Spring Final Review

REcuperating **A**dvanced **P**ropulsion **E**ngine **R**edesign

Customer: Air Force Research Lab

Advisor: Dr. Ryan Starkey

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

Presentation Agenda

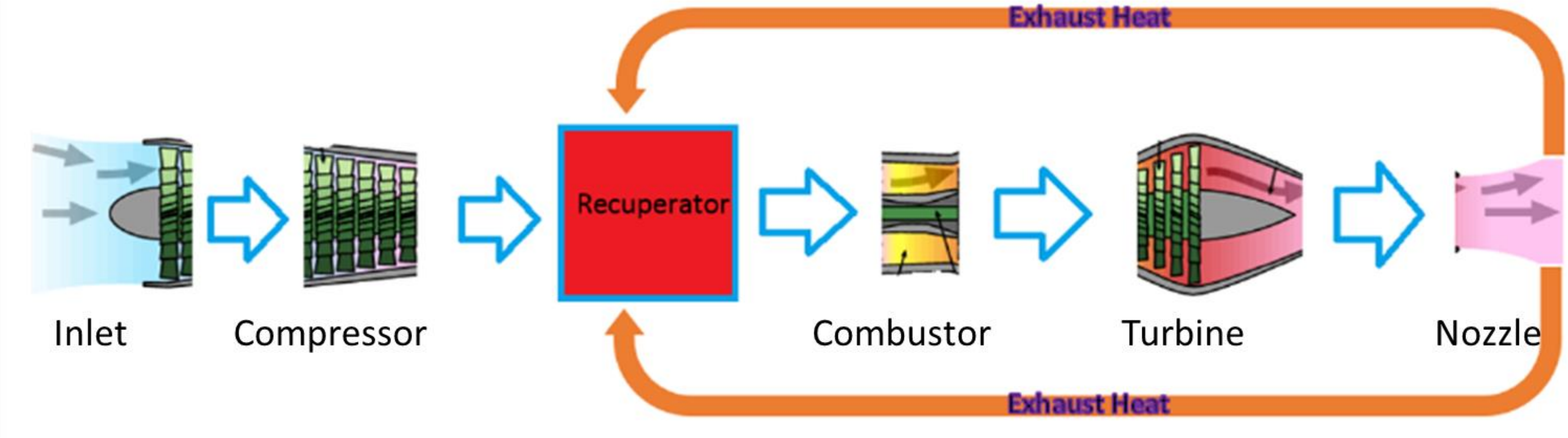
- Project Overview
- Executive Summary
- Heat Exchanger & Model Validation
- Electronics & Engine Testing Validation
- Systems Engineering
- Project Management

Field of Application

- Jet aircraft have a larger performance envelope than prop aircraft
- Jets burn more fuel making them less suited for long range applications.

