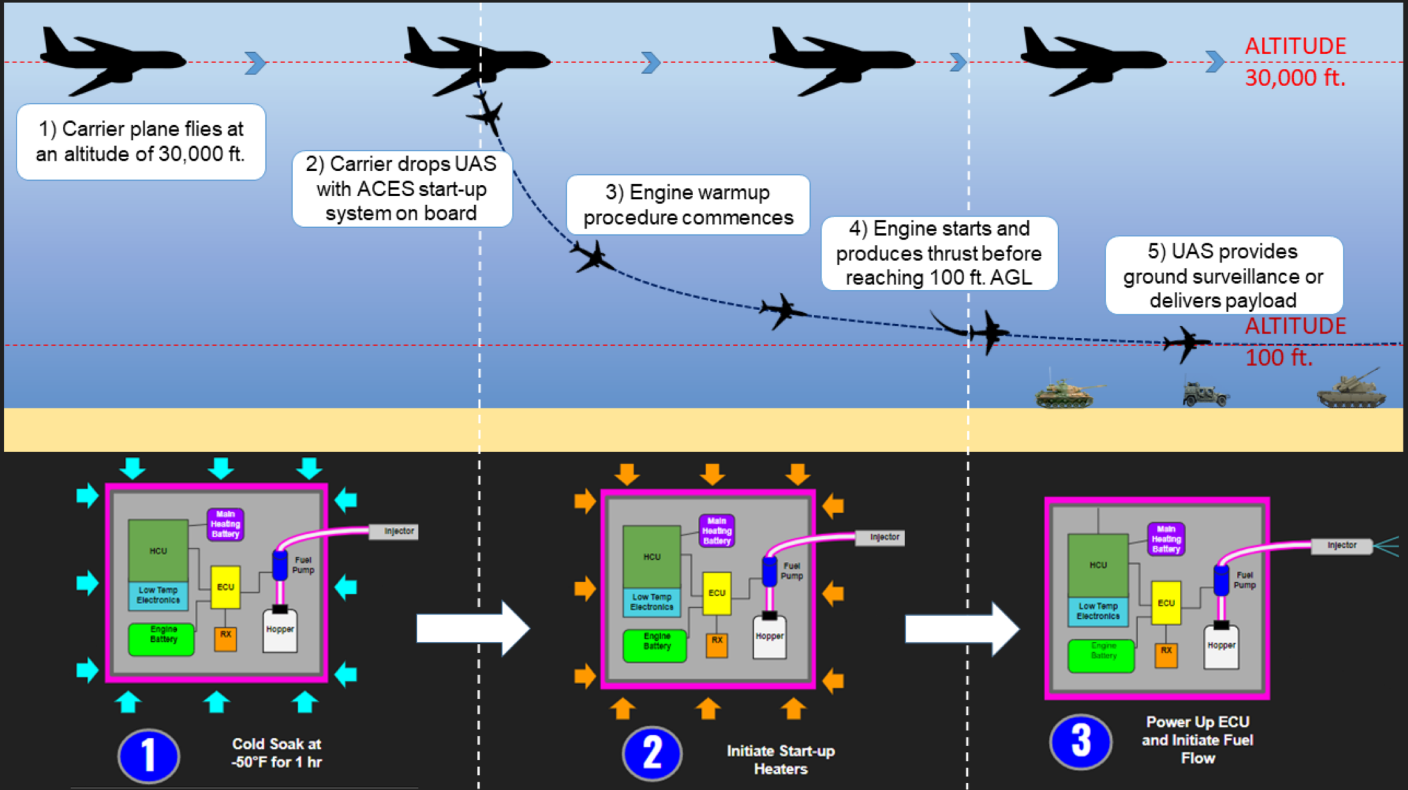
Motivation:

- 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.

Project CONOPS



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 the temperature of the heating systems

Functional Requirements

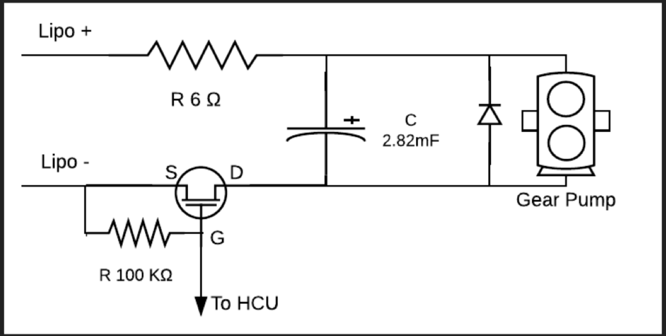
- ***FR 1.0) ENERGY:*** An initial energy source shall provide adequate power for the fuel delivery system heating and electronics heating.
- ***FR 2.1) FDS:*** The Fuel Delivery System shall provide a specified fuel flow rate from 0 to 4.8 g/s ± 0.13 g/s to the engine.
- ***FR 2.2) FDS:*** The Fuel 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 system.

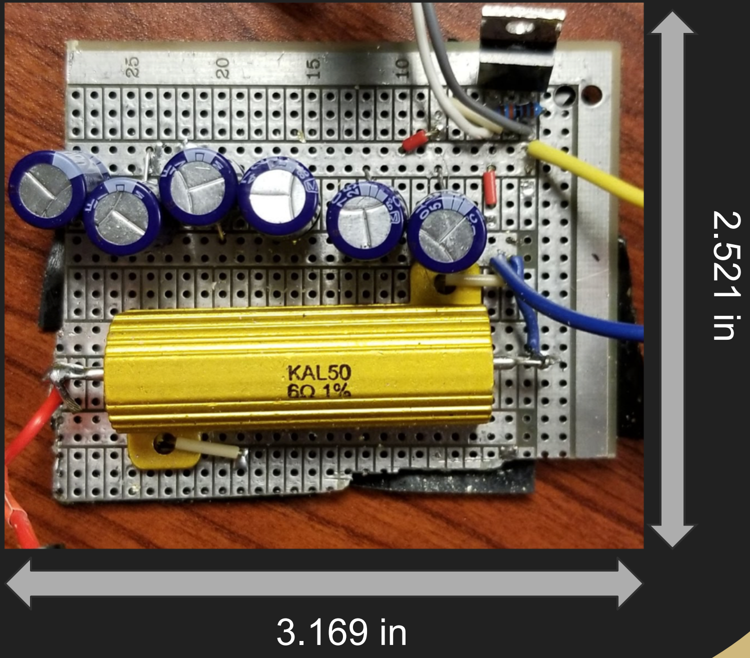
Design Description

Project Purpose | Design Description | Test Overview & Results | Systems Engineering | Project Management

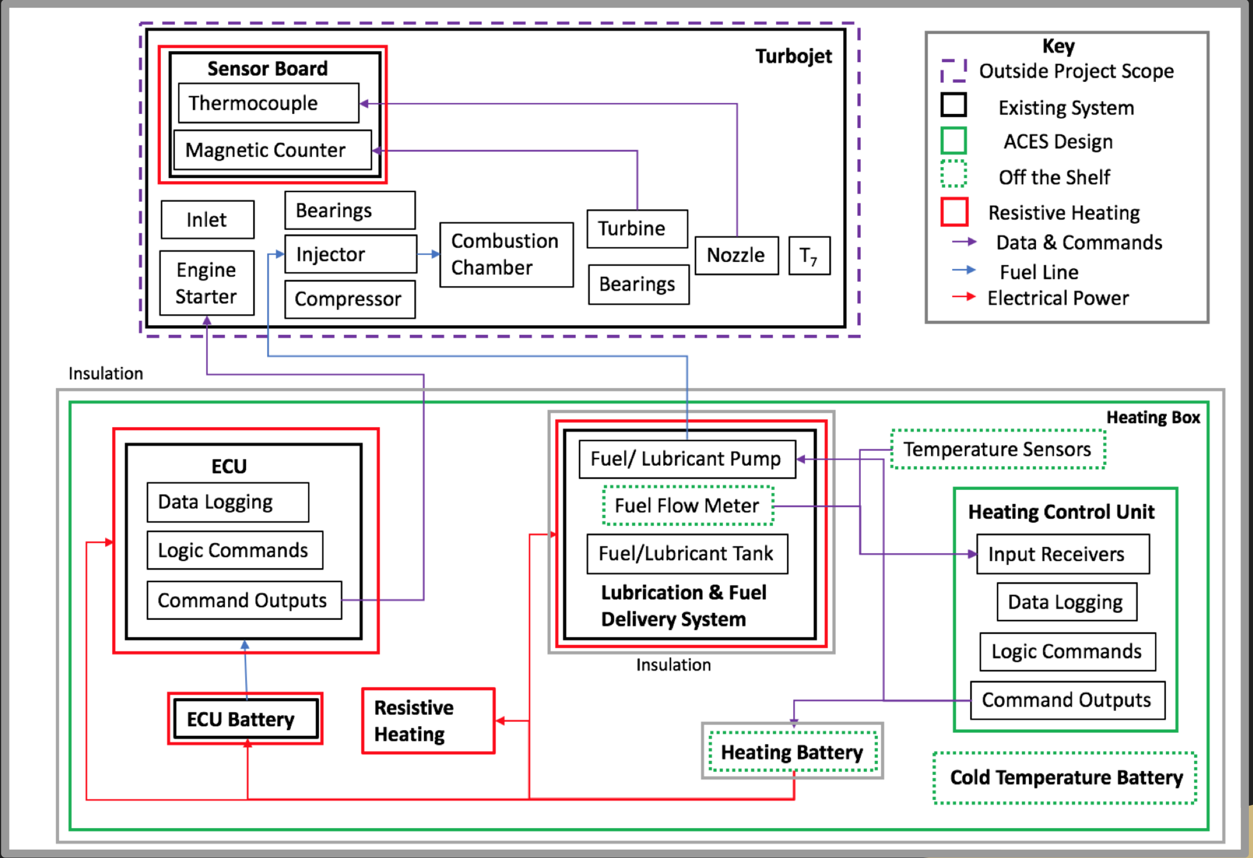
CHANGES SINCE TRR

- **Fuel Pump Motor Driver and Fly-back Diode**
  - RC filter which converts the PWM power to the fuel pump into a smooth and constant voltage
  - This prevents high voltage from being received by the fuel pump.

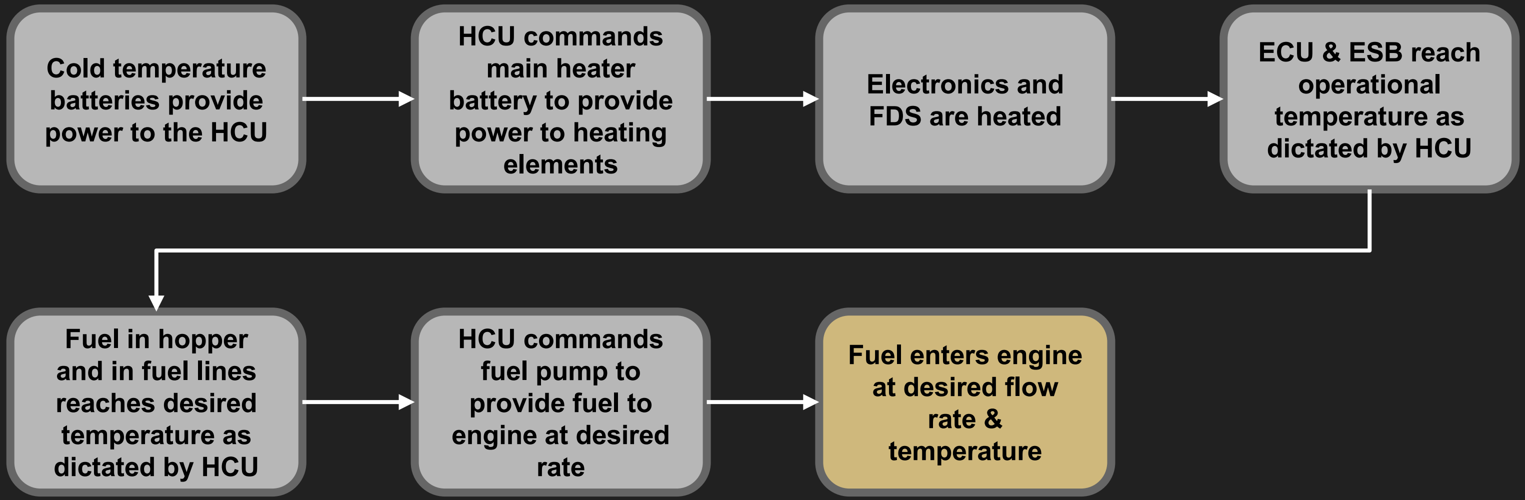




Functional Block Diagram



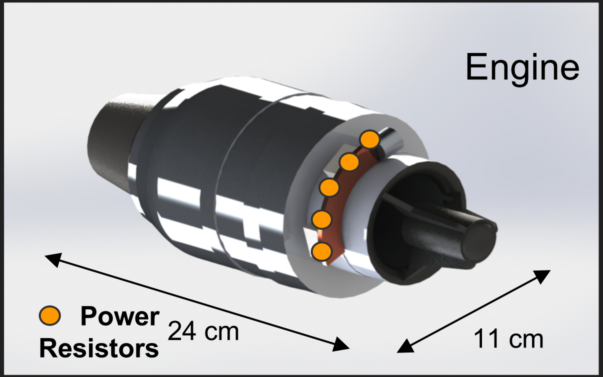
Process Flow Diagram



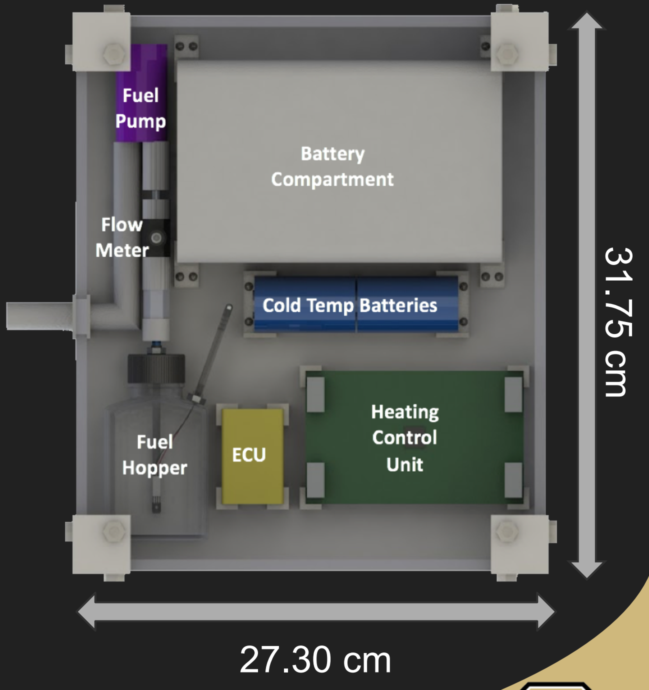
Baseline Design

Major Subsystems:

- **Power Source:** 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



Electronics Box



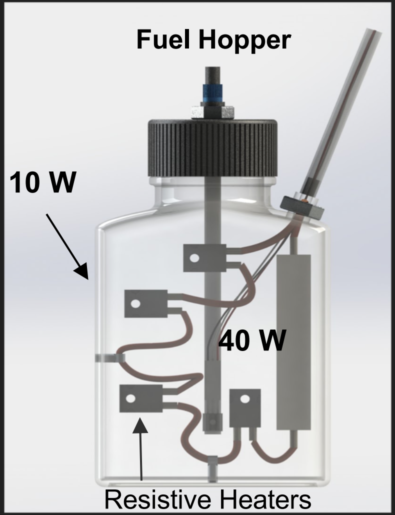
Baseline Design - FDS

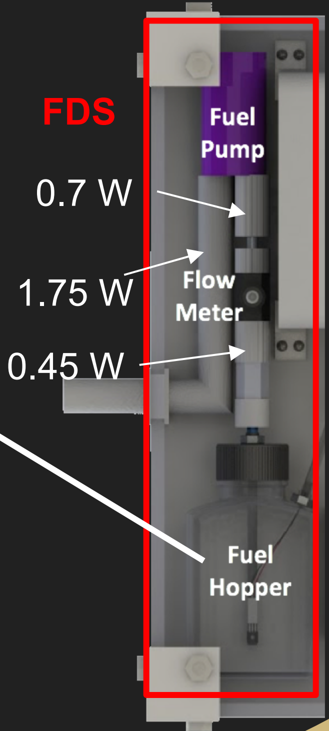
Fuel Delivery System Components:

- Fuel Hopper (Heated via power resistors inside, resistive wire outside)
- Fuel Pump
- Fuel Lines (Heated via resistive wire)
- Flow Meter
- Fuel Filter

Heated FDS Components:

- *Fuel Hopper:*
  - Exterior wrapped in resistive wire: **10 watts**
  - Interior contains power resistors: **40 watts**
- *Fuel Lines:*
  - Wrapped in resistive wire and Aerogel





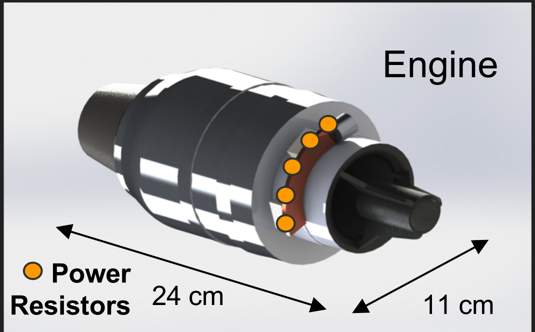
Baseline Design - Electronics Heating

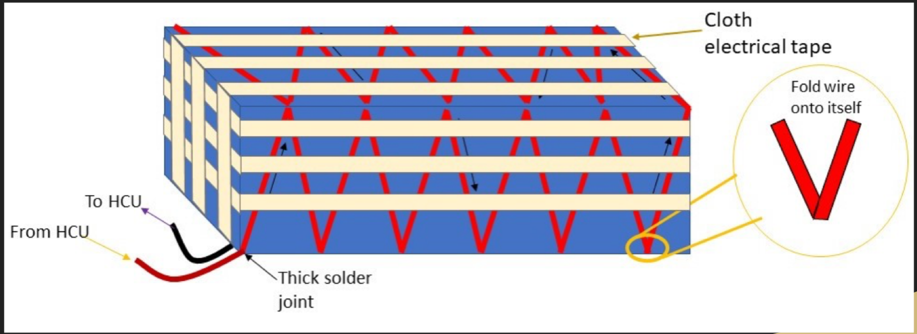
Resistive Heating Elements:

- *Resistive Wire:*
  - Used for the LiPo Batteries, Exterior of ECU
  - Wire will be wrapped around electronic components & batteries as shown on right
- *Power Block Resistors:*
  - Used for ESB

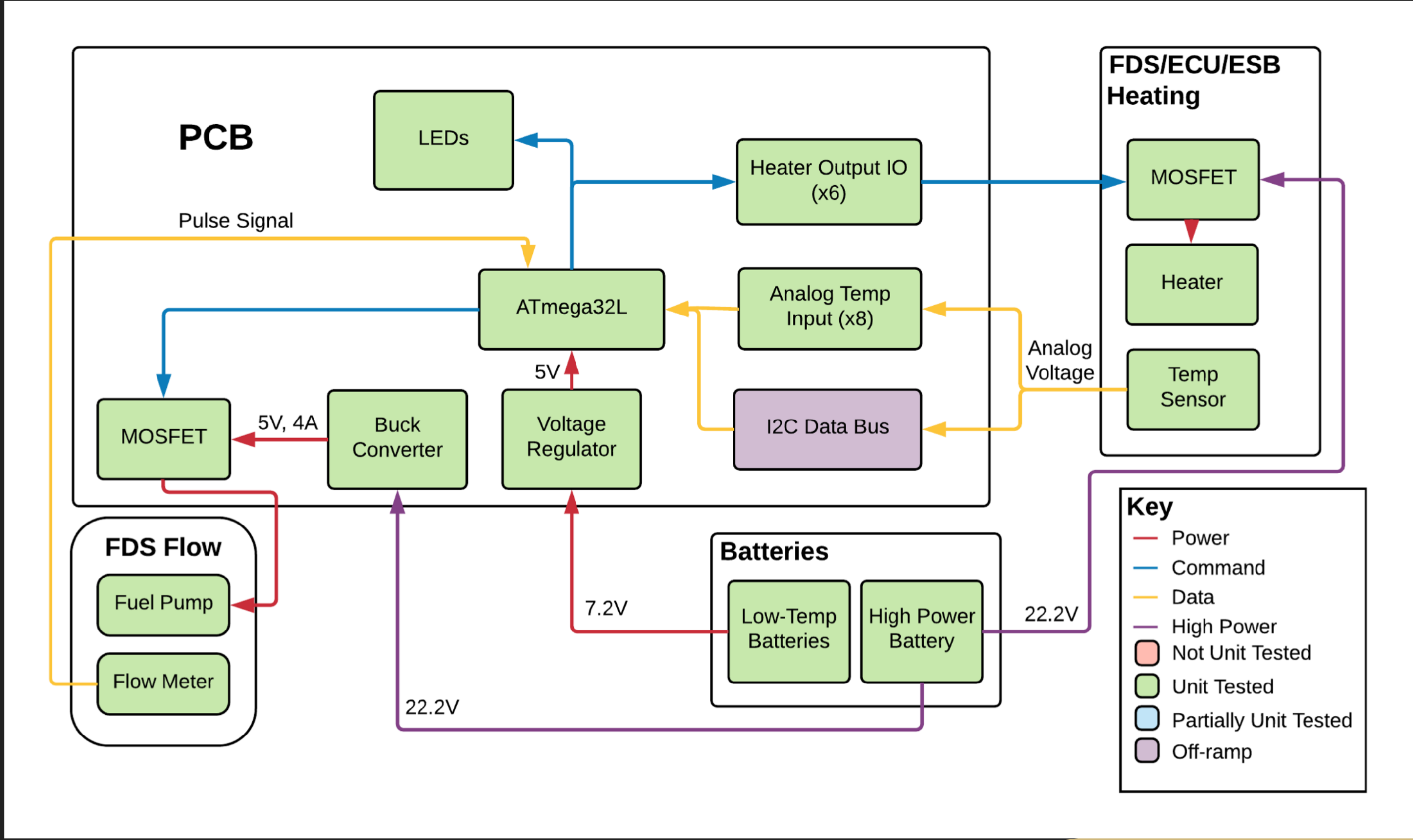
Design Concerns/Mitigation Strategies:

- Induced magnetism from wire coils could affect electronics and batteries
  - V shaped wrap pattern eliminates wire coils around electronic components
- Little room inside fuel hopper to place resistors
  - Bulky fuel filter within hopper removed, replaced with inlet at bottom of hopper





Heating Control Unit: FBD



Test Overview & Results

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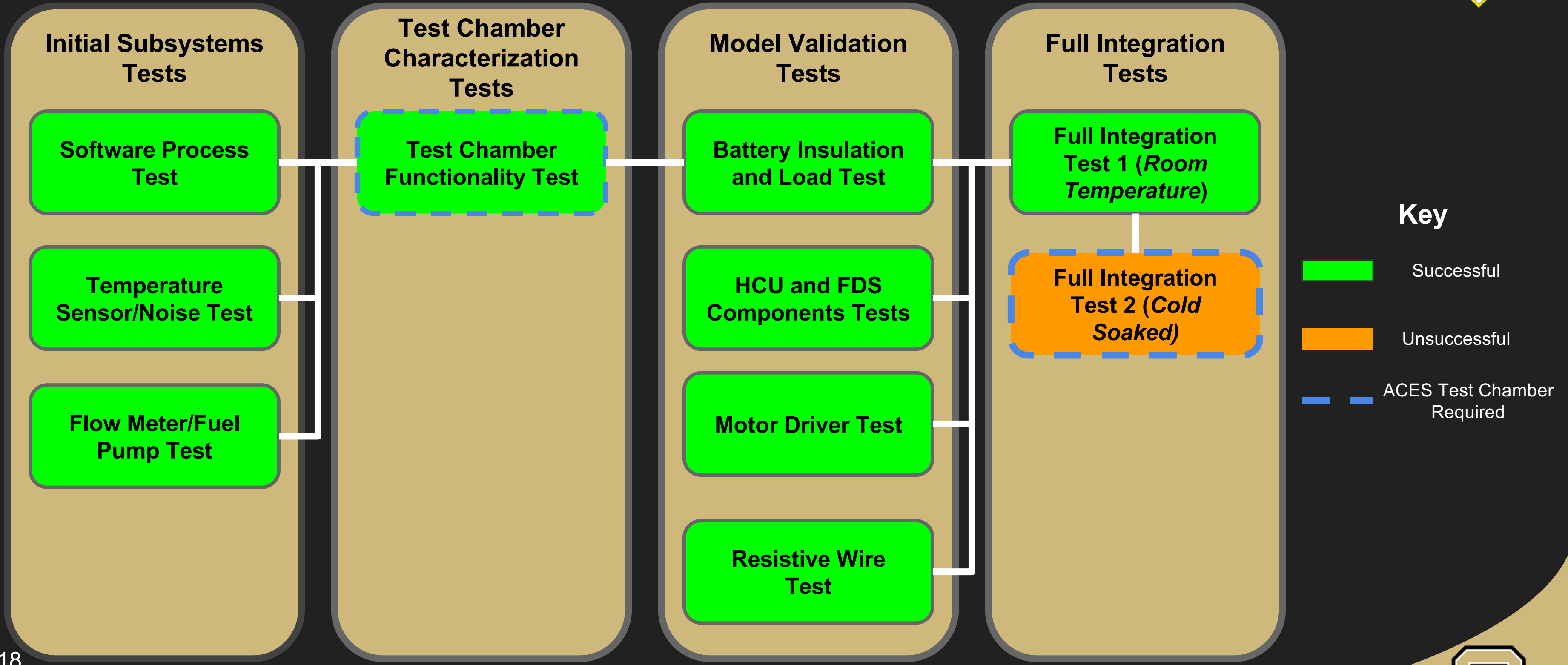
Tests Summary

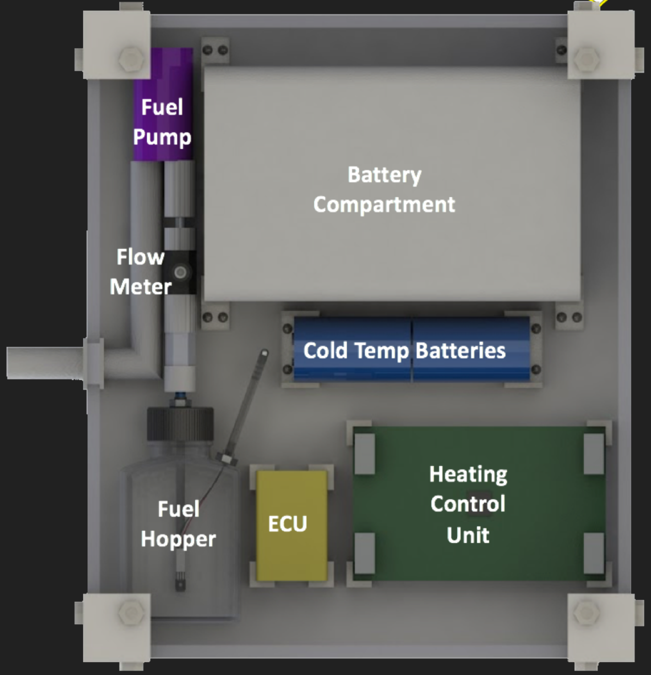


Test Overview & Results

Component Tests

Motor Driver Test

Full Integration Tests

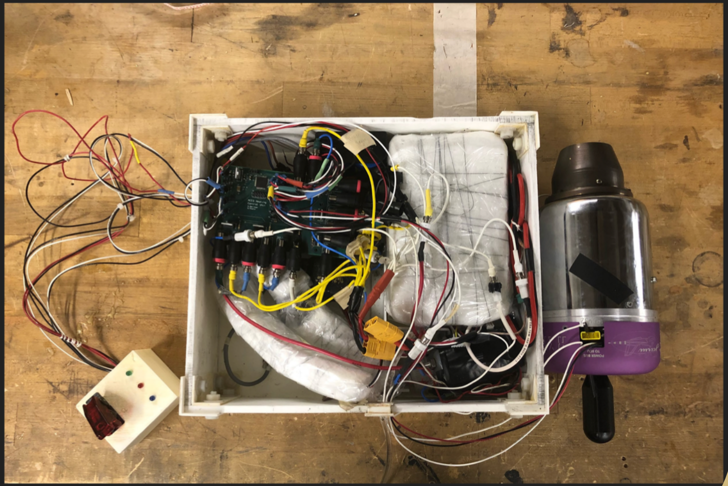


Component Tests Overview

Purpose:
- Heat components from room temperature to a desired temperature
  - Components: ECU, ESB, Battery, FDS
- Intended to prove functionality of the heating circuit around each component as well as HCU control
  - This was done at room temperature to ensure functionality before placing the system in the box

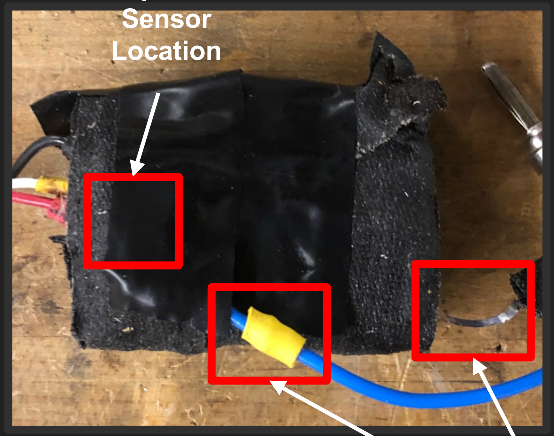
Plan:
- Use HCU, main heating LiPo battery, and resistive wire to heat the component

Expectation:
- Desired temperature is reached
- HCU turns off MOSFET when desired temperature is reached



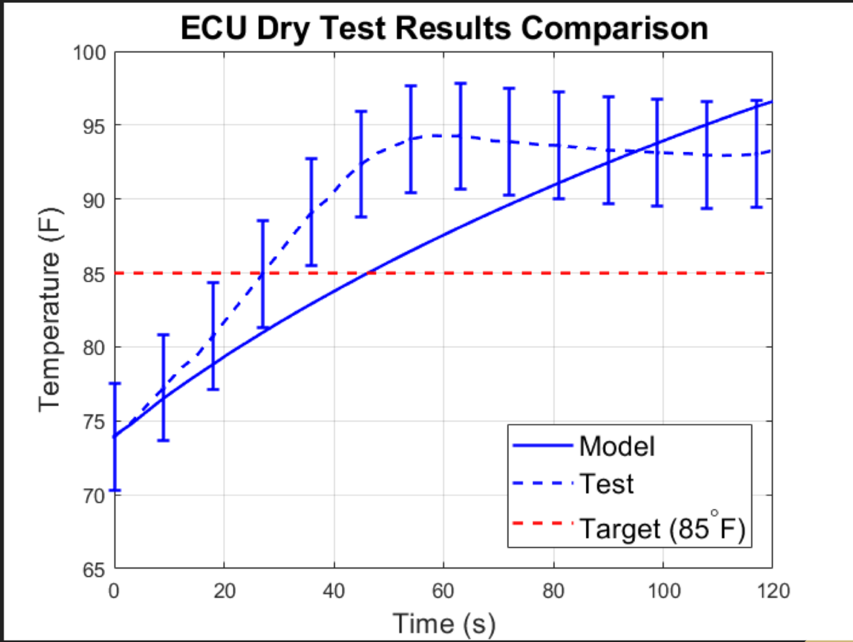
Component Tests: Engine Control Unit

Test Setup:



Absolute Error to Target:
ECU: 19 sec

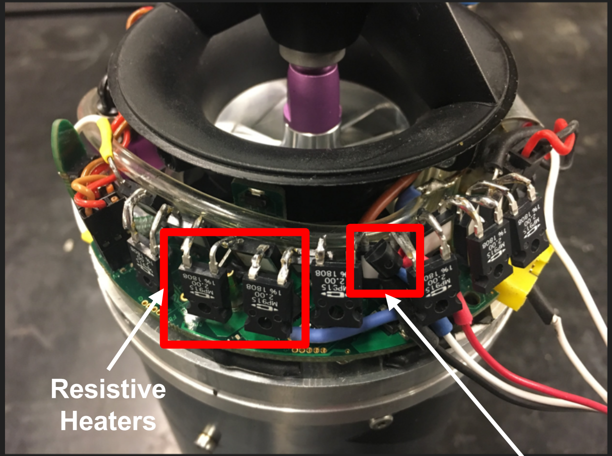
Relative Error to Target:
ECU: 67.86%



Date Completed:
4/8/2018

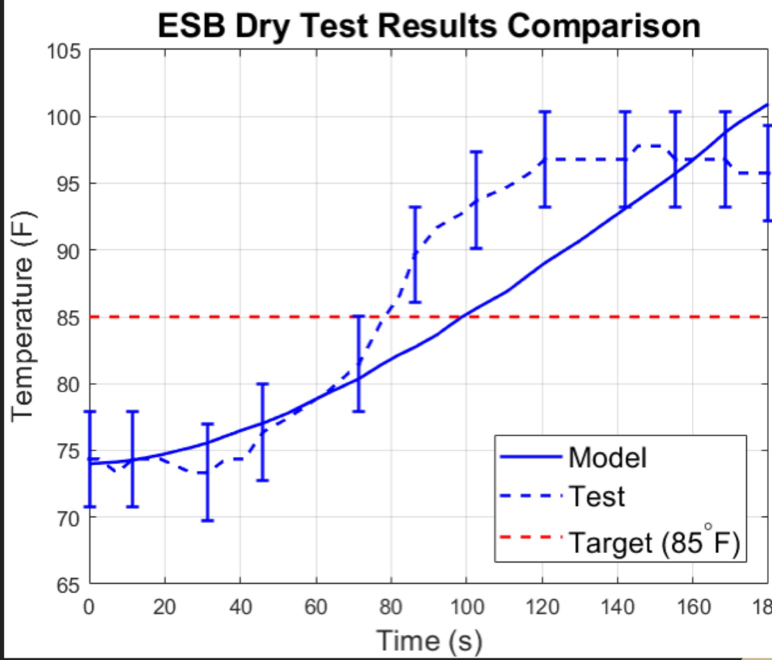
Component Tests: Engine Sensor Board

Test Setup:



Absolute Error to Target:
ESB: -20.4 sec

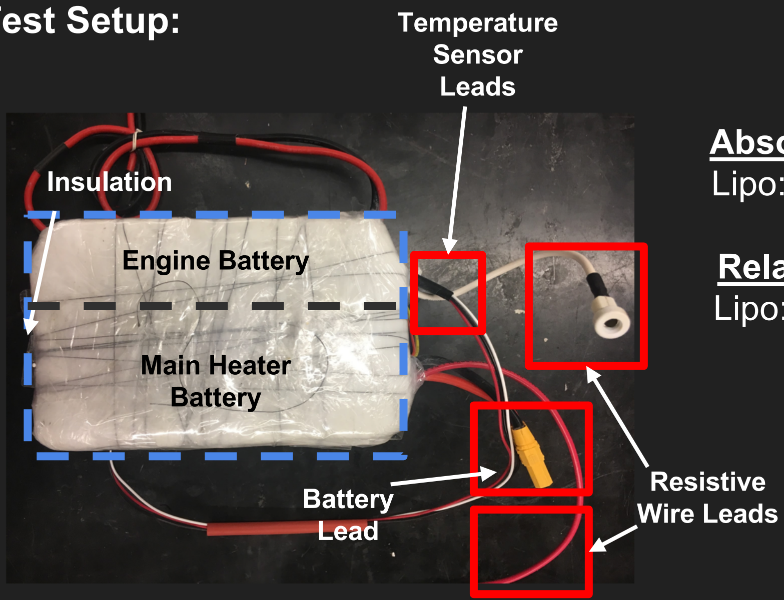
Relative Error to Target:
ESB: -26.09%



Date Completed:
4/8/2018

Component Tests: Battery Compartment

Test Setup:



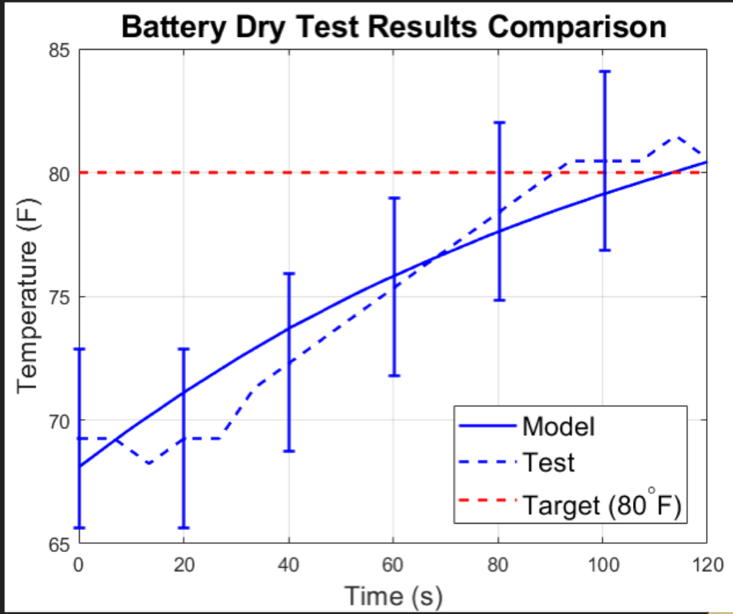
Date Completed:
4/12/2018

Absolute Error to Target:

Lipo: 20.64 sec

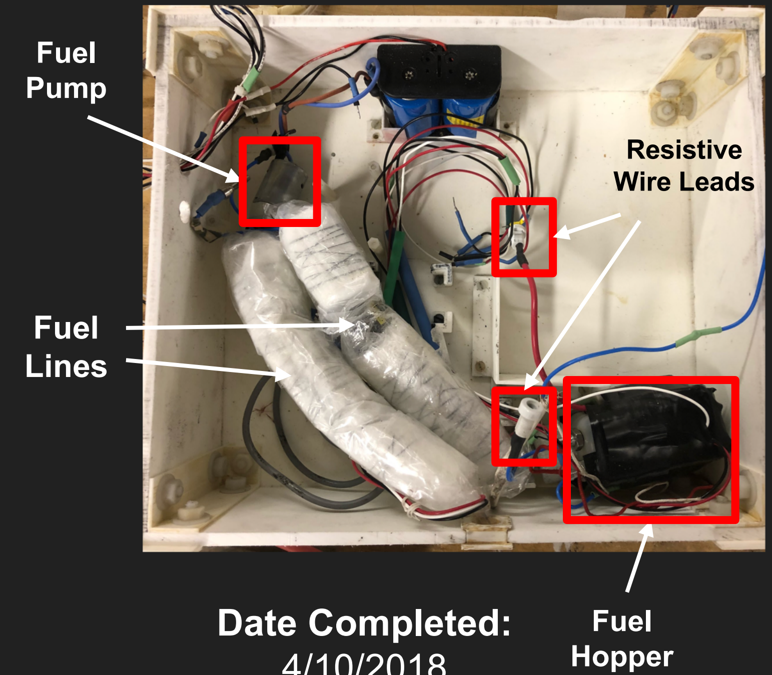
Relative Error to Target:

Lipo: 22.47%



Component Tests: FDS

Test Setup:

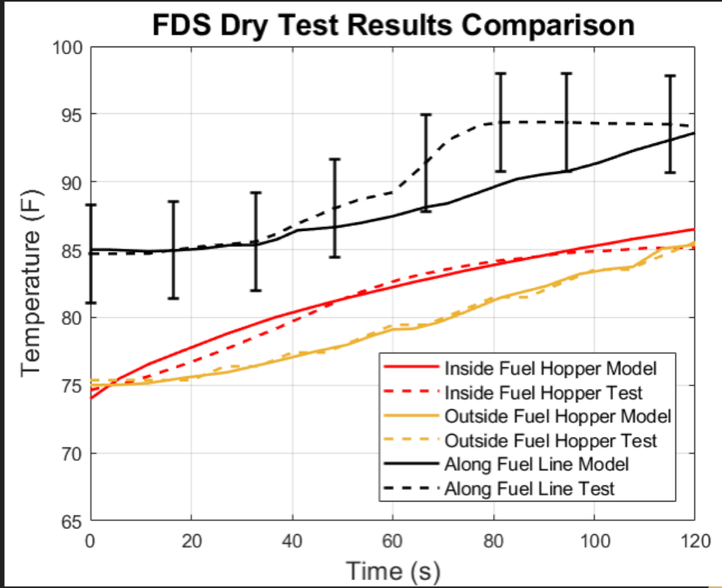


Absolute Error from Target:

Inside Hopper:	-9.02 sec
Outside Hopper:	-0.017 sec
Along Fuel Line:	18.08 sec

Relative Error from Target:

