REcuperating Advanced Propulsion Engine Redesign

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Presentation Agenda

• Project Overview
• Schedule
• Manufacturing
• Budget
Overview

Model, build, implement, and verify an integrated recuperative system into a JetCat P90-RXi miniature turbojet engine for increased fuel efficiency from its stock configuration.
Concept of Operations

Kerosene Fuel

Modified P90-RXi

Fuel Flow Sensor

Load Cell, Thermocouples

Transmitter

Engine Control Unit

Computer

SD Card

NI DAQ Chassis

Receiver
Baseline Design: Flow Path

1. Engine Starts Up
2. Air Enters Compressor
3. Air Passes Along Outside of Casing
4. Air Enters Recuperator
5. Recuperator Heats Passing Air
6. Air Enters Combustor
7. Exhaust Passes through Turbine
8. Exhaust heats Recuperator Manifold
<table>
<thead>
<tr>
<th>Levels of Success</th>
<th>Simulation</th>
<th>Recuperator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>- Develop first order, steady state model - Model heat exchanger effectiveness, specific fuel consumption and thrust - Recuperator designed and manufactured - Recuperator verified with engine analog</td>
<td></td>
</tr>
<tr>
<td>Level 2</td>
<td>- Model transient characteristics - Recuperator is integrated onto engine - Integrate engine system starts and runs</td>
<td></td>
</tr>
<tr>
<td>Level 3</td>
<td>- Develop CFD model - Model is verified with test data - Engine system operates for throttle range - Engine system meets design requirements</td>
<td></td>
</tr>
</tbody>
</table>

(CPE 1 - Model) (CPE 2 - Heat Exchanger) (CPE 3 - Engine Electronics) (CPE 4 - Testing)
Schedule

Electronics & Software

Key:
- Completed
- Planned Time
- Allotted Margin

Electronics
- Protoboard
- ECU: Engine Control Unit
- ESB: Electronic Sensor Board

Software
- Engine Control

Manufacturing
- SolidWorks Model
- Nozzle/Heat Exchanger
- Nozzle Shroud
- End Cap
- Forward Ring
- Forward Brackets
- Mounting Blocks
- Casings
- Misc. Assembly Hardware
- Final Integration

Testing
- Level One Test
- ECU & ESB Stock Engine Test
- Final Full System
- Manufacturing Spring Review
- Test Readiness Review
- AIAA Report
- Design Symposium
- Spring Final Review

Key:
- Completed
- Planned Time
- Allotted Margin

Electronics

Testing
Mechanical
Manufacturing: Parts Video

- Simulated Hanger
- Nozzle/Gigi Blocks (x4)
- Forward Ring
## Manufacturing: Overview

<table>
<thead>
<tr>
<th>Part</th>
<th>Manufacturing Method</th>
<th>Tolerance (inches)</th>
<th>Man Hours Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finned Nozzle</td>
<td>Direct Metal Laser Sintering</td>
<td>0.005</td>
<td>Completed</td>
</tr>
<tr>
<td>Inner/Outer Casing</td>
<td>Folsom Sheet Metal Roller</td>
<td>0.05</td>
<td>8 hours</td>
</tr>
<tr>
<td>Four Mounting Blocks</td>
<td>CNC Mill</td>
<td>0.005</td>
<td>7 hours</td>
</tr>
<tr>
<td>Two Forward Brackets</td>
<td>CNC Lathe, Manual Lathe, CNC Mill</td>
<td>0.005</td>
<td>11 hours</td>
</tr>
<tr>
<td>Forward Ring</td>
<td>CNC Mill and Lathe</td>
<td>0.005</td>
<td>9 hours</td>
</tr>
<tr>
<td>Nozzle Shroud</td>
<td>CNC Lathe</td>
<td>0.005</td>
<td>8 hours</td>
</tr>
<tr>
<td>End Cap</td>
<td>CNC Mill and Lathe</td>
<td>0.005</td>
<td>14 hours</td>
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</tbody>
</table>
Mounting Blocks: Location
Mounting Blocks: Manufacturing

- Use manual mill to square off stock piece
  ➢ 2 hours
- Use CNC mill to cut part out of stock and drill vertical holes
  ➢ 1.5 hours (x4)
- Band saw newly created piece from stock
  ➢ 0.5 hours (x4)
- Create fixture to hold mounting block while drilling horizontal hole
  ➢ 3 hours
- Drill horizontal hole
  ➢ 0.5 hours (x4)
Estimated Hours Remaining: 57 hours
Workforce: 5
Weekly Scheduled Hours: 53 hours
Scheduled Time after MSR: 159 hours
Engine Electronics
Engine Electronics

