A.C.E.S.

Air-breathing Cold Engine Start

Preliminary design Review

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Outline

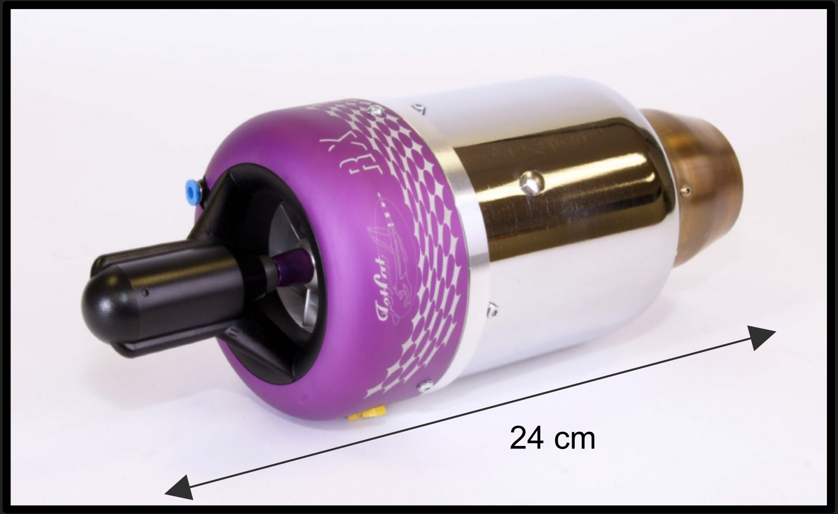
- Project Description
- Baseline Design
- Initial Energy Feasibility
- Fuel Delivery System (FDS) Heating Feasibility
- Electronic Heating Feasibility
- Project Summary

Project Description

- Design, build, and test a system to facilitate starting a JetCat P90-SXi jet engine at a temperature of -50°F by:
  - Providing fuel to the engine at a mass flow rate of 4.8 g/s ± 5%
  - 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



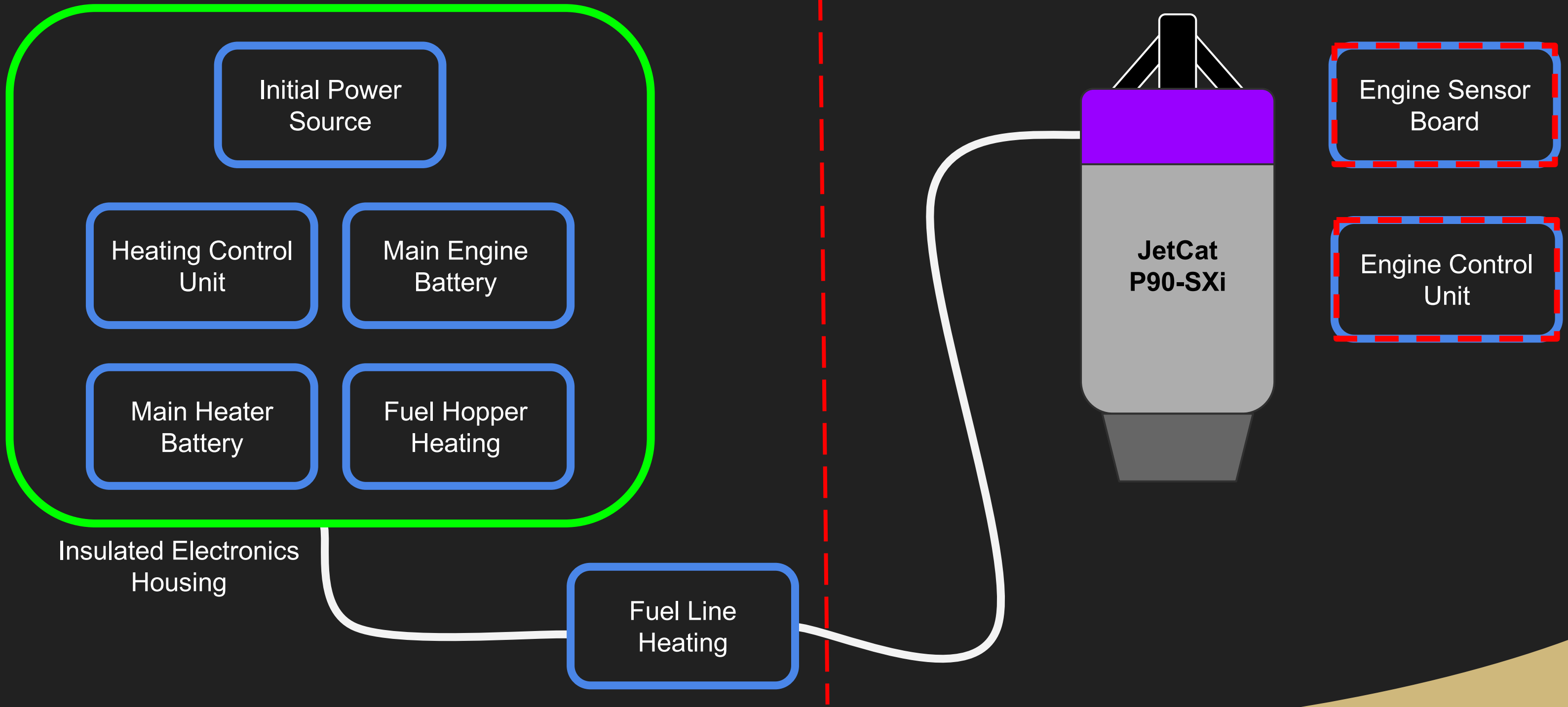
New Project Scope

- The project scope has been narrowed
- Original project involved fuel delivery, keeping electronics operational, creating a custom engine control unit (ECU) and engine sensor board (ESB)
- Starting the engine for the AFRL competition is no longer part of the project requirements
- The course design will focus on delivering the fuel to the engine at a specified flow rate and keeping the electronics operational

New Project Scope

Course Design Items

AFRL Design Items



Motivation

- **Fuel ignition redesigns are too difficult**
  - Ensure droplet size is in the micron range
  - Spray pattern must closely resemble nominal conditions
  - Nominal spray pattern is difficult to quantify
- **Modifications to the JetCat engine are notoriously difficult**
  - Our Engine Sensor Board has already broken when operating the engine
  - Original project would have been impossible to complete without working engine
- **No other undergraduate group has succeeded with custom engine electronics**
  - REAPER, SABRE, MEDUSA

Critical Project ELements

- Provide a source of initial electrical energy to heat main heater battery to operational temperature (30°F).

- Heat the fuel lines and hopper to 60°F in order to decrease the viscosity of the fuel and allow it to flow at 4.8 g/s.

- Heat the engine electronics (ECU and receiver) to their standard operating temperatures (60°F).

- Construct a Heating Control Unit (HCU) which will control the fuel and electronics heating systems.

Course Project Objectives

	Fuel Delivery System (FDS) Heating	Electronics Heating	Time	AFRL Competition
Level 1	Fuel delivery system will regulate Jet-A fuel at the flow rate of 4.8 g/s when initially cold soaked to -30°F.	The electronics will be heated to operational temperature when cold soaked to -30°F.	The fuel delivery and electronics heating systems objectives will be completed in less than 3 hours.	
Level 2	Fuel delivery system will regulate Jet-A fuel at the flow rate of 4.8 g/s when initially cold soaked to -40°F.	The electronics will be heated to operational temperature when cold soaked to -40°F.	The fuel delivery and electronics heating systems objectives will be completed in less than 1.5 hours.	
Level 3	Fuel delivery system will regulate Jet-A fuel at the flow rate of 4.8 g/s when initially cold soaked to -50°F.	The electronics will be heated to operational temperature when cold soaked to -50°F.	The fuel delivery and electronics heating systems objectives will be completed in less than 8 minutes and 42 seconds.	
Level 4				Entire system will be integrated with engine and successfully start within 3 hours.

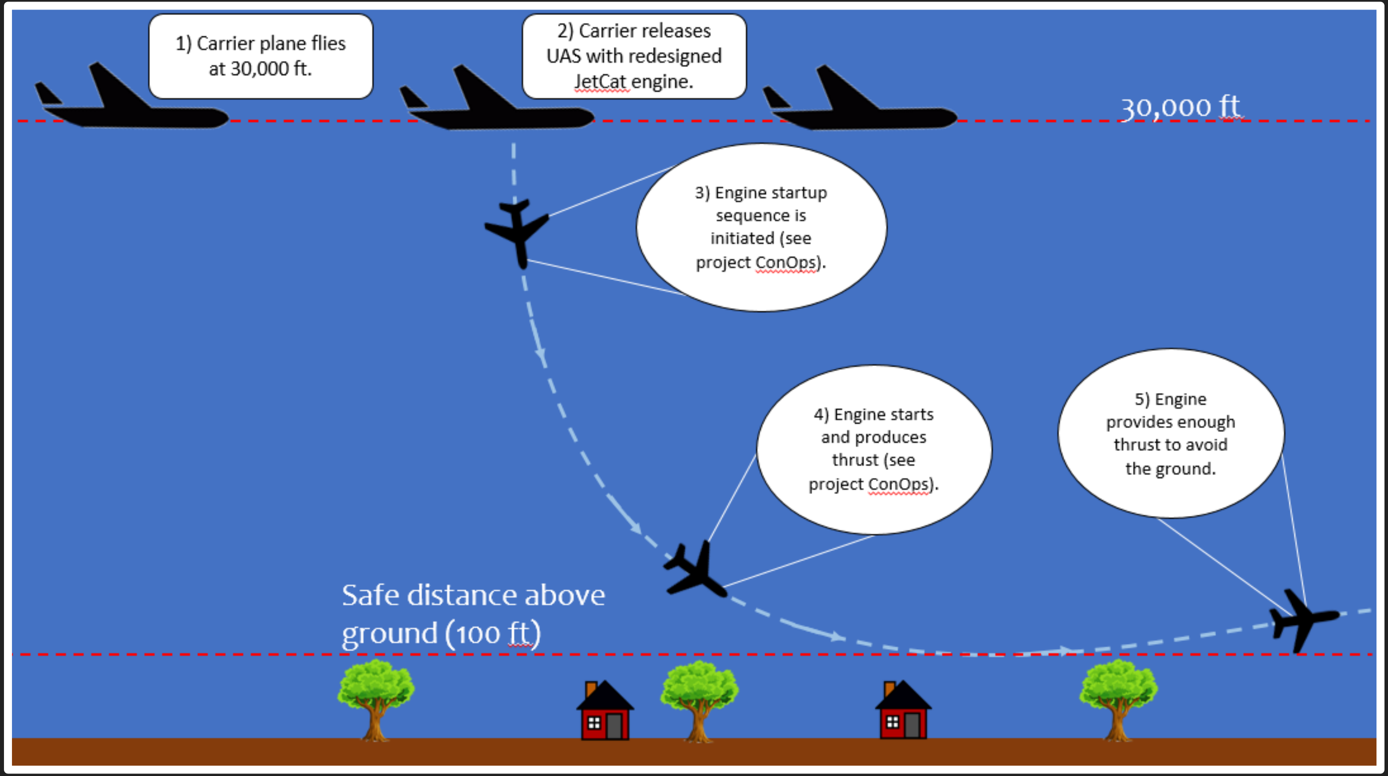
Functional Requirements

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

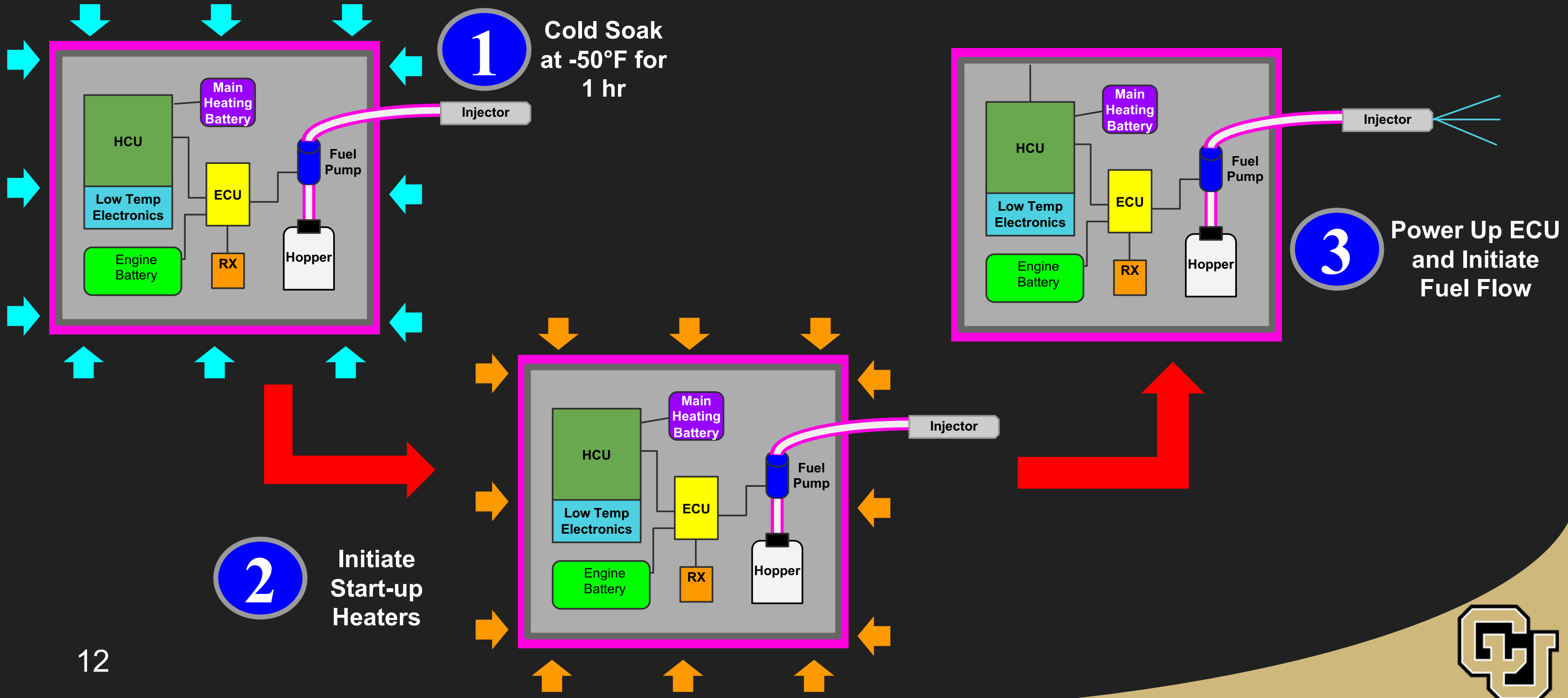
- ***FDS:*** The Fuel Delivery System shall provide adequate fuel flow for a successful start-up sequence and continued operation of the engine. This fuel flow is specified as 4.8 g/s for full throttle.

