A.C.E.S.

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

Critical Design Review

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OUTLINE

- Project Objectives
- Design Solution
- Critical Project Elements
- Design Requirements Satisfaction
- Project Risks
- Verification and Validation
- Project Planning

PROJECT OBJECTIVES

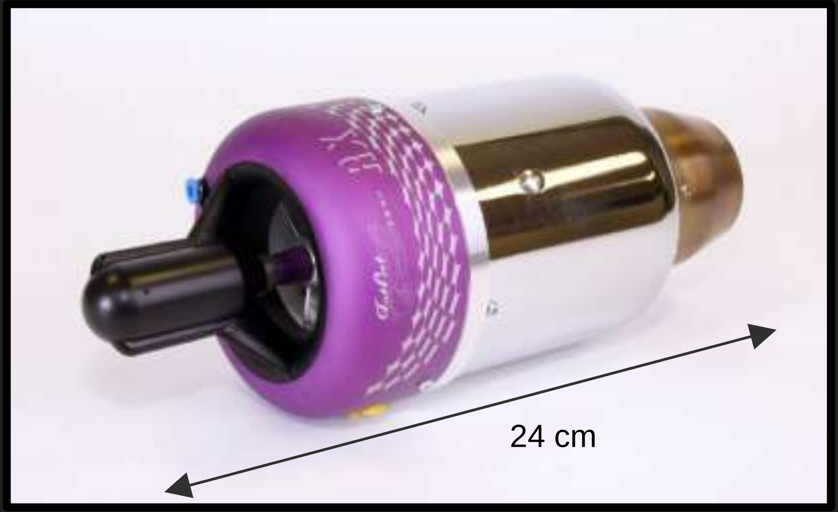
Project Objectives → Design Solution → Critical Project Elements → Design Requirement Satisfaction → Project Risks → Verification & Validation → Project Planning

Project Description

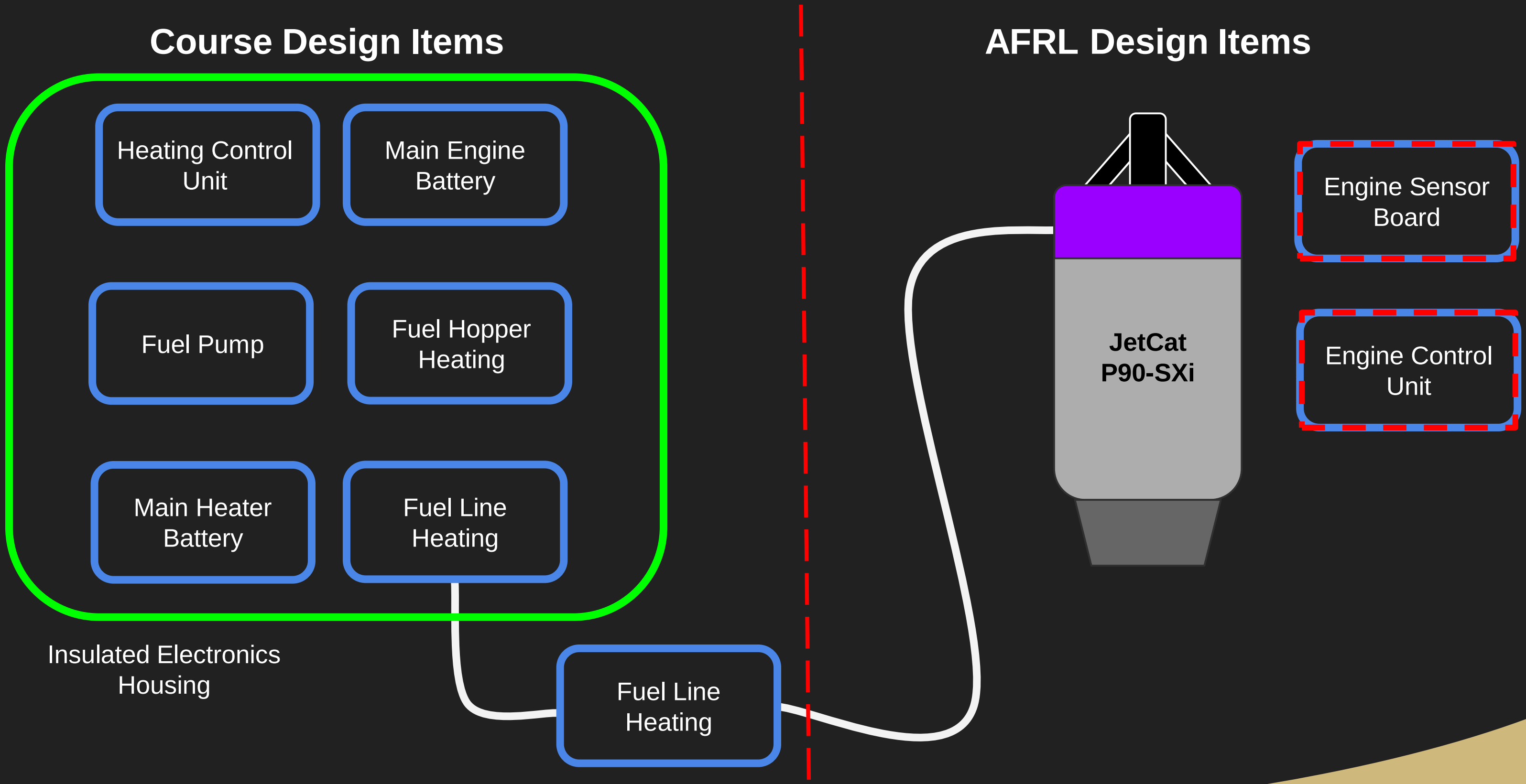
- Design, build, and test a system to facilitate starting a JetCat P90-SXi jet engine at a temperature of -50°F by:
  - Controlling the temperature and mass flow rate of the fuel into the engine
  - Ensuring that the engine electronics are within their operating temperature range
  - Ensuring that the heating system has sufficient power to heat the fuel delivery system and engine electronics
- Motivation
  - Air Force Research Lab (AFRL) competition
  - Proof of concept for high-altitude (cold-temperature) restart for jet-powered UAS

Engine: JetCat P90-SXI

- Miniature Jet Engine
- Fuel: Jet-A, Kerosene/Oil Mixture
- Specifications:
    - Maximum Thrust: 105 N
    - Maximum RPM: 130,000
    - Idle Fuel Flow Rate: 0.8 g/s
    - Maximum Fuel Flow Rate: 4.8 g/s
- Dimensions:
    - Length: 240 mm
    - Diameter: 97 mm
    - Weight: 1050 g



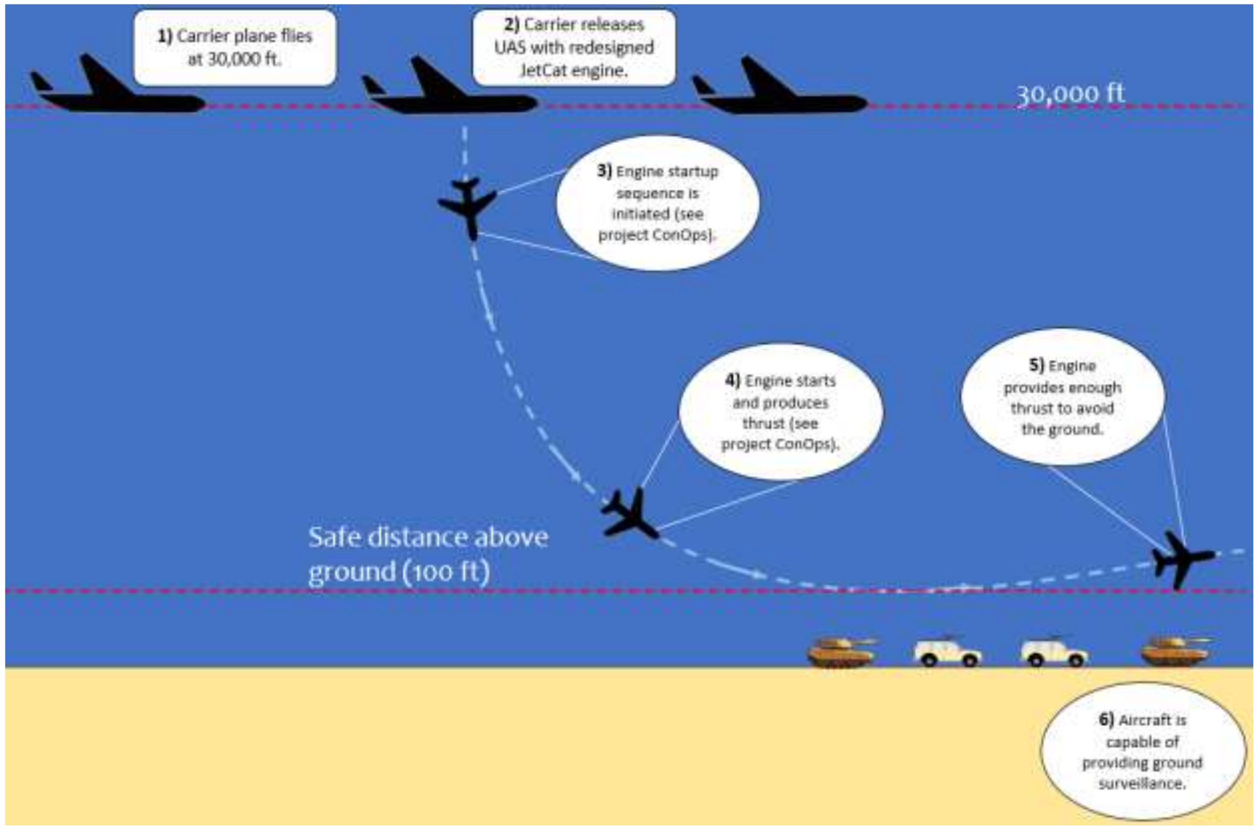
Project Scope



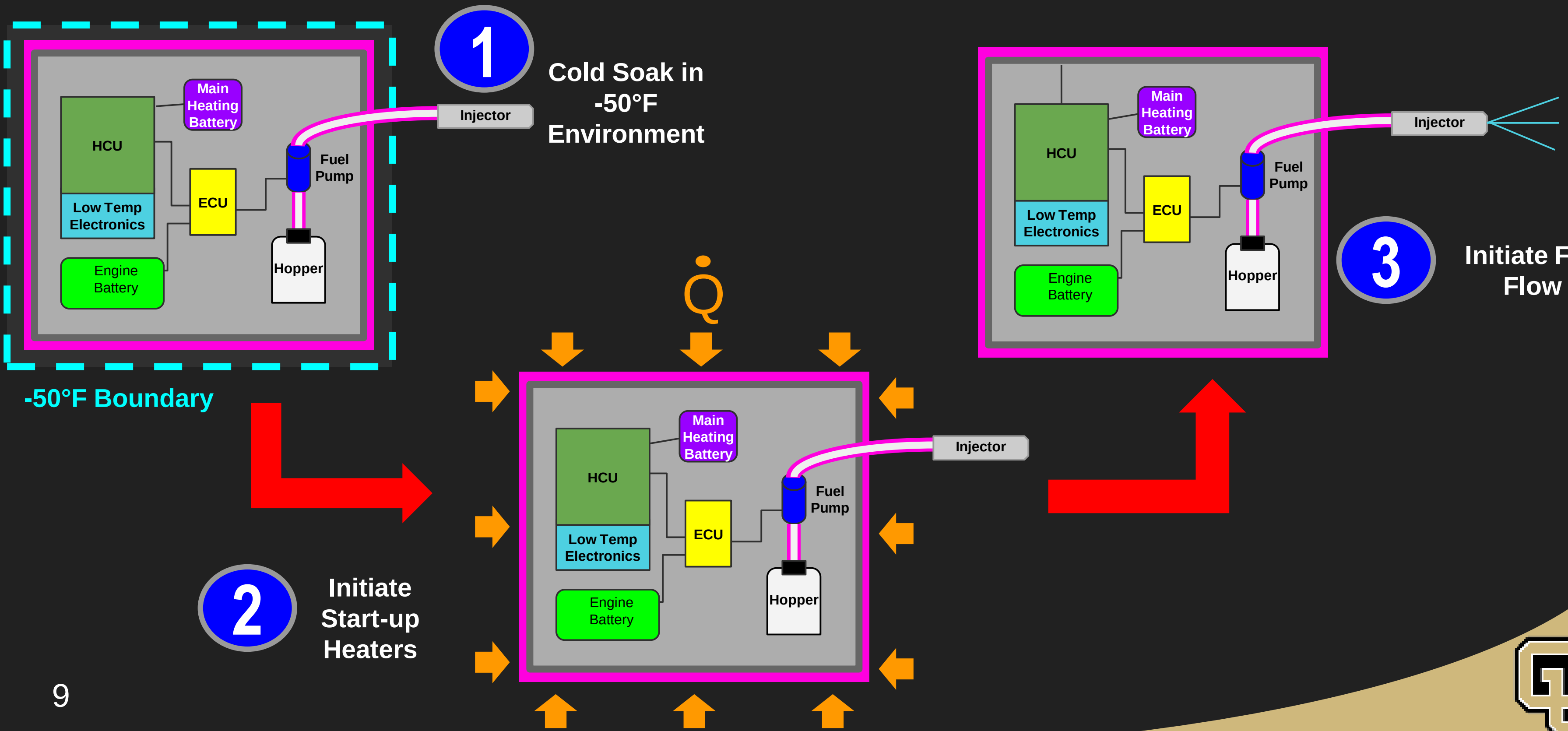
Course Project Objectives

	Fuel Delivery System (FDS)	Electronics Heating	Startup Time	AFRL Competition
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 Requirements

- ***FR 1) 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 115°F ± 3.6°F to the engine.
- ***FR 3) Electronics Heating:*** The electronics (ECU, ESB, batteries) shall be heated to their operating temperature of 60°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.

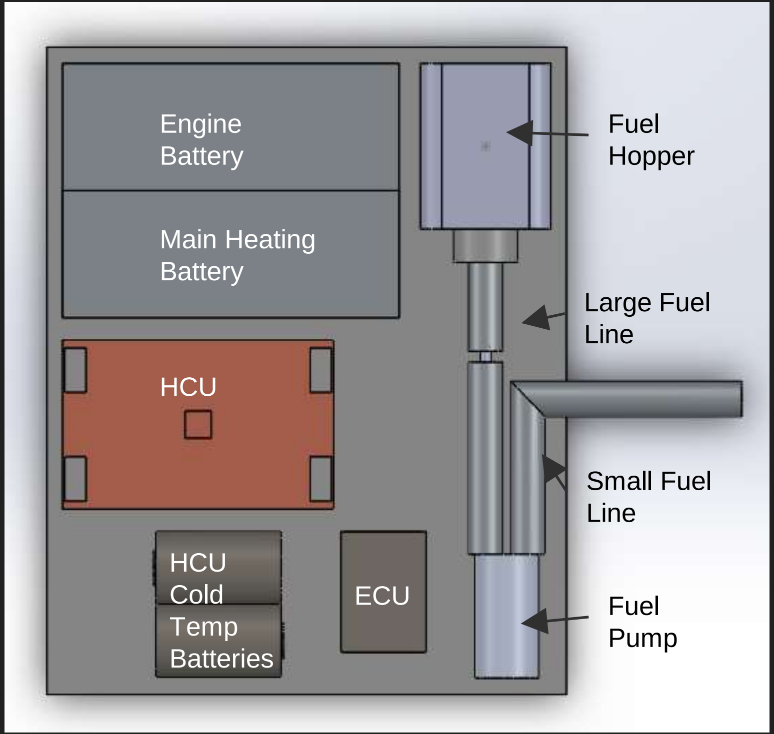
Design Solution

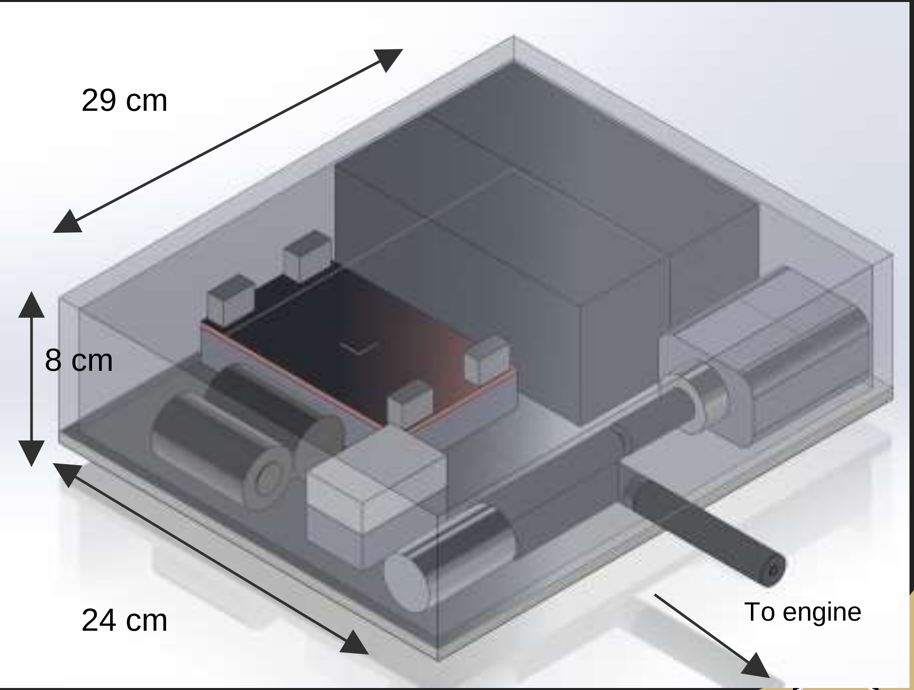
Project Objectives | Design Solution | Critical Project Elements | Design Requirement Satisfaction | Project Risks | Verification & Validation | Project Planning

Design Changes Since PDR

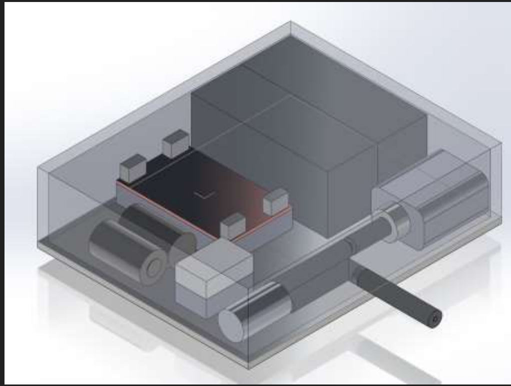
- **Supercapacitors are no longer required due to insulation research**
    - Cryogel keeps batteries within acceptable temperature range during cooling process
- Fuel flow rate and temperature control added
- Fuel line length decreased
- Increased power budget

Baseline Design





Baseline Design



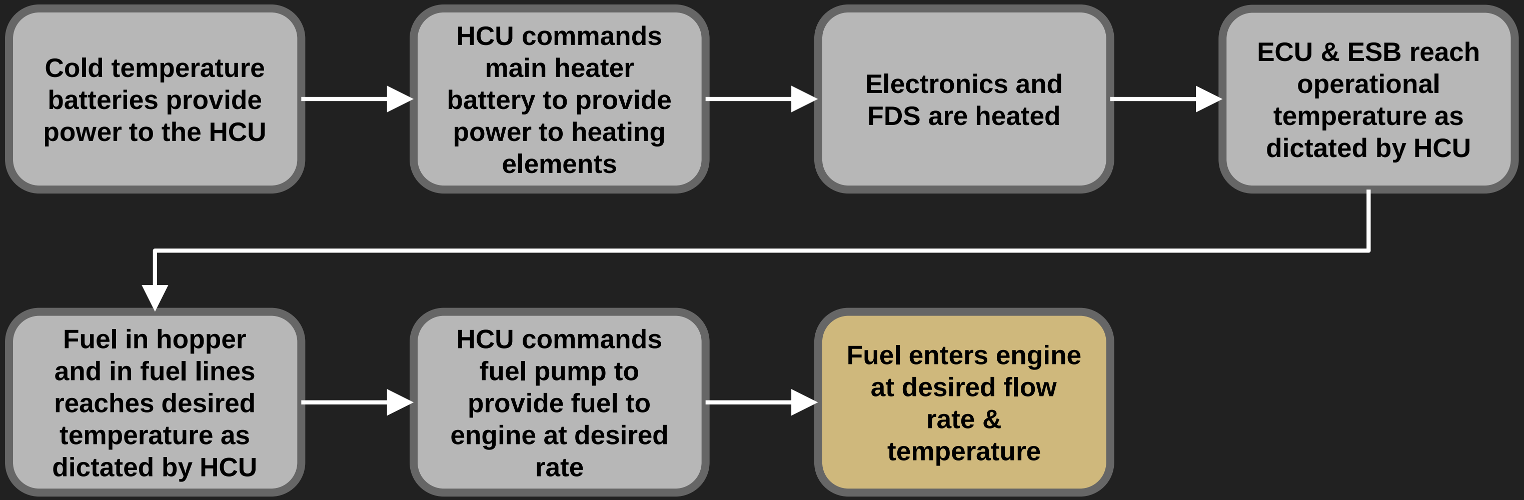
- Initial Energy: Main heating battery insulated in Cryogel

- Fuel Delivery System: Resistive heating
  - Resistive heating wire wrapped around fuel delivery components
  - Components insulated in Cryogel
  - Fuel pump provides specified mass flow rate to engine

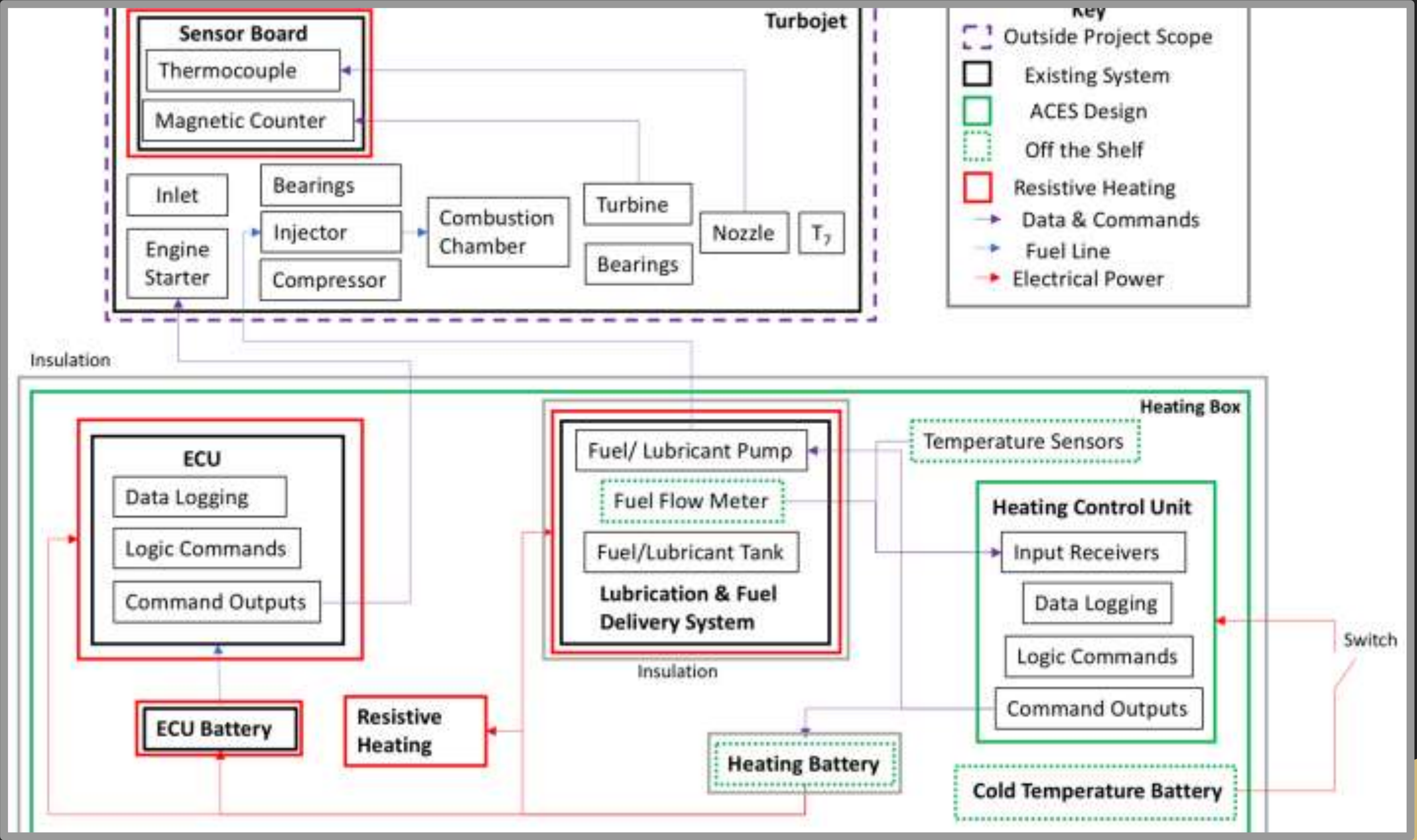
- Electronics Heating: Resistive heating within manufactured plastic box
  - ESB heated by power resistors inside cowling

- Heating Control Unit (HCU): Microcontroller powered by cold temperature batteries
  - Controls temperature of fuel delivery and electronics systems
  - Controls fuel flow rate into the engine
  - HCU remains functional at -50°F

Process Flow Diagram



Functional Block Diagram



Critical Project Elements

Critical Project Elements

CPE 1: Ensure that main heater battery is at or above the operational temperature (30°F), while not exceeding the maximum temperature (122°F).

CPE 2: Heat the engine electronics (ECU, ESB, and engine battery) to their standard operating temperatures (60°F) while not exceeding a maximum temperature of 122°F for the battery and 150°F for the ECU and ESB.

CPE 3: Heat fuel in fuel delivery system to a temperature between 60°F and the 115°F (below the cavitation temperature) to provide adequate fuel flow to the engine.

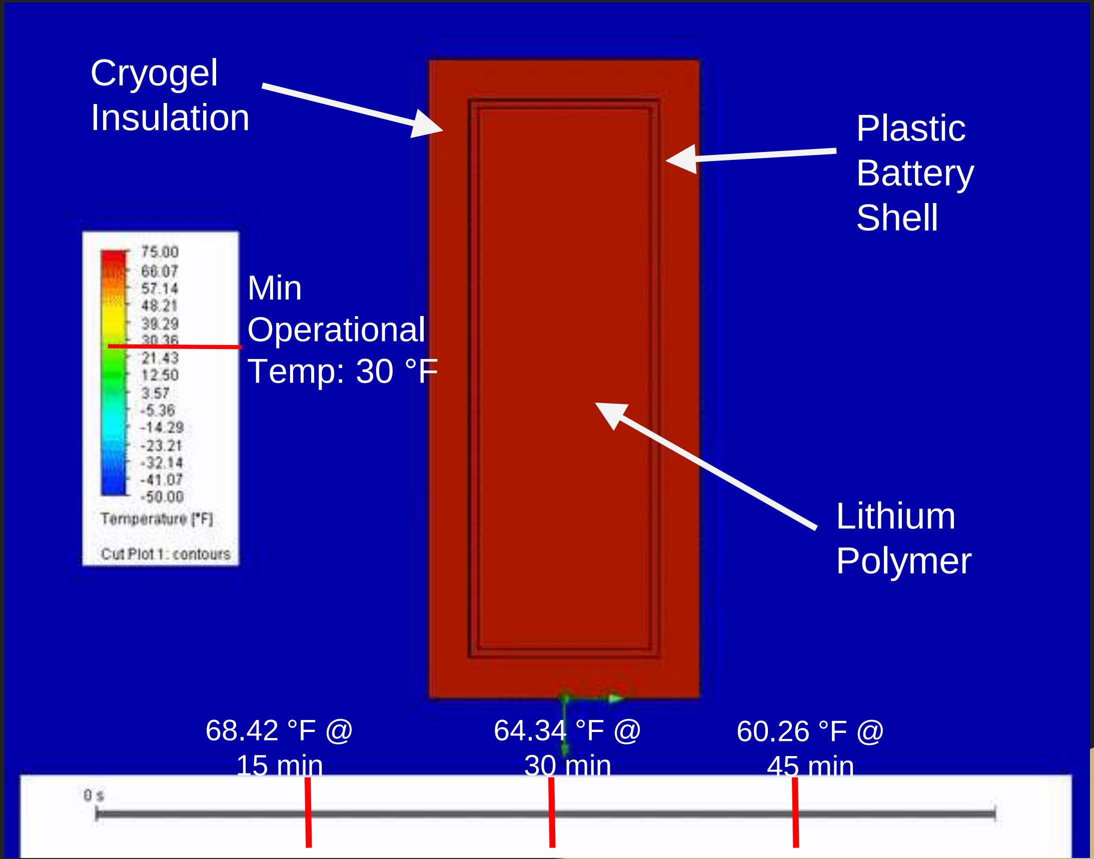
CPE 4: Construct a Heating Control Unit (HCU) which will control the mass flow rate and heating systems.

