Critical Design Review

REcuperating Advanced Propulsion Engine Redesign

Customer: Air Force Research Lab

Advisor: Dr. Ryan Starkey

Team: Kevin Bieri, David Bright, Kevin Gomez, Kevin Horn, Becca Lidvall, Carolyn Mason, Andrew Marshall, Peter Merrick, and Jacob Nickless
Outline

• Project Description
• Design Solution
• Critical Project Elements
• Design Requirement Satisfaction
• Risk Analysis
• Verification and Validation
• Project Planning
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.
Engine Recuperation

• Heat Exchanger that recovers waste heat from power cycle
• Advantages/Disadvantages
  • \( Q_{\text{Required}} = Q_{\text{Transfer}} + Q_{\text{Fuel}} \)
  • Best for shaft work systems (all exhaust is waste)
  • Difficult for flow work systems (exhaust velocity is valuable)
Customer Requests

CR 1: **Increase efficiency** of the engine through recuperative heat transfer

CR 2: **Characterize changes** in thrust and thrust specific fuel consumption

CR 3: **Minimize** thrust loss, weight, and volume additions
Functional Requirements

FR 1: Engine operates in modified state

FR 2: Thrust specific fuel consumption decreases at least 10% at full throttle

FR 3: Thermal-fluid simulation models the changes in engine performance

FR 4: Engine control electronics command the modified engine
# Levels of Success

<table>
<thead>
<tr>
<th>Level</th>
<th>Simulation</th>
<th>Recuperator</th>
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<tbody>
<tr>
<td>Level 1</td>
<td>-Develop first order, steady state model&lt;br&gt;-Model heat exchanger effectiveness, specific fuel consumption and thrust</td>
<td>-Recuperator designed and manufactured&lt;br&gt;-Recuperator verified with engine analog</td>
</tr>
<tr>
<td>Level 2</td>
<td>-Model transient characteristics</td>
<td>-Recuperator is integrated onto engine&lt;br&gt;-Integrate engine system starts and runs</td>
</tr>
<tr>
<td>Level 3</td>
<td>-Develop CFD model&lt;br&gt;-Model is verified with test data</td>
<td>-Engine system operates for throttle range&lt;br&gt;-Engine system meets design requirements</td>
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</tbody>
</table>
Design Overview: Differences from PDR Design

• Problems with PDR Design
  • Flow Impedance
  • Not enough mass flow through Heat Exchanger
• Problems found with improved models
Concept of Operations

Kerosene Fuel

Transmitter

Modified P90-RXi

Receiver

Engine Control Unit

Ground Station Unit

Computer
Concept of Operations

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
**Stock Thrust:** 105 N  
**Stock TSFC:** 4.46E-4 s⁻¹  

**REAPER Thrust:** 103.4±0.5 N  
**REAPER TSFC:** 4.40 ±0.05E-4 s⁻¹

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### Station Summary

<table>
<thead>
<tr>
<th>Station</th>
<th>Total Pressure [Atm]</th>
<th>Total Temperature [K]</th>
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<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>273.0</td>
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<tr>
<td>2</td>
<td>2.60 ± 0.01</td>
<td>403 ± 2</td>
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<tr>
<td>3</td>
<td>2.53 ± 0.01</td>
<td>408 ± 2</td>
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<tr>
<td>4</td>
<td>2.36 ± 0.02</td>
<td>1080 ± 3</td>
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<tr>
<td>5</td>
<td>1.33 ± 0.02</td>
<td>963 ± 3</td>
</tr>
<tr>
<td>6</td>
<td>1.33 ± 0.02</td>
<td>958 ± 4</td>
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</tbody>
</table>
Engine Electronics FBD

Project Description
Design Solution
Critical Project Elements
Design Requirements
Risk Analysis
Verification and Validation
Project Planning

Transmitter
Power Command
Throttle Command

Receiver

JetCat P90-RXi Engine

Engine Casing
Starter
Compressor
Compressor Bearings
Burner
Turbine Bearings
Nozzle

Fuel/Lubrication System
Heat Exchanger
Combustion Chamber
Fuel Pump
Lubrication Solenoid
Fuel Solenoid

Glow Plug

Engine Control Unit
Command Outputs
Control Software
Input Receivers

Engine Sensor Board
Temperature Sensors
Hall Effect Sensor (RPM)
Fuel Flow Sensor

Data Handling Device
DAQ
Thermocouples
Pitot/Manometer

Key
Data
Physical Contact
Command
Fuel
Designed/Modified
Pre-existing

Testing Electrical FBD
Critical Project Elements

CPE 1: Thermal-Fluid Modeling
  - System **Characterization**

CPE 2: Heat Exchanger
  - **Manufacturing**, Cost, Integration

CPE 3: Engine Electronics
  - **Control**, Safety, Sensors

CPE 4: Testing
  - **Model Validation**, System Verification, Sensors
CPE 1: Thermal-Fluid Modeling

**Goal:** Characterize system to enable heat exchanger design and validation
FR 3: Thermal-fluid simulation *models* the changes in engine performance

**DR 3.1:** Quantify changes in engine *thrust*

**DR 3.2:** Quantify changes in fuel consumption

**DR 3.3:** Quantify frictional and geometric *losses*
Conservation Laws

Mass: \[ \rho_1 A_1 V_1 = \rho_2 A_2 V_2 \]

Momentum: \[ \rho_1 A_1 v_1^2 + p_1 A_1 = \rho_2 A_2 v_2^2 + p_2 A_2 + gh_L \]

Energy: \[ \left( \frac{\dot{Q} - W_{shaft}}{m} \right) = C_{p,2} T_2 - C_{p,1} T_1 + \frac{v_2^2}{2} - \frac{v_1^2}{2} + K_L \]

Constitutive: \[ p = \rho RT \]

Assumptions/Correlations

- Ideal, thermally perfect gas
- 1-D flow; fully developed
- Engine component efficiencies from MEDUSA/COMET tests
- Colebrook-White friction correlation
- Gnielinski heat transfer correlation
Assumptions:
• 4x symmetry
• Boundary conditions independent of flow parameters
• K-ε turbulence model