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

Mission CONOPS



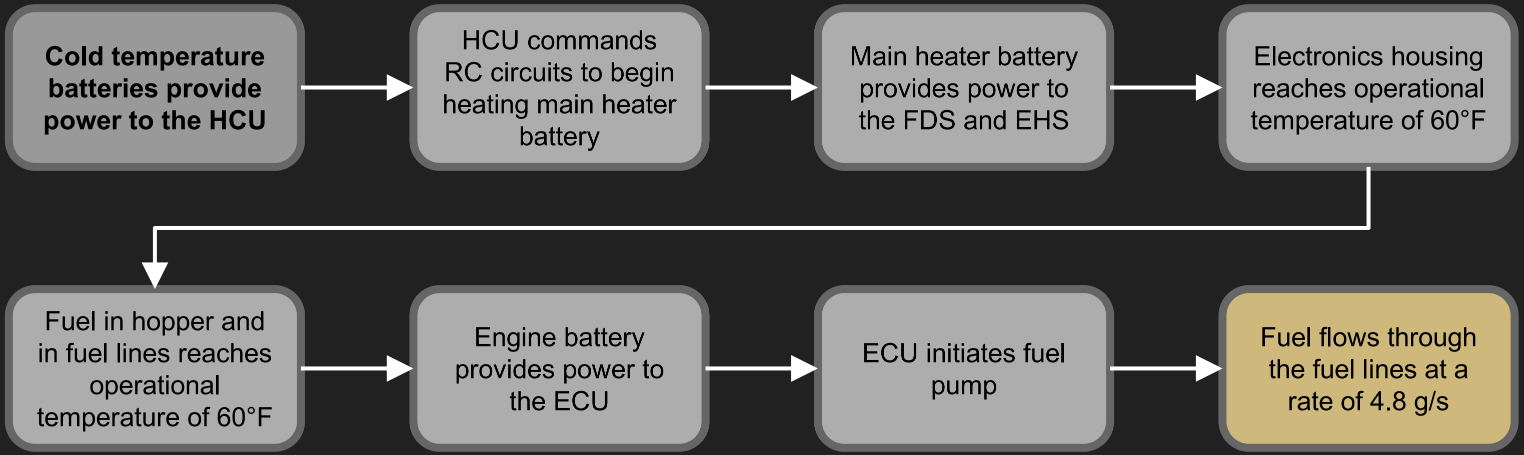
Project Conops



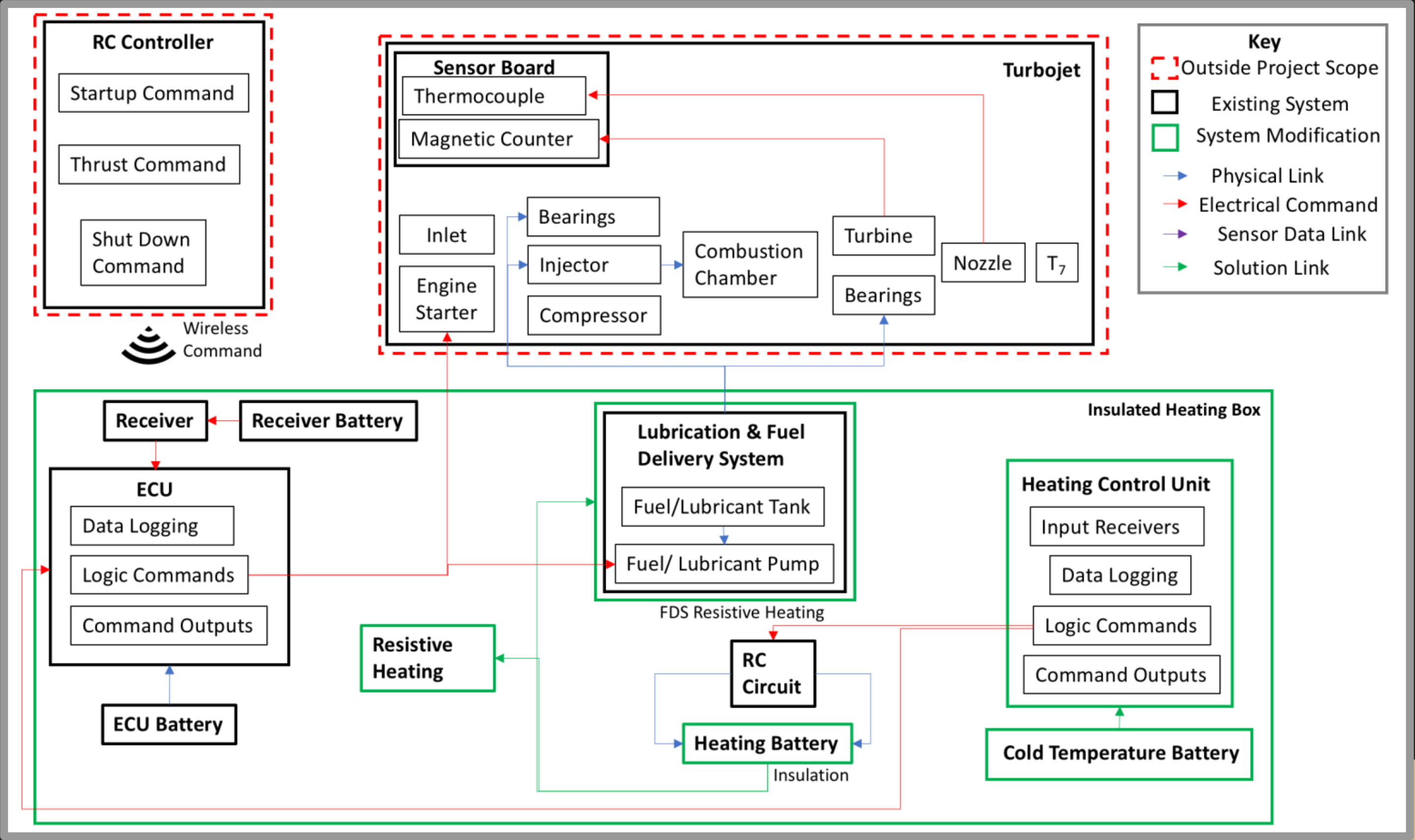
Baseline Design

- Initial Energy: Charged capacitor
  - Stores and discharges energy to heat main battery
- Fuel Delivery System: Resistive heating
  - Resistive heating wire wrapped around fuel delivery components
- Electronics Heating: Resistive heating within insulated box
- Heating Control Unit: Microcontroller powered by start-up batteries
  - Controls temperature of fuel delivery and electronics systems
  - Both components functional at -50°F

Process Flow Diagram



Functional Block Diagram



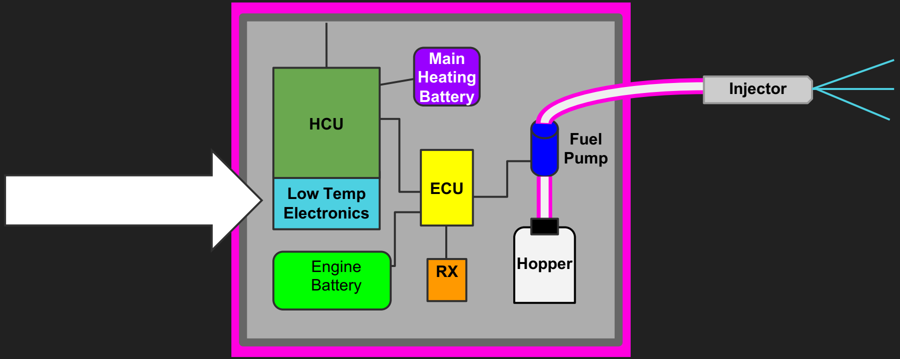
Initial Energy Feasibility

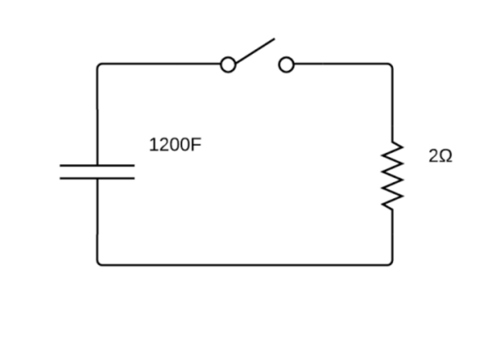
Initial Energy Trade Study

Factor	Weights	Chemical	Mechanical	Low-Temp Electronics	Cold Soak Active Heater
Reliability	0.3	4	2	5	5
Manufacturability	0.25	3	2	5	4
Safety	0.15	1	4	4	[illegible]
Start-up Time	0.15	4	3	5	[illegible]
Team Experience	0.1	1	3	4	[illegible]
Cost	0.05	4	2	4	5
Total	1	3.1	2.5	**4.7**	4.5

Initial Energy Design

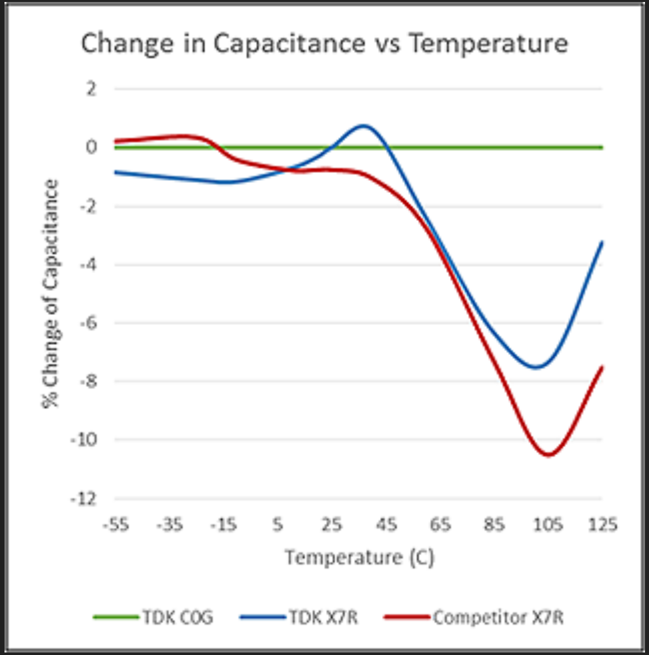
- 7 individual RC circuits, each with…
  - A 1200 Farad supercapacitor
  - 2Ω Resistive wire wrapped around the main heater battery





Initial Energy Feasibility

- Capacitor performance does not degrade at low temperatures
- Chosen 1200F capacitors can provide 3W with 2Ω resistive load
  - 7 RC circuits provide necessary power to warm batteries
- Chosen capacitors are cheaper, smaller, and more powerful than low temperature batteries



Credit to product.TDK.com

Initial Energy Capacitor Model

The performance of our capacitor system is modeled as a simple RC circuit

- 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**
  - 7 circuits will release about 10,094J, at 21W
  - Peak wattage will be 3.65W

$$V(t) = V_0\left(e^{-t/(RC)}\right)$$

$V(t)$ = Voltage (V)
V_0 = Initial Voltage (V)
t = Time (sec)
R = Resistance (Ω)
C = Capacitance (F)

$$I(t) = \frac{V_0}{R} e^{-t/(RC)}$$

$I(t)$ = Current (A)
V_0 = Initial Voltage (V)
t = Time (sec)
R = Resistance (Ω)
C = Capacitance (F)

Risk of Supercapacitors

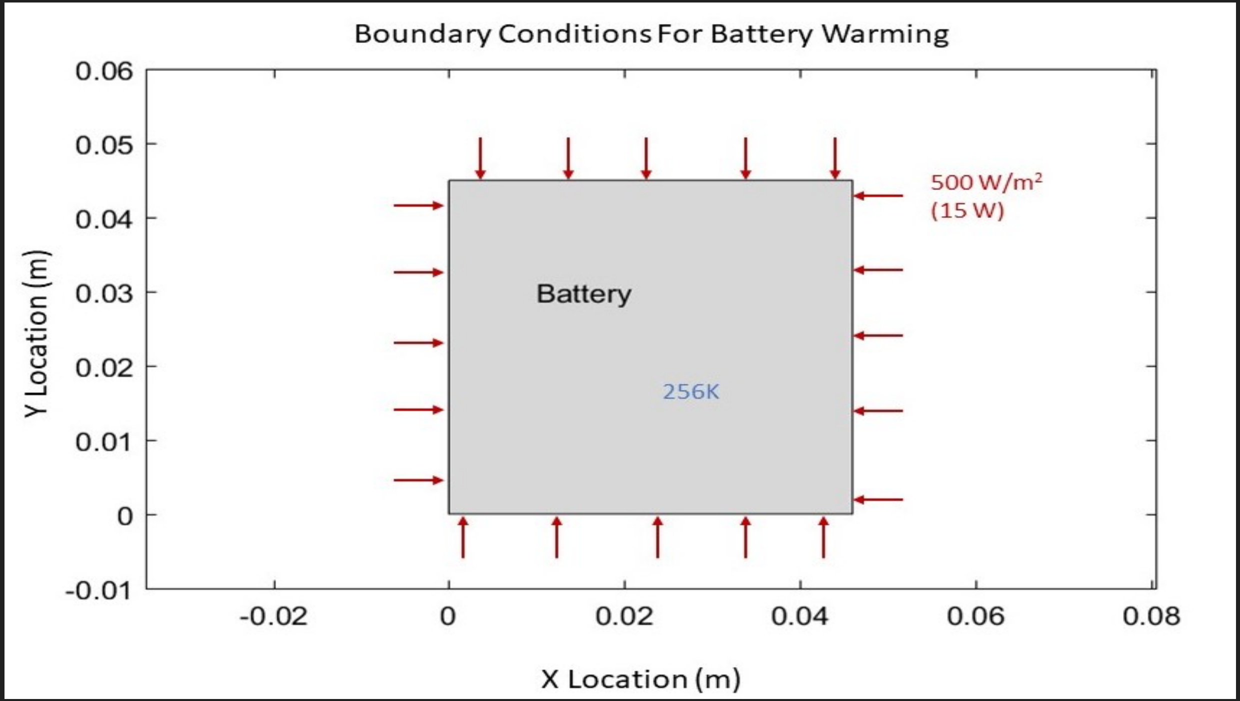
- Never charge a capacitor pasts its rated voltage.