Main Heater Battery

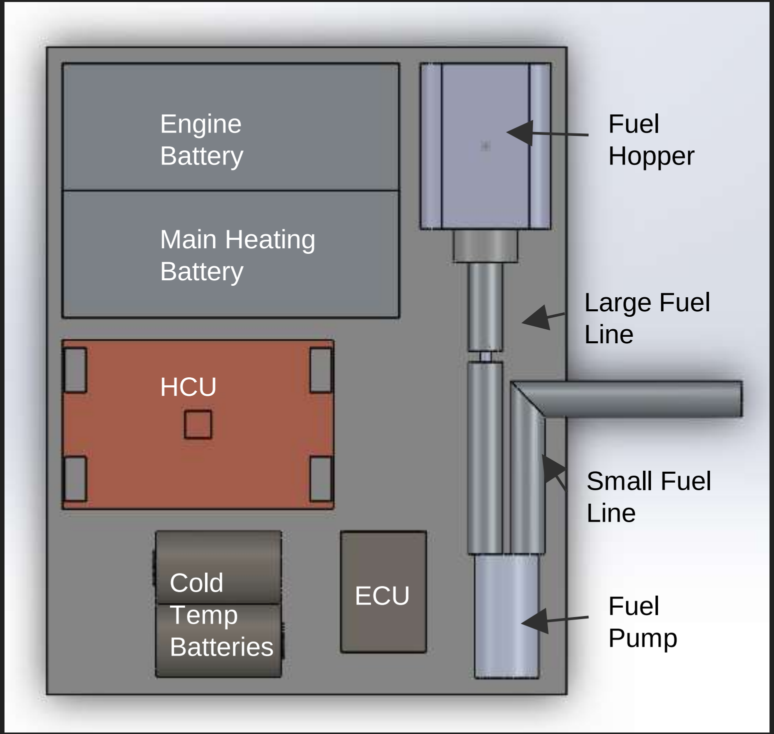
CPE 1: Ensure that main heater battery is at or above the operational temperature (30°F), while not exceeding the maximum temperature (122°F).

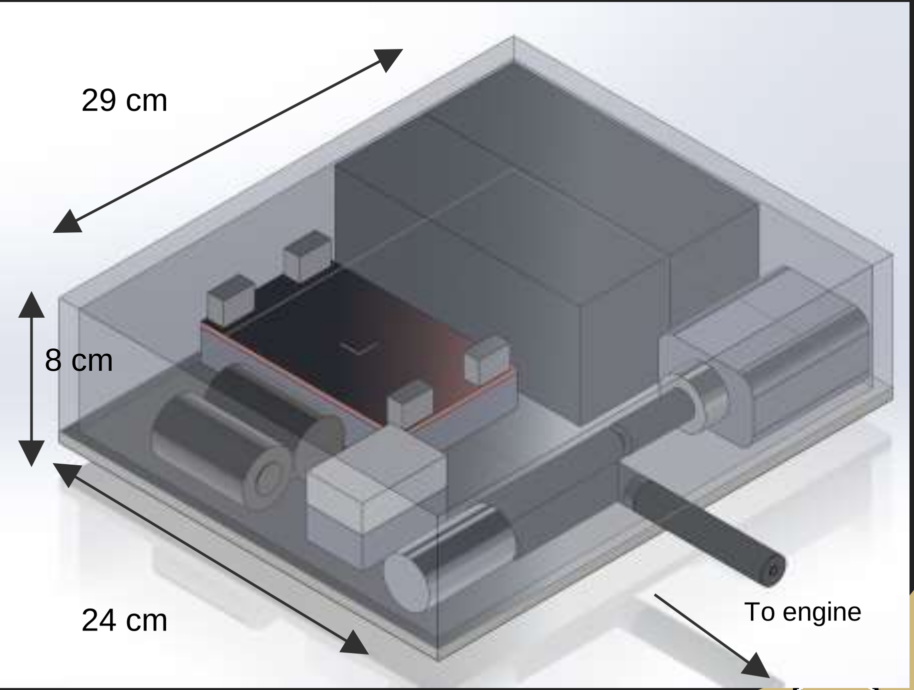
Battery Model

- Outside air temperature set to -50 °F
- The battery was set to a temperature of 70 °F
- Simulation run for 1 hr
- **Battery cools to a final temperature of about 56 °F**
  - **CPE 1** ✓



Electronics Housing





Cooling Model

- Outside air temperature set to -50 °F.
- The solids and internal air set to a temperature of 70 °F.
- Bottom face has imposed dirichlet condition of -109.3 °F to simulate box resting on block of dry ice.
- Material properties used in simulation are accurate for each component.
- Simulation run for 1 hr.

Electronics Cooling - Top Down

Main Heater Battery

HCU

Min LiPo Temp 30 °F

Min HCU Temp -57 °F

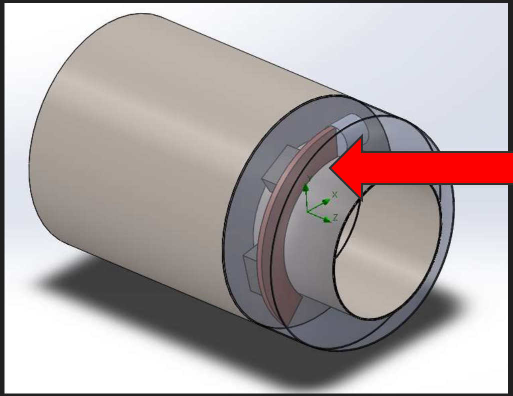
Electronics Box Heating

CPE 2: Heat the engine electronics (ECU, ESB, and engine battery) to their standard operating temperatures (60°F) while not exceeding a maximum temperature of 122°F for the battery and 150°F for the ECU and ESB.

CPE 3: Heat fuel in fuel delivery system to a temperature between 60°F and below the 115°F cavitation temperature to provide adequate fuel flow to the engine.

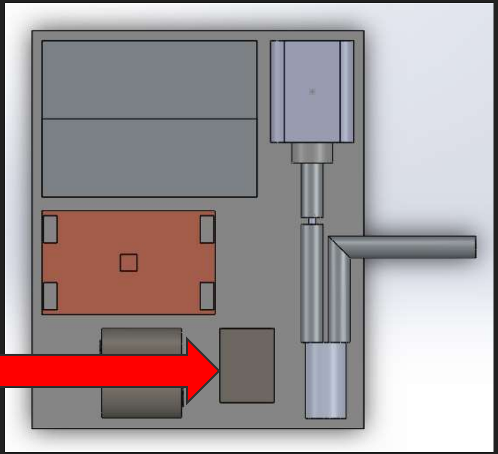
Design Requirements

- ***FR 3) Electronics Heating:*** The electronics (ECU, ESB, batteries) shall be heated to their operating temperature of 60°F.
    - DR 3.1) LiPo batteries must stay above 30°F and below 122°F at all times
    - DR 3.2) The ESB must be above 60°F and below 150°F after the heating period
    - DR 3.3) The ECU must be above 60°F and below 150°F after the heating period

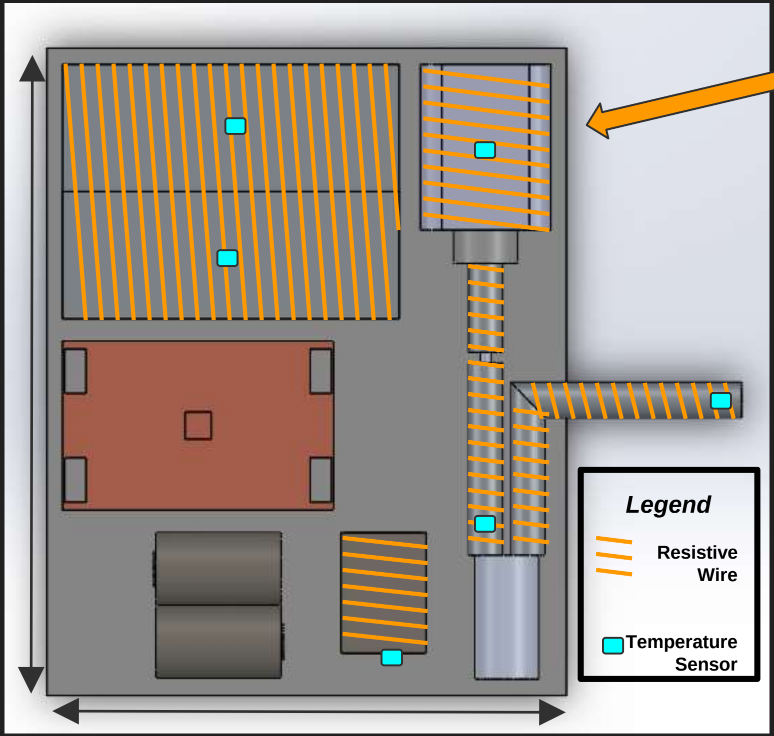


ESB

ECU



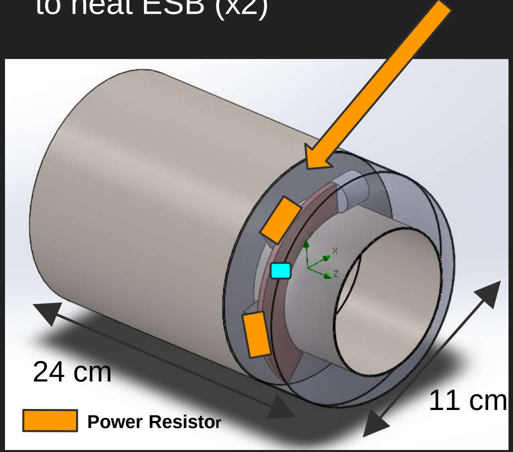
Placement of Resistive Wire & Temperature Sensors



29 cm

24 cm

- **Omega NCRR-34-100** resistive heating wire wrapped around components
- Models assume homogeneous heat distribution from wire
- ~21 ft of wire required
- **Vishay/Dale 12 Ohm 15W** power resistors to heat ESB (x2)



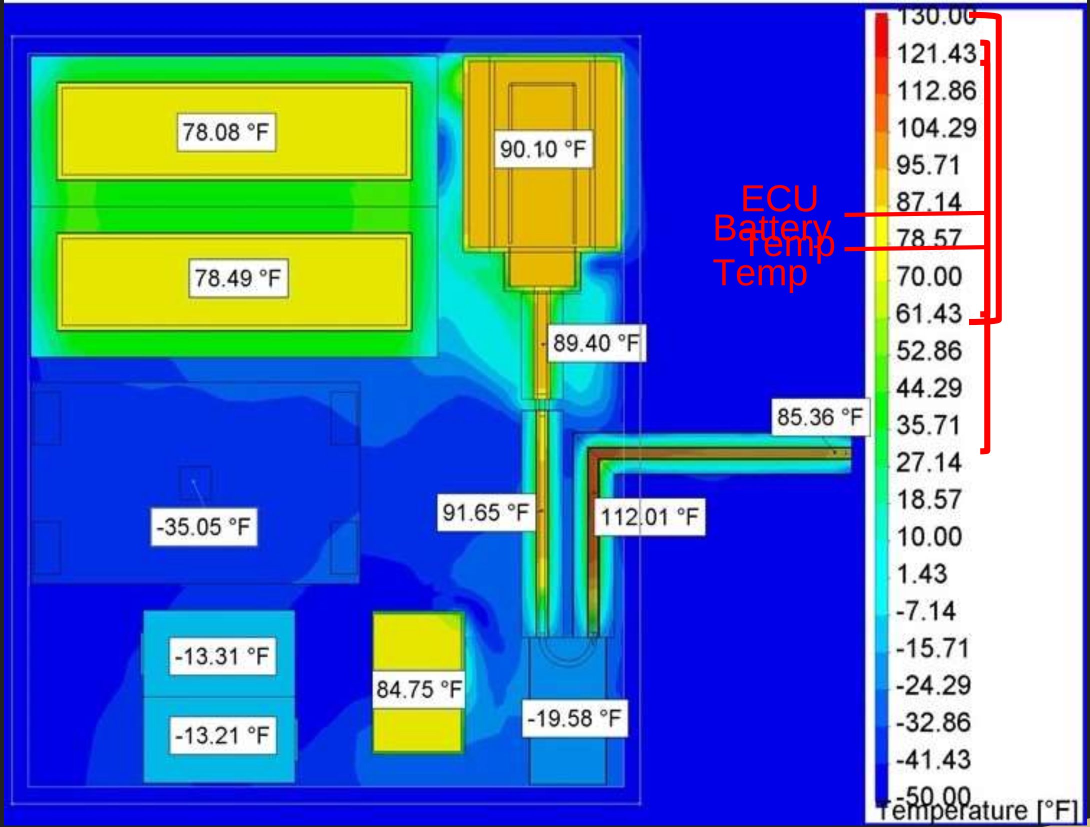
Heating Model

- Outside air temperature set to -50 °F.
- The solids and internal air set to results from previous simulation.
- Bottom face has imposed dirichlet condition of -109.3 °F to simulate box resting on block of dry ice.
- Material properties used in simulation are accurate for each component.
- Simulation run for 8 min.

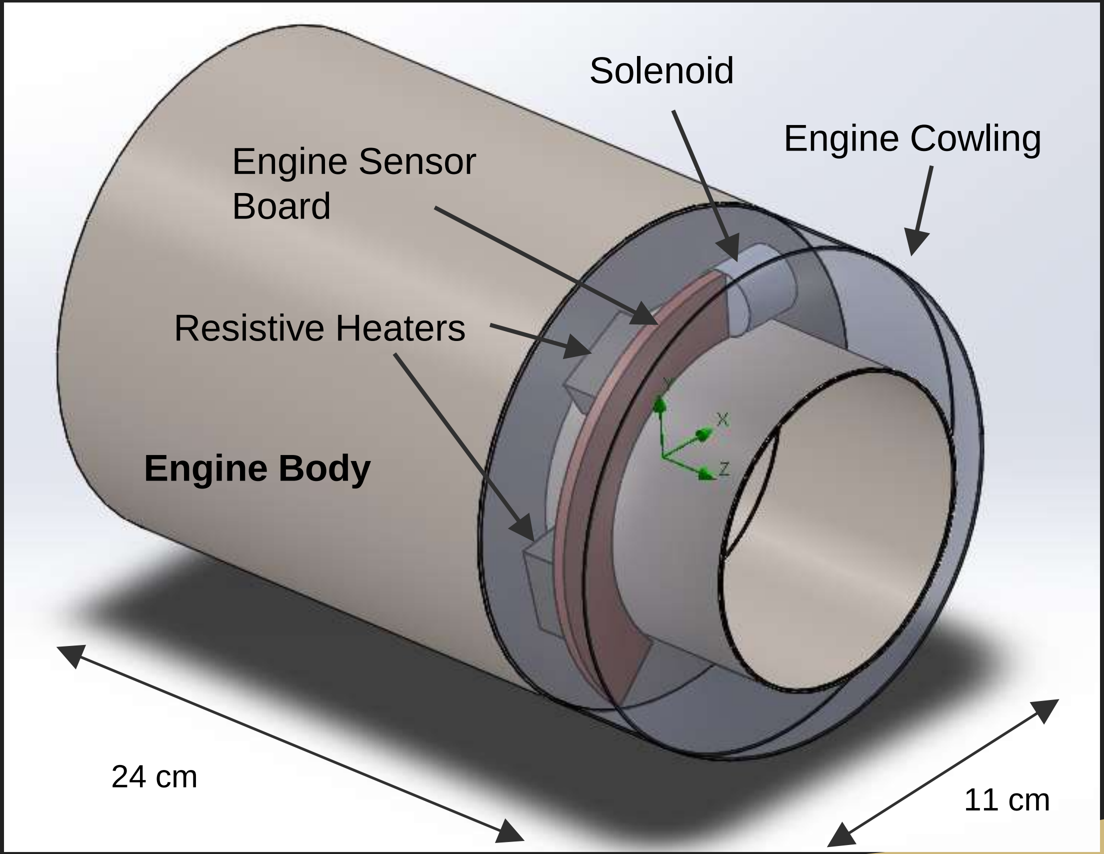
Electronics Heating - Top Down

FR 2.2 ✓
- Hopper
- Fuel Lines

FR 3 ✓
- Engine Battery
- ECU



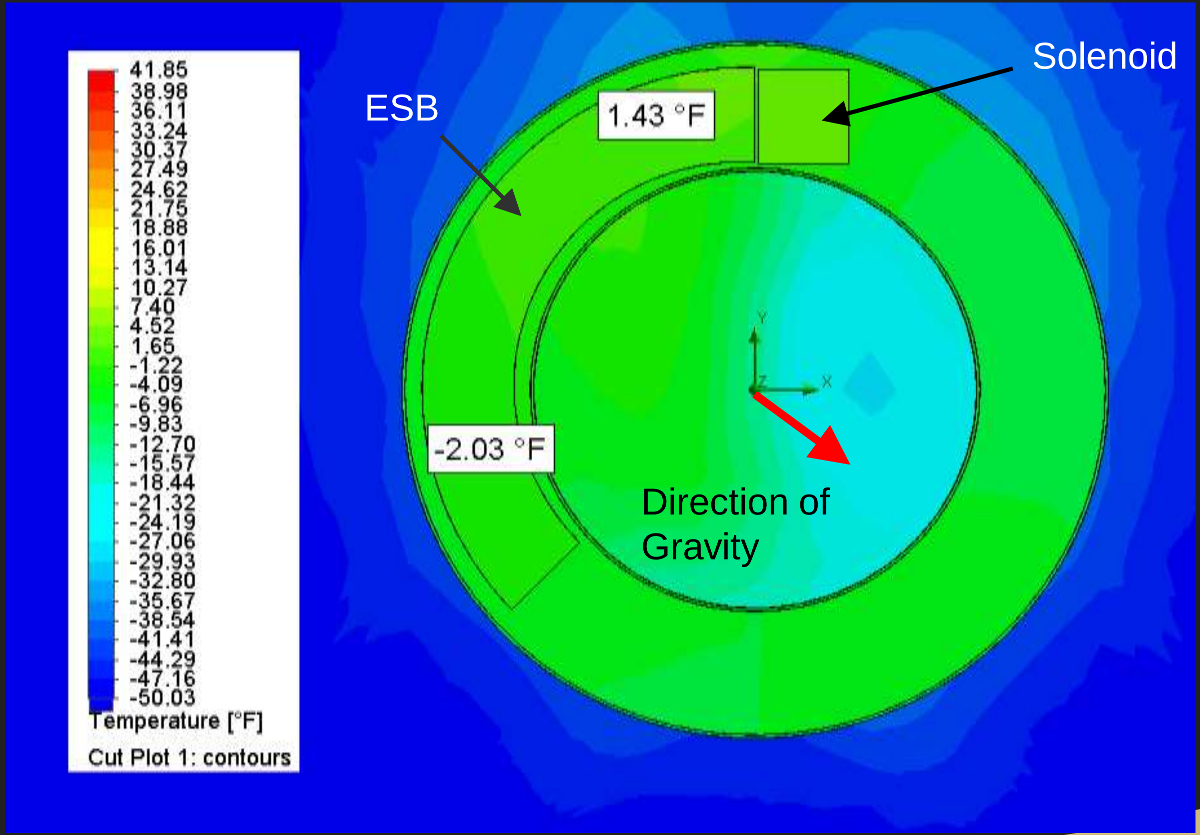
JetCat Engine Schematic



ESB Cooling Model

- Outside air temperature set to -50 °F.
- The solids and internal air set to a temperature of 70 °F.
- Material properties used in simulation are accurate for each component.
- Simulation run for 1 hr.
- Air inside the cowling is completely separate from the outside air.

JetCat Engine Cooling



ESB Heating Model

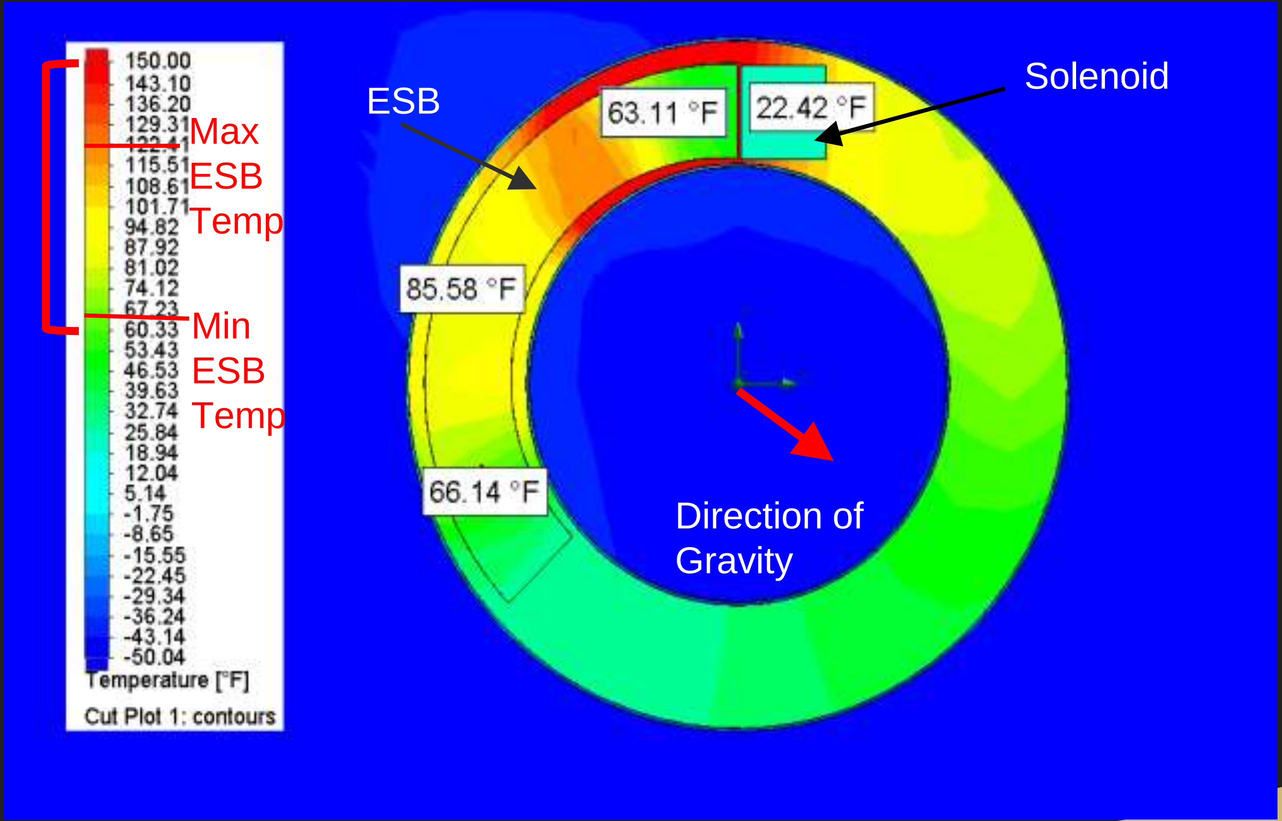
- Outside air temperature set to -50 °F.
- Air inside the cowling is completely separate from the outside air.
- Material properties used in simulation are accurate for each component.
- Initial temperature used from the cooling model
- 2 different 10W power resistors.
- Simulation run for 8 min.

JetCat Engine Heating

Operational Range

FR 3 ✓

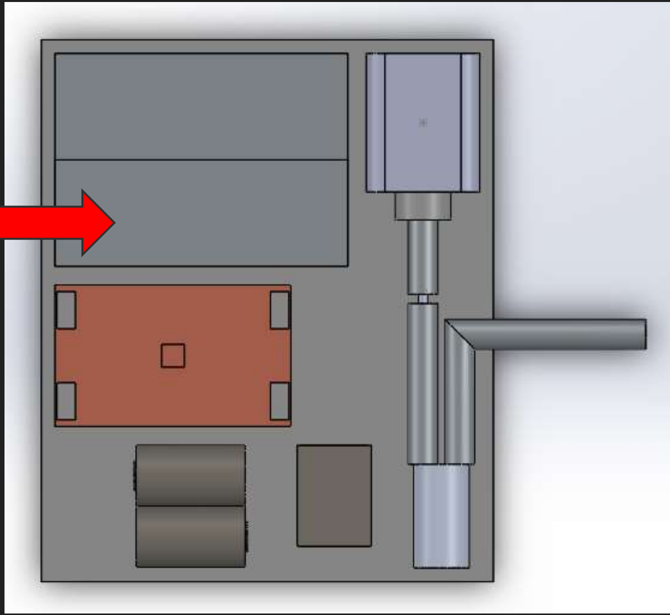
- ESB warming



Design Requirements

- ***FR 1) ENERGY:*** An initial energy source shall provide adequate power for the fuel delivery system heating and electronics heating.
  - DR 1.1) Initial Energy source shall provide a minimum of 110 W.