Inside Hopper:	-8.51%
Outside Hopper:	-0.02%
Along Fuel Line:	27.17%



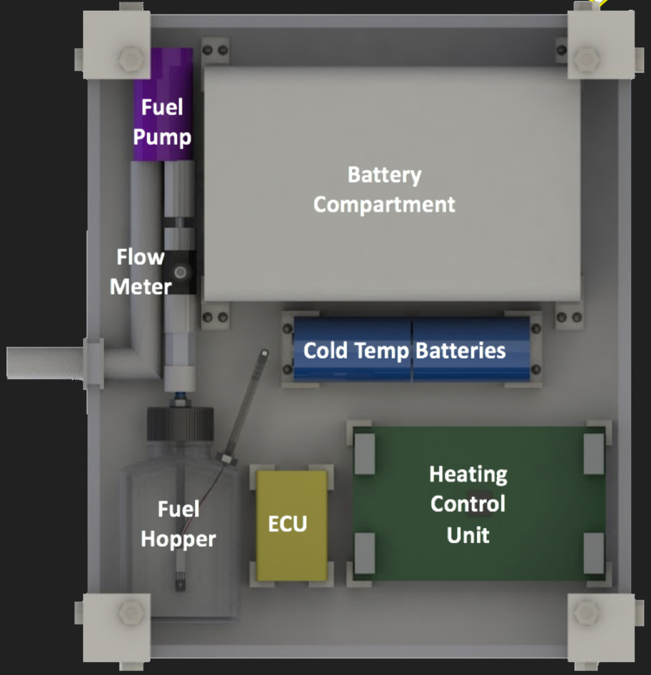
Date Completed:
4/10/2018

Test Overview & Results

Component Tests

Motor Driver Test

Full Integration Tests



Motor Driver Test

Purpose:

- Ensure that the voltage received by the fuel pump would not exceed its rated voltage (6V)

Plan:

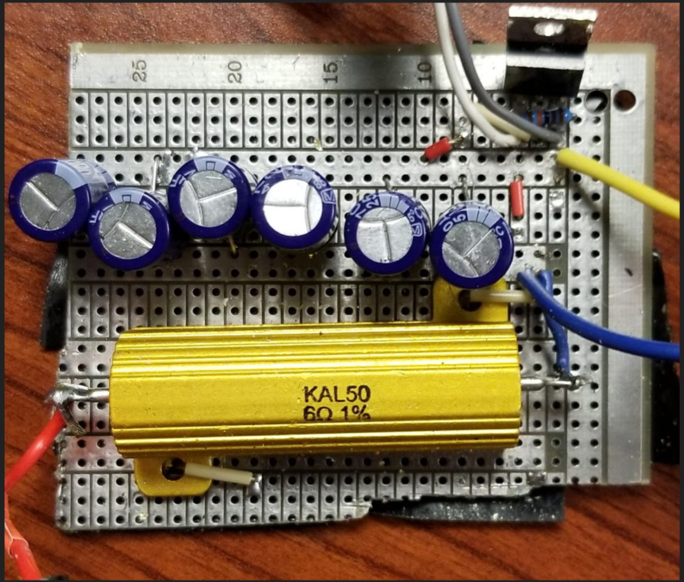
- Power motor driver with the LiPo battery
- Connect a representative power resistor load in place of the pump
- Control the duty cycle using the HCU

Expectation:

- The voltage will reach steady state

Date Completed:

- 4/18/2018

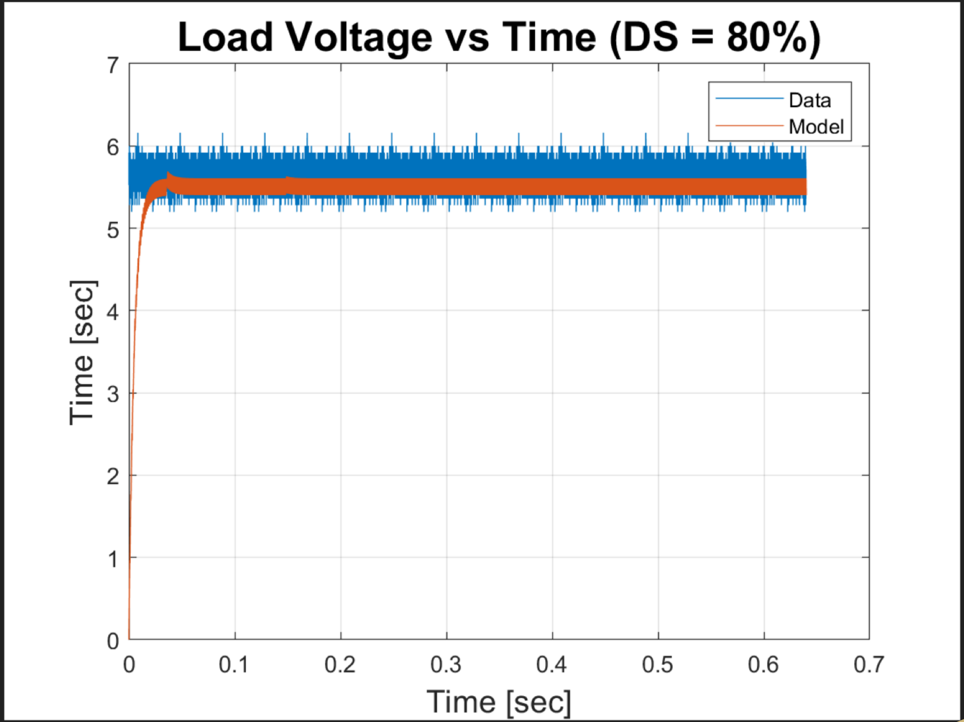


Motor Driver Results

Physical Parameters

- 1 KHz Duty, 80% duty cycle, 22.2 Vin
- Tests conducted with power resistors

Voltage received by pump will be reduced, therefore pump can be safely operated

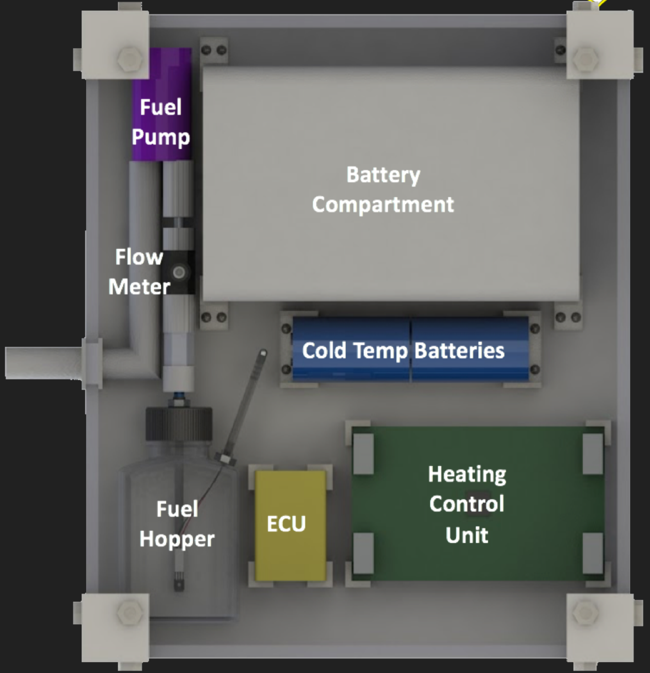


Test Overview & Results

Component Tests

Motor Driver Test

Full Integration Tests



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Room Temperature Systems Integration Test Results

Purpose:

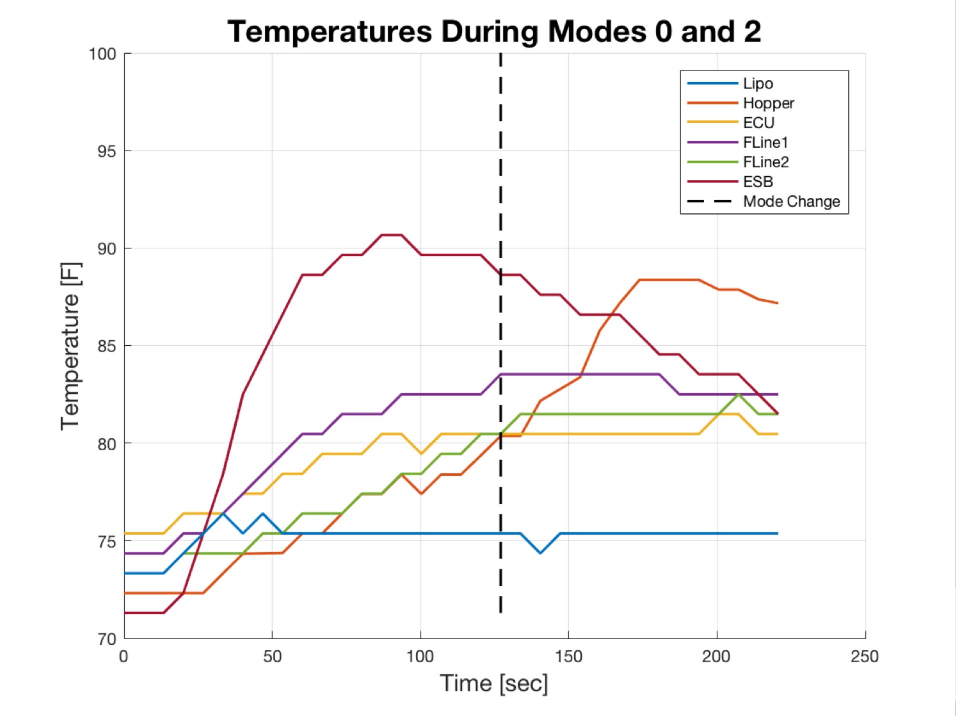
- Ensure each component was brought up to target temperatures simultaneously and then fuel will autonomously begin to flow.

Plan:

1. Begin code without heater power
2. Ensure proper temperature functionality
3. Connect heater power
4. Measure temperature using TMP's and outputted value from debugger.
5. Save values of flow rate after completion of pumping mode

Expectation:

- All components will heat up to target temperatures within time predicted by model.
- Fuel flow rate will be 4.8 g/s ± 0.13g/s

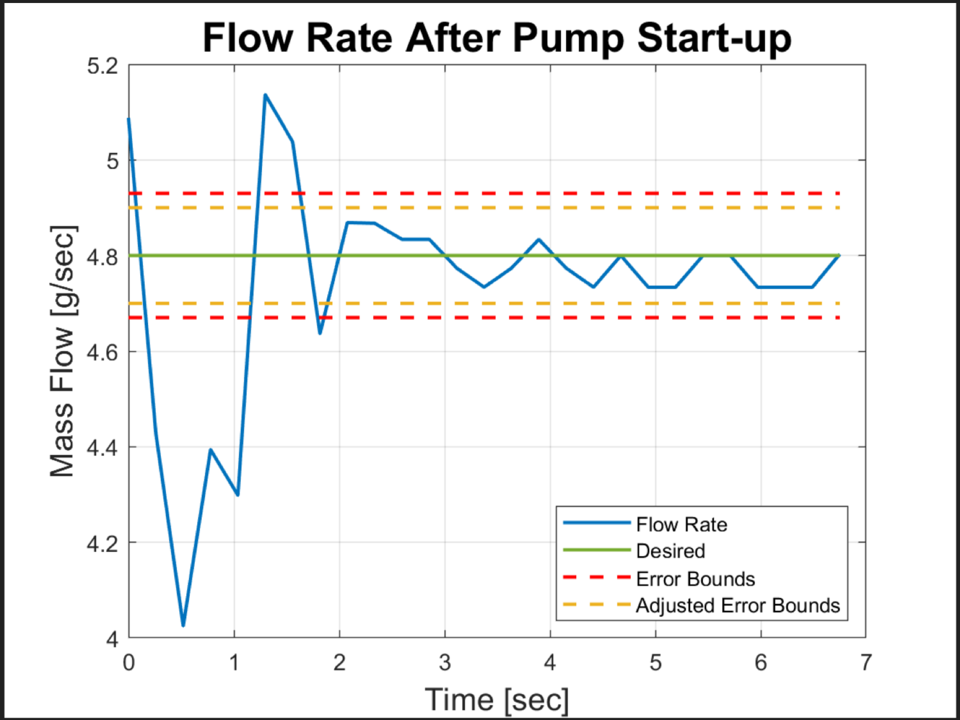


Room Temperature Pump Results

Results:

- Flow rate within acceptable bounds for 71.4% of the time pump was running

- **Gold** lines denote the tolerance to be confident **F.R. 2.1** has been satisfied
  - This assumes worst case behavior with the error on the sensor.

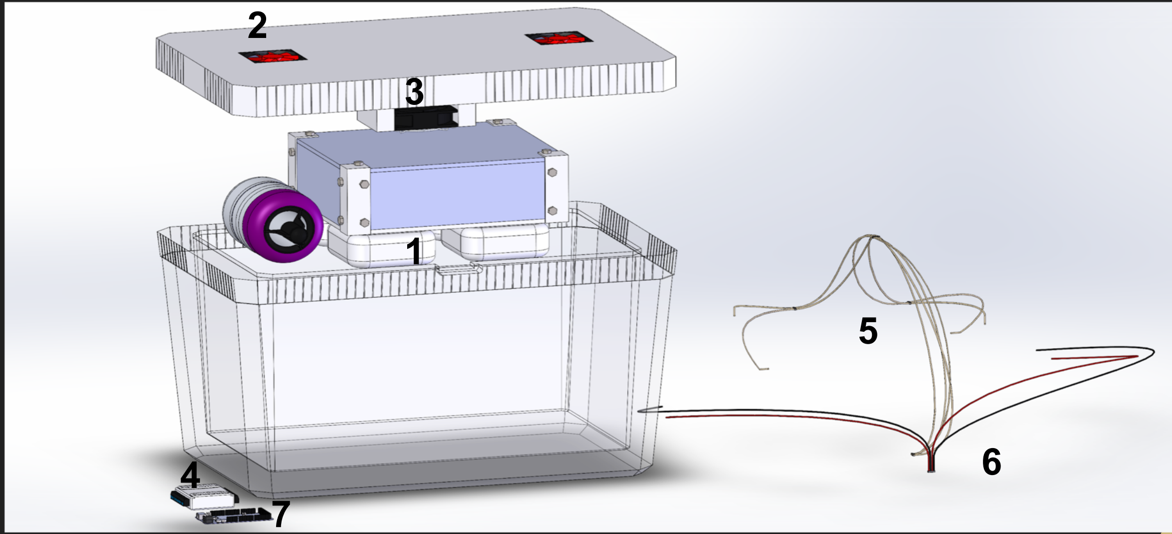


Full Integration Test Chamber

- Due to limitations gaining access to on-campus thermal chambers, the team created a custom test chamber to simulate the thermal conditions seen at 30,000 ft (-50°F ± 5°F)

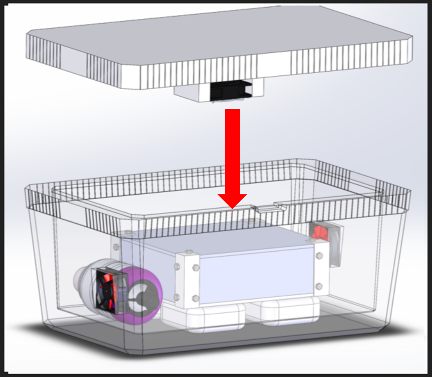
Foam cooler consisting of:

1. Dry ice blocks
2. 2 temperature control fans
3. 1 circulation fan
4. National Instruments DAQ
5. 4 type K thermocouples
6. Wiring for fan power
7. Arduino MEGA



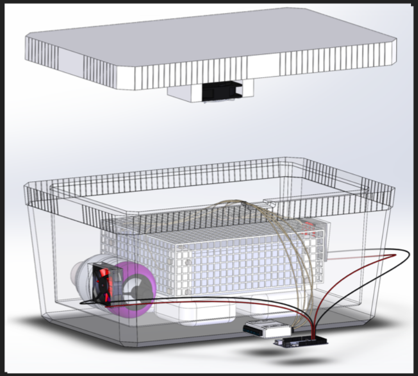
Full Integration Test Plan Summary

1



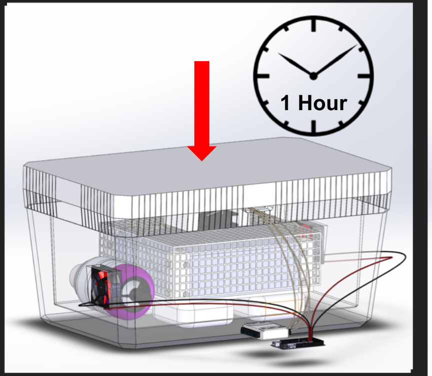
Place the electronics box and engine in test chamber with 20 lbs of dry ice

2



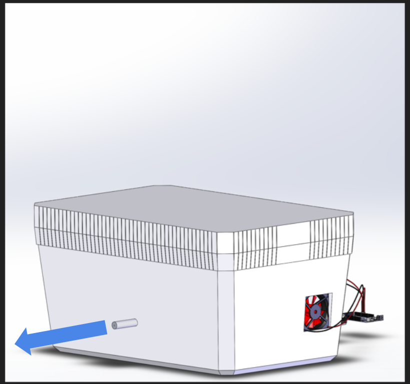
Insert the support cage over electronics box and attach thermocouples for DAQ and Arduino controller

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

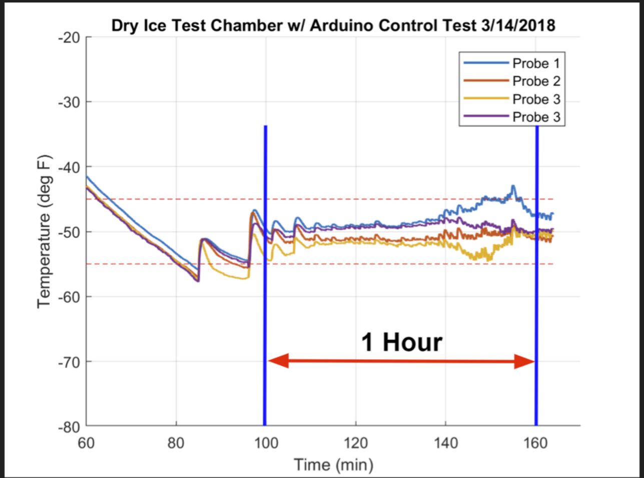
Test Chamber Verification Results

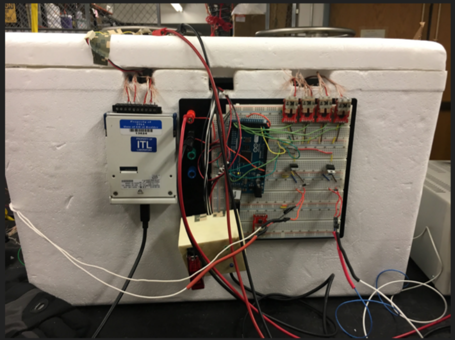
Test Chamber Results:

- All temperature readings within acceptable range (-50 +/- 5°F)
- Improvement over results shown at TRR (two thermocouples showed standard deviation outside acceptable range)
- **Functionality of dry ice test chamber verified**

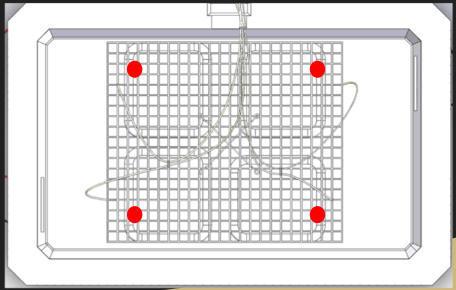
Average Temperature Readings

Probe	Temperature (°F)
1	-47.91 +/- 1.67
2	-50.58 +/- 0.58
3	-52.10 +/- 0.95
4	-49.38 +/- 0.64



