A.C.E.S.

Air-Breathing Cold Engine Start

Critical 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
Project Objectives

Design Solution

Critical Project Elements

Design Requirements Satisfaction

Project Risks

Verification and Validation

Project Planning
PROJECT OBJECTIVES
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

24 cm
**Project Scope**

**Course Design Items**
- Heating Control Unit
- Main Engine Battery
- Fuel Pump
- Fuel Hopper Heating
- Main Heater Battery
- Fuel Line Heating

**AFRL Design Items**
- Engine Sensor Board
- Engine Control Unit
- JetCat P90-SXi
- Insulated Electronics Housing
- Fuel Line Heating
## Course Project Objectives

<table>
<thead>
<tr>
<th>Fuel Delivery System (FDS)</th>
<th>Electronics Heating</th>
<th>Startup Time</th>
<th>AFRL Competition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System will control mass flow rate &amp; temperature of fuel when placed in an environment cold-soaked to -30°F.</td>
<td>The electronics will be heated to 60°F after being placed in an environment 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><strong>Level 2</strong></td>
<td></td>
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</tr>
<tr>
<td>System will control mass flow rate &amp; temperature of fuel when placed in an environment cold-soaked to -40°F.</td>
<td>The electronics will be heated to 60°F after being placed in an environment 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>
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</tr>
<tr>
<td><strong>Level 3</strong></td>
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<tr>
<td>System will control mass flow rate &amp; temperature of fuel when placed in an environment cold-soaked to -50°F.</td>
<td>The electronics will be heated to 60°F after being placed in an environment cold-soaked to -50°F.</td>
<td>The fuel delivery and electronics heating systems objectives will be completed in less than 8 minutes.</td>
<td></td>
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<tr>
<td><strong>Level 4</strong></td>
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<tr>
<td></td>
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<td></td>
<td>Entire system will be integrated with engine and successfully start within 3 hours.</td>
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</tbody>
</table>

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**AFRL Competition**

The entire system will be integrated with engine and successfully start within 3 hours.
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.

6) Aircraft is capable of providing ground surveillance.

Safe distance above ground (100 ft)
**PROJECT CONOPS**

1. **Cold Soak in -50°F Environment**
   - Cold Soak in -50°F Environment

2. **Initiate Start-up Heaters**
   - Initiate Start-up Heaters

3. **Initiate Fuel Flow**
   - Initiate Fuel Flow

-50°F Boundary
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
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

- **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
Cold temperature batteries provide power to the HCU

HCU commands main heater battery to provide power to heating elements

Electronics and FDS are heated

ECU & ESB reach operational temperature as dictated by HCU

Fuel in hopper and in fuel lines reaches desired temperature as dictated by HCU

HCU commands fuel pump to provide fuel to engine at desired rate

Fuel enters engine at desired flow rate & temperature
Functional Block Diagram
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

- Engine Battery
- Main Heating Battery
- HCU
- Cold Temp Batteries
- ECU
- Fuel Hopper
- Large Fuel Line
- Small Fuel Line
- Fuel Pump

Dimensions:
- 29 cm
- 8 cm
- 24 cm

To engine
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.
Min HCU Temp -57 °F
Min LiPo Temp 30 °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
Placement of Resistive Wire & Temperature Sensors

- **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)

**Legend**
- Resistive Wire
- Temperature Sensor
- Power Resistor

Dimensions:
- 24 cm
- 29 cm
- 11 cm
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

- Engine Body
- Engine Cowling
- Solenoid
- Engine Sensor Board
- Resistive Heaters

Dimensions:
- 24 cm
- 11 cm
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

Direction of Gravity

ESB

Solenoid

Temperature [°F]

Cut Plot 1: contours

1.43 °F

-2.03 °F
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**
  - **ESB Temp**
    - Max ESB Temp: 150.00°F
    - Min ESB Temp: 66.14°F
  - **ESB warming**
  - **FR 3 ✓**

- **Direction of Gravity**

- **Solenoid**

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

### Power Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (W)</th>
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</thead>
<tbody>
<tr>
<td>Electronics</td>
<td>89.45 W</td>
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<tr>
<td>Housing Power</td>
<td>20 W</td>
</tr>
<tr>
<td>ESB Power</td>
<td>0.45 W</td>
</tr>
<tr>
<td>Total Power Budget</td>
<td>109.45 W</td>
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</table>

**FR 1: Energy ✅**
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
- 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
CPE 4: Construct a Heating Control Unit (HCU) which will control the mass flow rate and heating systems.
**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**

Diagram showing the layout with various labeled components.
**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
SOFTWARE DESIGN IMPLEMENTATION
Software Design Implementation