- 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

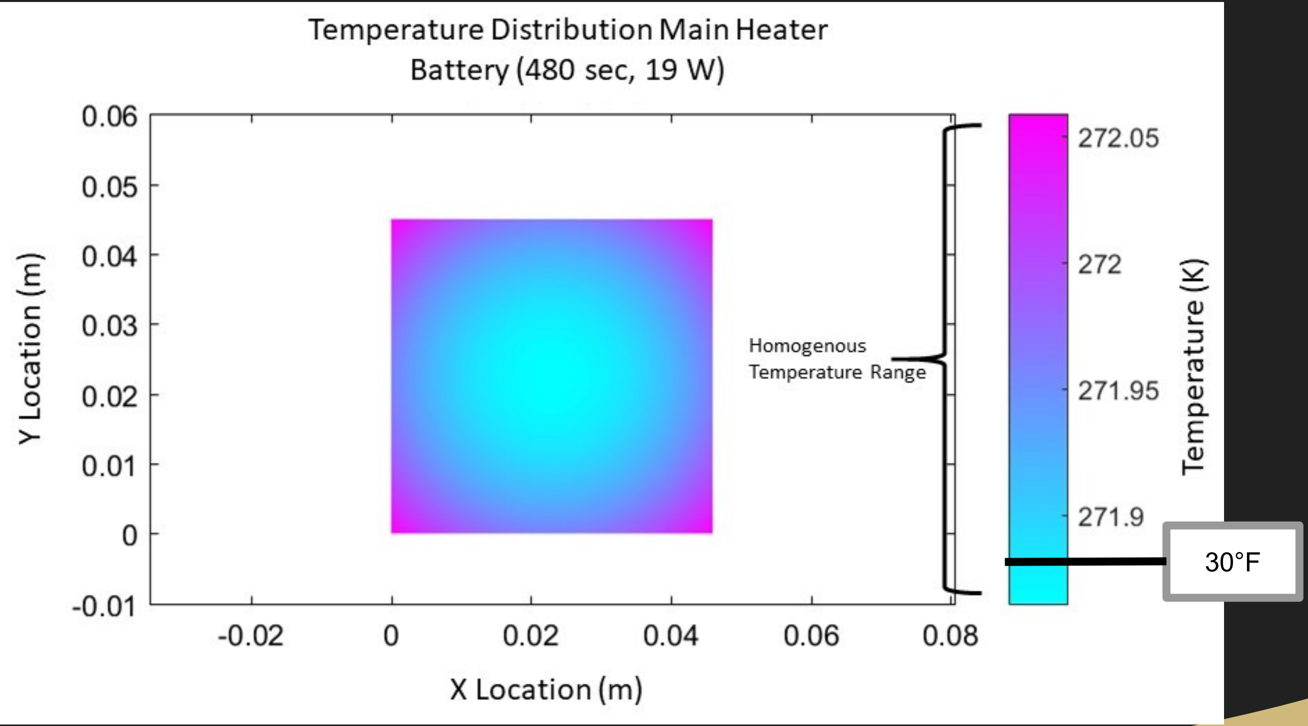
Initial Energy Feasibility

- Main Heating Battery



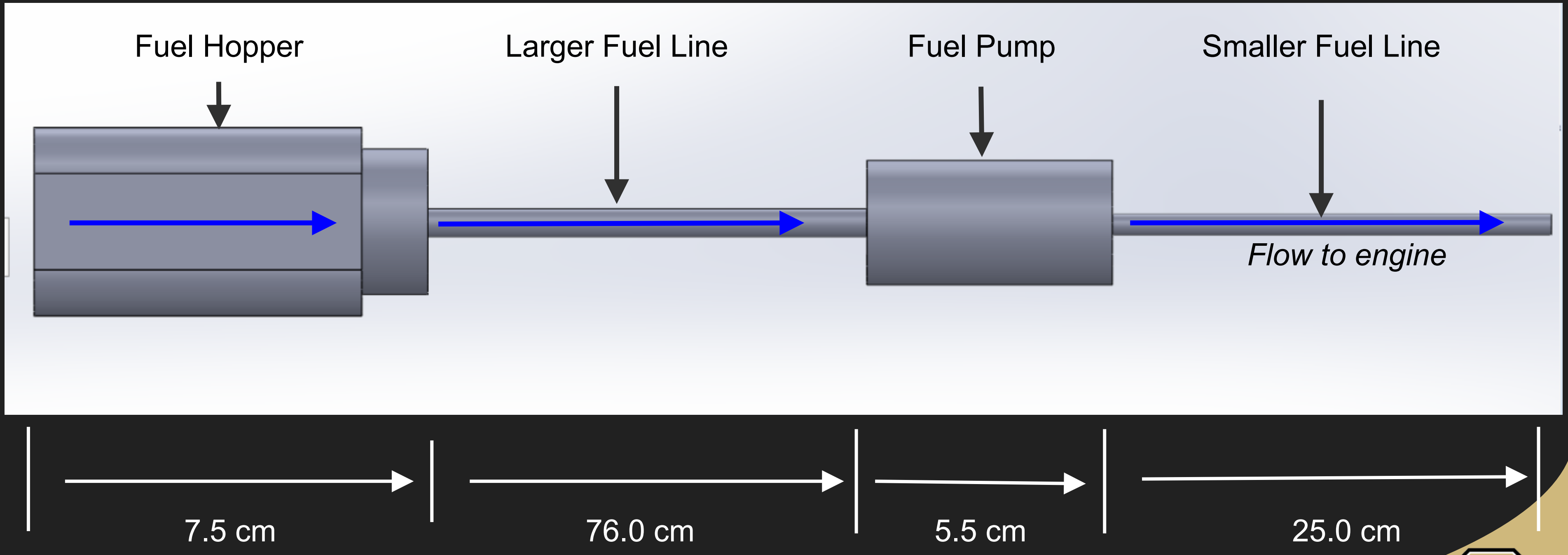
InITIAL ENERGY Feasibility

- Main Heating Battery



Fuel Delivery System

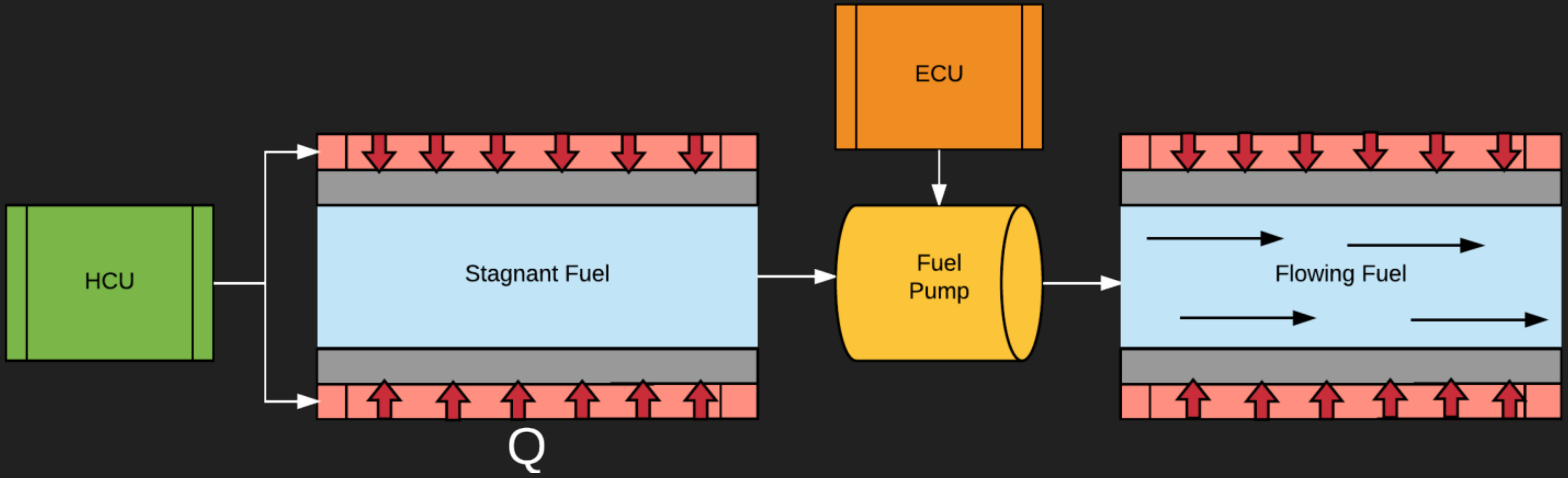
System Layout



Fuel System Trade Study

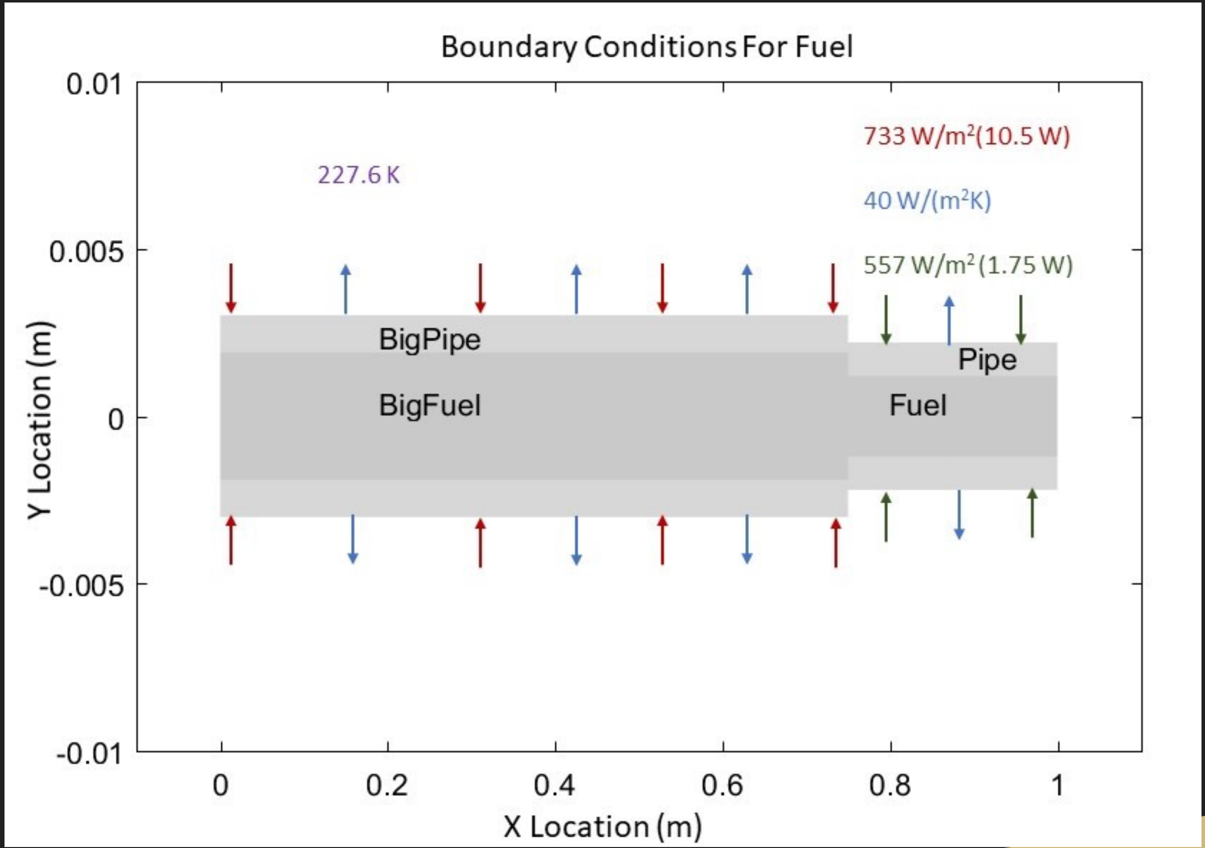
Factor	Weights	Resistive Heating	Fuel Additive	Circulating Fluid	Pressurized Fuel
Manufacturability	0.3	4	4	2	2
Reliability	0.25	4	3	2	2
Power Consumption	0.15	3	5	3	3
Safety	0.1	4	3	4	2
Start-up Time	0.1	4	5	2	4
Cost	0.1	5	3	4	3
Final Score	~	**3.85**	**4.05**	2.8	2.65