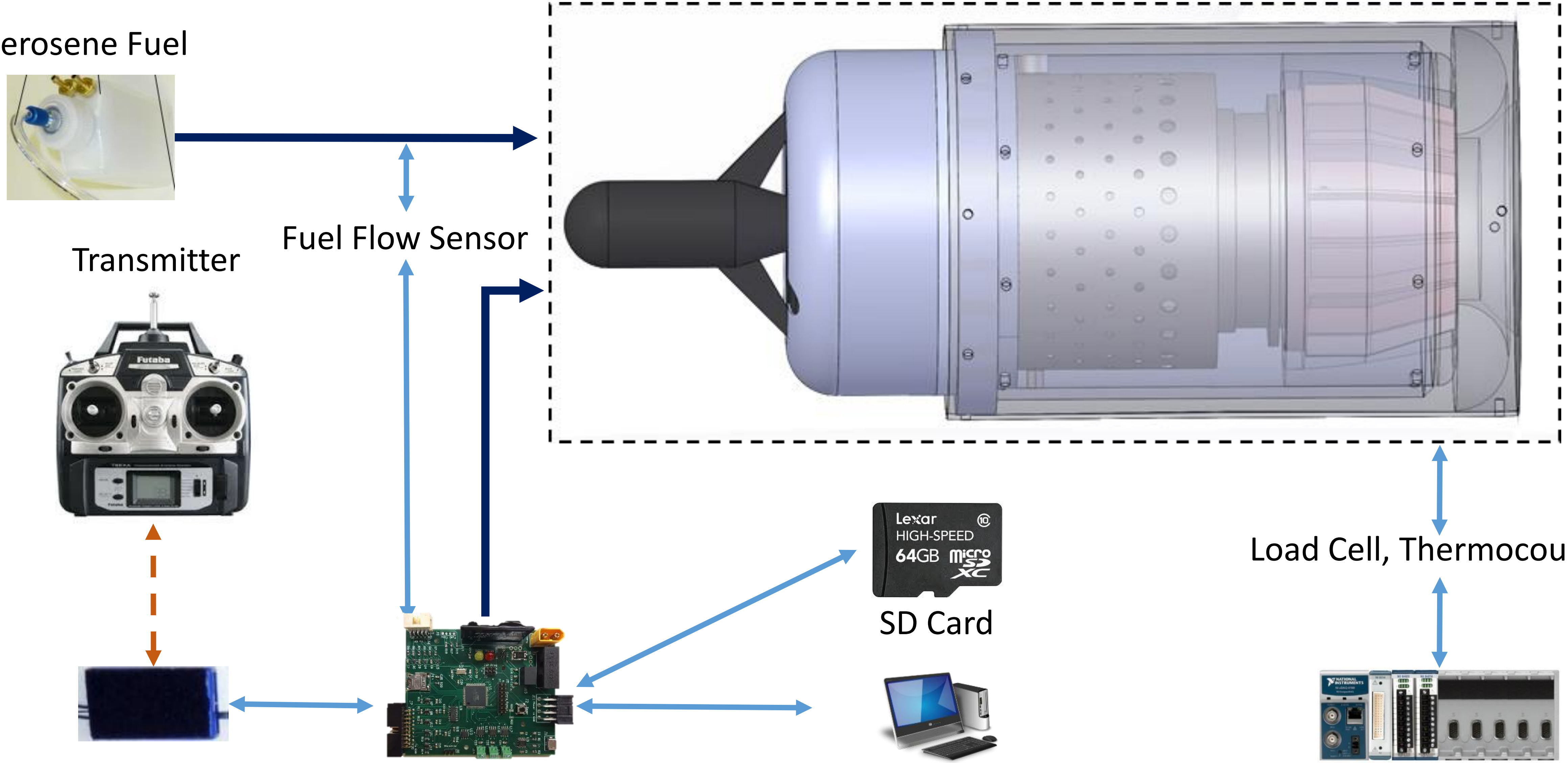
Project Mission

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



Ground based proof of concept for miniature turbojet

Concept of Operations



Kerosene Fuel

Fuel Flow Sensor

Transmitter

Load Cell, Thermocouples

SD Card

Receiver

Engine Control Unit

Computer

NI DAQ Chassis

Baseline Design: Flow Path

Engine Starts Up
1

Air Enters Compressor
2

Air Passes Along Outside of Casing
3

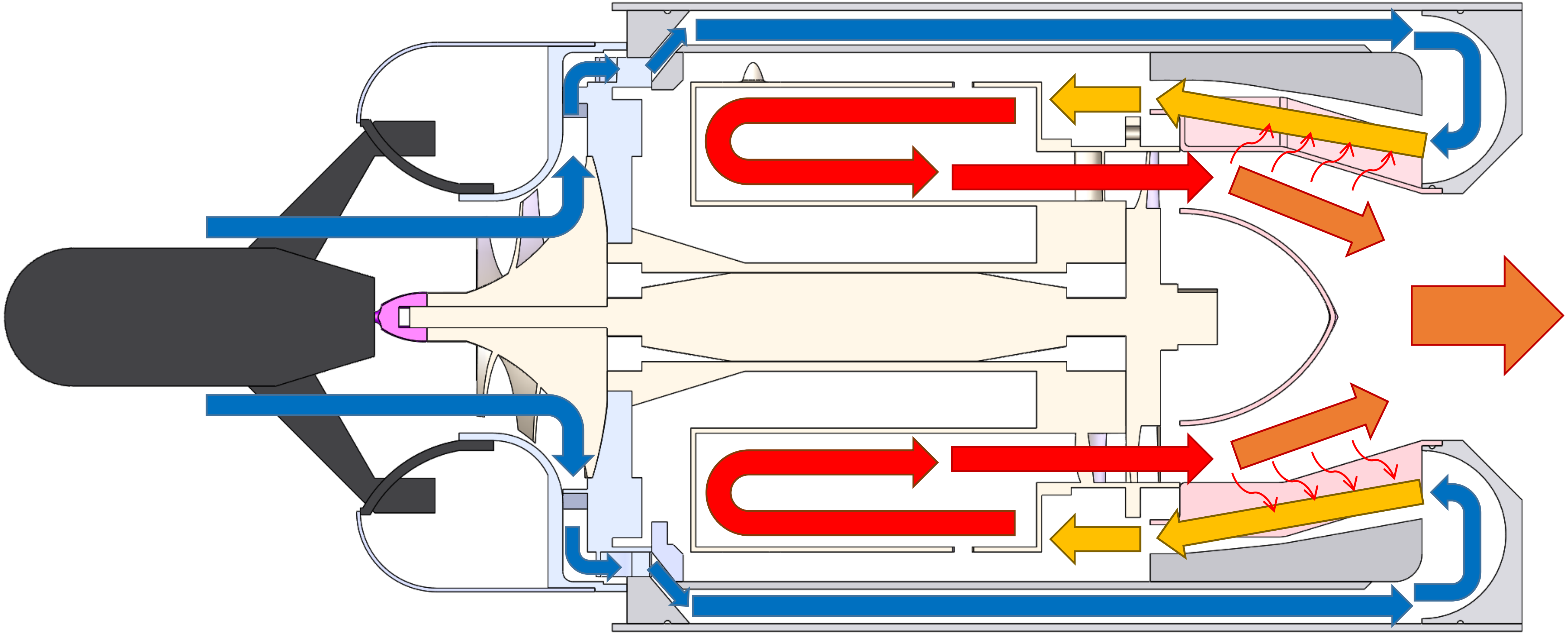
Air Enters Recuperator
4

Recuperator Heats Passing Air
5

Air Enters Combustor
6

Exhaust Passes through Turbine
7

Exhaust heats Recuperator Manifold
8



Critical Project Elements

CPE 1: Thermal-Fluid Modeling

- System **Characterization**

CPE 2: Heat Exchanger

- **Manufacturing**, Cost, Integration

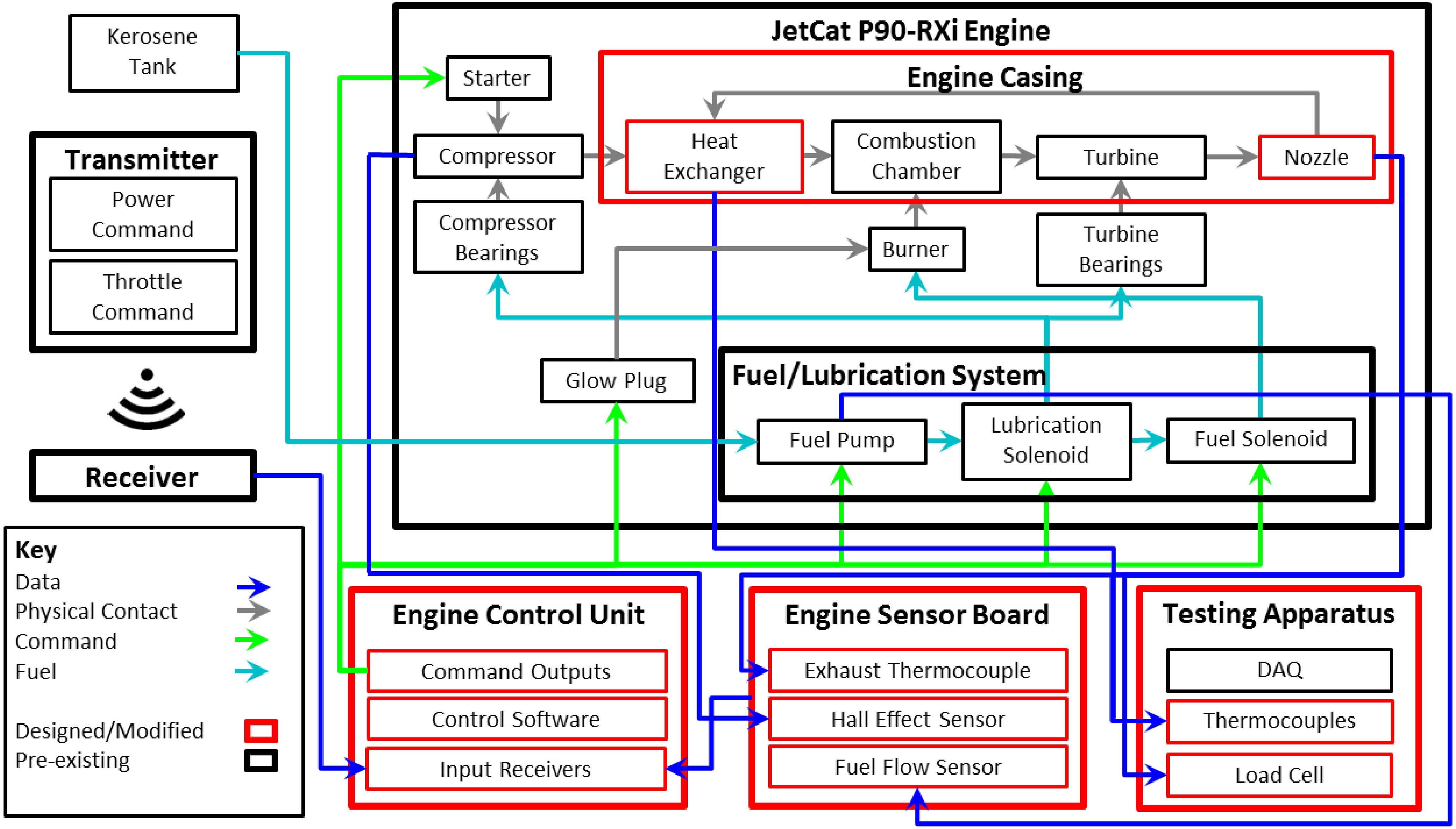
CPE 3: Engine Electronics

- **Control**, Safety, Sensors

CPE 4: Testing

- **Model Validation**, System Verification, Sensors

Functional Block Diagram



Kerosene Tank

Transmitter
- Power Command
- Throttle Command

Receiver

JetCat P90-RXi Engine

Starter

Compressor

Compressor Bearings

Engine Casing
- Heat Exchanger
- Combustion Chamber
- Turbine
- Nozzle

Burner

Turbine Bearings

Glow Plug

Fuel/Lubrication System
- Fuel Pump
- Lubrication Solenoid
- Fuel Solenoid

Engine Control Unit
- Command Outputs
- Control Software
- Input Receivers

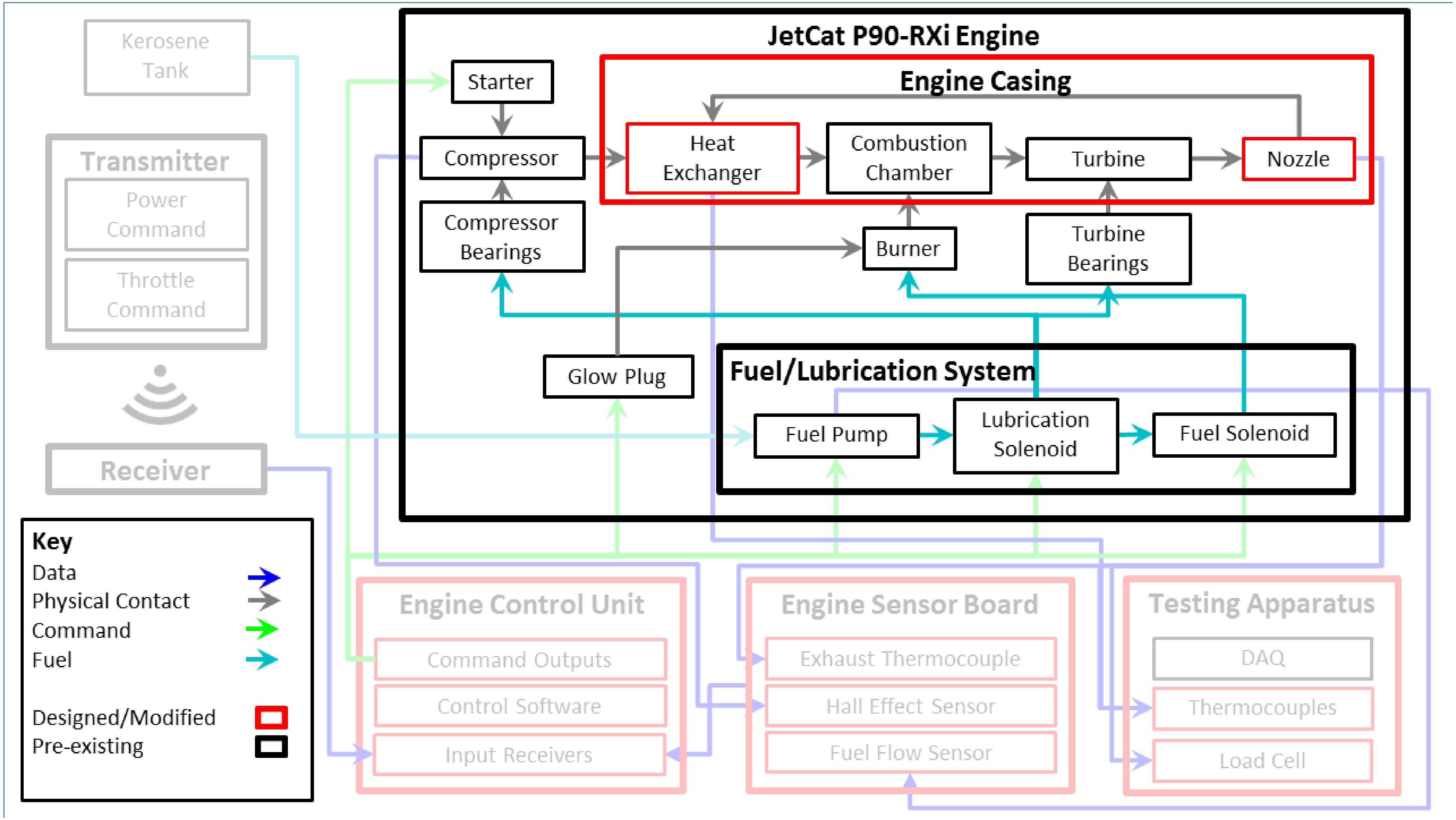
Engine Sensor Board
- Exhaust Thermocouple
- Hall Effect Sensor
- Fuel Flow Sensor

Testing Apparatus
- DAQ
- Thermocouples
- Load Cell

Key
- Data →
- Physical Contact →
- Command →
- Fuel →

- Designed/Modified 🟥
- Pre-existing ☐

Mechanical FBD



Mechanical Design Overview

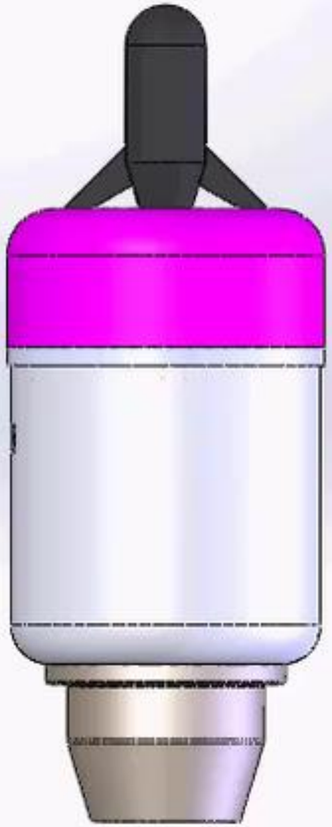
End Cap/Heat Exchanger

Mounting Blocks (x4)

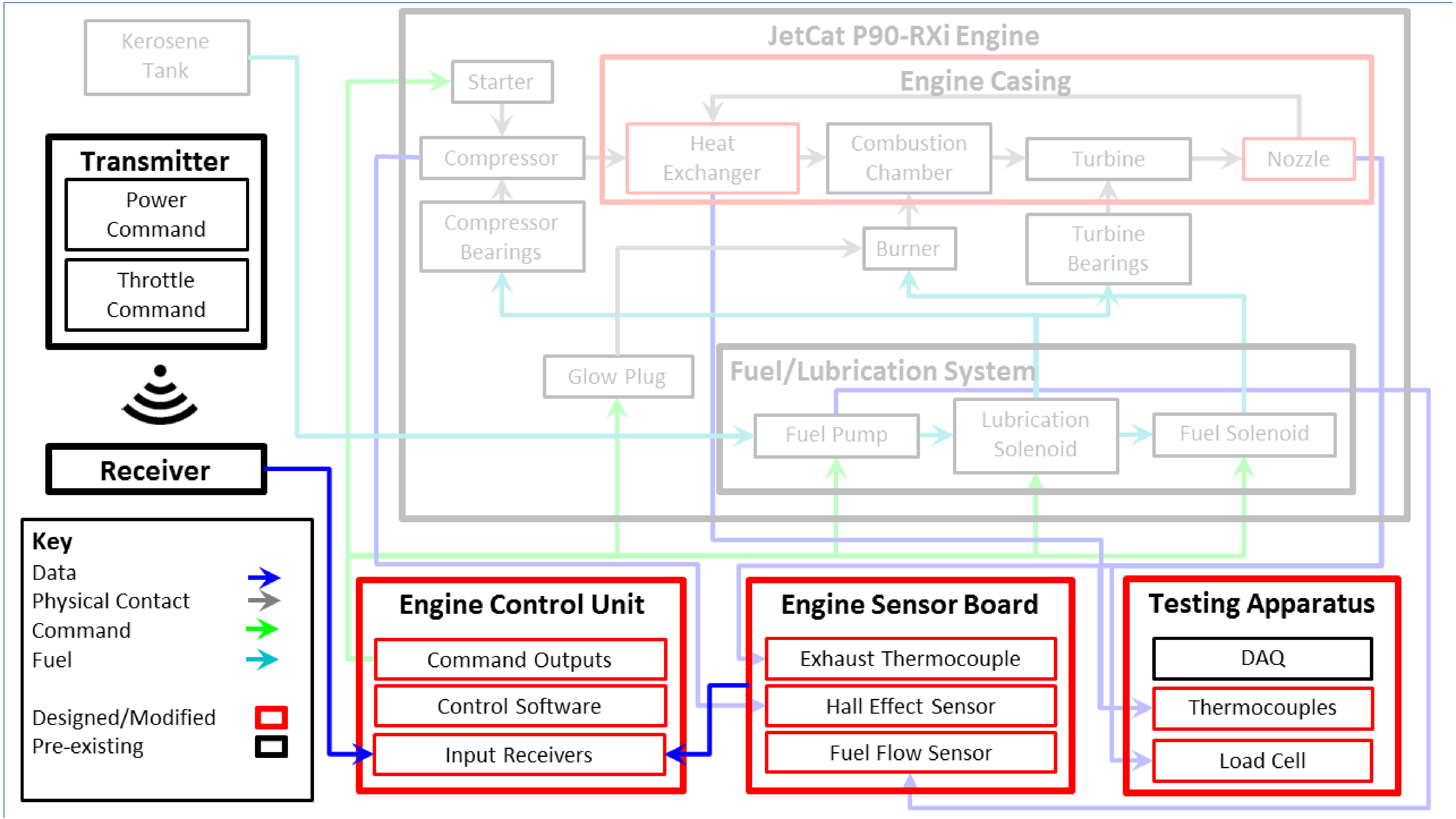
Outer Casing

Nozzle

Forward Ring



Electrical FBD



Kerosene Tank

Transmitter

Power Command

Throttle Command

Receiver

JetCat P90-RXi Engine

Starter

Compressor

Compressor Bearings

Engine Casing

Heat Exchanger

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Testing Apparatus

DAQ

Thermocouples

Load Cell

Key

Data →

Physical Contact →

Command →

Fuel →

Designed/Modified 🟥

Pre-existing □

Engine Electronics Design Overview

Custom printed circuit boards – based off MEDUSA design (~40%)


REAPER ECU

Engine Control Unit (ECU)

- Control Signal & Data Input
- Fuel Flow Sensor
- Save Data
- Process User Input

Engine Sensor Board (ESB)

