Specialized Propulsion Engine Control System

Critical Design Review

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Customer: Air Force Research Laboratory
POC: 1st Lt. Carol Bryant
Presentation Structure

Overview
- Purpose and Objectives, Design Solution, CPE’s

Thrust Modification

Electronics
- Design Requirements and their Satisfaction

Communication

Project Risks
- Iterated for each Design Requirement above

Verification and Validation

Project Planning

Overview → Thrust Modification → Electronics → Comms → Risk → Verification & Validation → Plans
Overview
Problem Statement

- Increase Thrust-to-Weight (T/W) Ratio of the JetCat P90-RXi Engine
- The engine must run for an ‘extended period of time’ as defined by CONOPS

Motivation

- The United States Air Force (USAF) would like to implement a T/W increasing modification into their fleet of Unmanned Aerial Vehicles (UAV)
- Ideal solution would be low cost and easy to implement with minimal modification to existing engine
Basic Jet Engine Operation Refresher

Brayton Cycle for Jet Engine
Concept of Operations (Mission Profile)

UAV Mission Profile

- Engine off
- Engine start, warmup and taxi
- Takeoff
- Climb
- Cruise
- Mission
- Descent
- Landing

- Stock Engine Power
  - 120%
  - 100%
  - 90%
  - 0%

- AFC Idle: 1.75 oz/min

- SPECs Engine
- Stock Engine

- Time [s]
  - t = 0
  - ~2 min
  - 2 min
  - 1 min

- Validate T/W Increasing Mod.

Mission
Command Max Thrust
Functional Requirements

**FR1** - The JetCat P90-RXi engine shall have an increased T/W ratio of 20% from stock parameters.

**FR2** - SPECS shall control the engine over the entire operational envelope.

**FR3** - SPECS shall run the engine in a manner which does not incur damage to property or personnel.

**FR4** - SPECS shall have a user interface for engine control.
Functional Block Diagram

LabVIEW GUI
116 ms avg
(On Laptop PC)

E-Stop Button

Power Supply Relay

2S Lipo 5000mAh 2SC Supply Battery

Electronics Control Unit (ECU)
75-125 ms
- Send/receive data and E-flags from ECM
- Initiate control sequences
- Send/receive data, E-flags, and commands from GUI

Arduino MEGA

SPI Bus

I2C Bus

Engine Control Module (ECM)
262 to 1030 µs

Start Sequence

CPU

Fuel Pump Control Loop

Sensor Monitoring

ECM installed within JetCat, controls engine onboard systems (ATmega 328P)

JetCat P90 RXi

Fuel Solenoid Shutoff Valve

Starter Motor

Ignition System

Fuel Pump

Exhaust Temperature Sensor

Hall Effect RPM Sensor

Additional Temp/Flow and Pressure Sensors for Future

Variable DC Closed Loop Control

Power Supply and Control

Sensory Input

DC Control Sequence

SPECs Designed ECM PCB

Existing Onboard Device/Sensor

Arduino MEGA ECU Controller

Power Supply and Control Device

JetCat Turbojet Engine

Modified Components

Thrust Improving Modification
Functional Block Diagram

LabVIEW GUI
(on Laptop PC)

E-Stop Button

Power Supply Relay

2S Lipo 5000mAh 25C Supply Battery

Electronics Control Unit (ECU)
- Arduino MEGA
  - 75-125 ms
  - SPI Bus
  - I2C Bus
  - 72 to 125 ms
  - Send/receive data and E-flags
  - Initiate control sequences
  - Send/receive data, E-flags, and commands from GUI

Engine Control Module (ECM)
- Start Sequence
- Fuel Pump Control Loop
- Sensor Monitoring
- ECM installed within JetCat, controls engine onboard systems
- Atmel 328P

JetCat P90 RXi
- Fuel Solenoid Shut-off Valve
- Starter Motor
- Ignition System
- Fuel Pump
- Exhaust Temperature Sensor
- Hall Effect RPM Sensor
- Additional Temp Flow and Pressure Sensors for future

Variable DC Closed Loop Control
Power Supply and Control
Sensory Input
DC Control Sequence

Thrust Improving Modification
Thrust Improvement Modification ($\pi_C$)

**Major Design Elements:**
- Recharacterizing the JetCat Engine for 20% Thrust Improvement
  - Increase RPM → Increase $\pi_C$ → Increase Thrust
- New Nozzle to properly expand for new, higher $\pi_C$

<table>
<thead>
<tr>
<th>Thrust</th>
<th>$\pi_C$</th>
<th>KRPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock</td>
<td>105 N</td>
<td>2.35</td>
</tr>
<tr>
<td>Improved</td>
<td>126 N</td>
<td>2.61</td>
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</table>

\[ \pi_C = \frac{P_{t_3}}{P_{t_2}} \]
Thrust Improving Modification (Nozzle)

**Major Design Elements:**
- Based on Stock Nozzle Design
- Exit area decreased to properly expand new nozzle pressure

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight</th>
<th>Thermal Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock</td>
<td>Inconel 718</td>
<td>82.43 g</td>
</tr>
<tr>
<td>Improved</td>
<td>Ti 6AL-4V</td>
<td>47.78 g</td>
</tr>
</tbody>
</table>

\[
F = \dot{m}_0(V_f - V_0) + (P_f - P_0)A_f
\]

Nozzle Drawing
Functional Block Diagram

**Electronics Control Unit (ECU)**
- LabVIEW GUI
  - 115 ms avg
- (On Laptop PC)
- Arduino MEGA
  - 75-125 ms
  - Send / receive data and E-flags from ECM
  - Initiate control sequences
  - Send / receive data, E-flags, and commands from GUI

**Engine Control Module (ECM)**
- Start Sequence
- CPU
- Fuel Pump Control Loop
- Sensor Monitoring
- ECM Installed within JetCat, controls engine onboard systems (ATmega 328P)

**JetCat P90 RXi**
- Fuel Solenoid Shutoff Valve
- Starter Motor
- Ignition System
- Fuel Pump
- Exhaust Temperature Sensor
- Hall Effect RPM Sensor
- Additional Temp / Flow and Pressure Sensors for Future

**Thrust Improving Modification**

**Diagram Key**
- SPECS Designed ECM PCB
- Existing Onboard Device / Sensor
- Arduino MEGA ECU Controller
- Power Supply and Control Device
- JetCat Turbojet Engine
- Modified Components

**Legend**
- Variable DC Closed Loop Control
- Power Supply and Control
- Sensory Input
- DC Control Sequence
Engine Electronics Assembly

GUI Labview Module

Electronics Control Unit (ECU) (Arduino Mega, Shield, LCD)

Engine Control Module (ECM) (328p Controller, Motor Controller)
Functional Block Diagram

**Electronics Control Unit (ECU)**
- Arduino MEGA
  - 75-125 ms
  - Send/receive data and E-flags from ECM
  - Initiate control sequences
  - Send/receive data, E-flags, and commands from GUI

**Engine Control Module (ECM)**
- 262 to 1030 µs
- Start Sequence
- Fuel Pump Control Loop
- Sensor Monitoring
- ECM installed within JetCat, controls engine onboard systems (ATmega 328P)

**JetCat P90 RXi**
- Fuel Solenoid Shutoff Valve
- Starter Motor
- Ignition System
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- Exhaust Temperature Sensor
- Hall Effect RPM Sensor
- Additional Temp/Flow and Pressure Sensors for Future

**LabVIEW GUI**
- 116 ms avg
- (On Laptop PC)

**Power Supply Relay**

**E-Stop Button**

**2S Lipo 5000mAh 2SC Supply Battery**

**Variable DC Closed Loop Control**
- Power Supply and Control
- Sensory Input
- DC Control Sequence

**Thrust Improving Modification**
Hall Effect Sensor and Inlet Design

Printed with Formlabs class printer using high strength FLGPBK04 Resin

New Hall Effect Sensor Location
## Critical Project Elements

<table>
<thead>
<tr>
<th>Designation</th>
<th>CPE</th>
<th>Critical Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPE-1</td>
<td>Material Properties (Thrust Improvement Modification)</td>
<td>Thermodynamic and structural analysis require numerous assumptions on materials and operating conditions. Further analysis will <strong>characterize and define risks</strong>.</td>
</tr>
<tr>
<td>CPE-2.1</td>
<td>Engine Control Loop (ECM)</td>
<td>Control algorithms are inherently complex and require additional validation prior to implementation. Certification through the <strong>use of an engine analog is necessary</strong>.</td>
</tr>
<tr>
<td>CPE-2.2</td>
<td>Engine Sensors (ECM)</td>
<td>Coordination of engine sensor data acquisition with its utilization by the processor is critical. <strong>Without accurate sensor data, the engine cannot safely operate</strong>.</td>
</tr>
<tr>
<td>CPE-3</td>
<td>Communication from User to Engine (ECU)</td>
<td>During initial testing and product development user oversight will <strong>verify safe operation and monitor for anomalies</strong>.</td>
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Thrust Modification
Design Requirements & Satisfaction

CPE-1: Material Properties (Thrust Improvement Modification)

FR.1: The JetCat P90-RXi engine shall have an increased T/W ratio of 20% from stock parameters.

○ DR 1.2: Any modifications to the engine will not reduce the factor of safety of any engine component below 1.3 per USAR.
Shaft Assembly FEA

FEA consistent with conclusions drawn from prior calculations

Ac: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
11/30/2019 4:20 PM

Max
8.218E8
6.910E8
6.031E8
5.213E8
4.544E8
3.478E8
2.697E8
1.792E8
6.707E7
2.218E5

Min
Thermomechanical Turbine Analysis

Goal: Determine the increase in stress on the turbine due to the higher RPM and temperature through thermomechanical simulation (FEA).