Master Flowchart

Stage 1

Begin Port and Alive LED Initialization

Toggle MOSFETS for warming circuits
SOFTWARE DESIGN IMPLEMENTATION
SOFTWARE DESIGN IMPLEMENTATION
SOFTWARE DESIGN IMPLEMENTATION
FR 4.1 ✓

- Temperature Control
SOFTWARE DESIGN IMPLEMENTATION
FR 4.2 ✔
- Flow control
**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

<table>
<thead>
<tr>
<th></th>
<th>Minimal</th>
<th>Minor</th>
<th>Major</th>
<th>Hazardous</th>
<th>Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Damage</strong></td>
<td>None</td>
<td>None</td>
<td>Considerable component damage</td>
<td>Serious</td>
<td>Irreparable</td>
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<tr>
<td><strong>Project Performance</strong></td>
<td>Marginal Decrease</td>
<td>Substantial Decrease</td>
<td>Unsatisfactory for Requirements</td>
<td>Unsatisfactory for Requirements</td>
<td>Unsatisfactory for Requirements</td>
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<tr>
<td><strong>Budget Impact</strong></td>
<td>No Cost Increase</td>
<td>Minor Cost Increase</td>
<td>Substantial Cost Increase</td>
<td>Serious Cost Increase</td>
<td>Unrecoverable Cost Increase</td>
</tr>
<tr>
<td><strong>Schedule Impact</strong></td>
<td>None</td>
<td>Minor</td>
<td>Substantial</td>
<td>Serious</td>
<td>Unrecoverable</td>
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</table>
# Pre Mitigation Risk Assessment Matrix

<table>
<thead>
<tr>
<th></th>
<th>Minimal</th>
<th>Minor</th>
<th>Major</th>
<th>Hazardous</th>
<th>Catastrophic</th>
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<tbody>
<tr>
<td><strong>Near Certainty</strong></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td><strong>Very Likely</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Likely</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Unlikely</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Very Unlikely</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>Minimal</th>
<th>Minor</th>
<th>Major</th>
<th>Hazardous</th>
<th>Catastrophic</th>
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<tbody>
<tr>
<td><strong>Near Certainty</strong></td>
<td></td>
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<tr>
<td><strong>Very Likely</strong></td>
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<tr>
<td><strong>Likely</strong></td>
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<td><strong>Unlikely</strong></td>
<td>2, 3</td>
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<tr>
<td><strong>Very Unlikely</strong></td>
<td></td>
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<td>1, 4, 5, 8</td>
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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
**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**

<table>
<thead>
<tr>
<th>Test Environment</th>
<th>Environmental Chamber</th>
<th>Dry Ice Chamber</th>
<th>Dry Ice and Cottonseed Oil Bucket</th>
<th>AFRL Test Chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applicable Tests</td>
<td>-Main heater battery with wiring and insulation</td>
<td>-HCU operation</td>
<td>-Fuel lines integrity</td>
<td>-Final system integration with JetCat engine</td>
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<tr>
<td></td>
<td>-Full box integration and validation</td>
<td>-Fuel pump verification of operation</td>
<td></td>
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</table>
Available TEST ENVIRONMENTS

Environmental Chamber

Dry Ice Chamber

Liquid Cold Soak

Available

Planned to be built
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 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.
**Equflow 0045**
- Flow Rate 0.1-2 L/min with 110,000 pulses/L ($\pm 0.00135$ g/s)
- Requirement: $\pm 0.13$ g/s

**NI DAQ USB-6009**
- 6 R-type thermocouples
- $\pm 2.7^\circ$F, +/-1V accuracy of 1.53mV
- Requirement: $\pm 3.6^\circ$F

**Omega Type J-K Thermocouple**
- Accuracy of $\pm 0.05^\circ$F
- Requirement: $\pm 0.5^\circ$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
Dr. Donna Gerren  
*Project Advisor*

Lt. Carol Bryant  
*AFRL Customer*

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**ACES**

Dr. James Nabity  
*Campus Liaison*

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**T.R. Mitchell**  
*Financial Lead*

**Lucas Sorensen**  
*Project Manager*

**Nicholas Taylor**  
*Systems Engineering Lead*

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**ELECTRONICS TEAM**

- Alex Bertman  
  *Electronics Lead*
- Nicholas Moore  
  *Software Lead*
- Alexander Johnson  
  *Electrical Hardware Lead*

**MANUFACTURING & TESTING TEAM**

- Matthew McKernan  
  *Testing and Safety Lead*

**THERMAL MODELING TEAM**

- Tristan Isaacs  
  *Heat Transfer Lead*
- Matthew Robak  
  *Fluids Lead*
Work Breakdown Structure