How the Fuel Line Solution Works

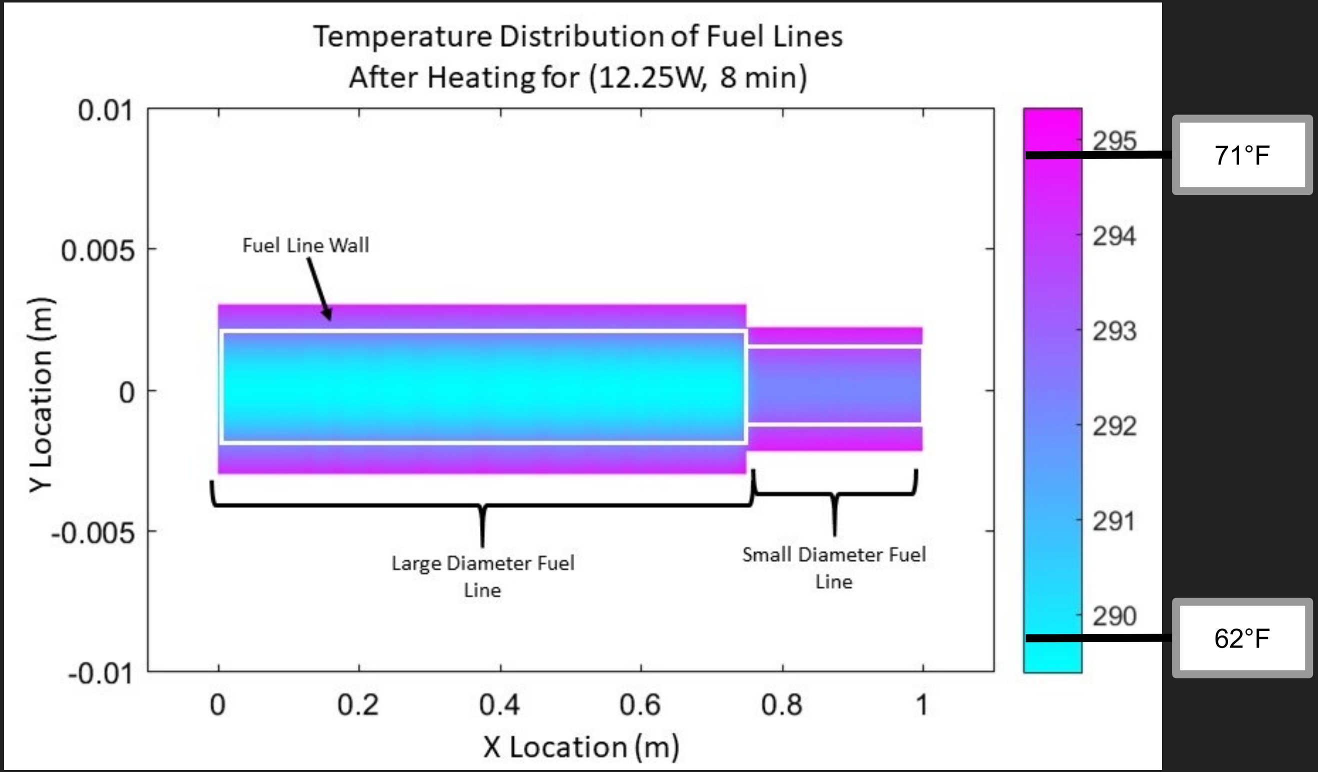


- **Light Red** - Resistive Heating Wire
- **Grey** - Polyurethane Fuel Line

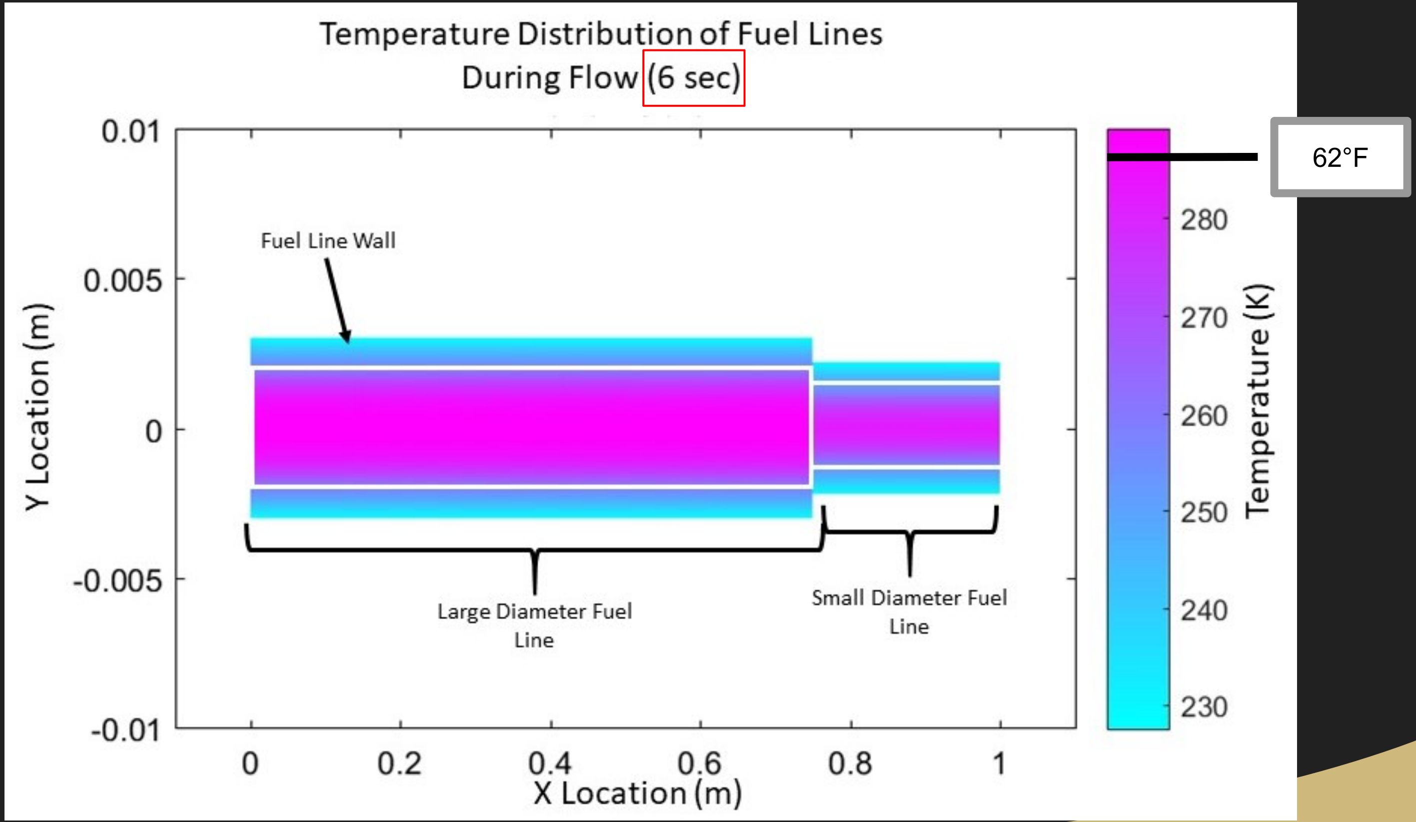
Fuel Line Heating Feasibility



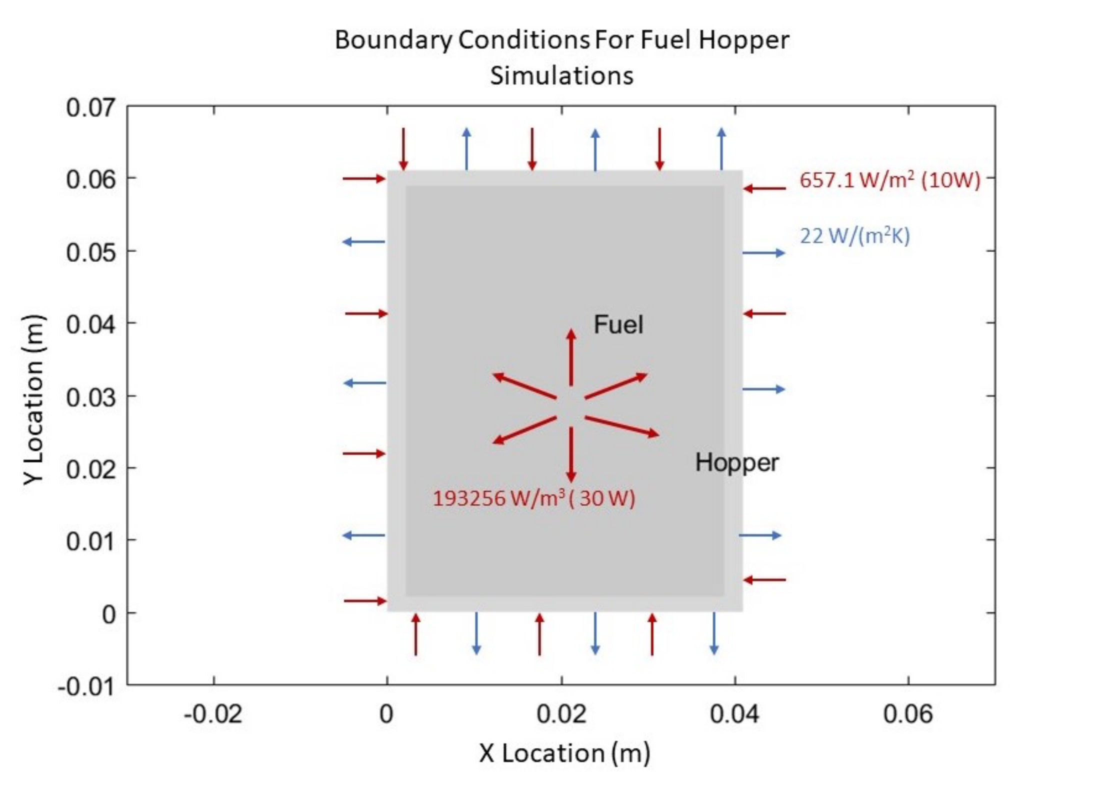
Fuel Line Heating Feasibility



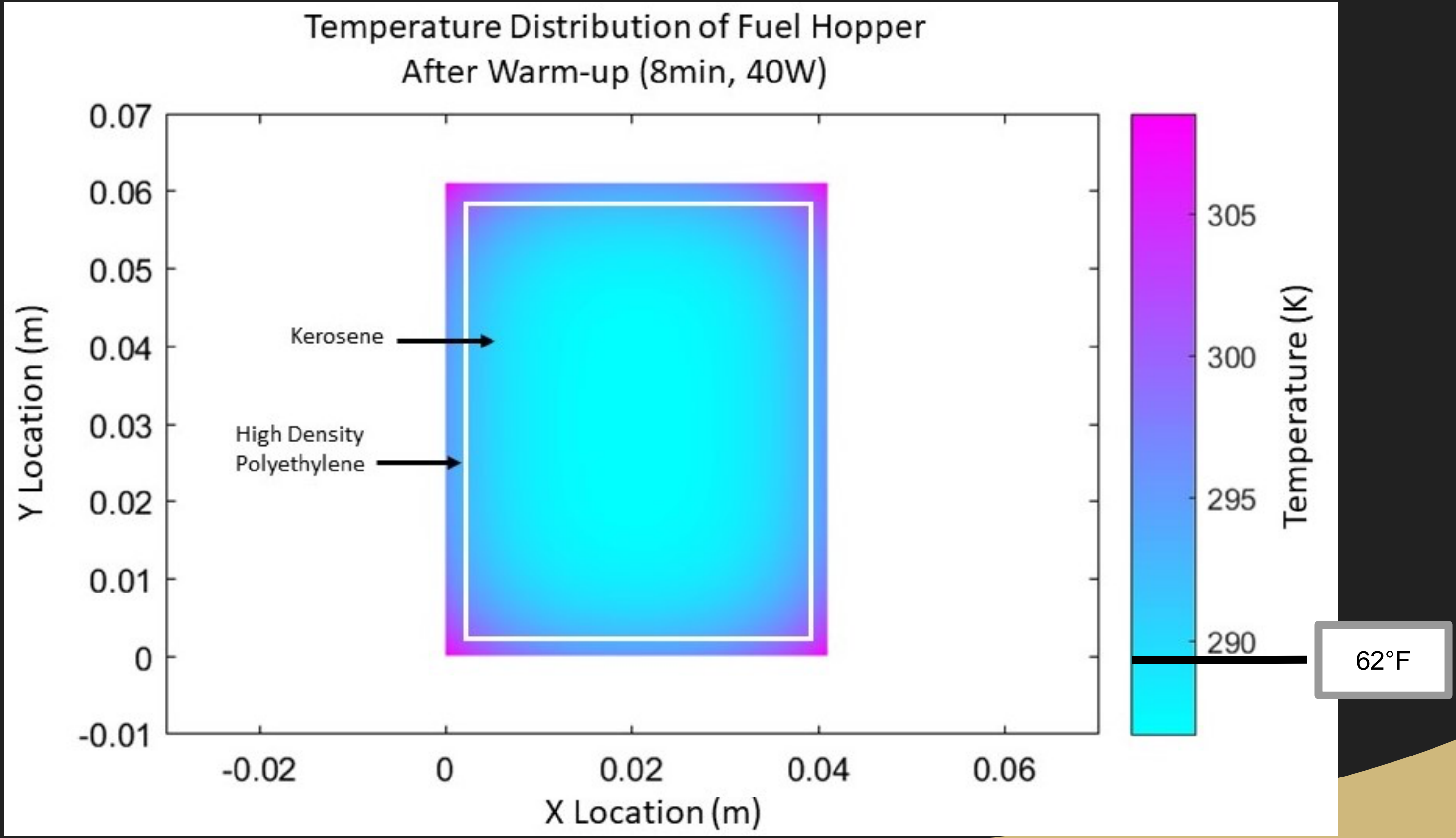
Fuel Line Heating Feasibility



Fuel Hopper Heating Analysis



Fuel Hopper Heating Analysis



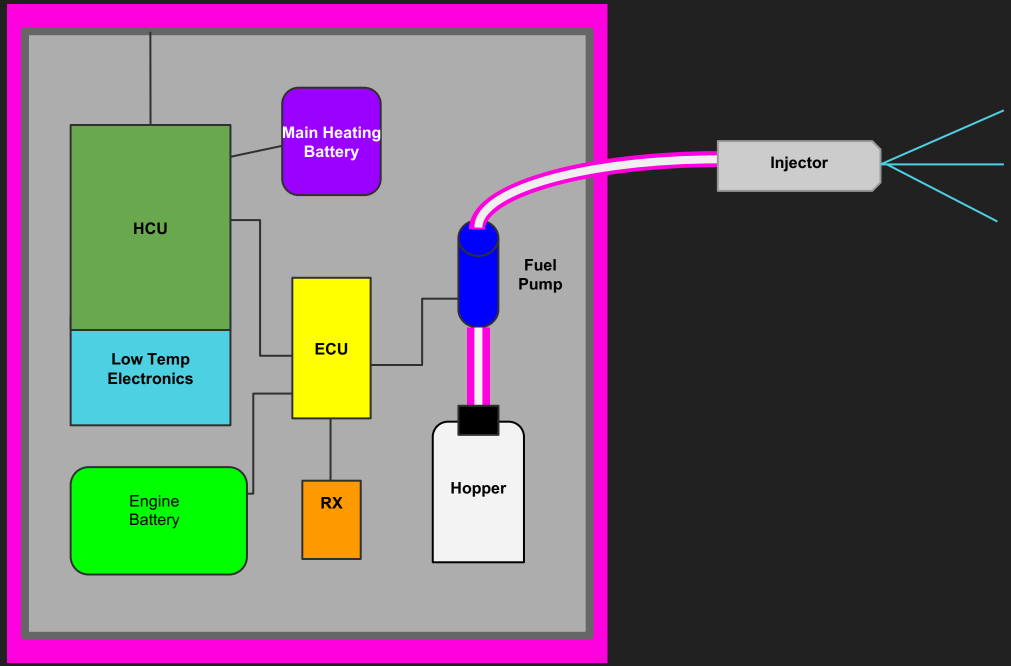