- Exhaust Gas Thermocouple
- Hall Effect Sensor
- Control Actuators

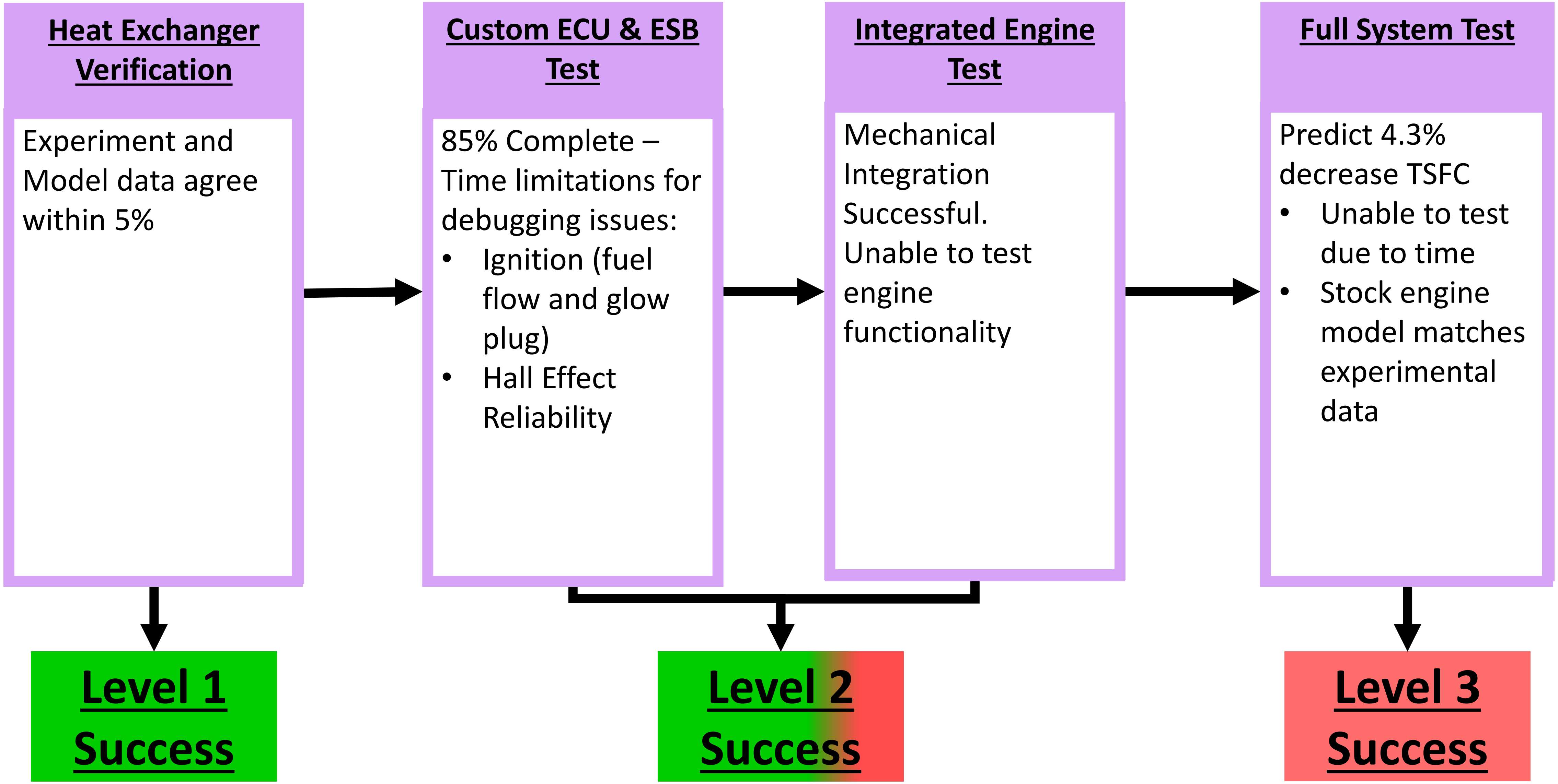

REAPER ESB

Two Revisions Altium Design Advanced Circuits Manufacturing Populated In House

Levels of Success

	Simulation	**Recuperator**
Level 1	-Develop first order, steady state model -Model heat exchanger effectiveness, specific fuel consumption and thrust **100%**	-Recuperator designed and manufactured -Recuperator verified with engine analog **100%**
Level 2	-Model transient characteristics **100%**	-Recuperator is integrated onto engine -Integrated engine system starts and runs **60%**
Level 3	-Develop CFD model -Model is verified with test data **90%**	-Engine system operates for throttle range -Engine system meets design requirements **0%**

Testing Summary



Heat Exchanger Verification

Experiment and Model data agree within 5%

Custom ECU & ESB Test

85% Complete – Time limitations for debugging issues:

- Ignition (fuel flow and glow plug)
- Hall Effect Reliability

Integrated Engine Test

Mechanical Integration Successful. Unable to test engine functionality

Full System Test

Predict 4.3% decrease TSFC

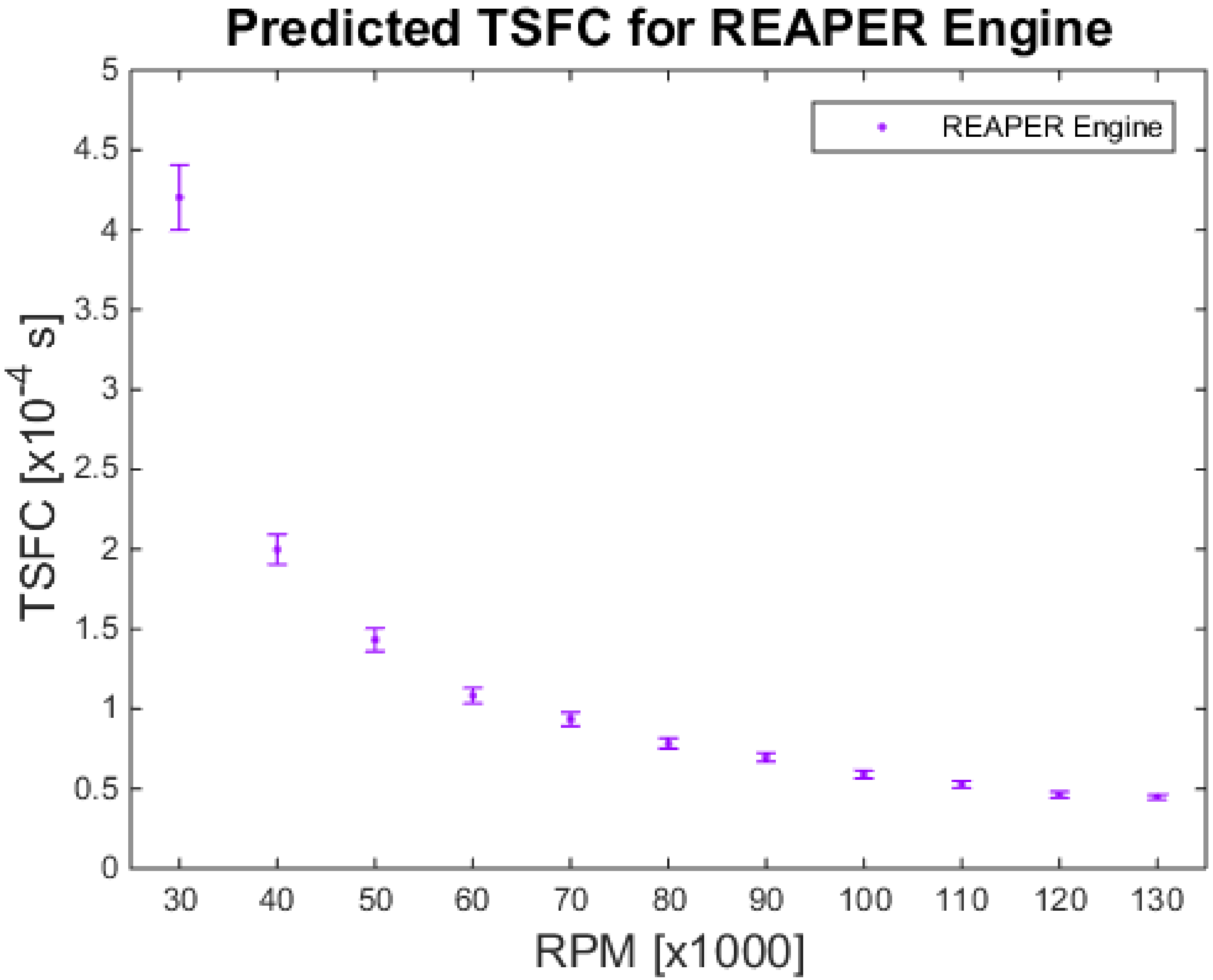
- Unable to test due to time
- Stock engine model matches experimental data

Level 1 Success

Level 2 Success

Level 3 Success

Integrated Engine Test Prediction



At Full Throttle:

- Stock Engine TSFC: $4.67 \times 10^{-4}\ [s^{-1}]$
- Predicted TSFC: $4.47 \times 10^{-4}\ [s^{-1}]$
- Percent Change in TSFC: -4.3%

Conclusions:

- Unable to meet FR 2 to decrease TSFC by 10% at maximum thrust
- Recuperation is better suited for shaft-work applications

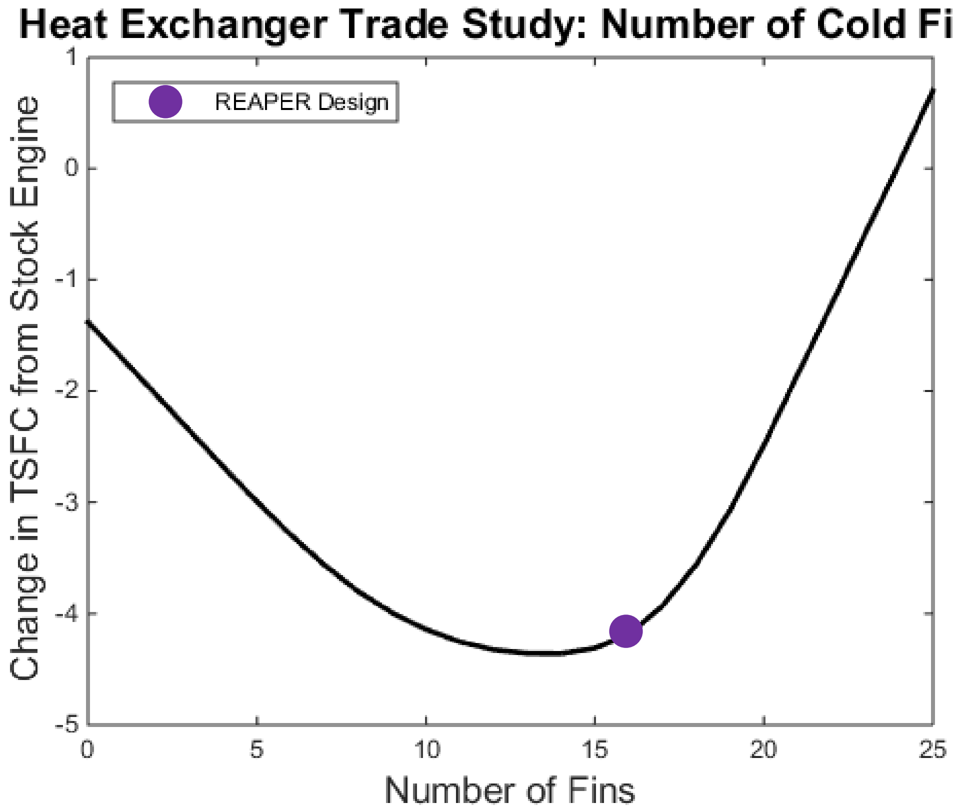
Heat Exchanger & Heat Transfer Model Validation

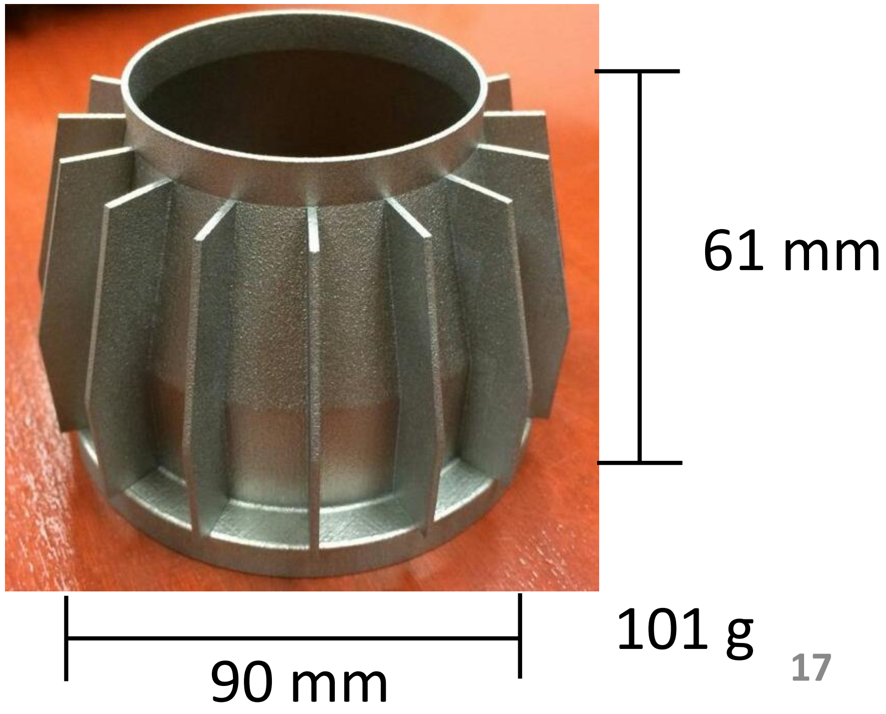
Goal: Verify heat exchanger design and heat transfer model