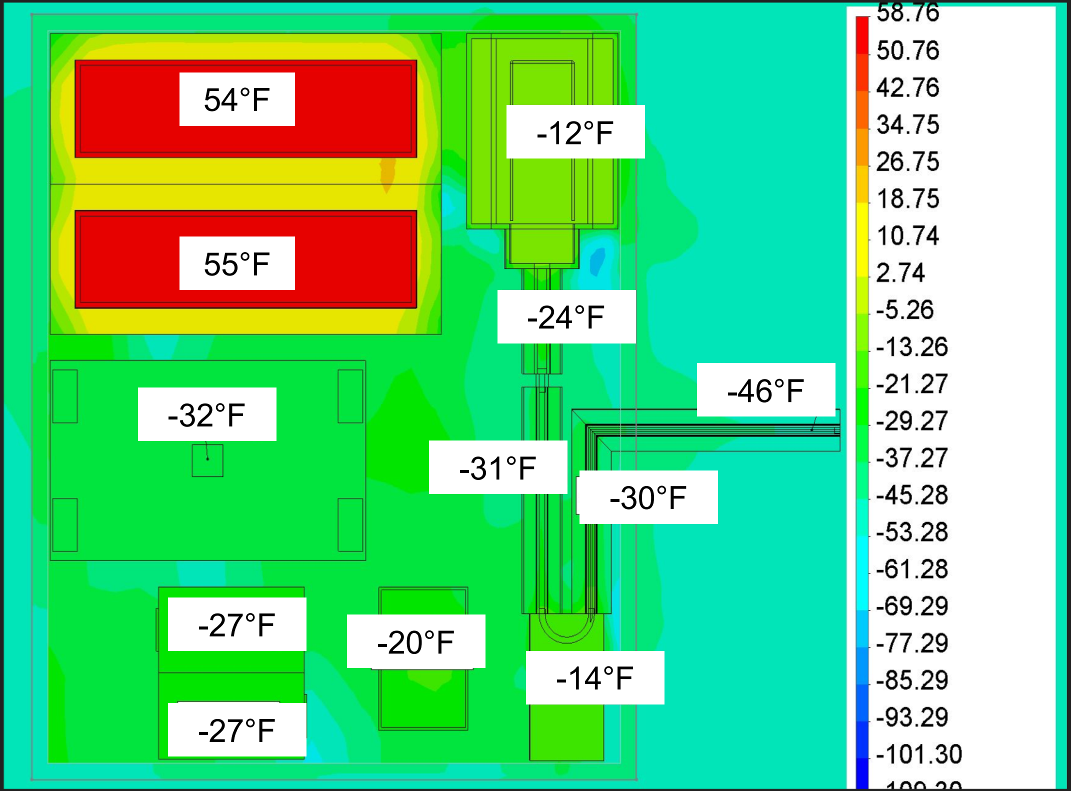


Top View



Thermocouple Locations

Cooling Model Validation



Component	Model (°F)	Data (°F)
Battery	54.22	38.58
Fuel Line 1	-30.69	-47.30
Fuel Line 2	-24.46	-23.86
Hopper	-12.30	-17.33
ECU	-20.49	-37.64
ESB	-1.33*	-75.10

*ESB model misses key variables, causing discrepancy

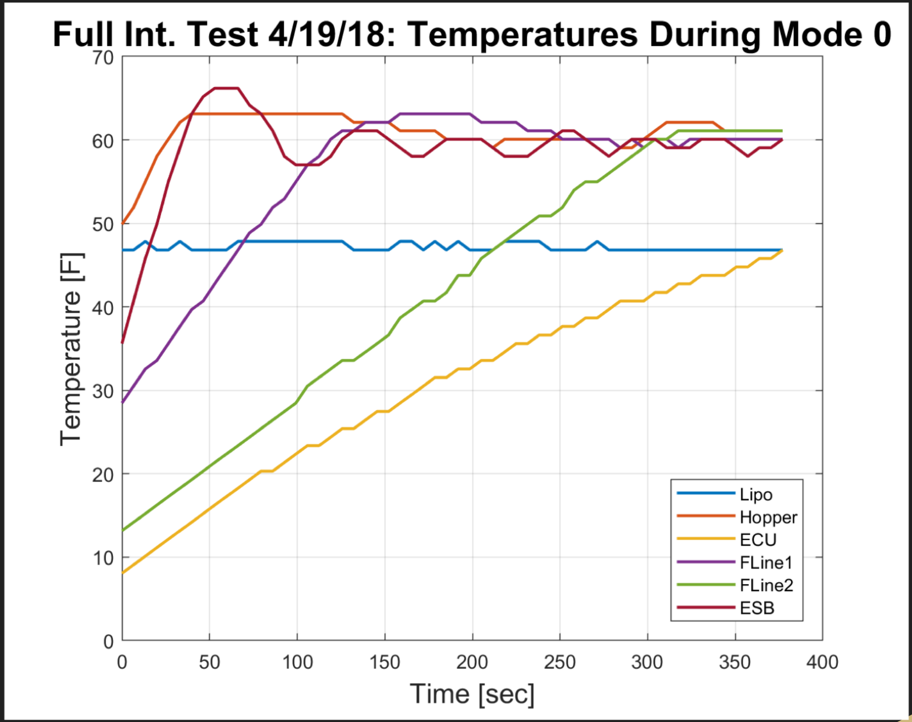
Integration Test Results

Results:

- **All temperatures were set to 60°F**
- Convergence to within **1.09°F** from target:
    - Hopper
    - Fuel Line 1
    - Fuel Line 2
    - ESB

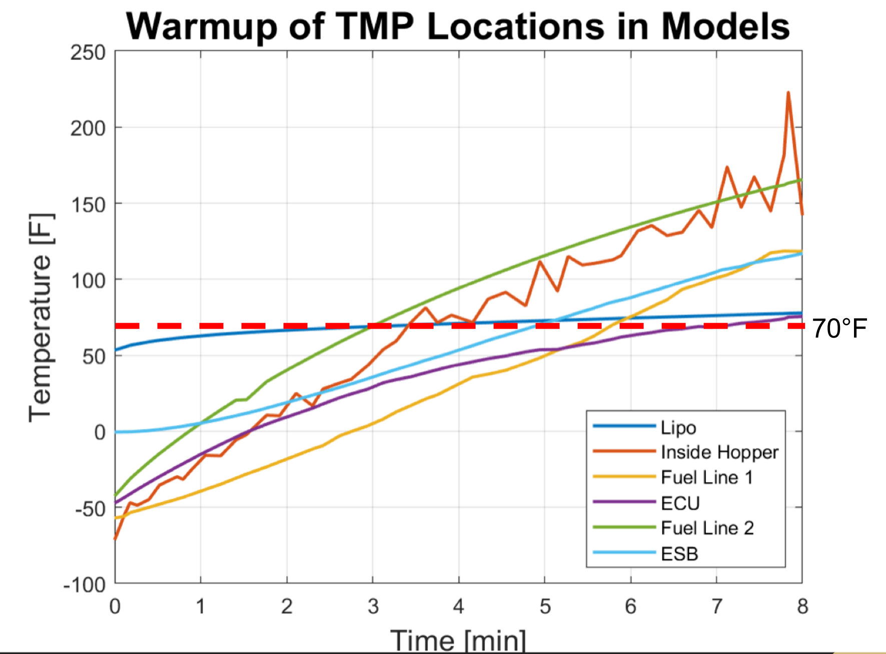
Problems/Solutions:

- ECU warming can be increased with duty cycle
- LiPo circuit connection was broken
    - Weak solder joints
    - Banana plug not completely plugged in
    - Subsequent tests confirm the **LiPo heating circuit is still operational**
- **FR 1.0, 2.2, and 4.1 satisfied**
- **FR 2.2 not satisfied**



Full Integration Test Models

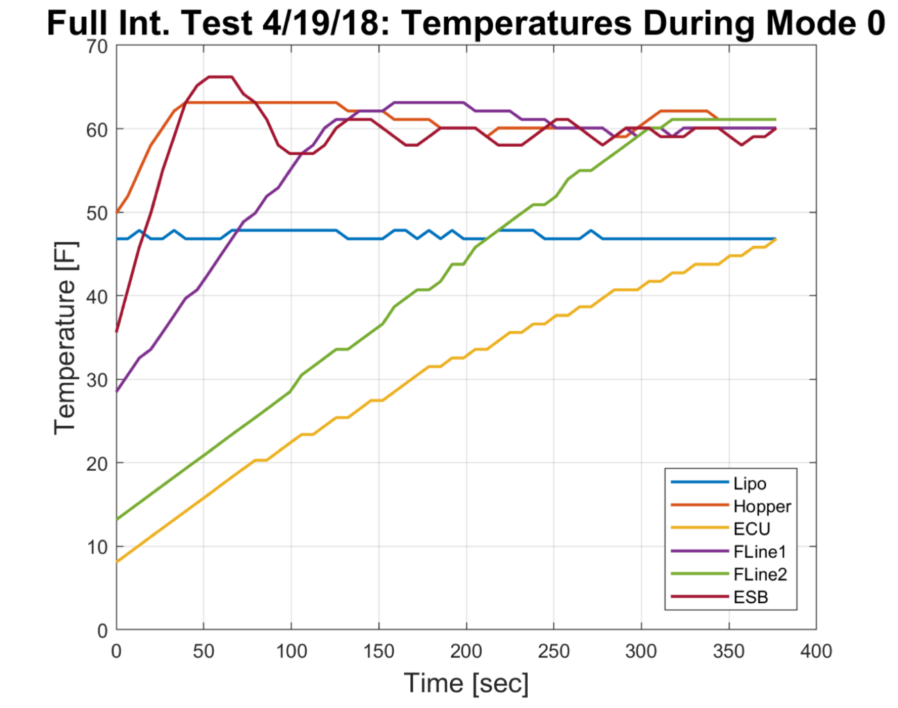
Component	Target Temp	Model Time
Lipo	70°F	3.6 min
Hopper	70°F	3.4 min
Fuel Line 1	70°F	5.8 min
ECU	70°F	7.2 min
Fuel Line 2	70°F	3 min
ESB	70°F	4.95 min



Direct comparison cannot be made between the model and integration test due to starting temperatures

Full Integration Test Models Comparison

Component	Acceptable Range	Test Results (Max.)
Battery	30 - 122 °F	46.82 °F
ECU	60 - 120 °F	46.82 °F
ESB	60 - 120 °F	66.19 °F
Fuel Line 1	60 - 115 °F	63.13 °F
Fuel Line 2	60- 115 °F	61.10°F
Inside Fuel Hopper	60 - 115 °F	63.13 °F

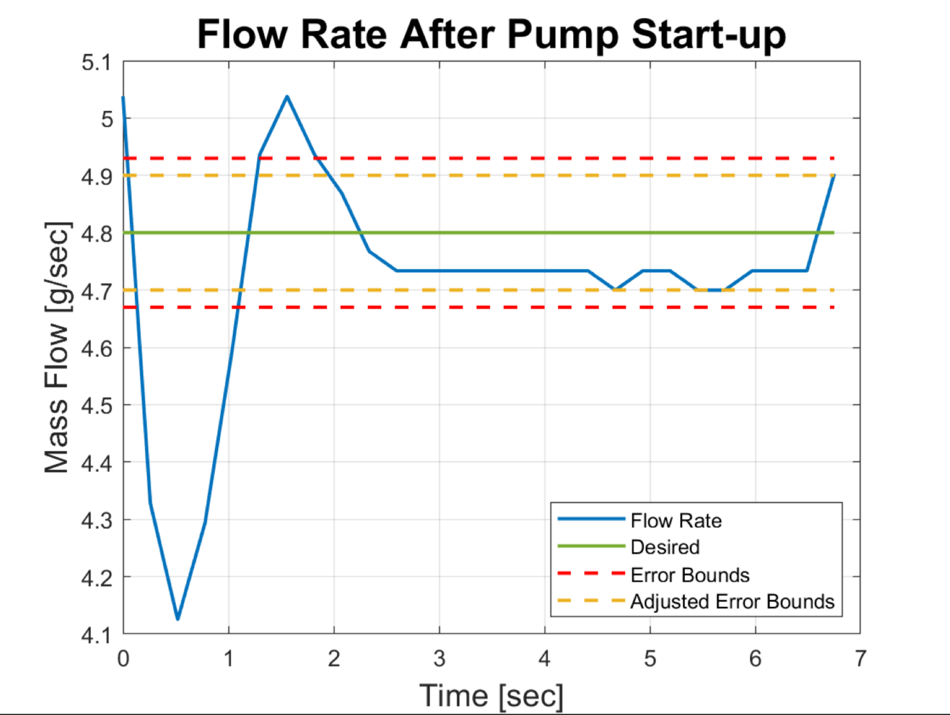


*All test results were achieved approximately **3-4 minutes** after system start; well below the required **8 minutes and 42 seconds***

Full Integration Pump Results (Cold Temperature)

Results:

- Flow rate within acceptable bounds for 71% of the time the pump was running
- **Gold** lines denote the tolerance to be confident **F.R. 2.1** has been satisfied
  - This assumes worst case behavior with the error on the sensor.
- FR 2.1 and 4.2 satisfied



Systems Engineering

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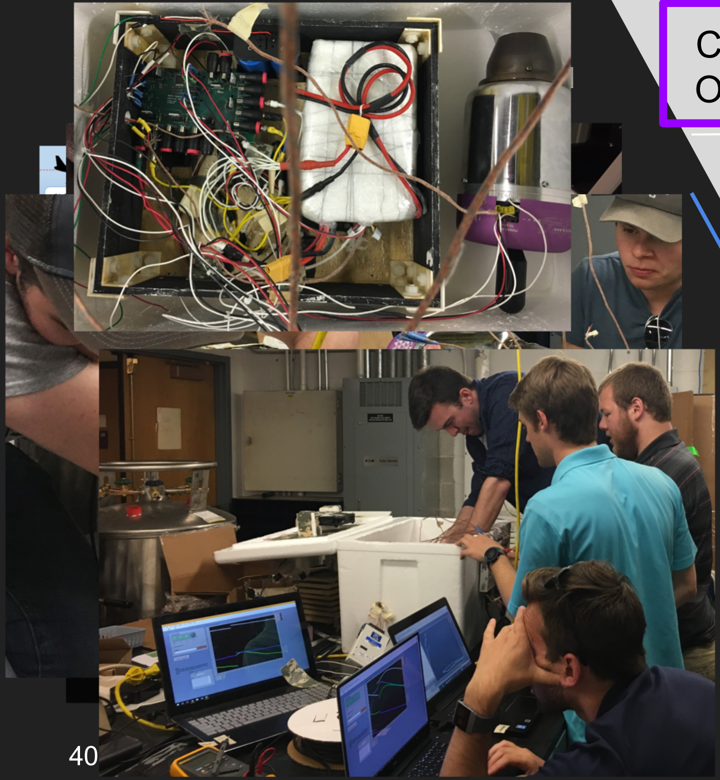
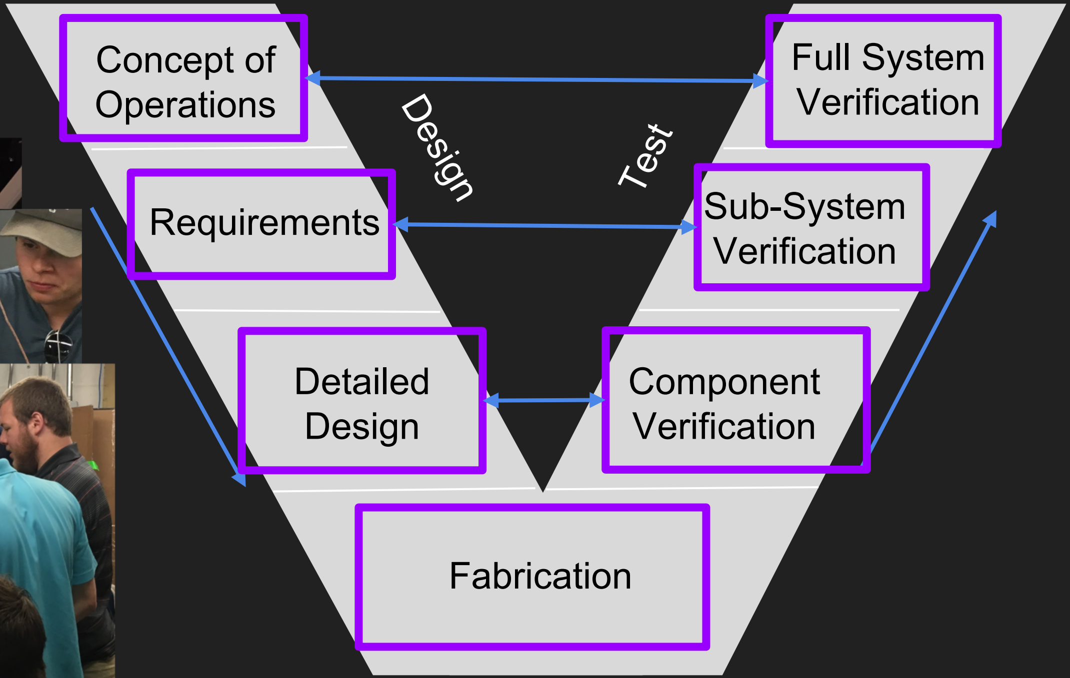
Systems Engineering Approach





Risk Assessment

Risk	Mitigation	Outcome
1: Fuel Line Melting	Testing for safe temperatures and conservative control law	Wrong length of resistor wire used, future testing performed at room temperature first for easier system access
2: Heating Wire Short Circuit	No mitigation strategy	Wire around ECU shorted, subsequently insulated with electrical tape
3: Jet Fuel Ignition	Keep fire extinguisher ready, examine connections before each test	Safety procedures followed, no issues occurred
4: Fuel Pump Failure	Unanticipated, no mitigation strategy	RC circuit developed to mitigate risk

Severity

Likelihood	Minimal	Minor	Major	Hazardous	Catastrophic
Near Certainty					
Very Likely					
Likely		1	2,4		
Unlikely				3	
Very Unlikely					

Unacceptable

Acceptable with mitigation

Acceptable

Unanticipated Risks

- ***Pump failure due to over-voltage***
  - Impact: Pump irreparably damaged, loss of fuel flow capabilities
  - Mitigation: Use of Fuel Pump Motor Drive and Fly-back Diode

- ***Fuel line overheating more likely than expected***
  - Impact: Loss of fuel line, failure of first partial integration test
  - Mitigation: Rewrapping fuel line, testing fuel delivery system heating outside of test chamber initially

Challenges Faced & Successes

Challenges Faced:

- Project scope changes
  - Difficult to maintain consistency in functional objectives and design requirements
- Change in point of contact with customer midway through first semester
- Lack of clarity in initial requirements from customer
  - Difficult to develop functional objectives and design requirements, perform trade studies
- Labor distribution on large, specialized tasks

Successes

- Initial Scope Change
- Good decisions after trade studies conducted
- Testing Schedule emphasized progression from component verification to subsystem verification to system verification

Lessons Learned

- Communicate with customer early and often to clarify requirements
- If scope must change, revisit and revise functional and design requirements
- Maintain a focus on project context: even if the engine is out of the project scope, it can't be ignored from a systems engineering perspective
- All members on the team should have testing software on their computers so that the testing work can be split more equally among team members.
- Establish and maintain a naming convention for data and documentation

Project Management

Project Purpose | Design Description | Test Overview & Results | Systems Engineering | Project Management

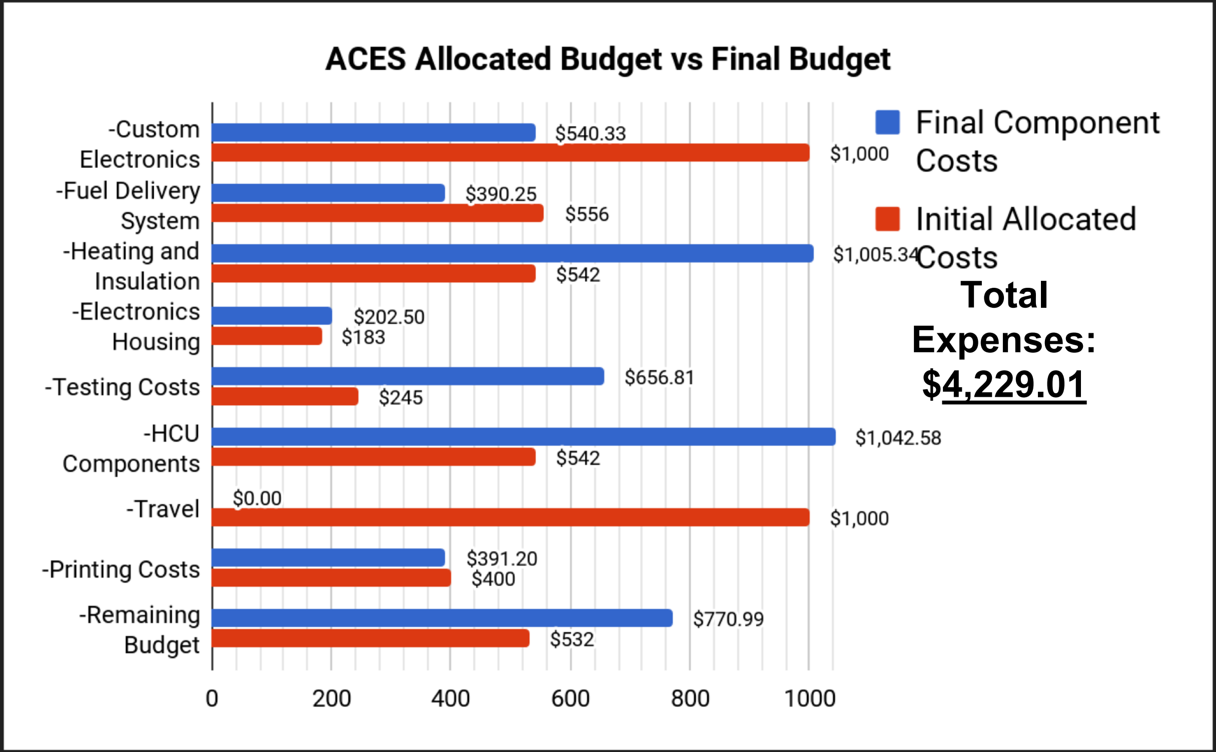
Management Approach

- **Bi-weekly full team meetings**
  - Additional full team meetings organized as needed
  - Subsystem meetings were self-organized
- **List of agenda items developed for each meeting**
- **High-level schedule was developed and maintained for spring semester**
  - Outlined major subsystem tasks
  - Minor tasks were left to subsystem teams to schedule
- **Provided extensive margin on tasks but an aggressive testing schedule**
  - Assumed problems would be encountered in testing, which did occur