Boundary Conditions:

1. Convective heat flux into turbine due to high velocity gas seen by the blades (h = 1653 W/m²-K)
2. Surface heat flux out of turbine due to flow of cooling oil (q= -155,000 W/m²)
3. Centrifugal force applied everywhere due to angular velocity about the +Z-axis

JetCat Turbine Model
Top View
Thermomechanical Turbine Analysis

Results:

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<tbody>
<tr>
<td>Stock</td>
<td>963</td>
<td>130,000</td>
<td>807</td>
<td>869</td>
<td>1.5</td>
</tr>
<tr>
<td>Improved</td>
<td>1000</td>
<td>140,000</td>
<td>892</td>
<td>906</td>
<td>1.36</td>
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The thrust improvement can feasibly be made without damage to the engine since S.F is > 1.3 as required. (DR 1.2)
Inlet Re-design FEA

<table>
<thead>
<tr>
<th>FLGPBK04 Resin</th>
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<tbody>
<tr>
<td>Tensile Modulus</td>
<td>2.8 GPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>1.03 GPa</td>
</tr>
<tr>
<td>Bulk Modulus</td>
<td>3.11 GPa</td>
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<tr>
<td>Ultimate Tensile Strength</td>
<td>65 MPa</td>
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<tr>
<td>Poisson’s Ratio</td>
<td>0.35</td>
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<tr>
<td>S.F.</td>
<td><strong>39</strong></td>
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Electrical Circuits and Assemblies
EGT Circuit

SPECS can accurately measure and transmit EGT temperature up to 730° C or above as needed. (DR 3.2)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SYMBOL</th>
<th>CONDITIONS</th>
<th>MIN</th>
<th>TYP</th>
<th>MAX</th>
<th>UNITS</th>
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<tbody>
<tr>
<td>MAX31855K Thermocouple Temperature Gain and Offset Error (41.276μV/°C nominal sensitivity) (Note 4)</td>
<td>T THERMOCOUPLE</td>
<td>-200°C to +700°C, T_A = -20°C to +85°C (Note 3)</td>
<td>-2</td>
<td>+2</td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>T THERMOCOUPLE</td>
<td>+700°C to +1350°C, T_A = -20°C to +85°C (Note 3)</td>
<td>-4</td>
<td>+4</td>
<td></td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>T THERMOCOUPLE</td>
<td>-270°C to +1372°C, T_A = -40°C to +125°C (Note 3)</td>
<td>-6</td>
<td>+6</td>
<td></td>
<td>°C</td>
</tr>
</tbody>
</table>
ECM Control Board

- MicroProcessor
- EGT Sense Circuit
- ICSP Header
- Hall Effect Circuit
- Battery Circuit

22mm x 50mm
ECM Motor Control Board

- Large trace pours for high current
- Standoffs for thermal isolation
- Stacked below Control Board

22mm x 50mm
ECM Controller Design Satisfaction Testing
Main Objectives: Determine the transfer function for the engine system response to satisfy control requirements.

FR 2: SPECS shall control the engine over the entire operational envelope.
Frequency Response Testing

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Frequency Response Testing

Main Objectives: Determine the transfer function for the engine system response to satisfy control requirements.

FR 2: SPECS shall control the engine over the entire operational envelope.

Engine System Characterization → Frequency Response Testing → Running Engine

Spring frequency response testing to satisfy FR 2

ECM

Controller D(s)

%PWM

Actuator A(s)

Sensor S(s)

Hall Effect

Fuel Pump
Main Objectives: Determine the transfer function for the engine system response to satisfy control requirements.

Test Details:
- Testing at several operating points from 55% to 90% max RPM.
Main Objectives: Determine the transfer function for the engine system response to satisfy control requirements.

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- Testing at several operating points from 55% to 90% max RPM.
Frequency Response Testing

Main Objectives: Determine the transfer function for the engine system response to satisfy control requirements.

Test Details:
- Testing at several operating points from 55% to 90% max RPM.
Communication
Design Requirements & their satisfaction

**CPE-3**

| Communication from User to Engine (ECU) | During initial testing and product development user oversight will verify safe operation and monitor for anomalies. |

**DR 4.1:** The SPECS user interface shall **display** to the user the **EGT** (10°C increments), **RPM** (1000 RPM increments), **battery voltage** (0.1V increments), and **calculated fuel flow rate** (oz/min).

**DR 4.2:** The SPECS user interface shall take user throttle inputs.

**DR 4.3:** The SPECS user interface shall have the ability to initiate the engine start up and shutdown sequences.

**DR 4.4:** The SPECS user interface shall display warnings for operation within 10% of safety limits to the operator.

**DR 4.5:** The SPECS user interface shall have an Emergency Stop (E-Stop) function.
Flowchart - Software

- User interface displays EGT, RPM, battery voltage, and fuel rate (DR 4.1).
- User interface displays safety warnings (DR 4.4).
- User interface allows changing engine state (start, stop, throttle, and emergency stops) (DR 4.2, 4.3, 4.5).
Software Timing of ECM/ECU

- **Total Collection Time:** 75 to 125 ms
  - Measured ECU Time:
    - Command: 125 ms
    - No command: 75 ms
  - Measured ECM Time: 267 to 1030 µs (3.81 to 0.97 kHz)
    - Measurement time dependent on engine RPM
      - 199µs at 130 kRPM
      - 963µs at 33 kRPM
    - Calculation time: 68.4µs
  - Sampling Delay: 50.0 ms

- **Ultimate Average GUI Sampling Time:** 116 ms

267µs < 462µs (130 kRPM) therefore communication is sufficiently fast
DR 3.1: SPECS will maintain operation below 130,000 RPM unless a new upper safety limit is determined from the engine characterization.

*SPECS analysis found the new RPM limit to be 140,000. This will be measured by the Hall effect sensor and verified to be accurate by simulation and engine test run.

DR 3.2: SPECS will maintain EGT below 700° Celsius unless a new upper safety limit is determined.

*SPECS analysis found new EGT upper safety limit is 730° C. This was determined through thermal analysis of engine materials.
ECM Compute Cycle Structure

Modular Programming
- Measure EGT
- Measure only the High pulse of RPM (Duty Cycle compensation)
- Compute system modification parameters
- Update “Engine Run” function
- Repeat

Start

Initialization
RunStatus = 0;
Eegt = 0;
Erpm = 0;

GetEGT → GetRPM

Main Flow

ShutdownSEQ

EngineRun

100 ms passed
Y

Compute system modification parameters

runstatus == 2

Y

FuelPump

Y

< StartSEQ and ShutdownSEQ return;
ECM Compute Cycle Timing

- Set simulation to “Engine Run”
- Disabled RPM Sense Function
- Measured Timing

Total compute time 68.4µs

Compute Window @ 130k = 267µs

SPECs can measure RPM in excess of 130K, and maintain control of all engine systems simultaneously. (DR 3.1)
Communication Overview: ECM/ECU (I2C)
Communication Overview: ECM/ECU (I2C)
Communication Overview: ECM/ECU (I2C)
Communication Overview: ECM/ECU (I2C)
Communication Overview: ECM/ECU (I2C)

EGT Data Bytes
Communication Overview: ECM/ECU (I2C)
Communication Overview: ECM/ECU (I2C)
Communication Overview: ECM/ECU (I2C)

ERROR Flag
Communication Overview: I2C and SPI clock zoomed out

- Top: I2C clock signal
- Bottom: SPI clock signal
- 50 ms between each I2C communication
- Parameters are still measured while ECM is gathering and preparing data for transmission
Communication Overview: I2C and SPI clock zoomed in

- Top: I2C clock signal
- Bottom: SPI clock signal
- No interference with clock signals when running I2C and SPI together
Safety Precautions

**E-Stop Button:** Disconnects all power. Last resort, no active cooling after use.

**GUI Manual:** User Emergency Stop, sends engine into shutdown.

**ECM Automatic:** Overspeed, Overtemp, Fuel Pump PWM to RPM Mismatch, Loss of ECU Communications.

*SPECS user interface provides an Emergency Stop (E-Stop) function (DR 4.5)*
CPE and DR Summary

CPE 2.1 - Engine Control Loop (ECM)
1) DR 3.1: SPECS will maintain operation below 140,000 RPM from the engine characterization.
2) DR 3.2: SPECS will maintain EGT below 730° Celsius

CPE 2.2 - Obtain accurate sensor data
1) DR 4.1: The SPECS user interface shall display to the user the EGT (10°C increments), RPM (1000 RPM increments), battery voltage (0.1V increments), and calculated fuel flow rate (oz/min).
2) DR 4.2: The SPECS user interface shall take user throttle inputs.
3) DR 4.3: The SPECS user interface shall have the ability to initiate the engine start up and shutdown sequences.
4) DR 4.4: The SPECS user interface shall display warnings for operation within 10% of safety limits to the operator.
5) DR 4.5: The SPECS user interface shall have an Emergency Stop (E-Stop) function.
Project Risks
Thrust Modification Risks and Mitigation

1) Engine Does Not Run
2) Turbine Failure
3) Other Engine Component Failure (Compressor, Shaft, etc.)
4) Foreign Object Damage

<table>
<thead>
<tr>
<th></th>
<th>ACCEPTABLE</th>
<th>MINOR ISSUE</th>
<th>MAJOR ISSUE</th>
<th>CATASTROPHIC</th>
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<tr>
<td>PROBABLE</td>
<td></td>
<td>1</td>
<td>2</td>
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<tr>
<td>HIGH POSSIBILITY</td>
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<td>LOW POSSIBILITY</td>
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<td>NOT LIKELY</td>
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</table>
1) **Engine Does Not Run**
   a) Engine Simulator
   b) Spare Engine Purchase

2) **Turbine Failure**

3) **Other Engine Component Failure** (Compressor, Shaft, etc.)