Motivation: Heat transfer from heat exchanger is the core aspect of the design

Heat Exchanger Design Overview

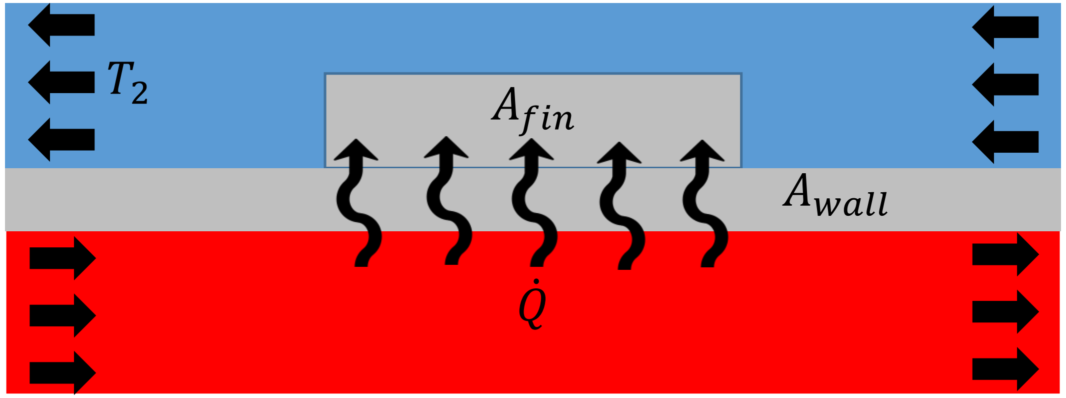
- Design obtained from parametric studies
- Interior fins and extended length considered but ultimately left out
- Direct Metal Laser Sintered by Protolabs
  - All dimensions within manufacturer tolerances ± 0.025 mm



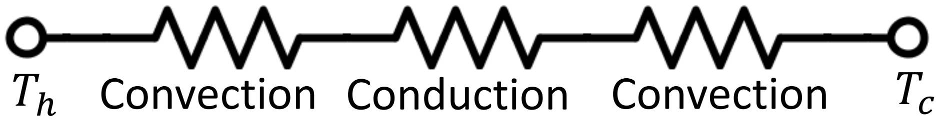


Heat Transfer Model

$$C_p(T_2 - T_1) = UA_{wall}(T_h - T_c)$$



$R_1 = \frac{1}{h_h}$ $R_2 = \frac{t_w}{k_w}$ $R_3 = \frac{A_{wall}}{\eta A_c h_h}$



$$\frac{1}{U} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Gnielinski H

ess

$Nu_D =$

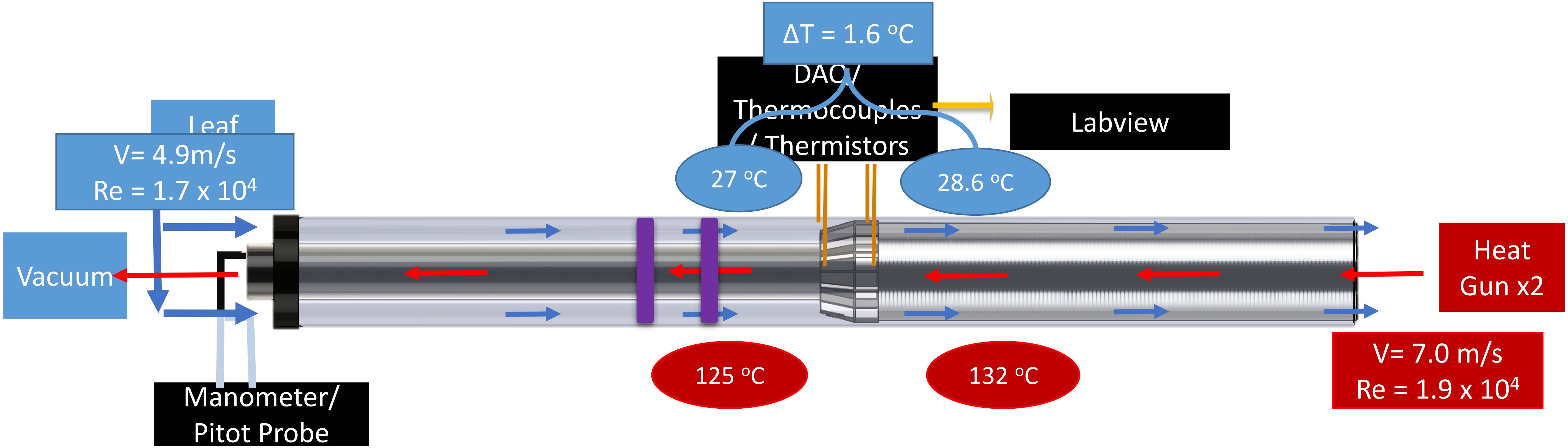
$\eta_f)$

Verification of the heat transfer model is core to understanding recuperative engine cycle

Applicable for

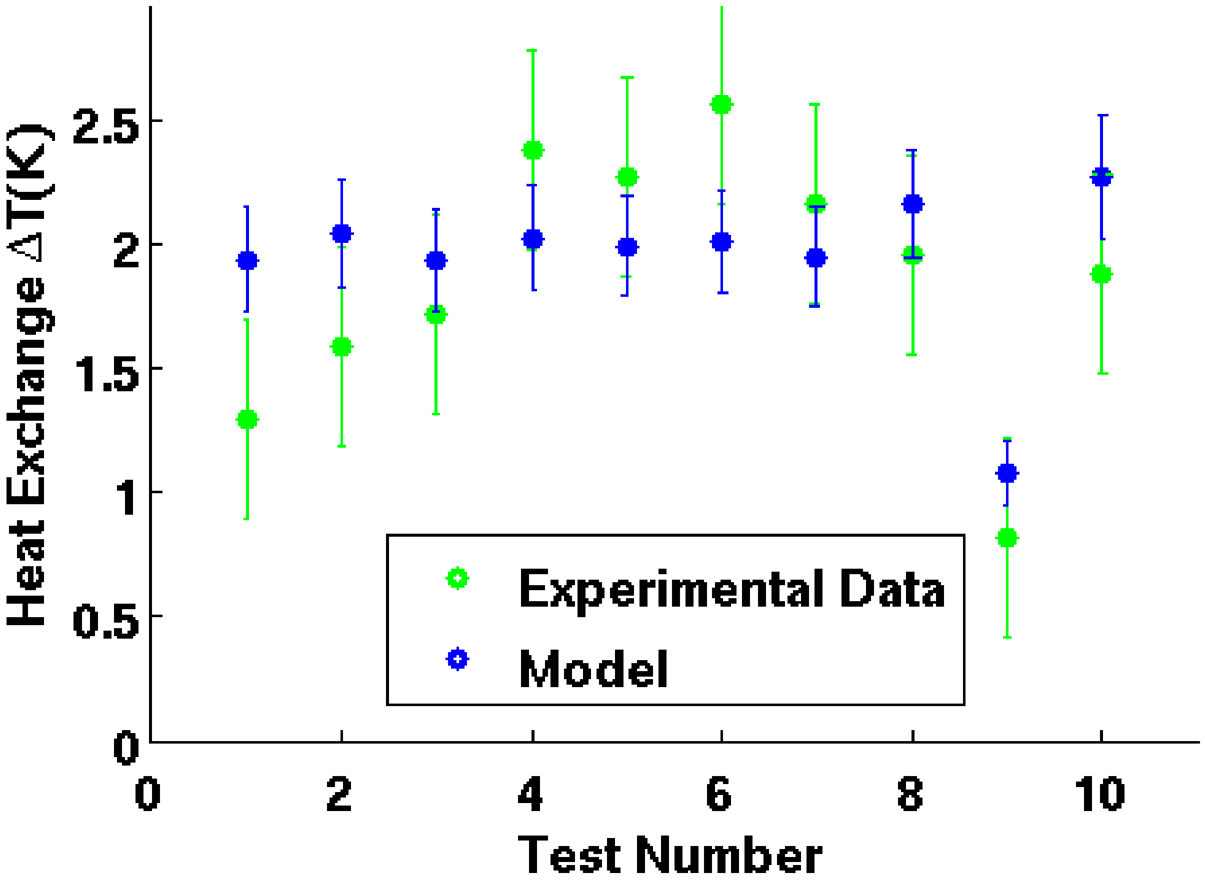
$Re_D \geq 3000$ $0.9 \leq Pr \leq 2000$

Heat Exchanger Verification



Sensor List	Error	Expected Sample Range	Sample Rate
Thermocouples	+/- 2°C	Hot Flow 100-300°C	1 Hz
Thermistors	+/- 0.2°C	Cold Flow 10-40°C	1 Hz
Pitot Static Tube	+/- 1 m/s	5-40m/s	N/A

Heat Exchanger Test Results


Experimental Test Data vs Model Prediction for Heat Exchange (ΔT) Across Test Section

Data Comparison:

- 10 tests conducted
  - 9 of 10 tests within 2σ of each other
- On average model 5% error from experimental data

Conclusion:

- Heat exchanger functioned as designed
- Model predicts the heat exchanger performance

Control Volume Model Validation

Goal: Verify ability of engine model to predict engine performance

Motivation: Need to model engine performance to predict effect of heat exchanger

Control Volume Model

Conservation Laws

Mass:

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

Momentum:

$$p_1 A_1 - p_2 A_2 + \tilde{P}(A_2 - A_1) - \left(\frac{\dot{W}_{shaft}}{V_m} + F_{fric}\right) = \dot{m}_2 V_2 - \dot{m}_1 V_1$$

Energy:

$$\left(\frac{\dot{Q} - \dot{W}_{shaft}}{\dot{m}}\right) - \frac{V_m^2}{2} K_L = C_{p,2} T_2 - C_{p,1} T_1 + \frac{1}{2}(V_2^2 - V_1^2)$$

Constitutive:

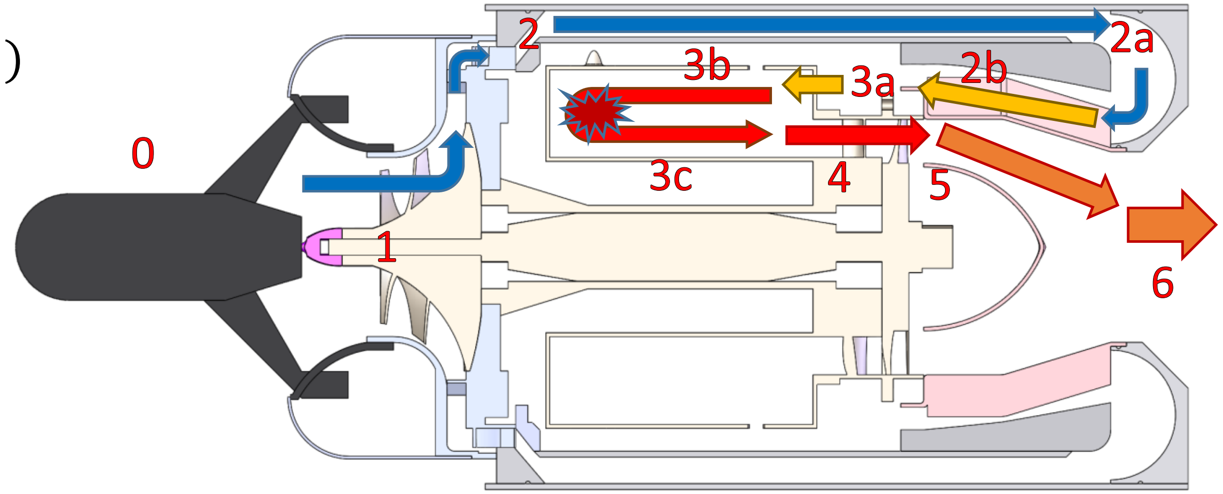
$$p = \rho R T$$

Loss Sources

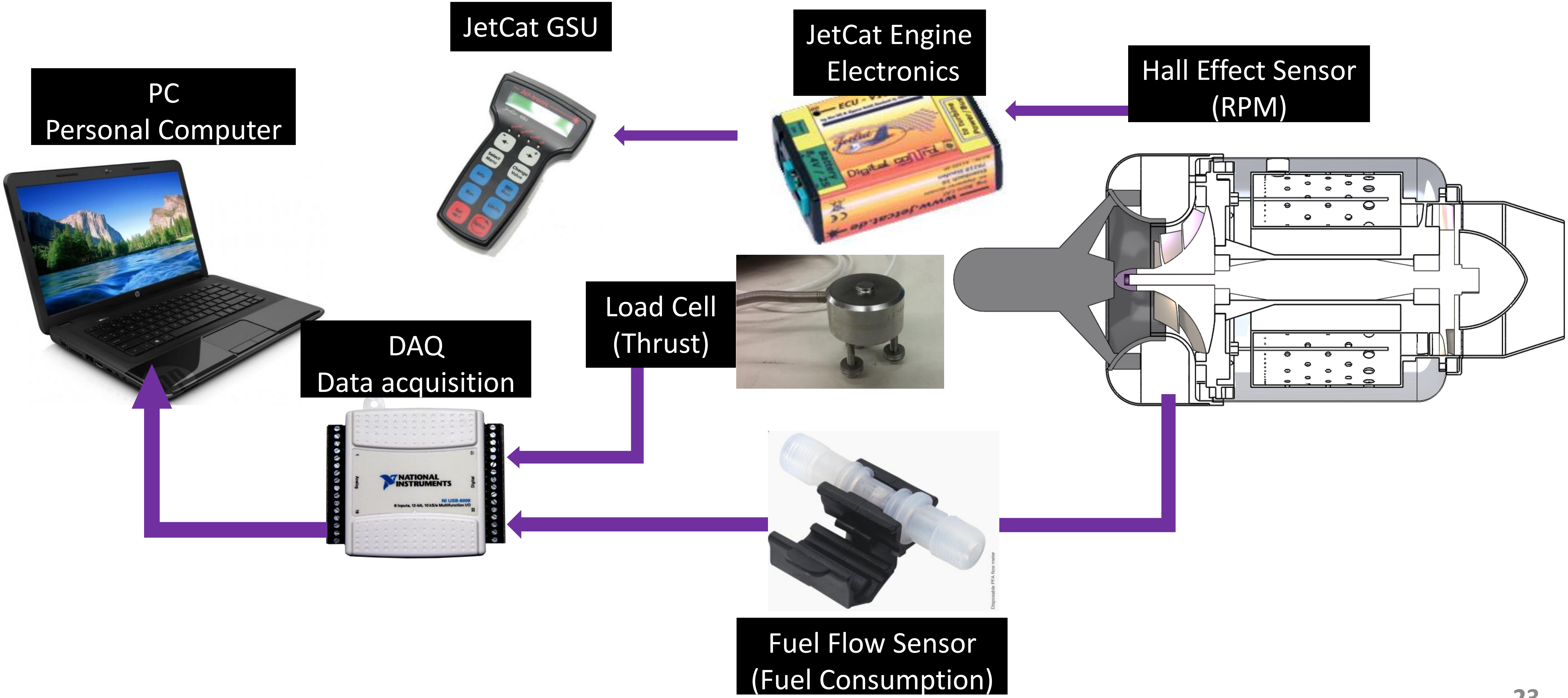
- Friction (Colebrook-White)
- Sudden expansion/contraction
- Gradual Expansion
- Turning the flow