Electronics Heating System

Electronics Heating Trade Study

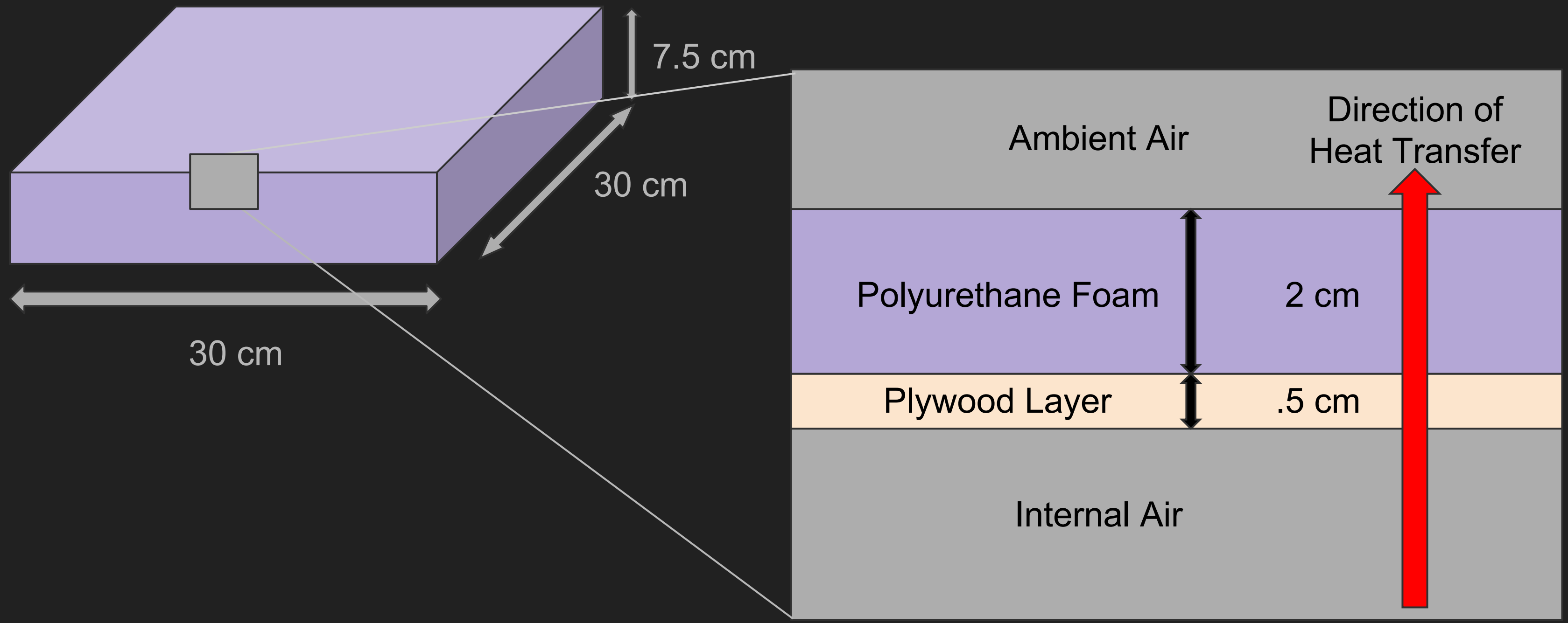
Factor	Weights	Conductive Heating Element	Radiative Ceramic Resistor	Fluid Heating
Safety	0.3	4	3	2
Reliability	0.2	5	5	3
Start-Up Time	0.2	5	4	3
Power Consumption	0.15	3	2	4
Manufacturability	0.1	4	4	2
Cost	0.05	5	5	4
Total	1	**4.45**	**4.1**	2.9

ELectronics Housing

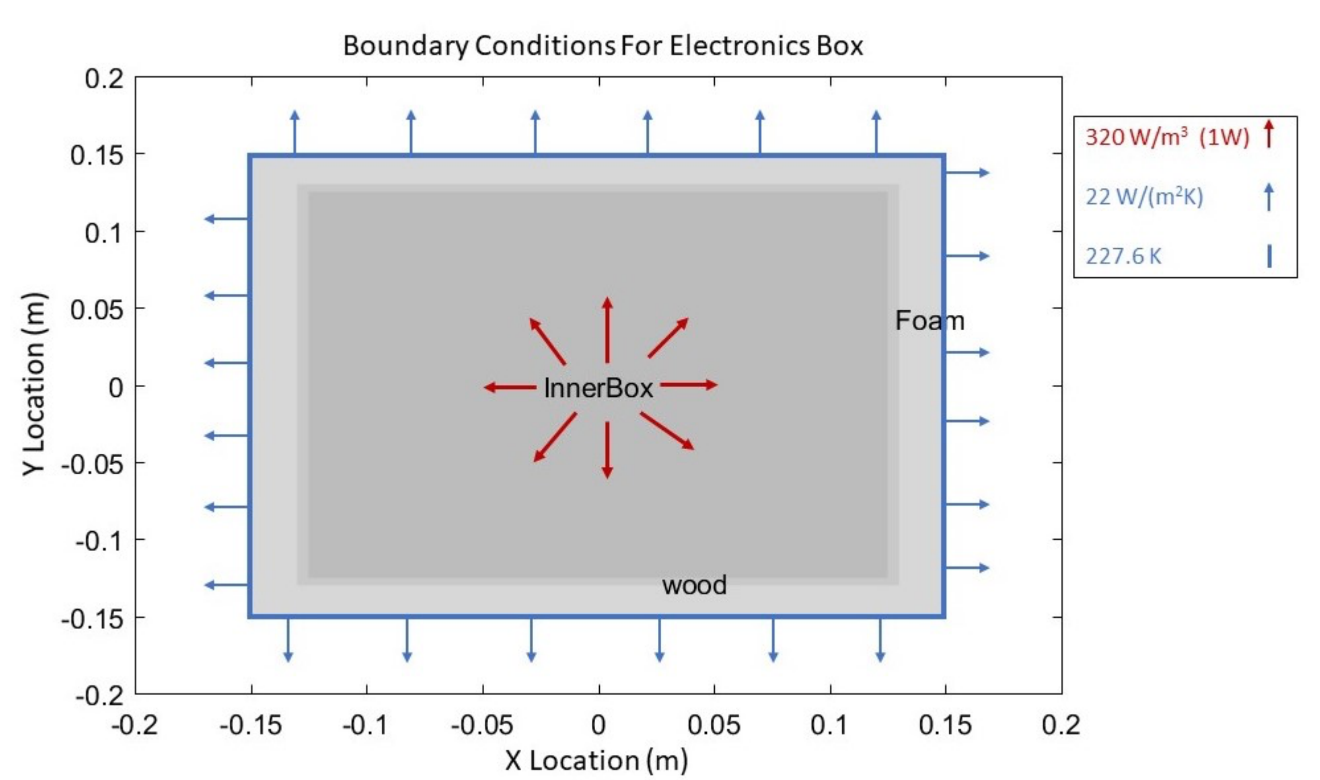
Electronics Housing
(Top View)