Convergence:
• All flow variables forced to converge within 0.5% across 3 travels

Mesh Independence
• 3 meshes (384k, 647k, 1328k fluid cells) showed similar results
Thermal Model: Results

DR 3.1/3.2
Quantify changes in thrust and fuel consumption

DR 3.3
Quantify geometric and frictional losses

<table>
<thead>
<tr>
<th>TSFC Reduction</th>
<th>Internal Pressure Drop [kPa]</th>
<th>External Pressure Drop [hPa]</th>
<th>Heat Transfer Rate [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>7.4</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>1.2</td>
<td>7.3</td>
<td>2.1</td>
<td>1.3</td>
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<td>7.3</td>
<td>2.0</td>
<td>1.3</td>
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<tr>
<td>1.2</td>
<td>7.3</td>
<td>2.6</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Control Volume | CFD - 384K | CFD - 647k | CFD - 1328k
Thermal Model: Results

Conclusion:
Control Volume Model is Sufficient
CPE 2: Heat Exchanger

**Goal:** Transfer exhaust heat and integrate with engine
FR 2: Thrust specific fuel consumption decreases at least 10% at full throttle

DR 2.1: Effectiveness of at least 13%

DR 2.3: Integrate with engine

DR 2.5: Less than 10% thrust decrease
Thrust Specific Fuel Consumption

Project Description

Design Solution

Critical Project Elements

Design Requirements

Risk Analysis

Verification and Validation

Project Planning

Reaper PDR Design

Reaper CDR Design

Change in TSFC $\Delta P_{\text{hot}} = 0 \text{ Pa}$

$\Delta P_{\text{cold}} = 10000 \text{ Pa}$

Percent Change in TSFC vs. Heat Transfer [W]

Reaper PDR Design

Reaper CDR Design

Change in TSFC $\Delta P_{\text{hot}} = 8000 \text{ Pa}$

$\Delta P_{\text{cold}} = 0 \text{ Pa}$

$\Delta P_{\text{cold}} = 10000 \text{ Pa}$

Percent Change in TSFC vs. Heat Transfer [W]
Thrust Specific Fuel Consumption

Key Conclusions:

1. 10% reduction in TSFC requires \( \sim 20 \) kW of heat transfer with no losses

2. Exhaust pressure losses supersede internal pressure losses

Reaper Design:

Heat Transfer Rate: \( \sim 1300 \) W
Internal Pressure Loss: \( \sim 1500 \) Pa
External Pressure Loss: \( \sim 200 \) Pa
\( \Delta TSFC: \sim 4.4E-4 \) \( s^{-1} \) (-1.2%)
Thrust: 103.4 N (-1.6%)
Heat Exchanger Performance

CR 1: Increase the efficiency of a jet engine by using a recuperative heat exchanger

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
<th>Reaper Design</th>
<th>Compliance</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR 2: Decrease in TSFC</td>
<td>10%</td>
<td>1.2%</td>
<td>Do Not Comply</td>
</tr>
<tr>
<td>DR 2.1 Heat exchanger</td>
<td>13%</td>
<td>1.0%</td>
<td>Do Not Comply</td>
</tr>
<tr>
<td>DR 2.5: Decrease in maximum thrust</td>
<td>&lt;10%</td>
<td>1.6%</td>
<td>Comply</td>
</tr>
</tbody>
</table>
Remaining Pieces

• Will be made in-house
  • Casings(8,9) - Rolled and welded
  • Ring(1), Brackets(2,3), Connectors(4-7), Nozzle Shroud(11), Endcap(12) - Milled

• Stainless Steel 304
  • Machinable
  • Weldable
  • Can withstand engine temperatures
Heat Exchanger: Finned Nozzle

- Created with Direct Metal Laser Sintering
  - Titanium
- Protolabs quote ~ $1200

Conclusion:
Heat exchanger is feasible

*Dimensions: inches*
CPE 3: Engine Electronics

Goal: Safely control modified engine and save sensor data
Engine Electronics – Overview

Custom printed circuit boards – based off MEDUSA design

**Engine Control Unit (ECU)**
- Control Signal & Data Input
- Fuel Flow Sensor
- Save Data
- Process User Input

**Engine Sensor Board (ESB)**
- Exhaust Gas Thermocouple
- Hall Effect Sensor
- Control Actuators

MEDUSA ECU

MEDUSA ESB
Engine Electronics– Overview

Detailed Schematics in the Backup Slides
**Project Description**

**Design Solution**

**Critical Project Elements**

**Design Requirements**

**Risk Analysis**

**Verification and Validation**

**Project Planning**

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**DR 1.3**

Save data at a rate of at least 5 Hz.

**DR 1.9**

Start, shutdown, and be throttle-able according to user input.

* Micro USB also included to send data and status to computer during testing

**DR 1.4**

Measure and control the fuel flow rate to the engine.
Engine Electronics—Saving Data

• SD storage
  • Tested and fully functional
  • Up to 32 GB
  • Full File System

• Transfer rate of 16 Mbs write/read
  • 1 ms start up time per write
  • 512 byte buffer

SD Testing Configuration

- SD storage
- Tested and fully functional
- Up to 32 GB
- Full File System

- Transfer rate of 16 Mbs write/read
  - 1 ms start up time per write
  - 512 byte buffer
Engine Electronics – Fuel Flow Sensor

• Equflow 0045

• Disposable insert (~$50)
  • Fuel pump too weak to include filter in line

• 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)
  • Predicted 580±5 pulses/s

• 34mA current at 5V
DR 1.9
Start, shutdown, and be throttle-able according to user input.

DR 1.10
Display status with indicator LEDs.

- **Arm**: Indicates normal start procedure
  - For electronic reset safety
- **Run**: Begin start procedure
**DR 1.1**
Read the state of the engine at a rate of at least 113 Hz.

