A.C.E.S.
Air-breathing Cold Engine Start

Preliminary design Review

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

- 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

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- Dimensions:
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  - 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
- Initial Power Source
- Heating Control Unit
- Main Engine Battery
- Main Heater Battery
- Fuel Hopper Heating
- Insulated Electronics Housing
- Fuel Line Heating

AFRL Design Items
- JetCat P90-SXi
- Engine Sensor Board
- Engine Control Unit
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

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

**AFRL Competition:**

The 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

1) Carrier plane flies at 30,000 ft.
2) Carrier releases UAS with redesigned JetCat engine.
3) Engine startup sequence is initiated (see project ConOps).
4) Engine starts and produces thrust (see project ConOps).
5) Engine provides enough thrust to avoid the ground.

Safe distance above ground (100 ft)
1. Cold Soak at -50°F for 1 hr

2. Initiate Start-up Heaters

3. Power Up ECU and Initiate Fuel Flow

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
Cold temperature batteries provide power to the HCU

HCU commands RC circuits to begin heating main heater battery

Main heater battery provides power to the FDS and EHS

Electronics housing reaches operational temperature of 60°F

Fuel in hopper and in fuel lines reaches operational temperature of 60°F

Engine battery provides power to the ECU

ECU initiates fuel pump

Fuel flows through the fuel lines at a rate of 4.8 g/s
Functional Block Diagram
Initial Energy Feasibility
### Initial Energy Trade Study

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weights</th>
<th>Chemical</th>
<th>Mechanical</th>
<th>Low-Temp Electronics</th>
<th>Cold Soak Active Heater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>0.3</td>
<td>4</td>
<td>2</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>0.25</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Safety</td>
<td>0.15</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Start-up Time</td>
<td>0.15</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Team Experience</td>
<td>0.1</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>0.05</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>3.1</td>
<td>2.5</td>
<td>4.7</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Initial Energy Design

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

The voltage $V(t)$ as a function of time $t$ is given by:

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

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

The current $I(t)$ as a function of time $t$ is given by:

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

Where:
- $I(t)$ = 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

Temperature Distribution Main Heater Battery (480 sec, 19 W)

Y Location (m)

X Location (m)

Homogenous Temperature Range

Temperature (K)

272.05
272
271.95
271.9

30°F
Fuel Delivery System
System Layout

- **Fuel Hopper**
- **Larger Fuel Line**
- **Fuel Pump**
- **Smaller Fuel Line**

**Flow to engine**

- 7.5 cm
- 76.0 cm
- 5.5 cm
- 25.0 cm
## Fuel System Trade Study

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weights</th>
<th>Resistive Heating</th>
<th>Fuel Additive</th>
<th>Circulating Fluid</th>
<th>Pressurized Fuel</th>
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<tbody>
<tr>
<td>Manufacturability</td>
<td>0.3</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Reliability</td>
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<td>4</td>
<td>3</td>
<td>2</td>
<td>2</td>
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<tr>
<td>Power Consumption</td>
<td>0.15</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Safety</td>
<td>0.1</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Start-up Time</td>
<td>0.1</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Cost</td>
<td>0.1</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Final Score</td>
<td>~</td>
<td>3.85</td>
<td>4.05</td>
<td>2.8</td>
<td>2.65</td>
</tr>
</tbody>
</table>
How the Fuel Line Solution Works

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

Temperature Distribution of Fuel Lines
After Heating for (12.25W, 8 min)

- Fuel Line Wall
- Large Diameter Fuel Line
- Small Diameter Fuel Line

Y Location (m)
X Location (m)

Temperature Scale:
- 71°F
- 62°F

Fuel Line Heating Feasibility
Fuel Hopper Heating Analysis

Boundary Conditions For Fuel Hopper Simulations

- 657.1 W/m² (10W)
- 22 W/(m²*K)
- 193256 W/m² (30W)

X Location (m)

Y Location (m)
Fuel Hopper Heating Analysis

Temperature Distribution of Fuel Hopper
After Warm-up (8min, 40W)

- Kerosene
- High Density Polyethylene

Temperature (°F): 62°F
Electronics Heating System
## Electronics Heating Trade Study