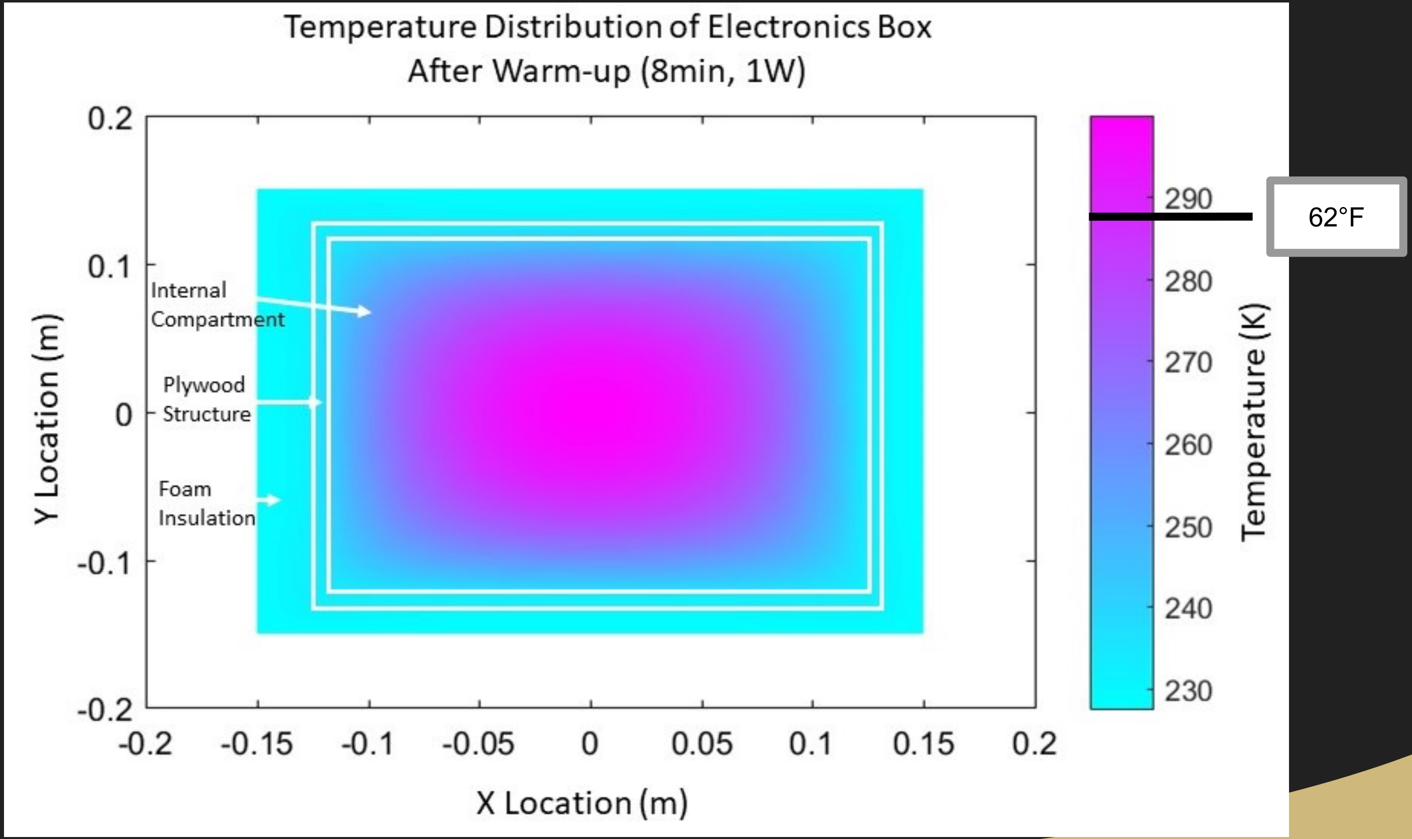
Electronics Housing Dimensions



Transient ELectronics Heating



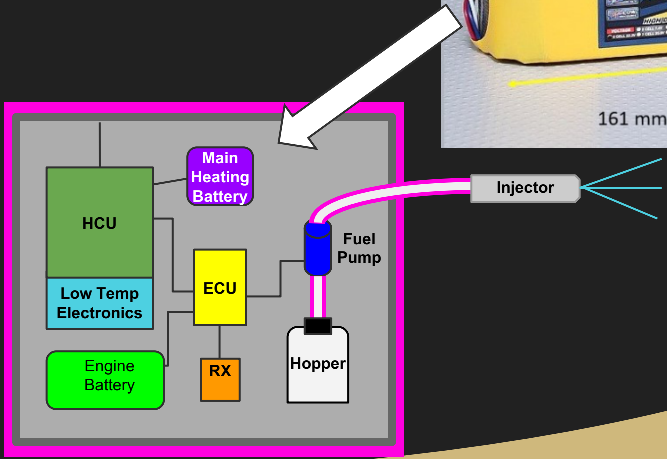
Transient ELectronics Heating



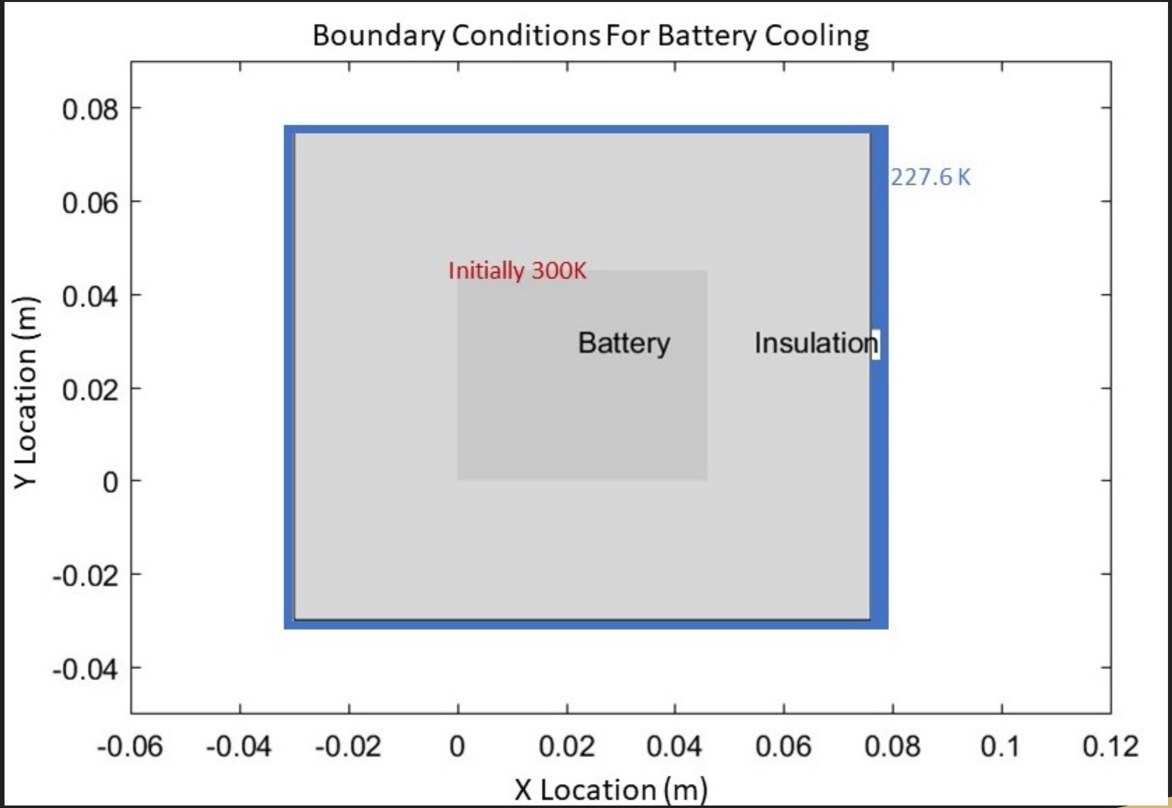
Main Heater Battery Feasibility

Heating Power Requirements	
Model Type	Transient
FDS Fuel Lines	12.25 W
FDS Fuel Hopper	40 W
Electronics Box	20 W
Total	**72.25 W**

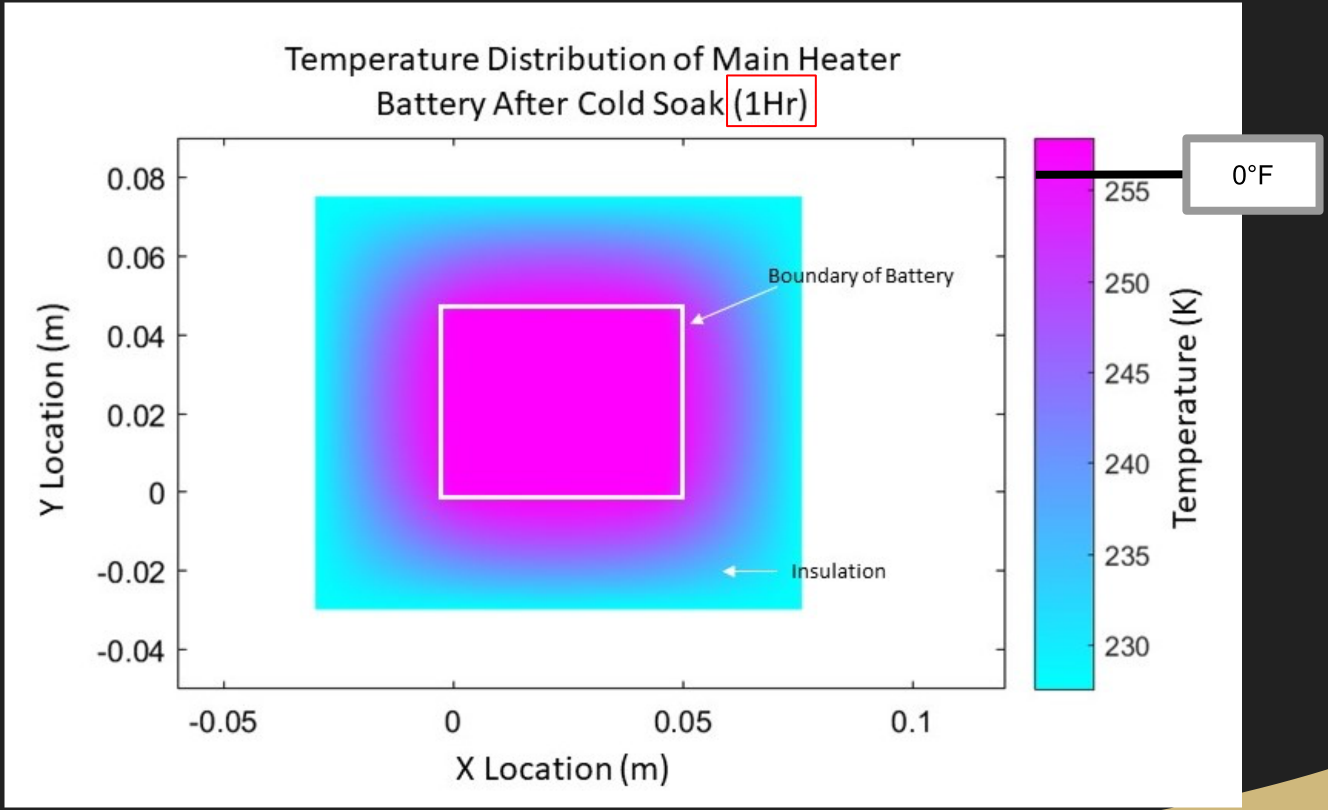
- 5000 mAh, 22.6 V, 25 C Lipo Battery
- For 30min of discharge, this battery can provide 226 W.



Main Heater Battery Feasibility



Main Heater Battery Feasibility

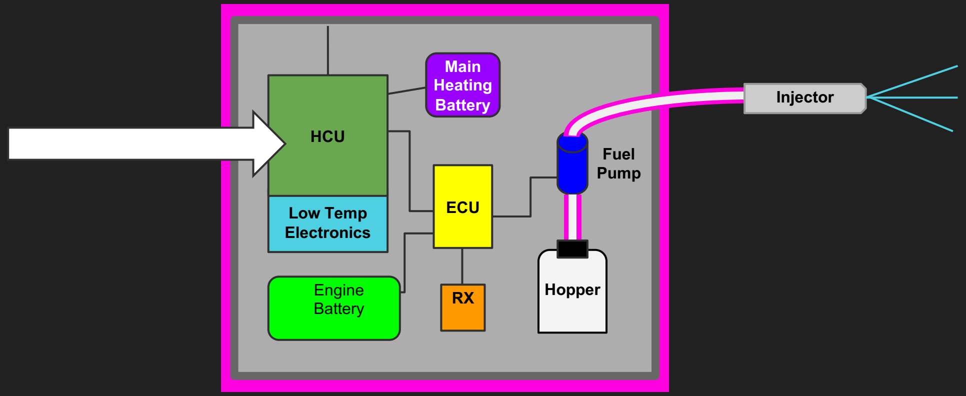


Heating Control Unit

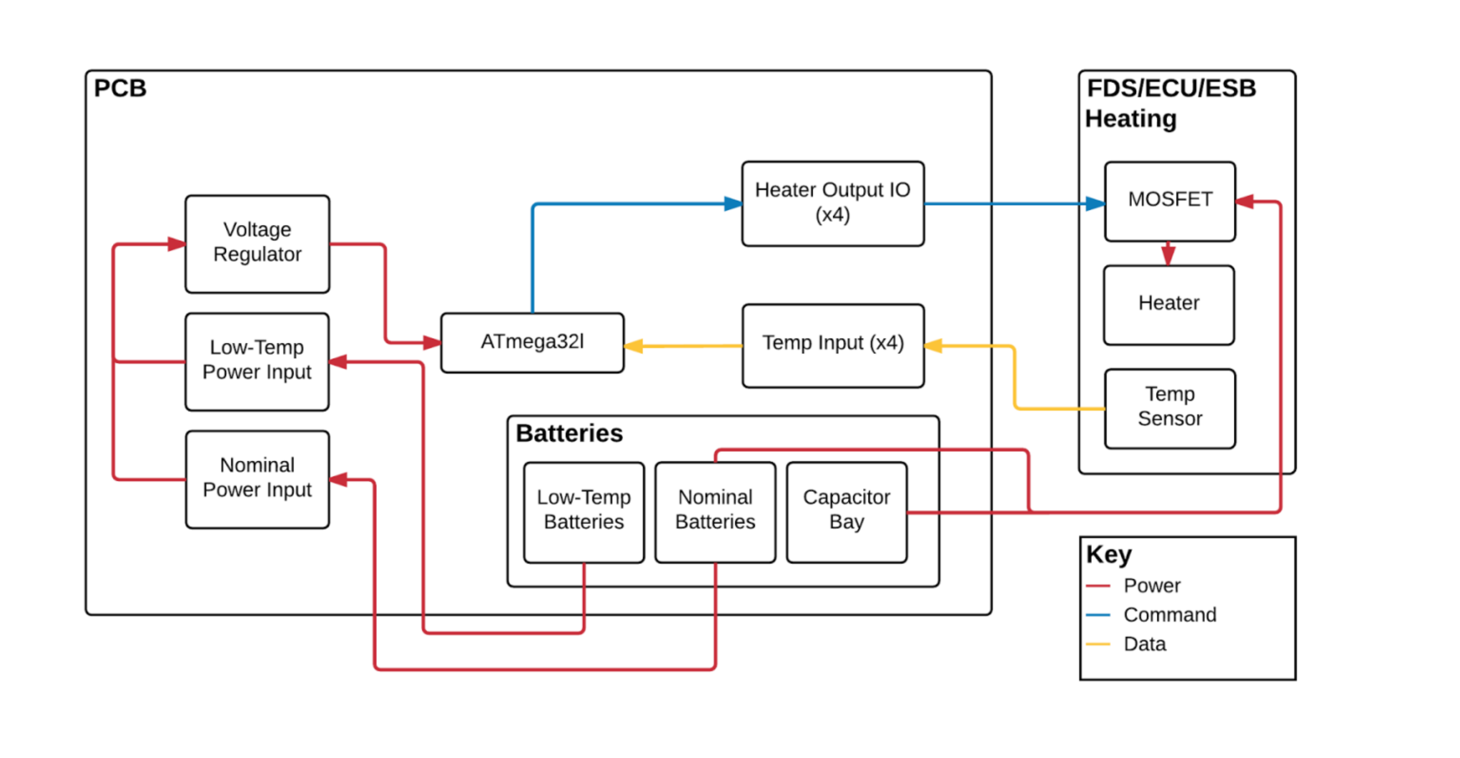
HEating Control Unit (HCU)

The Heating Control Unit will be designed to:

- Monitor the temperatures of the electronic and FDS components
- Regulate these temperatures through the use of resistive heaters
- Provide a start-up signal to the ECU once fuel viscosity has been decreased
- Responsible for closing the RC CIrcuits