Management Lessons Learned

- **Maintaining strong lines of communication with all team members is important**
- **Allocate more resources to testing**
- **Testing will always take far longer than expected**
- **How to manage conflict between team members**
    - Dodging issues is never effective
    - Issues must be discussed openly in a professional setting
    - Members must discuss issues openly with each other in order to come to a solution
    - Having a neutral moderator during discussions helps avoid escalation of the conflict
- **Distribute work more evenly among team members to eliminate single points of failure**

Budget Comparison



Estimated Industry Cost

Hourly Salary	$31.25
Total Team Hours Fall	2359 hrs
Total Team Salary Fall	$73,718.75
Total Team Hours Spring	2744 hrs
Total Team Salary Spring	$85,750
Total Salary Without Overhead	$159,468.75
Total Salary With Overhead	$478,406.25
Materials Cost (Budget)	$4,229
Total Cost	**$482,635.25**

- Based on $65,000 a year average salary for 2080 hours of work
- Overhead rate is 200%

Course Project Objectives

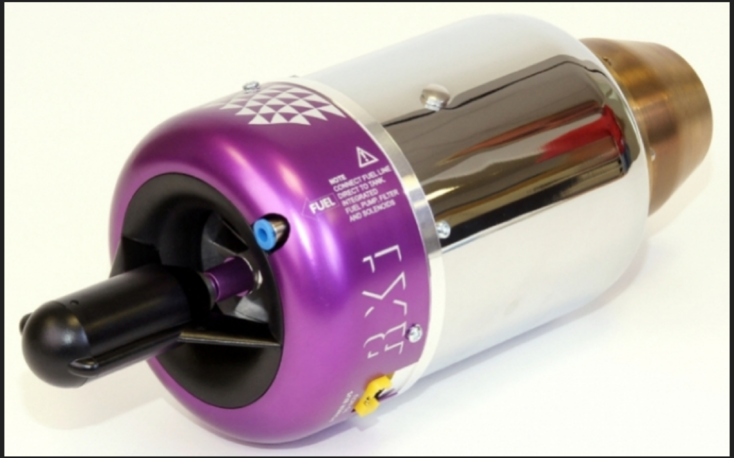
	Fuel Delivery System (FDS)	Electronics Heating	Startup Time	AFRL Conference
Level 1	System will control mass flow rate & temperature of fuel when placed in an environment cold-soaked to -30°F.	The electronics will be heated to 60°F after being placed in an environment cold-soaked to -30°F.	The fuel delivery 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.

summary

- LiPo battery provided sufficient power for the heating systems and insulation prevented it from being damaged by cold temperatures
  - FR 1.0 satisfied
- Control of the mass flow rate of the fuel with the HCU was successful after several pumps were damaged
  - FR 2.1, 4.2 satisfied
- HCU successfully activated heating circuits and controlled temperature
  - FR 4.1 satisfied
- Component heating was proven functional but not all components reached their desired temperatures in a single test
  - FR 2.2, 3.0 not satisfied yet
- The team anticipates meeting all functional requirements before PFR
- Test chamber was functional and effectively fulfilled its purpose in the project

Future work

- Additional full integration tests in test chamber to attempt to satisfy all functional requirements
- Preparation for AFRL conference on May 21st
- Create custom ECU to directly manage the startup of the jet engine



Acknowledgements

- Dr. Donna Gerren
- Matt Rhode
- Trudy Schwartz
- Bobby Hodgkinson
- Tim May
- Lee Huynh
- Tim Kiley
- Lt. Carol Bryant
- Air Force Research Laboratory

Questions?

BACKUP SLIDES

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Design Description

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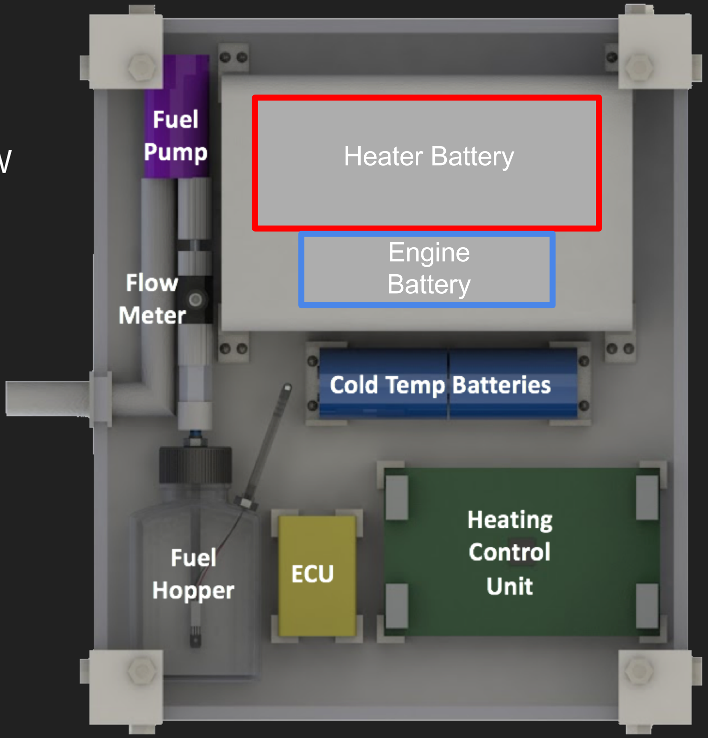
Baseline Design - Power Source

Main Heater LiPo Battery

- 5000 mAh, 22.2 V, 60C LiPo Battery
- For 30min of discharge, this battery can provide 222 W

Electronics Housing Power	89.45 W
ESB Power	20 W
Pump Actuation	9 W
Total Power Budget	118.45

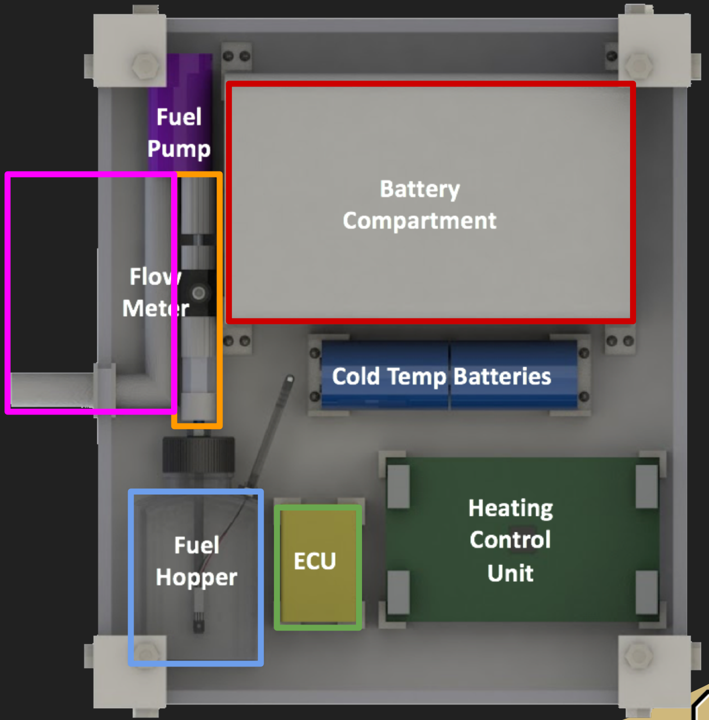


Power Resistors for ESB

- **Caddock 15W 2Ω** power resistors to heat ESB (x20)
  - These have temperature ranges of -67 to 482°F
- These will be mounted to the underside of the ESB using Cyanoacrylate glue

Lengths of Resistor Wire

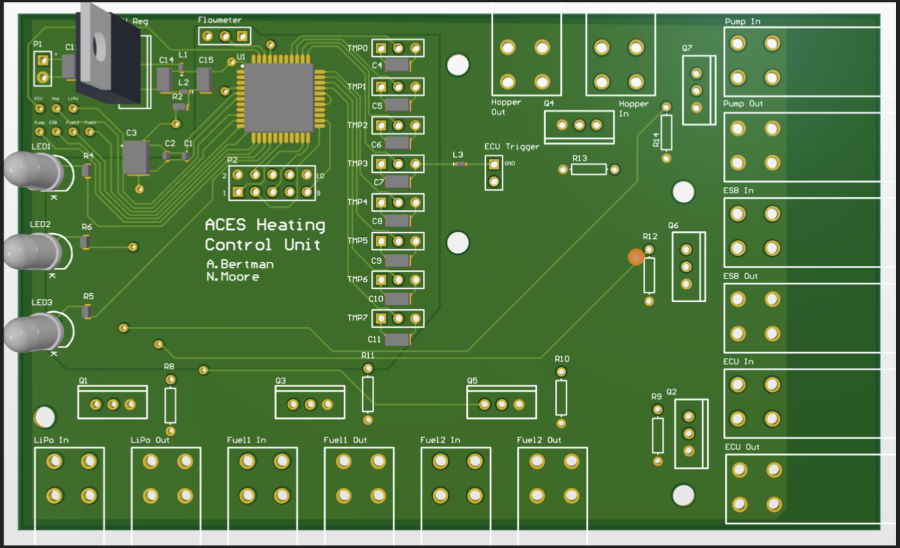
- 18.9 ft (0.88Ω/ft) for both LiPo batteries
- 3.9 ft (3.17 Ω/ft) for the ECU
- 13.8 ft (3.17 Ω/ft) for outside the hopper
- 0.8 ft (3.17 Ω/ft) for Fuel line section 1
- 2.4 ft (3.17 Ω/ft) for Fuel line section 2



Baseline Design - HCU

Main Components:

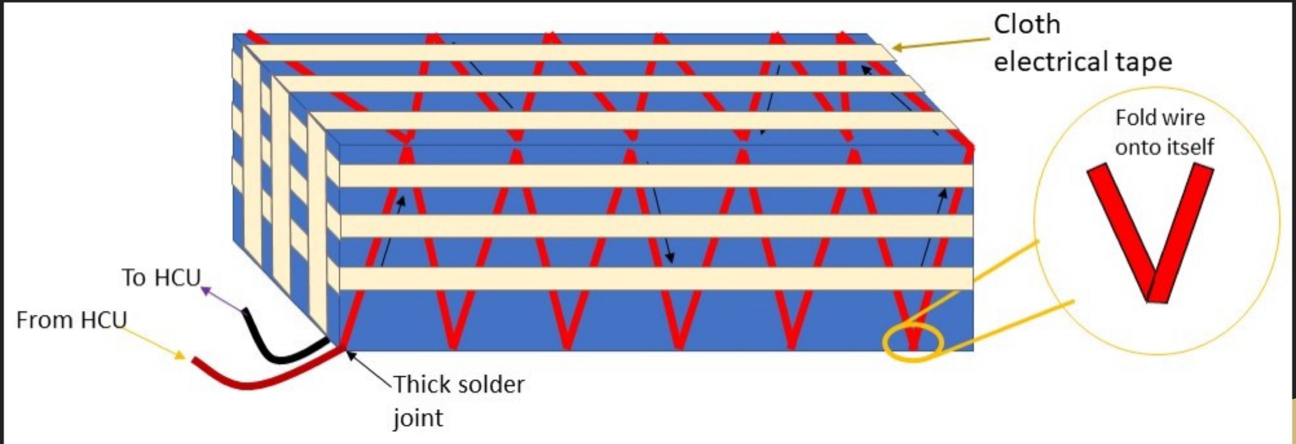
- ATmega32L Microcontroller
- TMP36 Analog Temperature Sensor
  - Monitors all heated components
- Heaters
  - Controlled with feedback from TMP36s via PWM signals generated by ATmega
- Fuel Pump
  - Controlled with feedback from flowmeter



Manufacturing

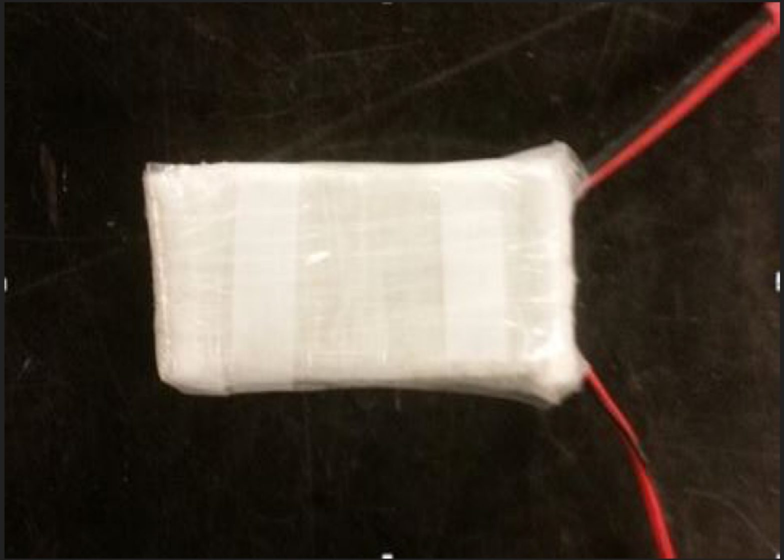
Wire Wrapping

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



Insulation

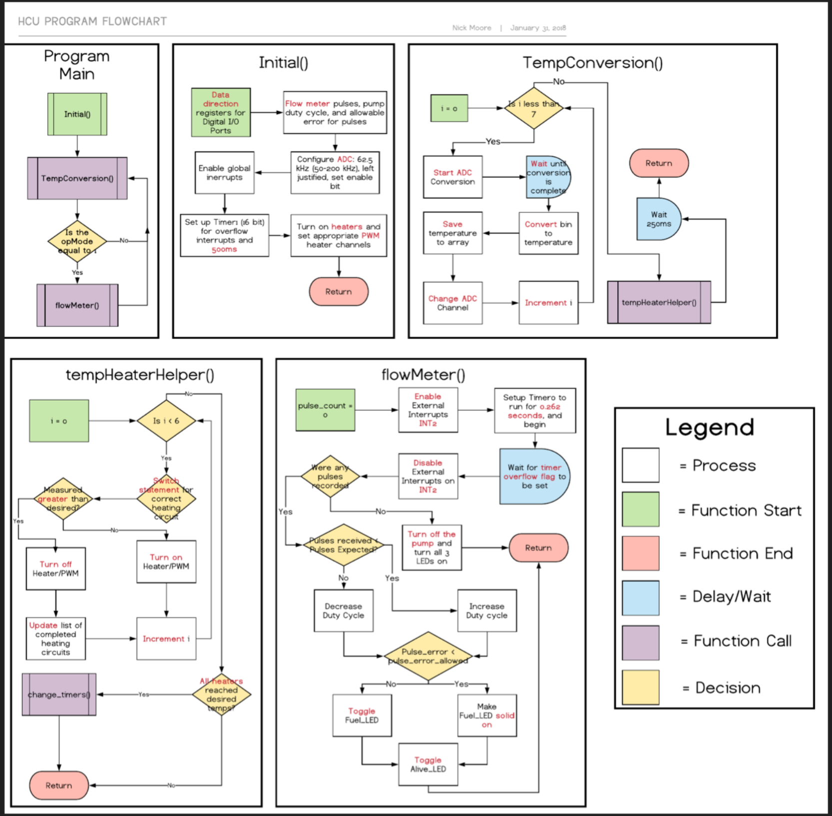
- Wrapping Method of Aerogel Insulation
  - Pieces Cut to Fit Faces of Each Component
    - Proper Measurements/Cuts Minimize Thermal Gaps
  - Pieces Secured Around Component with Thread
    - Ensures Insulative Properties are Uniformly Maintained
  - Saran Wrap Around Exterior of Insulation
    - Prevents dust from getting on essential electrical components
    - Small pieces of clear tape secures the saran wrap in place



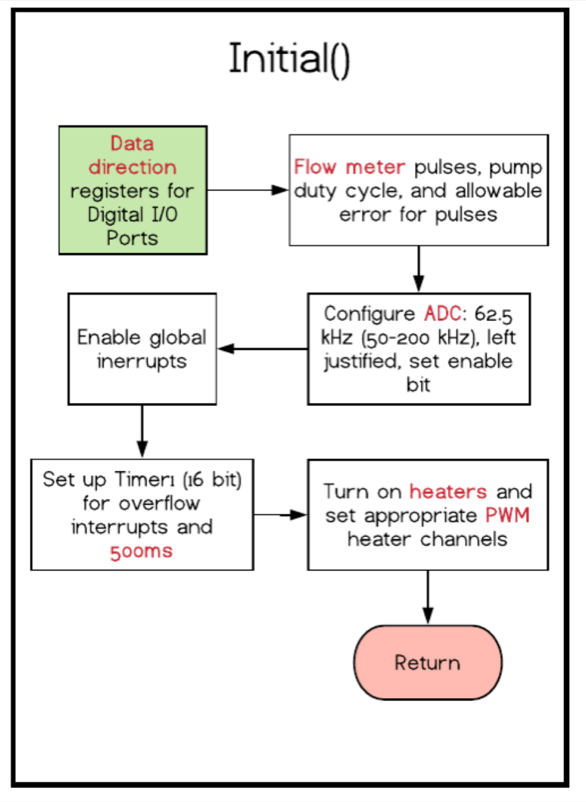
software

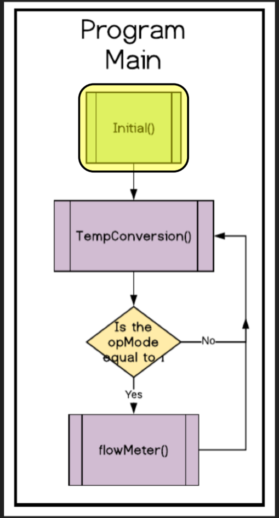
Project Purpose | Design Description | Test Overview & Results | Systems Engineering | Project Management