4) **Foreign Object Damage**

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**NOT LIKELY**

**HIGH POSSIBILITY**

**LOW POSSIBILITY**

**ACCEPTABLE MINOR ISSUE MAJOR ISSUE CATASTROPHIC**

**PROBABLE**

Thrust Modification Risks and Mitigation
1) Engine Does Not Run
   a) Engine Simulator
   b) Spare Engine Purchase

2) Turbine Failure
   a) Engine Model Validation
   b) Controller Safety Limits

3) Other Engine Component Failure (Compressor, Shaft, etc.)

4) Foreign Object Damage

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   a) **Engine Simulator**
   b) Spare Engine Purchase

2) Turbine Failure
   a) **Engine Model Validation**
   b) Controller Safety Limits

3) Other Engine Component Failure (Compressor, Shaft, etc.)
   a) **Component FEA**

4) Foreign Object Damage

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a) **Engine Simulator**  
b) **Spare Engine Purchase**  

2) Turbine Failure  
a) **Engine Model Validation**  
b) **Controller Safety Limits**  

3) Other Engine Component Failure (Compressor, Shaft, etc.)  
a) **Component FEA**  

4) Foreign Object Damage  
a) **Stock Inlet Filter**  

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<td>63</td>
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**Thrust Modification Risks and Mitigation**
1) Hall effect failure
2) Loss of engine control
3) Electrical component failure
4) Starter motor failure
5) Communication corruption

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<td>HIGH POSSIBILITY</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOW POSSIBILITY</td>
<td>4 5</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>NOT LIKELY</td>
<td>1 2</td>
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</tr>
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</table>

Electronics Risk and Mitigation
# Electronics Risk and Mitigation

1) Hall effect failure  
   a) **Fuel to RPM check**
2) Loss of engine control
3) Electrical component failure
4) Starter motor failure
5) Communication corruption

<table>
<thead>
<tr>
<th></th>
<th>ACCEPTABLE</th>
<th>MINOR ISSUE</th>
<th>MAJOR ISSUE</th>
<th>CATASTROPHIC</th>
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<tr>
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<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
<td>LOW POSSIBILITY</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
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<td>1</td>
<td>4</td>
<td>5</td>
<td>2</td>
</tr>
</tbody>
</table>
1) Hall effect failure
   a) Fuel to RPM check
2) Loss of engine control
   a) Physical emergency stop
3) Electrical component failure
4) Starter motor failure
5) Communication corruption

<table>
<thead>
<tr>
<th></th>
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<tr>
<td><strong>PROBABLE</strong></td>
<td></td>
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<td>HIGH POSSIBILITY</td>
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</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOW POSSIBILITY</td>
<td></td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>4</td>
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</tr>
<tr>
<td>NOT LIKELY</td>
<td>1,2</td>
<td></td>
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</table>

Electronics Risk and Mitigation
1) Hall effect failure
   a) Fuel to RPM check
2) Loss of engine control
   a) Physical emergency stop
3) Electrical component failure
   a) Simulation
   b) Testing/Redesign
4) Starter motor failure
5) Communication corruption

<table>
<thead>
<tr>
<th></th>
<th>ACCEPTABLE</th>
<th>MINOR ISSUE</th>
<th>MAJOR ISSUE</th>
<th>CATASTROPHIC</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
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<tr>
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</tr>
<tr>
<td>LOW POSSIBILITY</td>
<td>4</td>
<td>5</td>
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</tr>
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<td>NOT LIKELY</td>
<td>1,2,3</td>
<td></td>
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1) Hall effect failure  
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2) Loss of engine control  
   a) Physical emergency stop
3) Electrical component failure  
   a) Simulation  
   b) Testing/Redesign
4) Starter motor failure  
   a) Spare motors
5) Communication corruption

### Electronics Risk and Mitigation

<table>
<thead>
<tr>
<th>Probable</th>
<th>Acceptable</th>
<th>Minor Issue</th>
<th>Major Issue</th>
<th>Catastrophic</th>
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<tbody>
<tr>
<td>LOW</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOT LIKELY</td>
<td>1,2,3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIGH</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PROBABLE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1, 2, 3: Not likely
4: Low possibility
5: Probable
### Hall effect failure
- a) **Fuel to RPM check**

### Loss of engine control
- a) **Physical emergency stop**

### Electrical component failure
- a) **Simulation**
- b) **Testing/Redesign**

### Starter motor failure
- a) **Spare motors**

### Communication corruption
- a) **Message filtering**

---

**Electronics Risk and Mitigation**

<table>
<thead>
<tr>
<th>PROBABLE</th>
<th>ACCEPTABLE</th>
<th>MINOR ISSUE</th>
<th>MAJOR ISSUE</th>
<th>CATASTROPHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH</td>
<td></td>
<td>1,2,3</td>
<td>5</td>
<td></td>
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<tr>
<td>LOW</td>
<td>4</td>
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<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Verification & Validation
Electronics/Software Validation
Engine Test Rig Components

- Engine Assembly
- Thermocouple
- Glow plug
- Fuel Pump
- RPM Simulation
- Rotary Encoder
- "Fuel" Tank
- Battery
- LCD
- Emergency Stop
- ECU
- 328P Microprocessor
- EGT Circuit
- Motor Control Circuits
ECM Verification and Validation

Testing Objective: Verify operation and control of all ECM circuits on breadboard and PCB.

Location: On assembled Test Rig

Method and Parameters:

1) Complete a startup, run and shutdown sequence on test rig.
2) Verify RPM measurements using oscilloscope.
3) Verify EGT measurement using infrared pyrometer.
4) Implement and test all emergency stop programming functions
   - GUI Command Emergency Stop
   - Engine Overspeed
   - Engine EGT Overtemp
   - Fuel command to measured RPM mismatch (Hall effect failure, max engine RPM)
JetCat Engine LabView Simulator

Simulator Objectives:
- Verify entire SPECS electronics work as designed before integration with real JetCat engine.

Items to Verified:
- Control
- Communication
- Electronics (Post PCB) operation
- Safety Limits
- Emergency Stop
- Anomaly Handling

Simulated Outputs:
- RPM
- EGT
Software Results Validated

RPM and EGT collection successful ✔️
Engine Run SPECS Validation
## JetCat Engine Run Validation Testing

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Engine RPM</th>
<th>Results Desired</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock Engine Run</td>
<td>Idle - 130,000 RPM</td>
<td>Glow Plug, Fuel Pump PWM (Controls)</td>
</tr>
<tr>
<td>Stock Engine Run - Max Thrust</td>
<td>130,000 RPM</td>
<td>Max Thrust Statistical Data</td>
</tr>
<tr>
<td><strong>Integrate SPECS with JetCat</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPECS Engine Run (Stock Nozzle)</td>
<td>130,000 RPM</td>
<td>Verify Safety and Control of modified Eng.</td>
</tr>
<tr>
<td>SPECS Engine Run (Stock Nozzle)</td>
<td>140,000 RPM</td>
<td>New Max Thrust</td>
</tr>
<tr>
<td>SPECS Engine Run (SPECS Nozzle)</td>
<td>140,000 RPM</td>
<td>Modified Max Thrust, New Nozzle effectiveness</td>
</tr>
</tbody>
</table>
1) Main Objective of Testing is to verify all of the requirements, verify models.

2) Engine runs will be conducted at the CU East Power Plant.

3) The test platform will measure EGT, Tt4, flow velocities and thrust.
Full System Verification

Primary objective of testing: engine run for engine characterization

Requirements to be Verified

Required Systems/Sensors

Parameters Required for Verification

Thrust

Inlet Mass Flow

Exhaust Flow Characterization

Engine RPM

Total Temperature at Turbine

Exit Gas Temperature

Exit Flow Velocity

Total and Static Pressure at Exit

Load Cell

Control Volume & Differential Pressure System

Thermocouple (Stock Installed)

Thermocouple

Maintain Exhaust Temperature Below Upper Safety Limit (DR 3.2)

Redesign of Nozzle for New Operating Conditions (FR 1)

Maintain RPM Below Upper Safety Limit (DR 3.1)

Turbine Factor of Safety of 1.36 (DR 1.2)
Mass Flow Characterization

Primary objective of testing: engine run for engine characterization

- Thrust
  - Load Cell
    - 20% Increase of Engine T/W (FR 1)
- Inlet Mass Flow
  - Control Volume & Differential Pressure System
- Exhaust Flow Characterization
  - Exit Gas Temperature
  - Exit Flow Velocity
- Engine RPM
  - Total and Static Pressure at Exit
  - Hall Effect Sensor
  - Maintain RPM Below Upper Safety Limit (DR 3.1)
  - Turbine Factor of Safety of 1.36 (DR 1.2)
- Total Temperature at Turbine
  - Thermocouple
  - Redesign of Nozzle for New Operating Conditions (FR 1)
  - Maintain Exhaust Temperature Below Upper Safety Limit (DR 3.2)

Requirements to be Verified
- Required Systems/Sensors
- Parameters Required for Verification
Mass Flow Characterization

Test Objectives:
- Measure mass flow to verify simulation models
- Control volume created to measure inlet flow

Measurements:
- SPD1108R Differential Pressure sensor:
  Range = 0 - 500 Pa ± 1%
  Resolution = 0.0075 mV/Pa
Thrust Modification Validation

Primary objective of testing: engine run for engine characterization

- Requirements to be Verified
- Required Systems/Sensors
- Parameters Required for Verification

Thrust

- Inlet Mass Flow
  - Thrust
  - Load Cell
    - Control Volume & Differential Pressure System
  - Entrance Mass Flow Characterization
  - Exit Gas Temperature
  - Exit Flow Velocity
  - Total and Static Pressure at Exit

- Engine RPM
  - Total Temperature at Turbine
  - Hall Effect Sensor
  - Thermocouple

20% Increase of Engine T/W (FR 1)

- Maintain Exhaust Temperature Below Upper Safety Limit (DR 3.2)
- Redesign of Nozzle for New Operating Conditions (FR 1)
- Maintain RPM Below Upper Safety Limit (DR 3.1)
- Turbine Factor of Safety of 1.36 (DR 1.2)
Thrust Improvement Verification

Test Objectives:
- Measure thrust and verify proper expansion of flow by nozzle.
- Engine Run 140,000 RPM Stock Nozzle
- Engine Run 140,000 RPM SPECS Nozzle

Requirements Verified:
- FR 1: 20% increase of T/W.