Main Heater Battery

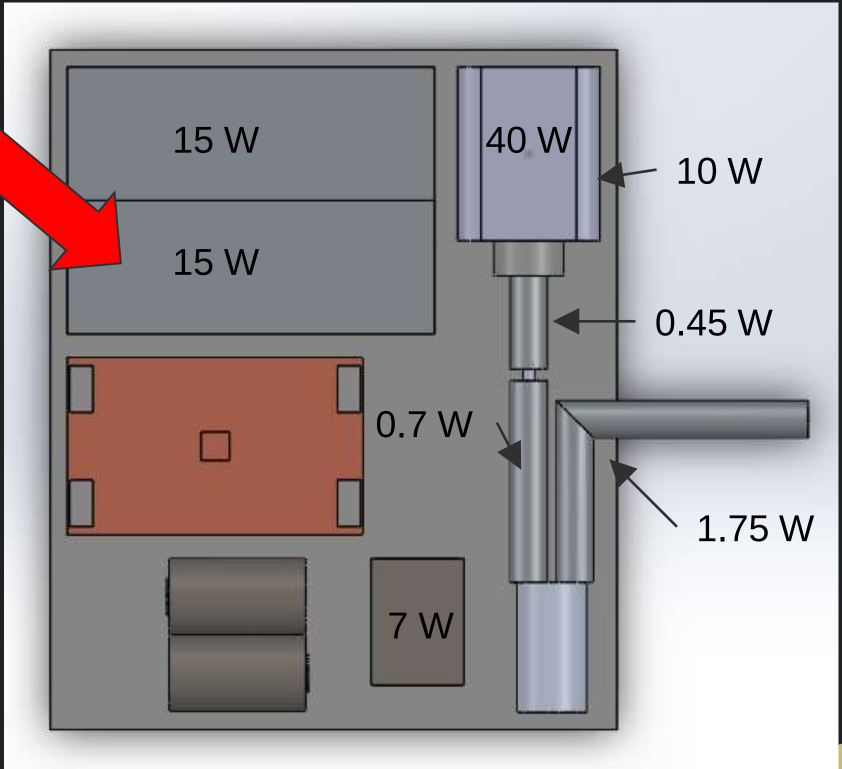


Power Budget

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

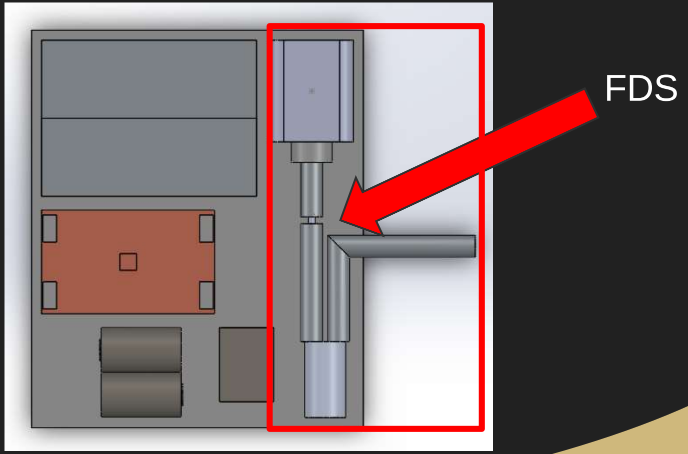
Electronics Housing Power	89.45 W
ESB Power	20 W
Total Power Budget	109.45 W

FR 1: Energy ✓

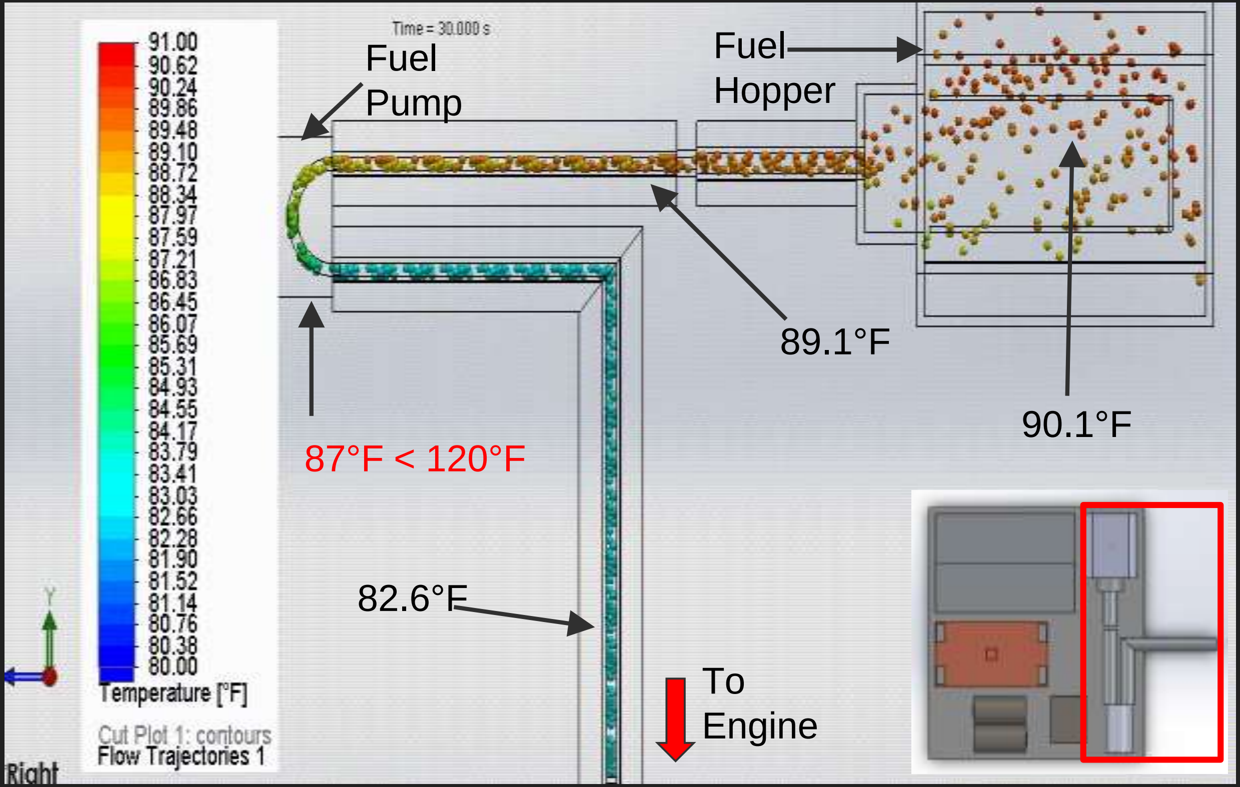


Design Requirements

- ***FR2) FDS:*** The Fuel Delivery System shall provide adequate fuel flow for a successful start-up sequence and continued operation of the engine. This fuel flow is specified as 4.8 g/s +/- 0.13 g/s for full throttle.
  - DR 2.1) Fuel pump must be operational
  - DR 2.2) Fuel must be heated to decrease viscosity enough to be pumped
  - DR 2.3) Fuel lines must not exceed 140°F
  - DR 2.4) Fuel must not exceed 115°F when flowing through fuel pump



FDS FLOW



- Outside air set to -50 F
- Fluid set to kerosene
- Initial fluid temperature set to 90.1 °F
- Initial structure temperature of fuel lines set to 62.8 °F
- Aluminum temperature set to -24 °F
- Mass flow set to 4.8 g/s
- Run for 30 s to see the cooling in the lines from hopper to engine
- **Minimum temperature ~ 82 °F**

Heating Control Unit

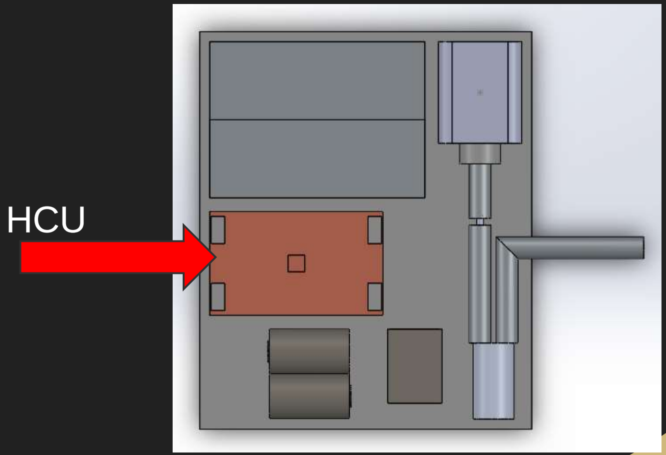
CPE 4: Construct a Heating Control Unit (HCU) which will control the mass flow rate and heating systems.

Project Objectives | Design Solution | Critical Project Elements | Design Requirement Satisfaction | Project Risks | Verification & Validation | Project Planning

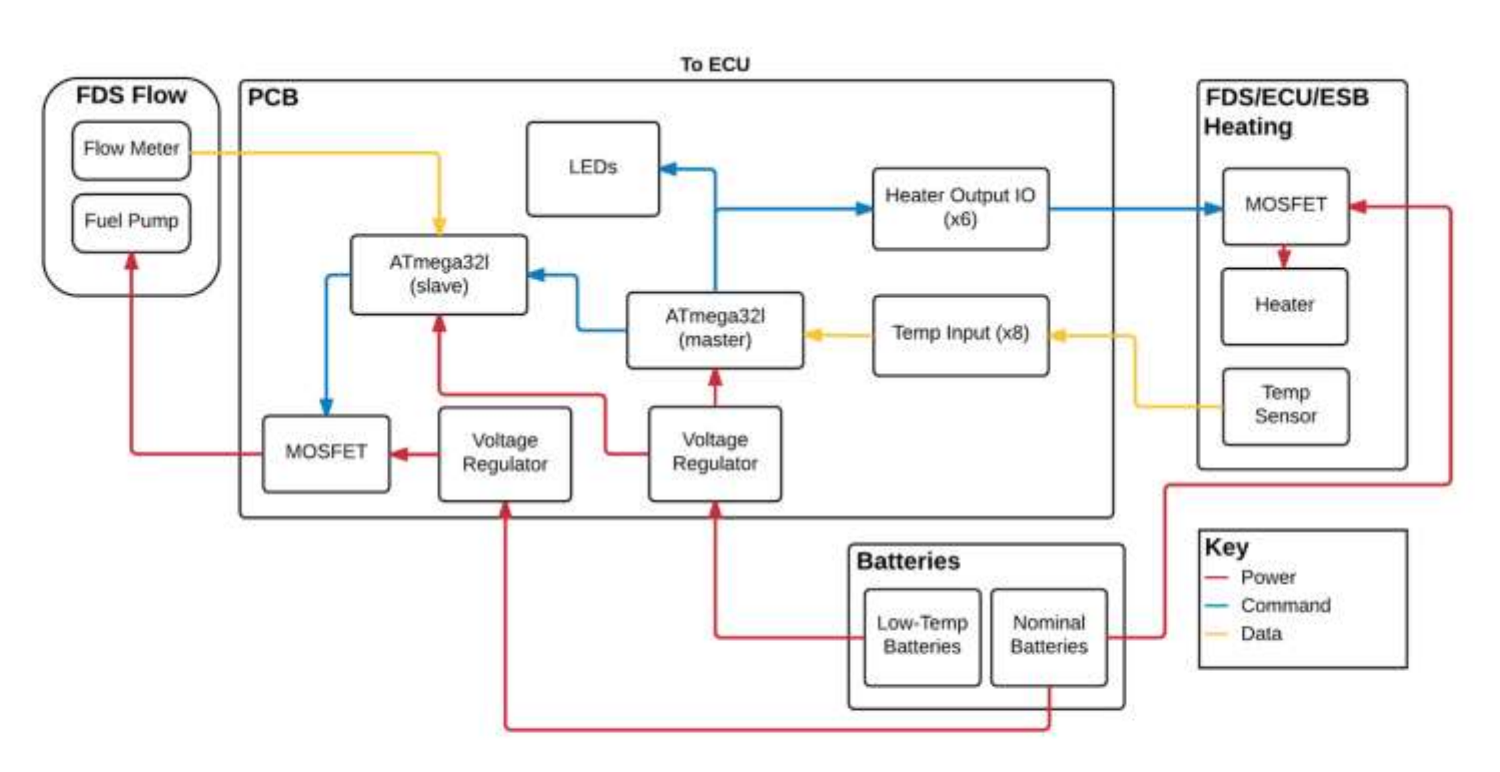
Design Requirements

- ***FR 4.1) HCU:*** The Heating Control Unit (HCU) shall monitor and regulate the temperature of the electronic components and fuel delivery system.
  - DR 4.1.1) Operates at and below -50°F
  - DR 4.1.2) Receives inputs from 8 temperature sensors
  - DR 4.1.3) Controls output for 6 heating circuits
  - DR 4.1.4) Signals when heated components reach operational temperatures
  - DR 4.1.5) Regulates power output to heaters
    - DR 4.1.5.1) Prevents overheating
    - DR 4.1.5.2) Increase heating where needed
  - DR 4.1.6) Provide system ready signal

- ***FR 4.2) HCU:*** The Heating Control Unit (HCU) shall monitor and regulate the mass flow rate of the fuel.
  - DR 4.2.1) Regulate duty cycle for mass flow through fuel pump



Heating Control Unit Block Diagram

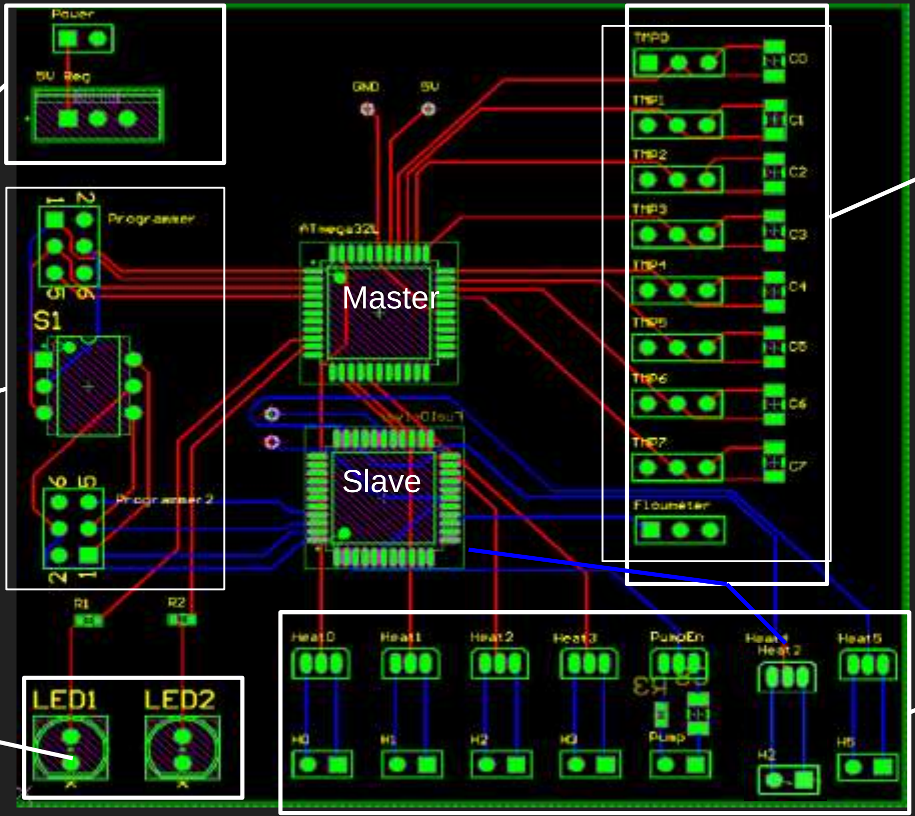


Heating Control Unit PCB Layout

Power Input

Programmers and SPI connections

Status LEDs



Temperature and Flow Inputs

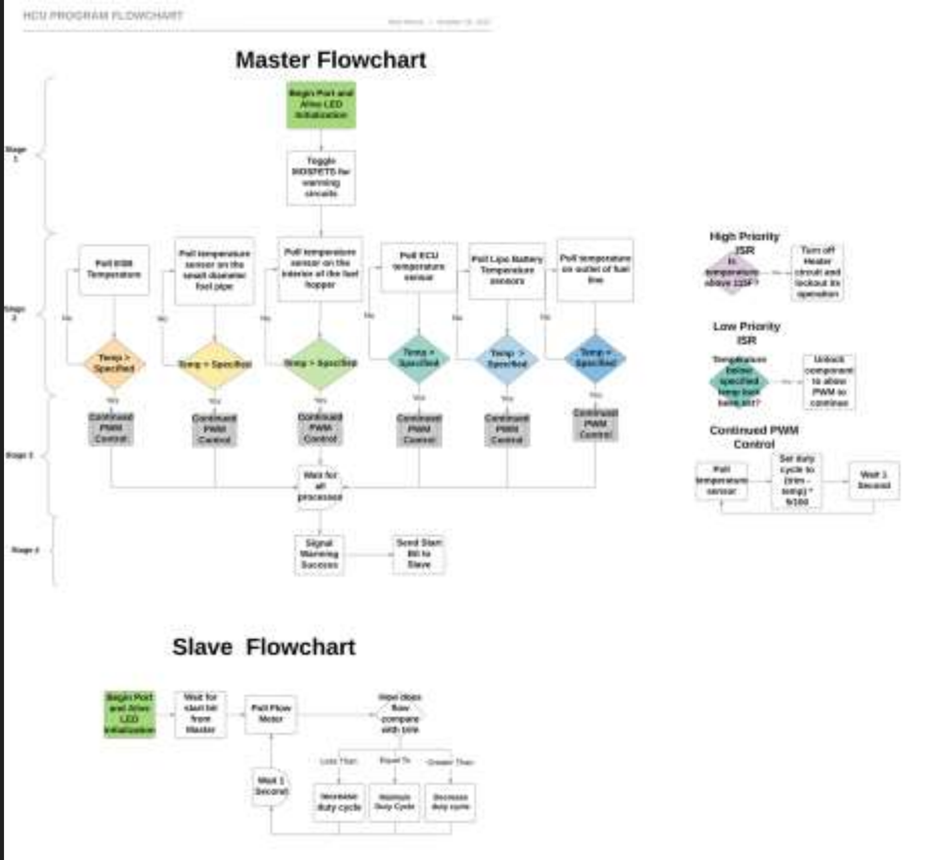
Heater/Pump Outputs

HCU Component Breakdown

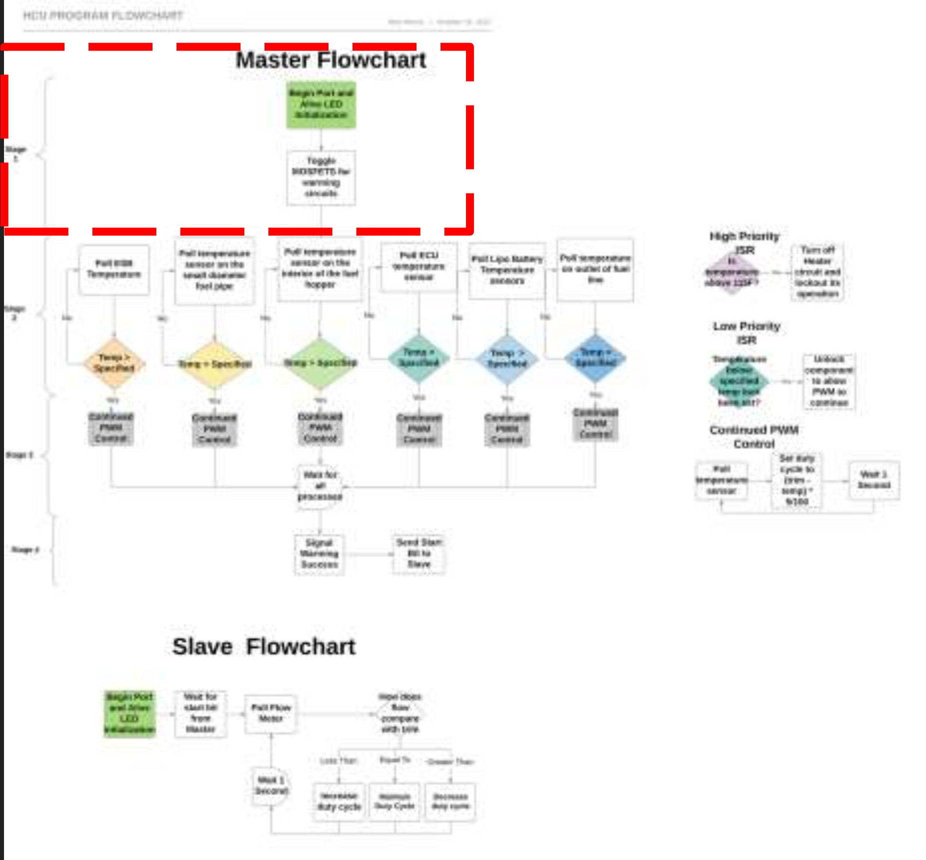
- **Atmega32L Microcontroller** (x2)
- **TMP36 Analog Temperature Sensors** (x6)
- **LM2490T-5.0/NOPB Voltage Regulator** (x1)
  - To reduce voltage from primary lithium batteries
- **Primary Lithium Batteries** (x2)
  - High performance at low temperature
- **FAIRCHILD N-Channel MOSFET** (x5)
  - Can handle 60V at 30A
- **Atmel In-Circuit Debugger** (x1)
- **NCRR-34-100 Resistive Heating Wire** (100ft Spool)
- **LM317 Voltage Regulator**
  - Regulate voltage to fuel pump

In-circuit debugger

Software Design Implementation



Software Design Implementation



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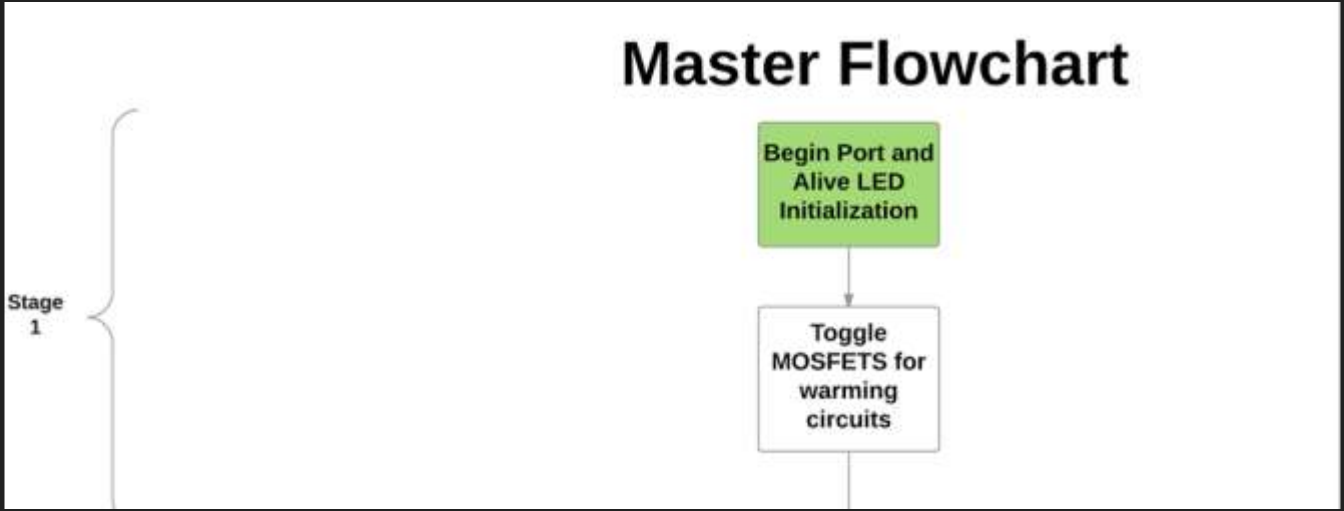

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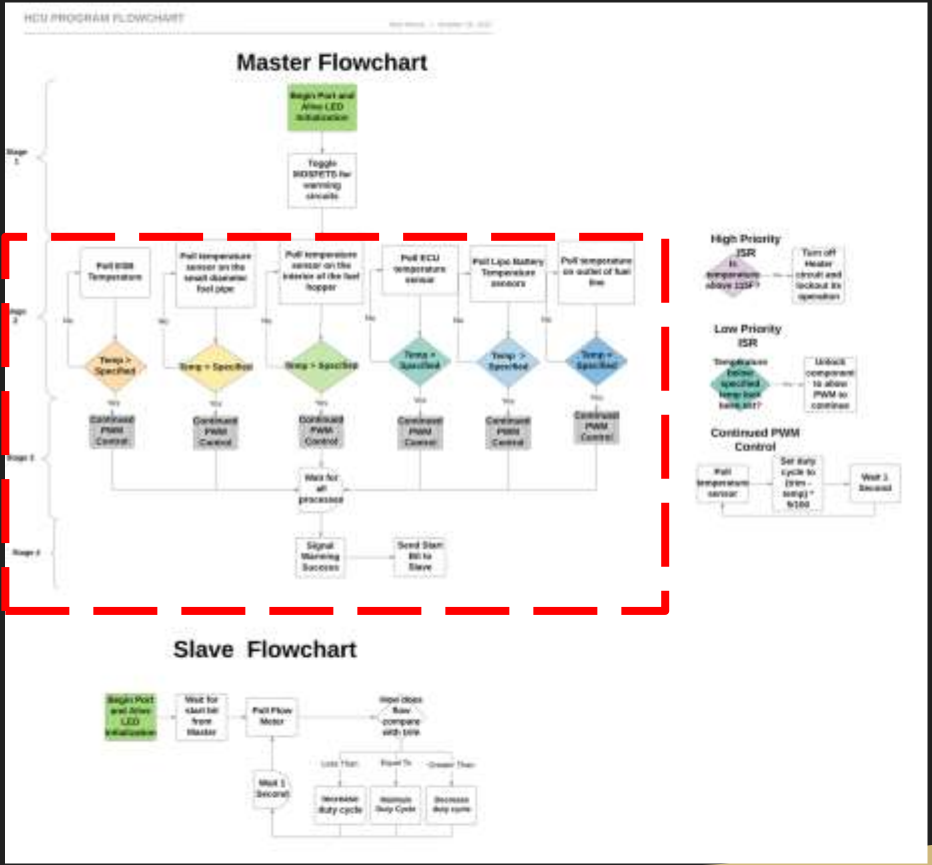

