COMET: Colorado Mini Engine Team Critical Design Review
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Team members:
Julia Contreras-Garcia
Eric James
Matthew McClain
Benjamin Woeste
Emily Ehrle
Jonathan Lumpkin
Megan O'Sullivan
Kevin Wong

Customer: Lt. Joseph Ausserer, USAF

University of Colorado
Outline

- Project description
  - Design solution

- Critical elements and design requirements
  - Test Stand
  - Engine
  - ECU
  - Generator
  - Regulator
  - All interfaces between these elements

- Risks
- Verification and validation
- Project planning
  - Organizational chart
  - Work breakdown structure and work plan
  - Schedule
  - Cost plan
  - Test plans
Project Description
Project Description

• Design and build a Power Extraction Unit (PEU) for a JetCat P-80 SE mini-turbojet engine that will generate 500 Watts of electrical power at 24-28VDC.

• Sponsored by Air Force Research Laboratory’s Aerospace Propulsion Outreach Program (APOP)
Jet Cat P80-SE Engine Specs

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust</td>
<td>22 LB @ 125,000 RPM</td>
</tr>
<tr>
<td>Weight</td>
<td>2.9 LB, incl. starter</td>
</tr>
<tr>
<td>Diameter</td>
<td>4.4 inches</td>
</tr>
<tr>
<td>RPM Range</td>
<td>35,000 - 125,000</td>
</tr>
<tr>
<td>Exhaust gas temp.</td>
<td>580°C - 690°C</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>9 oz per/min at full power</td>
</tr>
<tr>
<td>Fuel</td>
<td>Jet A1, 1-K kerosene</td>
</tr>
</tbody>
</table>

Jet Cat P80-SE Engine
Objectives

• Level one
  ▫ PEU must generate 500 Watts of power at 24-28 Volts DC
  ▫ PEU must produce this power after the engine has been running no longer than 1 min 20 s, twice the average start up time
  ▫ Engine and PEU must be compatible with the WPAFB test stand

• Level two
  ▫ Reducing thrust by no more than 25%
  ▫ Increasing specific fuel consumption by no more than 50%
  ▫ Producing 500 W throughout the engine’s RPM operating range

• Level three
  ▫ Add no more than the weight than an equivalent battery pack with 30 minutes of power (8 lbs)

• Level four
  ▫ PEU to be entirely external to the JetCat engine, making the most modular solution.
CONOPS Diagram
Design Solution: Tapping the Shaft

- Remove starter engine with alternator to utilize rotational energy of drive shaft
  - Placement reduces negative effects on thrust
  - Necessary to have a different system to start engine
- Alternator placed on rod extending from shaft
  - Extension from original drive shaft
  - Rod extends from inlet of engine
Functional Block Diagram

- **Heat**
- **Load**
  - **Signal Conditioner**
    - Mass: 0.554 kg
  - **Power Rectifier**
    - Mass: 0.0085 kg
- **Starter/generator control unit**
  - Mass: 0.56028 kg
- **Engine to Alternator Interface**
  - Coupling to shaft and Mounting to Engine Mass: 0.0415 kg
- **Engine Performance Model**
  - Thrust
  - Specific Fuel Consumption

**Critical Elements**
- Power Rectifier to Signal Conditioner: DC Volts and Amps
- Power Rectifier to Power Rectifier Interface: A/C Volts and Amps
- Alternator to Power Rectifier Interface: A/C Volts and Amps
- Engine to Alternator Interface: Coupling to shaft and Mounting to Engine Mass: 0.0415 kg

**Future Work**
- Logistic
- Critical Elements
- Project Description
Critical Project Element Design Requirements
Detailed Design Project Elements

- Test stand
  - Interface to engine
- Engine
  - Modeling
- Starter/generator
  - Interface with engine
  - Operational specifications
  - Detailed design
- Voltage regulator
  - Detailed design
Project Elements Not Addressed Here

- Detailed testing diagrams*
- Thermal analysis of circuitry*
- Calculations for needed fastener dimensions*
- Vibration analysis*

* indicates content is covered in back up slides
Test Stand to Engine Interface

• Req. 4: The design solution, when integrated with the JetCat P80-SE engine, shall interface with the test stand designed by the customer and the test stand available through CU.

• Req. 4.1: The dimensions of the design solution integrated with the engine shall not exceed the limitations in place by APOP.

• Req. 4.1.1: The test stand shall support clamps that are fitted to the engine.

• Req. 4.1.2: The test stand shall have an axial load cell for means of measuring thrust.
Test Stand to Engine Interface

- WPAFB test stand dimensions
Test Stand to Engine Interface

• Physical
  ▫ The Engine shall be held in place to the current test stand using customized clamps.

  All measurements are in inches
  Requires aluminum sheet metal and Chunks of aluminum
  • $33.56 for raw materials
Engine: Software Model Construction

- Engine: Jetcat P80-SE w/ station numbering

0 – Free stream
1 – Inlet Entrance
2 – Inlet Exit
3 – Compressor Exit
4 – Combustor Exit
5 – Turbine Exit
6 – Nozzle Exit
Engine: Software Model Construction

- Basic Dynamic Model Equations
  - **State Vector**
    \[ \dot{X}(P_3, P_5, N) \]
  - Iterate model until \( \dot{X} \rightarrow 0 \)

Future Work

Logistics

Critical Elements

Project Description

Future Work
Engine: Software Model Construction

• Basic Model Equations
  ▫ Characteristic Equation for Pressures \((P_3, P_5)\)
    \[
    \dot{P} = \frac{RT}{V} \dot{m}
    \]
    \[
    \dot{m}_3 = \dot{m}_c + \dot{m}_f - \dot{m}_t
    \]
    \[
    \dot{m}_5 = \dot{m}_t - \dot{m}_n
    \]
  ▫ Characteristic Equation for Rotation Rate \((N)\)
    \[
    \dot{N} = \frac{\mu \dot{m} \tau_{turbine} - \tau_{compressor} - \tau_{generator}}{I_{spool}}
    \]
Engine: Software Model Construction