Measurements:
- Load Cell FC22:
  \[ \text{Range} = 44.5 - 444.8 \text{ N} \pm 1\% \]
  \[ \text{Resolution} = 0.00125 \text{ mV/N} \]
Exit Flow Validation

Primary objective of testing: engine run for engine characterization

- Thrust
  - Load Cell
    - 20% Increase of Engine T/W (FR 1)
- Inlet Mass Flow
  - Control Volume & Differential Pressure System
- Exhaust Flow Characterization
  - Exit Gas Temperature
  - Exit Flow Velocity
  - Total and Static Pressure at Exit
- Engine RPM
- Total Temperature at Turbine
- Requirements to be Verified
- Required Systems/Sensors
- Parameters Required for Verification

- Thermocouple (Stock Installed)
  - Maintain Exhaust Temperature Below Upper Safety Limit (DR 3.2)
- Thermocouple
  - Turbine Factor of Safety of 1.36 (DR 1.2)
- Hall Effect Sensor
  - Maintain RPM Below Upper Safety Limit (DR 3.1)
- Exhaust Pitot-Static Pressure Transducer
  - Redesign of Nozzle for New Operating Conditions (FR 1)
Exit Temperature Characterization

Test Objectives:
- Measure the exit gas temperature

Requirements Verified:
- DR 3.2: SPECS will maintain EGT below 700° Celsius unless a new upper safety limit is determined.
- New safety limit was determined to be 730° Celsius

Measurements:
- JetCat Stock Thermocouple:
  Range = -100 to 1300°C ±1.1°C
Exit Flow Characterization

Test Objectives:

- Measure exit pressure differential to verify flow is properly expanded by modified nozzle

Requirements Verified:

- Model validation & thrust improvement

Measurements:

- Differential Pressure Transducer PX137-015DV:
  Range = 0-206.84 kPa ± 1.5%
  Resolution = 0.43 mV/kPa
DAQ Selection

- Selected USB 6009 for data acquisition
- 8 analog inputs for data collection
- Input Resolution: 13 bits
- Maximum Sampling Rate: 48 kS/s
- 500 Hz Square Wave on software timed digital I/O, sufficient for 150000 RPM simulation
Project Plans
Work Breakdown Structure

**Course Deliverables**
- CDR
- FFR
- MSR
- TTR
- AIAA Paper
- SFR
- PFR
- AFRL Competition

**Management**
- Schedule
- Assess Risk
- WBS
- Budget
- Part Procurement
- Design Req. Satisfaction

**Electrical**
- PCB Design
- PCB Sim.
- Test Bed Development
- Manufacture
- PCB ECM
- PCB ECU
- Test Rig Integration

**Software & Simulation**
- GUI Dev.
- E-Stop
- Engine Simulation
- Controller - Simulation Interface
- Control Algorithms
- Anomaly - Safe Design
- Refine Control
- User Manual

**Thermal - Mechanical**
- Nozzle CAD
- Spectroscopy Analysis
- Data Based Model Refinement
- Manufacture
- Nozzle Al.
- Nozzle Ti.

**Testing**
- Test Stand Design
- Procedures
- Safety Plan
- Stock Eng. Run Data
- Mass Flow
- EGT
- Glow Plug
- RPM
- Thrust
- Modified Eng. Run

**Legend**
- Completed
- Future Work
Project Planning

SPECs - AFRL L/D Ratio

- Conceptual Design Document: 100%
- Preliminary Design Review: 76%
- Conceptual Design Review: 0%
- Fall Final Report: 0%
- Manufacturing Status Review: 0%
- PCB Design and Manufacturing: 0%
- PCB Integration: 0%
- Software Development: 0%
- Hardware Development: 0%
- Test Readiness Review: 0%
- Stock Testing Verification: 0%
- Modification Implementation: 0%
- Analysis: 0%
- Spring Final Review: 0%
Project Planning

- **PCB Design and Manufacturing**
  - PCB Design 1-Breadboard Testing
  - PCB Order 1
  - PCB Design 2
  - PCB Order 2
  - PCB Design 3
  - PCB Order 3

- **PCB Integration**
  - Electronics T/S - Integration
  - Electronics - Engine Integration

- **Software Development**
- **Hardware Development**

- **Test Readiness Review**
- **Stock Testing Verification**
  - Test Bench Engine SPECS control
  - Stock Engine characterization

- **Modification Implementation**
  - Modified Engine Run Testing

- **Analysis**
  - Data Analysis

**Critical Path**
- Thermo
- Mechanical
- Electronics
- Critical Events

**Critical Path**
- Electronic Manufacturing/Design/Test/Redesign
- Electronic T/S Electronics Integration
- Electronic T/S Electronics Integration/Test
- Modified Engine Run
- Data Analysis/Presentation

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## Cost Plan

<table>
<thead>
<tr>
<th>Costs</th>
<th>Amount</th>
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<tbody>
<tr>
<td>Electrical</td>
<td>$1354.70</td>
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<tr>
<td>Mechanical</td>
<td>$1557.55</td>
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<tr>
<td>Engine</td>
<td>$930.00</td>
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<tr>
<td>Test Bed</td>
<td>$220.00</td>
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<tr>
<td>Presentation</td>
<td>$100.00</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>$4162.25</strong></td>
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<tr>
<td><strong>Budget</strong></td>
<td><strong>$5000.00</strong></td>
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<tr>
<td><strong>Margin</strong></td>
<td><strong>$837.75</strong></td>
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</table>

- Margin is positive, therefore the project is financially feasible.
# Cost Plan Major Items + EEF

## High Cost Items

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium Round Bar 3.75” x 10”</td>
<td>$1307.55</td>
</tr>
<tr>
<td>Custom PCB (ECU/ECM) 3 Iterations</td>
<td>$792.00</td>
</tr>
<tr>
<td>JetCat V.10 ECU</td>
<td>$500.00</td>
</tr>
<tr>
<td>JetCat Refurbishment</td>
<td>$400.00</td>
</tr>
</tbody>
</table>

## Requested EEF Fund

- New JetCat P90-Rxi Engine: $2195.00
- JetCat V.10 ECU: $500.00
- Test Stand Refurbishment: $200.00
- Differential Pressure Transducer: $100.00

Total: $2995.00
# Upcoming Testing Schedule

<table>
<thead>
<tr>
<th>Test to be Conducted</th>
<th>Date Scheduled</th>
<th>Test Plan</th>
<th>Materials</th>
<th>Facility</th>
<th>Test Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Rig “Engine Run” 1</td>
<td>28 DEC</td>
<td>✓</td>
<td>PCB 1.0</td>
<td>ITLL/EC</td>
<td></td>
</tr>
<tr>
<td>Test Rig “Engine Run” 2</td>
<td>07 JAN</td>
<td>✓</td>
<td>PCB 2.0</td>
<td>ITLL/EC</td>
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<tr>
<td>Test Rig “Engine Run” 3</td>
<td>16 JAN</td>
<td>✓</td>
<td>PCB 3.0</td>
<td>ITLL/EC</td>
<td></td>
</tr>
<tr>
<td>Test Rig Anomaly Simulation Interface</td>
<td>11 FEB</td>
<td>✓</td>
<td>PCB 3.0</td>
<td>ITLL/EC</td>
<td></td>
</tr>
<tr>
<td>Stock Engine Run Start</td>
<td>18 FEB</td>
<td>✓</td>
<td></td>
<td>* CU Boulder E. Power Plant</td>
<td></td>
</tr>
<tr>
<td>SPECS Engine Run Start</td>
<td>11 MAR</td>
<td>✓</td>
<td></td>
<td>* CU Boulder E. Power Plant</td>
<td></td>
</tr>
</tbody>
</table>

* 1 week notice + test plan required for engine run at CU Boulder E. Power Plant
Questions?


References


References


Backup Slides
Electronics
I2C vs. SPI & Why

- Problem: ECM has master emergency control of engine. With SPI only one master device, Master initiates communications.
- If ECM is SPI master, cannot guarantee that E-Stop from GUI would be read in an emergency, internal interrupts would overwrite incoming commands.
- If ECU is SPI master, EGT is a native SPI device, EGT monitoring could not occur on ECM. Adds complexity, EGT required for sequence and monitoring resulting in multiple transmissions between devices.
- Solution: Use both
  - ECM as SPI master and ECU as I2C master.
ECU Shield PCB
Motor Control Circuit (Starter / Fuel Pump)

PWM frequency must be greater than $5\tau$ for stable operation, higher PWM results in smooth operation with less noise.

Calculated optimal PWM = 1.138kHz
Setpoint = 976.56 Hz (Closest Prescale > 5$\tau$)
Concept of Operations (SPECS)

Using JetCAT electronics to test engine performance. Identify control methods and develop baseline.

Remove all JetCAT electronic control components. Starter, fuel pump, temp sensors and ignition system remain.

Install SPECS ECU/ECM control system onto JetCAT turbojet engine. Install additional sensors.

Tune system performance to approach new safe operation limits to improve thrust to weight ratio.

SPECS controller will allow future engine modification beyond stock system capabilities.