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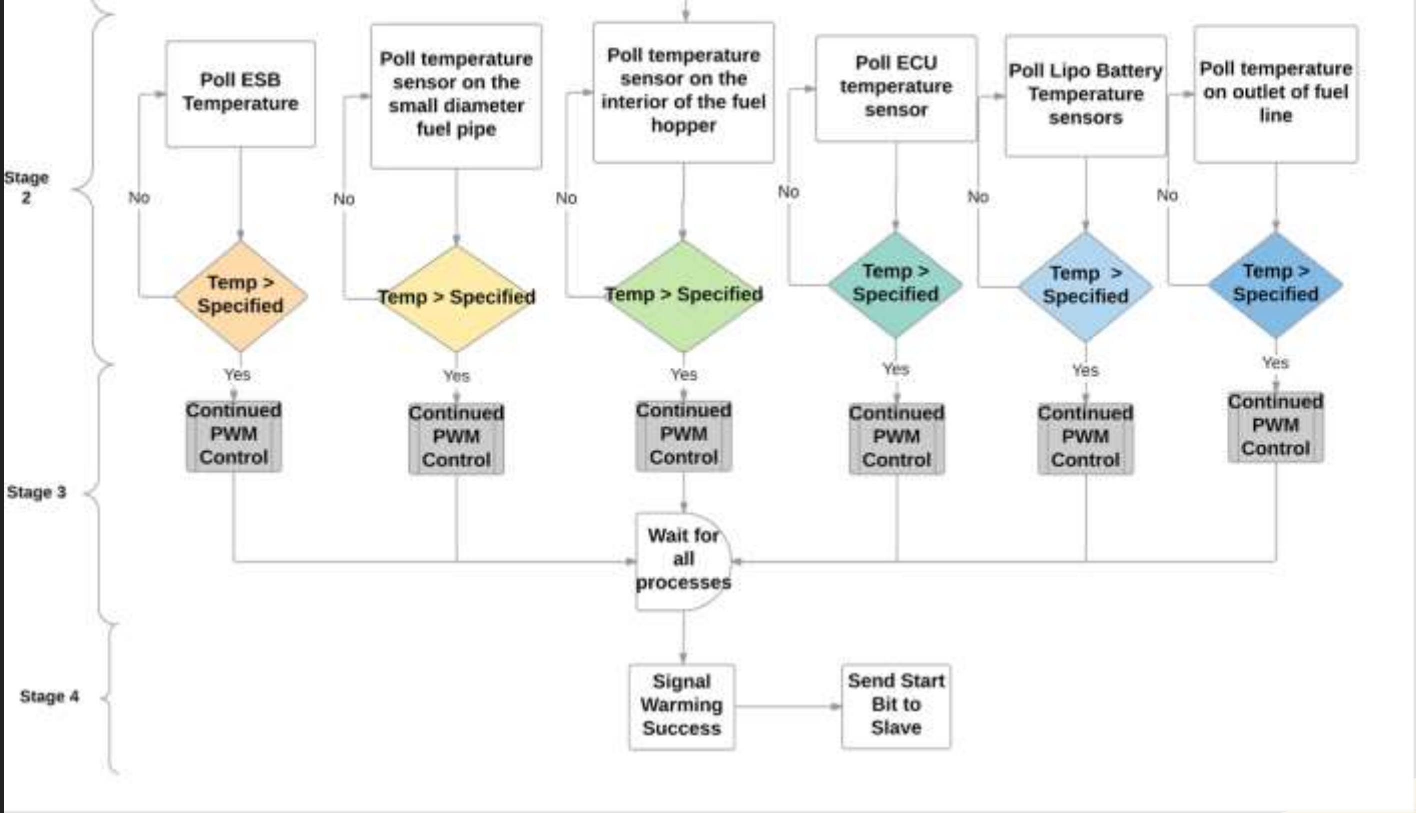
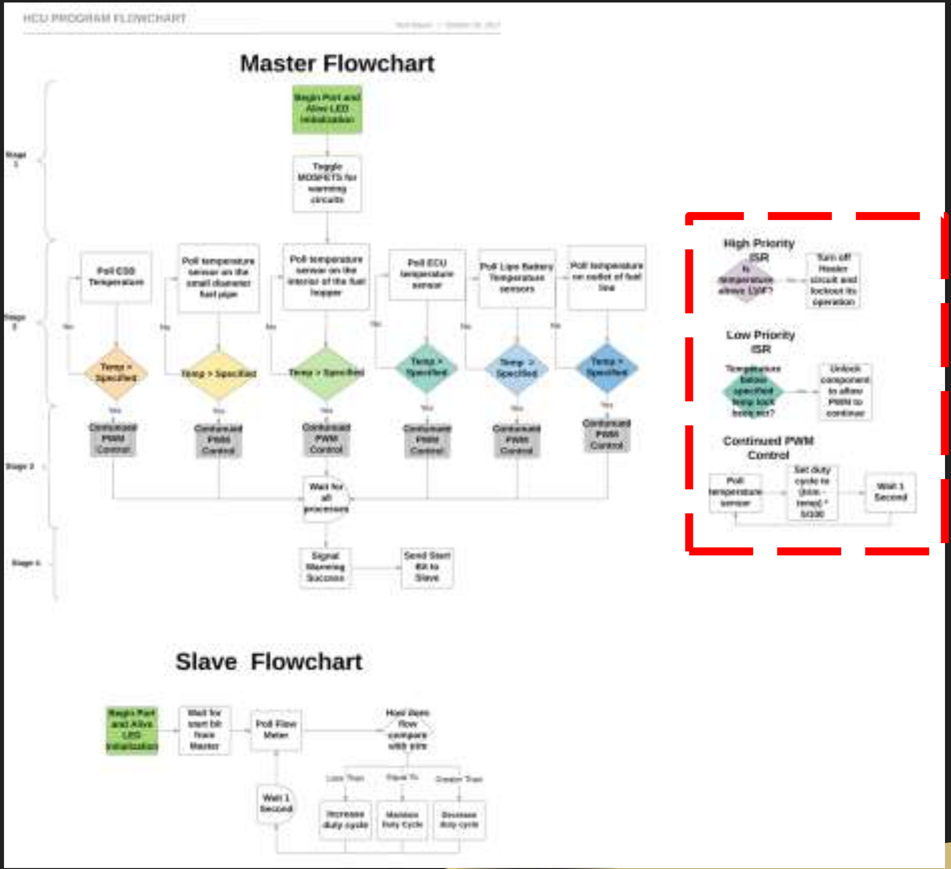


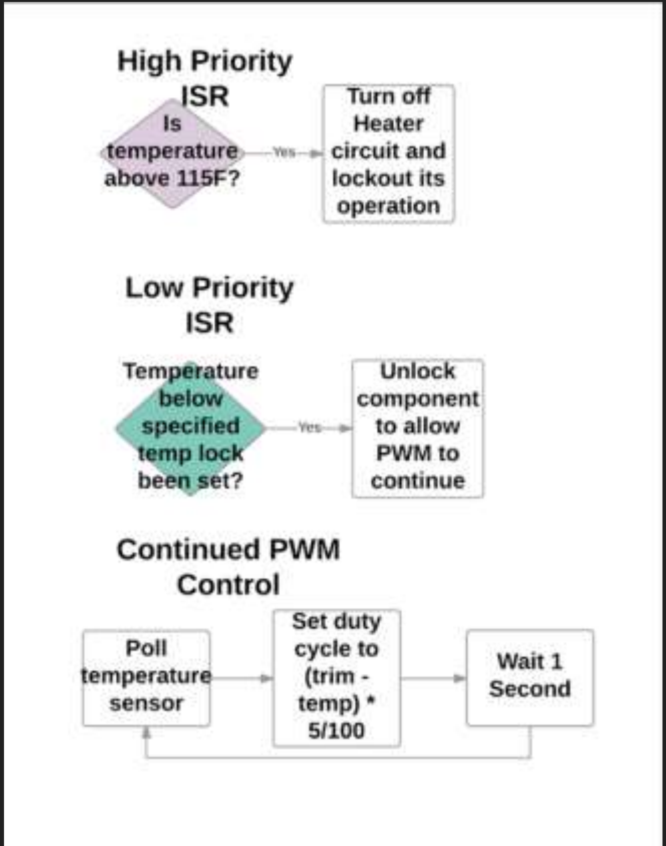
Software Design Implementation



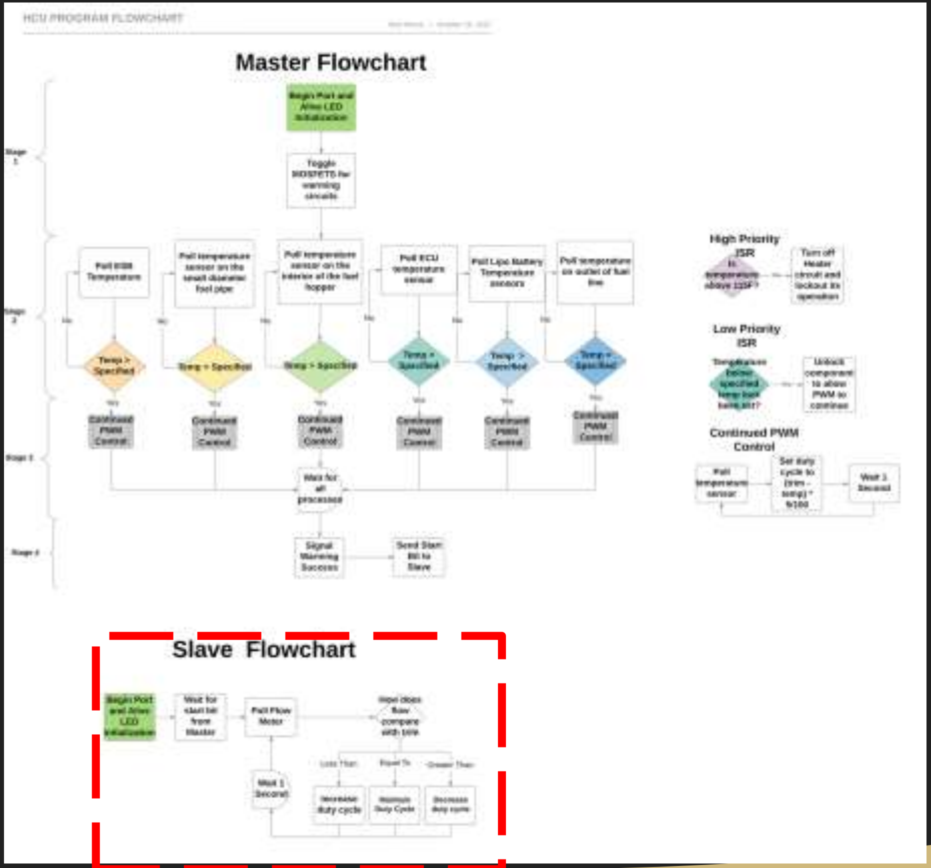
Software Design Implementation

FR 4.1 ✓

- Temperature Control

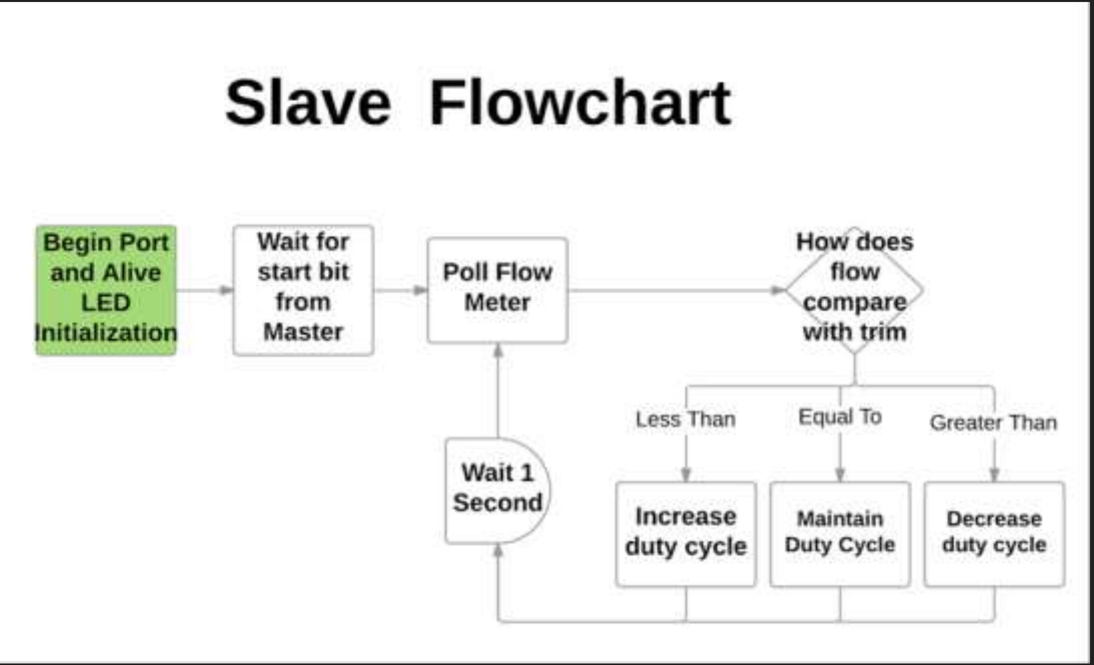


Software Design Implementation



Software Design Implementation

FR 4.2 ✓
- Flow control



Project Risks

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

Pre Mitigation Risk Assessment Matrix

	Minimal	Minor	Major	Hazardous	Catastrophic
Near Certainty					
Very Likely	7				
Likely	6				
Unlikely		3	5	2, 8	
Very Unlikely			1, 4		

1. Heater Battery Insulation Failure
2. Runaway Temperature
3. Fuel line stoppage
4. Fuel line cracks
5. Fuel line melting
6. Heating wire short circuit
7. Inaccurate thermal modeling
8. Jet fuel ignition

Risk Mitigation

- **#2**: *HCU control law malfunction leading to runaway temperature*
  - Conservative control law and/or temperature fail-safes
- **#5**: *Fuel line melting due to high temperature resistor wire*
  - Testing/research to determine safe temperature for our polyurethane tubing, conservative control law to avoid approaching this temperature
- **#7**: *Solidworks model inaccuracy*
  - Verification testing to confirm accuracy of models
- **#8**: *Accidental fuel ignition*
  - Keep fire extinguisher ready, examine fuel lines and connections before each test

Post Mitigation Risk Assessment Matrix

	Minimal	Minor	Major	Hazardous	Catastrophic
Near Certainty					
Very Likely					
Likely	6, 7				
Unlikely		2, 3			
Very Unlikely			1, 4, 5, 8		

1. Heater Battery Insulation Failure
2. Runaway Temperature
3. Fuel line stoppage
4. Fuel line cracks
5. Fuel line melting
6. Heating wire short circuit
7. Inaccurate thermal modeling
8. Jet fuel ignition

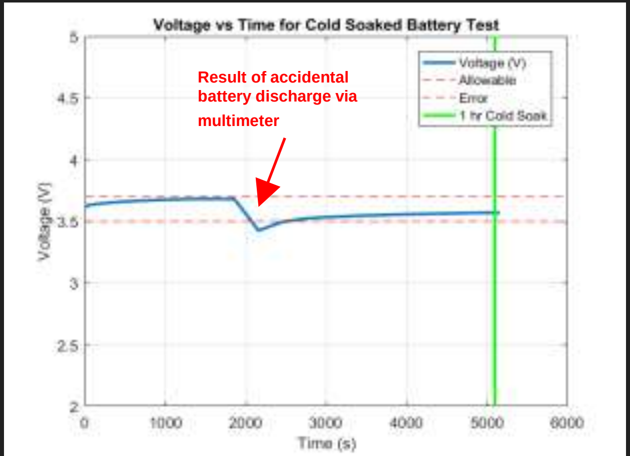
Verification and Validation

Project Objectives | Design Solution | Critical Project Elements | Design Requirement Satisfaction | Project Risks | Verification & Validation | Project Planning

Previous Tests Performed

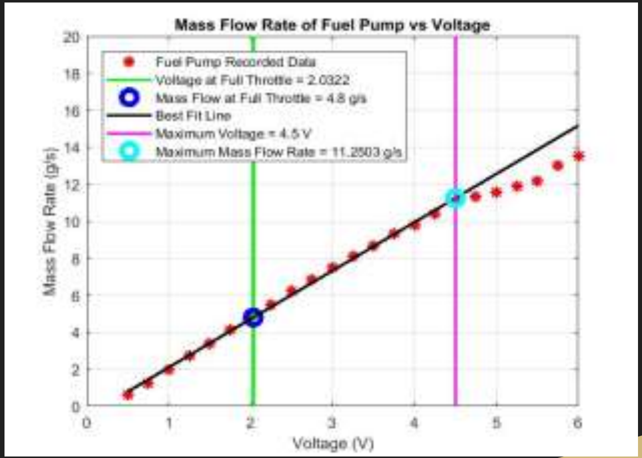
HCU Battery Test

- Verified nominal battery operation at -50°F
- Battery was able to maintain 3.6±0.1V drop



Fuel Pump Control Test

- Verified feasibility of fuel pump control
- Demonstrated linear relationship between voltage input and mass flow rate
- FR 4.2 Mass Flow Rate Control ✓



Tests to be Performed

*All tests are designed to prove **level 3** feasibility - **cold soak to -50°F**, **8 min 42 sec startup***

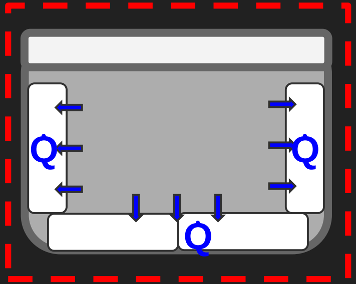
Test Environment	***Environmental Chamber***	***Dry Ice Chamber***	***Dry Ice and Cottonseed Oil Bucket***	***AFRL Test Chamber***
Applicable Tests	-Main heater battery with wiring and insulation	-HCU operation -Full box integration and validation	-Fuel lines integrity -Fuel pump verification of operation	-Final system integration with JetCat engine

Available Test Environments

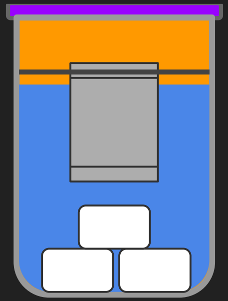
Environmental Chamber

Available

Dry Ice Chamber



Liquid Cold Soak



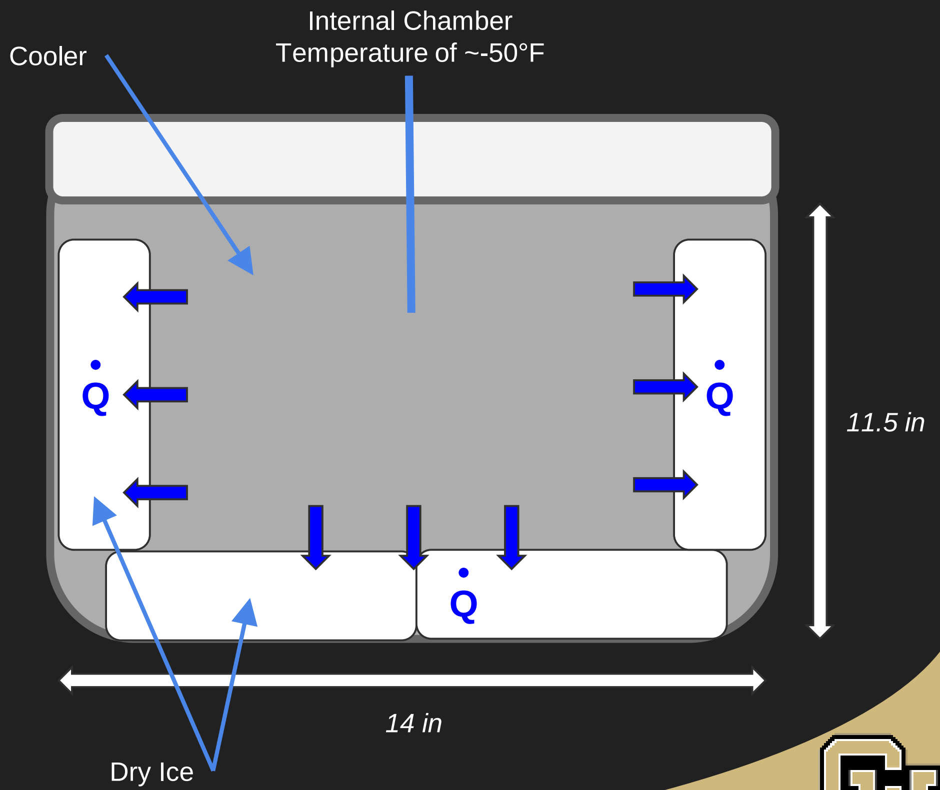
Planned to be built

Dry Ice Test Bed

Overview of Testbed:

- Provides the ability to run fuel delivery system **tests** **without risk of damaging expensive test equipment**

- Applicable tests:
    - Fuel line integrity
    - HCU operation
    - Full box integration and validation



Model Validation

Model Validation and Requirements Verification

Fuel Flow Sensor

- Validate mass flow rate of fuel out of electronics box

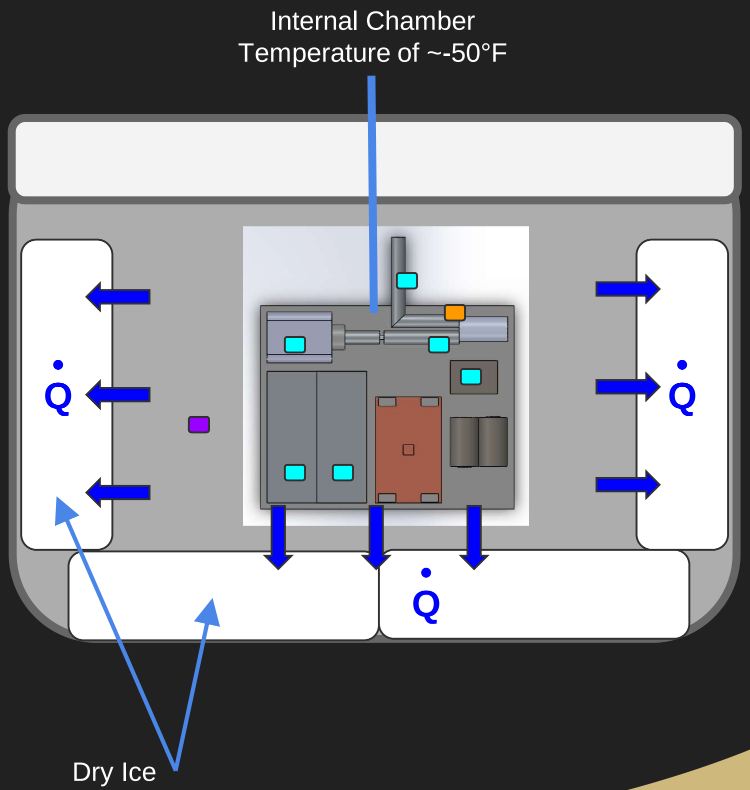
6 Channel DAQ connected to R-type thermocouples

- Validate individual component surface temperatures

Test Chamber Temperature sensor

- Verify -50±0.5°F ambient air temperature is met

Temperature and mass flow rate values will be compared to models at identical points for validation



Instrumentation Requirements

Equflow 0045

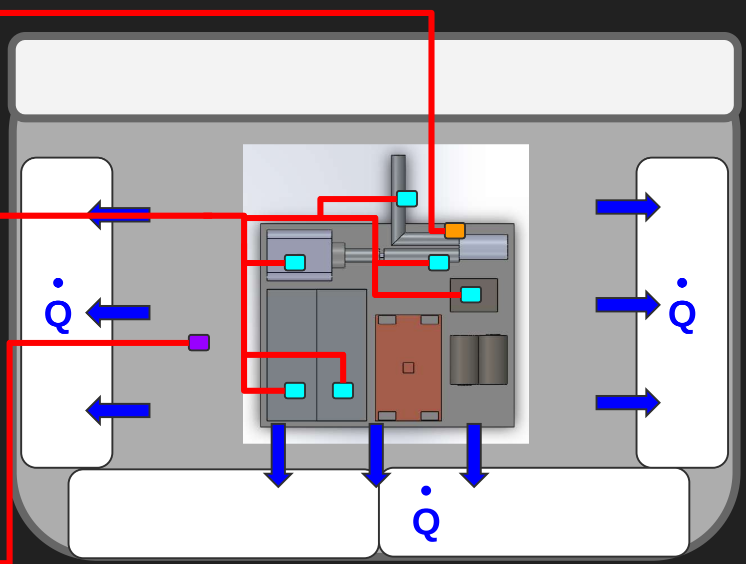
- Flow Rate 0.1-2 L/min with 110,000 pulses/L (**±0.00135 g/s**)
- Requirement: **±0.13 g/s** ✓

NI DAQ USB-6009

- 6 R-type thermocouples
- **±2.7°F**, +/-1V accuracy of 1.53mV
- Requirement: **±3.6°F** ✓

Omega Type J-K Thermocouple

- Accuracy of **±0.05°F**
- Requirement: **±0.5°F** ✓



Verification of Functional Requirements

Equflow 0045

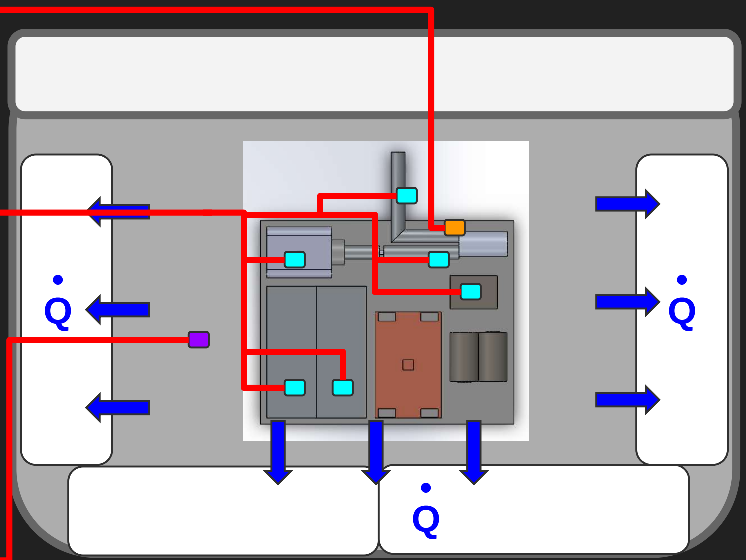
- Verifies **FR 2.1 and 4.2**

NI DAQ USB-6009

- Verifies **FR 1.0, 2.2, 3.0, and 4.1**

Omega Type J-K Thermocouple

- Verifies the customer specifications for ambient air conditions



ALL FUNCTIONAL REQUIREMENTS VERIFIED

Test Safety Summary

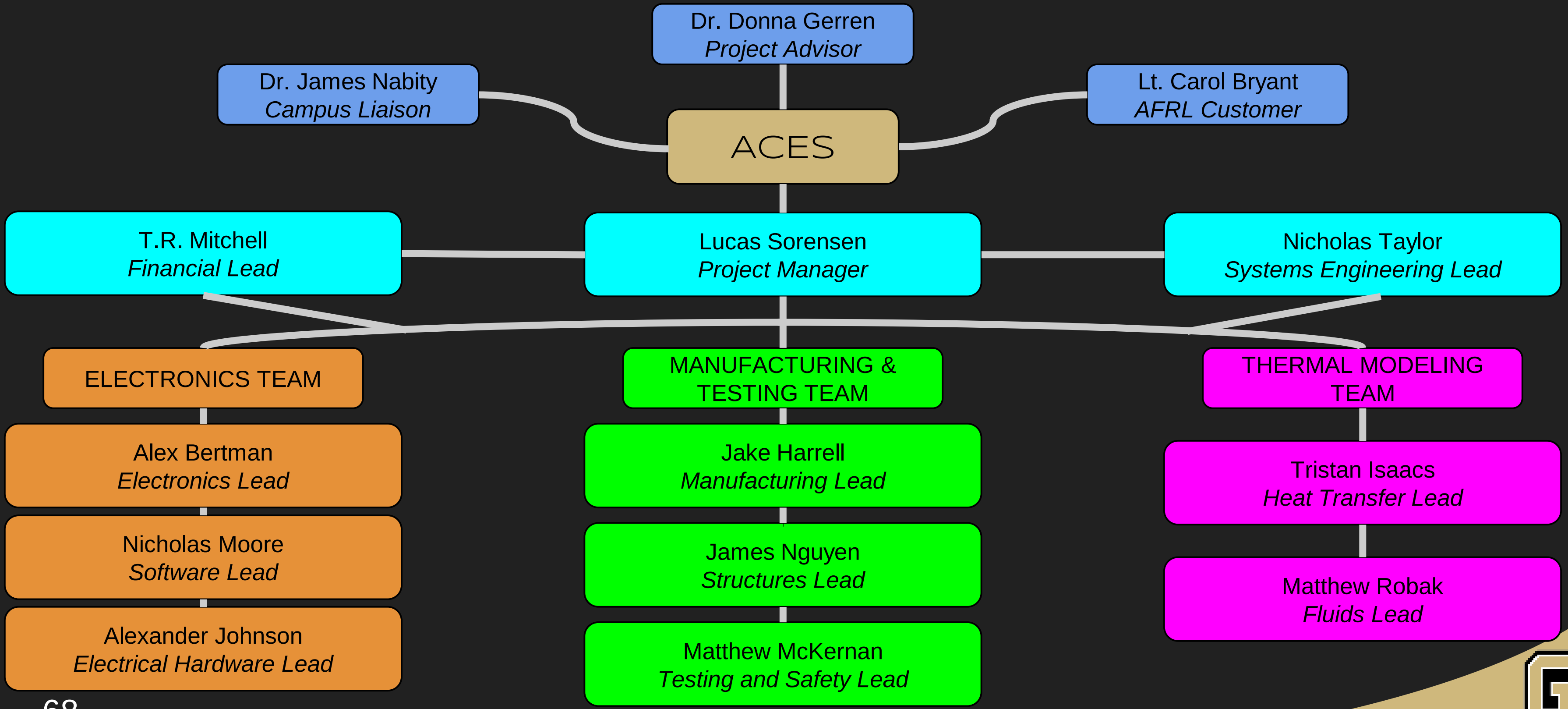
- Risk assessment and mitigation procedures will be outlined in respective test plan
- All tests involving fuel or other flammable liquids will be performed in an open outdoor environment with extinguishing equipment ready
- All fuel and electrical connections will be checked and tested prior to full tests