HEating Control Unit (HCU)



pROJECT SUMMARY

Feasibility Overview

CPE:
Provide a source of initial electrical energy to heat main batteries to operational temperature (30°F):

- RC circuits can provide 21W in 8 minutes
- The main heater battery requires 19W to be heated to 30°F
- Power available: 21W > 19W power required

FEASIBLE

Feasibility Overview

CPE:
Heat the fuel lines and hopper to decrease the viscosity of the fuel and allow it to flow at 4.8 g/s

- Since increasing temperature decreases viscosity, the temperature must be increased to nominal (60°F) so that nominal viscosity and therefore nominal flow rate can be reached
- It takes 12.25W to heat the fuel lines and 40W to heat the fuel hopper to 60°F
- 12.25W + 40W = 52.25W - Chosen battery provides 226W. 52.25W < 226W

FEASIBLE

Feasibility Overview

CPE:
Heat the engine electronics (ECU and receiver) to their standard operating temperatures (60°F)

- It takes 20W to heat the air in the electronics housing along with the engine battery to 62°F in 8 minutes
- The main heater battery's insulation never allows its temperature to drop below 0°F
- 52.25W (for fuel heating) + 20W = 72.25W
- 72.25W < 226W provided by main heater battery

FEASIBLE

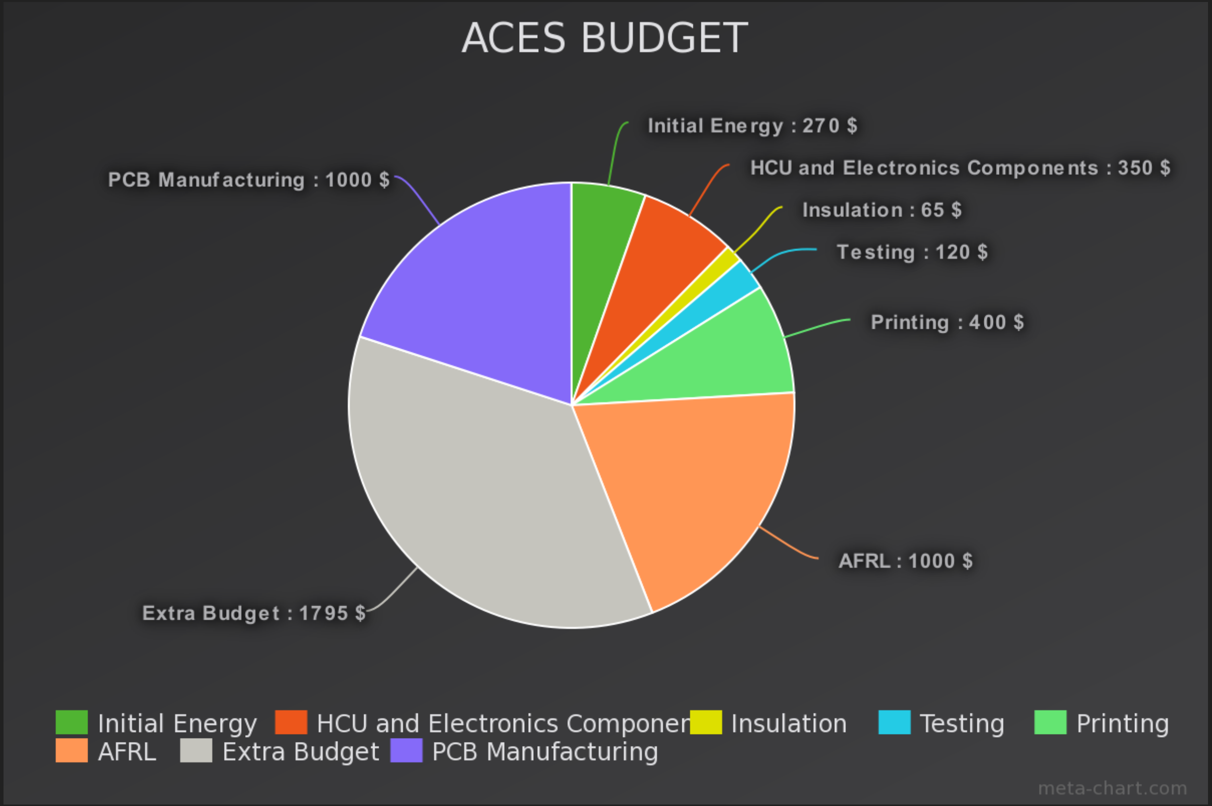
Feasibility Overview

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

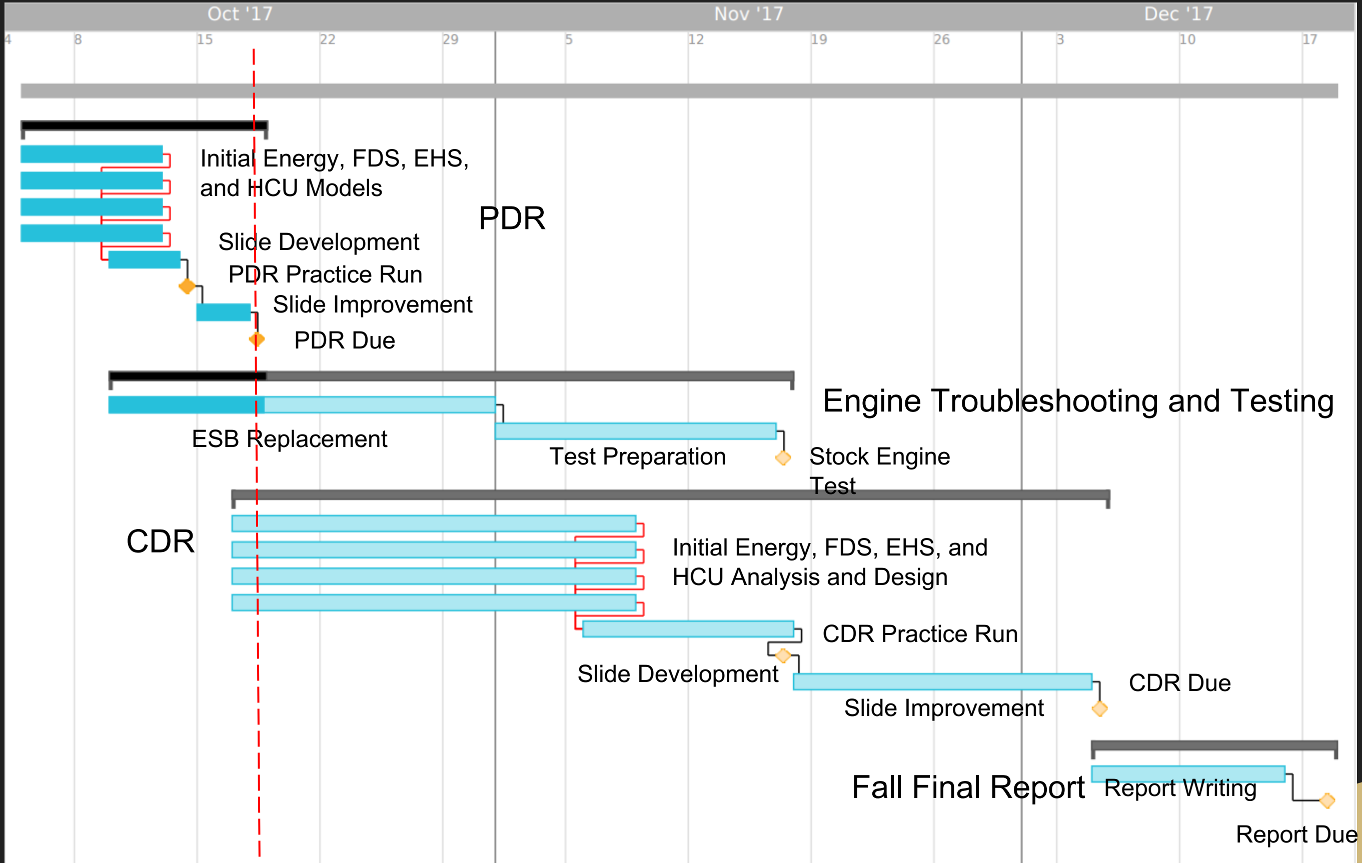
- All HCU components are readily obtainable
- All HCU components can operate at -50°F

FEASIBLE

Projected Budget



Gantt Chart



Oct '17
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Dec '17
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Initial Energy, FDS, EHS, and HCU Models
PDR
Slide Development
PDR Practice Run
Slide Improvement
PDR Due
Engine Troubleshooting and Testing
ESB Replacement
Test Preparation
Stock Engine Test
CDR
Initial Energy, FDS, EHS, and HCU Analysis and Design
CDR Practice Run
Slide Development
CDR Due
Slide Improvement
Fall Final Report
Report Writing
Report Due

ACknowledgements

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Questions?

Backup Slides

BAck of The Envelope Calculations

Basic Change in Heat Equation for Warming of System Components

- Equation Used: $\dot{Q}_{req} = \frac{mc_p(Temp_{final} - Temp_{initial})}{Time}$
  - Time = 8 minutes
  - Temp final = 290 K (62 °F)
  - Temp Initial = 227.6 K (-50 °F)

Results:

$$\dot{Q}_{tubing} = 2.242\ W$$

$$\dot{Q}_{Hopper} = 32.9\ W$$

$$\dot{Q}_{Electronics\ Box} = 0.47\ W$$

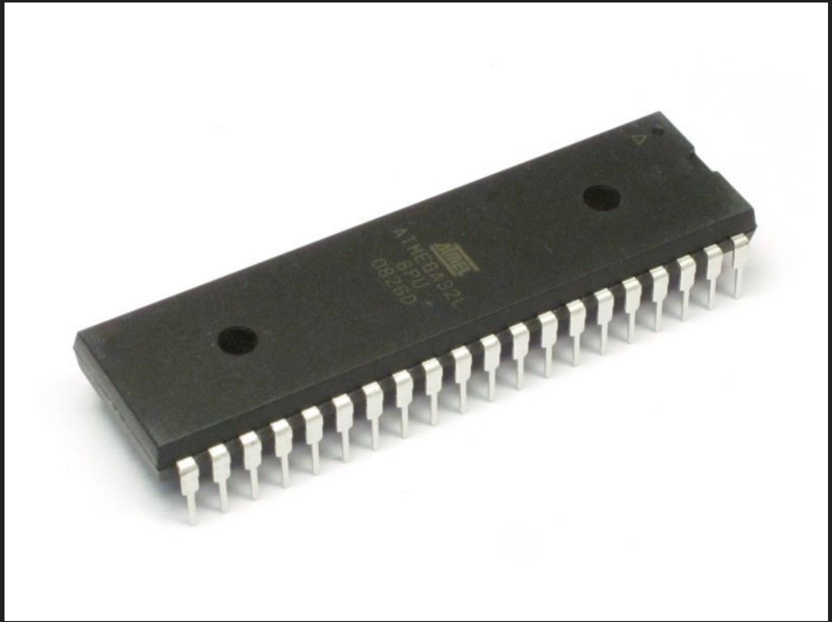
$$\dot{Q}_{Battery} = 16.95\ W$$

HCU
BackUP Slides

HCU Components

ATmega32/L Microprocessor

- Operational Temperature Range: -55℃ to 125℃
- Operational Voltage Range: 2.7V to 5.5V
- DC Current per I/O pin: 40 mA
- Data Processing:
  - 9600 Baud Rate (0.2% Error)
  - 8 Channel, 10-bit ADC
  - 4 PWM Channels



HCU Components

LM35 Temperature Sensor

Operational Temperature Range: -55℃ to 150℃

Operational Voltage Range: 4V to 30V

Current Draw: 60μA

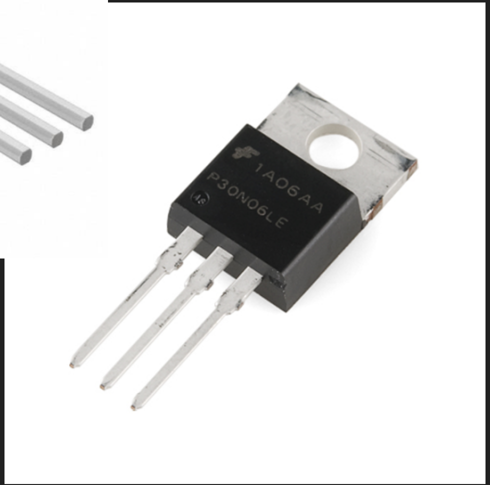
Accuracy: ±0.25℃

MOSFET (RFP30N06LE)

Operational Temperature Range: -55℃ to 75℃

Start Time: 140 ns Rise Time: 88 ns

Delay Time: 11 ns Fall Time: 40n ns



Initial Energy BackUP Slides

Trade Study Result Analysis

Low Temperature Batteries

- 3.6V, 19Ah Primary Lithium chosen

- *PROS:*
  - Operating Temperature: -55C to 85C, well within our operating envelope
  - High power capacity and density
- *CONS:*
  - Non-rechargeable
  - Voltage is approximately 2.5V at -50F
  - Can only source <150mA before cells are damaged
    - 375mW per battery
  - Would require 54 batteries to get the necessary power
    - Very costly ($20.00 x 54 + shipping + tax > $1080.00)