**DR 1.4**
Measure and control the fuel flow rate to the engine.

**DR 1.5-1.8**
Control the existing engine starter motor, glow plug, fuel solenoid, and lubrication solenoid.
Engine Electronics – Hall-Effect

• Used to calculate RPM
  • Limit of 130,000 RPM
  • 2116 pulses per second
  • Pull rate of at least 31 Hz
    • Maximum error of 0.5% at any moment

• Best option: Stock part
  • Off ramp: SS56AT (Honeywell)
Engine Electronics – Thermocouple

- K-type thermocouple
  - Limit of 700°C
  - Cold junction compensate chip
    - Max31855
  - Sample at 113 Hz minimum
    - Max error 3 degrees Celsius
- SPI interface

Stock Engine Sensor Board: Thermocouple Location
Engine Electronics – Software Main Loop

Main Loop

- **Safety Checks**
  - Initialization
  - Set the Pump and Solenoid for fuel lines
  - Pull Sensors
  - Write to SD card
  - RC Input read/parse
  - Set Flags
  - Check Flags
  - Check Switches

- **Loop Timing**
  - 5 ms
  - 1 ms
  - 3 ms

- **Fails**
  - System Shutdown

- **Pass**
  - Write to LED
  - Write to Watch dog
  - Remote Control PWM
  - Hall-Effect Sensor
  - Fuel Flow Sensor

Interrupts

Critical Project Elements
- Project Description
- Design Solution
- Design Requirements
- Risk Analysis
- Verification and Validation
- Project Planning
Engine Electronics – Software Progress

High Level
Final Implementation

Hardware Interface Layer
- SD Card
- Hall Effect
- Glow Plug
- Thermocouples
- Fuel Flow
- Starter motor

Low Level Interface
- SPI
- Oscillator
- Interrupts
- USART
- PWM
- I2C
- EEPROM

KEY
- Complete
- Incomplete

Project Description
Design Solution
Critical Project Elements
Design Requirements
Risk Analysis
Verification and Validation
Project Planning
CPE 4: Testing

**Goal:** Validate model and verify requirements
Model Validation Test

• Purpose:
  • Verify the 1-D thermal model is on the correct order of magnitude
  • Precursor to level 1 test

• Test Overview:
  • Hot and cold counter-flow in concentric pipes
  • Cold flow from leaf blower
  • Hot flow from heat gun
  • Flow fully turbulent and developed in test section
Model Validation Test
Model Validation Test: Takeaway

• ΔT within 0.36K (12%) of 1D model prediction
  • ΔT_{model} = 2.9K ± 0.3K
  • ΔT_{analog} = 2.6K ± 0.2K
  • Between 2% and 22% of model prediction

• Decrease error:
  • Take more measurements
  • Switch thermocouple position between tests
  • Increase speed of hot flow for a turbulent Reynolds number

Conclusions:
Model is Feasible
Analog Test is Valid
Risk Analysis
1. Modified Engine
   1.1 Modified engine does not start
   1.2 Primary air flow extinguishing flame
   1.3 Fuel flow rate cannot be precisely controlled
   1.4 Pressure leaks degrade engine performance

2. Data Collection
   2.1 Smalls changes in properties cannot be accurately measured

3. Engine Analog Tests
   3.1 Sensor placement in flows to achieve correct readings
## Risk Matrix

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Minimal</th>
<th>Minor</th>
<th>Major</th>
<th>Serious</th>
<th>Catastrophic</th>
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<tbody>
<tr>
<td>Near Certainty</td>
<td>1.4</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Highly Likely</td>
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<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Likely</td>
<td>3.1</td>
<td>1.3</td>
<td>2.1</td>
<td></td>
<td></td>
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<tr>
<td>Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extremely Unlikely</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

**Project Description**
- Design Solution
- Critical Project Elements
- Design Requirements
- Risk Analysis
- Verification and Validation
- Project Planning

**Risk Analysis**
- Modified engine does not start
  - Have starter motor run longer
- Primary air flow extinguishes flame
  - Can achieve level 2 success
- Fuel pump resolution unknown
  - Test fuel pump and sensor
- Pressure leaks degrade performance
  - High temperature gasket compound
- Performance changes within sensor error
  - Multiple engine tests, finer sensors
- Validation requires field measurements
  - Several sensors, vary locations
Verification and Validation
Verification

• Level 1:
  • Recuperator operates without critical failure
  • Verifies heat transfer from 1D Model

• Level 3:
  • Engine runs with recuperator attached
  • Throttle time met
  • Verifies effectiveness, Thrust Specific Fuel Consumption (TSFC), and thrust reduction match 1D and CFD models
Engine Analog Level 1 Verification

Sensor List | FR Validation | Error          | Sample Rate | Acquired/ Tested |
-------------|---------------|----------------|-------------|------------------|
Thermocouples| Temperature (DR 3.3) | +/- 1.2 K  | 1Hz         | yes/ yes         |
Pitot Static Tube | Exit Velocity (DR 3.3) | +/-1.4 m/s | N/A         | yes/ yes         |
**Engine Integration Level 3 Verification**

**Sensor List**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>FR Validation</th>
<th>Error</th>
<th>Sample Rate</th>
<th>Acquired/ Tested</th>
</tr>
</thead>
<tbody>
<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>
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</table>
Engine Integration Level 3 Verification

**Throttle Time** = \( \Delta t \)

\( TSFC = \dot{w}_f / F \)

**Effectiveness** = \( \frac{Tt3 - Tt2}{Tt5 - Tt2} \)
Project Planning
**Organizational Chart**

**Lead positions:**

*Project Manager:* Andrew Marshall  
*Systems Engineer:* Jacob Nickless  
*Electrical Lead:* Becca Lidvall  
*Software Lead:* Peter Merrick  
*Mechanical Design Lead:* Kevin Gomez  
*Manufacturing Lead:* David Bright  
*Testing Lead:* Carolyn Mason  
*Safety Lead:* Kevin Horn  
*Thermal Modeling Lead:* Kevin Bieri