Assumptions/Correlations

- Ideal, thermally perfect gas
- 1-D flow; fully turbulent
- Engine component efficiencies from MEDUSA/COMET component maps
- Colebrook-White friction correlation
- Gnielinski heat transfer correlation



Stock Engine Test Setup



JetCat GSU

JetCat Engine Electronics

Hall Effect Sensor (RPM)

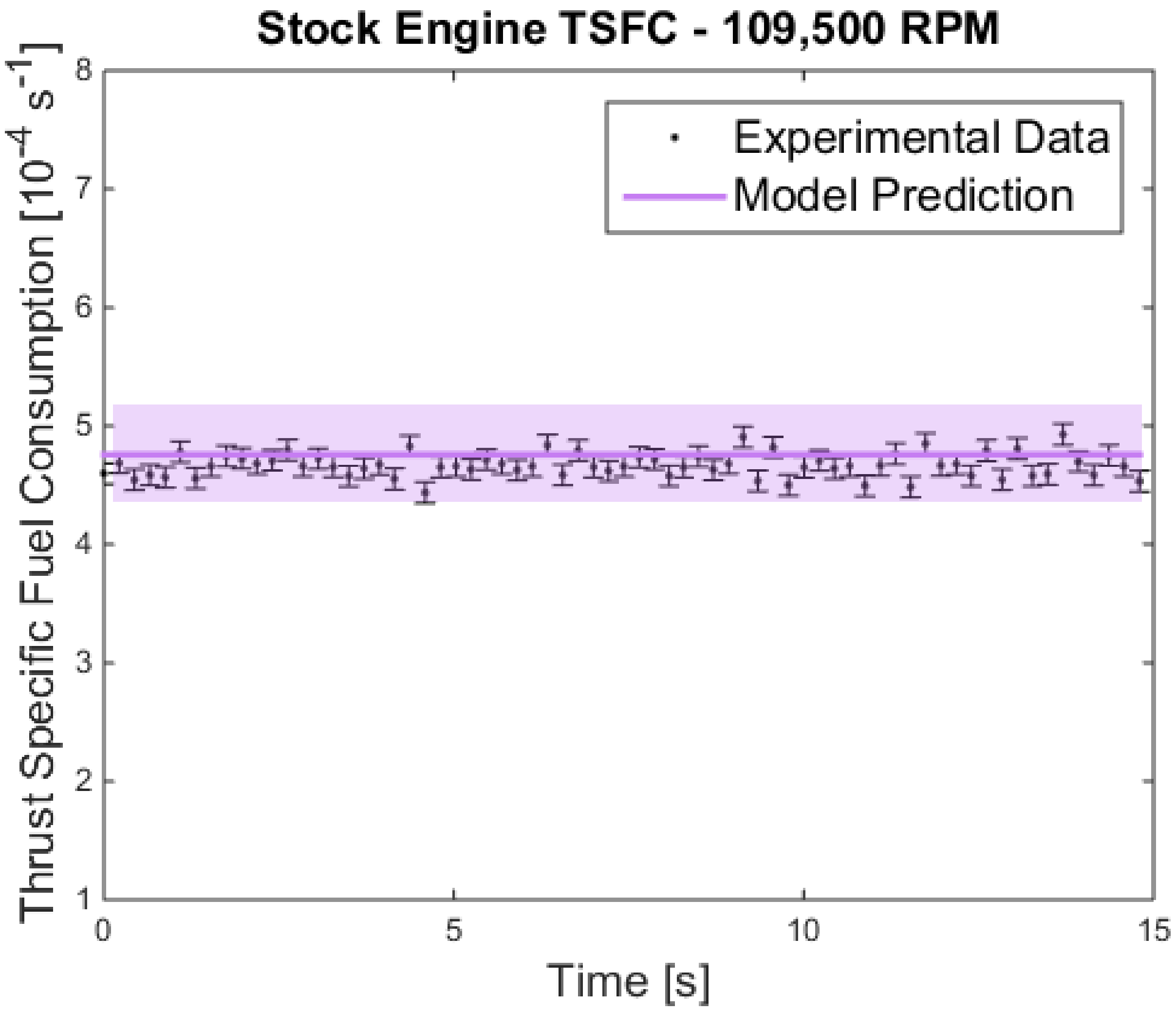
PC Personal Computer

Load Cell (Thrust)

DAQ Data acquisition

Fuel Flow Sensor (Fuel Consumption)

Control Volume Model Validation: TSFC



Predicted TSFC: $4.8 \pm 0.3 * 10^{-4}\ [s^{-1}]$

Measured Average TSFC: $4.67\ \pm 0.09 * 10^{-4}[\ s^{-1}]$

Percent Difference: 2.8%

Conclusion:

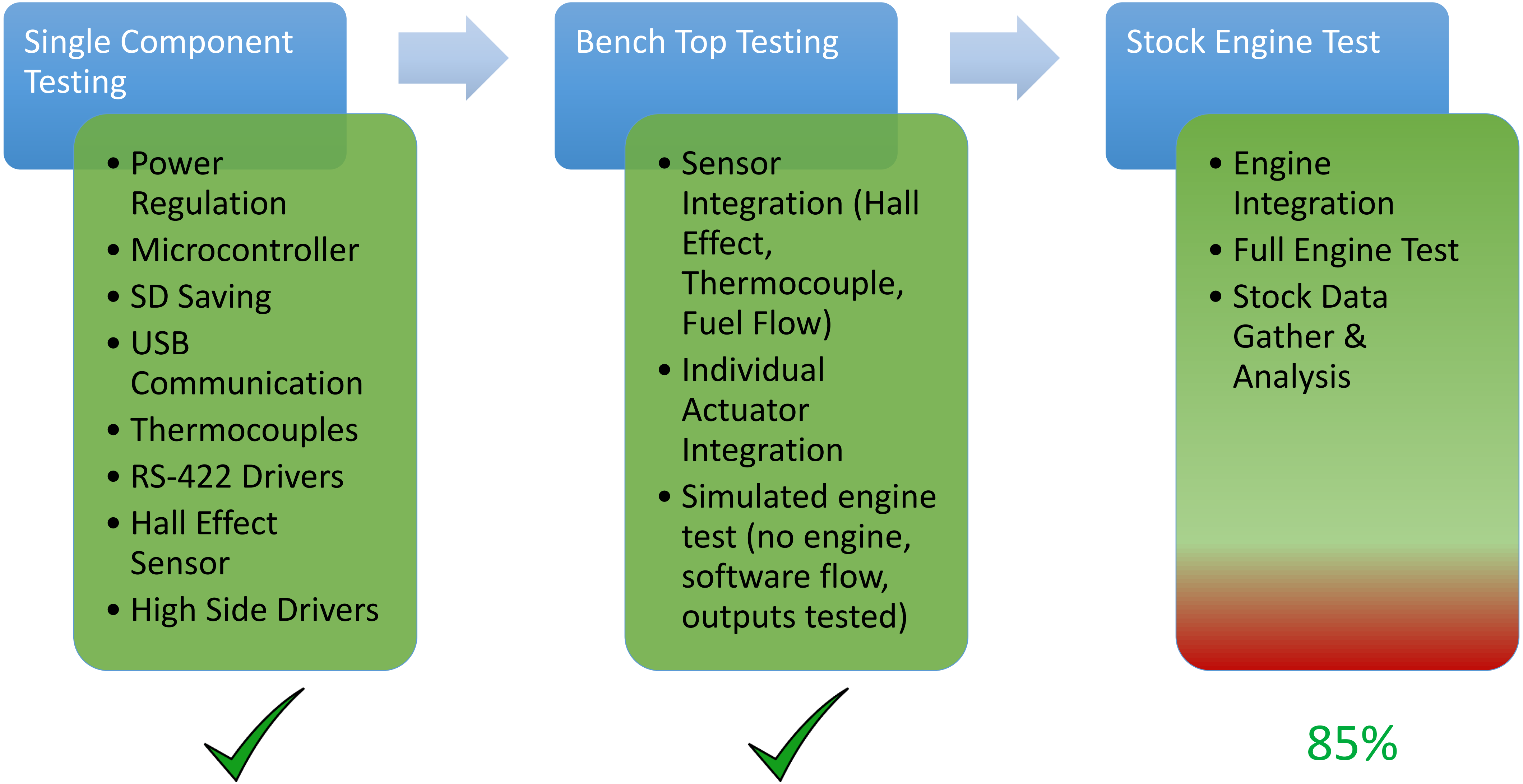
Control Volume model can predict the performance of the P90-RXi

Engine Electronics

Goal: Safely control engine and save testing data

Motivation: Stock electronics cannot be modified to work with recuperating engine

EE: Testing Tree



Single Component Testing

- Power Regulation
- Microcontroller
- SD Saving
- USB Communication
- Thermocouples
- RS-422 Drivers
- Hall Effect Sensor
- High Side Drivers

✓

Bench Top Testing

- Sensor Integration (Hall Effect, Thermocouple, Fuel Flow)
- Individual Actuator Integration
- Simulated engine test (no engine, software flow, outputs tested)