Future
Effect of Thermal Expansion on Nozzle Area

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Coefficient</th>
<th>Area After Expansion</th>
<th>Percentage Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti 6AL-4V</td>
<td>7x10^{-6} in/in/F</td>
<td>498.8226 mm²</td>
<td>1.6193 %</td>
</tr>
<tr>
<td>Inconel 718</td>
<td>11x10^{-6} in/in/F</td>
<td>503.3934 mm²</td>
<td>2.5505 %</td>
</tr>
<tr>
<td>Cobalt Chrome</td>
<td>8.4x10^{-6} in/in/F</td>
<td>500.4152 mm²</td>
<td>1.9439 %</td>
</tr>
<tr>
<td>N60 Stainless Steel</td>
<td>10.3x10^{-6} in/in/F</td>
<td>502.5904 mm²</td>
<td>2.3869 %</td>
</tr>
</tbody>
</table>
Thermomechanical Calculations

Modeling the heat transfer into the turbine blades due to the combustion gases with a Convective heat flux on a flat plate:

\[ h = \frac{k}{L} \left( 0.037 Re^{0.8} Pr^{1/3} \right) \]

\[ Pr = \frac{\mu c_p}{k} \quad Re = \frac{\rho V L}{\mu} \]
Thermomechanical Calculations

Modeling the heat transfer out of the turbine blades due to the cooling oil with a surface heat flux on a flat plate:

\[ \Delta h = m c_p \Delta T \]
\[ q = \dot{m} \Delta h c_p \]
# Shaft Assembly FEA Results

<table>
<thead>
<tr>
<th>Component (Stock)</th>
<th>MATERIAL</th>
<th>YIELD STRENGTH OF MATERIAL</th>
<th>Maximum Stress</th>
<th>S.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPRESSOR</td>
<td>Al 7075</td>
<td>440.57 MPa</td>
<td>223.5 MPa</td>
<td>1.97</td>
</tr>
<tr>
<td>SHAFT</td>
<td>AISI 301</td>
<td>2123.60 MPa</td>
<td>279 MPa</td>
<td>7.61</td>
</tr>
</tbody>
</table>

- Component materials were determined from Alibaba, a vendor of JetCat replacement parts
- All material properties were found in
  - Military Handbook-5H --- Metallic Materials and Elements for Aerospace Vehicle Structures
Modal Blade FEA
Vibration

- Strouhal Number:
  \[ St = \frac{fL}{V} \]

- Blade Passing Frequency:
  \[ BPF = \frac{nt}{60} \]

Fig. 1. (a) Centrifugal pump with a 4-blade impeller \((N_b = 4)\), and (b) vibration spectrum for pump/fan/compressor with four blades/cylinders.
Fatigue

- Marin Factors:

\[ S_e = K_a K_b K_c K_d K_e K_f S_e' \]
Creep

- Arrhenius Equation:
  \[ \dot{\varepsilon}_s = Ce^{-Q/RT} \]
  - Activation Energy Approximation:
  \[ \Delta H = -0.23\sigma + 209.64 \]

- Power Relation:
  \[ \dot{\varepsilon}_s = \left( \frac{\sigma}{E} \right)^n \]
Creep

Figure 6.3.5.1.7(a). Average isothermal 0.10% creep curves for Inconel 718 forging.
EDS Spectroscopy Results

Summary of EDS signals tested at 5 different locations. C, Al, Si, Cr, Ni are found in all of 5 locations. Mn, Mo, and Ta are found in several points.

EDS spectral of jet engine material sample at point #1.
<table>
<thead>
<tr>
<th>Process Function/Part</th>
<th>Potential Failure Mode</th>
<th>Potential Effect(s) of Failure</th>
<th>Severity</th>
<th>Potential Cause(s)/Mechanism(s) of Failure</th>
<th>Occurrence</th>
<th>Current Process Controls</th>
<th>Detection</th>
<th>Recommended Action(s)</th>
<th>Responsibility and Target Completion Date</th>
<th>Action Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Blades</td>
<td>High-Cycle Fracture</td>
<td>Damage Engine/Personnel Harm</td>
<td>4</td>
<td>Torsional Resonance/Design Factors</td>
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Predictive Model

Advanced engine model required to test ECU/ECM prior to installation on hardware.

Incorporation of component efficiencies provides more accurate results (<2% error on test/manufacturer data).

Verifies Model

...with manufacturer/past test data.

...with theoretical model and future $T_{t4}$ test data.
Simulation

Thermodynamic analysis necessitates a more advanced model.

Incorporation of component efficiencies provides more accurate results (<2% error from engine data).
GUI Flowchart

while (stop != T)

- **engine start**
  - Y: visa.write(1)
  - N: engine stop

- **engine stop**
  - Y: visa.write(2)
  - N: RPM

- **RPM**
  - Y: >=33, Y: visa.write(RPM)
  - N: <30

- **Estop**
  - Y: disable inputs
  - N: visa.write(10)

- **stopall**
  - Y: stop = T
  - N: continue

- continue: enable stopall

_text_

while (stop != T)

- isim in queue
  - Y: dequeue
  - display RPM
  - display EGT

- file.write (time, RPM, EGT)

- visa.read

- bytes available
  - Y: >=6
  - pull RPM/EGT

- error
  - Y: display error
  - N: enqueue

Stop
ECU Flowchart
Testing Backup Slides
Differential Pressure Sensor Selection Process I

- Assumed model mass flow:

\[ \dot{m} = (4.26 \times 10^{-6})(kRPM)^2 + (1.77 \times 10^{-4})(kRPM) + 0.16523 \]

- Flow velocity:

\[ V = \frac{\dot{m}}{\rho A} \]

- Differential pressure:

\[ \Delta P = \frac{V^2 \times \rho}{2} \]

- Mass flow had been modelled across entire operational range of RPM

- Used model to find flow velocity assuming constant density

- Found differential pressure using flow velocity
Differential Pressure Sensor Selection Process II

Modelled Differential Pressure Over Operational RPM Range

- ΔP = 129.84 Pa
- ΔP = 314.62 Pa
- 185.61 kRPM
Modelled Mass Flow Rate

Modelled Mass Flow Through Control Volume as a Function of Engine RPM

- Mass Flow vs RPM
- Engine Idle (33 kRPM)
- Maximum Thrust (140 kRPM)

Control Volume Mass Flow [kg/s]

Engine RPM [kRPM]

- Mass Flow: 0.2735 kg/s
- Mass Flow: 0.1757 kg/s
EGT probe data sheet

Fast Response EGT Temperature Probe

- Type K thermocouple probe
- Exposed sensing junction for fastest response
- Includes 316 SS adjustable compression fitting
- Stainless steel protected wires
- Designed for engine test & racing environments

Specifications

Thermocouple type: K
Range: -148 to 2372°F (-100 to 1300°C)
Accuracy: +/−0.4% of reading or about +/− 1.1°C (Special Limits of Error)

Probe diameter: 3/16 inch (0.187 inch) (4.75 mm)
Sensing Junction: Exposed, Ungrounded
Response Time*: 250 mS
*Time Constant: Defined as the time required to reach 63.2% of an instantaneous temperature change
Five time constants are required to approach 100% of the step change value

Outer Sheath Material: Inconel, melting point 2550°F (1400°C)
Cable: Stainless steel overbraiding over Teflon™ insulated, stranded wires, 20 gage
Compression Fitting: 316 stainless steel, double ferrule, adjustable, 1/8 inch −27 NPT male thread
Wiring: + = Yellow − = Red
## Thrust Modification Risk Analysis

1. Nozzle Inefficiencies
2. Bearing Wear
3. Compressor Fatigue
4. Fuel System Failure
5. Sensor Failure
6. FOD
7. Compressor Failure
8. Bearing Failure
9. Shaft Failure
10. Pressure Vessel Failure
11. Turbine Failure

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<th>JETCAT Beyond Repair</th>
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- **Acceptable**: No repair required.
- **Minor Issue**: Repair required.
- **JETCAT Repair Required**: Jetcat repair required.
- **JETCAT Beyond Repair**: Jetcat repair not possible.
Controls Backup Slides
Frequency Domain Testing

Test details:
- 0.005 to 0.4 Hz multisine with 0.01 Hz increments covering turbine dynamics\textsuperscript{11}
- Testing at several operating points from 55% to 90% max RPM.
- 5 Hz sampling frequency
- Amplitude +/- 10% fuel rate
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Engine Simulation Flowchart (1)
Engine Simulation Flowchart (2)
Engine Simulation Flowchart (3)
PDR Backup Slides
**Purpose:** Offboard communication device between ECM and user interface. Performs computation of system parameters to output to GUI

**Needs:**
- Send engine state requirements to ECM
- Send engine throttle commands from user to ECM
- Receive sensor data from ECM for processing

**Capabilities: (Arduino Mega)**
- I2C communication
- 54 Digital I/O pins
- 256 kB Flash Memory (store program and data)
- 4 x 16 bit timers (control complex timing sequence)
- 4 UART (connect many devices)
BASELINE DESIGN - ECM

Purpose:
- Control engine sequence operation: Start, Run, Shutdown.
- Control engine to commanded throttle setting from ECU

Needs:
- Read RPM and temperature data from Hall effect and thermocouple respectively
- Perform DAC/ADC
- PWM motor control
- I2C & SPI communication

Capabilities: (ATmega 328P)
- 6 PWM channels
- 20 MHz oscillator
- 32 kBytes flash memory
- 8-channel 10-bit ADC
- I2C and SPI capable
- 500 kHz internal sampling rate for digital inputs
BASELINE DESIGN - ECM (HALL EFFECT SENSOR)
**Purpose:** Sense RPM, output square wave for engine control

**Needs:** Sense RPM >130 kRPM, output to microprocessor, read pulse width to calculate RPM

**Capabilities:** Hall effect Honeywell SS40A - Measured pulse width duty cycle at 42.5% for 5 kRPM. Pulse width at 130 kRPM is 197.5 µs; 13 µs minimum pulse width for rise / fall and response time of Hall effect sensor

**Application Note:** Starter assembly - redesign and 3D print to capture Hall effect sensor and route wire to ECM without inlet obstruction
MODIFICATION FEASIBILITY PROCESS

Increase engine thrust by 20%

What $\pi_C$ is required?