- Software Model Assumptions (Corresponding equations are included in the Appendix)
  - 0-1 (Free Stream to Inlet)
    - Isentropic and Low Speed Flow (No shocks)
  - 1-2 (Through Inlet)
    - Adiabatic and Non Reversible
  - 2-3 (Through Compressor)
    - Adiabatic and Non Reversible
  - 3-4 (Through Combustor)
    - Total Pressure loss and <100% combustion
  - 4-5 (Through Turbine)
    - Adiabatic and Non Reversible
  - 5-6 (Through Nozzle)
    - Adiabatic and Non Reversible
Engine: Software Model Results

- Without Generator (Thrust)
  - Max error 21.5%
    - @70,000 RPM
  - Min error 0.56%
    - @100,500 RPM
Engine: Software Model Results

- Without Generator (Cj)
  - Max error 17%
    - 125,000 RPM
  - Min error 0.43%
    - 82,200 RPM
Engine: Software Model Results

- With Generator vs. Without Generator (Thrust)
Engine: Software Model Results

- With Generator vs. Without Generator (Thrust)
Engine: Software Model Results

- Performance Reduction (Thrust)
Engine: Software Model Results

- Performance Reduction (Cj)
Engine to Generator Interface

- Req. 3.1.1: The generator shall physically attach to the P80-SE main engine shaft.
- Req. 3.1.2: The connection shall be secure for RPMs from 35,000 to 125,000.
- Req. 3.3: The design solution shall be supported by stanchions attached to the engine housing so any extra weight does not act on the shaft.
- Req. 3.4.1: The design solution shall add mass/weight in a radially symmetric distribution around the shaft.
Engine to Generator Interface

- Diagram of attachment system

Brackets
Engine to Generator Interface

- Starter/generator is designed for larger engine
- Attach stanchions to outer edge of casing instead of inlet using brackets
Engine to Generator Interface

- Cut stanchions to size and remove ring from bottom of stanchions
- Make brackets
- Remove original stanchions for stock starter from original intake
- Solder wire from electrical connection at bottom of stanchion to ECU
- Attach screws, nuts, lock washers
- Total cost: $49.00 (includes shipping)
- Total mass: 0.0154 kg
Coupling System to Shaft

• Shaft of the Starter-Alternator will be coupled to shaft of P80 Engine via Key Way Slot System.
  ▫ This entails a Steel Pin put in slot on both shaft until they are flesh with one another.
Cost and mass for shaft connection

- Tight Tolerancing on the cut made on the shaft of the engine (±0.001”).
- Steel pin requires special drill bits: $15.08.
- Mass in total is equivalent to the mass of the Steel pin: Less than 0.028 kg
Generator

- Req. 1: The design solution shall generate 500 W of electrical power.
- Req. 1.3: The design solution shall generate the required power while the engine is operating between 35,000 and 125,000 RPM.
Generator

• Looked at high RPM motors, generators
  ▫ Limited availability for high enough RPM (125,000)
  ▫ Many options too expensive for this budget, some motors up to $12,000

• Details
  ▫ From Jetcat P300
  ▫ Operating range 35,000-112,000 RPM
  ▫ Brushless
  ▫ 3 phase non-rectified AC output
Generator

• Cost
  ▫ $599.99

• Mass
  ▫ Approximately 0.454 kg
  ▫ Not all of this mass is “added” since the original starter will be removed

• Dimensions
  ▫ 0.036 m (1.42”) in diameter
  ▫ 0.068 m (2.67”) long
Engine Control Unit for Unmodified P80-SE

P80-SE Engine

- Engine RPM
- Exhaust Gas Temperature (EGT)

ECU V5.1

- Throttle
- Power supply voltage

Starter Motor

- DC PWM signal

Other ECU Functions

NiCad 7.2 V battery

USER

Project Description | Critical Elements | Logistics | Future Work
Converting Brushed DC (BLDC) signal into 3 Phase Brushless signal

- **Current motor driving signal**
  - Single PWM signal
  - Linear relationship between RMP and armature voltage

- **Required motor driving signal**
  - 3 phase AC signal (each separated by 120 degrees)
  - Linear relationship between RMP and armature voltage
  - Rotor positioning data
    - Sensorless (calculates through back EMF)
More info about 3 phase power
More info about 3 phase power

Vsource  
MOSFET  
MOSFET  
MOSFET  

MOSFET  
MOSFET  
MOSFET  

A  
B  
C  

a  
b  
c  
COM  

Project Description  Critical Elements  Logistics  Future Work
BACK EMF
Back EMF

When Back EMF is zero in the floating pole this is known as the zero crossing.
Back EMF

- 30 degrees after zero crossing next phase initiates
- Time between phase initiation and zero crossing help determine rotor position and speed
Motor Control

• All motor control will be done on the PIC16F685
  ▫ Inexpensive
  ▫ Configurable PWM output channels
  ▫ I/O pin count high enough to control 3 phase motor
  ▫ PIC app notes detailing design of BLDC motor control
Driving the MOSFETs

- MOSFETs will be driven an engaged through LT1160 MOSFET drivers
  - High frequency and range PWM acceptance
  - Easy to implement in the LTspice model

![LT1160 schematic diagram]
MOSFETS

- MOSFETS were selected based upon
  - High Source Voltage (60V)
    - 12 V requires
  - High Drain current (50 A)
    - 30 A required
Back EMF Circuitry

- Need the Virtual Neutral because VDC voltage will increase with increasing RPM
- Circuitry in model is based upon PIC AN for the same Back EMF sensing application
Design Solution of Driving signal conversion