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**Project Description**  
**Design Solution**  
**Critical Project Elements**  
**Design Requirements**  
**Risk Analysis**  
**Verification and Validation**  
**Project Planning**
## Work Plan

<table>
<thead>
<tr>
<th></th>
<th>November</th>
<th>December</th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
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<tr>
<td><strong>Thermal Modeling</strong></td>
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<td><strong>Manufacturing</strong></td>
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<td><strong>Integration</strong></td>
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<td><strong>Testing</strong></td>
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<td><img src="image41.png" alt="Diagram" /></td>
<td><img src="image42.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

- **November**:
  - CDR: 11/30
  - FFR: 12/14

- **December**:
  - MSR: 2/1

- **January**:
  - TRR: 2/29
  - AIAA: 3/11

- **February**:
  - Design Symp.: 4/15

- **March**:
  - SFR: 4/18

- **April**:
  - UROP: 4/30
  - PFR: 5/2
# Cost Plan

## Category: Major Components

<table>
<thead>
<tr>
<th>Category</th>
<th>Major Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics</td>
<td>ECU Board (3 revs)</td>
</tr>
<tr>
<td></td>
<td>ESB Board (3 revs)</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>DMLS Manufacturing</td>
</tr>
<tr>
<td></td>
<td>Shipping</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>Outer Casing</td>
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<tr>
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<td>Inner Casing</td>
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<tr>
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<td>Endcap</td>
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<td>Pressure Sealing</td>
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<tr>
<td>Testing</td>
<td>Materials</td>
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<td>Sensors</td>
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<tr>
<td>Software</td>
<td>Testing PCB</td>
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<tr>
<td>Engine Repair</td>
<td>ESB damage</td>
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</tbody>
</table>

## Project Description

- **Design Solution**
  - Critical Project Elements
  - Design Requirements
  - Risk Analysis
  - Verification and Validation
  - Project Planning

- **Class Budget** $5,000
- **UROP** + $975
- **Total Budget** $5,975
- **Total Expenses** $4,420

### Margins

- Heat Exchanger: $1,200
- Electronics: $1,000
- Manufacturing: $1,000
- Testing: $800
- Engine Repair: $350
- Software: $70
- Margin: $1,555 (26%)

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*Project Budget Breakdown*
Test Plan

- **Project Description**
- **Design Solution**
- **Critical Project Elements**
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- **Verification and Validation**
- **Project Planning**

October
- Engine Test

November
- Analog Test 0

December
- 11/12 Analog Test 0

January
- 1/15 Analog Test 0.1

February
- March
- April
Test Plan

1/23 Engine Analog Level 1

2/8 Fully Characterize Stock Engine

Project Description
Design Solution
Critical Project Elements
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Verification and Validation
Project Planning

October            November           December             January            February             March              April

Engine Analog Level 1

Fully Characterize Stock Engine
Test Plan

Test Readiness Review

2/29 TRR

3/28 Final Full System Test

October           November           December           January           February           March              April

TRR               Final Full System Test

Project Description
Design Solution
Critical Project Elements
Design Requirements
Risk Analysis
Verification and Validation
Project Planning
Conclusion

CR 1: Increase efficiency of the engine through recuperative heat transfer ✓
CR 2: Characterize changes in thrust and thrust specific fuel consumption ✓
CR 3: Minimize thrust loss, weight, and volume additions ✓

- Thermal modeling currently meets Level 3 success
- Testing analog prepared for Level 1 success
- Heat Exchanger and Electronics on track for Level 1 success in early spring

On track for project success
Questions?
References

Backup Slides
**FR 1:** Engine operates in modified state

**DR 1.1:** Integrate with engine

**DR 1.2:** Throttle response characterization

**DR 1.3:** Less than 10% thrust decrease
FR 2: Thrust specific fuel consumption decreases at least 10% at full throttle

**DR 2.1:** Effectiveness of at least 13%

**DR 2.2:** Thermal survivability

**DR 2.3:** Integrate with engine

**DR 2.4:** Throttle response characterization

**DR 2.5:** Less than 10% thrust decrease
FR 3: The thermal-fluid simulation models the changes in engine performance

DR 3.1: Quantify changes in engine thrust

DR 3.2: Quantify changes in fuel consumption

DR 3.3: Quantify frictional and geometric losses

DR 3.4: Limited required sensors to validate model
Engine Control Design Requirements

**FR 4:** Engine control electronics shall operate the JetCat P90-RXi engine with integrated recuperator.

- **DR 1.1:** Know the state of the engine.
- **DR 1.2:** Ability to shut down engine with greater than with 31 Hz response time.
- **DR 1.3:** Save data at a rate of at least 5 Hz.
- **DR 1.4:** Measure and control the fuel flow rate to the engine.
- **DR 1.5:** Control the existing engine starter motor.
- **DR 1.6:** Control the existing engine glow plug.
- **DR 1.7:** Control the existing engine fuel solenoid.
- **DR 1.8:** Control the existing engine lubrication solenoid.
- **DR 1.9:** Engine shall start, shutdown, and be throttle-able according to user input.
- **DR 1.10:** Display status with indicator LEDs.
Model Backup Slides
Correlations and Loss Coefficients

### Colebrook-White Equation

\[
\frac{1}{\sqrt{f}} = -2.0 \log \left( \frac{\epsilon/D}{3.7} + \frac{2.51}{Re\sqrt{f}} \right)
\]

### Gnielinski Correlations

\[ h = \frac{k(f/8(Re - 1000)Pr)}{D \left(1 + 12.7f/8(Pr^{2/3} - 1)\right)} \]

### Frictional Drag

\[ D = \frac{1}{2} \rho V^2 A_w C_f \]
\[ C_f = f/4 \]