Is the engine physically capable of new P, T and RPM?

SABRE data correlates $\pi_C$ to RPM

Ideal cycle calculations verify

Energy balance for $W_c$ to $W_t$

Work capability of turbine

Work requirements of compressor

Engine component properties
Pressure ratio ($\pi_C$) calculation for 20% increase in thrust assuming:

- Ideal Brayton cycle
- Axial compressor

**Model results:** Ideal Brayton cycle requires $\pi_C = 2.61$ to feasibly obtain 20% thrust increase
Pressure ratio observation for 20% increase in thrust:

- Observed in SABRE data
  - Provides a lower bound for expected value of $\pi_C$
- Required $\pi_C$ therefore expected to fall between:
  - 2.46 (real) - 2.61 (ideal)

**Model results:** Increased thrust with $\pi_C = 2.46$ is feasible to obtain with ~10,000 RPM increase
PRESSURE RATIO FEASIBILITY

<table>
<thead>
<tr>
<th>Ideal</th>
<th>Compressor Work (required)</th>
<th>Turbine Work (available)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock</td>
<td>19.99 kW</td>
<td>48.01 kW</td>
</tr>
<tr>
<td>20% Increase</td>
<td>22.3 kW</td>
<td>46.1 kW</td>
</tr>
</tbody>
</table>

**Result:** Thrust increase is feasible since there is excess work available from the turbine.
ENGINE COMPONENT ANALYSIS MODEL

- Compressor/Turbine
  - Angular Motion
    - Low angular acceleration, high angular velocity
    - Stress at blade tip compared to material yield stress to verify integrity
- Nozzle/Engine Case
  - Thin Wall Pressure Vessel
    - Stresses calculated with total pressure at corresponding stations, compared to yield strength for estimated materials
- Shaft
  - Power-Torque Relation
    - Shear stresses from compressor and turbine calculated and compared to ultimate shear for assumed material
NOZZLE FEASIBILITY

- With new pressure ratio, the required exit area for perfectly expanded flow at sea level is 0.00138 m²
- This is a 26% decrease in stock nozzle exit area
- New dimensions can be manufactured

<table>
<thead>
<tr>
<th>MATERIAL DESIGN</th>
<th>MATERIAL</th>
<th>TENSILE YIELD FAILURE</th>
<th>ACTUALLY EXPERIENCED</th>
<th>S.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOZZLE DESIGN</td>
<td>CoCrMo</td>
<td>350 MPa</td>
<td>5.8 MPa</td>
<td>60.34</td>
</tr>
</tbody>
</table>

- Material property was found from The Japan Institute of Metals --- Mechanical Properties of Biomedical Co-33Cr-5-Mo-0.3N Alloy at Elevated Temperatures
ECM HALL EFFECT SENSOR TESTING

Hall Effect Honeywell SS40A

System Settings: TEAG = 5 mm

Method: Commanded starter to run. Measured Hall effect waveform properties using oscilloscope. Duty cycle 42.52%, Freq = 37.97Hz. ECU LCD readout = 2275 RPM (37.91Hz), RPM calculation confirmed

Test Results: Verified Hall effect sensor functional, communicates and maps correct RPM
JetCat implementation of Hall effect sensor has been problematic. Sensor set beyond datasheet max distance for estimated magnetic field (35mm). Sensor measured <20% duty cycle (high RPM near sensor limit DC varied).

Specs Solution:

- Upgrade Hall effect sensor, relocate closer to magnet for precision
- New location provides 42% or better duty cycle with higher accuracy
- **Verified new sensor will read RPM up to 300 kRPM (5 mm away)**
ECM DATA SAMPLING RATE: RPM

Microprocessor Pulse Injection

**System Settings:** Square wave duty cycle = 35% benchtop waveform generator

**Method:** Using waveform generator, supplied frequencies from 50 Hz to 5 kHz (3 - 300 kRPM). Waveform measured on ECM, then transmitted to ECU, then converted to RPM and sent to LCD. Total communication time <20ms.

**Test Results:** Verified ECM can measure RPM in excess of 300 kRPM
Method: MEDUSA engine run EGT data showing max temp rate of change from throttle command

Needs: Design controller to limit temperature change to less than 113.7°C/s

Future Test Requirements: Use proportional linear ramp controller to characterize fuel delivery and correlate to temperature rate of rise across RPM spectrum. Adjust fuel pump ramp rate to maintain less than 113.7°C/s temperature increase.
FUEL PUMP CHARACTERIZATION TESTING

Methods:

● Applied 0.28-5V to fuel pump, 0.5V increments for 10 seconds
● Video recorded weight of fuel tank and stop clock simultaneously
● Analyzed change in weight to find mass flow & voltage relationship

Test Results: Stock fuel flow at max thrust: 4.7 g/s. Pump can support higher fuel flows needed to increase $T_{t4}$ & RPM

DR 2.2.3: SPECS shall send PWM fuel pump command rate as a percentage of full power

Fuel Pump Curve through Manifold

- Current Max Operating Level

Data
Best Fit
ECU DATA LINK FEASIBILITY

Communications testing:

1. Verify communications protocol GUI⇒ECU⇒ECM to send command and execute.
2. Calculate minimum data transfer values, test ECM to evaluate processing time.
3. Test at maximum data transfer quantity, test ECM to evaluate processing time.

Results:

1. I2C communications verified through start/shutdown sequence and LCD display.
2. Minimum data transfer found to be 5 bytes, transfer time <20ms.
3. 32 byte (I2C maximum) tested time <50 ms per request (<200ms maximum)
At 8.4VDC (2S LiPo full charge) or 5V (Vcc), used large benchtop power supply to measure component current consumption during design operation

- 11.2A cumulative total
- Select 2S 5200mAh battery with 50C rating
  - 260A peak current
  - ~20 min runtime at full 100% power
  - Less heating for motor control compared to 3S
  - Starter exceeded 5k RPM at 5V

**Test Result:** Supplied amperage from battery exceeds max current demand by SPECS
FUEL PUMP CAPACITY TEST SETUP

- Linear Relationship at 2 (g/s)/V

- Mass Flow rate = -0.11V^2 + 2.57V - 0.57

- This provides < 5% error throughout the 5V range
Second Order fit is:

\[ \text{Thrust} = 0.0073(\text{RPM})^2 - 0.4(\text{RPM}) + 9.29 \]

This provides ~20% thrust increase with ~10 kRPM increase
IDEAL CYCLE ASSUMPTIONS

- Ideal Brayton Cycle
  - Standard Air
    - Calorically Perfect Gas
    - Constant Specific Heat
  - Isentropic Inlet, Compression, Turbine, and Nozzle
  - Constant Pressure Heat Addition & Rejection
    - Fuel mass flow << Air mass flow
  - Perfectly Expanded Flow Exiting Nozzle
  - Closed System, no losses

- Steady 1D flow
- Axial Compressor
- Sea Level Atmospheric Conditions
- Compressor Pressure Ratio Scales Linearly with Mass Flow Rate
IDEAL BRAYTON CYCLE ANALYSIS
## IDEAL BRAYTON CYCLE ANALYSIS

### Calculation of temperature and pressure relationships

\[
\pi_c = \frac{P_{t_3}}{P_{t_2}}, \quad \tau_c = \pi_c^{\frac{\gamma-1}{\gamma}}, \quad \tau_r = 1 + \frac{\gamma - 1}{2} M_0^2
\]

\[
\tau_b = \frac{fh_{pr}}{c_p T_0 \tau_r \tau_c} + 1
\]

\[
T_{t_3} = \tau_r \tau_c T_0, \quad T_{t_4} = \tau_b T_{t_3}
\]

\[
\tau_\lambda = \frac{T_{t_4}}{T_0}, \quad \tau_t = 1 - \frac{\tau_r}{\tau_\lambda} (\tau_c - 1)
\]

### Calculation of uninstalled thrust

\[
a_0 = \sqrt{\gamma R T_0}
\]

\[
\left( \frac{V_9}{a_0} \right) = \sqrt{\frac{2}{\gamma - 1} \frac{\tau_\lambda}{\tau_r \tau_c} (\tau_r \tau_c \tau_t - 1)}
\]

\[
F_{\text{uninstalled}} = \dot{m}_0 (V_9 - a_0 M_0)
\]
## PRESSURE RATIO FEASIBILITY

<table>
<thead>
<tr>
<th></th>
<th>Compressor Work</th>
<th>Turbine Work</th>
<th>$\eta$</th>
<th>Thrust loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock</td>
<td>19.99 kW</td>
<td>48.01 kW</td>
<td>1</td>
<td>0%</td>
</tr>
<tr>
<td>20% Increase</td>
<td>22.3 kW</td>
<td>46.1 kW</td>
<td>0.98</td>
<td>4.5%</td>
</tr>
</tbody>
</table>

Baseline Compressor efficiency decrease of ~2% (with 10,000 RPM increase)
Component Analysis: Nozzle/ Engine Case

- Hoop ($\sigma_h$) and longitudinal ($\sigma_l$) stresses calculated at location where values are theoretically maximum, inlet:
- Total Pressure at nozzle inlet ($P_{t5}$), radius of nozzle inlet ($R_i$), thickness of nozzle inlet ($t_i$):

$$\sigma_l = \frac{P_T R_i}{2t_i} \quad \sigma_h = \frac{P_T R_i}{t_i}$$

- Results compared to material properties, verify structural capability.
Component Analysis: Shaft

- Power (P) and rotation rate (ω) known for compressor and turbine.
- Calculate torque for each using:

\[ T = \frac{P}{\omega} \]

- Force from both then found using radius of turbine and compressor:

\[ F = \frac{T}{R} \]

- Shear stress (τ) then calculated and compared to ultimate shear of assumed material, area of shaft in contact with turbine and fan used (A):

\[ \tau = \frac{F}{A} \]
Material Yield Analysis (AI 7075)