ACES

Course Deliverables
- CDR
- FFR
- MSR
- TRR
- AIAA Paper
- SFR
- PFR

Management
- Schedule
- WBS
- Risk Matrix
- Budget

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

Testing
- Cold Temp Battery
- Fuel Pump Characterization
- Model Verification
- Test Result Analysis

Systems Integration
- HCU - FDS integration
- HCU - Electronics Housing Integration
- Full Systems Integration

ACES

Complete at CDR

Incomplete at CDR

Spring Logistics

WBS

Risk Matrix

Schedule

PCB Design

Electronics Box Design

1-D Models

Model Verification

Test Result Analysis

Cold Temp Battery

Fuel Pump Characterization

Main Heater Battery Insulation

Fuel Pump

Fuel Line Integrity

HCU Operation

Fuel Flow

Final Integration Test

HCU - FDS integration

HCU - Electronics Housing Integration

Full Systems Integration

Spring Logistics

PCB Design

Software Architecture

Software Development

PCB Fabrication

Software Verification

HCU Verification

ACES

Complete at CDR

Incomplete at CDR
Work Plan - Gantt Chart

Winter Break
Cost Plan

ACES Budget

- Initial Energy Circuit and HCU: $541.27
- Custom Electronics: $1,000.00
- Fuel Delivery System: $556.28
- Heating Components/Insulation: $542.10
- Electronics Housing Supplies: $183.39
- Testing Costs: $245.32
- Traveling Costs for Competition: $1,000.00
- Printing Costs: $400.00
- Extra Budget: $531.64

Total Budget: $3,539.88
## TESTING SCHEDULE AND PLANNING

<table>
<thead>
<tr>
<th>Test to be Conducted</th>
<th>Applicable Functional Requirements</th>
<th>Date Scheduled</th>
<th>Test Plan Complete</th>
<th>Materials Acquired</th>
<th>Test Complete</th>
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<tbody>
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<td>HCU Cold Temp Battery</td>
<td>4.1</td>
<td>11/5/2017</td>
<td>☑</td>
<td>☑</td>
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<td>Main Heater Battery w/ Insulation</td>
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<td>2/9/2018</td>
<td>☑</td>
<td>☺</td>
<td>☒</td>
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<td>☒</td>
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<td>Fuel Line integrity</td>
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<td>☒</td>
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<td>4.1, 4.2</td>
<td>3/23/2018</td>
<td>☺</td>
<td>☺</td>
<td>☒</td>
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<tr>
<td>Full Box Integration and Validation 1</td>
<td>2.1, 2.2, 3.0</td>
<td>3/30/2018 &amp; 4/6/2018</td>
<td>☺</td>
<td>☒</td>
<td>☒</td>
</tr>
</tbody>
</table>

**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
The team would like to 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

- MATLAB pdetool
- SOLIDWORKS and SOLIDWORKS flow simulation
- Steady Heat Conduction, [https://www.sfu.ca/~mbahrami/ENSC%20388/Notes/Steady%20Conduction%20Heat%20Transfer.pdf](https://www.sfu.ca/~mbahrami/ENSC%20388/Notes/Steady%20Conduction%20Heat%20Transfer.pdf)
- Thermo Scientific Nalgene Bottles, [https://tools.thermofisher.com/content/sfs/brochures/D01705.pdf](https://tools.thermofisher.com/content/sfs/brochures/D01705.pdf)
Backup Slides
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

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Fuel Lines</td>
<td>6.824 ft</td>
<td>6.005 Ω</td>
<td>3.697</td>
<td>82.07</td>
</tr>
<tr>
<td>Fuel Hopper</td>
<td>14.157 ft</td>
<td>12.458 Ω</td>
<td>1.782</td>
<td>39.56</td>
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</tbody>
</table>

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
HCU

BACKUP SLIDES
HCU ALTUIM 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: $V_0 = V_{ref}$
  - $V_0 = V_{ref} \times (1 + \frac{R_2}{R_1}) + (I_{adj} \times R_2)$
- 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
- $k=0.015 \text{ W/m}^*\text{K}$
- $\rho=160 \text{ kg/m}^3$
- 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.
INTERNAL RESISTANCE OF BATTERY
RC CIRCUIT EQUATIONS

- Battery heat transfer

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

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

RC Circuit

Positive Lead
Banana Plug-ins
Negative Lead

C 1230 F

DPDT Switches to simplify design

R 2k

HCU

Signal from HCU

RC Circuit

RC Circuit

RC Circuit

RC Circuit

RC Circuit

RC Circuit

R 10kΩ
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

Charging Circuit

240 V

AC/DC Power Adapter to 5V SMAKN

TPS74041

1 = IN
2 = EN
3 = BIAS
4 = SS
5 = GND
6 = FB
7 = OUT
8 = PG

Rpullup 50kΩ
R1 2.375kΩ
R2 1kΩ

Charging

8 Positive Leads (Banana Plugs) to RC circuits

Recharge 1Ω

+Vcc = 5V

R 50kΩ

LED

Inverting Comparator

8 Negative Leads (Banana Plugs) to RC circuits
Initial Energy Discharge Circuit

Discharge Circuit

8x

- 5 V
- R 1k Ω
- R 0.5Ω
- R 50k Ω
- Positive Lead
- Negative Lead
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 past 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
Custom ECU design provided by REAPER
  ○ Hall Effect Sensor issues
    ■ Mitigated by Andrew Quinn
      ● Schmitt Trigger
  ○ Schematics available to team
Reaper ECU