### Loss

<table>
<thead>
<tr>
<th>Loss</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction</td>
<td>[ h_L = f \frac{l V^2}{D 2g} ]</td>
</tr>
<tr>
<td>Expansion</td>
<td>[ h_L = \frac{V_1^2 \rho_1}{2g \rho_2} (K_c + 1 - \sigma^2) ]</td>
</tr>
<tr>
<td>Contraction</td>
<td>[ h_L = \frac{V_1^2 \rho_1}{2g \rho_2} (K_e + 1 - \sigma^2) ]</td>
</tr>
<tr>
<td>Turn (0-45 degrees)</td>
<td>[ h_L = 0.3 \frac{V^2}{2g} (\alpha/45) ]</td>
</tr>
<tr>
<td>Sharp 90 degree turn</td>
<td>[ h_L = 0.9 \frac{V^2}{2g} ]</td>
</tr>
<tr>
<td>180 degree smooth bend</td>
<td>[ h_L = 0.7 \frac{V^2}{2g} ]</td>
</tr>
</tbody>
</table>

\[ H_L = \sum \rho gh_L \]
### CFD: Boundary Conditions/Assumptions

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Condition Type</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Inlet</td>
<td>Total Pressure</td>
<td>$P_t = 2.58 \text{ atm } T = 400K$</td>
</tr>
<tr>
<td>Cold Outlet</td>
<td>Mass Flow</td>
<td>$\dot{m} = 0.260 \text{ kg/s}$</td>
</tr>
<tr>
<td>Hot Inlet</td>
<td>Total Pressure</td>
<td>$P_t = 1.38 \text{ atm } T = 850K$</td>
</tr>
<tr>
<td>Hot Outlet</td>
<td>Mass Flow</td>
<td>$\dot{m} = 0.264 \text{ kg/s}$</td>
</tr>
<tr>
<td>Solid Walls</td>
<td>Heat Transfer Allowed</td>
<td>$\text{Titanium } k = 6.7W/(m \text{ K})$</td>
</tr>
<tr>
<td>Surroundings</td>
<td>Adiabatic</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Surface Roughness:**
\[ \epsilon = 4.8E - 5 \text{ m} \]

**Turbulence Intensity:**
\[ I = 0.16Re_D^{-1/8} \]

- Cold Side Inlet: 3%
- Hot Side Inlet: 8%

**Fluid:**
- Air
- Ideal gas
- Thermally perfect
Method:
• Propagates calculation forward from initial conditions
• Tracks change between each iteration
• Once change drops below specified goals for all goals end of 1 "travel"
• Averages results across several (3) travels to give final steady-state solution
## Thermal Model: Results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Volume</td>
<td>7403</td>
<td>158</td>
<td>1321</td>
<td>4.70E⁻²</td>
<td>104.8</td>
<td>4.40E⁻⁴</td>
</tr>
<tr>
<td>CFD – 384k</td>
<td>7281</td>
<td>207</td>
<td>1278</td>
<td>4.69E⁻²</td>
<td>104.6</td>
<td>4.41E⁻⁴</td>
</tr>
<tr>
<td>CFD – 647k</td>
<td>7261</td>
<td>194</td>
<td>1265</td>
<td>4.70E⁻²</td>
<td>104.7</td>
<td>4.41E⁻⁴</td>
</tr>
<tr>
<td>CFD – 1328k</td>
<td>7279</td>
<td>235</td>
<td>1309</td>
<td>4.68E⁻²</td>
<td>104.7</td>
<td>4.39E⁻⁴</td>
</tr>
<tr>
<td>Mean</td>
<td>7306</td>
<td>204</td>
<td>1286</td>
<td>4.69E⁻²</td>
<td>104.7</td>
<td>4.40E⁻⁴</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>65</td>
<td>40</td>
<td>75</td>
<td>0.00E⁻²</td>
<td>0.1</td>
<td>0.01E⁻⁴</td>
</tr>
</tbody>
</table>
Testing Backup Slides
Model Validation Test

- Manometer
- DAQ
- Pitot Probe
- Thermocouples
- Heat Gun
- Leaf Bower
- Manometer
- Pitot Probe
### Model Validation Test

<table>
<thead>
<tr>
<th>Model</th>
<th>Analog Test</th>
</tr>
</thead>
</table>
| \[
\frac{1}{U_h A_h} = \frac{1}{\eta_{0,h} A_h h_h} + \frac{t_w}{A_w k_w} + \frac{1}{\eta_{0,c} A_c h_c}
\]
| \[
\dot{Q} = UA(Th - Tc)
\]
| \[
\dot{m} = \rho_c V_c A
\]
| \[
\Delta T_{\text{model}} = \frac{\dot{Q}}{\dot{m} c_p}
\ |
| \[
\Delta T_{\text{analog}} = \Delta T_c
\]
Model Verification

T0: Cold Entrance (29.1 +/- 1.2 °C)
T1: Cold Exit (31.7 +/- 1.2 °C)
T2: Hot Entrance (280.7 +/- 1.2 °C)
T3: Hot Exit (260.8 +/- 1.2 °C)
Model Verification
Model Verification
Model Verification: Results

• Percent difference: -12% +/- 10%
  • $\Delta T_{\text{model}} = 2.9 \text{ K} +/- 0.3\text{K}$
  • $\Delta T_{\text{analog}} = 2.6 \text{ K} +/- 0.2\text{K}$

• Measurement Errors:
  • Thermocouples +/- 1.2 K
  • Pitot Probe +/- 2.8 m/s
Model Verification: Results

- Mass flow rate cold flow: 0.0602 kg/s
- Qdot: 176.6370 J/s
- Heat Transfer Coefficient (U): 21.9360
- Cold Flow:
  - Velocity: 9.37 m/s
  - Reynolds Number: 4.27 * 10^3
- Hot Flow:
  - Velocity: 4.20 m/s
  - Reynolds Number: 2.73 * 10^4
Model Verification Error: DAQ + Thermocouple

- NI 9211 w/ K type Thermocouple:
  - Temperature Range: -270 - 1200 C
  - Temperature Accuracy: 0.05 C