HCU SOFTWARE OVERVIEW

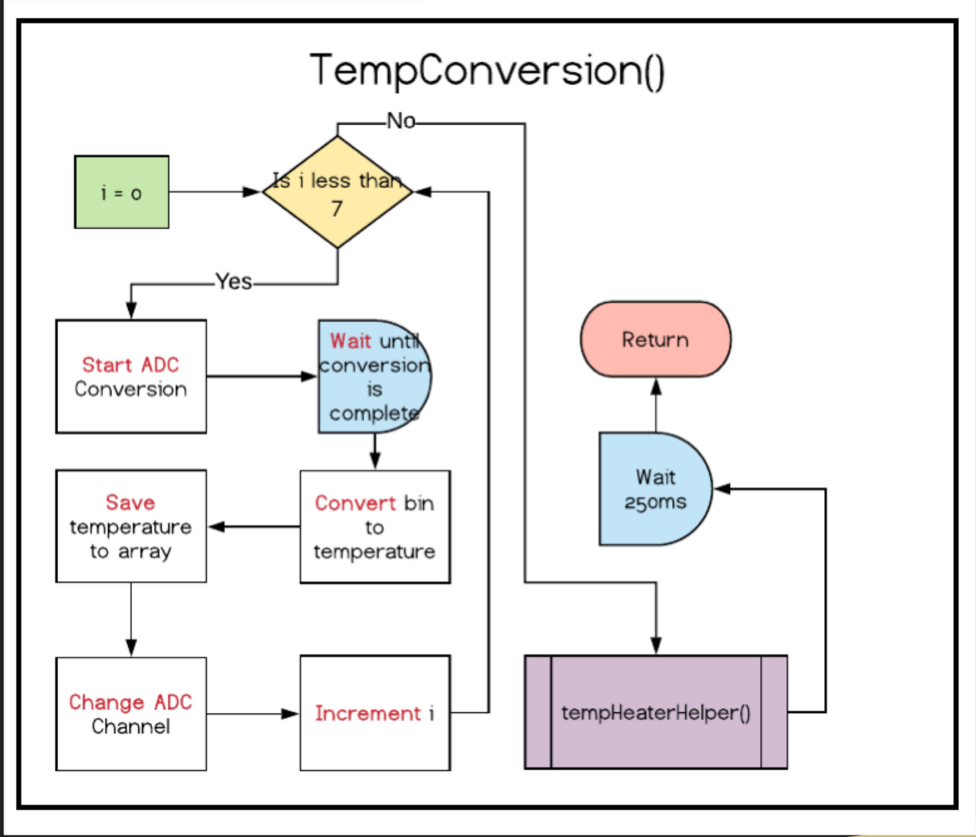


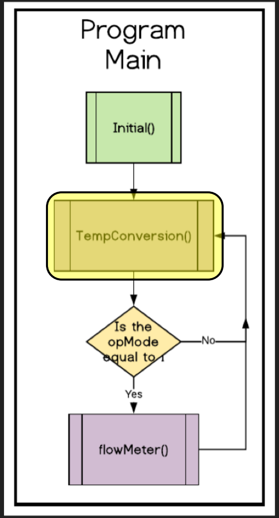
HCU: SOFTWARE

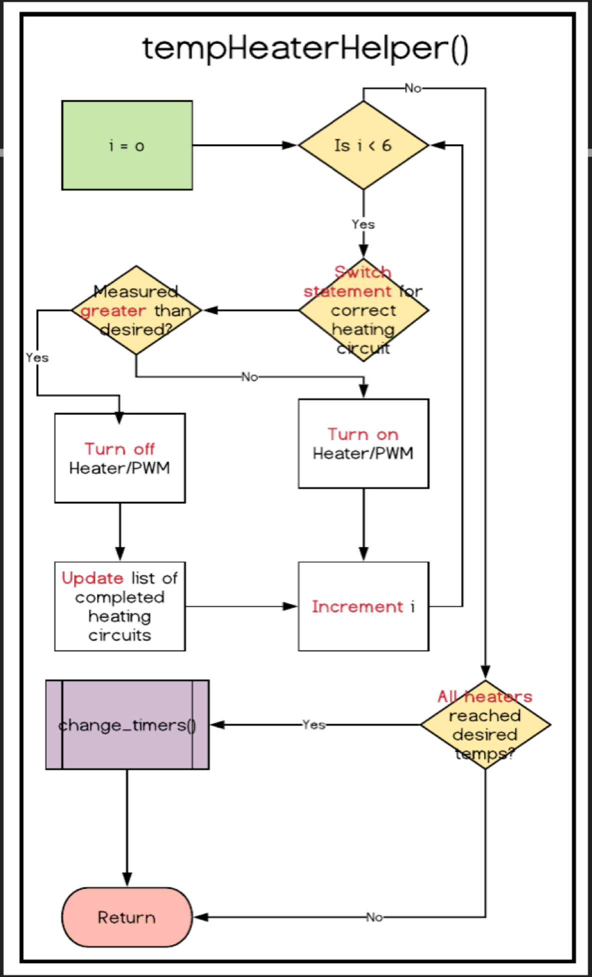


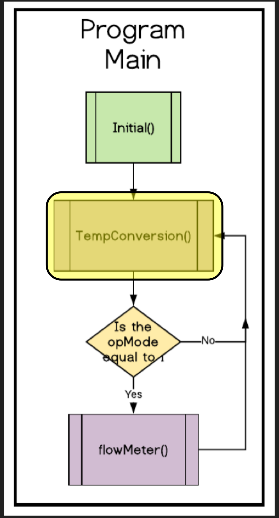


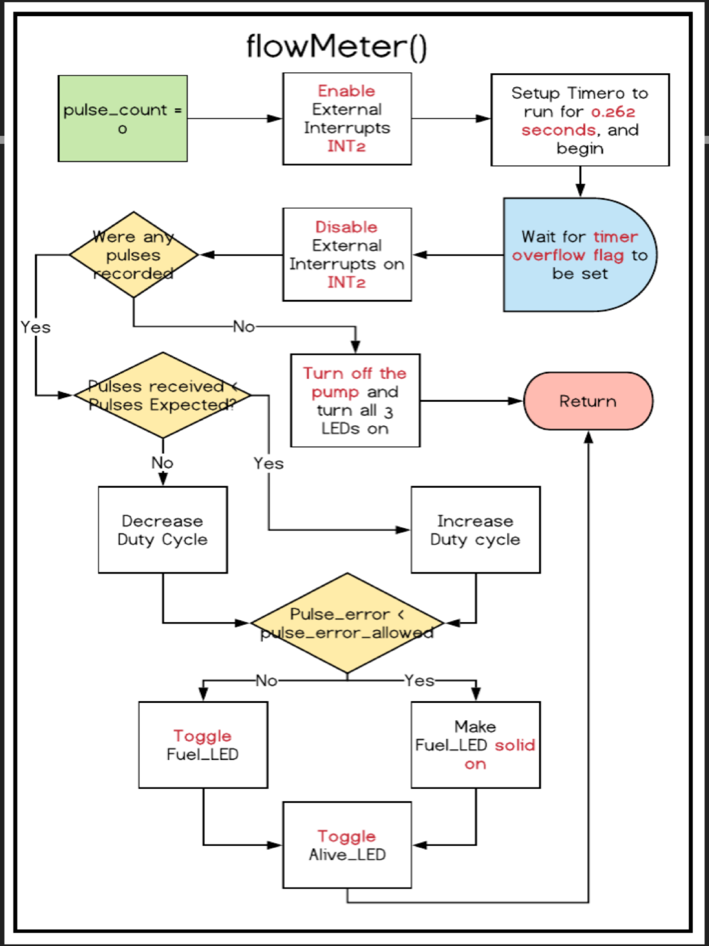
HCU: SOFTWARE

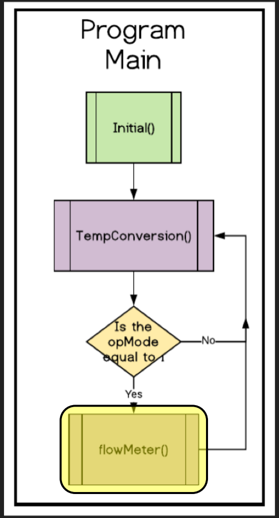




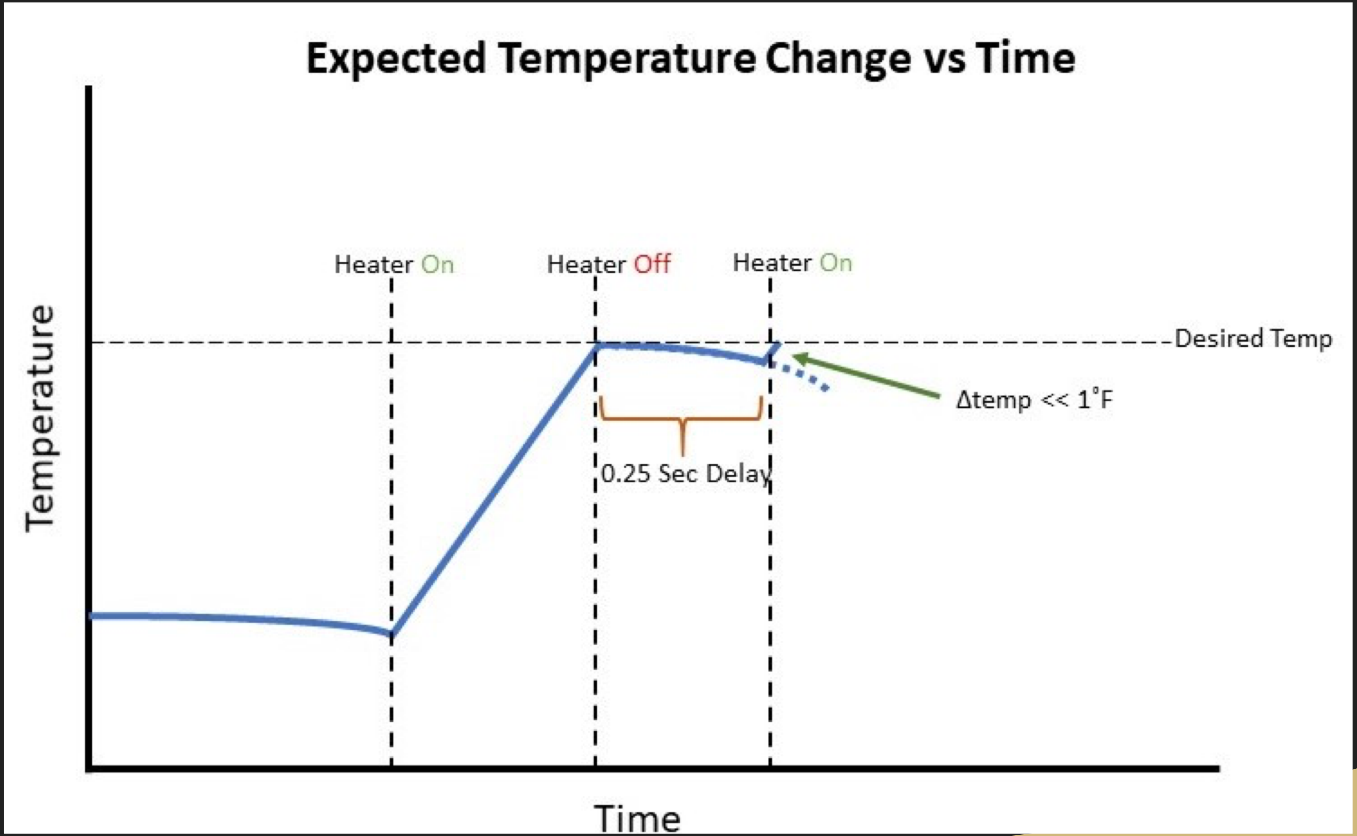

tempHeaterHelper()
i = o
Is i < 6
No
Yes
Switch statement for correct heating circuit
Measured greater than desired?
Yes
No
Turn off Heater/PWM
Turn on Heater/PWM
Update list of completed heating circuits
Increment i
All heaters reached desired temps?
change_timers()
Yes
Return
No


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



Test Overview & Results

Project Purpose | Design Description | Test Overview & Results | Systems Engineering | Project Management

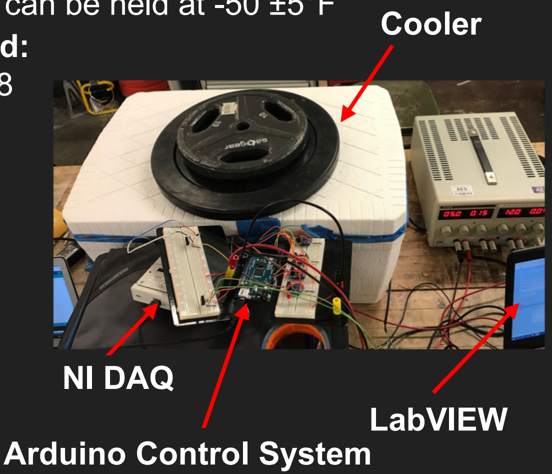
Test Chamber Verification

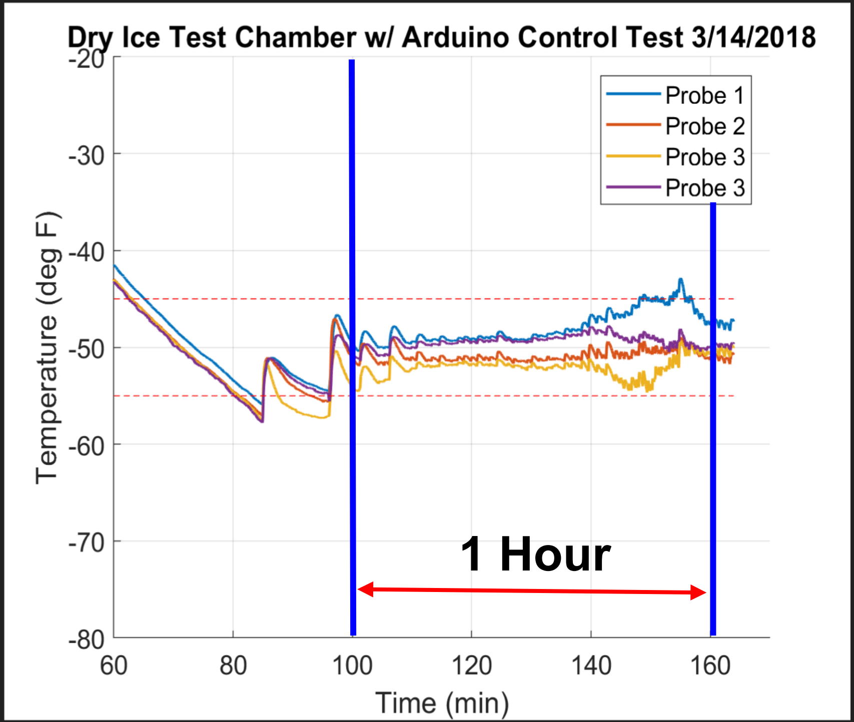
Purpose:
- Testing chamber must maintain homogenous cold soak environment ±5°F for 1 hour

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

Expectation:
- Results confirm that temperature inside the chamber can be held at -50 ±5°F

Date Completed:
- 3/14/2018





Full Integration Test Background

Purpose:

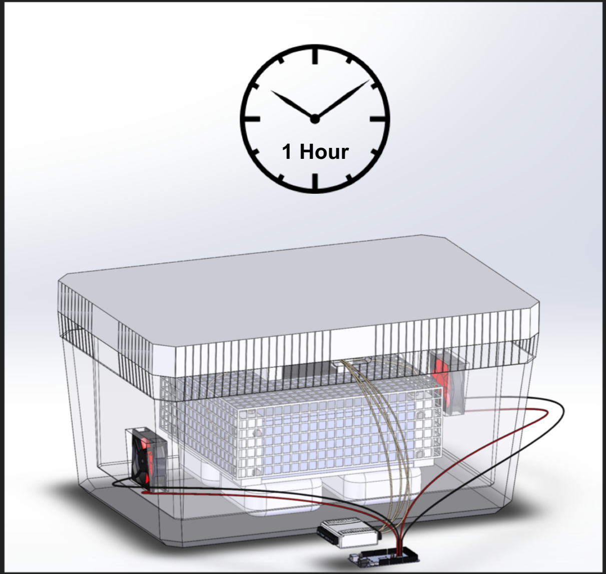
- Need to verify that the project’s subsystems function and interact as expected at -50°F as a complete setup
- **Simultaneously verify all Functional Requirements**

Plan:

- Full electronics box placed in -50°F test chamber for one hour.
- System initialized, heating begins.
- Recorded temperatures via TMP’s within debugger.
- 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 warm and maintain electronics and fuel delivery system at operational temperatures and supply fuel at desired flow rate and temperature.



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:

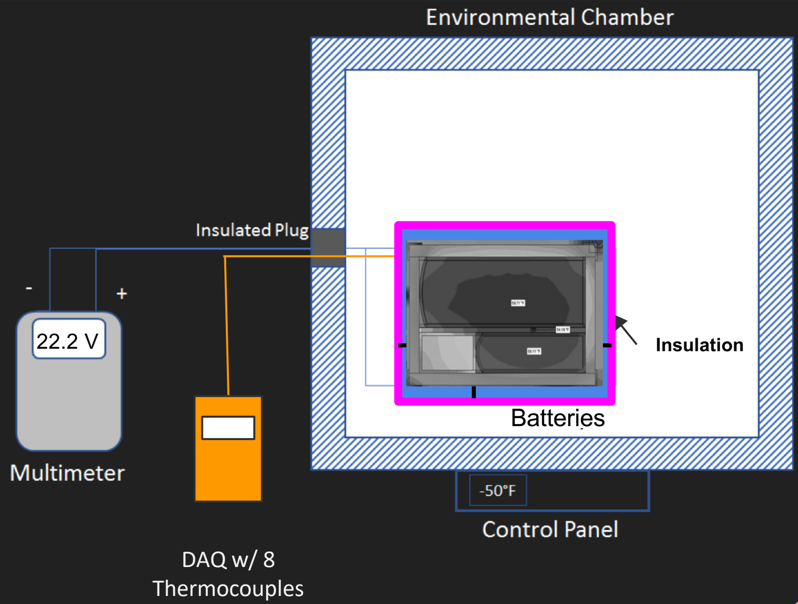
- Cold soak main heater and ECU battery with insulation for 1 hour at -50°F in chamber
- Record battery surface temperature

Expectations:

- Temperature readings that validate model

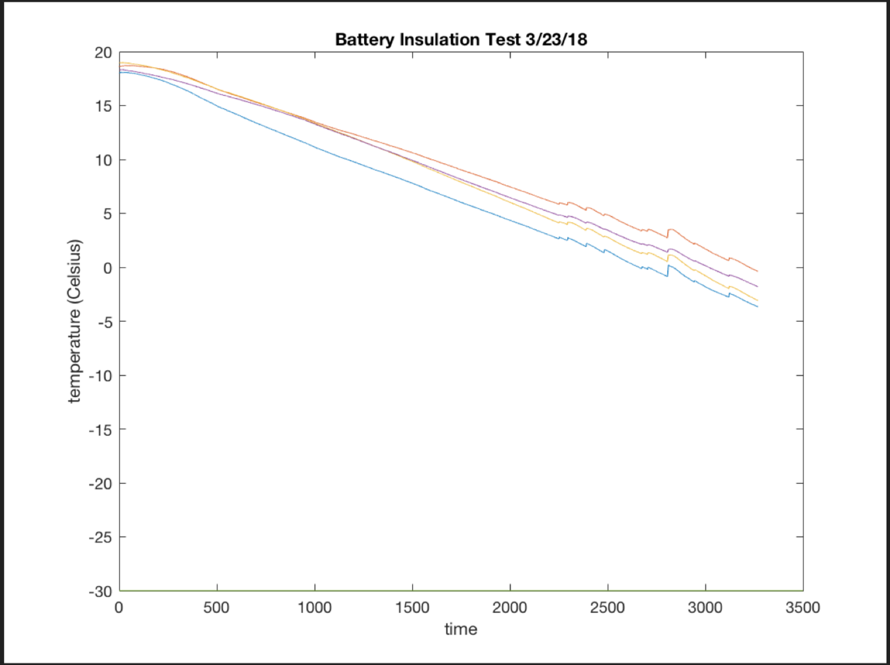
Date Scheduled:

- __/__/2018



Battery Insulation and Load Test Results

Battery Voltage During Cold Soak			
Main Heater Battery	0 min	30 min	60 min
	22.4 V	22.5 V	22.53 V
ECU Battery	0 min	30 min	60 min
	9.74 V	9.74 V	9.75 V



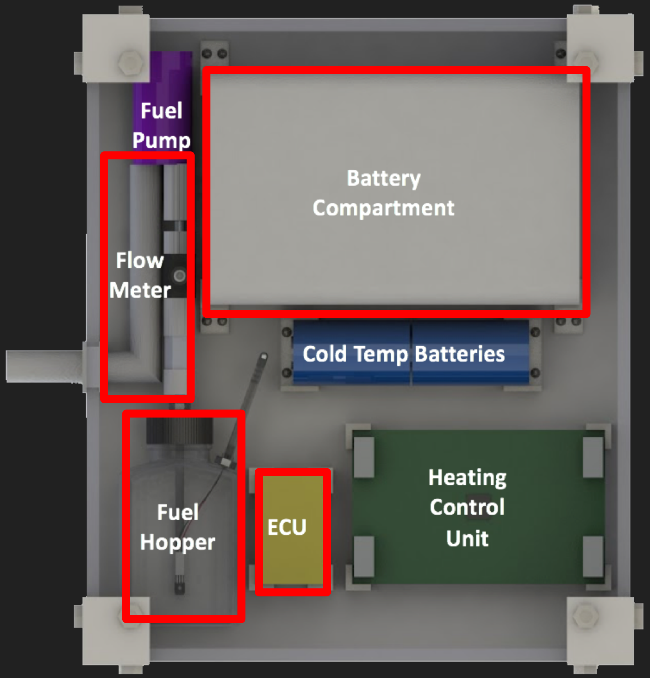
Battery Load Test

Purpose:
- Test Battery's capacity to heat all components in box after cold soak
- Voltage must not fall below 3.0V to avoid damage to cells
- **Verify FR 1.0**

Plan:
- Representative loads applied to circuit in place of each component
- Battery placed in cold soak thermal chamber for one hour
- Voltage monitored to verify 22.2V throughout warm-up period.