DC PWM signal for brushed DC motor

PWM signal stepped down to allowable voltages for the MCU

Lower amplitude PWM signal

MCU

Back EMF sensing circuitry

Gate Driver

Gate Driver

Gate Driver

Gate Driver

Gate Driver

Gate Driver

INVERTER

MOSFET

MOSFET

MOSFET

MOSFET

MOSFET

MOSFET

BLDC Motor

BLDC Motor

BLDC Motor

BLDC Motor

Project Description

Critical Elements

Logistics

Future Work
Power Flow

NiCad 7.2 V Battery -> ECU

Regulator to Gate Drivers Voltage

14.1V LiPo Battery

Regulator to MCU voltage -> MCU

V* -> Gate Driver

Gate Driver

Op amps

MCU

INVERTER

MOSFET

MOSFET

MOSFET

MOSFET

ETMOSF
Motor to Generator Switching

- Need to switch between motor and generator
- If switching does not occur generator will feed power back to motor driver and fry circuitry
- 9 relays were chosen
  - 3 high voltage/high current relays from motor to rectification
    - Crydom solid state relays
    - Ratings: 40A, 200V
    - Calculated maximum: 32.4A, 36V
  - 6 high voltage/low current relays
    - IXYS solid state relays
    - Ratings: 1.5A, 100V
    - Maximum values from model: 500mA, 12V
Motor to Generator switch circuitry
Generator to Regulator Interface

- **Req. 2.2.3**: Power regulator shall be able to accept voltage input from generator.
- **Req. 2.2.4**: Power regulator shall be able to accept input frequencies between 583 Hz and 2084 Hz.
Generator to Regulator Interface
Generator to Regulator Interface

- **Cost**

<table>
<thead>
<tr>
<th>Item</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor</td>
<td>$2.92</td>
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<tr>
<td>Circuit Breaker</td>
<td>$30.10</td>
</tr>
<tr>
<td>Three Phase Rectifier</td>
<td>$9.93</td>
</tr>
<tr>
<td>Drain Resistor</td>
<td>$0.57</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$43.52</strong></td>
</tr>
</tbody>
</table>

- **Mass**

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor</td>
<td>0.005</td>
</tr>
<tr>
<td>Circuit Breaker</td>
<td>0.057</td>
</tr>
<tr>
<td>Three Phase Rectifier</td>
<td>0.0085</td>
</tr>
<tr>
<td>Drain Resistor</td>
<td>0.005</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.0755</strong></td>
</tr>
</tbody>
</table>
Voltage Regulator

• Req. 2: Power generated shall be transmitted using 24 -28 VDC current.
• Req. 2.2: Voltage shall be regulated with a Switching Mode Power Regulator (SMPR).
• Req. 2.2.1: Power regulator shall keep voltage ripple below 0.25 Volts.
Voltage Regulator

VFB600-D24-S24:
Max power: 600W
Vin(min): 18V
Vin(max): 36V

DAQ is capable of handling 10 Volts

Voltage Divider provides 3.1 Volts with 24 Volt output from regulator

\[ V_{out,DAQ} = \frac{0.15}{1.15} V_{total} \]
Generator to Regulator Mass and Costs

- **Cost**

<table>
<thead>
<tr>
<th>Item</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-DC Regulator</td>
<td>$304.33</td>
</tr>
<tr>
<td>Dissipative Resistor 1</td>
<td>$46.37</td>
</tr>
<tr>
<td>Dissipative Resistor 2 &amp; 3</td>
<td>$10.42</td>
</tr>
<tr>
<td>PCB boards &amp; printing</td>
<td>$47.45</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$408.57</strong></td>
</tr>
</tbody>
</table>

- **Mass**

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-DC Regulator</td>
<td>0.26</td>
</tr>
<tr>
<td>Dissipative Resistor 1</td>
<td>N/A</td>
</tr>
<tr>
<td>Dissipative Resistor 2 &amp; 3</td>
<td>N/A</td>
</tr>
<tr>
<td>Regulator PCB</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.54</strong></td>
</tr>
</tbody>
</table>
Voltage Regulator

- Project Description
- Critical Elements
- Logistics
- Future Work
Voltage Regulator

- Performance at max power

Generator
- 19.3-36 V
- 17.3-32.4 A
- 624.3 W

Rectifier
- 18-34.7 V
- 16.9-32.5 A
- 585.6 W

Regulator
- 24 V
- 22 A
- 527 W

Dissipater
- 527 W

- Assume 1.28 V drop
- Assume 90% efficiency
- Assume Lower 5% of resistor values

- 63,700-125,000 RPM to operate PEU
Circuit Production

• Voltage Regulator
  ▫ Circuit will be produced by Advanced Circuits
  ▫ Component will then be soldered to PCB in electronics lab

• Dissipation Circuit
  ▫ Will be mounted on separate fiberglass board
  ▫ Solder lug connections permit circuit to be built without traces.
# Project Risks

## COMET Risk Assessment Matrix

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Severity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequent</strong></td>
<td>Insufficient</td>
<td>Weather delaying testing</td>
</tr>
<tr>
<td><strong>Probably</strong></td>
<td>Minor</td>
<td>Differences in performance in Boulder and Ohio</td>
</tr>
<tr>
<td><strong>Occasional</strong></td>
<td>Moderate</td>
<td>Lab scheduling issues</td>
</tr>
<tr>
<td><strong>Remote</strong></td>
<td>Critical</td>
<td>Engine balance issues, engine will not start/run</td>
</tr>
<tr>
<td><strong>Improbably</strong></td>
<td>Catastrophic</td>
<td>Engine supplies sufficient torque to operate generator, Rotor positioning failure, Secure shaft/generator connection at all RPMS, Over-generation of power could damage electronics, Engine vibrations due to change in setup</td>
</tr>
</tbody>
</table>

**Unacceptable** | **Acceptable with mitigation** | **Inconsequential**
Project Risks: Mitigations of Unacceptable Risks

- **Engine balance issues**
  - If shaft is removed for manufacturing, have JetCat professionally rebalance the engine
  - $100, including shipping, 2 weeks

- **Engine will not start/run**
  - Use electric motor at lower RPMs to test generator
  - Test circuitry using function generators

- **Secure shaft/generator connection at all RPMs**
  - Use standard JetCat attachment procedure for attaching the starter/generator to engine shaft
## Test Plan

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Jan 12</th>
<th>Jan 19</th>
<th>Jan 26</th>
<th>Feb 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test three-phase diode component</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test functionality and accuracy of flow meter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test functionality and accuracy of accelerometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline characterization test (integrate engine to test stand)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Test Plan (cont.)