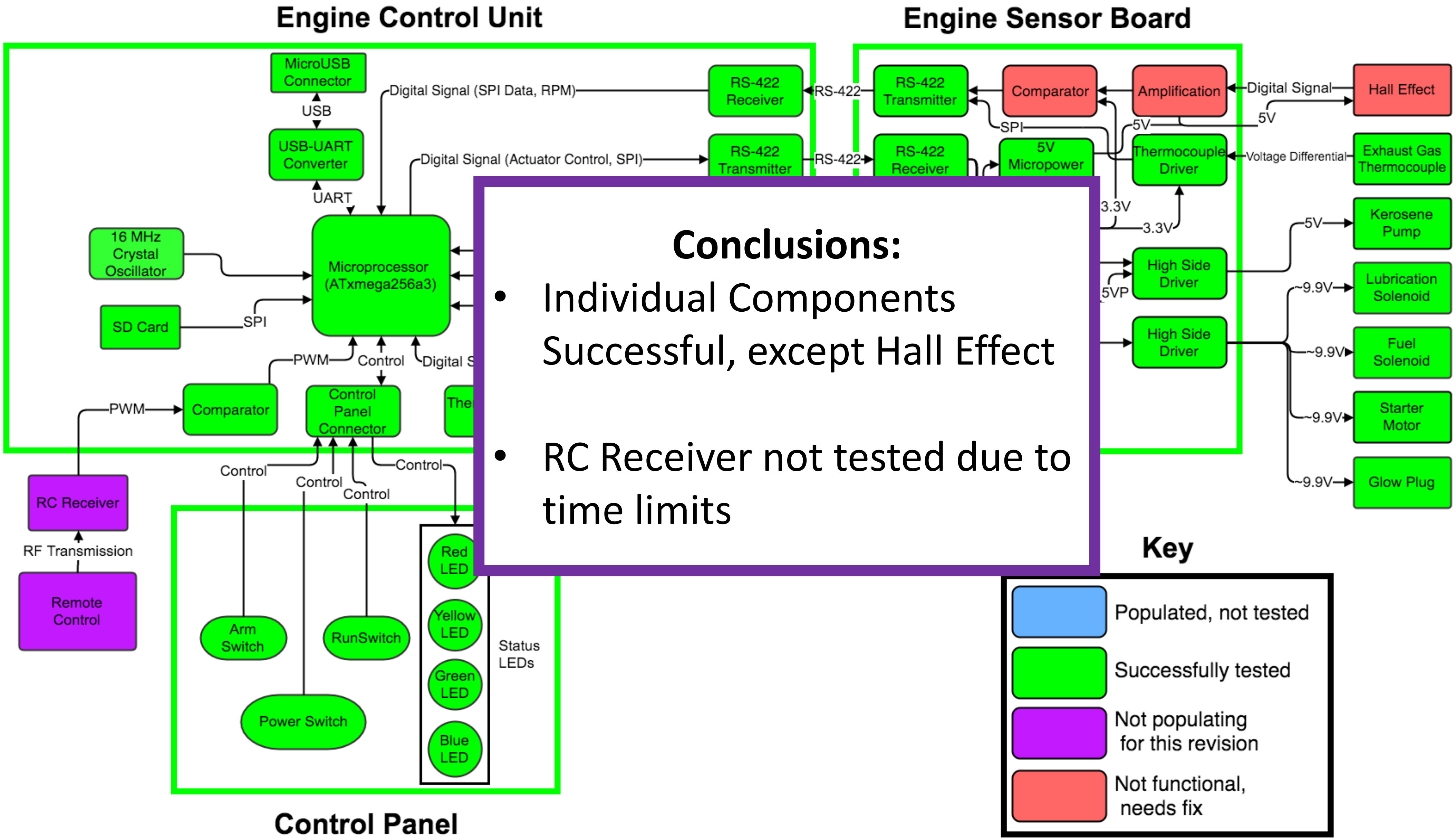
✓

Stock Engine Test

- Engine Integration
- Full Engine Test
- Stock Data Gather & Analysis

85%

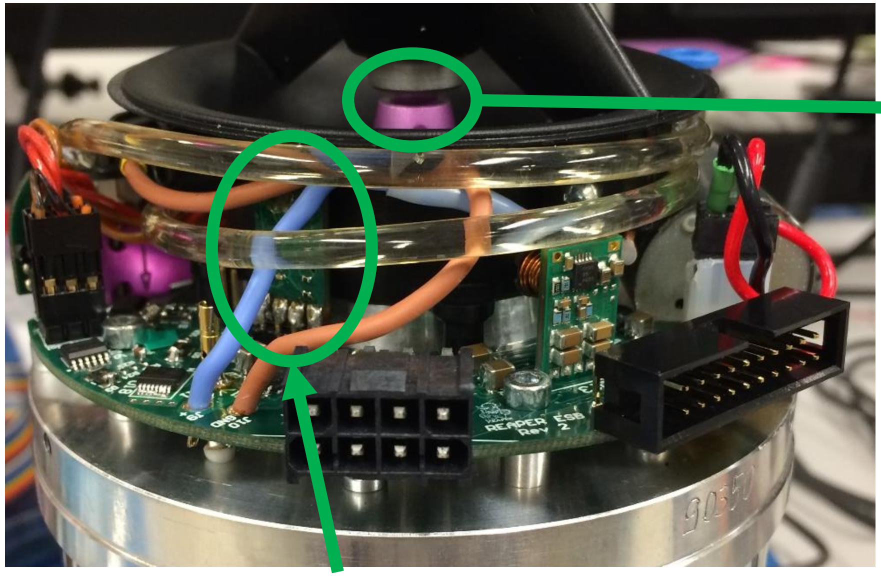
EE: Rev. 2 Final Design Status



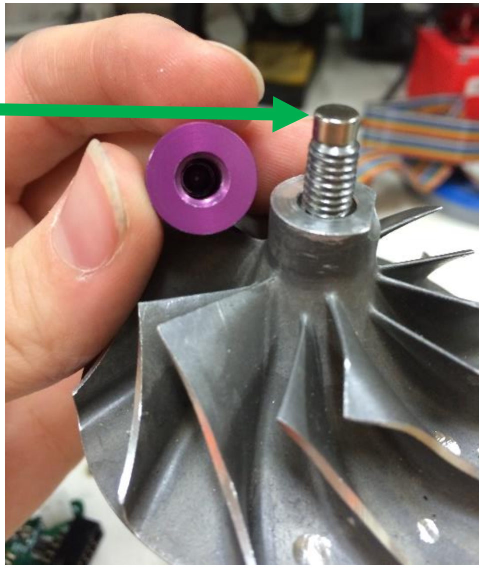
Conclusions:

- Individual Components Successful, except Hall Effect
- RC Receiver not tested due to time limits

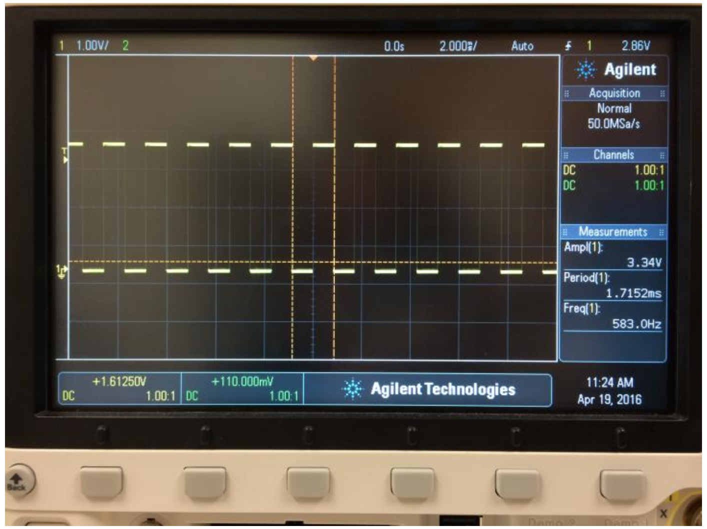
Engine Sensor Testing – Hall Effect



Hall Effect Integration

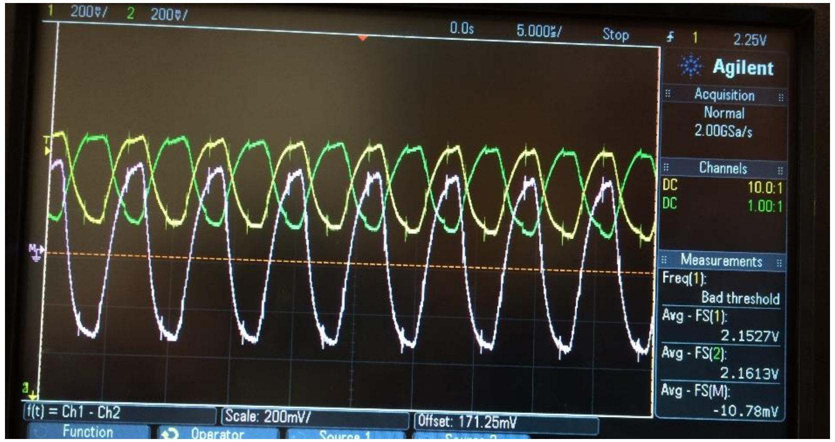


Internal Magnet



Initial Testing – Successful

~20mV Difference –> Amplified for microcontroller

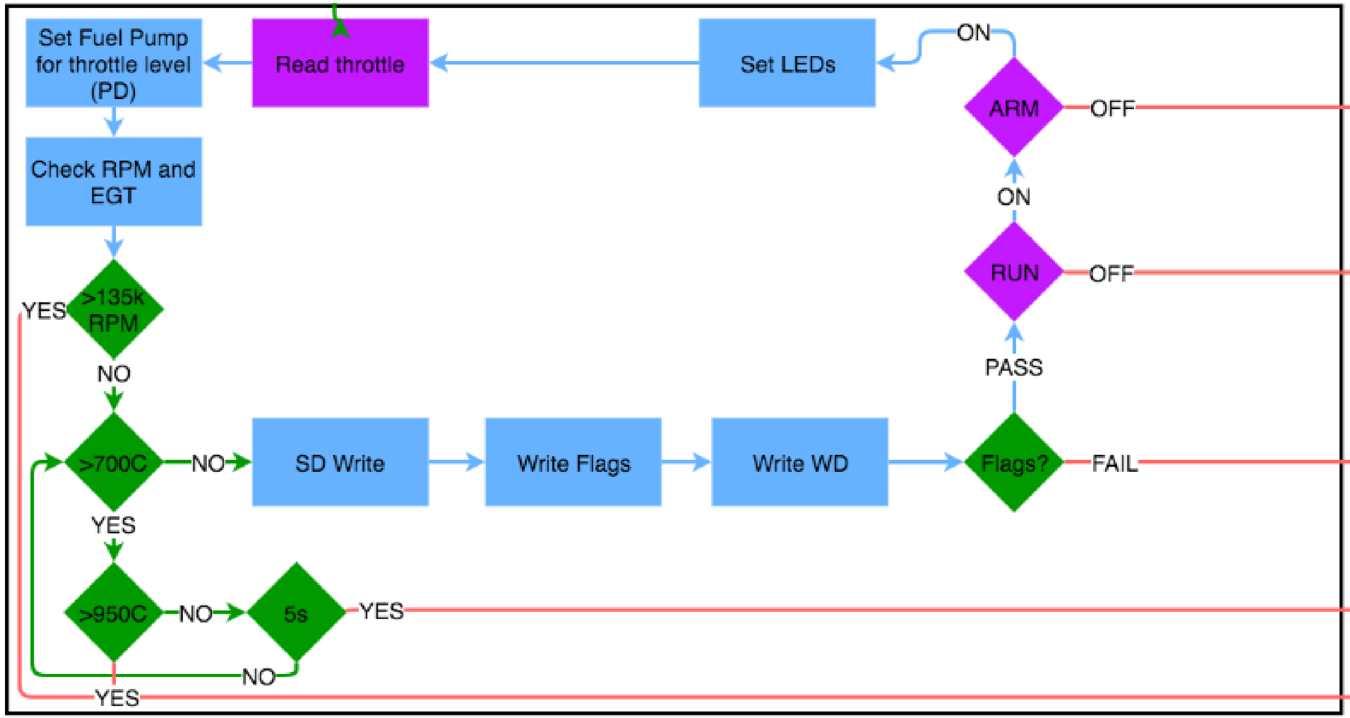


Raw Differential Output

Issue Encountered after Testing – Signal not square

Software Flow

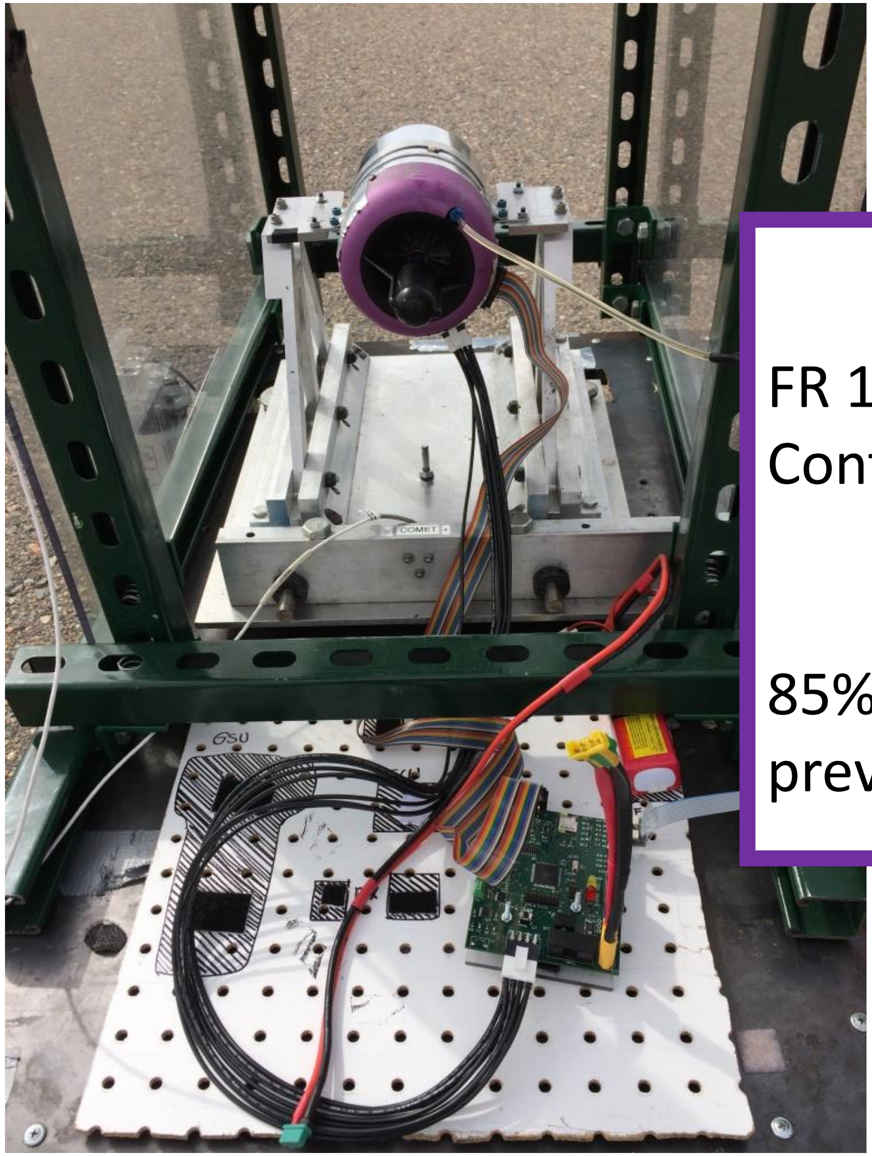
Start Signal	Wait for ARM and RUN signals from Control Box
Warmup	Spin starter motor to start compression
Ignition	Heat glow plug; add fuel; check temperature and RPM for combustion
Idle Test	Set fuel pump to idle; tweak as needed until idle RPM (35,000) is reached
Running Loop (Throttle Input)	Set fuel pump to reach RPM correlating with throttle level; check safeties and switches
Shutdown Sequence	Run starter motor until engine is below 80ºC



KEY

- 🟪 User Input
- 🟥 Shutdown
- 🟦 Processor Action
- ◆ Decision Point

Engine Testing



Engine Test at Boulder Airport

Start Signal ✓

Conclusions:

FR 1: Engine Electronics Shall Control the Engine.