- Temperature Error:
  - +/- 2.2C or +/- 0.75%
Model Verification Error: Pitot

- Airflow PVM100 Micromenometer:
  - Velocity Range: 2.8 - 76 m/sec
  - Pressure Range: 0 - 3500 Pa
  - Pressure Resolution: 1 Pa

- Pitot Positioning Error:
  - +/- 3%
Model Verification Error: Load Cell

• National Instruments Daq USB-6009
  • Analog Input:
    • +/-10V, accuracy 7.73mV
    • +/-1V, accuracy 1.53mV

• Load Cell: LCGD-100
  • Range 0-100lbs
  • Repeatability +/-0.10% Full Scale Output
Heat Gun and Leaf Blower

- **Heat Gun:**
  - Amperage (amps) 6.6, 12.1
  - Temperature range (deg F): 572°/1112°
  - Wattage (watts): 1500

- **Leaf Blower:**
  - Dual speed: 120 and 150mph
**Engine Analog Level 2 Verification - Off Ramp**

<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>
</tbody>
</table>

**Diagram:**
- **Jet Cat P90Rxi Engine**
- **Daq/Thermocouples**
- **Manometer/Pitot Probe**
- **Leaf Bower**
- **Heat Gun x2**
Heat Exchanger & Manufacturing Backup Slides
### Design Overview: Specifications

<table>
<thead>
<tr>
<th></th>
<th>Stock JetCat Engine</th>
<th>REAPER Design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net Thrust (N)</strong></td>
<td>105</td>
<td>103</td>
</tr>
<tr>
<td><strong>Thrust Specific Fuel Consumption (s(^{-1}))</strong></td>
<td>4.46(\times)10(^{-4})</td>
<td>4.40(\times)10(^{-4})</td>
</tr>
<tr>
<td><strong>Mass (kg)</strong></td>
<td>1.435</td>
<td>4.871</td>
</tr>
<tr>
<td><strong>Volume (cm(^3))</strong></td>
<td>~2614</td>
<td>~3894</td>
</tr>
</tbody>
</table>
**DR 2.3:** The heat exchanger shall maintain structural integrity at steady-state operating temperatures.

**Maximum Casing Temperature:** 124°C (from CFD model)

\[
\sigma_{\theta\theta} = \frac{p_R}{t} = \frac{(0.26 - 0.101) \text{ MPa} \times 0.054 \text{ m}}{0.0015 \text{ m}} = 5.7 \text{ MPa}
\]
DR 2.3: The heat exchanger shall maintain structural integrity at steady-state operating temperatures.

Maximum End Cap Temperature: 664°C (from CFD model)

\[
\sigma_{\theta\theta} = \frac{p_g R}{t} = \frac{(0.26 - 0.101) \text{MPa} \times 0.018m}{0.001m} = 2.9 \text{MPa}
\]

Safety Factor: 2.4
DR 2.3: The heat exchanger shall maintain structural integrity at steady-state operating temperatures.

**Maximum Heat Exchanger Temperature**: 806°C (1482°F)

\[
\sigma_{\theta\theta} = \frac{p_{gR}}{t} = \frac{(0.26-0.101)MPa + 0.0335m}{0.0012m} = 4.4MPa \text{ (638 psi)}
\]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Room temp., hardness (Rc)</th>
<th>Ultimate tensile strength (psi)</th>
<th>Room temp. yield strength (0.2% offset) (psi)</th>
<th>Percent elongation (2 in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Room temp.</td>
<td>1000°F</td>
<td>1200°F</td>
<td>1400°F</td>
</tr>
<tr>
<td>555</td>
<td>31</td>
<td>126 300</td>
<td>78 000</td>
<td>59 300</td>
</tr>
<tr>
<td>6242</td>
<td>35</td>
<td>150 500</td>
<td>103 500</td>
<td>77 700</td>
</tr>
<tr>
<td>52</td>
<td>35</td>
<td>142 100</td>
<td>80 800</td>
<td>59 200</td>
</tr>
<tr>
<td>64</td>
<td>35</td>
<td>142 500</td>
<td>78 200</td>
<td>62 300</td>
</tr>
<tr>
<td>HT 64*</td>
<td>37</td>
<td>160 000</td>
<td>99 000</td>
<td>54 900</td>
</tr>
</tbody>
</table>
Thermal Expansion - Analysis Setup

• Materials
  • Titanium 6Al-4V ELI
  • Stainless Steel 304

• Mean Coefficient of Thermal Expansion (μm/m*K)
  • Ti 6Al-4V ELI: 10.6*10^{-6}
  • SS 304: 10*10^{-6}
Thermal Expansion – Outer Casing
Thermal Expansion – Inner Casing
Thermal Expansion – Nozzle Shroud
Thermal Expansion - Endcap
Thermal Expansion - Nozzle
Manufacturing Parts
Manufacturing Overview

• 12 Total Parts
  1) Forward Ring
  2,3) Brackets (2 halves)
  4,5,6,7) Case Connectors (x4)
  8) Inner Casing
  9) Outer Casing
  10) Nozzle
  11) Nozzle Shroud
  12) Endcap
Design Overview: Assembly: Start

• Stock Components
Design Overview: Assembly: Part 1

- Connection of two forward brackets to stator
Connection of secondary bracket rings to first set of brackets
Design Overview: Assembly: Part 3

• Connection of nozzle to turbine
• Connection of casing ring
• Connection of inside case
Design Overview: Assembly: Part 6

• Case over Nozzle
Design Overview: Assembly: Part 7

• Connection of endcap to nozzle
Design Overview: Assembly: Part 8

- Connection of Outer Casing
• Complete Assembly
Manufacturing: Bolts

- Stainless Steel 304
- Variable Length
- Available from McMaster
- Inexpensive
Manufacturing: Forward Ring

- Milled from solid bar
- Will need round “puck”
- Material: 5" diameter, 1" length bar = $28.15[2]
Manufacturing: Brackets