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Feb 9</th>
<th>Feb 16</th>
<th>Feb 23</th>
<th>Mar 2</th>
<th>Mar 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Identify days and days of the week for each task]</td>
<td>[Bars representing tasks]</td>
<td>[Bars representing tasks]</td>
<td>[Bars representing tasks]</td>
<td>[Bars representing tasks]</td>
<td>[Bars representing tasks]</td>
</tr>
</tbody>
</table>

- **Test PR/SC component**
- **Test motor control circuit**
- **Test diode component + PR/SC functionality**
- **Test voltage/current sensor suite**
- **Test power regulation subsystem functionality**

**Critical Elements**

**Future Work**

**Logistics**

**Project Description**
Test Plan (cont.)

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Mar 16</th>
<th>Mar 23</th>
<th>Mar 30</th>
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</thead>
<tbody>
<tr>
<td>Test power regulation subsystem for functionality</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test functionality of motor control system with microcontroller</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test engine assembly + test stand + ECU functionality</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Project Description | Critical Elements | Logistics | Future Work
Test Plan (cont.)

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Apr 6</th>
<th>Apr 13</th>
<th>Apr 20</th>
<th>Apr 27</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 Test engine assembly/test stand and ECU</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>functionality</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 Test functionality of full system (engine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>assembly + power assembly + ECU)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Critical Elements

Future Work
V&V - Testing Phases

**Phase I – Component Inspection and Testing**
- Electrical: voltage rectifier, signal conditioner, sensor suite board, power diffuser, motor driver
- Mechanical: Generator and mount, shaft coupling system, engine, test stand
- Software: MATLAB engine model, LabVIEW data collector and VI

**Phase II – Subsystem Testing**
- Electrical: power regulation, generator controller
- Mechanical: generator assembly, engine assembly
- Software: MATLAB model, LabVIEW data collector and VI

**Phase III – Subsystem Integration Testing**
- Electrical: power regulator to generator
- Mechanical: Generator assembly to engine, generator to generator controller, engine assembly to LabVIEW data collector

**Phase IV – Full Integrated System Testing**
- Final system checkouts
- Final system vibration testing
- Rehearsal for final demonstration at WPAFB
LabView Testing VI’s

• Major VI’s
  ▫ **Engine Characterization/ Testing VI**
    • Exit Temperature Reading
    • Accelerometer Reading
    • Voltage Reading From PEU
    • Current Reading From PEU
    • Load Cell Reading
    • Fuel Flow Meter Reading
    • Ambient Readings (Temperature & Pressure)
LabView Testing VI’s Continued

• **Major VI’s Continued**
  - Generator/Power Regulator Testing VI
    - Voltage Reading from PEU
    - Current Reading from PEU
    - RPM Reading from electric motor
Critical Sensor: Button-Type Load Cell

- Mounted on Test Stand
- Max Load: 445 N (100 lbf)
- Our Max Load: 100 N (22 lbf)
- DAQ: NI 9205 (16 bit)
- Sampling rate: 5 Hz
Critical Sensor: Equiflow Disposable PVDF Flow Meter

- Range: 0.06 – 2 L/min
- Cost: ~$171.86 / $66.84
- Inserts
- Material: PVDF for kerosene compatibility

- Req Range: .095-.3 L/min
- Tube Connection: 7mm hose barb
- Sensor Satisfies measurement requirements

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DAQ</th>
<th>Sampling Rate (Hz)</th>
<th>Ideal Resolution</th>
<th>Sensor Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Flow Meter</td>
<td>NI 9402 (32 bit)</td>
<td>5</td>
<td>80 μV</td>
<td>0.01 L/min</td>
</tr>
</tbody>
</table>
Voltage and Current Suite

- These two sensors are designed into the Power Regulation System
- Voltage directly measured by the NI 9205 (16 bit) DAQ on test stand
- Current DAQ: NI 9205 (16 bit)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DAQ</th>
<th>Sampling Rate (Hz)</th>
<th>Ideal Resolution</th>
<th>Sensor Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Sensor</td>
<td>ITLL station DAQ (12 bit)</td>
<td>5</td>
<td>(38 μV)</td>
<td>.045 V/A</td>
</tr>
<tr>
<td>Voltage Measurement</td>
<td>ITLL station DAQ (12 bit)</td>
<td>5</td>
<td>0.145 mV</td>
<td>6220 μV</td>
</tr>
</tbody>
</table>
Engine Characterization Test

- **Purpose**: Characterize thrust and fuel consumption for model validation

- **Equipment**: Test Stand, 1 Pressure/Temperature sensor, 1 k-type thermocouple, fuel flow meter, accelerometer, LabView data collector

- **Facility**: Boulder Airport
  - **Contact**:
    - Tim Head
    - Boulder Airport Manager
    - 303-441-3108

- **Engine Test Stand Clamps**:
Power Regulator Test

- **Purpose:** Ensure the Power Regulation system can take in a variable AC signal and output a constant (within accepted tolerance) DC signal

- **Equipment:** Function Generator, Power Diffuser, DAQ, LabView Data Collector, Power Supply, VRSCC board

- **Facility:** ITLL
Power Regulator -> Generator

- **Purpose:** Ensure the Power Regulation system can handle the signal coming from the generator

- **Equipment:** Electric motor, Generator, DAQ, power supply, power diffuser, LabView Data Collector, VRSC board

- **Facility:** ITLL

- **Basic Test Diagram:**

  ![Diagram](image-url)

  - **Generator**
  - **Electric Motor**
  - **RPM Sensor**
  - **DAQ**
  - **LabView Data Collector**
  - **Power Diffuser**

  - Red lines = Electrical Lines
  - Blue lines = Data Lines
Electric Motor 1: ElectroCraft DC Servo Motor

- Max RPM: 20,000
- Shaft Diameter: 8mm
- RPM Sensor integrated into motor
- Integration Method to Generator: Drill into shaft coupling method
- Cost: Free
Engine -> Generator -> Generator Controller

• **Purpose:** Ensure the generator can interface with the engine correctly. Run the generator as a starter motor with generator controller to test generator connections with the drive shaft.