↓

85% complete – Time limitations prevent full verification

Actuators ON ✓

RPM Readings ✓

perature Readings ✓

Fuel Ignition ✗

(Throttle Input)

Shutdown Sequence

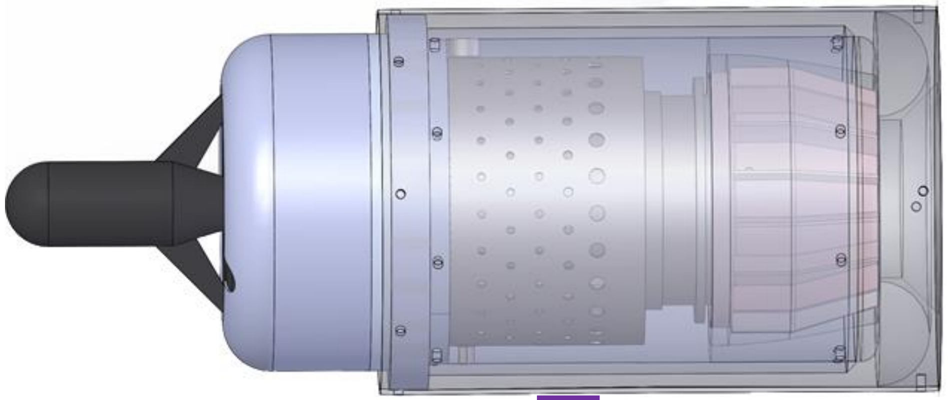
Possibly due to:

- Under/over fueling
- Glow plug heat too low

Systems Engineering

Systems Approach

- **<u>Design Solution: Top Down</u>**
  - Customer Design Requirement
    - → Levels of Success and Functional Requirements
  - Design Concept Selection
    - → Heat Exchanger/Engine Control Trade Study
  - Risk Analysis
    - → Engine Control Trade Study
  - Full Subsystem Design
    - → CAD model, Component/Material Selection
- **<u>Development, Integration, Testing: Bottom Up</u>**
  - Benchtop Testing, Mechanical Fit Check
  - Heat Exchanger Validation
  - Full System Test



Trade Studies

- Key Trade Study
  - Engine Control → Custom Engine Control Unit and Engine Sensor Board
  - Heat Exchanger → Gas to Gas Heat Transfer

	Weight	Stock	Custom PCB	Programmable

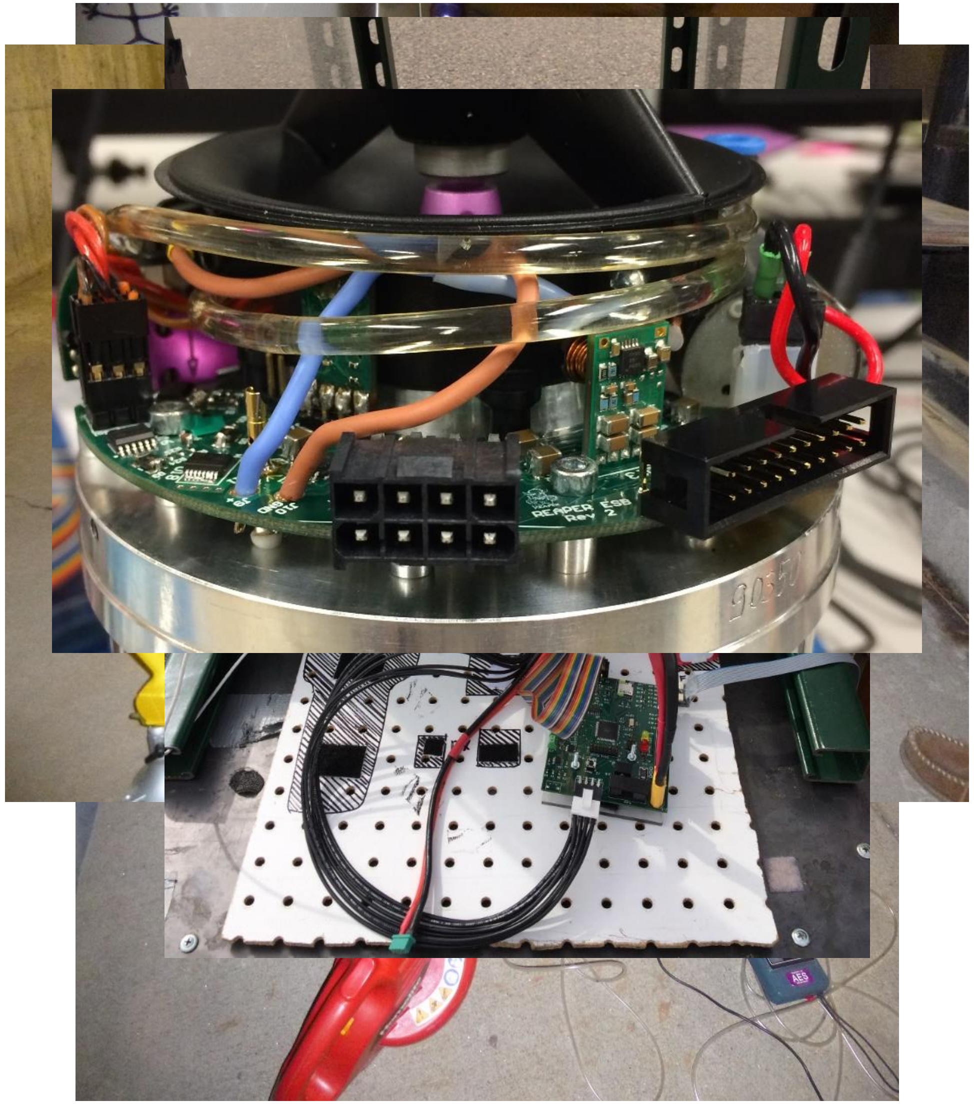
	Weight	Heat Pipe	Gas-Gas Multi-pass	Gas-Gas Single Passed Finned	Gas-Gas Counter Flow
Mass	10	1	2	4	1
Volume	10	3	2	3	3
Manufacturability/ Cost	30	1	3	4	3
Integrality	30	4	1	2	2
Flow Impedance	20	5	4	5	1
Total	100	**2.9**	**2.4**	**3.5**	**2.1**

- Increase weight of development time
- Will not change overall outcome

- Increase weight of flow impedance
- Potential change in trade outcome

Challenges and Lessons

- Expect System Integration Problems
  - Custom electronics took longer to test and integrate
  - Sensors issues caused scheduling slippage
- Plan for Iterations & Allocated Resources Early
  - Iterations were needed to prove model
  - Became main focus of project success
- Risks developed in CDR did not address the electronics and testing scheduling slippage

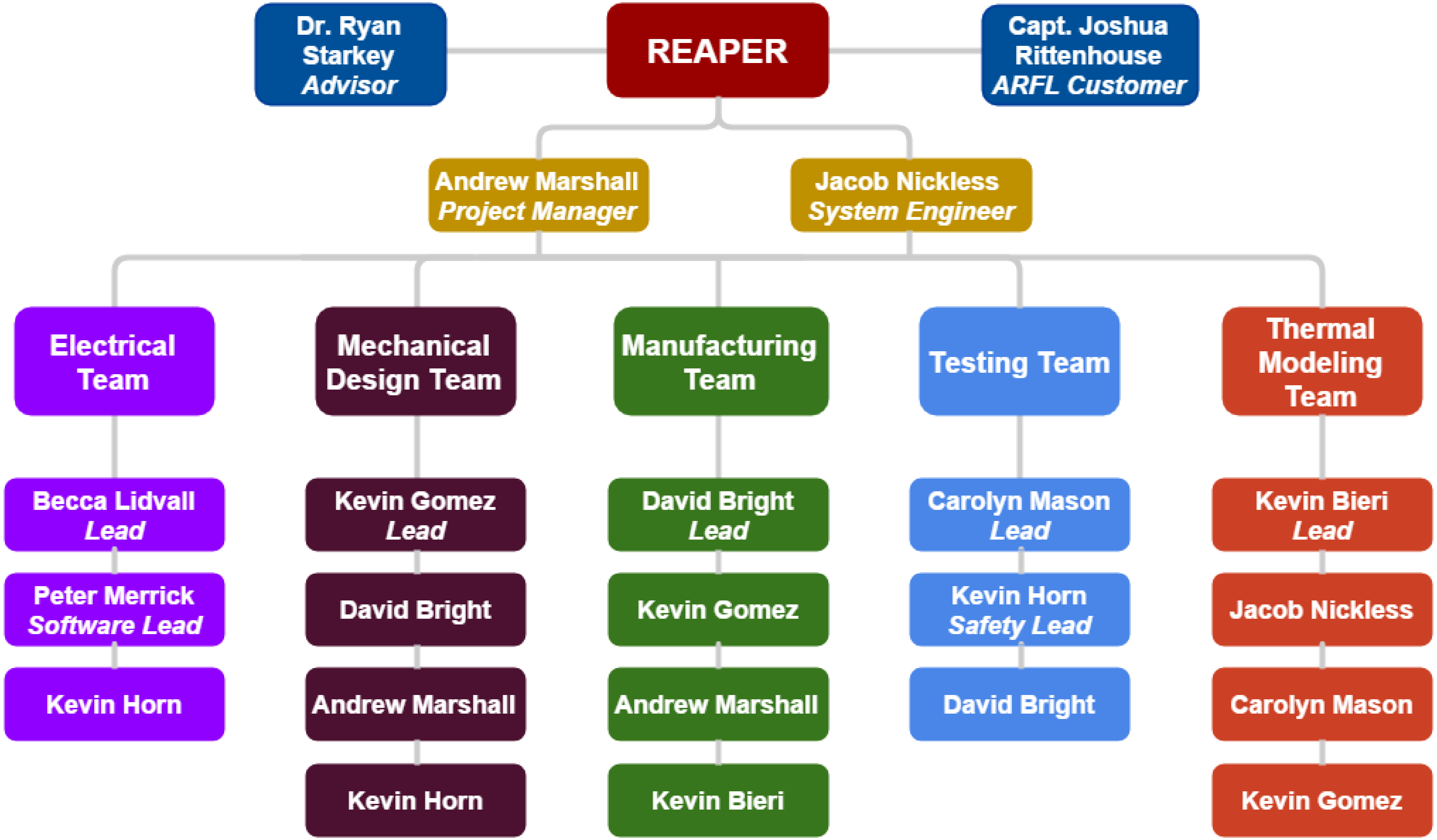


Project Implications

- Turbo Jet Recuperator Proof of Concept
  - Weight increase of **230%** paired with **4.3%** decrease in TSFC
  - Different manufacturing method and material selection
    - Reduce the weight of recuperator
- Recuperation on Mini-turbo jet turbine
  - Initial findings show recuperation may not be applicable to turbo jet
    - Possible application to shaft work engine
- Future Work
  - Hall Effects sensor debugging
  - Full stock engine characterization
  - Recuperator integration testing
  - Iteration of high level design → Heat Pipes

Project Management

Management Structure



Dr. Ryan Starkey
Advisor

REAPER

Capt. Joshua Rittenhouse
ARFL Customer

Andrew Marshall
Project Manager

Jacob Nickless
System Engineer

- **Electrical Team**
  - **Becca Lidvall** *Lead*
  - **Peter Merrick** *Software Lead*
  - **Kevin Horn**
- **Mechanical Design Team**
  - **Kevin Gomez** *Lead*
  - **David Bright**
  - **Andrew Marshall**
  - **Kevin Horn**
- **Manufacturing Team**
  - **David Bright** *Lead*
  - **Kevin Gomez**
  - **Andrew Marshall**
  - **Kevin Bieri**
- **Testing Team**
  - **Carolyn Mason** *Lead*
  - **Kevin Horn** *Safety Lead*
  - **David Bright**
- **Thermal Modeling Team**
  - **Kevin Bieri** *Lead*
  - **Jacob Nickless**
  - **Carolyn Mason**
  - **Kevin Gomez**