Risk assessments, risk mitigation, and all other safety procedures shall be outlined in the test plans and will be reviewed by a member of the PAB for approval

Project Planning

Project Objectives → Design Solution → Critical Project Elements → Design Requirement Satisfaction → Project Risks → Verification & Validation → Project Planning

organizational chart



Work Breakdown Structure

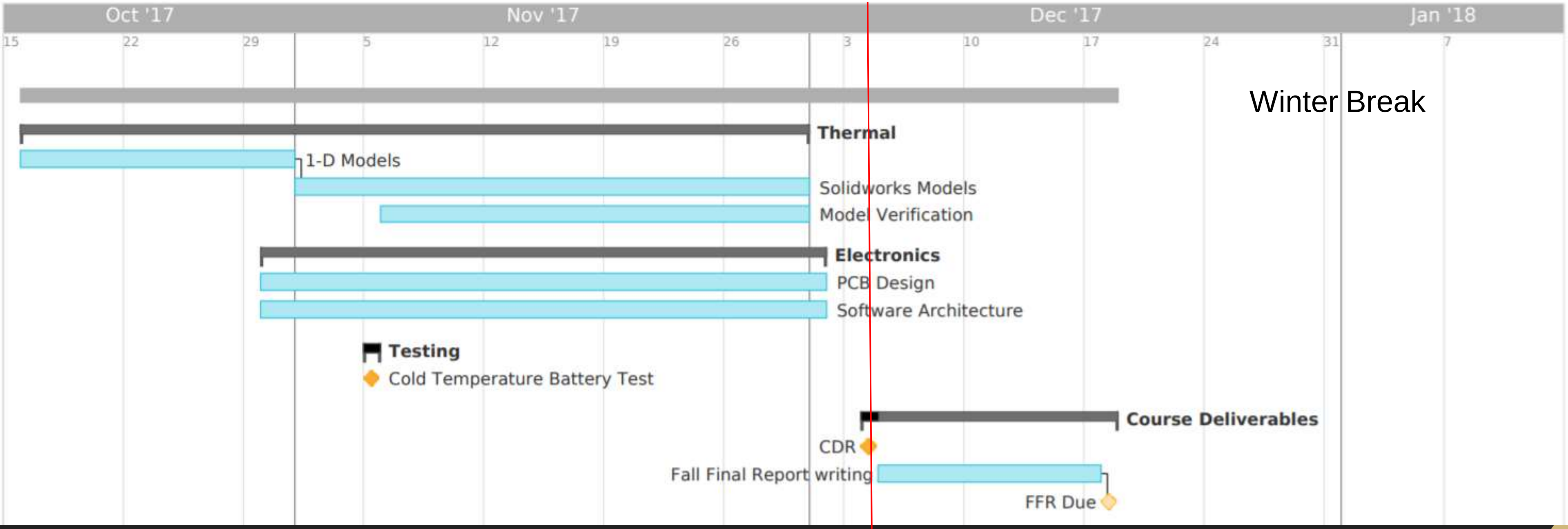
Incomplete at CDR

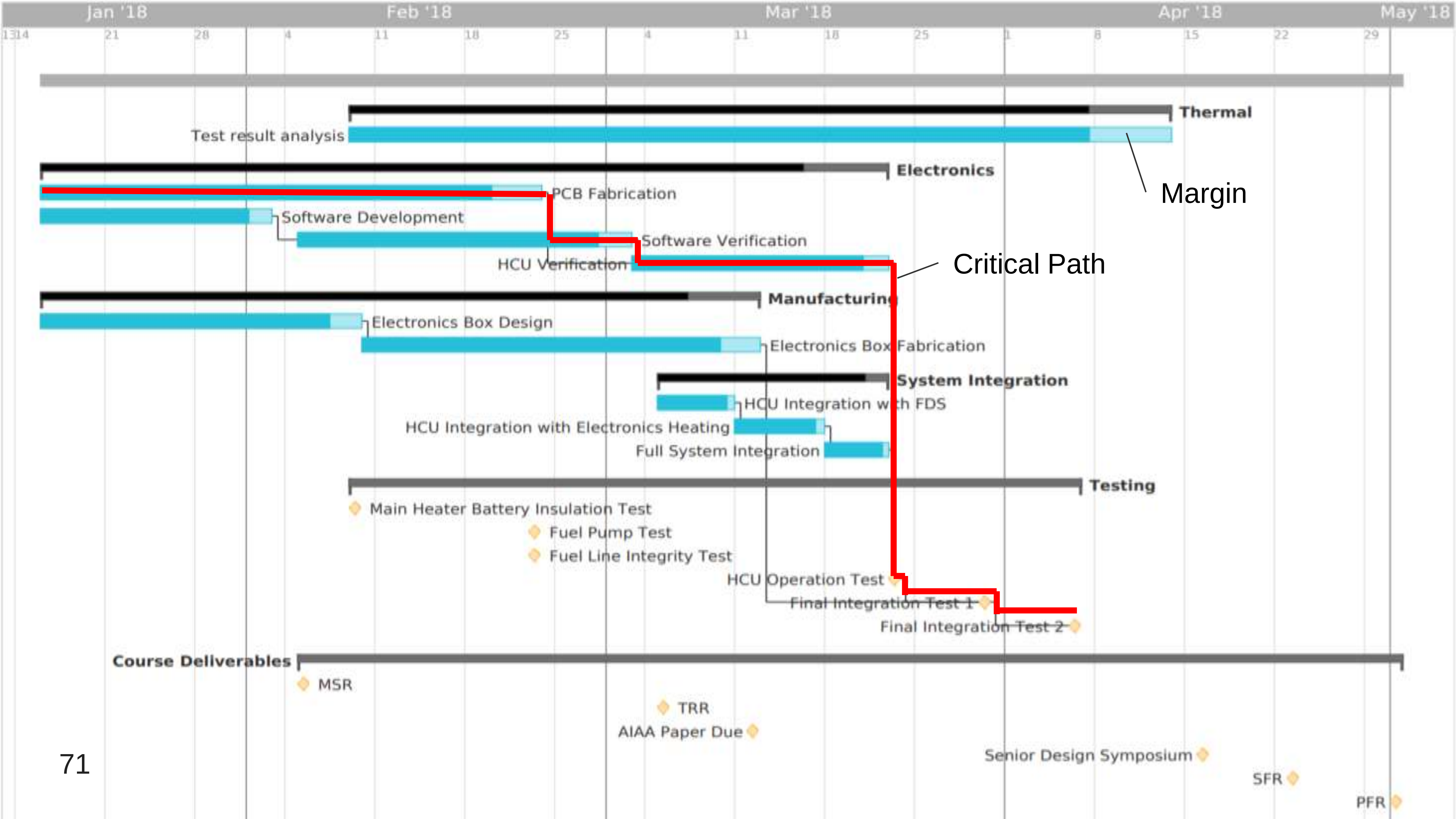
Complete at CDR

ACES

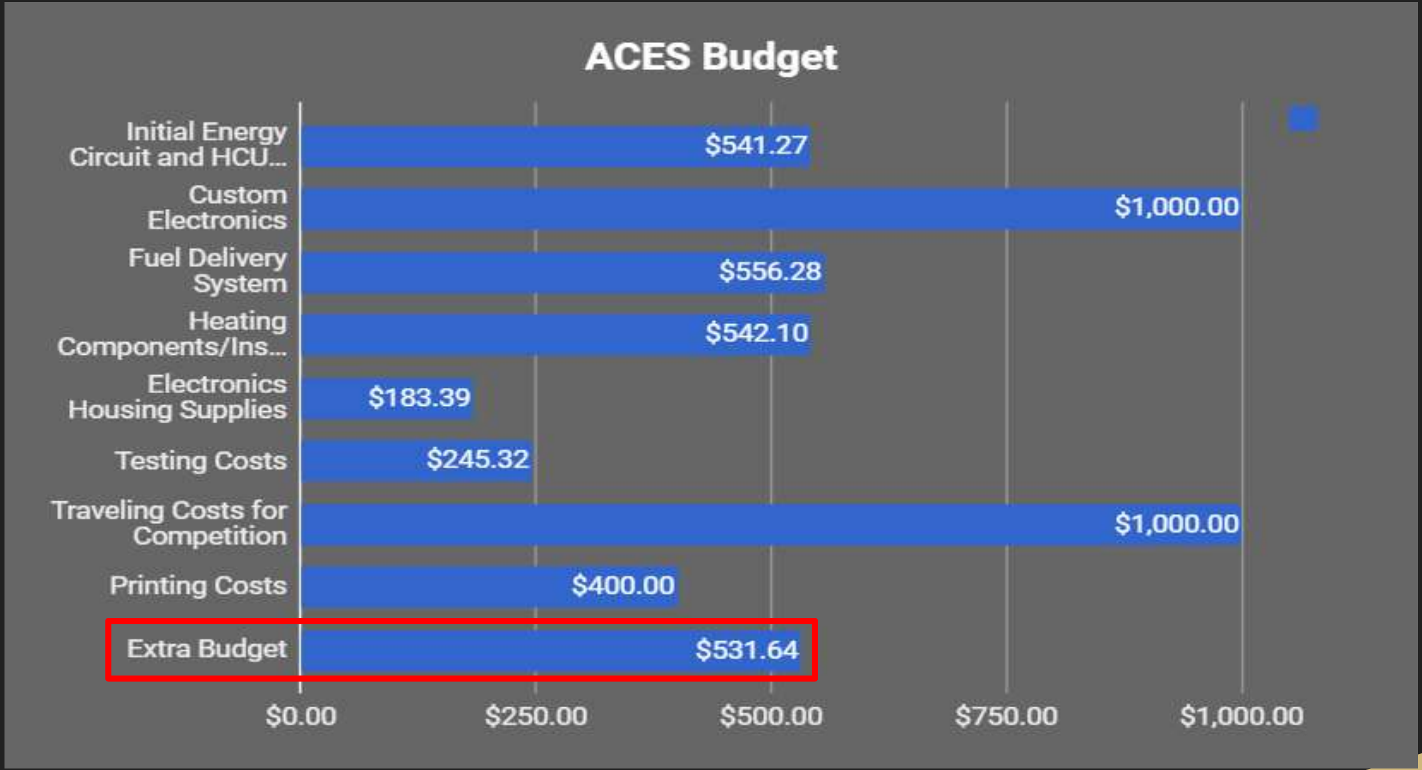
- **Course Deliverables**
  - CDR
  - FFR
  - MSR
  - TRR
  - AIAA Paper
  - SFR
  - PFR
- **Management**
  - Schedule
  - WBS
  - Risk Matrix
  - Budget
  - Spring Logistics
- **Electronics**
  - PCB Design
  - Software Architecture
  - Software Development
  - PCB Fabrication
  - Software Verification
  - HCU Verification
- **Manufacturing**
  - Electronics Box Design
  - Box Fabrication
- **Thermal**
  - 1-D Models
  - Solidworks Models
  - Model Verification
  - Test Result Analysis
- **Testing**
  - Cold Temp Battery
  - Fuel Pump Characterization
  - Main Heater Battery Insulation
  - Fuel Pump
  - Fuel Line Integrity
  - HCU Operation
  - Fuel Flow
  - Final Integration Test
- **Systems Integration**
  - HCU - FDS integration
  - HCU - Electronics Housing Integration
  - Full Systems Integration

Work Plan - Gantt Chart




Jan '18
Feb '18
Mar '18
Apr '18
May '18
13
14
21
28
4
11
18
25
4
11
18
25
1
8
15
22
29
Thermal
Test result analysis
Margin
Electronics
PCB Fabrication
Software Development
Software Verification
HCU Verification
Critical Path
Manufacturing
Electronics Box Design
Electronics Box Fabrication
System Integration
HCU Integration with FDS
HCU Integration with Electronics Heating
Full System Integration
Testing
Main Heater Battery Insulation Test
Fuel Pump Test
Fuel Line Integrity Test
HCU Operation Test
Final Integration Test 1
Final Integration Test 2
Course Deliverables
MSR
TRR
AIAA Paper Due
Senior Design Symposium
SFR
PFR

COST PLAN


ACES Budget
Initial Energy Circuit and HCU...
Custom Electronics
Fuel Delivery System
Heating Components/Ins...
Electronics Housing Supplies
Testing Costs
Traveling Costs for Competition
Printing Costs
Extra Budget
$541.27
$1,000.00
$556.28
$542.10
$183.39
$245.32
$1,000.00
$400.00
$531.64
$0.00
$250.00
$500.00
$750.00
$1,000.00

Testing Schedule and Planning

Test to be Conducted	Applicable Functional Requirements	Date Scheduled	Test Plan Complete	Materials Acquired	Test Complete
HCU Cold Temp Battery	4.1	11/5/2017	Complete	Complete	Complete
Main Heater Battery w/ Insulation	1.0	2/9/2018	Complete	In Progress	Not Started
Fuel Pump Verification	2.1	2/23/2018	Complete	In Progress	Not Started
Fuel Line integrity	2.1	2/23/2018	In Progress	In Progress	Not Started
HCU Operation	4.1, 4.2	3/23/2018	In Progress	In Progress	Not Started
Full Box Integration and Validation 1 and 2	2.1, 2.2, 3.0	3/30/2018 & 4/6/2018	In Progress	Not Started	Not Started

Legend

✓	*Complete*
●	*In Progress*
✗	*Not Started*

Conclusion

CPE 1: Ensure that main heater battery is at or above the operational temperature (30°F), while not exceeding the maximum temperature (122°F). ✓

CPE 2: Heat the engine electronics (ECU, ESB, and engine battery) to their standard operating temperatures (60°F) while not exceeding a maximum temperature of 122°F for the battery and 150°F for the ECU and ESB. ✓

CPE 3: Control the temperature of the fuel lines and hopper and the mass flow rate of the fuel in order to provide fuel for start up procedure of engine. ✓

CPE 4: Construct a Heating Control Unit (HCU) which will control the fuel and electronics heating systems. ✓

- Thermal Modeling shows capacity to meet Level 3 Success
- Heating and Electronics on track to meet Level 3 Success
- Testing analogs prepared to meet Level 3 Success

On Track for Project Success

Acknowledgements

The team would like thank the following people for their assistance in this project.

- Donna Gerren
- Bobby Hodgkinson
- Dale Lawrence
- James Nabity
- Matt Rhode
- Trudy Schwartz
- Lee Huynh
- Timothy Kiley

Questions?

sources

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- Engineering Toolbox, http://www.engineeringtoolbox.com/
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- Polyurethane Tubing, http://ca01.smcworld.com/catalog/New-products-en/mpv/13-e617-tu-x217/data/13-e617-tu-x217.pdf
- Kanthal, https://www.kanthal.com/en/products/material-datasheets/wire/resistance-heating-wire-and-resistance-wire/cuprothal-49-49tc/
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Backup Slides

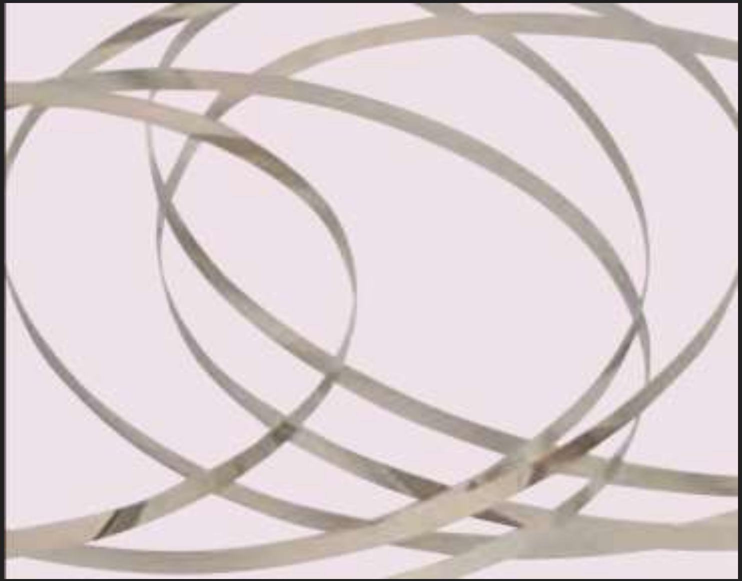
INDEX

Presentation:

Backup:

Resistance Heating Wire

- Omega Resistance Heating Ribbon Wire
- NCCR-34-100
- ⅛” width, .0056” thickness, 100 ft length
- .88 Ω/ft
- Chosen using matlab code for heat production vs. wire model with ⅛” gaps between wire on elements.
- Code also accounted for temperature vs. current to ensure safe temperature levels



Heating Wire Analysis

- Total heating wire length for ⅛” width & ⅛” gaps was determined using surface area of components.
- Total resistance was determined using the resistance-per-foot value of .88Ω/ft and wire lengths
- A set voltage of 22.2 V was used to find current and power

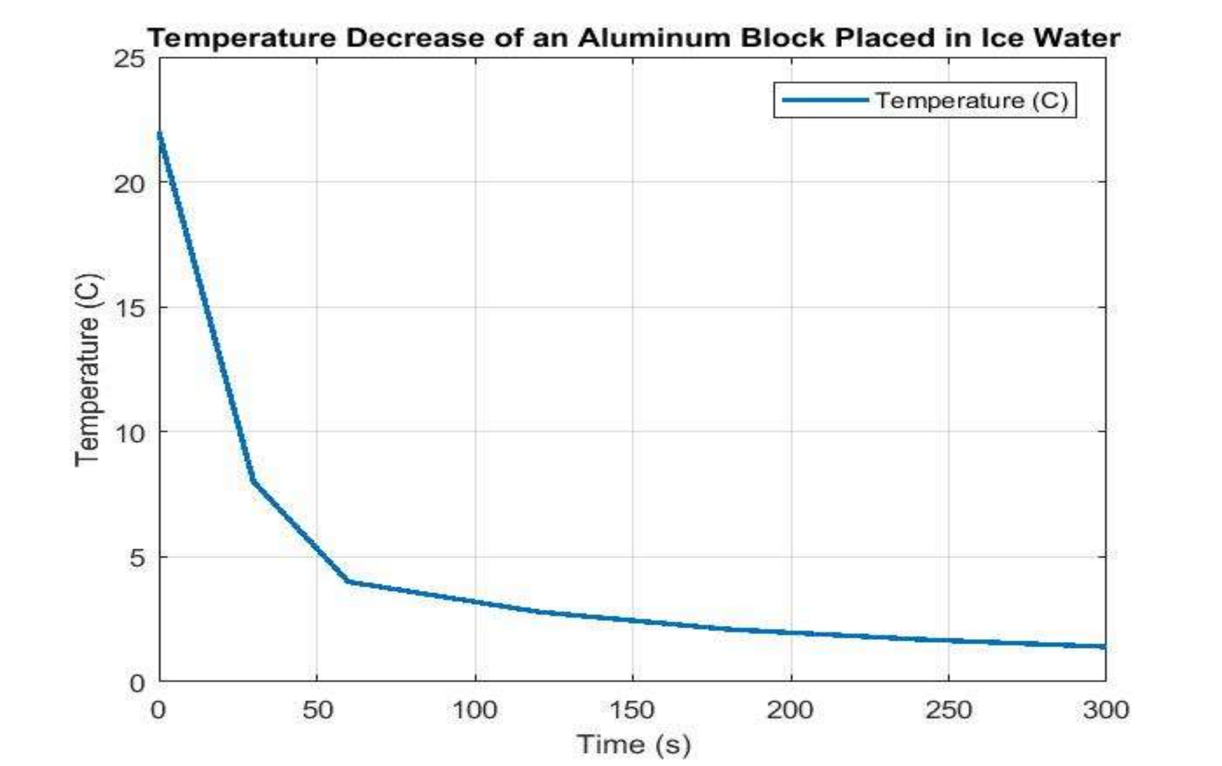
	Wire Length [ft]	Total Resistance [Ω]	Current [A]	Power [W]
Fuel Lines	6.824 ft	6.005 Ω	3.697	82.07
Fuel Hopper	14.157 ft	12.458 Ω	1.782	39.56

Temperature vs. Current data was only available for 1/64”, 1/32”, and 1/16”wire widths. However, at the 22.2 V, the temperature of these wires never reached problematic levels. Therefore, excess temperature was not a major concern.

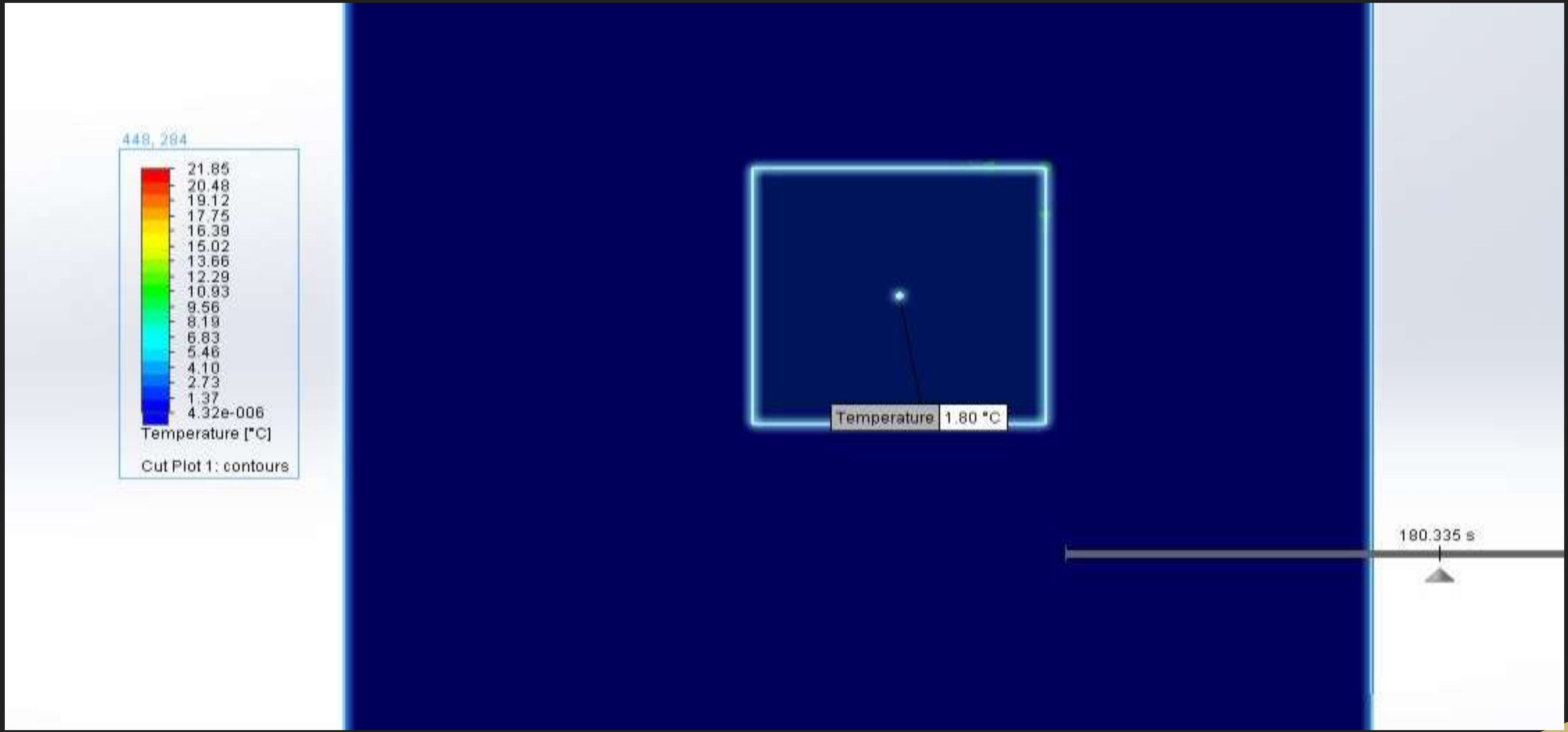
Thermal Model Verification

Aluminum Block Test

- Block Initial Temperature: 22.0 C
- Water Initial Temperature: 0.0 C
- Test Time: 5 minutes