• **Equipment:** Accelerometer, LabView Data Collector, Test Stand (with DAQ), Engine, Generator, Generator Controller.

• **Facility:** ITLL

• **Basic Test Diagram:**

![Test Diagram](image)
Full System Checkout

- **Purpose:** Ensure the system as a whole can work together and produce the required amount of power

- **Equipment:** Accelerometer, Flow Meter, Exit Thermocouple, LabView Data Collector, Test Stand (with DAQ), Engine, Generator, Generator Controller, Power Regulator, Power Diffuser

- **Facility:** Boulder Bomb Squad

---

**Basic Test Diagram:**

- Engine
- Test Stand
- Generator
- Generator Controller
- Power Regulator
- Power Diffuser
- Acc
- DAQ
- Load
- LabView Data Collector
Organizational Chart

Air Force

- CFO (Ben)
- Project Manager (Matt)
- Safety Lead (Ben)
- Systems Lead (Kevin)
- Testing Lead (Megan)

- Software Lead (Eric)
- Electrical Lead (Jon)
- Manufacturing Lead (Julia)
- Mechanical Lead (Emily)
Work Breakdown Structure (WBS)

**Structures**
- Manufacture engine clamps for CU test stand
- Manufacture L-brackets
- Coupling for P300 starter generator to P80-SE driveshaft
- Updated test stand with flow meter and accelerometer
- Baseline characteristic of turbine
- Rebalance engine with starter generator attached
- Testing procedure documents
- Requirements verification documents

**Electrical**
- Three-phase diode voltage signaling component
- Power rectifier and signal conditioning (PR/SC) component
- DC-DC regulator IC
- Integrated power regulation system
- Voltage and sensor suite to measure power output
- Motor control circuit for ECU
- Testing procedure documents
- Requirements verification documents

**Software**
- MATLAB model of JetCat engine
- Updated ECU microcontroller
- Data retrieval platform from test stand
- Testing procedure document
- Requirements verification document

**Systems**
- Procure JetCat P80-SE
- Procure P300 starter generator (SG)
- Procure electrical components for power regulation subsystem
- Procure microcontroller, MOSFET’s, resistors, wires, and power supply for ECU manufacturing
- Procure flow meter and accelerometer for test stand
- Financial budget
- Risk matrix
- Detailed work flow schedule for spring term
- Subsystems/systems integration plans
- Safety and testing procedures
# Work Plan

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Jan 12</th>
<th>Jan 19</th>
<th>Jan 26</th>
<th>Feb 2</th>
<th>Feb 9</th>
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<tr>
<td>Procure JetCat P80-SE engine</td>
<td></td>
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<tr>
<td>Procure P300 starter generator (SG)</td>
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<tr>
<td>Procure electrical components for power rectifier and signal conditioning</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Procure microcontroller, wires, MOSFETs, operational amplifiers, power supply, and resistors for ECU</td>
<td></td>
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<tr>
<td>Procure test stand flow meter and accelerometer</td>
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<tr>
<td>Engine test fire</td>
<td></td>
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<tr>
<td>Manufacture three-phase diode component</td>
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<tr>
<td>Compare Matlab engine model to baseline characterization to verify accuracy of model</td>
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<tr>
<td>Manufacture engine clamps</td>
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<tr>
<td>Manufacture flow diffuser</td>
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<tr>
<td>Manufacture DC-DC regulator IC and signal conditioning (PR/SC for power rectification and signal conditioning)</td>
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<tr>
<td>Manufacture L-brackets</td>
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<td></td>
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<tr>
<td>Manufacture coupling (generator and engine)</td>
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**Logistics**

**Critical Elements**

**Future Work**

**Project Description**
## Work Plan (cont.)

<table>
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<tr>
<th>Task Name</th>
<th>Feb 16</th>
<th>Feb 23</th>
<th>Mar 2</th>
<th>Mar 9</th>
<th>Mar 16</th>
<th>Mar 23</th>
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<tr>
<td>Build motor control circuit</td>
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<tr>
<td>Manufacture voltage and current sensor suite to measure output power</td>
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<tr>
<td>Program microcontroller</td>
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<td>Send engine assembly (SG + engine) to JetCat to rebalance the shaft</td>
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## Cost Plan

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<thead>
<tr>
<th>Component</th>
<th>Price ($)</th>
<th>Mass (kg)</th>
<th>Quantity</th>
<th>Total price ($)</th>
<th>Total mass (kg)</th>
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<td>0.4536</td>
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</table>
## Cost Plan

<table>
<thead>
<tr>
<th>Component</th>
<th>Price ($)</th>
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<th>Quantity</th>
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<th>Total mass (kg)</th>
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<tbody>
<tr>
<td>Clamps for test stand</td>
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<td>Shaft connector for electric motor to starter/generator</td>
<td>108.64</td>
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<td>Brackets</td>
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<td>Nuts</td>
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<td>10.35</td>
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<td>Shipping for fasteners</td>
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<td>Extra engine housing</td>
<td>130</td>
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<td>MOSFET drivers</td>
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<td>11.25</td>
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<td>MOSFETs</td>
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<td>6</td>
<td>5.08</td>
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<td>PIC Micro-controller</td>
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<td>1.99</td>
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<td>Battery for power of interface</td>
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<td>isolation resistors (300 Ohm)</td>
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<td>0.00005</td>
<td>5</td>
<td>0.40</td>
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<td>10kOhm resistors</td>
<td>0.07</td>
<td>0.00005</td>
<td>15</td>
<td>1.07</td>
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<td>0.00005</td>
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<td>0.45</td>
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<td>100 kOhm resistors</td>
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<td>0.00005</td>
<td>10</td>
<td>0.65</td>
<td>0.0005</td>
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<tr>
<td>1 MOhm resistors</td>
<td>0.09</td>
<td>0.00005</td>
<td>5</td>
<td>0.45</td>
<td>0.00025</td>
</tr>
</tbody>
</table>
## Cost Plan