- 2 custom Printed Circuit Boards (PCBs)
- Designed in Altium
- Manufactured by Advanced Circuits
- Populated in house
- 1st revision received

Engine Sensor Board (ESB) - Printed Circuit Board
Engine Control Unit (ECU) - Altium Design
Engine Electronics: Status Update

Engine Control Unit

- MicroUSB Connector
- USB-UART Converter
- 16 MHz Crystal Oscillator
- SD Card
- RC Receiver
- Comparator
- Control Panel Connector
- Voltage Divider
- Power Connector
- Microprocessor (ATXmega256a3)
- RS-422 Receiver
- 3.3V Regulator
- Power Connector
- RS-422 Transmitter
- Digital Signal (SPI Data, RPM)
- Digital Signal (Actuator Control, SPI)
- Reset Button
- PWM
- Digital Signal

Engine Sensor Board

- RS-422 Transmitter
- Comparator
- Amplification
- Digital Signal
- Hall Effect
- Exhaust Gas Thermocouple
- Kerosene Pump
- Lubrication Solenoid
- Fuel Solenoid
- Starter Motor
- Glow Plug
- 5V
- 3.3V
- Voltage Differential
- 5V
- 3.3V
- Control
- Control
- Control
- Control
- Digital Signal
- Fuel Flow
- 3-cell LiPo (nominal 11.1V)
- Red LED
- Yellow LED
- Green LED
- Blue LED
- Arm Switch
- RunSwitch
- Status LEDs
- Power Switch
- Control Panel

Key:
- Populated, not tested
- Tested Successfully
- Incorrect, needs fix
Engine Electronics: Power

Power Plane Issue

Incorrectly Designed Vias
Engine Electronics: Summary

Estimated Hours Remaining: 60 hours
Workforce: 2
Scheduled Time after MSR: 90 hours
Engine Electronics: Software Progress

High Level

Final Implementation

Hardware Interface Layer

SD Card  Hall Effect  Thermocouples  Fuel Flow
Glow Plug  Starter motor

Low Level Interface

SPI  Oscillator  Interrupts  USART
PWM  I2C  EEPROM

KEY

Validated
Written
Incomplete
Testing
Testing: Level 1

Key Components:
- Verification of Thermal Model & Heat Exchanger
- Heat exchange data analysis
- Thermocouple VI
- Pitot Probe Velocity Recording
Testing: Level 3 (Full System Test)

- Fully Integrated Engine Test
- Ready:
  - Test stand available
  - LabVIEW VI’s created
- In Progress:
  - Sensor calibration
  - Stock engine with fuel flow
  - Engine electronics
  - Mechanical components
  - Data analysis code
Budget
Budget

<table>
<thead>
<tr>
<th>Category</th>
<th>Spent</th>
<th>Remaining Budget</th>
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<tbody>
<tr>
<td>Heat Exchanger</td>
<td>$1,234.22</td>
<td>$0.00</td>
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<tr>
<td>Mechanical</td>
<td>$397.96</td>
<td>$802.04</td>
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<tr>
<td>Electronics/Software</td>
<td>$583.15</td>
<td>$267.85</td>
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<tr>
<td>Testing</td>
<td>$156.94</td>
<td>$643.06</td>
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<tr>
<td>Miscellaneous</td>
<td>$356.64</td>
<td>$143.36</td>
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<tr>
<td>Contingency</td>
<td>$-</td>
<td>$1,389.78</td>
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</table>