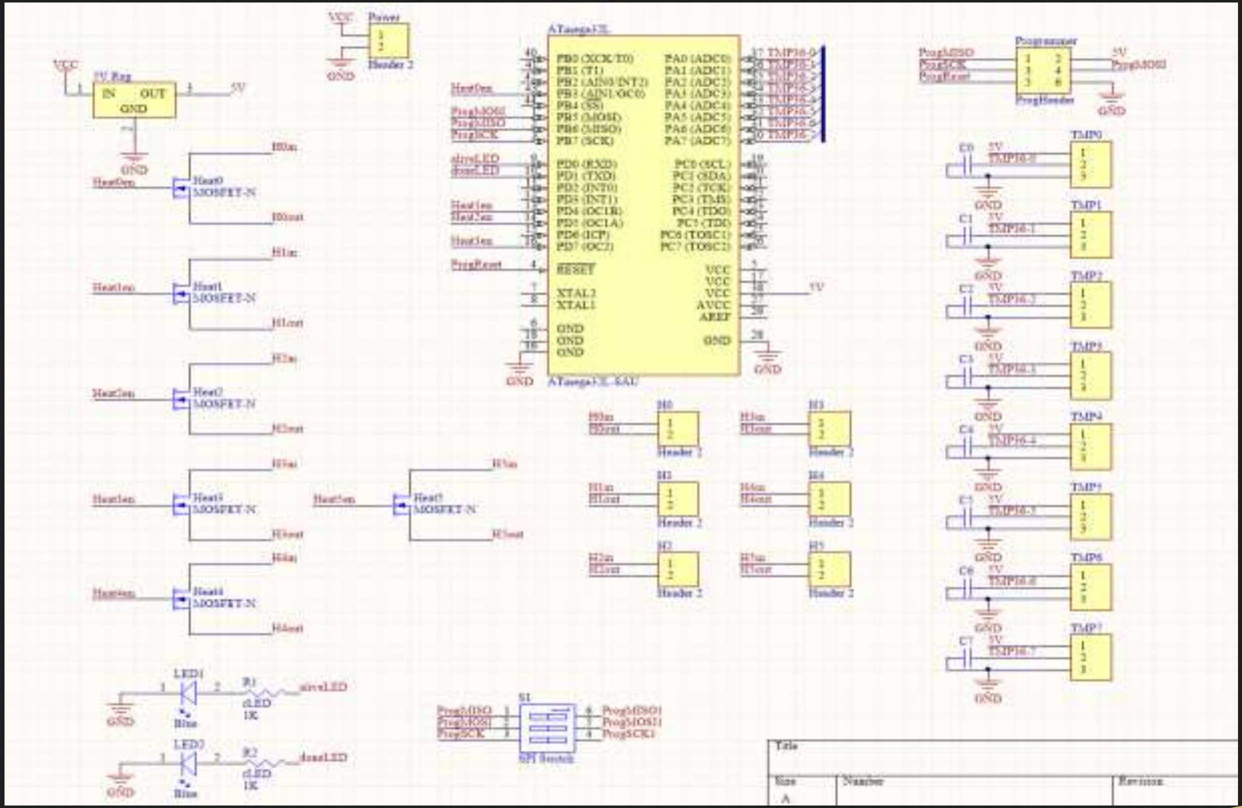


Aluminum Block SolidWorks Model

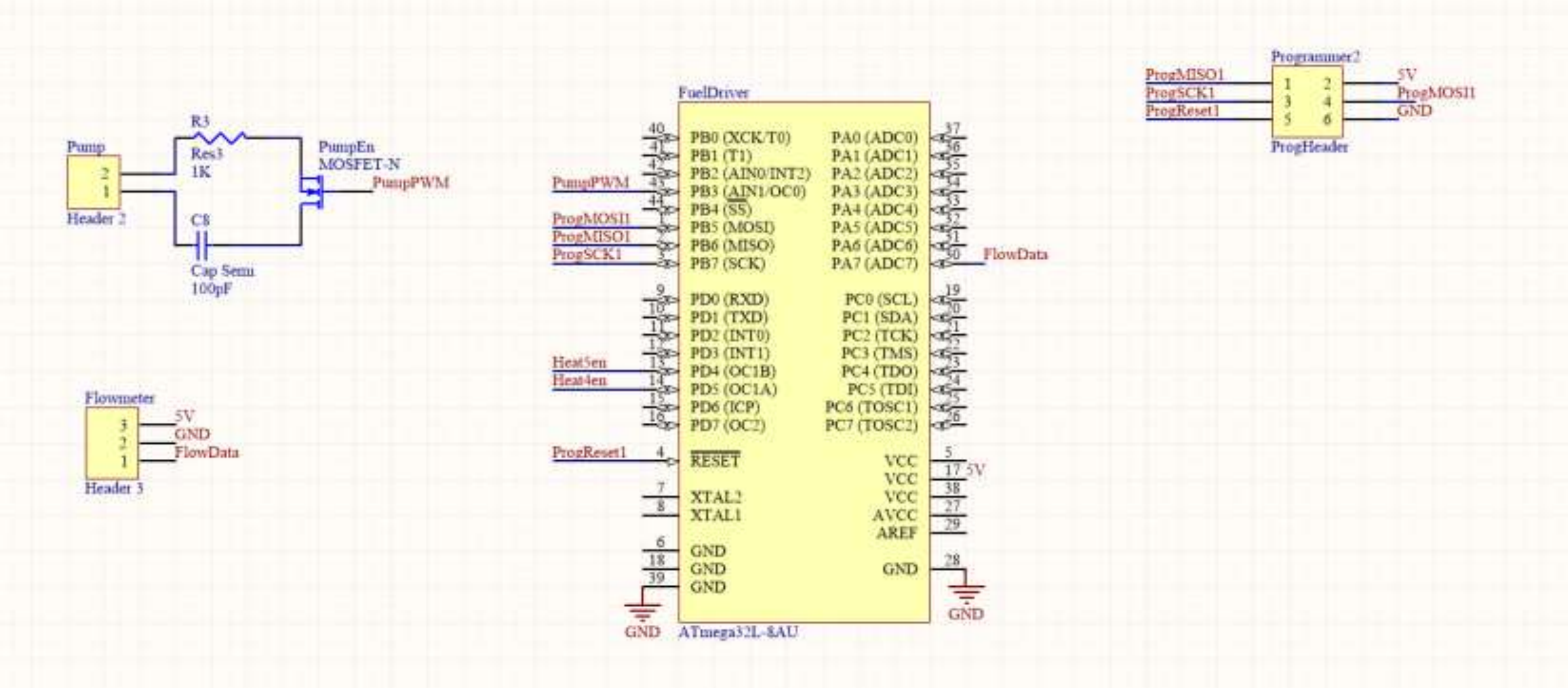


HCU
Backup Slides

HCU Altium Schematic

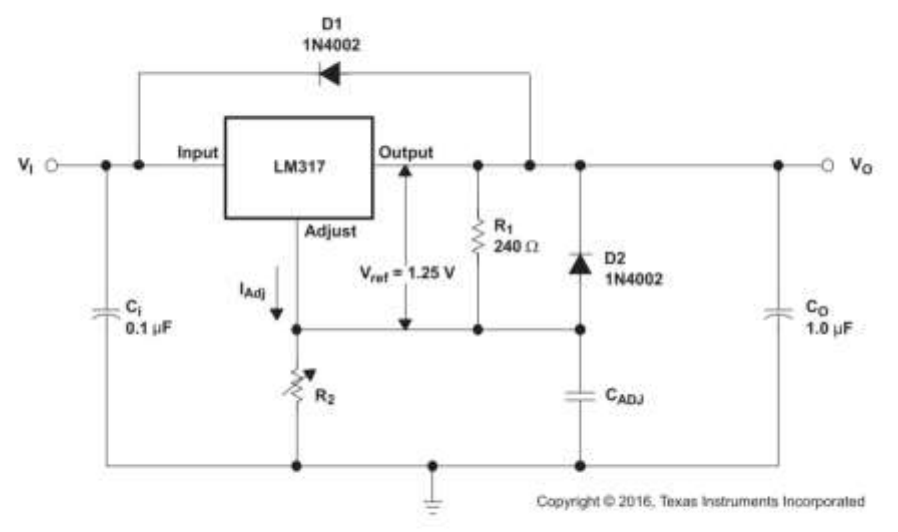


HCU Altium Schematic



LM317 Voltage Regulator

- Adjustable Voltage Regulator capable of regulating output voltage between 1.25V and 32V at greater than 1.5A
- Drops PWM voltage from LiPo Batteries from 22.2V to 6V for fuel pump
- Relevant Equations: V0 = Vref
    - V0 = Vref*(1+R2/R1) + (Iadj*R2)
- Including Copper Heat Sink to prevent overheating



Initial Energy Backup Slides

Cryogel Insulation

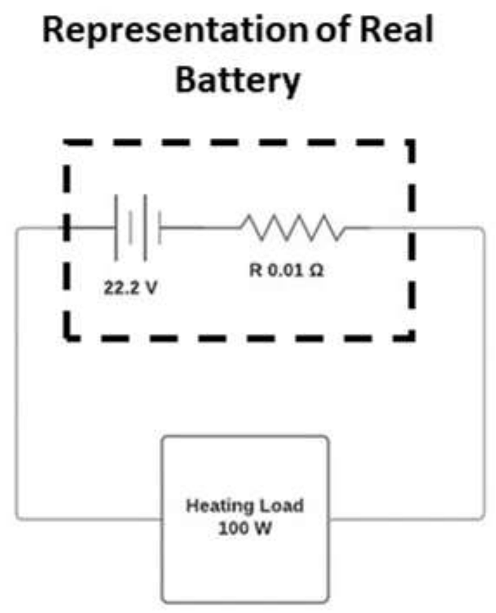
- Produced by Aspen Aerogels
- Uses Aerogel, a lightweight solid derived from a silica gel
- k=0.015 W/m*K
- ρ=160 kg/m^3
- 10mm thickness
- Designed for low temperature applications

Internal Resistance of Battery

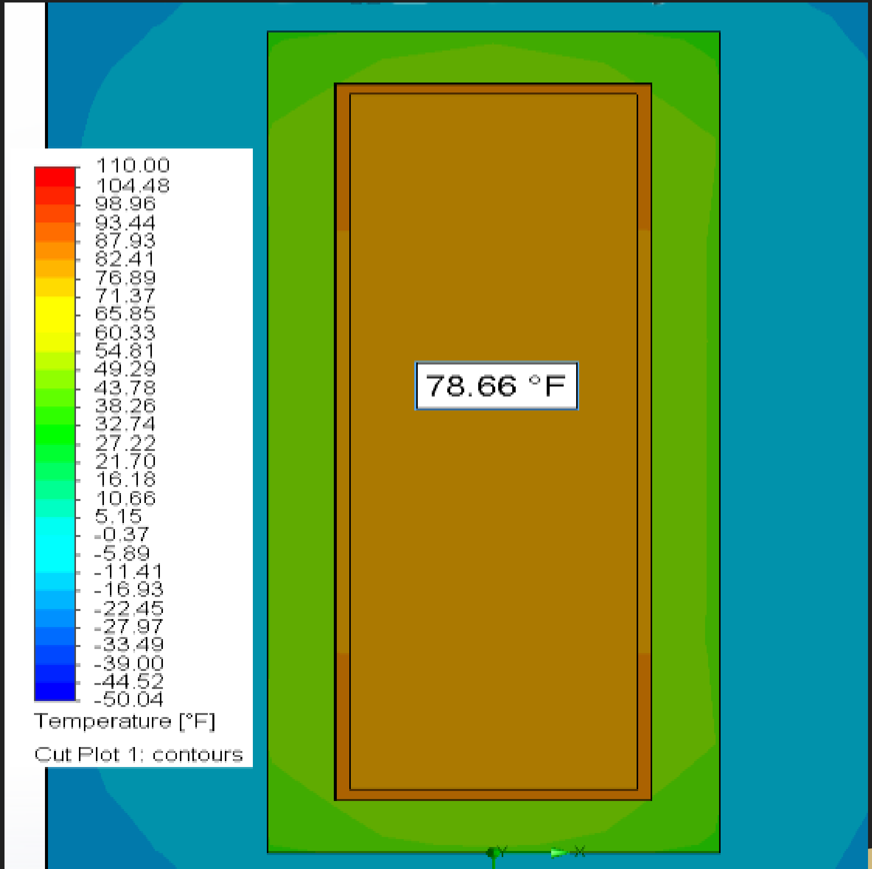
- Resistance for the heating load is 5.1076 Ω (assumes 22.2 V voltage drop across load)
- Voltage drop across internal resistive load is 0.04416 V
- Power dissipated by internal resistive load is 0.195 W
- The battery simulation was allowed to progress for 30 min with heat generation.

$$P = \frac{V^2}{R}$$

$$V_1 = \frac{R_1 V_{in}}{R_1 + R_2}$$



Internal Resistance of Battery



RC Circuit Equations

- Battery heat transfer

$$\dot{Q}_{in} = mc_p \Delta T$$
$$q_{in} = mc_p \Delta T dt$$

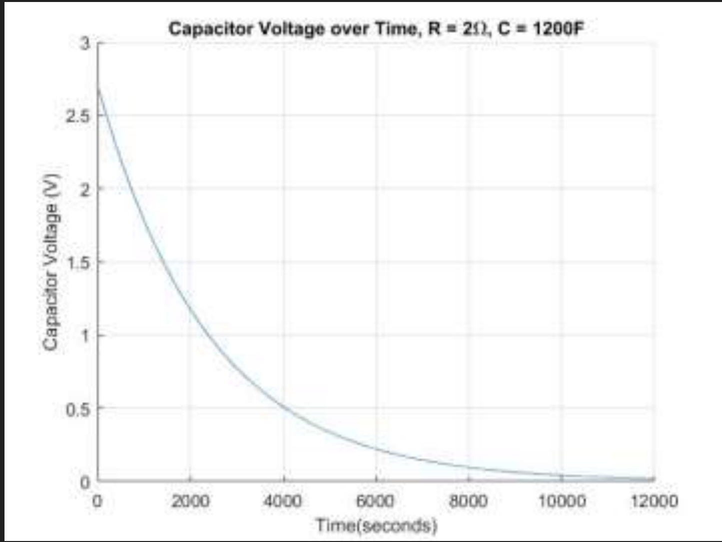
$$\dot{Q}_{in} = power\ in\ (W\ or\ J/s)$$
$$q_{in} = energy\ in\ (J)$$
$$m = mass(kg)$$
$$c_p = coefficient\ of\ temperature\ \left({}^{J}/_{kgK}\right)$$
$$\Delta T = change\ in\ temperature\ (K)$$
$$dt = change\ in\ time\ (s)$$

Management of Supercapacitors

1. The team will never charge the capacitor with higher voltage than 2.7 V.

1. The team will never handle a charged capacitor without proper safety equipment
   a. Thermal and electrical insulation will need to be worn.

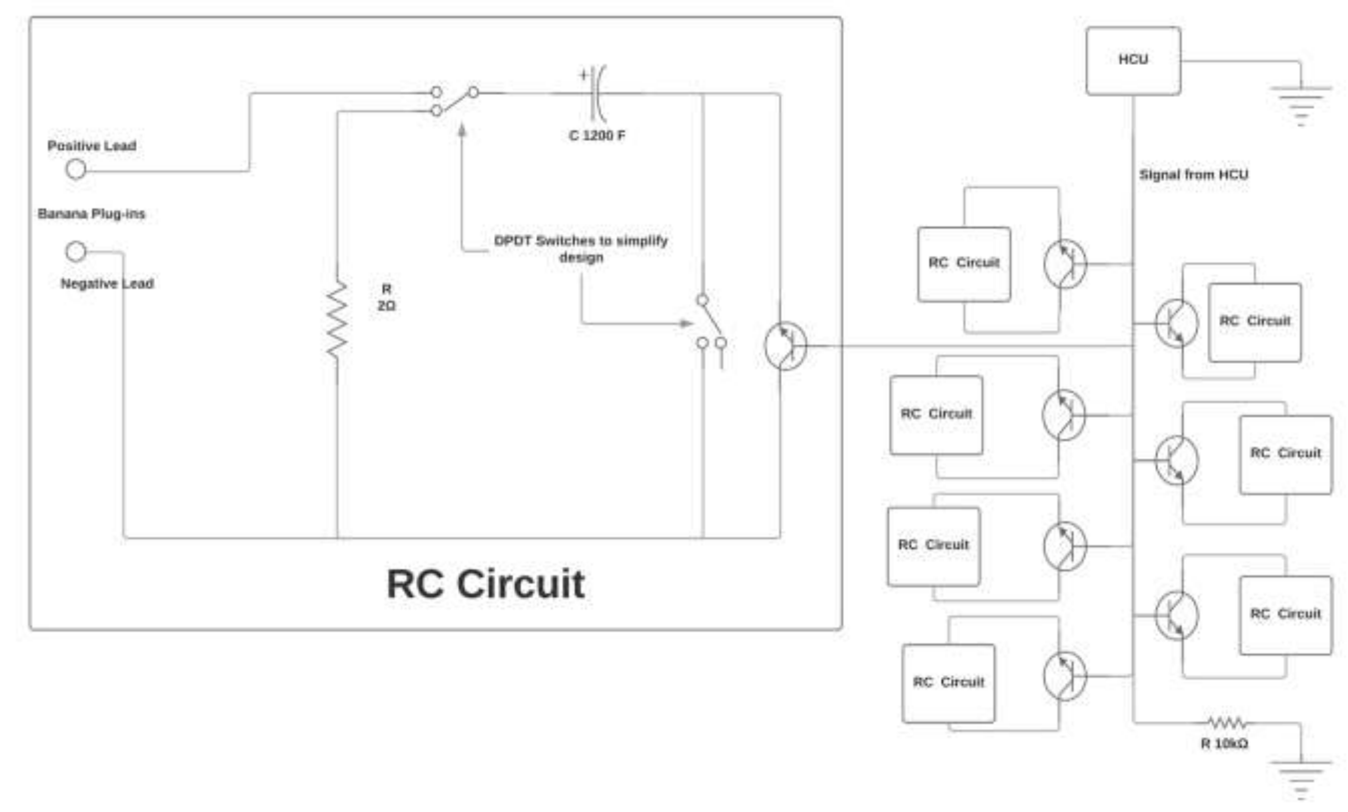
1. Capacitors retain voltage for a long time after disconnected from circuit
   a. Our capacitor will take 3 hours to fully discharge



Initial Energy Requirements

- To heat batteries at a safe temperature takes 8 minutes
- In the 8 minute heating window, each circuit releases 1,442J, at an **average 3W**
  - 8 circuits will provide 24W
  - Peak wattage per RC circuit will be 3.65W

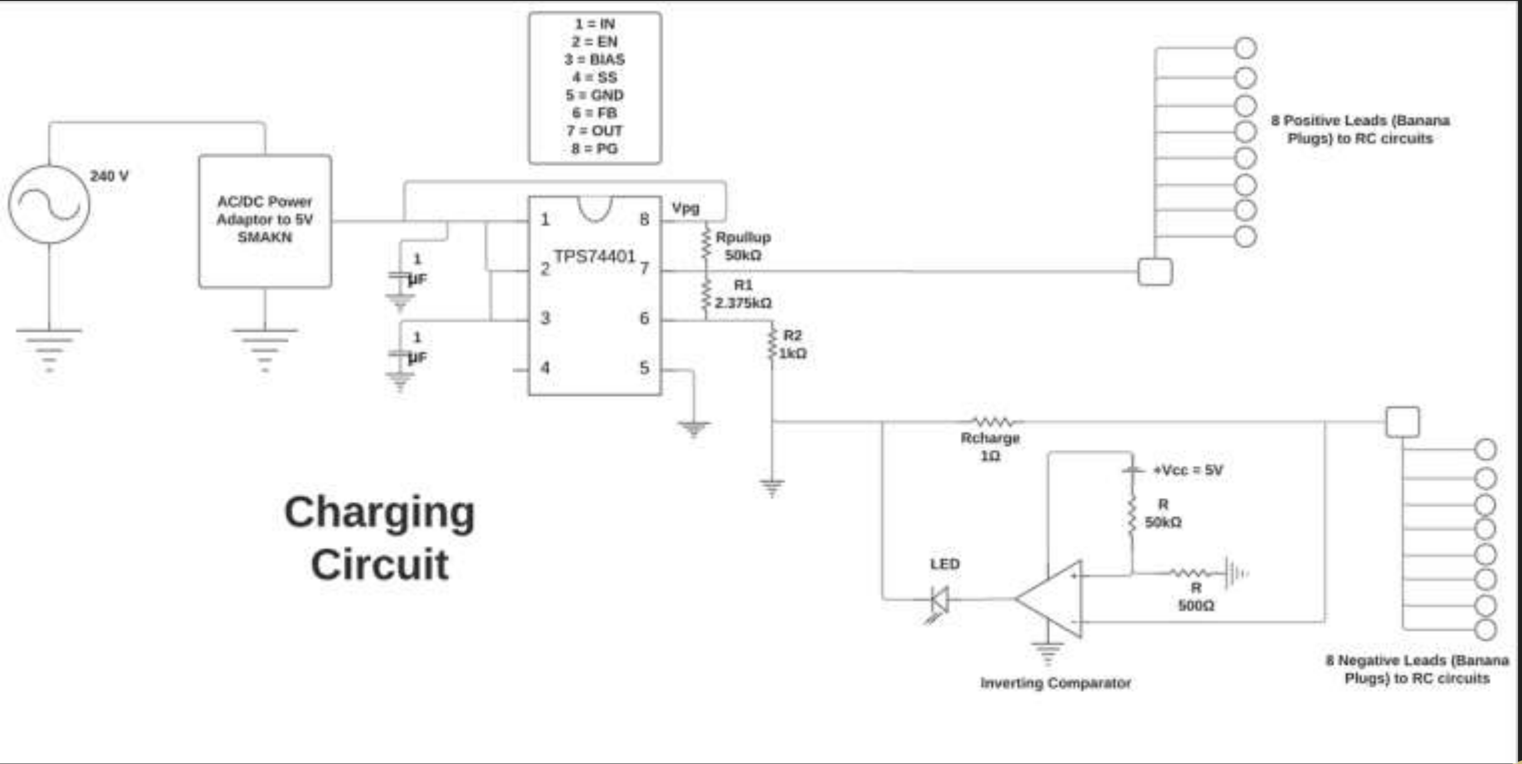
Initial Energy Circuit Design



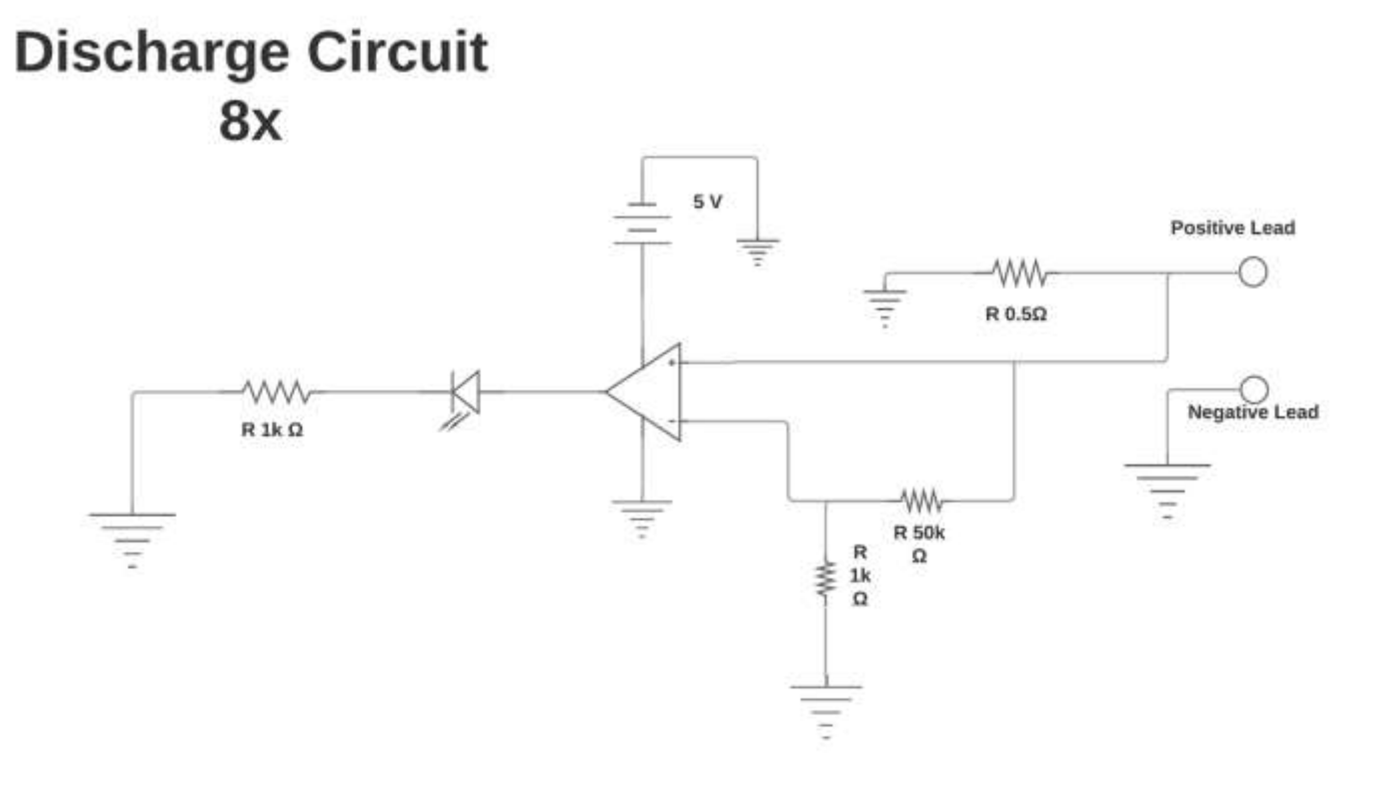
Initial Energy Charging/Discharging

- Charging
  - RC Circuit will be charged via wall outlet
  - Single charging circuit for all 8 RC Circuits
  - DPDT switch for each RC circuit
    - Shift between charging and heating
  - LED to signify capacitor is charging
- Discharging
  - Grounding terminals from RC circuits
  - Comparator with LED set to turn off when voltage falls below 0.025V

Initial Energy Charging Circuit



Initial Energy Discharge Circuit



Initial Energy RC Components

- SMAKN ACDC Power Adapter
- N-Channel MOSFET 60V 30A
- GTCAP Cold Starting Supercapacitor 2.7V 1200F
- 1 Ohm Resistor Wire Wound 5% Tolerance
- Taiyo Yuden Resistors
- Taiyo Yuden Capacitors
- TPS74401 Regulator
- 4 DPDT Heavy Duty Toggle Switches
- LEDs
- Texas Instruments Comparator

Risk of Supercapacitors

- Never charge a capacitor pasts its rated voltage.

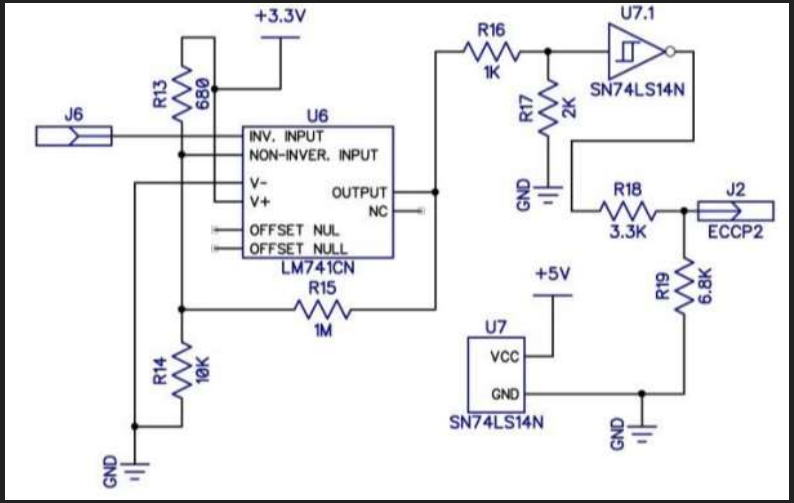
- Shorting a capacitor will create a large amount of heat
  - Can burn wire leads and fry other components
  - Potential injury to personnel

- Capacitors retain voltage for a long time after disconnected from circuit
  - From hours up to days

ECU
Backup Slides

ECU Heritage

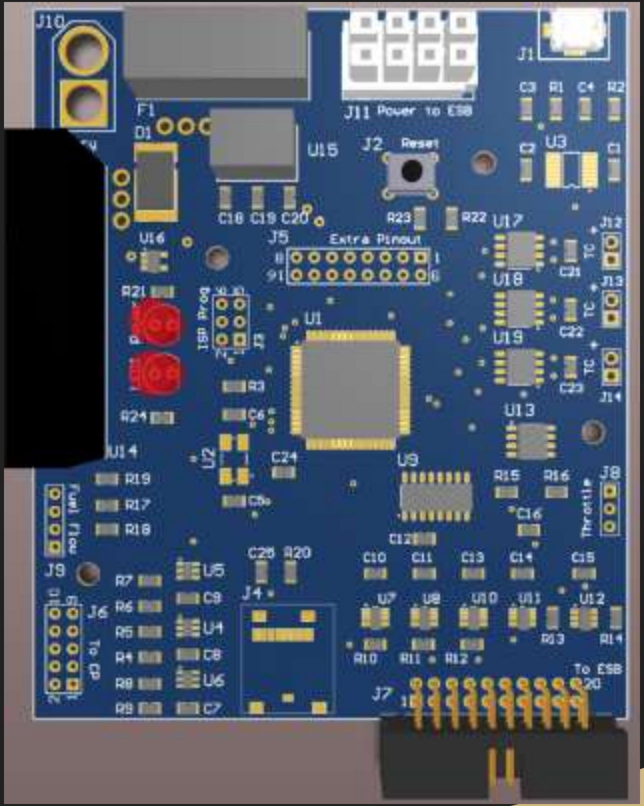
- Custom ECU design provided by REAPER
  - Hall Effect Sensor issues
    - Mitigated by Andrew Quinn
      - Schmitt Trigger
  - Schematics available to team