<table>
<thead>
<tr>
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<th>Price ($)</th>
<th>Mass (kg)</th>
<th>Quantity</th>
<th>Total price ($)</th>
<th>Total mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>47nF capacitors</td>
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<td>0.00008</td>
<td>3</td>
<td>10.80</td>
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<td>22nF capacitors</td>
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<td>0.00008</td>
<td>4</td>
<td>13.12</td>
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<td>100nF capacitors</td>
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<td>1uF capacitors</td>
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<td>10uF capacitors</td>
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<td>1.75</td>
<td>0.0004</td>
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<td>100uF capacitor</td>
<td>0.52</td>
<td>0.00008</td>
<td>2</td>
<td>1.04</td>
<td>0.00016</td>
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<td>Single supply op amps</td>
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<td>3</td>
<td>5.76</td>
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<td>Diodes</td>
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<td>0.60</td>
<td>0.004</td>
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<td>Motor driver board</td>
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<td>50.00</td>
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<td>High current relays</td>
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<td>0.028</td>
<td>3</td>
<td>236.61</td>
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<td>Low current relays</td>
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<td>FFR binding</td>
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<td>FFR printing (pages)</td>
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<td>Gift card for JetCat USA</td>
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<td>50</td>
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</table>
Cost Plan Summary

- Total cost excluding engine: $2,434.03
- Total mass: 1.7529 kg
- Cost of engine (including shipping): $2,209
- Total predicted cost: $4,643.03
References

- Pictures of engines from JetCat USA.
- FENIX CDR
- Images of JetCat engines courtesy of JetCat USA, located in CA.
- “How its Made” Episode 217: Model Jet Turbines Directors: Gabriel Hoss and Francois Senecal-Tremblay, Producers Andre Douillard and Jean-Marc St-Pierre
- Mattingly: Elements of Gas Turbine Engines Table 6.1
References

- Accelerometer: http://www.pcb.com/Products.aspx?m=422E51#.UpT54Y2RtT1
Questions?
Compressor Map Interpolation

- Compressor Map for Garrett GTX2863R Turbocharger
  - Corrected Mass Flow Rate
    \[ \dot{m}_c^* = \frac{\dot{m}_c \sqrt{T_{t,3}/T_{std}}}{P_{t,3}/P_{std}} \]
  - Corrected RPM
    \[ N_c^* = \frac{N}{\sqrt{T_{t,3}/T_{std}}} \]
Internal Engine Equations

• Ambient Conditions \((T_0, P_0, M_0)\)

\[
T_{t,0} = T_0 \left(1 + \frac{\gamma - 1}{2} M^2\right)
\]

\[
P_{t,0} = P_0 \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}
\]
Internal Engine Equations

- Inlet Entrance to Inlet Exit

\[ P_{t,2} = \eta_{inlet} P_{t,0} \]

\[ T_{t,2} = T_{t,0} \left( \frac{P_{t,2}}{P_{t,0}} \right)^{\frac{\gamma-1}{\gamma}} \]
Internal Engine Equations

- Inlet Exit to Compressor Exit

\[ \Delta T_{23} = \frac{1}{\eta_{comp}} T_2 \left[ \left( \frac{P_{t,3}}{P_{t,2}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \]

\[ \tau_{comp} = \frac{\dot{m}_c c_p \Delta T_{23}}{N} \]

- Defined by Compressor Map Interpolation

\[ N, \dot{m}_c, P_{t,3} \]
Internal Engine Equations

- Compressor Exit to Combustor Exit

\[
\Delta T_{34} = \eta_b \left( \frac{\dot{m}_f}{\dot{m}_c} \right) \frac{HV_{fuel}}{c_p}
\]

\[
P_{t,4} = P_{t,3} (1 - P_{loss})
\]
Internal Engine Equations

- Combustor Exit to Turbine Exit

\[ \Delta T_{45} = \eta_{turb} T_4 \left[ 1 - \left( \frac{P_{t,5}}{P_{t,4}} \right)^{\frac{\gamma - 1}{\gamma}} \right] \]

\[ \tau_{turb} = \frac{\dot{m}_t c_p \Delta T_{45}}{N} \]

- Defined by Compressor Map Interpolation

\[ N, \dot{m}_t, P_{t,5} \]
Internal Engine Equations

• Turbine Exit to Nozzle Exit

\[ \text{Pr} = \frac{P_{t,6}}{P_0} \]

\[ V_{\text{jet}} = \sqrt{2c_p T_{t,6} \left( 1 - \text{Pr}^{-R/c_p} \right)} \]

\[ \dot{m}_n = \frac{A_n P_{t,6}}{R} (\text{Pr})^{-1/\gamma} \sqrt{\frac{2c_p}{T_{t,5}}} \left( 1 - \text{Pr}^{-R/c_p} \right) \]
Internal Engine Equations

- Turbine Exit to Nozzle Exit

\[ F = m_n (V_{jet} - V_0) + A_n (P_{t,6} - P_0) \]

\[ C_j = \frac{m_n}{F} * 3600 \]
Strength Needed in Brackets

- Find worst case scenario for force on brackets
- Little force in axial direction, most force from the torque of the starter/generator (radial)
- Max power output of starter/generator = 800W
- Min speed for power production = 35,000 RPM

\[ P = \tau \omega \rightarrow \tau_{\text{max}} = \frac{P_{\text{max}}}{\omega_{\text{min}}} = \frac{800 \text{ W}}{3519 \text{ rad/s}} = 0.227 \text{ Nm} \]