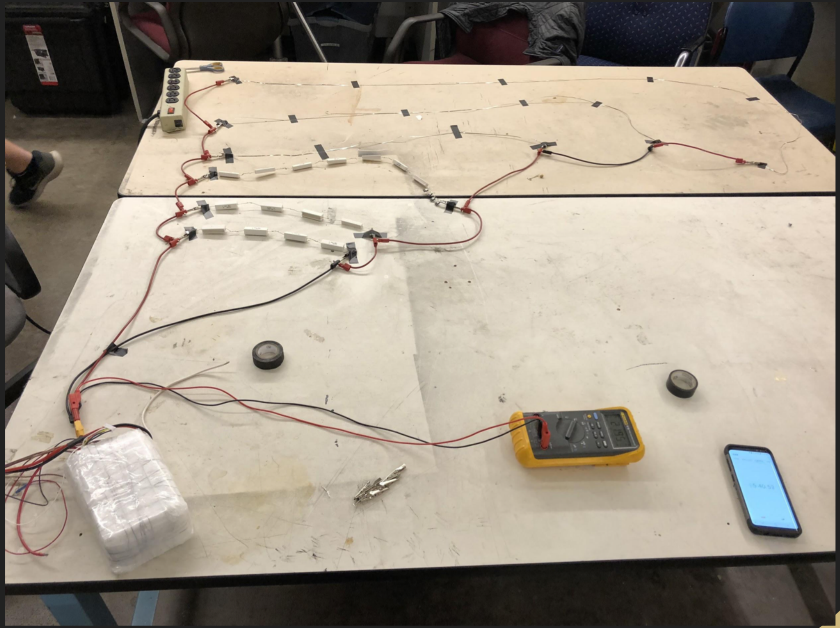
Expectation:
- Battery voltage remains within acceptable range and provides adequate power to resistive loads

Date Scheduled:
- __/__/2018

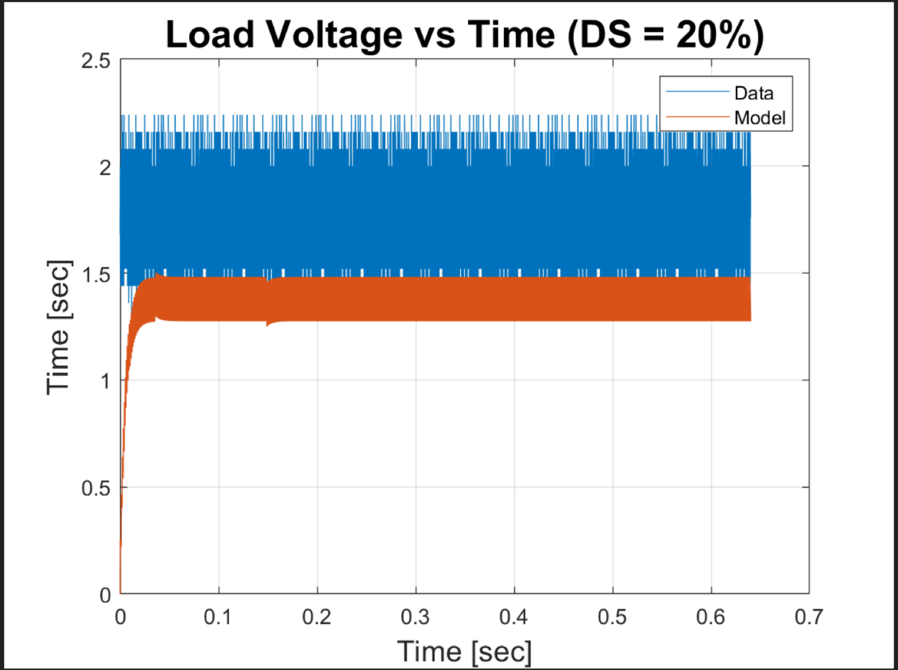


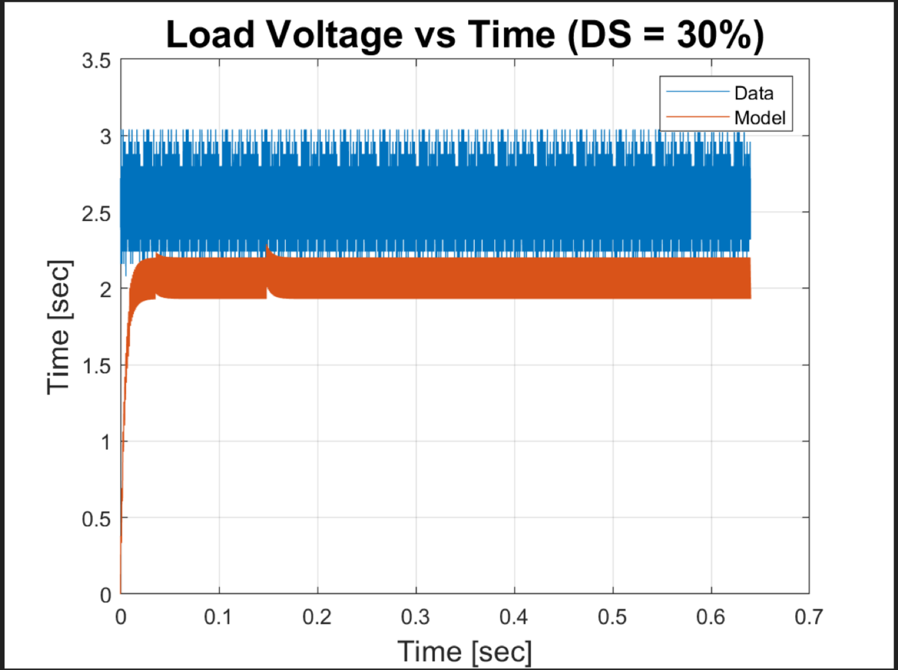
Resistive Wire Test Results

Resistive Wire Test Results:	
Trial 1	
Before Cold Soak:	22.4 V
After Cold Soak:	21.2 V
Trial 2	
Before Cold Soak:	22.72 V
After Cold Soak:	22.25 V

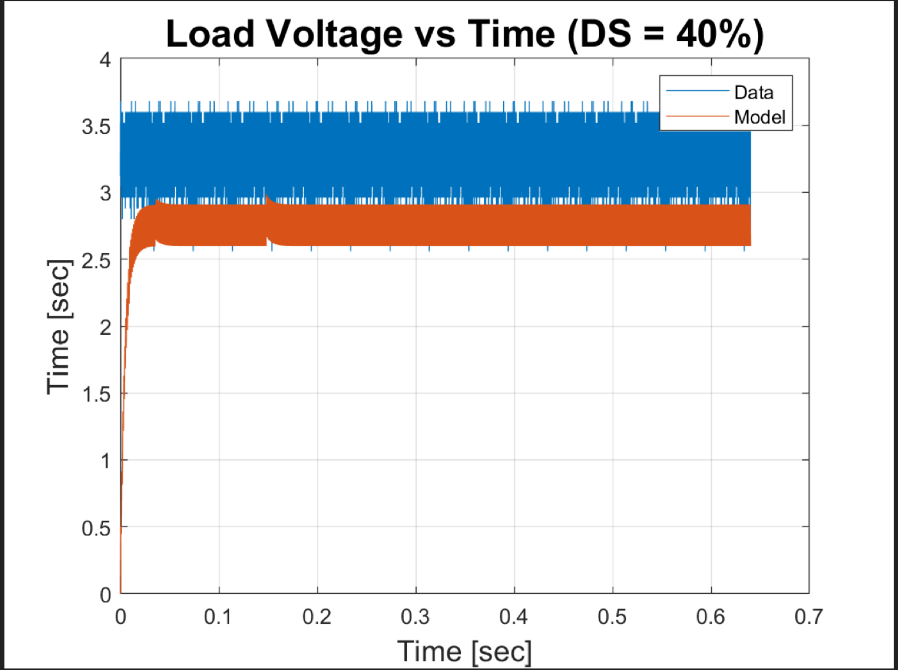


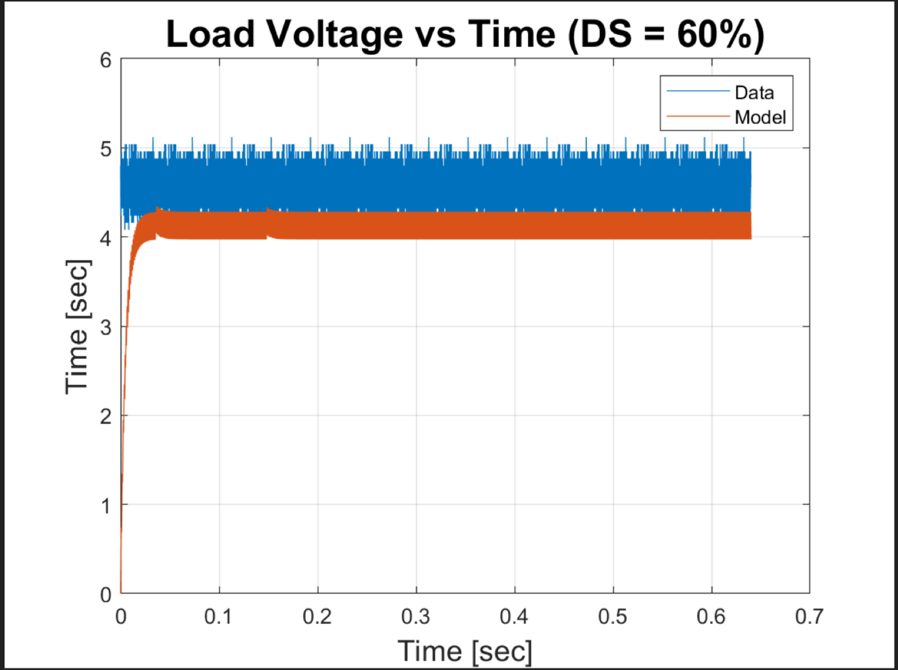
Motor Driver Additional Results



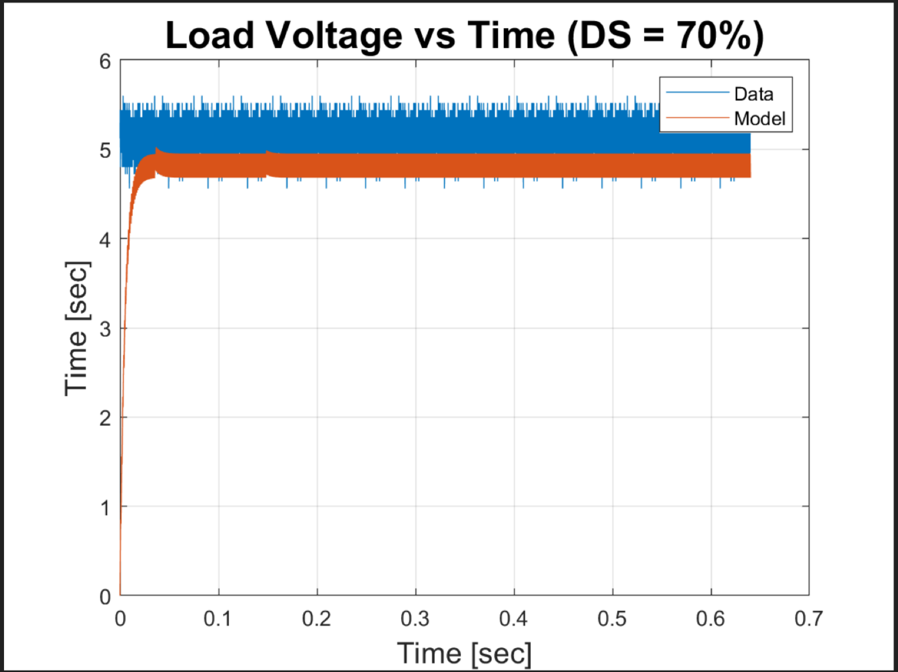


Motor Driver Additional Results

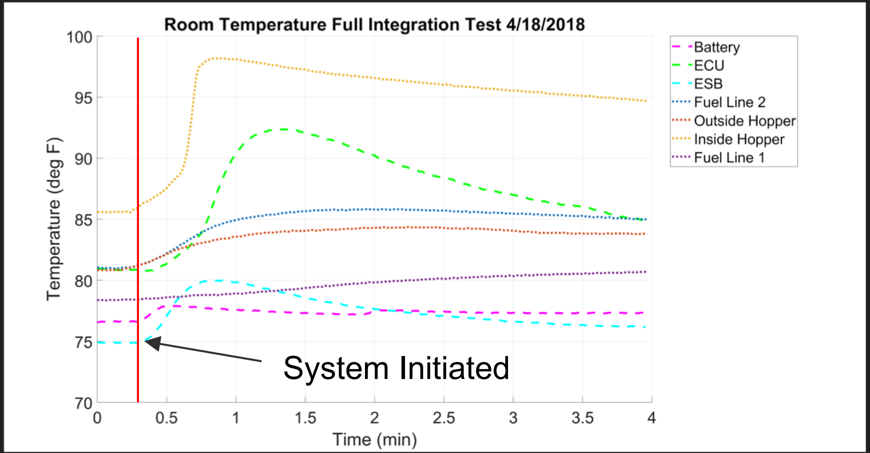


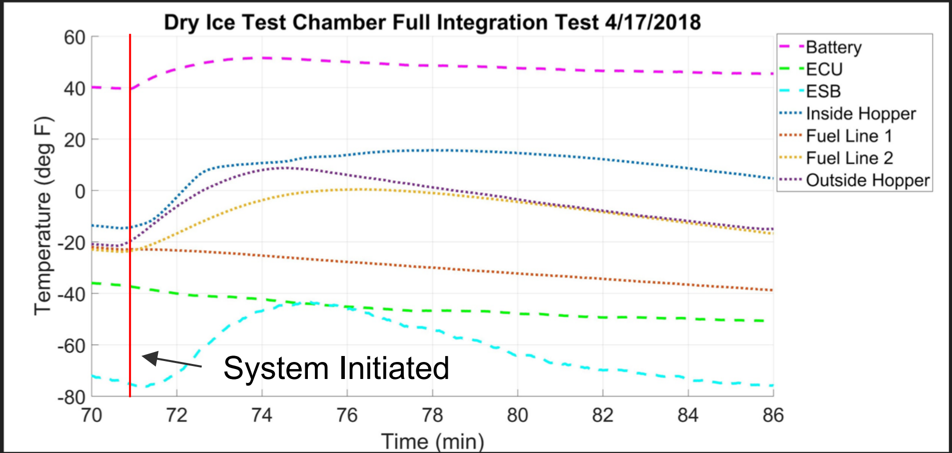


Motor Driver Additional Results



Full Integration Test Results





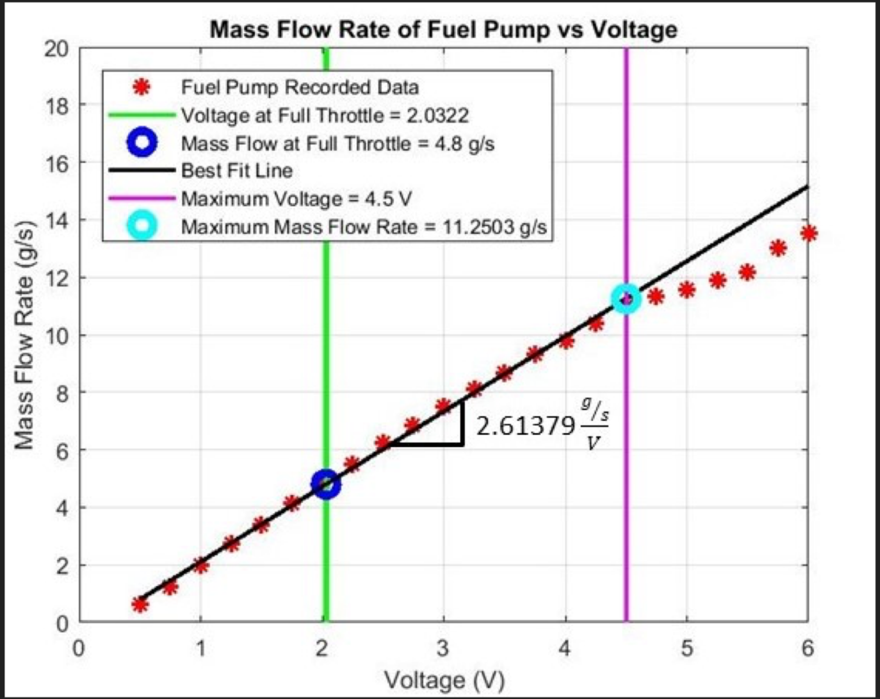
Room Temperature Integration Test:

- All components reached desired temperatures
- Overshoot was caused by heat retention in components

Test Chamber Full Integration Test:

- Heater battery failed partway through test, thus some components did not heat up or stopped heating
- Battery has been recharged, further testing will be performed

HCU: Software Mass Flow



$$\frac{4.8\ \text{g}}{1\ \text{s}} \cdot \frac{1\ \text{mL}}{0.81\ \text{g}} \cdot \frac{1\ \text{L}}{1000\ \text{mL}} \cdot \frac{110{,}000\ \text{pulses}}{1\ \text{L}} \cdot \frac{0.262144\ \text{s}}{1\ \text{period}} = \text{141 pulses per period}$$

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

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

Flow Meter Calibration

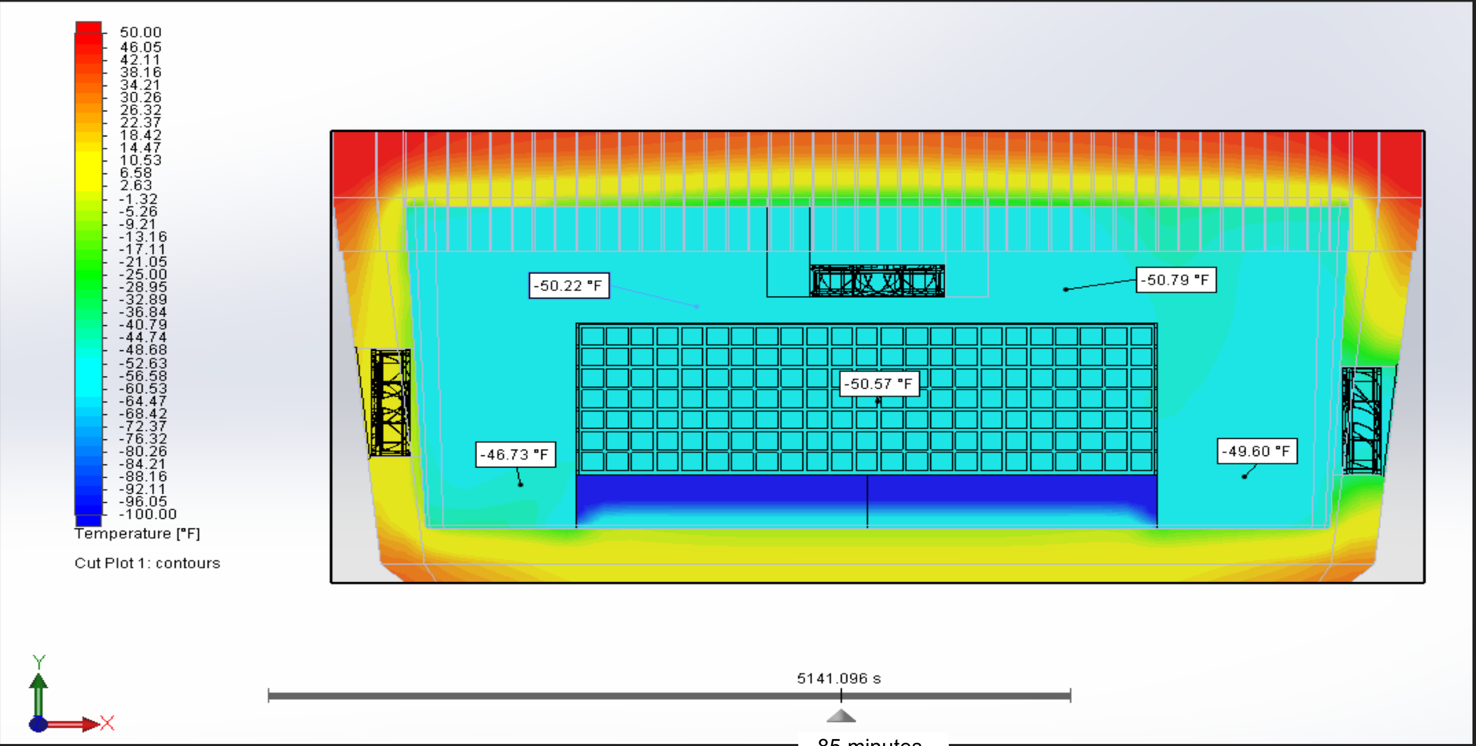
Status:

- **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**	

Test Chamber Functionality CAD

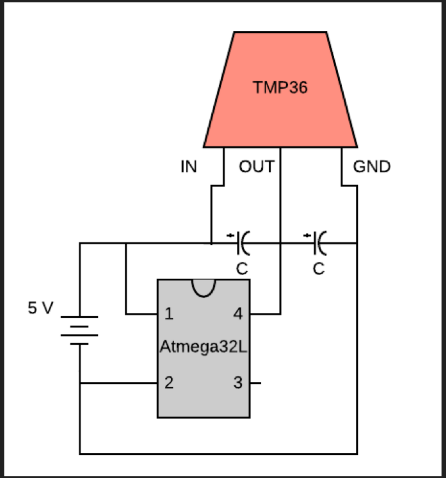


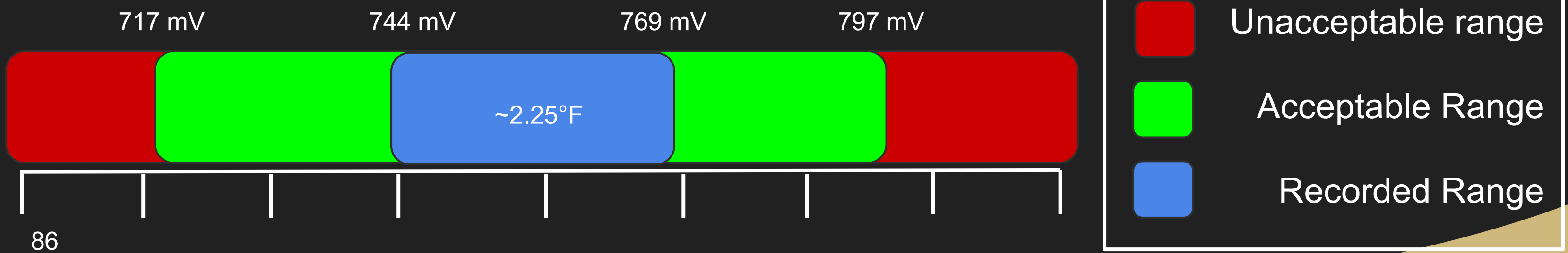
85 minutes

Temperature Sensor/ Noise Test Overview

Temperature Sensor/Noise Test

- Ensure the temperature sensor output are within allowable error (± 3.6°F)
- **Verify FR 2.2 and 3.0**
- Test Format:
  - 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
- Result:
  - **Completed on 2/28/2018**
  - Noise generation minimized with introduction of Two 47 μF, 16V capacitors

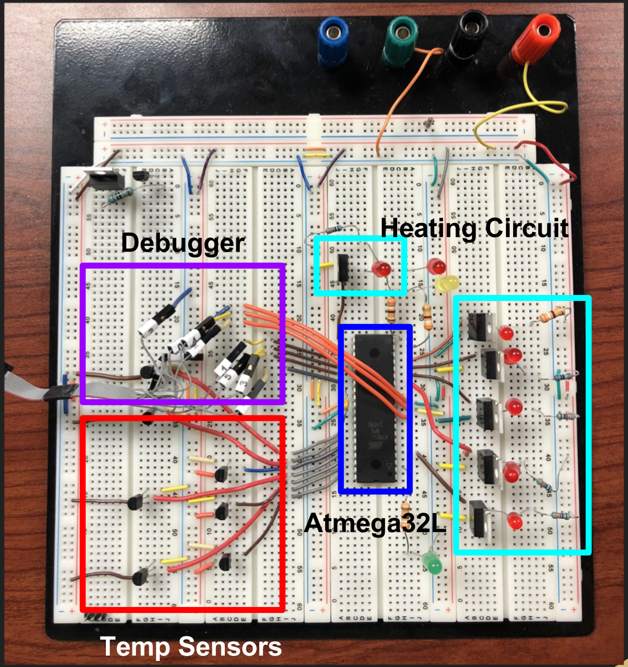




Software Process Test Overview

Software Process Test

- Ensure HCU can transition between the 3 modes of operation by stepping through code:
  - Warming
  - Pumping (and still warming)
  - Warming (fuel exhausted)
- Verify FR 4.1 & FR 4.2
- Result:
  - **Completed on 2/8/2018 with no experienced bugs**



Systems Engineering

Project Purpose
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Trade Study Summary

- **Initial Energy**
  - Options: Chemical, mechanical, low temperature electronics
  - Choice: Low temperature electronics
  - Justification: Reliability, manufacturability
- **Fuel Delivery System**
  - Options: Resistive heating, fuel additive, pressurized fuel
  - Choice: Resistive heating
  - Justification: Manufacturability, cost
- **Electronics Heating System**
  - Options: Conductive heating element, radiative ceramic resistors, fluid heating
  - Choice: Conductive heating element
  - Justification: Reliability, start-up time

Initial Energy Trade Study

Factor	Weights	Chemical	Mechanical	Low-Temp Electronics
Reliability	0.3	4	2	5
Manufacturability	0.25	3	2	5
Safety	0.15	1	4	4
Start-up Time	0.15	4	3	5
Team Experience	0.1	1	3	4
Cost	0.05	4	2	4
Total	1	3.1	2.5	**4.7**

Requirements Flow-Down

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

- **FR 1.0.1:** The initial energy source will provide the required power at -50°F
  - Motivation: At -50◦F most batteries and electronic systems will not operate. Therefore a small amount of initial energy is required in order initiate the start up procedure.

Requirements Flow-Down

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.
Motivation: The engines full throttle fuel flow rate is 4.8 g/s, so the system should be able to control the fuel flow rate up to that. The fuel flow meter can measure with an accuracy down to 0.13 g/s.

- **FR 2.1.1)** The fuel pump shall pump the appropriate amount of fuel given the voltage from the HCU
  - Motivation: A linear regression of data from a fuel pump test has been performed, giving the team an approximate conversion between voltage supplied to the fuel pump and the mass flow rate of fuel through the pump.The fuel pump should pump the appropriate amount of fuel for the specified rate given the correct voltage from the HCU

- **FR 2.1.2)** Resistive heating elements and insulation shall keep the fuel above its freezing point (-40°F).
  - Motivation: Below -40°F, the fuel becomes very viscous and is difficult to pump at the desired rate.

Requirements Flow-Down

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.
Motivation: Controlling the temperature of the fuel entering the engine could help facilitate cold engine restart by ensuring best conditions for ignition inside the test chamber

- **FR 2.2.1)** Insulation around the fuel lines shall keep that fuel above its freezing temperature (-40°F)
  - Motivation: Once the fuel inside the lines freezes, it takes more time and requires more energy to both melt the fuel and to get it to its specified temperature

- **FR 2.2.2)** Resistive heating elements inside and around the fuel delivery system shall provide sufficient heat to heat the fuel to its specified temperatures
  - Motivation: Once the HCU sends voltages to the heating elements, these elements must provide enough power to heat the fuel.

Requirements Flow-Down

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.
Motivation: To facilitate engine restart, the electronics should be working

- **FR 3.0.1)** Insulation shall keep essential, temperature sensitive electronics within their operational temperature range during the cold soak process.
  - Motivation: Certain temperature sensitive electronics could be damaged during the cold soak process if components are not protected by insulation.

- **FR 3.0.2)** Resistive heating elements shall provide sufficient power to heat electronics to within their operating temperature range.
  - Motivation: Once the HCU provides voltages to the resistive heating elements, these elements must provide enough power to heat the electronics to operational temperature.

Requirements Flow-Down

FR 4.1) HCU: The Heating Control Unit (HCU) shall monitor and regulate the temperature of the electronic components and fuel delivery heating systems.
Motivation: In order to keep the electronics within their operating temperature range, the HCU must control the heating process.

- **FR 4.1.1)** The HCU shall monitor current electronics and fuel temperatures using temperature sensors.
    - Motivation: The HCU must be informed as to the current temperature of various electronic components and fuel in order to adjust its behavior accordingly.

- **FR 4.1.2)** The HCU shall provide the appropriate voltage to heating elements to regulate the temperature of components and fuel
    - Motivation: With the information from the temperature sensors, the HCU should modulate the power it provides to various heating elements in order to regulate the temperature of electronic components and fuel.

Requirements Flow-Down

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

- **FR 4.1.1)** The HCU shall monitor the current fuel flow rate using a flow meter.
    - Motivation: The HCU must be informed as to the current fuel flow rate in order to adjust its behavior accordingly.

- **FR 4.1.2)** The HCU shall provide the appropriate voltage to the fuel pump to provide desired mass flow rate of fuel.
    - Motivation: With the information from the flow meter and the information from prior fuel pump tests, the HCU should modulate the power it supplies to the pump in order to regulate the mass flow rate of fuel.

Risk Identification

1. Risk of insulation failure to sufficiently protect the heating battery
2. HCU control law does not function as intended, leading to runaway temperature
3. Fuel line stoppage due to fuel freezing
4. Fuel line cracks due to low temperature
5. Fuel line melting due to high temperature resistor wire
6. Heating wire short circuit
7. Solidworks thermal models are not accurate, leading to colder than anticipated components
8. Accidental ignition of jet fuel

Risk Assessment Terminology

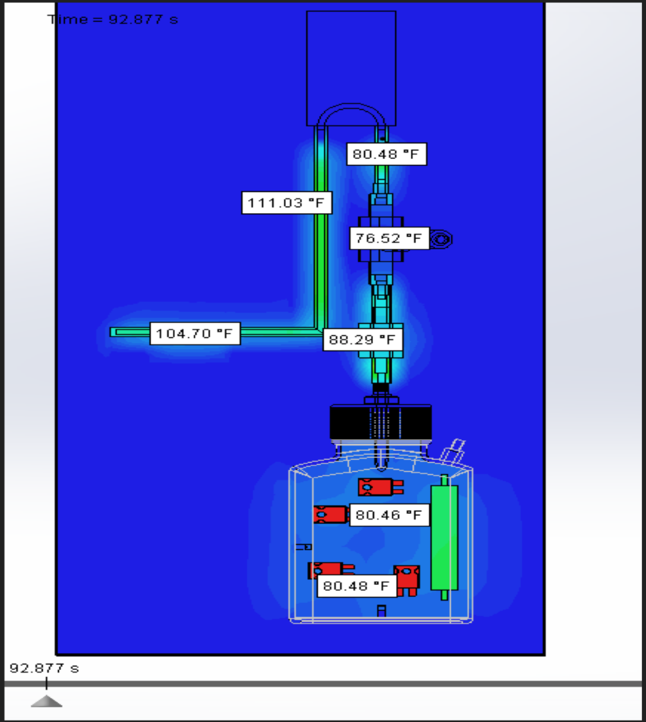
	Minimal	Minor	Major	Hazardous	Catastrophic
Project Damage	None	None	Considerable component damage	Serious	Irreparable
Project Performance	Marginal Decrease	Substantial Decrease	Unsatisfactory for Requirements	Unsatisfactory for Requirements	Unsatisfactory for Requirements
Budget Impact	No Cost Increase	Minor Cost Increase	Substantial Cost Increase	Serious Cost Increase	Unrecoverable Cost Increase
Schedule Impact	None	Minor	Substantial	Serious	Unrecoverable

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

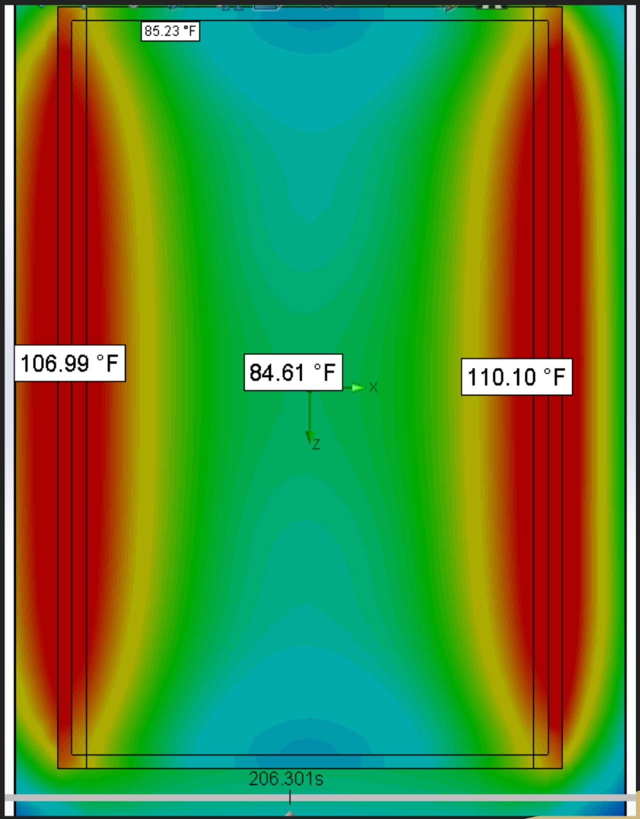


Expected Component Temperatures

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

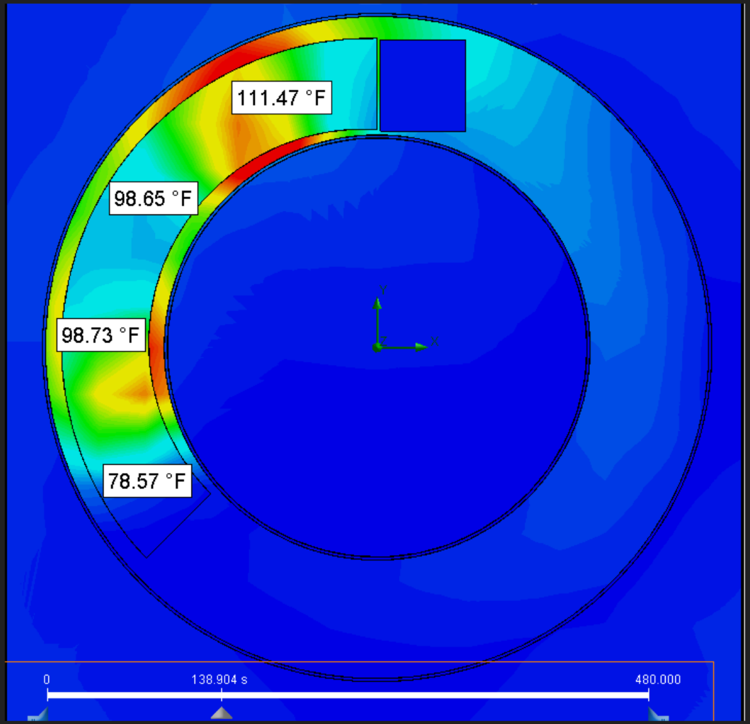


Expected Component Temperatures

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

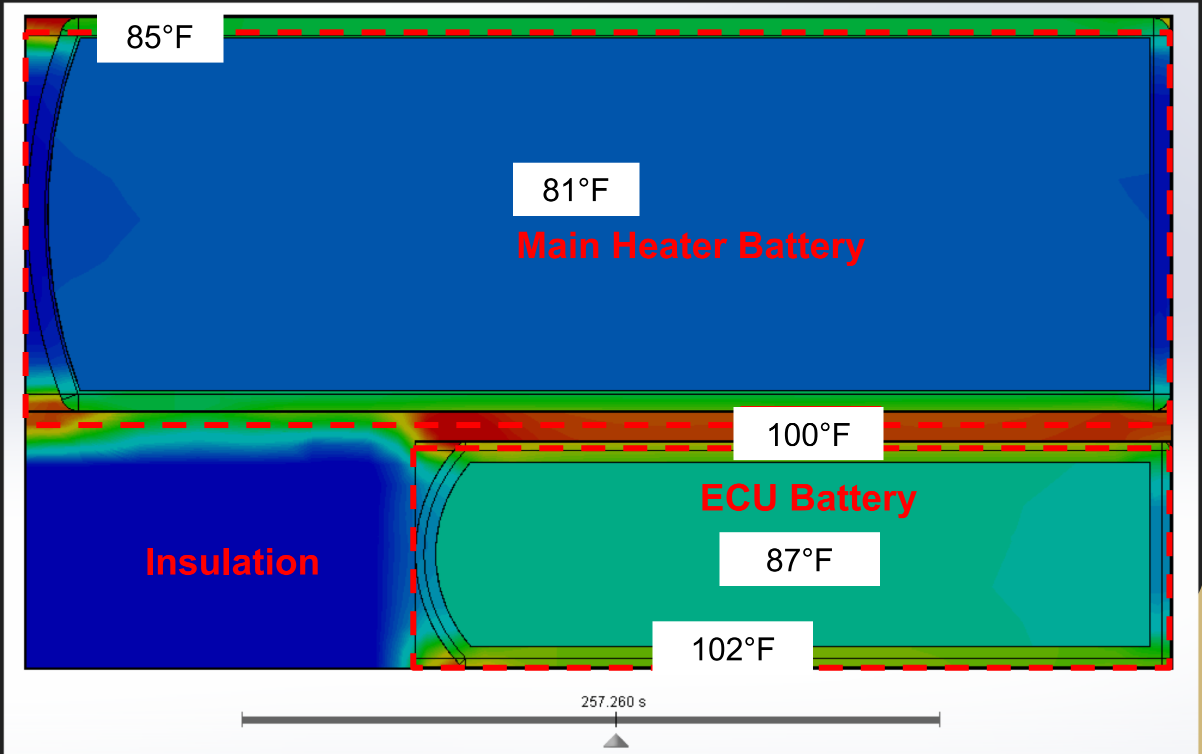


Expected Component Temperatures

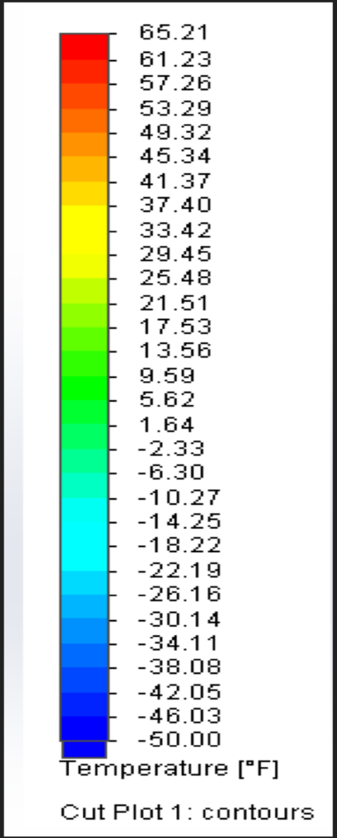
Surface Temperatures After **4.25 minutes** of Resistive Heating:

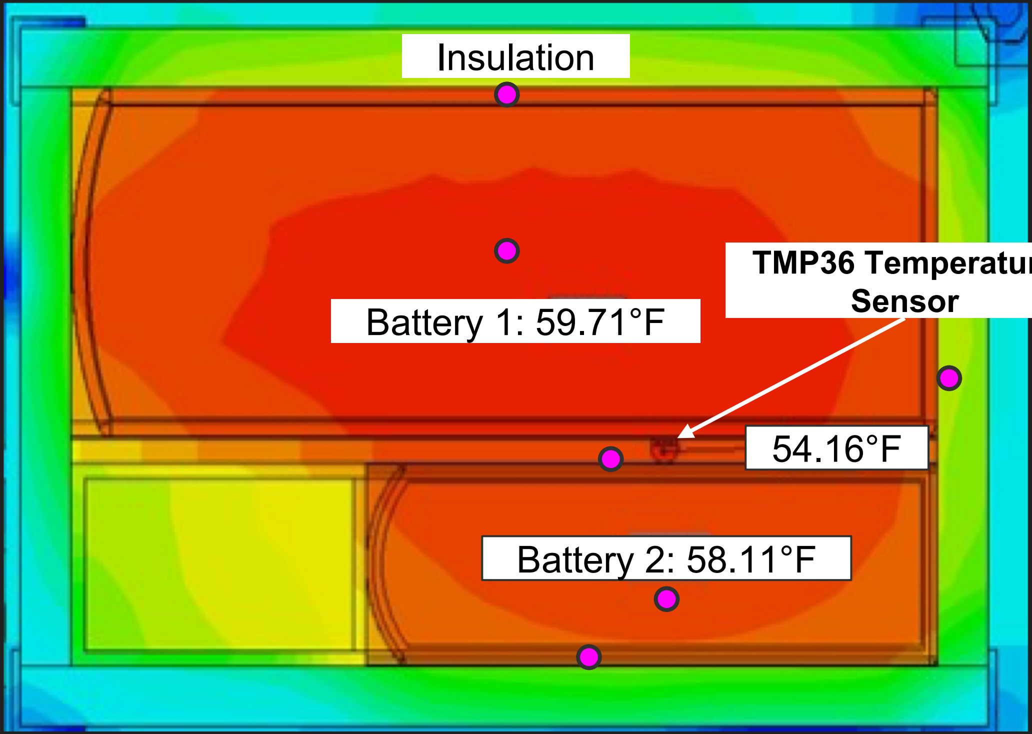
- **Batteries: 100.31°F**

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.



Battery Insulation Test Model





● Surface Thermocouple Location