Reaper ECU

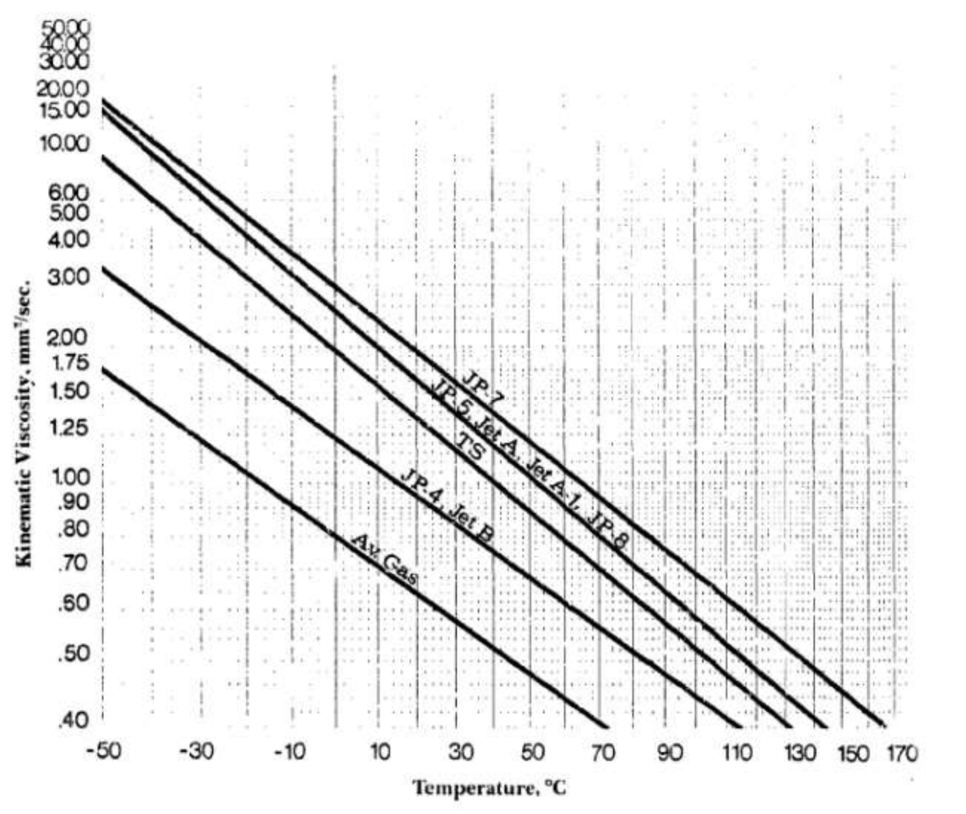
<u>Components:</u>

- Atmega256A3-AU
- RS422 Recieiver/Transmitter
- FT230x USB-UART
- SD Card Holder
- NC7WZ17P6X Dual Buffers
- CMX60D20 Relay
- LT1761 Micropower Regulator
- CMOS Comparator
- PM05S Series Switching Regulator
- MAX31855KASA+ Thermocouple Driver
- Fuel Flow Sensor
- WE-2 Box Header
- 2SMX Oscillator
- LED's
- COM-00097Push Button Reset
- ISP Programmer Header
- MicroUSB Header
- Multiple Resistors, Capacitors, Diodes



Fuel Delivery System Backup Slides

Jet Fuel Viscosity vs Temperature



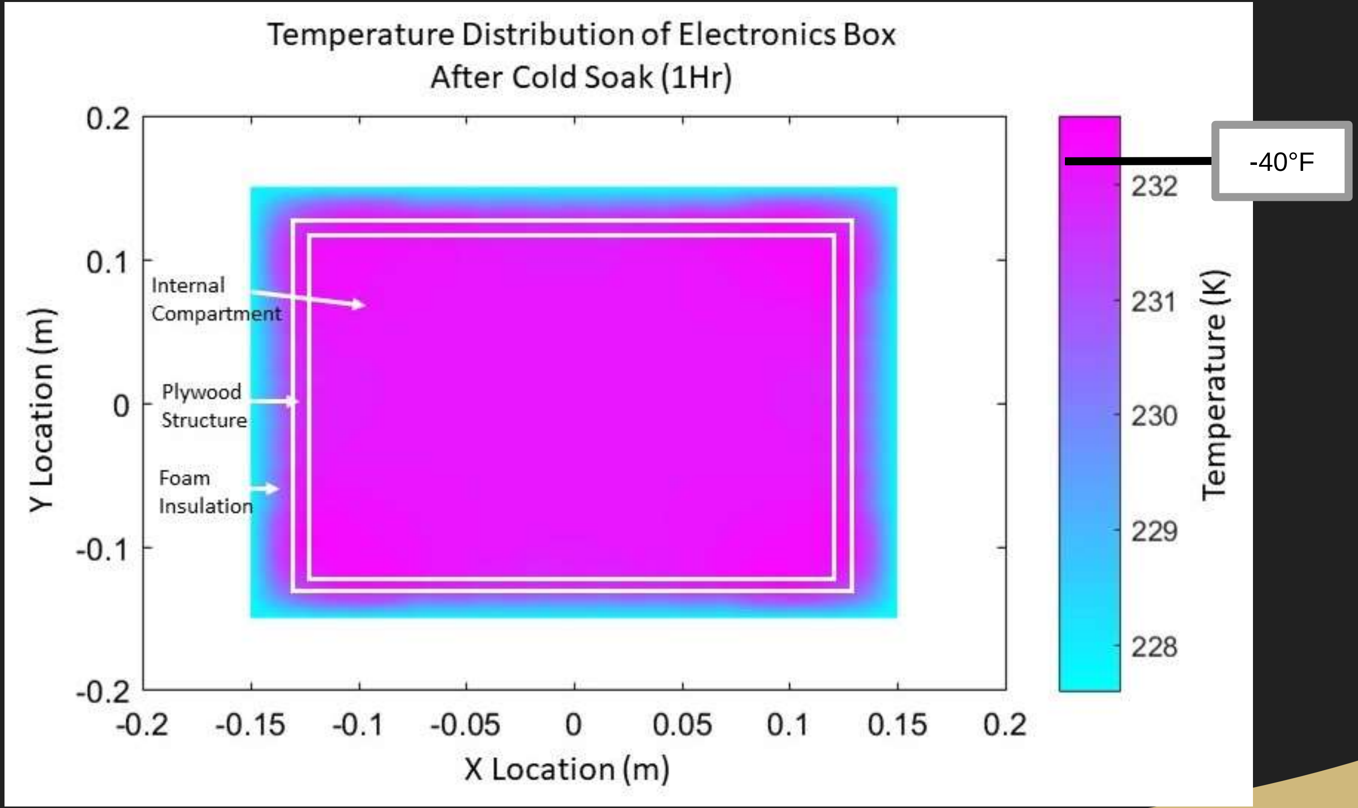
FEM Setup Slides

SOLIDWORKS Parameters

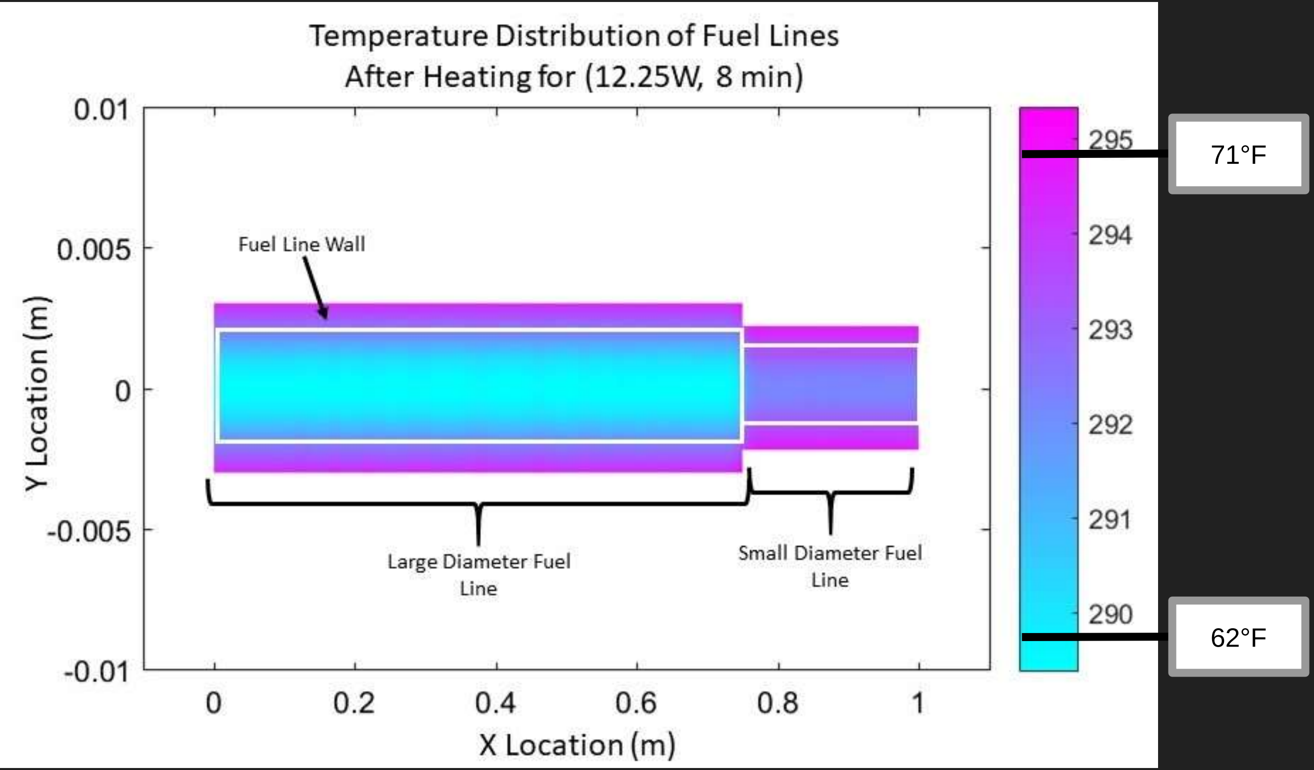
Material Properties			
Material	**Nickel Chromium**	**Aerogel**	**Lithium Polymer**
Density (kg/m^3)	8400	160	2109.4
Specific Heat (J/kg*k)	450	2000	795
Thermal Conductivity (W/m*k)	11.3	0.015	73.98

Transient Model Backup Slides

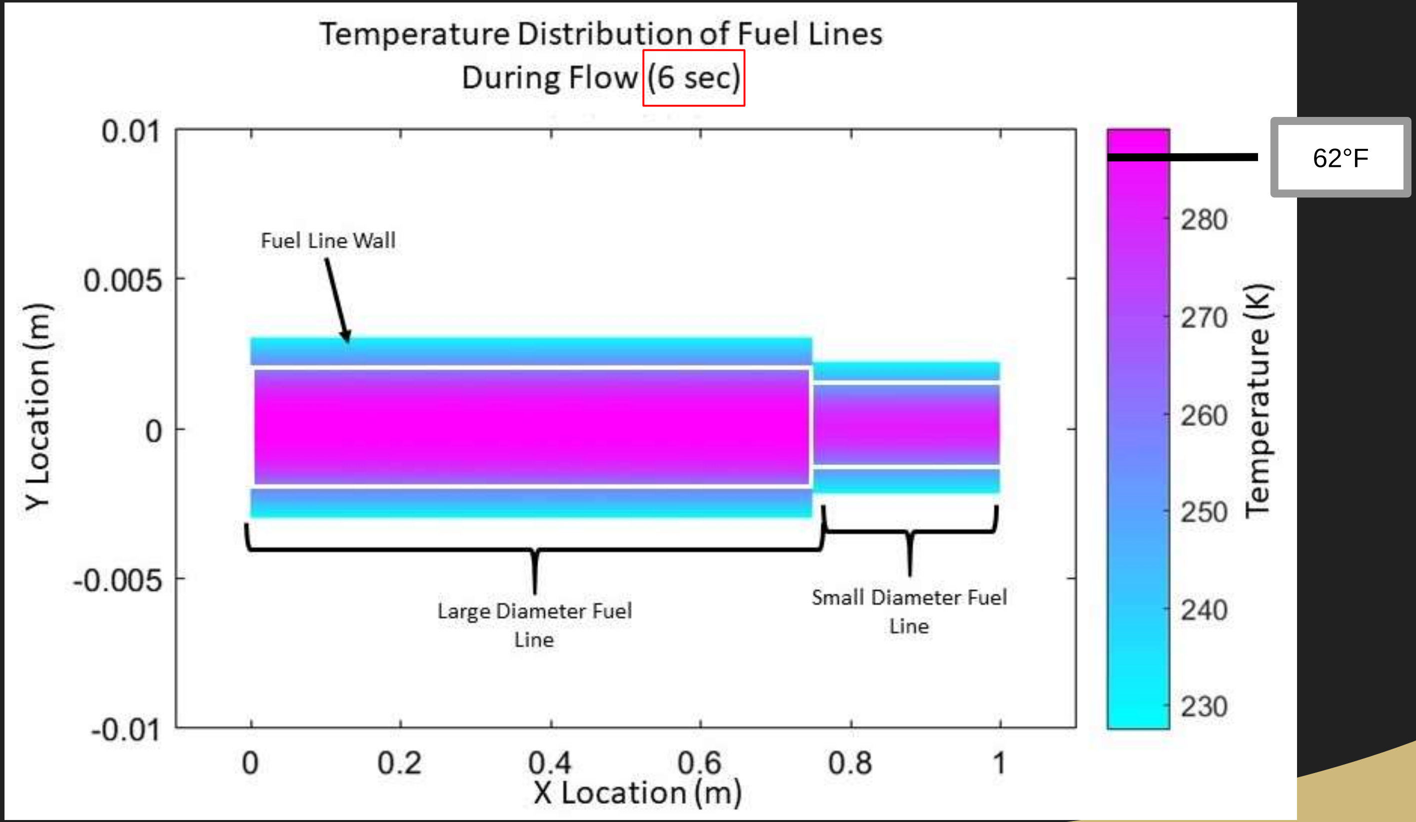
Cooling of Electronics Box



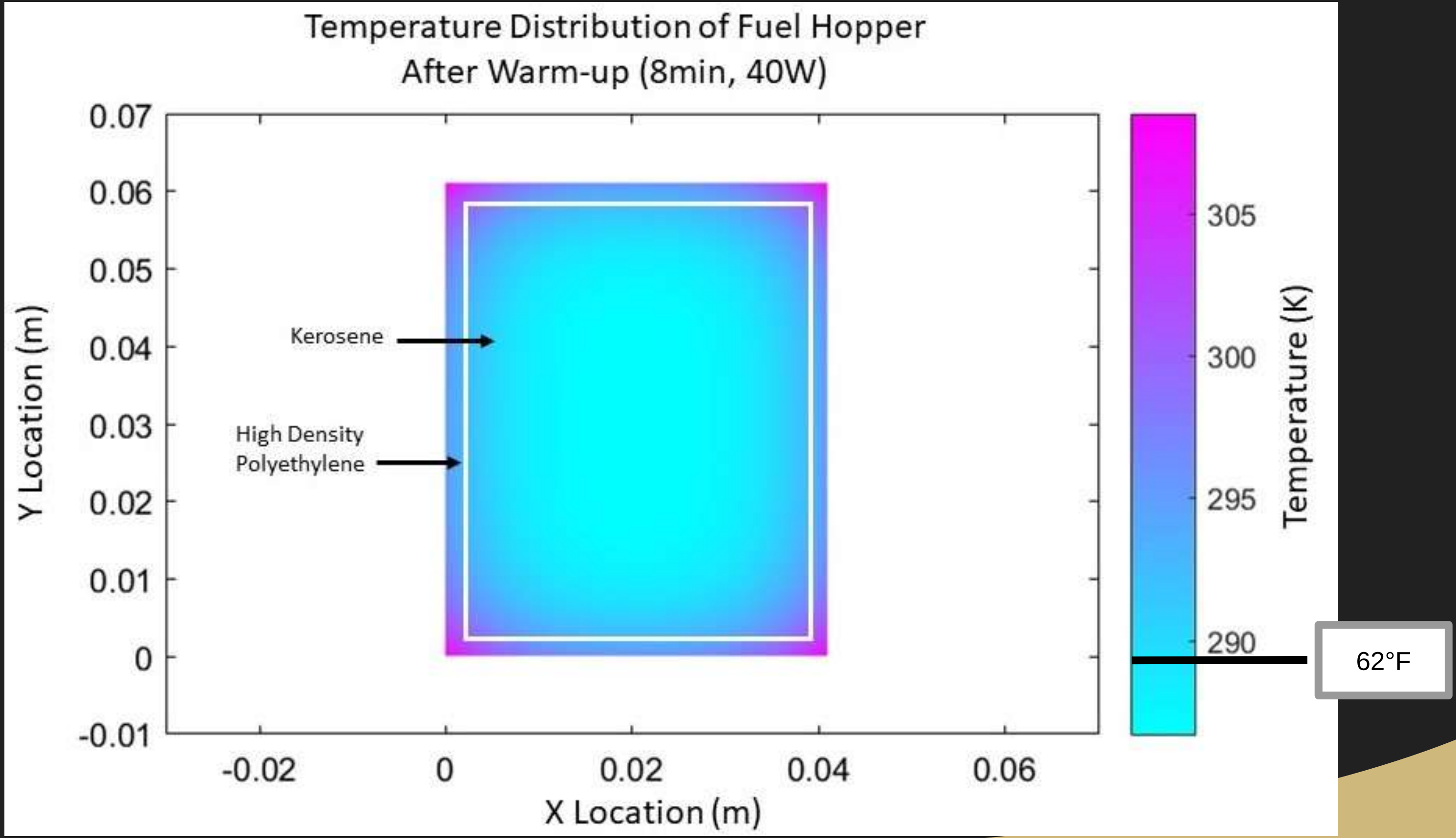
Fuel Line Heating Feasibility



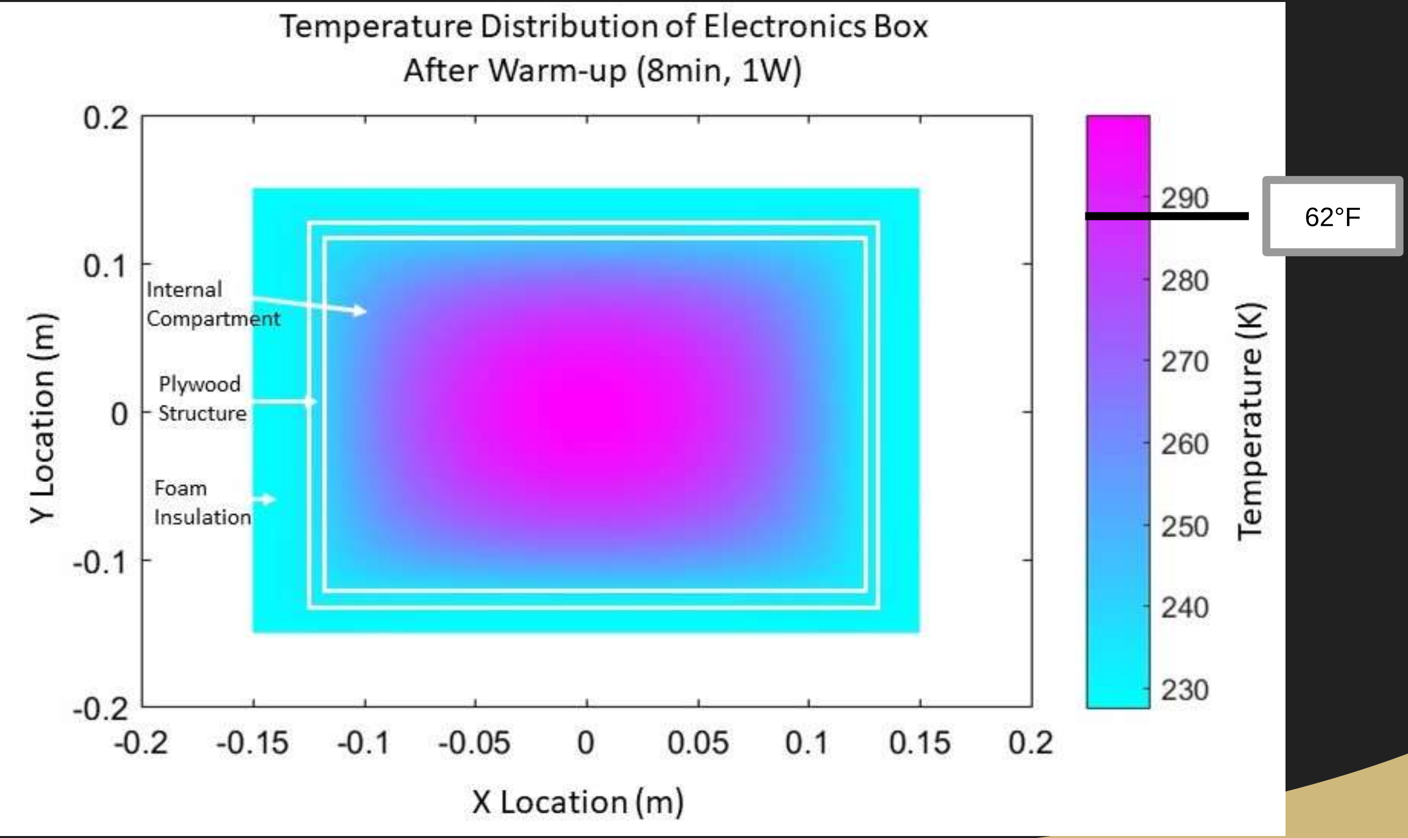
Fuel Line Heating Feasibility



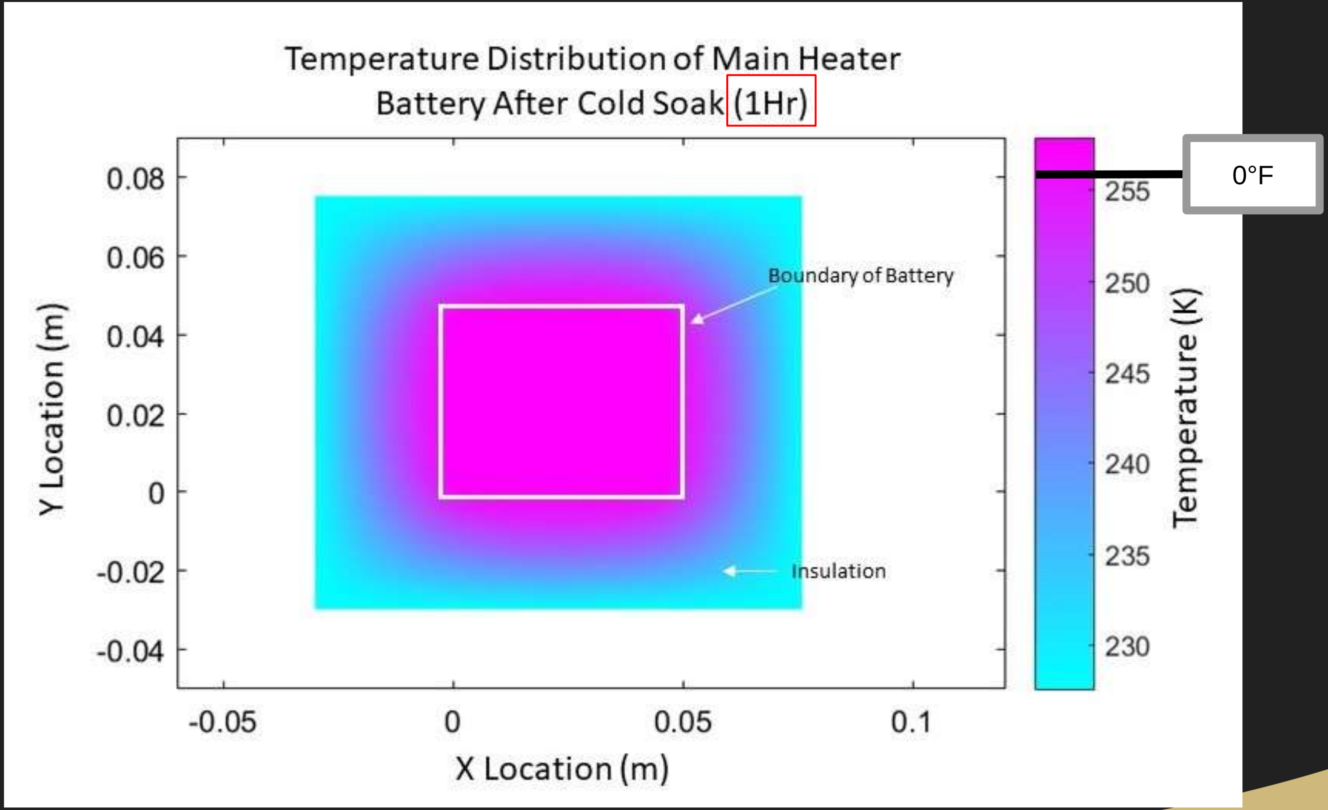
Fuel Hopper Heating Analysis



Transient Electronics Heating



Main Heater Battery Feasibility



Verification and Validation Backup Slides

Summary of Test Process

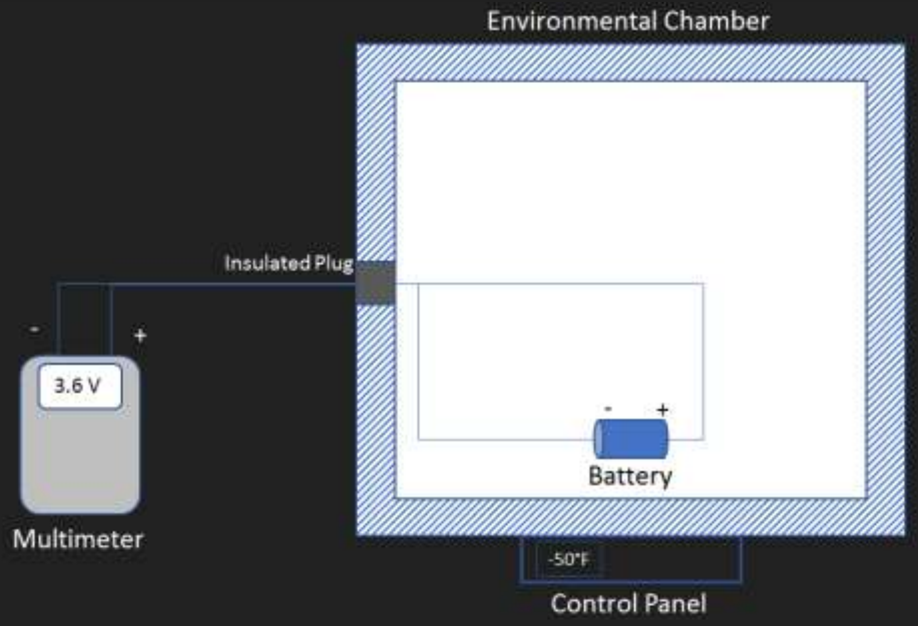
Creation of Test and Safety Plan → Review of Test and Safety Plan with PAB → Test Setup and Operations Coordination → Test Execution and Data Collection

Summary of Previous Tests

Cold Battery Environmental Chamber Test

Objectives:

- Verify that the cold temperature battery can provide voltage required to power the HCU in cold soak conditions
- Confirm that the test process outlined earlier provides the planning, preparation, and coordination needed for subsequent tests
- Prove the validity of the environmental chamber as a viable test bed for future project elements