- Torque causes greatest force at nearest distance
  - Use inner radius of housing (where stanchion will attach)

\[ \tau = F \times r \rightarrow F_{\text{max}} = \frac{\tau_{\text{max}}}{r} = \frac{0.227 \text{ Nm}}{0.04318 \text{ m}} = 5.26 \text{ N} \]
Strength Needed in Brackets

- Bracket surface area = 0.00016129 square meters
- Use this area and force to find stress

\[ \sigma = \frac{F}{A} = \frac{5.26 N}{0.00016129 m^2} = 32612 \text{ Pa} \approx 33 \text{ kPa} \]

- **Use aluminum 6061-T6**
  - Density: 2.7 g/cc
  - Ultimate tensile strength: 210 MPa
  - Tensile yield strength: 276 MPa
  - Elongation at break for 1/16 in thickness: 12%
  - Ultimate bearing strength: 607 MPa
  - Bearing yield strength: 386 MPa
  - Shear strength: 207 MPa
- **Aluminum 6061-T6 is much stronger than required in terms of shear stress**
Strength Needed in Brackets

- Bearing stress is limiting factor for thickness (bolt holes cause this)

\[ \sigma_{\text{bearing}} = \frac{F}{t \times d} \]

- Apply a factor of safety (3) to the material shear strength and the bearing yield strength and use the lower of those numbers (69 MPa)

\[ 69 \times 10^6 \text{Pa} \geq \frac{5.26 \text{N}}{t \times d} \rightarrow t \times d \geq 7.62 \times 10^{-8} \text{m}^2 \]

- Engine housing is 0.83 mm (0.0327 in) thick so use 0.04 in thick aluminum for brackets

- Bracket mass: 0.0009 kg
Fasteners

- Need 18 bolts, 18 nuts, 6 washers
- For bolts, use large diameter truss head machine screws (better for thin materials)
- Cost: $10.24 for 100
- Mass: 0.000384 kg each
Fasteners

• **Nuts**
  - Cost: $2.36 for 100
  - Mass: 0.000128 kg each

• **Lock washers**
  - Cost: $2.95 for 100
  - Mass: 0.000128 kg each
Anticipated Circuit Diagram
Thermal Analysis of Regulation Circuitry

- Three Phase Rectifier
  - Anticipated temperature: 158 C
  - Max allowable temperature: 175 C
- Capacitor Bleed Resistor (analysis skipped)
  - Max Power dissipation: 1.296 mW
  - Allowable power dissipation: 250 mW
Thermal Analysis of Regulation Circuitry

- Circuit Breaker (Analysis skipped)
  - Max of 3.7 Watts Dissipated
- Regulator (Analysis skipped)
  - No information about thermal Properties
  - System Designed for 600W, our system uses max of 527W
  - Comparable systems do not require special cooling at their rated power.
### Vibrational Analysis

<table>
<thead>
<tr>
<th>Mode No.</th>
<th>Frequency (Rad/sec)</th>
<th>Frequency (Hertz)</th>
<th>Period (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1.00E+32</td>
</tr>
<tr>
<td>2</td>
<td>4651.7</td>
<td>740.34</td>
<td>0.001351</td>
</tr>
<tr>
<td>3</td>
<td>4653.3</td>
<td>740.6</td>
<td>0.00135</td>
</tr>
<tr>
<td>4</td>
<td>9629.4</td>
<td>1532.6</td>
<td>0.000653</td>
</tr>
<tr>
<td>5</td>
<td>9631.1</td>
<td>1532.8</td>
<td>0.000652</td>
</tr>
<tr>
<td>6</td>
<td>21996</td>
<td>3500.7</td>
<td>0.000286</td>
</tr>
<tr>
<td>7</td>
<td>22004</td>
<td>3502</td>
<td>0.000286</td>
</tr>
<tr>
<td>8</td>
<td>23549</td>
<td>3747.9</td>
<td>0.000267</td>
</tr>
<tr>
<td>9</td>
<td>33494</td>
<td>5330.7</td>
<td>0.000188</td>
</tr>
</tbody>
</table>
Vibrational Analysis

Project Description Baseline Feasibility Status Future Studies
Motor Control Model
<table>
<thead>
<tr>
<th>Risk</th>
<th>Severity (1-5)</th>
<th>Likelihood (1-5)</th>
<th>Score</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine vibrations due to change in set-up (addition of the PEU) could cause catastrophic failure</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>basic vibration modeling and testing</td>
</tr>
<tr>
<td>Engine could fail to start due to extra load on drive shaft from PEU</td>
<td>4</td>
<td>3</td>
<td>12</td>
<td>testing</td>
</tr>
<tr>
<td>Over-generation of power could damage electronics</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>power modeling</td>
</tr>
<tr>
<td>Boulder Airport could close or not allow us access on a test day</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>find alternate location e.g. boulder bomb range or parking lot</td>
</tr>
<tr>
<td>Test Stand and other equipment could not be available to us on a test day</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>Schedule tests around GoJett testing</td>
</tr>
<tr>
<td>Borrowed/loaned testing equipment could not work</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>Test all borrowed equipment before it is put into a test</td>
</tr>
<tr>
<td>Electronics could get shorted during testing</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>Have detailed set up procedures for electronics tests and wear grounding straps during testing</td>
</tr>
<tr>
<td>Weather could inhibit testing</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>have back up weather days planned in the schedule in case a test has to be pushed back</td>
</tr>
</tbody>
</table>
Phase I - Component Inspections and Tests

Component Inspections and Tests

Electrical
- Voltage Rectifier
- Power Diffuser
- Generator Motor Driver Board

Mechanical
- Generator and Mount
- Shaft Coupling System
- Engine
- Test Stand

Software
- Simulink Engine Model
- LabView Data Collector VI

Future Work
- Logisitics
- Critical Elements
- Project Description
Phase II - Subsystem Tests

Subsystem Tests

- Power Regulator
- Generator Controller
- Generator Assembly
- Engine Assembly
- Simulink Engine Model
- LabView Data Collector
Phase III - Subsystem Integration Tests