RC Circuit Equations

- Battery heat transfer

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

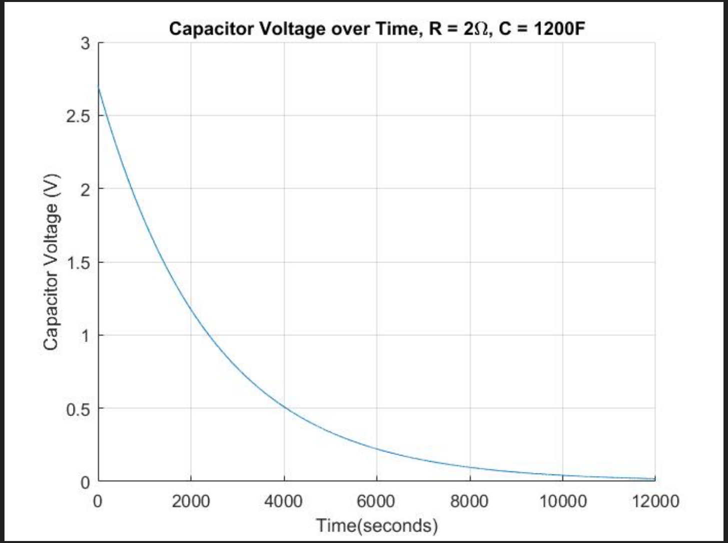
$$\dot{Q}_{in} = power\ in\ (W\ or\ J/s)$$
$$q_{in} = energy\ in\ (J)$$
$$m = mass(kg)$$
$$c_p = coefficient\ of\ temperature\ (J/_{kgK})$$
$$\Delta T = change\ in\ temperature\ (K)$$
$$dt = change\ in\ time\ (s)$$

Management of Supercapacitors

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

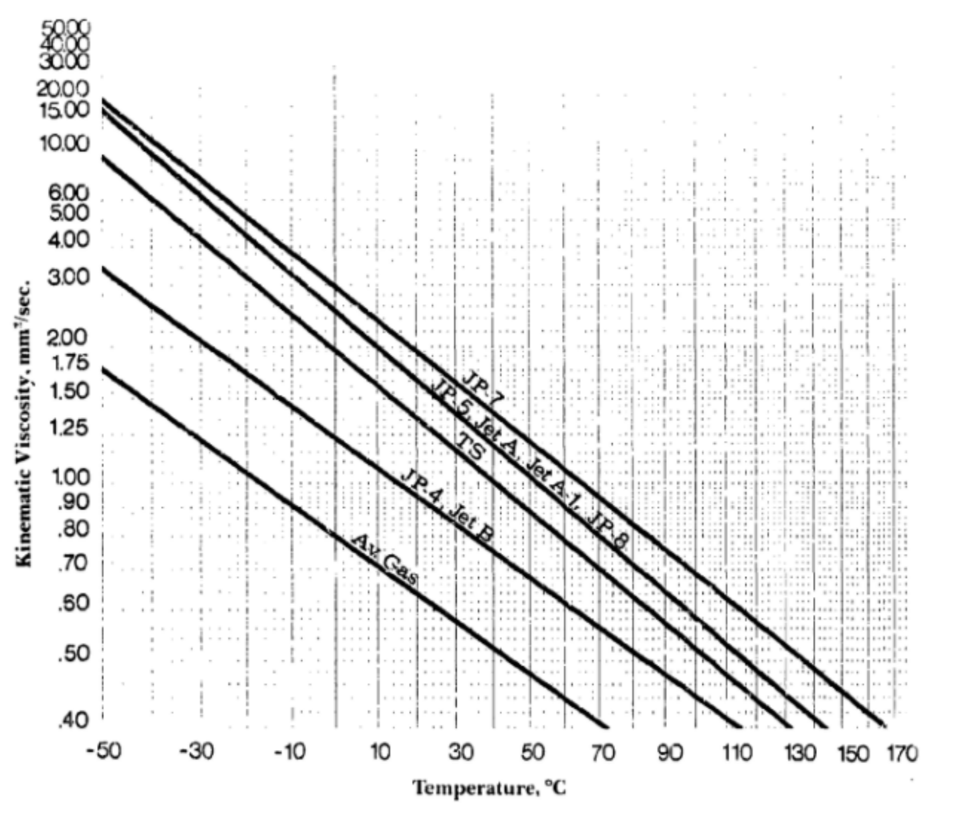
1. The team will never handle a charged capacitor without proper safety equipment
   a. Thermal and electrical insulation will need to be worn.

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



Fuel Delivery System Backup Slides

Viscosity vs Temperature



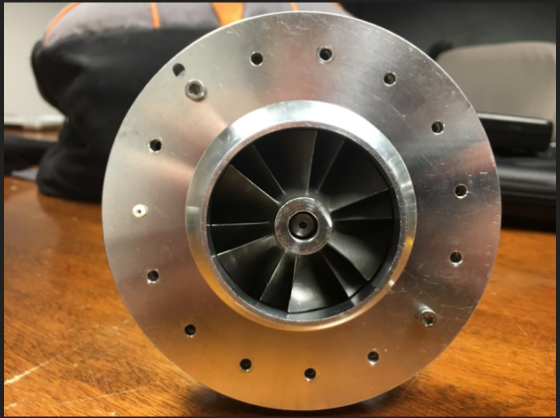
Structures BackUP Slides

Engine Structural Feasibility -Blade Tolerances

Compressor Blade Clearances

Blade material: Inconel
Housing material: 6061 Aluminum

Blade radius: 23.385 +/- 0.0005 mm
Housing radius: 23.400 +/- 0.0005 mm
Clearance: 0.1905 +/- 0.01275mm



Turbine Blade Clearances

Blade material: Inconel
Housing material: Inconel

Blade radius: 33.235 +/- 0.0005 mm
Housing radius: 33.550 +/- 0.0005 mm
Clearance: 0.1397 +/- 0.01275 mm

Engine Structural Feasibility -Blade Tolerances (Cont.)

	r_n (mm) [Housing radius]	ℓ_n (mm) [Blade length]
Compressor	23.3825	23.3494
Turbine	33.5249	33.2102

Thermal expansion for 1D material (blade): $\ell_n = \ell_0 \cdot (1 + \alpha \cdot \Delta T)$

Thermal expansion for a ring (housing): $r_n = r_o \cdot (1 + \alpha \cdot \Delta T)$

For structural integrity: $r_n > \ell_n$

- $\Delta T = -65$ C
- $\alpha_{inc} = 23.4 \cdot 10^{-6}$ [C^{-1}] (for Inconel)
- $\alpha_{Al} = 11.5 \cdot 10^{-6}$ [C^{-1}] (for Al-6061)

Engine Structural Feasibility
-Bearing Analysis

Bearing and Housing radii [mm]:

- Material: Stainless Austenitic Steel 304 *
- Housing material: Aluminum 6061
- Ball material: Silicon Nitride (Si_3N_4)
- Bearing diameter: 21.98 +/- 0.01
- Housing diameter: 21.92 +/- 0.01

*Also material of shaft

Engine Structural Feasibility -Bearing Analysis (Cont.)

- Because bearing and shaft have same material properties, will contract at same rate
  - Concern: shaft casing

	r_n (mm) [housing radius]	ℓ_n (mm) [bearing radius]
Ball Bearing	21.9036	21.9553

Thermal expansion for 1D material (bearing): $\ell_n = \ell_0 \cdot (1 + \alpha \cdot \Delta T)$

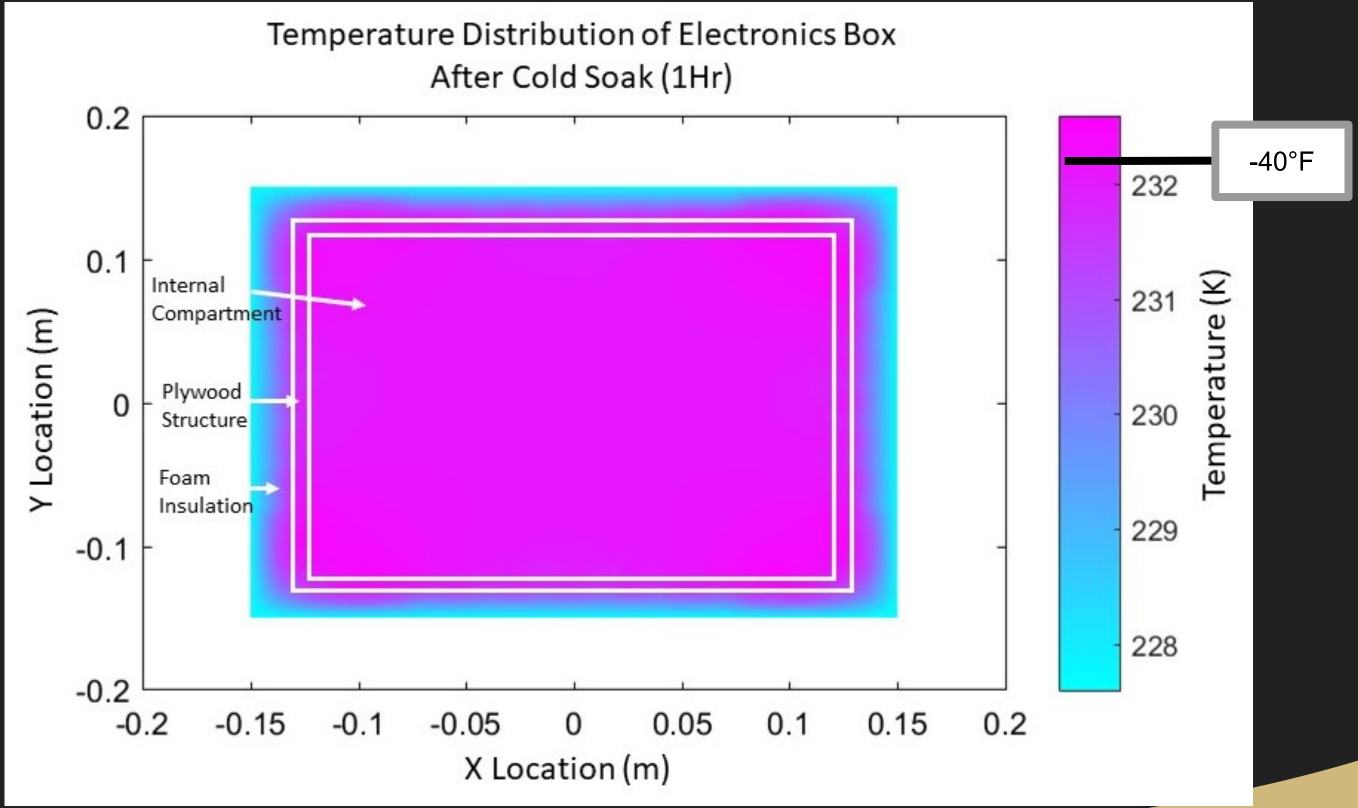
Thermal expansion for a ring (housing): $r_n = r_o \cdot (1 + \alpha \cdot \Delta T)$

For structural integrity of ball bearing in housing: $r_n < \ell_n$

- $\Delta T = -65$ C
- $\alpha_{Steel} = 17.3 \cdot 10^{-6}$ [C^{-1}] (for Stainless Steel Austenitic 304)
- $\alpha_{Al} = 11.5 \cdot 10^{-6}$ [C^{-1}] (for Al- 6061)

Electronics Heating BackUP Slides

Cooling of Electronics Box



BUdget BackUP Slides

Projected Budget

1. Initial power and batteries ~$270
   a. About 6 cold temperature batteries at $20 each plus $10 shipping=$135
   b. 2 LifePo batteries at $65 each plus $5 shipping=$135
   c. 2 LiPo batteries at $50 each plus $5 shipping=$105
2. HCU and Electronic Components ~ $1350
   a. 10 supercapacitors at $27 each plus $5 shipping=$275
   b. 100 ft of insulated resistive heating wire at $10/100ft plus $5 shipping=$15
   c. Development and Printing PCB $1000
3. Insulation ~ $65
   a. 2”x24”x82” Polyurethane foam at $50 plus $5 shipping=$55
   b. Plywood <$10
4. Testing ~ $120
   a. Dry Ice at $1-3 per pound, 10 pounds per test, 4 tests= $120

Known Total: $805

FEM Setup Slides

Fuel Line Parameters

- Used MATLAB's built in PDE tool
  - Numerical FEM Solver

Material Properties		
Material	**Polyurethane**	**Kerosene**
Density (kg/m^3)	1100	862.4
Specific Heat (J/kg*k)	1800	2010
Thermal Conductivity (W/m*k)	0.29	0.15
Coefficient of Heat Transfer (W/m^2*k)	22	N/A

Fuel Hopper Feasibility

- Used MATLAB's built in PDE tool
  - Numerical FEM Solver

Material Properties		
Material	**High Density Polyethylene**	**Kerosene**
Density (kg/m^3)	960	862.4
Specific Heat (J/kg*k)	2250	2010
Thermal Conductivity (W/m*k)	0.47	0.15
Internal Heat Generation (W/m^3)	0	193256 TS, 64419 SS
Coefficient of Heat Transfer (W/m^2*k)	22	N/A

Electronic Box Feasibility

- **Used MATLAB's built in PDE tool.**
  - **Numerical FEM Solver**

Material Properties			
Material	Polyurethane	Plywood	Air
Density (kg/m^3)	1100	680	1.569
Specific Heat (J/kg*k)	1800	1215	715.6
Thermal Conductivity (W/m*k)	0.29	0.12	0.0202
Coefficient of Heat Transfer (W/m^2*k)	22	N/A	N/A

Main Heater Parameters

- **Used MATLAB's built in PDE tool.**
  - **Numerical FEM Solver**

Material Properties		
Material	Lithium Polymer	Polyurethane
Density (kg/m^3)	2109.4	1100
Specific Heat (J/kg*k)	795	1800
Thermal Conductivity (W/m*k)	73.98	0.29
Coefficient of Heat Transfer (W/m^2*k)	N/A	40