### Table 3.7.4(b). Design Mechanical and Physical Properties of 7075 Aluminum Alloy Sheet and Plate

<table>
<thead>
<tr>
<th>Specification</th>
<th>Sheet</th>
<th>Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td>AMS-4045 and AMS-QQ-A-25012</td>
<td></td>
</tr>
<tr>
<td>Temp</td>
<td>T6 and T651</td>
<td></td>
</tr>
<tr>
<td>Thickness, in.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basis</td>
<td>S A B</td>
<td>A E A B A B A B A B</td>
</tr>
<tr>
<td>Mechanical Properties:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_y$ ksi</td>
<td>77 78 78 80 78 80</td>
<td>77 78 78 79 78 79</td>
</tr>
<tr>
<td>ST ksi</td>
<td>77 78 78 80 78 80</td>
<td>77 78 78 79 78 79</td>
</tr>
<tr>
<td>$F_p$ ksi</td>
<td>69 70 70 70 69 71</td>
<td>69 70 70 70 69 71</td>
</tr>
<tr>
<td>ST ksi</td>
<td>67 68 68 68 67 69</td>
<td>67 68 68 68 67 69</td>
</tr>
<tr>
<td>$F_y$ ksi</td>
<td>53 70 71 70 69 71</td>
<td>53 70 71 70 69 71</td>
</tr>
<tr>
<td>ST ksi</td>
<td>51 68 69 69 68 70</td>
<td>51 68 69 69 68 70</td>
</tr>
<tr>
<td>$F_p$ ksi</td>
<td>46 47 47 47 46 47</td>
<td>46 47 47 47 46 47</td>
</tr>
<tr>
<td>ST ksi</td>
<td>44 44 44 44 44 44</td>
<td>44 44 44 44 44 44</td>
</tr>
<tr>
<td>$F_y$ ksi</td>
<td>118 121 121 121 121 121</td>
<td>118 121 121 121 121 121</td>
</tr>
<tr>
<td>$F_p$ ksi</td>
<td>100 102 105 105 105 105</td>
<td>100 102 105 105 105 105</td>
</tr>
<tr>
<td>ST ksi</td>
<td>117 122 122 122 122 122</td>
<td>117 122 122 122 122 122</td>
</tr>
<tr>
<td>$F_{yield}$ (Total) ksi</td>
<td>5 5 5 5 5 5</td>
<td>5 5 5 5 5 5</td>
</tr>
<tr>
<td>ST ksi</td>
<td>10 10 10 10 10 10</td>
<td>10 10 10 10 10 10</td>
</tr>
<tr>
<td>$F_{yield}$ (Total) ksi</td>
<td>3.9 3.9 3.9 3.9 3.9 3.9</td>
<td>3.9 3.9 3.9 3.9 3.9 3.9</td>
</tr>
<tr>
<td>Physical Properties:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{E}$ (Total)</td>
<td>0.101</td>
<td></td>
</tr>
</tbody>
</table>

See Figure 3.7.4.

Figure 3.7.4.1(b). Effect of temperature on the tensile yield strength ($F_y$) of 7075-T6, T651, T6510, and T6511 aluminum alloy (all products).
Material Yield Analysis (AISI 301)

<table>
<thead>
<tr>
<th>Specification</th>
<th>MIL-S-5059</th>
<th>AMS 5517 &amp; MIL-S-5059</th>
<th>AMS 5518 &amp; MIL-S-5059</th>
<th>AMS 5519 &amp; MIL-S-5059</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td>Sheet and strip</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Condition</td>
<td>Annealed</td>
<td>% Hard</td>
<td>% Hard</td>
<td>% Hard</td>
</tr>
<tr>
<td>Thickness, in.</td>
<td>0.0187</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basis</td>
<td>S</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
</tbody>
</table>

**Mechanical Properties:**

- $F_y$, kpsi:
  - LT: 73, 75, 75
  - LT: 69, 67, 50

- $F_y$, kpsi:
  - LT: 73, 75, 75
  - LT: 69, 67, 50

- $F_y$, kpsi:
  - LT: 73, 75, 75
  - LT: 69, 67, 50

**Physical Properties:**

- $\nu$, Brinell:
  - $\nu$: 0.286

**Figure 2.7.1.3.1.** Effect of temperature on the tensile ultimate strength ($F_{u}$) and the tensile yield strength ($F_{y}$) of AISI 301 1/2-hard stainless steel sheet.
Material Yield Analysis (Inconel 718)

### Table 6.3.5.0(b). Design Mechanical and Physical Properties of Inconel 718

<table>
<thead>
<tr>
<th>Specification</th>
<th>AMS 5596</th>
<th>AMS 5597</th>
<th>AMS 5588</th>
<th>AMS 5590</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td>Sheet</td>
<td>Plate</td>
<td>Sheet and plate</td>
<td>Tubing</td>
</tr>
<tr>
<td>Condition</td>
<td>Solution treated and aged per indicated specification</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness, in</td>
<td>0.010-0.187</td>
<td>0.188-0.249</td>
<td>0.259-1.000</td>
<td>0.010-1.000</td>
</tr>
<tr>
<td>Basis</td>
<td>A</td>
<td>B</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Mechanical Properties: $F_y$, ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_y$, ksi</td>
<td>L</td>
<td>180</td>
<td>192</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>180</td>
<td>191</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>145</td>
<td>156</td>
<td>148</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>147</td>
<td>158</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>133</td>
<td>167</td>
<td>128</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>138</td>
<td>170</td>
<td>161</td>
</tr>
<tr>
<td>$F_y$, ksi</td>
<td>124</td>
<td>132</td>
<td>124</td>
<td>...</td>
</tr>
<tr>
<td>$F_y$, ksi</td>
<td>291</td>
<td>300</td>
<td>281</td>
<td>...</td>
</tr>
<tr>
<td>$F_y$, ksi</td>
<td>380</td>
<td>403</td>
<td>380</td>
<td>...</td>
</tr>
<tr>
<td>$F_y$, ksi</td>
<td>208</td>
<td>223</td>
<td>212</td>
<td>...</td>
</tr>
<tr>
<td>$F_y$, ksi</td>
<td>241</td>
<td>259</td>
<td>246</td>
<td>...</td>
</tr>
<tr>
<td>$F_y$, ksi</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Physical Properties: $E$ ( modulus of elasticity), ksi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E$, ksi</td>
<td>30.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G$, 100 ksi</td>
<td>11.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.29</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Figure 6.3.5.1.** Effect of temperature on the tensile ultimate strength ($F_u$) and tensile yield strength ($F_y$) of solution-treated and aged Inconel 718.
# Fabrication Cost Feasibility: CNC Machine & Tool Room Lathe

<table>
<thead>
<tr>
<th>Family:</th>
<th>Species:</th>
<th>Dimensions (in):</th>
<th>Cost:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>N60</td>
<td>3” x 10”</td>
<td>$242.45</td>
</tr>
<tr>
<td>Aluminum</td>
<td>7075</td>
<td>3” x 10”</td>
<td>$87.20</td>
</tr>
<tr>
<td>Titanium</td>
<td>6AL-4V (Grade 5)</td>
<td>3” x 10”</td>
<td>$870.30</td>
</tr>
<tr>
<td>Nickel</td>
<td>Inconel 718</td>
<td>3” x 10”</td>
<td>$873.69</td>
</tr>
</tbody>
</table>

- Cost of production solely based on cost of material.
- All materials are round bar, diameter x length
## Fabrication Cost Feasibility: Direct Metal Laser Sintering

<table>
<thead>
<tr>
<th>Family:</th>
<th>Species:</th>
<th>Dimensions (in):</th>
<th>Cost:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>ALSi10Mg</td>
<td>3.25” x 3.25” x 2.17”</td>
<td>$1017.00</td>
</tr>
<tr>
<td>Nickel</td>
<td>Inconel 625</td>
<td>3.25” x 3.25” x 2.17”</td>
<td>$822.00</td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti64</td>
<td>3.25” x 3.25” x 2.17”</td>
<td>$956.00</td>
</tr>
<tr>
<td>Cobalt Chrome</td>
<td>CoCrMo</td>
<td>3.25” x 3.25” x 2.17”</td>
<td>$983.00</td>
</tr>
</tbody>
</table>

- Cost of production includes the cost of materials, manufacturing and finishing
- The dimension of the nozzle is based on SABRE’s nozzle
- It will take approximately three weeks to receive the nozzle from manufacturing facility
<table>
<thead>
<tr>
<th>Material</th>
<th>N60</th>
<th>Al7075</th>
<th>Ti6Al-4V</th>
<th>Inconel 718</th>
<th>ALSi10Mg</th>
<th>Inconel 625</th>
<th>CoCrMo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Rating (k)</td>
<td>1422</td>
<td>686</td>
<td>1933</td>
<td>922</td>
<td>933</td>
<td>1563</td>
<td>1670</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>8.5</td>
<td>2.81</td>
<td>4.52</td>
<td>8.22</td>
<td>2.7</td>
<td>8.44</td>
<td>8.28</td>
</tr>
<tr>
<td>Volume (cm³)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.16</td>
<td></td>
</tr>
<tr>
<td>Mass (gram)</td>
<td>86.36</td>
<td>28.55</td>
<td>45.92</td>
<td>83.52</td>
<td>27.43</td>
<td>85.75</td>
<td>84.12</td>
</tr>
</tbody>
</table>
## MANUFACTURING CAPABILITIES

<table>
<thead>
<tr>
<th>Manufacturing Method</th>
<th>Tool Room Lathe</th>
<th>Computer Numerical Control (CNC) Machine</th>
<th>Direct Metal Laser Sintering (DMLS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerances</td>
<td>Depends on Measurement Tool</td>
<td>+/- 0.005&quot;</td>
<td>+/- 0.005&quot; + 0.002 in/in</td>
</tr>
</tbody>
</table>
STOCK ENGINE THRUST-RPM LINEARITY

![Stock Engine Thrust - RPM Relationship](chart.png)
Notes: Ripples on waveform are from the power supply maxing out on supply current (5A). The selected battery would be able to supply much higher currents, and allow higher RPM with smaller voltage ripple. This is only present when starter is running (needed for this test but not normal operation) and does not affect functionality or reliability.
TESTING COMMUNICATION: SPECS

**Method:** Connected all components and verified I2C and SPI control separately. Designed startup sequence to simulate a “Start” and “Shutdown” command.