- Milled from solid bar
- Will need 2 “pucks” - 1 for each bracket
- Material: 4.25" diameter, 1" length bar = $20.34$
Manufacturing: Casing Connectors

- Machined from solid block
- Will need 1 rectangular bar (cut into 4 to make connectors)
- Material: 0.375" x 0.75" cross section, 4" length bar = $3.44[^4]
Manufacturing: Casings

• Roll 1/16" stainless steel sheets and weld seam
• Heat, then shrink onto "puck" and anneal to ensure roundness at ends

• Outer Casing
  • Needs to seal to Forward Ring and End Cap
  • 2.44" inner radius -> 15.33" circumference
  • 7.19" length
  • 16"x7.5" = $14.40[^5]

• Inner Casing
  • 2.11" inner radius -> 13.26" circumference
  • 5.95" length
  • OnlineMetals.com - 14"x6" = $10.08[^5]
Manufacturing: Nozzle Shroud

- Machined from solid rod of stainless steel
- 4.25" diameter, 2.2" length = $44.75\textsuperscript{[3]}
Manufacturing: End Cap

- Machined from solid disk of stainless steel
- 5" diameter rod, 1" length = $28.15\ [2]
- Needs to seal with outer casing and end of nozzle
Manufacturing: Other Costs

- Machining Tools: $350 (estimate from Matt Rhode)
- Connection Hardware: $20 (bolts, nuts, etc.)
- Deacon 3300 Sealant: $100
Manufacturing: Cost Breakdown

Total: $670
Pressure Vessel Analysis

• Outer Casing
• Thin Walled?
  • \( \frac{r}{t} \geq 10? \rightarrow \frac{62 \text{ mm}}{1.52 \text{ mm}} = 40.8 \geq 10 \checkmark \)

• Longitudinal Stress
  • \( \sigma_{\text{long}} = \frac{Pr}{2t} \rightarrow \sigma_{\text{long}} = \frac{(263445 \text{ Pa})(.062 \text{ m})}{2(.00152 \text{ m})} \)
    \[ \sigma_{\text{long}} = 5372891.45 \text{ Pa} = 5.4 \text{ MPa} \]

• Hoop Stress
  • \( \sigma_{\text{hoop}} = \frac{Pr}{t} \rightarrow \sigma_{\text{hoop}} = \frac{(263445 \text{ Pa})(.062 \text{ m})}{.00152 \text{ m}} \)
    \[ \sigma_{\text{hoop}} = 10745782.89 \text{ Pa} = 10.7 \text{ MPa} \]

• Stainless Steel 304 Yield Strength = \( \sigma_{\text{yield}} = 205 \text{ MPa} \)

• \( \sigma_{\text{long}} \text{ and } \sigma_{\text{hoop}} \leq \sigma_{\text{yield}} \checkmark \)
Casing Strength Analysis

• Shear Out of Casing?
  • Force on Endcap

\[ F_{\text{case}} = P \times A \]
\[ A = \pi \left( r_{\text{outer}}^2 - r_{\text{inner}}^2 \right) \]
\[ A = \pi \left( 62^2 - 26^2 \right) = 9952.57 \text{ mm}^2 = 9.95 \times 10^{-3} \text{ m}^2 \]
\[ P = 2.6 \text{ atm} = 263445 \text{ Pa} \]
\[ F_{\text{case}} = 263445 \text{ Pa} \times 9.95 \times 10^{-3} \text{ m}^2 = 2621 \text{ N} = F_{\text{case}} \]

• Bolt hole shear path

Stainless 304 yield strength: 205 Mpa
\[ F_{\text{yield}} = \sigma_{\text{yield}} \times A \]
\[ F_{\text{yield}} = 205 \times 10^6 \text{ Pa} \times 2 	imes .006 \times .00152 = 3767 \text{ N} = F_{\text{yield}} \]

\[ F_{\text{case}} \leq F_{\text{yield}} \]
Bolt Strength Analysis

\[ F_{\text{case}} = F_{\text{bolt}} = 2621 \, N \]

Bolt Cross Section
\[
F_{\text{yield}} = \sigma_{\text{yield}} \times A
\]
\[
\sigma_{\text{yield}} = 205 \, MPa
\]
\[
A = \pi r^2 = \pi (0.0015 \, m)^2 = 7.07 \times 10^{-6} \, m^2
\]
\[
F_{\text{yield}} = 205 \times 10^6 \, Pa \times 7.07 \times 10^{-6} \, m^2 = 1449 \, N
\]

Need 2 bolts to hold case \((2 \times 1449 \, N = 2898 \, N = F_{\text{yield}} \leq F_{\text{bolt}})\)

Using 4 bolts \(\Rightarrow F_{\text{bolt}} \leq F_{\text{yield}} \checkmark\)
Pressure Leak: Magnitude

- Most likely to occur at joint of Endcap and Nozzle

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

- \( A_{\text{leak}} \rightarrow \)

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

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

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

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

- \( C = 0.625 \rightarrow \text{hole flow coefficient, between } 0.6 \text{ and } 0.65 \)

\[ \dot{m} = 0.014 \frac{\text{kg}}{\text{s}} \]
Pressure Leak: Effect on Efficiency

Sensitivity of TSFC to Mass Loss due to Leaks

Percent Change in TSFC vs. Change in Mass Flow [kg/s]
<table>
<thead>
<tr>
<th>Metric</th>
<th>Weighting</th>
<th>Welding</th>
<th>Putty</th>
<th>O-Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time for Installation</td>
<td>0.2</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Difficulty of Installation</td>
<td>0.25</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Cost</td>
<td>0.2</td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Dissassembly</td>
<td>0.35</td>
<td>1</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>1</strong></td>
<td><strong>2.05</strong></td>
<td><strong>3.75</strong></td>
<td><strong>3.7</strong></td>
</tr>
</tbody>
</table>
### Sealant Trade Heuristic