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weights</th>
<th>Conductive Heating Element</th>
<th>Radiative Ceramic Resistor</th>
<th>Fluid Heating</th>
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<tr>
<td>Safety</td>
<td>0.3</td>
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<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Reliability</td>
<td>0.2</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Start-Up Time</td>
<td>0.2</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Power Consumption</td>
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<td>2</td>
<td>4</td>
</tr>
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<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Cost</td>
<td>0.05</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td><strong>4.45</strong></td>
<td><strong>4.1</strong></td>
<td><strong>2.9</strong></td>
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</table>
Electronics Housing
(Top View)
Electronics Housing Dimensions

- Electromagnetic Wave
- Polyurethane Foam: 2 cm
- Ambient Air
- Internal Air
- Direction of Heat Transfer
- Plywood Layer: .5 cm
Transient Electronics Heating

Boundary Conditions For Electronics Box

- 320 W/m² (1W)
- 22 W/(m²K)
- 227.6 K

Y Location (m)
-0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2

X Location (m)
-0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2

Foam
InnerBox
wood
Transient Electronics Heating

Temperature Distribution of Electronics Box After Warm-up (8min, 1W)

- Internal Compartment
- Plywood Structure
- Foam Insulation

X Location (m)

Y Location (m)

Temperature (K)

62°F
# Main Heater Battery Feasibility

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

## Heating Power Requirements

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Power Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDS Fuel Lines</td>
<td>12.25 W</td>
</tr>
<tr>
<td>FDS Fuel Hopper</td>
<td>40 W</td>
</tr>
<tr>
<td>Electronics Box</td>
<td>20 W</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>72.25 W</strong></td>
</tr>
</tbody>
</table>
Main Heater Battery Feasibility

Temperature Distribution of Main Heater Battery After Cold Soak (1Hr)

- X Location (m)
- Y Location (m)
- Temperature (K)

Boundary of Battery
Insulation

0°F
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
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
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
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

ACES BUDGET

- Initial Energy: $270
- HCU and Electronics Components: $350
- Insulation: $65
- Testing: $120
- Printing: $400
- AFRL: $1000
- Extra Budget: $1795

- Initial Energy
- HCU and Electronics Components
- Insulation
- Testing
- Printing
- AFRL
- Extra Budget
- PCB Manufacturing

meta-chart.com
Gantt Chart

<table>
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<tr>
<th>Oct '17</th>
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<th>Dec '17</th>
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<tr>
<td>4</td>
<td>8</td>
<td>15</td>
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<tr>
<td>22</td>
<td>29</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>29</td>
<td>26</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>17</td>
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**PDR**
- Initial Energy, FDS, EHS, and HCU Models
- 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
- Slide Improvement
- CDR Due

**Fall Final Report**
- Report Writing
- Report Due
The team would like thank the following people for their assistance in this project.

- John Evans
- Donna Gerren
- Bobby Hodgkinson
- Dale Lawrence
- James Nabity
- Matt Rhode
- Trudy Schwartz
Sources

- MATLAB pdetool
Questions?
Backup Slides
Basic Change in Heat Equation for Warming of System Components

- Equation Used: \( \dot{Q}_{\text{req}} = \frac{mc_p(T_{\text{final}} - T_{\text{initial}})}{\text{Time}} \)

- Time = 8 minutes
- Temp final = 290 K (62 °F)
- Temp Initial = 227.6 K (-50 °F)

Results:
\[ \dot{Q}_{\text{tubing}} = 2.242 \, W \]
\[ \dot{Q}_{\text{Hopper}} = 32.9 \, W \]
\[ \dot{Q}_{\text{Electronics Box}} = 0.47 \, W \]
\[ \dot{Q}_{\text{Battery}} = 16.95 \, W \]
HCU
BackUP Slides
HCU Components

ATmega32/L Microprocessor
- Operational Temperature Range: -55°C to 125°C
- 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°C to 150°C
- Operational Voltage Range: 4V to 30V
- Current Draw: 60μA
- Accuracy: ±0.25°C

MOSFET (RFP30N06LE)
- Operational Temperature Range: -55°C to 75°C
- Start Time: 140 ns  Rise Time: 88 ns
- Delay Time: 11 ns  Fall Time: 40n ns
Initial Energy
BackUP Slides
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

\[ \dot{Q}_{in} = mc_p \Delta T \]
\[ q_{in} = mc_p \Delta T \, dt \]

\[ \dot{Q}_{in} = \text{power in (W or J/s)} \]
\[ q_{in} = \text{energy in (J)} \]
\[ m = \text{mass (kg)} \]

\[ c_p = \text{coefficient of temperature (J/kgK)} \]
\[ \Delta T = \text{change in temperature (K)} \]
\[ dt = \text{change in time (s)} \]
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 +/- 0.01275 mm

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.)