Summary of Previous Tests

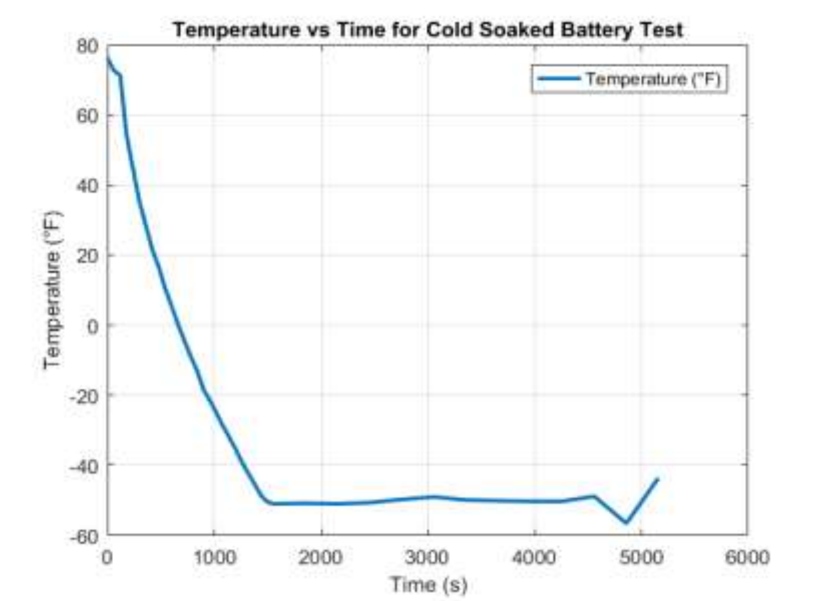
Cold Battery Environmental Chamber Test

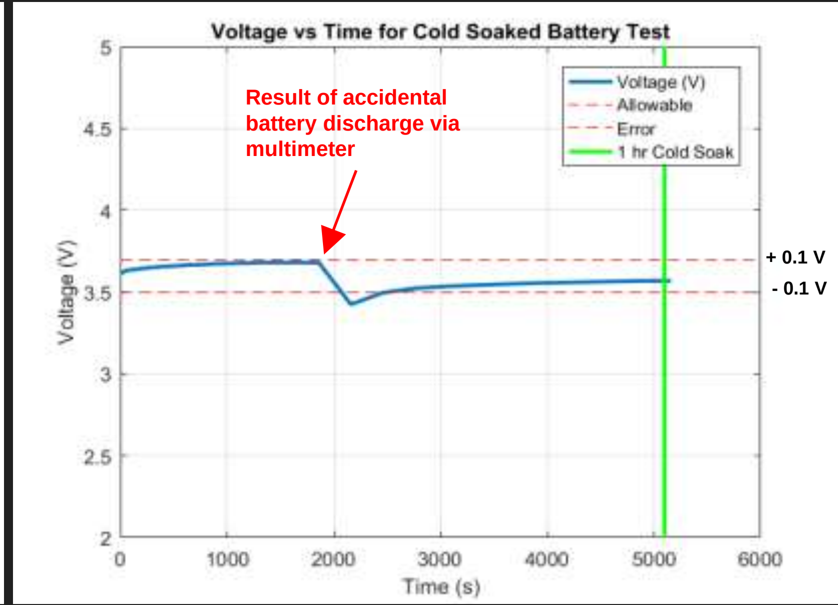
Results:

- The cold temperature battery was shown to provide its nominal voltage (±0.1V) after being cold soaked at -50°F
- Demonstrated near identical (±5%) voltage and current draw on small motor when compared with power supply
- **Full results shown in following slide**

Summary of Previous Tests

Cold Battery Environmental Chamber Test

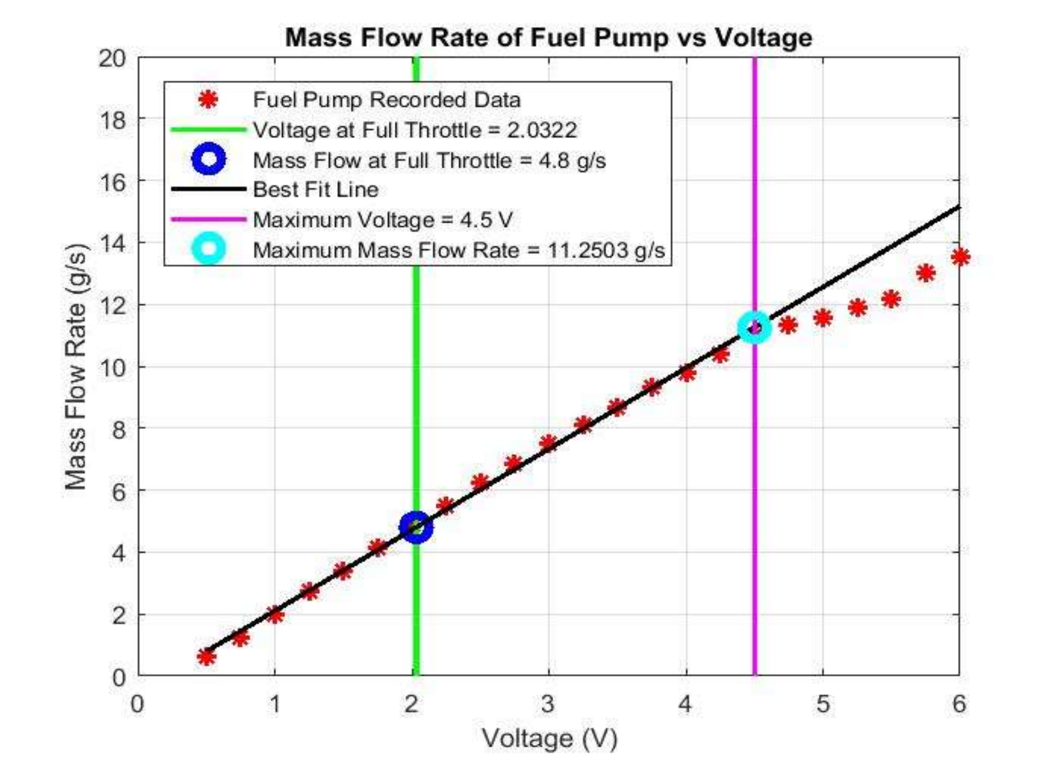




Summary of Previous Tests

Measuring Mass Flow Rate with Voltage Inputs

- Determined relationship between input voltage and mass flow produced by pump
  - **Relationship is Linear**
- Linear Regression used to determine error in mass flow
  - **Error calculated: +/- 0.13 g/s**
- Determined upper bound for input voltage based on increased deviations from Linear Regression
  - **Upper voltage limit is 4.5 V**

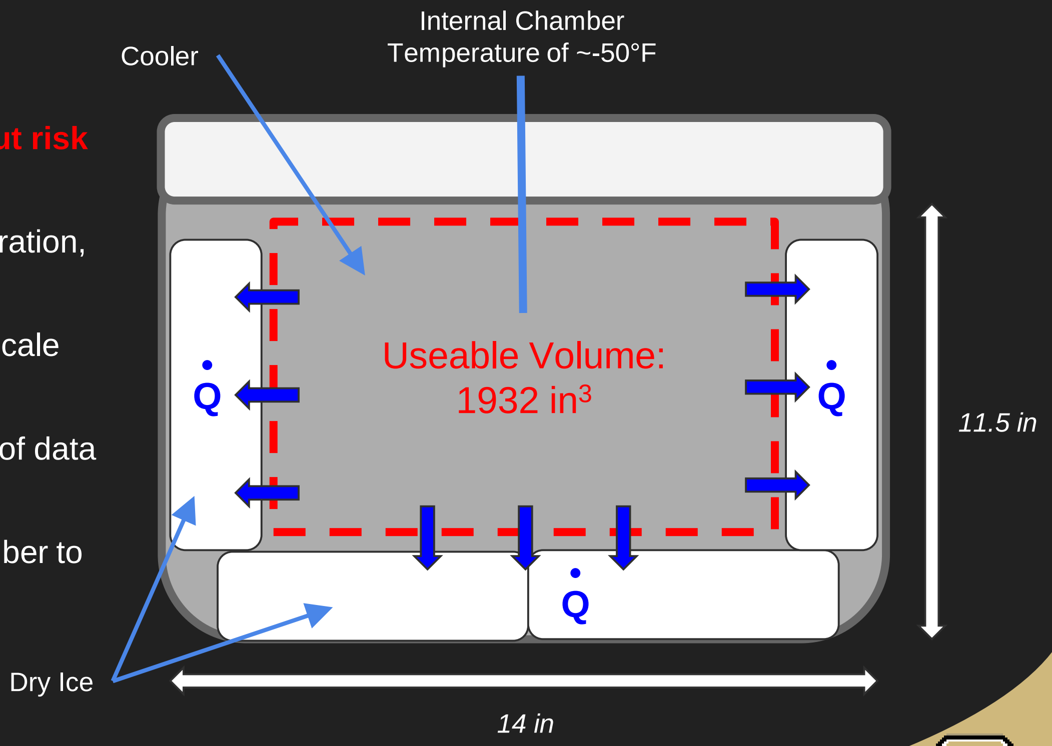


Dry Ice Test Bed

Overview of Testbed:

- Ability to run fuel delivery system **tests without risk of damaging expensive test equipment**
- Applicable tests: Fuel lines integrity, HCU operation, Full box integration and validation
- **Usable volume >> volume required** for full scale electronics box
- Ability to accommodate required **8 channels** of data transmission
- **~½ Block of dry ice necessary** for test chamber to reach -50°F

Standard Block of Dry Ice: 10x10x2 in



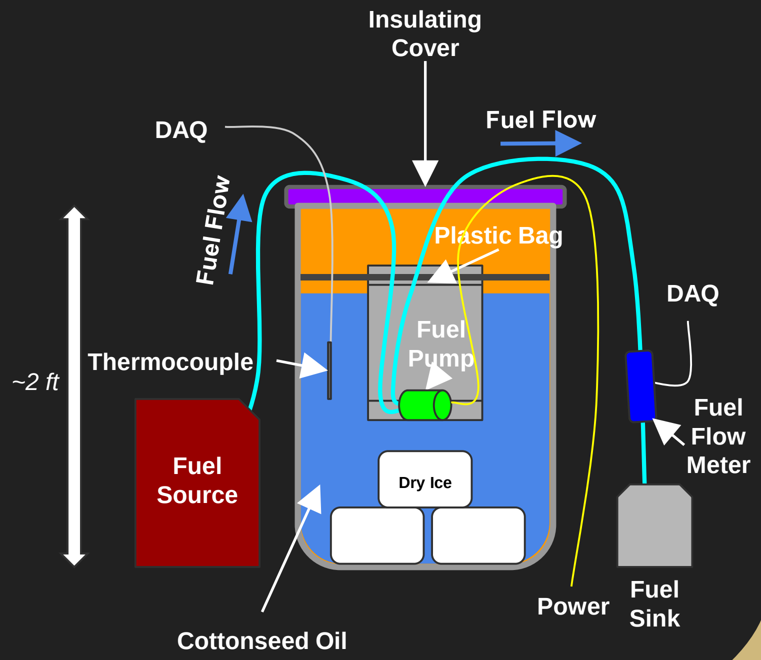
Fuel Pump/Fuel Line Test

Objective:

- *Determine the minimum operational temperature of the stock JetCat fuel pump*
- *Verify that the integrity of the fuel lines can be maintained in the cold soak conditions*

Test Overview:

- Cottonseed Oil: non-flammable, cost effective, readily available, freezing point of -55°F, **faster more uniform heat transfer**
- Ability to slowly lower the environment temperature while motoring component temperature and fuel mass flow rate



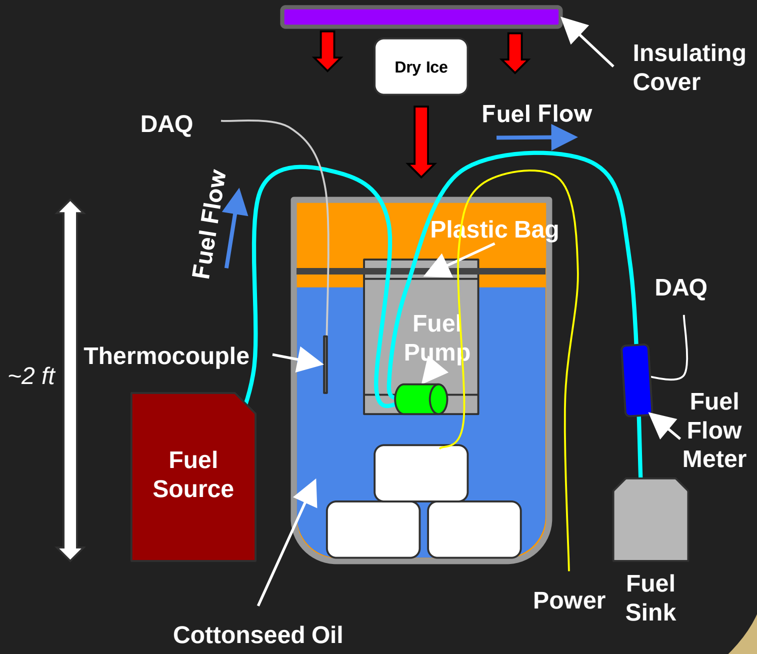
Fuel Pump Test

Objective:

- *Determine the if the minimum operational temperature of the stock JetCat fuel pump is above -50°F.*

Test Overview:

- Submerge the fuel pump in the cottonseed oil bucket at room temperature and begin to pump fuel
- Insert dry ice blocks into bucket to lower the temperature of the fluid
- Monitor fluid temperature and fuel flow rate until the flow meter registers a flow rate outside desired **4.8 ± 0.1 g/s**
- Assuming 2.5 gallons of cottonseed oil (freezing temp of -55°F), approximately 39.1 lbs or **4 blocks of dry ice is needed** to lower the temperature of the oil to -50°F
- Required **bucket volume of ~6 gallons**



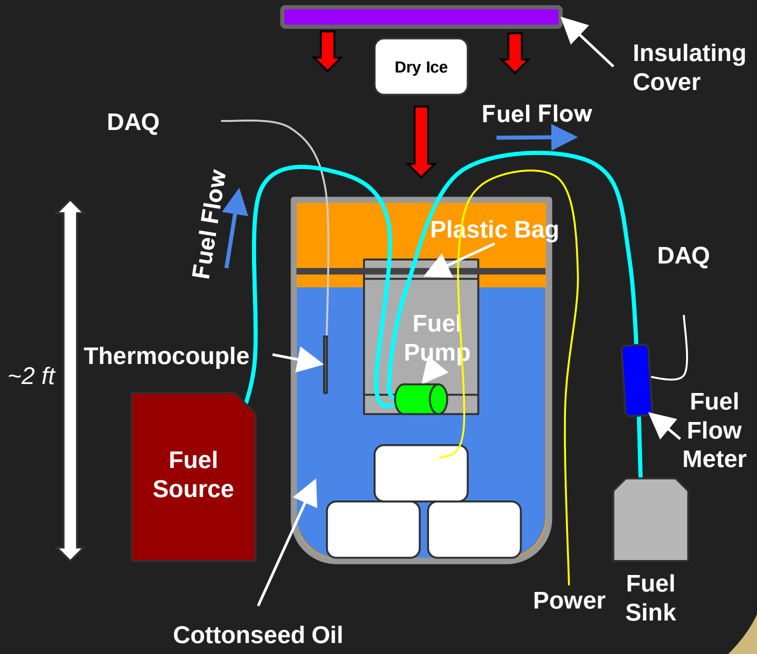
Fuel Line Test

Objective:

- *Determine the if the minimum operational temperature of the stock fuel lines is above -50°F.*

Test Overview:

- Submerge the fuel pump and lines in the cottonseed oil bucket at room temperature and begin to pump fuel
- Insert dry ice blocks into bucket to lower the temperature of the fluid
- Visually examine fuel lines for cracks and bulges.
- Visually examine bag containing the fuel pump and lines for extra fuel. Fuel inside the bag could indicate a leak.



Main Heater Battery Test

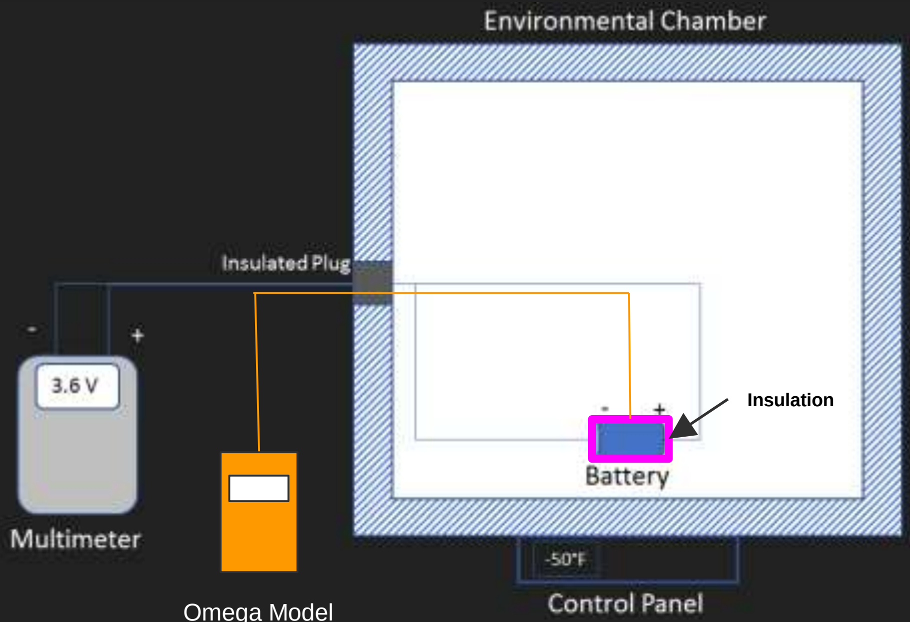
Main Heater Battery Environmental Chamber Test

Objectives:

- Verify that the main heater battery can provide voltage required to power the FDS and EHS in cold soak conditions
- Validate thermodynamic models

Test Overview:

- Identical to the Cold Temperature Battery test with added temperature recording



Omega Model HH2 Type J-K Thermocouple w/ Digital Readout

Test Chamber Calculations

Dry Ice Chamber

- 8.36 gallons of air = 0.038783 kg
- 1 block of dry ice = 10 lbs = 4.53592 kg
- Surface temp of dry ice = -109°F = 194.65 K
- Need ambient air final temp of -50°F (227.6 K), start at room temp of 70°F (294.3 K)

$$227.6\ K = 0.038783\ kg/(0.038783\ kg + x) * (294.3\ K) + x/(0.038783\ kg + x) * (194.7\ K)$$

$$8.82704 + 227.6x = 11.4139 + 194.7x$$

$$1.16898\ x = 2.58683 \Rightarrow 2.2129\ kg\ of\ Dry\ Ice\ Needed$$

= 4.8786 lbs or **1/2 Block of Dry Ice**

Test Chamber Calculations

Cottonseed Oil Test Chamber

- 2.5 gallons of cottonseed oil = 8.75376 kg
- ρ_{CSO}=0.925 g/cm^3
- 1 block of dry ice = 10 lbs = 4.53592 kg
- Surface temp of dry ice = -109°F = 194.65 K
- Need cottonseed oil final temp of -50°F (227.6 K), start at room temp of 70°F (294.3 K)

$$227.6\ K = 8.75376\ kg/(8.75376\ kg + x) * (294.3\ K) + x/(8.75376\ kg + x) * (194.7\ K)$$

$$1992.355 + 227.6x = 2575.8814 + 194.7x$$

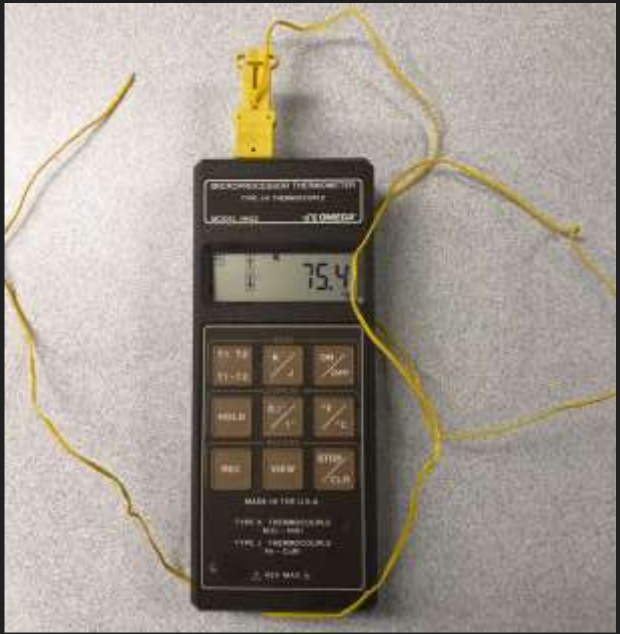
$$32.95x = 583.525\ x \Rightarrow 17.709\ kg\ of\ Dry\ Ice\ Needed$$

= 39.042 lbs or **4 Blocks of Dry Ice**

Test Instrumentation

Temperature Sensors

- *Test Bed Environment Temperature:*
  - 1 Omega Model HH22
  - Type J-K Thermocouple
  - Accuracy of **±0.05°F**
- *Individual Component Temperature:*
  - DAQ capable of supporting up to 8 individual temperature sensors



Test Instrumentation

Mass Flow Sensor

- Equflow 0045
- Readily Available, $50 pack of disposable inserts
- Flow Rate **0.1-2L/min** with 110,000 pulses/L
  - Engine fuel flow rate: **0.370 L/min**
  - Accurate to 1% of reading (**±0.0001 L/min**)
- 34mA current at 5V
- If the interface with the microcontroller is not possible then mass flow will be calculated via pressure potential function utilizing applied voltage and temperature.

**Information courtesy of CU REAPER senior projects team*

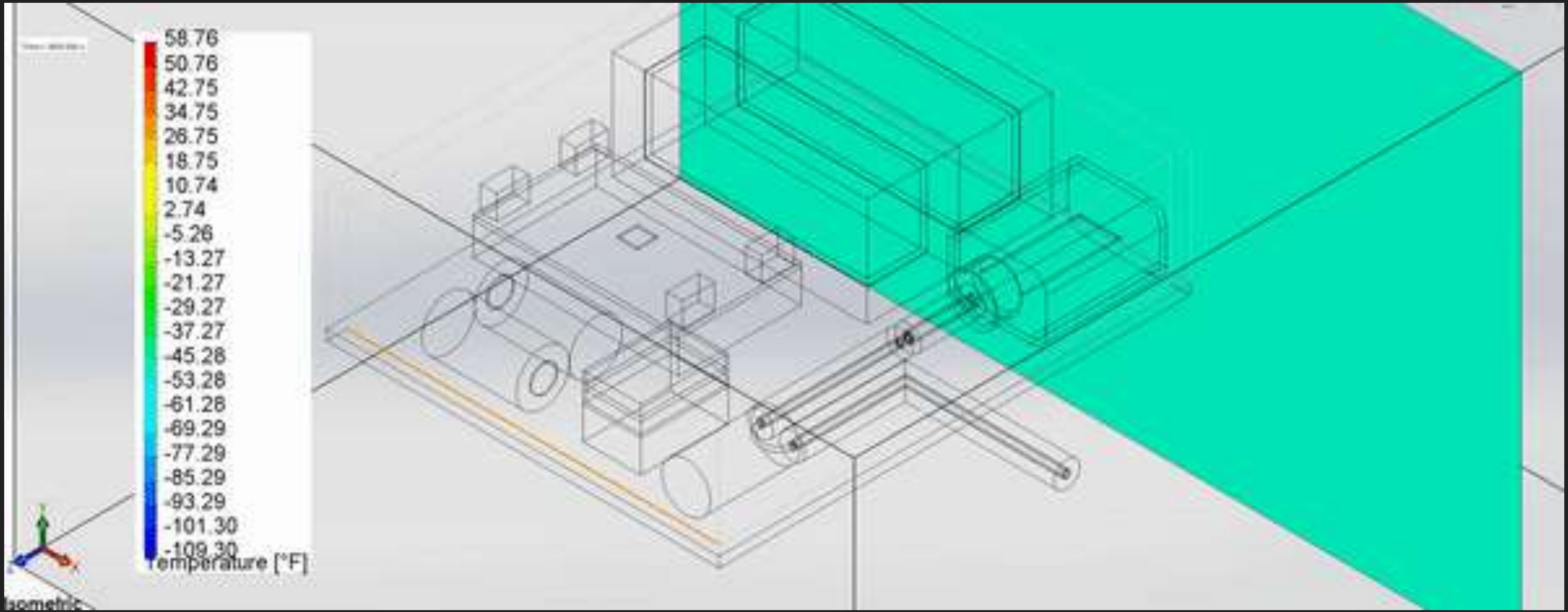
Test Instrumentation

Data Acquisition System (DAQ)

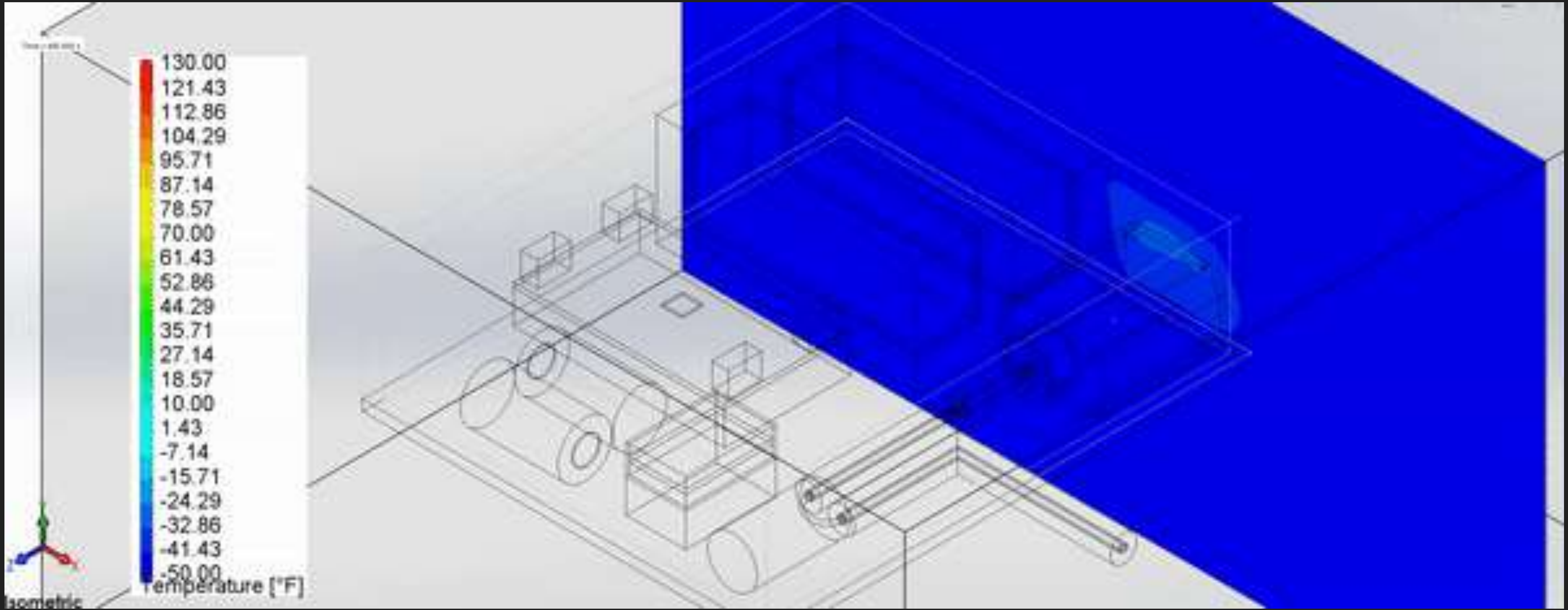
- National Instruments DAQ USB-6009
    - Analog Input (8 inputs):
        - +/-10V, accuracy 7.73mV
        - +/-1V, accuracy 1.53mV
- 12 Bit
- On-campus resource, readily available

Thermal Model Animations

COOLING


58.76
50.76
42.75
34.75
26.75
18.75
10.74
2.74
-5.26
-13.27
-21.27
-29.27
-37.27
-45.28
-53.28
-61.28
-69.29
-77.29
-85.29
-93.29
-101.30
-109.30
Temperature [°F]

Heating


130.00
121.43
112.86
104.29
95.71
87.14
78.57
70.00
61.43
52.86
44.29
35.71
27.14
18.57
10.00
1.43
-7.14
-15.71
-24.29
-32.86
-41.43
-50.00
Temperature [°F]
Isometric