<table>
<thead>
<tr>
<th>Ranking</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time for Installation</strong></td>
<td>4+ hrs</td>
<td>3-4 hrs</td>
<td>2-3 hrs</td>
<td>1-2 hrs</td>
<td>0-1 hrs</td>
</tr>
<tr>
<td><strong>Difficulty of Installation</strong></td>
<td>Done out-of-house</td>
<td>Done in house entirely by Matt Rhode</td>
<td>Done in-house with a lot of assistance from Matt Rhode</td>
<td>Done in-house with some assistance from Matt Rhode</td>
<td>Done in-house without Matt Rhode's assistance</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>$100 - $125</td>
<td>$75 - $100</td>
<td>$50 - $75</td>
<td>$25 - $50</td>
<td>$0 - $25</td>
</tr>
<tr>
<td><strong>Dissassembly</strong></td>
<td>Permanently Assembled</td>
<td>N/A</td>
<td>Endcap can be removed</td>
<td>Outer Casing and Endcap can be removed</td>
<td>Recuperator can be completely removed</td>
</tr>
</tbody>
</table>
Pressure Sealing

• Deacon 3300 Extruded Gasket Compound
  • Thermal reactive sealing compound of high temperature, pressure, and chemical tolerance
  • Designed to produce mechanical seal on metal-to-metal surfaces, without chemical adhesion.
  • High flexibility, pliability and resistance to wear
  • Compatible with thermal cycling. Seal achieved before full cure.
  • Compressible to within a few thousandths of an inch
  • Temperature Range: 600°F to 1600°F (585K to 1140K)
Pressure Seal Locations

- Outer Casing to Forward Ring (Gasket Compound)
- Inner Casing to Nozzle Shroud (Weld)
- Endcap to Nozzle (Gasket Compound)
- Outer Casing to Endcap (Weld)
Engine Electronics Backup Slides
SD card Initialization

- Set up low level SPI
- Generate file system structure
- Generate DISKIO layer for in between communication
- Create first file
- Create directory listing
- Open File

- All functionality complete
Engine Control Electronics – Software

**Program Start**
- Read ARM Switch
  - Switch Open
    - Check WD Flag
      - Flag Set
        - Check EEPROM
          - Not Set
            - Clear EEPROM Flag
              - Switch Closed
                - Write to LED
                  - Save state to SD
                    - Shutdown System
                      - Not Set
                        - Initialization
                          - Main System Loop
                            - Switch Closed
                              - Wait 1 Second
                                - Wait for RUN switch
                                  - Not Set
                                    - Switch Open
                                      - Switch Closed
                                        - Shutdown System
                                          - Switch Open
                                            - Switch Closed
                                              - Check RUN Switch
                                                - Not Set
                                                  - Flag Set
                                                    - Flag Set
                                                      - Switch Closed
                                                        - Program Start
System Shutdown

- Close Fuel Valves
- Leave lube solenoid open during shutdown
- Kill all power going to pump.
- Once stopped, close solenoid
  - Stop based on hall effect rpm
- Finalize all data
  - Flush buffers
- Reset flags
Watchdog

• Made to prevent software errors from harming hardware.
• Updated every 40 ms
• Will always check watchdog reset flags on restart
  • If set will go into shut down
• Timer is adjustable based on loop time.
• This is hardware based and must be written to.
Critical Component: Processor

- Atxmega256a3
  - 64 pins - 50 IO
    - 1 to 3 SPI
    - 2 to 6 I2c
    - 2 to 6 USART
    - 12 bit ADC
  - 32 MHz Clock Speed
    - External 16 MHz utilized as well
  - Easily Available
    - ~$8.00 – Digikey
    - Large quantity in stock
Fuel Flow Sensor

- Equflow 0045
- Disposable insert (~$50)
- 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)
  - Predicted 580±5 pulses/s
- 34mA current at 5V
  - Not using filters
  - Replace as needed
- Store pulses in buffer collect at every read cycle
Critical Component: Hall-Effect and Comparator

- Used to calculate RPM
  - Reads magnetic changes
  - Must be sent through comparator circuit
  - 2116 pulses per second
- Circuit will be interrupt driven
  - Placed into buffer
  - Will work with processor
    - Enough clock cycles (3 instructions per pulse)
  - Buffer collected with every red cycle.
- Options
  - Part off of stock ESB
  - SS56AT (Honeywell)
Hall Effect Sensor SNR

• Magnetic field proportional to distance:
  • Sensor 37±0.2 mm from magnet

\[ B \propto \frac{1}{r^3} \quad \frac{B(r + \Delta r)}{B(r)} = \frac{37^3}{37.2^3} = 0.984 = 98.4\% \text{ field} \]

\[ 20 \log 0.984 = -0.14 \text{ dB} \]

• Field: 15mT
• Sensitivity: 50mV/mT

\[ \frac{50 \text{ mV}}{\text{mT}} \times 0.15 \text{mT} = 7.5 \text{ mV} \]

• Sensor noise: 10μT

\[ \frac{50 \text{ mV}}{\text{mT}} \times 10 \mu\text{T} = 0.5 \text{ mV} \]

• Signal to noise ratio:

\[ SNR = 20 \log \frac{7.5}{0.5} = 23.5 \text{ dB} \]
**Thermocouple Sample Rate**

- **Thermocouple Sample Rate:**
  - Safety range: 0 – 700 °C
  - Desire: 1°C maximum sampling error
    - Current significant digits on ECU
  - Max rate of change = 113.7 °C/s

  Min sampling Rate = \( \frac{113.7 \, ^\circ C}{s} \) = 113.7 Hz

- Maximum rate of change: 113.7 °C/s

Temperature vs Time of EGT for steepest section
• **Hall Effect Sample Rate:**
  - Safety range: 0 – 130,000 RPM
  - Desire: 0.50% (650 RPM) maximum sampling error
  - Max rate of change = 20,360 RPM/s

  \[
  \text{Min sampling Rate} = \frac{20,360 \text{ RPM}}{650 \text{ RPM}} = 31 \text{ Hz}
  \]

  Maximum rate of change: 20,360 RPM/s