Components:
- Atmega256A3-AU
- RS422 Receiver/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-00097 Push Button Reset
- ISP Programmer Header
- MicroUSB Header
- Multiple Resistors, Capacitors, Diodes
Fuel Delivery System
Backup Slides
Jet Fuel Viscosity vs Temperature
FEM SETUP SLIDES
## Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Nickel Chromium</th>
<th>Aerogel</th>
<th>Lithium Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>8400</td>
<td>160</td>
<td>2109.4</td>
</tr>
<tr>
<td>Specific Heat (J/kg$^\circ$k)</td>
<td>450</td>
<td>2000</td>
<td>795</td>
</tr>
<tr>
<td>Thermal Conductivity (W/m$^\circ$k)</td>
<td>11.3</td>
<td>0.015</td>
<td>73.98</td>
</tr>
</tbody>
</table>
Transient Model
Backup Slides
COOLING OF ELECTRONICS BOX

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

-40°F
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

X Location (m)  Y Location (m)
0 0
0.2 0.005
0.4 0.005
0.6 0.005
0.8 0.005
1 0

Y-axis: Fuel Line Wall
X-axis: Large Diameter Fuel Line, Small Diameter Fuel Line

Temperature Scale:
- 295°C (71°F)
- 290°C (62°F)
Temperature Distribution of Fuel Lines During Flow (6 sec)

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

Temperature (°F): 62°F
Fuel Hopper Heating Analysis

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

- Kerosene
- High Density Polyethylene

Temperature (K)
- 305
- 300
- 295
- 290

Y Location (m)
- 0.07
- 0.06
- 0.05
- 0.04
- 0.03
- 0.02
- 0.01
- 0
- -0.01

X Location (m)
- 0.07
- 0.06
- 0.05
- 0.04
- 0.03
- 0.02
- 0.01
- 0
- -0.01

62°F
Transient Electronics Heating

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

- Internal Compartment
- Plywood Structure
- Foam Insulation

Temperature (K):
- 290
- 280
- 270
- 260
- 250
- 240
- 230

X Location (m):
-0.2 to 0.2

Y Location (m):
-0.2 to 0.2

62°F
Main Heater Battery Feasibility

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

- Boundary of Battery
- Insulation

0°F
verification and validation backup slides
summary of test process

1. Creation of Test and Safety Plan
2. Review of Test and Safety Plan with PAB
3. Test Setup and Operations Coordination
4. 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

Result of accidental battery discharge via multimeter

+ 0.1 V
- 0.1 V
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**
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
- Useable 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

Useable Volume: 1932 in³

Internal Chamber Temperature of ~50°F
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 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 \(4.8 \pm 0.1\) 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.*
Objective:

- Determine if the minimum operational temperature of the stock fuel lines is above \(-50^\circ F\).

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 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
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)

\[
227.6 \, K = \frac{0.038783 \, kg}{0.038783 \, kg + x} \times (294.3 \, K) + \frac{x}{0.038783 \, kg + x} \times (194.7 \, K)
\]

\[
8.82704 + 227.6x = 11.4139 + 194.7x
\]

\[
1.16898 \, x = 2.58683 \implies 2.2129 \, kg \, of \, Dry \, Ice \, Needed
\]

= 4.8786 lbs or \textit{1/2 Block of Dry Ice}
Test Chamber Calculations

Cottonseed Oil Test Chamber

- 2.5 gallons of cottonseed oil = 8.75376 kg
- $\rho_{CSO}=0.925 \text{ g/cm}^3$
- 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)

\[
227.6 \text{ K} = \frac{8.75376 \text{ kg}}{(8.75376 \text{ kg} + x) \times (294.3 \text{ K})} + \frac{x}{(8.75376 \text{ kg} + x) \times (194.7 \text{ K})}
\]

\[
1992.355 + 227.6x = 2575.8814 + 194.7x
\]

\[
32.95x = 583.525 \Rightarrow 17.709 \text{ kg of Dry Ice Needed}
\]

\[
= 39.042 \text{ lbs or 4 Blocks of Dry Ice}
\]
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

- Equiflow 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
Heating