**Need:** Verify application of more than one communication protocol on system. Ensure that specified components can accept multiple commands from different sources and maintain normal operation without conflict or failure.

**Results:** Test completed successfully. Serial (SPI) command start/shutdown from PC resulted in start/shutdown sequence on ECM.

LCD displayed real time data for RPM, EGT, and command state. Further verifying I2C communication feasibility between ECU and ECM.
ECU/ECM DATA LINK FEASIBILITY

Needs:
- Allotted 3 bytes for RPM value (μs wave period measurement), 1 byte for EGT value (~3°C resolution 255 values), 1 byte for command status (responds with RPM command input value at state). (At max transmission)
- I2C has a 32 byte maximum transmission per cycle limit, though if needed split transmissions are possible.
- SPI communications are only limited to the extent that they do not block ECU from sending or receiving data from ECM on time.

Method:
- Set up basic communications through I2C to all components.
- Established serial communications with Arduino MEGA.
- Initiated timer on command send.
- Transmitted request event, received data packets from ECM, processed data, wrote to LCD, read timer value at end of write transmission.

Results:
- Minimum Data transfer found to be 5 bytes, total transfer time <20ms.
- 32 byte (I2C maximum) tested time <50 ms per request.
- Verified communications can occur concurrently on time schedule while both microprocessors are tasked with other operations and will respond on schedule within required time constraint of <200ms.
Magnetic Position Sensors
Low-Cost, Bipolar, Hall-effect Sensors

SS40A/SS50AT Series

FEATURES
- Small size
- Low cost
- Reverse polarity protection
- Sensitive - bipolar
- Magnetics respond to
  alternating north and south
  poles
- Thermally balanced,
  integrated circuit over a full
  temperature range
- Stable operation

TYPICAL APPLICATIONS
- Cooling fan control in
  computers and appliances
- RPM (revolutions per
  minute) sensing, speed
  control
- Brushless dc motor
  commutation
- Position sensing and motor
  control
- Simple magnetic encoder
- Flow-rate sensor

The SS40A/SS50AT Series sensors are low-cost, bipolar, Hall-effect sensors. These sensitive magnetic sensors offer reverse polarity protection and deliver stable output over a -40 °C to 125 °C [-40 °F to 257 °F] temperature range. Operation from any dc supply voltage from 4.5 Vdc to 24.0 Vdc is acceptable.

The SS40A/SS50AT Series sensors build upon Honeywell's popular magnetic position sensors and offer several competitive advantages. These sensors have been designed with the latest technologies to provide reliable, cost-effective solutions to commercial, computer, medical, and/or consumer applications requiring motor control and RPM sensing.

These products are available in a variety of package styles to suit a number of applications. Ammpack versions, along with tape-and-reel, are standard. The surface mount version is mounted directly on the electrical traces on a PC (printed circuit) board. It is attached by an automatic solder reflow operation which requires no hole, so it reduces the cost of the PC board.

ELECTRICAL CHARACTERISTICS
At VCC = 4.5 V to 24 V with 20 mA load with Ta = -40 °C to 125 °C [-40 °F to 257 °F] unless otherwise noted.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cond.</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>4.5</td>
<td>24.0</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Supply current</td>
<td>10.0</td>
<td></td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>Supply current</td>
<td>-</td>
<td>113</td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>Output current</td>
<td>20.0</td>
<td></td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>Output leakage</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td>μs</td>
</tr>
<tr>
<td>Fall time</td>
<td>0.2</td>
<td>1.5</td>
<td></td>
<td></td>
<td>μs</td>
</tr>
<tr>
<td>Response time</td>
<td>4.0</td>
<td>5.0</td>
<td></td>
<td></td>
<td>μs</td>
</tr>
<tr>
<td>Operate</td>
<td>110</td>
<td></td>
<td></td>
<td></td>
<td>Gauss</td>
</tr>
<tr>
<td>Release</td>
<td>50</td>
<td>130</td>
<td></td>
<td></td>
<td>Gauss</td>
</tr>
<tr>
<td>Release</td>
<td>55</td>
<td>170</td>
<td></td>
<td></td>
<td>Gauss</td>
</tr>
<tr>
<td>Release</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td>Gauss</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>40 °C to 125 °C [-40 °F to 257 °F]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage temperature</td>
<td>-55 °C to 165 °C [-67 °F to 329 °F]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ECU DATASHEET
ECM DATASHEET

Introduction

The Atmel® picPower® ATmega328/P is a low-power CMOS 8-bit microcontroller based on the AVR® enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the ATmega328/P achieves throughput close to 1MHz per MHz. This empowers system designers to optimize the device for power consumption versus processing speed.

Feature

High Performance, Low Power Atmel® AVR® 8-Bit Microcontroller Family
- Advanced RISC Architecture
  - 131 Powerful Instructions
  - Most Single Clock Cycle Execution
  - 32 x 8 General Purpose Working Registers
  - Fully Static Operation
  - Up to 20 MIPS Throughput at 20MHz
  - On-chip 2-cycle Multiplier
- High Endurance Non-volatile Memory Segments
  - 32kB bytes of In-System Self-Programmable Flash program Memory
  - 1kB bytes EEPROM
  - 2kB bytes Internal SRAM
  - Write/Erase Cycles: 10,000 Flash/100,000 EEPROM
  - Data Retention: 20 years at 85°C/100 years at 25°C(1)
  - Optional Boot Code Section with Independent Lock Bits
    - In-System Programming by On-chip Boot Program
    - True Read-While-Write Operation
    - Programming Lock for Software Security
- Atmel® QTouch® Library Support
  - Capacitive Touch Buttons, Sliders and Wheels
  - QTouch and QMatrix® Acquisition
  - Up to 64 sense channels

Peripheral Features
- Two 8-bit Timer/Counters with Separate Prescaler and Compare Mode
- One 16-bit Timer/Counter with Separate Prescaler, Compare Mode, and Capture Mode
- Real Time Counter with Separate Oscillator
- Six PWM Channels
- 8-channel 10-bit ADC in TQFP and QFN/MLF package
  - Temperature Measurement
- 6-channel 10-bit ADC in PDIP Package
  - Temperature Measurement
- Two Master/Slave SPI Serial Interface
- One Programmable Serial UART
- One Byte-oriented 2-wire Serial Interface (Philips PC compatible)
- Programmable Watchdog Timer with Separate On-chip Oscillator
- One On-chip Analog Comparator
- Interrupt and Wake-up on Pin Change
- Special Microcontroller Features
  - Power-on Reset and Programmable Brown-out Detection
  - Internal Calibrated Oscillator
  - External and Internal Interrupt Sources
  - Six Sleep Modes: Idle, ADC Noise Reduction, Power-save, Power-down, Standby, and Extended Standby
- I/O and Ports
  - 23 Programmable I/O Lines
  - 28-pin PDIP, 32-lead TQFP, 28-pad QFN/MLF and 32-pad QFN/MLF
- Operating Voltage:
  - 1.8 - 5.5V
- Temperature Range:
  - -40°C to 105°C
- Speed Grade:
  - 0 - 4MHz @ 1.8 - 5.5V
  - 0 - 10MHz @ 2.7 - 5.5V
  - 0 - 20MHz @ 4.5 - 5.5V
- Power Consumption at 1MHz, 1V, 25°C
  - Active Mode: 2.3mA
  - Power-down Mode: 0.1μA
  - Power-save Mode: 0.75μA (Including 32kHz RTC)
Motor Driver MOSFET n-Channel

Circuit low side driver application, will measure real drain current for application to verify thermal properties are sufficient for given Rds(on)(Max.) value for PCB mount application.

- **Outline**
  - Low on-resistance
  - High Power Package (HSMT8)
  - Pb-free lead plating; RoHS compliant
  - Halogen Free
  - 100% Rg and UIS tested

- **Application**
  - Switching

- **Absolute maximum ratings** (Tamb = 25°C unless otherwise specified)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drain - Source voltage</td>
<td>VGS</td>
<td>-40</td>
<td>V</td>
</tr>
<tr>
<td>Continuous drain current</td>
<td>IGD1</td>
<td>±27</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>T(A)</td>
<td>±10</td>
<td>A</td>
</tr>
<tr>
<td>Pulsed drain current</td>
<td>IGD2</td>
<td>±40</td>
<td>A</td>
</tr>
<tr>
<td>Gate - Source voltage</td>
<td>VGS</td>
<td>±20</td>
<td>V</td>
</tr>
<tr>
<td>Avalanche current, single pulse</td>
<td>IAS</td>
<td>10</td>
<td>A</td>
</tr>
<tr>
<td>Avalanche energy, single pulse</td>
<td>EAS</td>
<td>15</td>
<td>μA</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>Pd</td>
<td>15</td>
<td>W</td>
</tr>
<tr>
<td>Junction temperature</td>
<td>Tj</td>
<td>150</td>
<td>°C</td>
</tr>
<tr>
<td>Operating junction and storage temperature range</td>
<td>Tja</td>
<td>-55 to +150</td>
<td>°C</td>
</tr>
</tbody>
</table>

- **Features**
  1. Low on-resistance
  2. High Power Package (HSMT8)
  3. Pb-free lead plating; RoHS compliant
  4. Halogen Free
  5. 100% Rg and UIS tested