Subsystem Integration Tests

- Power Regulator -> Generator
- Generator Assembly -> Engine
- Generator -> Generator Controller
- Engine Assembly -> LabView Data Collector

Critical Elements
Phase IV - Full Integrated System Tests

Fully-Integrated System Tests

Full System Checkout

Final WPAFB Rehearsal Test
**V&V - Major Tests**

- A major test is a test that will satisfy our current system requirements
- Specific Phase II, III, and IV are designated as major tests:
  - Engine Characterization Test
  - Power Regulator Test
  - Power Regulator->Generator
  - Engine ->Generator -> Generator Controller
  - Full System Checkout Test
## Characterization Test Sensor Details

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DAQ</th>
<th>Sampling Rate (Hz)</th>
<th>Ideal Resolution</th>
<th>Sensor Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Pressure</td>
<td>NI 9205 (16 bit)</td>
<td>5</td>
<td>61 μV</td>
<td>.04 V/psi</td>
</tr>
<tr>
<td>Axial Load Cell</td>
<td>NI 9205 (16 bit)</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerometer</td>
<td>NI 9234 (24 bit)</td>
<td>10 kHz</td>
<td>.6 μV</td>
<td>3 pC/g (±10%)</td>
</tr>
<tr>
<td>Fuel Flow Meter</td>
<td>NI 9402 (32 bit)</td>
<td>5</td>
<td>80 μV</td>
<td>0.01 L/min</td>
</tr>
<tr>
<td>Ambient Thermocouple</td>
<td>NI 9213 (24 bit)</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exit Thermocouple (K-Type)</td>
<td>NI 9213 (24 bit)</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Power Regulator Test Sensor Details

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DAQ</th>
<th>Sampling Rate (Hz)</th>
<th>Ideal Resolution</th>
<th>Sensor Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Sensor (part of system)</td>
<td>ITLL station DAQ (12 bit)</td>
<td>5</td>
<td>(38 μV)</td>
<td>.045 V/A</td>
</tr>
<tr>
<td>Voltage Measurement (part of system)</td>
<td>ITLL station DAQ (12 bit)</td>
<td>5</td>
<td>0.145 mV</td>
<td>6220 μV</td>
</tr>
</tbody>
</table>
## Power Regulator -> Generator Test Sensor Details

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DAQ</th>
<th>Sampling Rate (Hz)</th>
<th>Ideal Resolution</th>
<th>Sensor Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Sensor (part of system)</td>
<td>ITLL station DAQ (12 bit)</td>
<td>5</td>
<td>(38 μV)</td>
<td>.045 V/A</td>
</tr>
<tr>
<td>Voltage Measurement (part of system)</td>
<td>ITLL station DAQ (12 bit)</td>
<td>5</td>
<td>0.145 mV</td>
<td>6220 μV</td>
</tr>
<tr>
<td>RPM Sensor</td>
<td>ITLL Station DAQ (12 bit)</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Engine -> Generator -> Generator Controller Test

### Sensor Details

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DAQ</th>
<th>Sampling Rate (Hz)</th>
<th>Ideal Resolution</th>
<th>Sensor Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>NI 9234 (24 bit)</td>
<td>10 kHz</td>
<td>.6 μV</td>
<td>3 pC/g (±10%)</td>
</tr>
</tbody>
</table>
## Full System Test Sensor Details

<table>
<thead>
<tr>
<th>Sensor</th>
<th>DAQ</th>
<th>Sampling Rate (Hz)</th>
<th>Resolution</th>
<th>Sensor Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Sensor (part of system)</td>
<td>NI 9025 (16 bit)</td>
<td>5</td>
<td>(38 μV)</td>
<td>.045 V/A</td>
</tr>
<tr>
<td>Voltage Measurement (part of system)</td>
<td>NI 9025 (16 bit)</td>
<td>5</td>
<td>0.145 mV</td>
<td>6220 μV</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>NI 9234 (24 bit)</td>
<td>10 kHz</td>
<td>.6 μV</td>
<td>3 pC/g (±10%)</td>
</tr>
<tr>
<td>Exit Temperature (K-Type)</td>
<td>NI 9213 (24 bit)</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Flow Meter</td>
<td>NI 9402 (32 bit)</td>
<td>5</td>
<td>80 μV</td>
<td>0.01 L/min</td>
</tr>
<tr>
<td>Axial Load Cell</td>
<td>NI 9205 (16 bit)</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Engine Characterization Test

<table>
<thead>
<tr>
<th>Type of Measurement</th>
<th>Sensor</th>
<th>Implementation/Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust</td>
<td>Axial Load Cell</td>
<td>Already on Test Stand</td>
</tr>
<tr>
<td>Ambient Pressure</td>
<td>Low Temp Pressure Sensors</td>
<td>Already on Test Stand</td>
</tr>
<tr>
<td>Exhaust Temperature</td>
<td>K-Type Thermocouple</td>
<td>Already on Test Stand</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>K-Type Thermocouple</td>
<td>Already on Test Stand</td>
</tr>
<tr>
<td>Mass Flow of Fuel</td>
<td>Equiflow Flow Meter</td>
<td>Insert on Fuel Line</td>
</tr>
<tr>
<td>Engine RPM</td>
<td>RPM Sensor</td>
<td>Internal Engine RPM Sensor</td>
</tr>
</tbody>
</table>
Electric Motor 2 (Backup): Maxson EC 40 Motor

- Max RPM: 18,000
- Shaft Diameter: 12mm
- RPM Sensor integrated into motor
- Integration Method to Generator: Shaft Coupler
- Cost: Free
Secondary Engine Component Test: Drive Shaft Torque

• **First Test: Find Moment of Inertia of Drive Shaft Assembly**
  - Use handheld torque meter to measure torque of an electric motor spinning at a certain RPM
  - Spin drive shaft with electric motor at known torque at known RPM, calculate MOI

• **During Engine Characterization**
  - Accelerate engine linearly, measure RPM
  - Calculate Torque as a function of RPM
Image of test stand