<table>
<thead>
<tr>
<th></th>
<th>( r_n ) (mm) [Housing radius]</th>
<th>( \ell_n ) (mm) [Blade length]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>23.3825</td>
<td>23.3494</td>
</tr>
<tr>
<td>Turbine</td>
<td>33.5249</td>
<td>33.2102</td>
</tr>
</tbody>
</table>

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

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

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

For structural integrity: \( r_n > \ell_n \)
Bearing and Housing radii [mm]:

- Material: Stainless Austenitic Steel 304 *
- Housing material: Aluminum 6061
- Ball material: Silicon Nitride \((\text{Si}_3\text{N}_4)\)
- 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

<table>
<thead>
<tr>
<th></th>
<th>( r_n ) (mm) [housing radius]</th>
<th>( \ell_n ) (mm) [bearing radius]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball Bearing</td>
<td>21.9036</td>
<td>21.9553</td>
</tr>
</tbody>
</table>

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: \( r_n < \ell_n \)

- \( \Delta T = -65 \, \text{C} \)
- \( \alpha_{\text{Steel}} = 17.3 \cdot 10^{-6} \, \text{[C}^{-1}] \)
  (for Stainless Steel Austenitic 304)
- \( \alpha_{\text{Al}} = 11.5 \cdot 10^{-6} \, \text{[C}^{-1}] \)
  (for Al-6061)
Electronics Heating BackUP Slides
Cooling of Electronics Box

Temperature Distribution of Electronics Box
After Cold Soak (1Hr)

-40°F
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
- Used MATLAB’s built in PDE tool
  - Numerical FEM Solver

### Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Polyurethane</th>
<th>Kerosene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>1100</td>
<td>862.4</td>
</tr>
<tr>
<td>Specific Heat (J/kg*k)</td>
<td>1800</td>
<td>2010</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m²*k)</td>
<td>0.29</td>
<td>0.15</td>
</tr>
<tr>
<td>Coefficient of Heat Transfer (W/m²*k)</td>
<td>22</td>
<td>N/A</td>
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</tbody>
</table>
Fuel Hopper Feasibility

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

### Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>High Density Polyethylene</th>
<th>Kerosene</th>
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</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>960</td>
<td>862.4</td>
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<tr>
<td>Specific Heat (J/kg*k)</td>
<td>2250</td>
<td>2010</td>
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<tr>
<td>Thermal Conductivity (W/m*k)</td>
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<tr>
<td>Internal Heat Generation (W/m³)</td>
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<td>193256 TS, 64419 SS</td>
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<tr>
<td>Coefficient of Heat Transfer (W/m²*k)</td>
<td>22</td>
<td>N/A</td>
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</table>
Electronic Box Feasibility

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

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Polyurethane</th>
<th>Plywood</th>
<th>Air</th>
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</thead>
<tbody>
<tr>
<td>Material</td>
<td>Polyurethane</td>
<td>Plywood</td>
<td>Air</td>
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<tr>
<td>Density (kg/m$^3$)</td>
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<td>680</td>
<td>1.569</td>
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<tr>
<td>Specific Heat (J/kg*k)</td>
<td>1800</td>
<td>1215</td>
<td>715.6</td>
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<tr>
<td>Thermal Conductivity (W/m*k)</td>
<td>0.29</td>
<td>0.12</td>
<td>0.0202</td>
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<tr>
<td>Coefficient of Heat Transfer (W/m$^2*$k)</td>
<td>22</td>
<td>N/A</td>
<td>N/A</td>
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</tbody>
</table>
Main Heater Parameters

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

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Lithium Polymer</th>
<th>Polyurethane</th>
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<tbody>
<tr>
<td>Material</td>
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<tr>
<td>Density (kg/m³)</td>
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<td>Specific Heat (J/kg*k)</td>
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<td>Thermal Conductivity (W/m*k)</td>
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<td>Coefficient of Heat Transfer (W/m²*k)</td>
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