Total Budget $5,975
Total Spent $2,729
Remaining Expenses $1,856
Contingency $1,390
Questions?
Backup Slides
Testing Backup Slides
## Planned Tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Purpose</th>
<th>Required Setup</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Level 1 success</strong>&lt;br&gt;• Recuperator operates without critical failure&lt;br&gt;• Verifies heat transfer from model</td>
<td><strong>Concentric pipe test rig with recuperator integrated</strong>&lt;br&gt;• Use heat guns, leaf blowers, thermocouples, and pitot probe from Level 0 testing&lt;br&gt;• Use manometer and Daq/Labview for data collection</td>
<td><strong>Built and withstands high heat tests</strong>&lt;br&gt;<strong>Matlab model complete</strong>&lt;br&gt;• Analysis underway for Level 1 success</td>
</tr>
<tr>
<td></td>
<td><strong>Level 3 success</strong>&lt;br&gt;• Engine runs&lt;br&gt;• Meet Throttle time&lt;br&gt;• Effectiveness, Thrust Specific Fuel Consumption (TSFC), and thrust reduction match model</td>
<td><strong>Manufacturing complete with recuperator integrated onto the engine</strong>&lt;br&gt;• Use REAPER electronics&lt;br&gt;• Use thermocouples and pitot probe from Level 0 testing&lt;br&gt;• Use load cell, fuel flow sensors, and hall effect sensor</td>
<td><strong>Manufacturing and electronics on track</strong>&lt;br&gt;• Labview GUIS created and tested for thermocouples and load cell&lt;br&gt;<strong>Matlab and CFD models complete</strong></td>
</tr>
</tbody>
</table>
Testing- Level 1

- Recuperator **operates** without critical failure
- Verifies **heat transfer** from 1D Model

<table>
<thead>
<tr>
<th>Sensor List</th>
<th>FR Validation</th>
<th>Error</th>
<th>Sample Rate</th>
<th>Acquired/ Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouples</td>
<td>Temperature (DR 3.3)</td>
<td>+/- 1.2 K</td>
<td>1Hz</td>
<td>yes/ yes</td>
</tr>
<tr>
<td>Pitot Static Tube</td>
<td>Exit Velocity (DR 3.3)</td>
<td>+/- 1.4 m/s</td>
<td>N/A</td>
<td>yes/ yes</td>
</tr>
<tr>
<td>Sensor List</td>
<td>FR Validation</td>
<td>Error</td>
<td>Sample Rate</td>
<td>Acquired/ Tested</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------</td>
<td>----------</td>
<td>-------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Fuel Flow Sensor</td>
<td>TSFC (FR 2)</td>
<td>±1%</td>
<td>31 Hz</td>
<td>No / No</td>
</tr>
<tr>
<td>Load Cell</td>
<td>Thrust (DR 2.5)</td>
<td>±0.2%</td>
<td>1 Hz</td>
<td>Yes / No</td>
</tr>
<tr>
<td>Hall Effect</td>
<td>RPM (DR 2.4)</td>
<td>±0.05%</td>
<td>31 Hz</td>
<td>No / No</td>
</tr>
</tbody>
</table>
Mechanical Backup Slides
Nozzle/Heat Exchanger: Location
Nozzle/Heat Exchanger: Dimensioned Drawing

- Scale: 2:1
- Dimensions are in inches
- Tolerances ±0.005
- Material: Titanium
Nozzle/Heat Exchanger: Manufacturing

- Direct Metal Laser Sintered (DMLS) from Titanium → Done out of House
- Drill mounting holes → 1 man hr

Required Man Hrs: 1

Completed Man Hrs: 0
End Cap: Location
End Cap: Dimensioned Drawing

Dimensions are in inches.
Tolerances: ±0.006 inches

Material: Stainless Steel 304
End Cap: Manufacturing

- Band saw off appropriate length from stock → 2 mans hrs
- Drill center hole for Computer Numerical Control (CNC) lathe → 2 man hrs
- Create outer and inner diameters, and inner chamfer, with CNC lathe → 5 man hrs
- Use CNC mill to create channel on upper surface, shelf on inner diameter, and channel on inner diameter → 7 man hrs

**Required Man Hrs: 16**

**Completed Man Hrs: 0**
Nozzle Shroud: Location
Nozzle Shroud: Dimensioned Drawing

Dimensions are in inches. Tolerances: ±0.005 inches. Material: Stainless Steel 304.
Nozzle Shroud: Manufacturing

- Band saw off appropriate length of material from stock → 2 man hrs
- Drill center hole for (CNC) lathe → 2 man hrs
- Create outer and inner diameters with CNC lathe → 5 man hrs
- Add fillet with CNC lathe → 1 hrs

Required Man Hrs: 10

Completed Man Hrs: 0
Outer Casing: Location
Outer Casing: Dimensioned Drawing

Dimensions are in inches.
Tolerances: ±0.05 inches.
Material: Stainless Steel 304.
Scale: 1:2.
Outer Casing: Manufacturing

- Cut sheet metal to size → 0.5 man hrs
- Drill holes for attachment bolts → 1 man hr
- Roll sheet into tube → 0.5 man hrs
- Weld edges to close tube → 1.5 man hrs

Required Man Hrs: 3.5

Completed Man Hrs: 0
Inner Casing: Location
Inner Casing: Dimensioned Drawing
Inner Casing: Manufacturing

• Cut sheet metal to size → .5 man hrs
• Drill holes for attachment bolts and glow plug → 1 man hr
• Create rolling guide part → 2 hrs man
• Roll sheet into tube → .5 man hrs
• Weld edges to close tube → 1.5 man hrs

Required Man Hrs: 5.5

Completed Man Hrs: 0
Forward Brackets: Location
Forward Brackets: Dimensioned Drawing

FORWARD BRACKET 1
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005 INCHES
MATERIAL: STAINLESS STEEL 304
SCALE 1:1

FORWARD BRACKET 2
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.005 INCHES
MATERIAL: STAINLESS STEEL 304
SCALE 1:1
Forward Brackets: Manufacturing

- Band saw off appropriate piece of stock → 2 man hrs
- Drill center hole for CNC lathe → 2 man hrs
- Create outer and inner diameters, and inner chamfer with CNC lathe → 5 man hrs (x2)
- Band saw off newly created ring → 2 man hrs (x2)
- Create outer chamfer with manual lathe → 3 man hrs (x2)
- Drill all holes and create mounting “nubs” with CNC mill → 2 man hrs (x2)
- Create custom fixture to hold brackets during final cutting → 1 man hr
- Cut off unneeded half of bracket → 1 man hr (x2)

**Required Man Hrs: 31**

**Completed Man Hrs: 4**
Forward Ring: Location
Forward Ring: Dimensioned Drawing

Dimensions are in inches
Tolerances: ±0.005 inches
Material: Stainless Steel 304
Scale: 2x

FORWARD RING
Forward Ring: Manufacturing

• Band saw off appropriate length from stock → 2 man hrs
• Drill center hole for CNC lathe → 2 man hrs
• Use CNC lathe to create outer and inner diameters, and inner chamfer → 5 man hrs
• Use CNC mill to drill holes and create channel on outer diameter → 3 man hrs

**Required Man Hrs: 12**

**Completed Man Hrs: 0**
Other Manufacturing

- Weld End Cap to Outer Casing → 1.5 man hrs
- Weld Nozzle Shroud to Inner Casing → 1.5 man hrs
- Assembly of final recuperating engine → 6 man hrs

Required Man Hrs: 9
Pressure Leak: Magnitude

• Most likely to occur at joint of Endcap and Nozzle

\[ \dot{m} = C \times A_{\text{leak}} \sqrt{2 \rho_{\text{engine}} (P_{\text{engine}} - P_{\text{atm}})} \]

• \( A_{\text{leak}} \rightarrow \)

\[ A_{\text{leak}} = \pi (r_{\text{Nozzle}} + \text{gap})^2 - r_{\text{Nozzle}}^2 \]

\[ A_{\text{leak}} = 2 \times 10^{-5} \ m^2 \]

• \( \rho_{\text{engine}} = 3.6 \ \frac{kg}{m^3} \)

• \( P_{\text{engine}} = 2.6 \ \text{atm} = 263445 \ Pa, P_{\text{atm}} = 1 \ \text{atm} = 101325 \ Pa \)

• \( C = 0.625 \rightarrow \) hole flow coefficient, between 0.6 and 0.65

• \[ \dot{m} = 0.014 \ \frac{kg}{s} \]
Leak Analysis – Test Setup

Assume Ideal Gas \[ \rho = \frac{P}{RT} \]

\[
m = V \frac{\partial \rho}{\partial t} = V \left( \frac{\partial \rho}{\partial P} \frac{\partial P}{\partial t} + \frac{\partial \rho}{\partial R} \frac{\partial R}{\partial t} + \frac{\partial \rho}{\partial T} \frac{\partial T}{\partial t} \right)
\]

\[
m = V \left( \frac{1}{RT} \frac{\partial P}{\partial t} \right)
\]
Pressure Leak: Performance Impact

![Graph: Sensitivity of TSFC to Mass Loss due to Leaks](image)

- **Y-axis:** Percent Change in TSFC
- **X-axis:** Change in Mass Flow [kg/s]