Management - Approach

- Weekly Meetings
  - Prepared agenda based on previous meetings to cover
  - Summarize meeting/action items

- Centralized team communication with GroupMe messenger
  - Extremely effective for real-time updates
  - Provided scheduling ability for testing-day attendance RSVP’s

- Utilized Microsoft Project to track project progress
  - Extremely versatile and powerful project tracking

- Centralized budget and financial obligations to CFO
  - Streamlined purchases and provided flexibility with last minute purchases

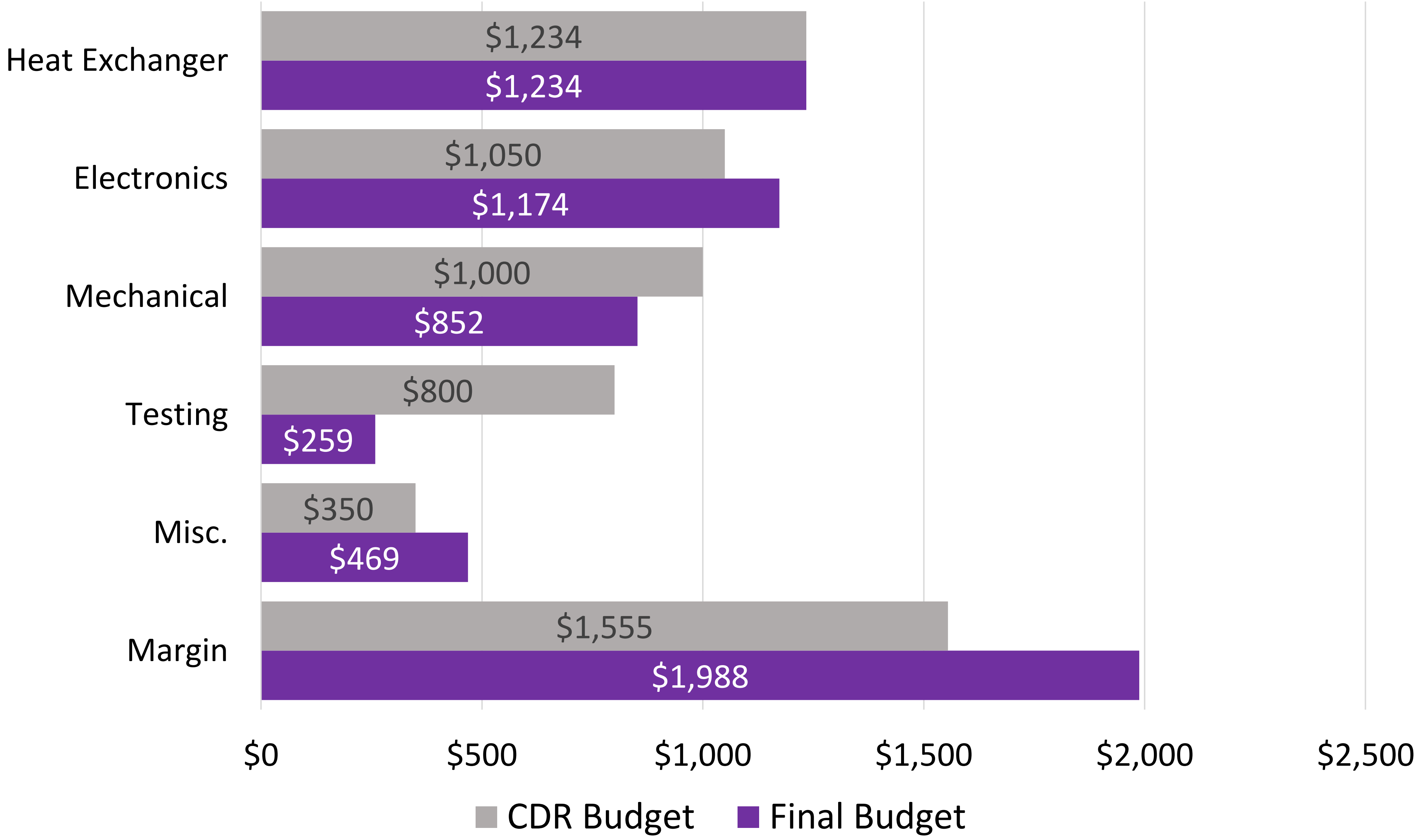
Management – Lessons Learned

- Weekly Meetings
  - Having an agenda is most effective
  - Keep track of and follow up on action items frequently
  - Ensure team members always have a task to work on

- Microsoft Project
  - Should have been continuously updated
  - Sometimes difficult to use

- JetCat
  - Unreliable with impractical lead times

Budget - Final



CDR Budget
- Budget: $5,975
- Expenses: $4,420

Final Budget
- Spent: $3,987

Difference from CDR:
- $446 unspent

EEF Contribution:
- $1,131.20

Engine purchase:
- $2,240

Project Cost

Assumptions:

$65,000 annual salary of entry-level aerospace engineers

Full Time Equivalent of 2080 hours/year

+Overhead rate of **200%**

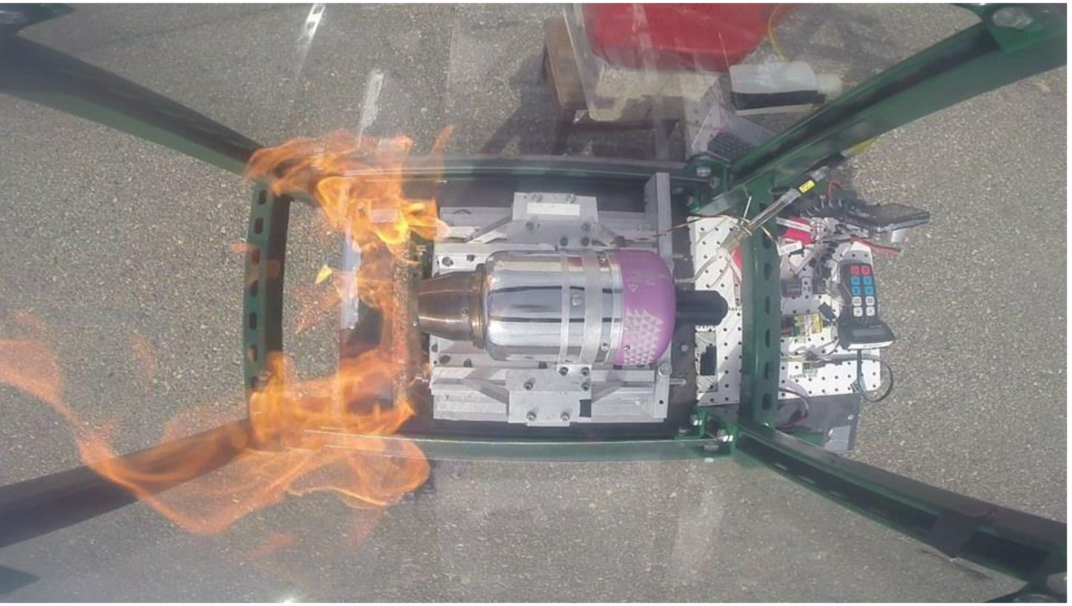
Total Hours	**4169.4 hours**
Total Direct Labor Cost	**$130,293.75**
Overhead Rate	**200%**
Overhead Cost	**$260,587.50**
Material Cost	**$7,000**
Total Industry Cost	**$397,881.25**

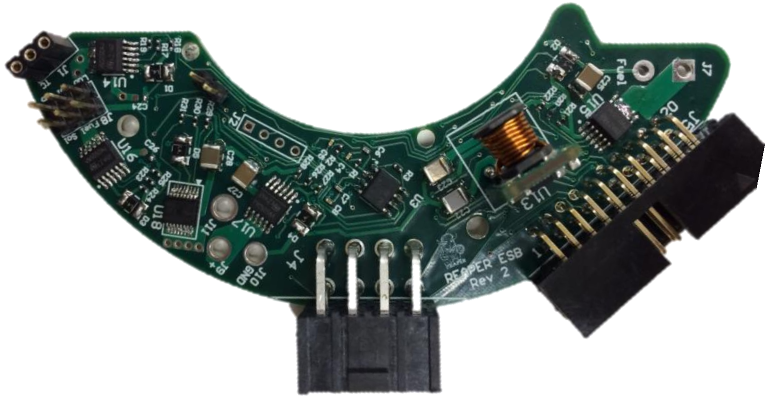
Acknowledgements

REAPER would like to thank:

- The Project Advisory Board
- Professor Ryan Starkey
- Course Assistant, Thomas Green
- Trudy Schwartz, Bobby Hodgkinson, Matt Rhode
- Previous engine teams (MEDUSA, COMET)
- Boulder Municipal Airport
- Air Force Research Lab

Questions?





Backup Slides

Mechanical Backup Slides

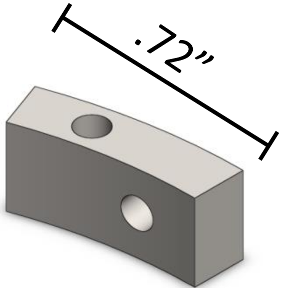
Full Mechanical System

Total Added Weight: 3.36 kg

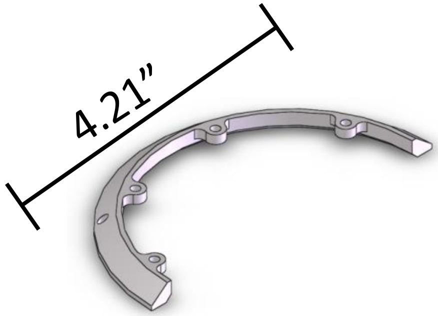
234 % Mass Increase

Different Materials or total redesign needed to meet 50% mass increase requirement (130% increase all Titanium)

Other Mechanical Components

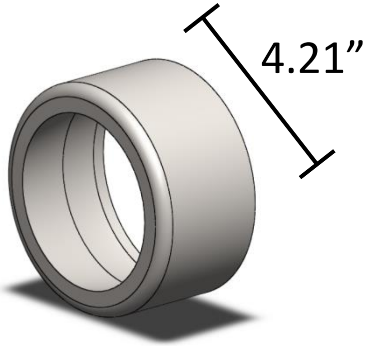


Mounting Blocks (x4)
4.5 g

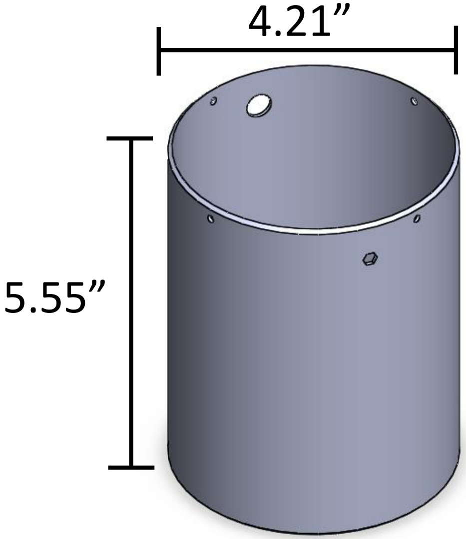


Mount Brackets (x2)
44.5 g

Forward Ring
220 g

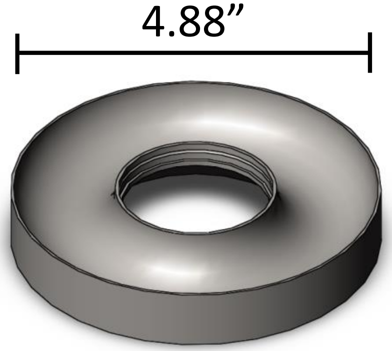


Nozzle Shroud

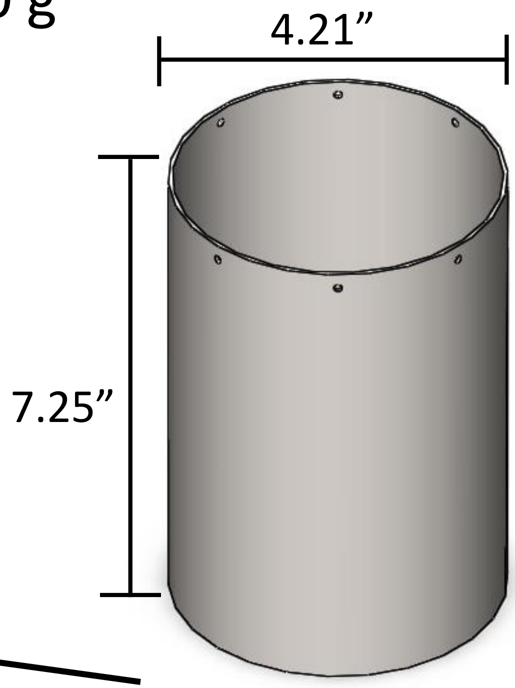


Inner Casing

1.68 kg



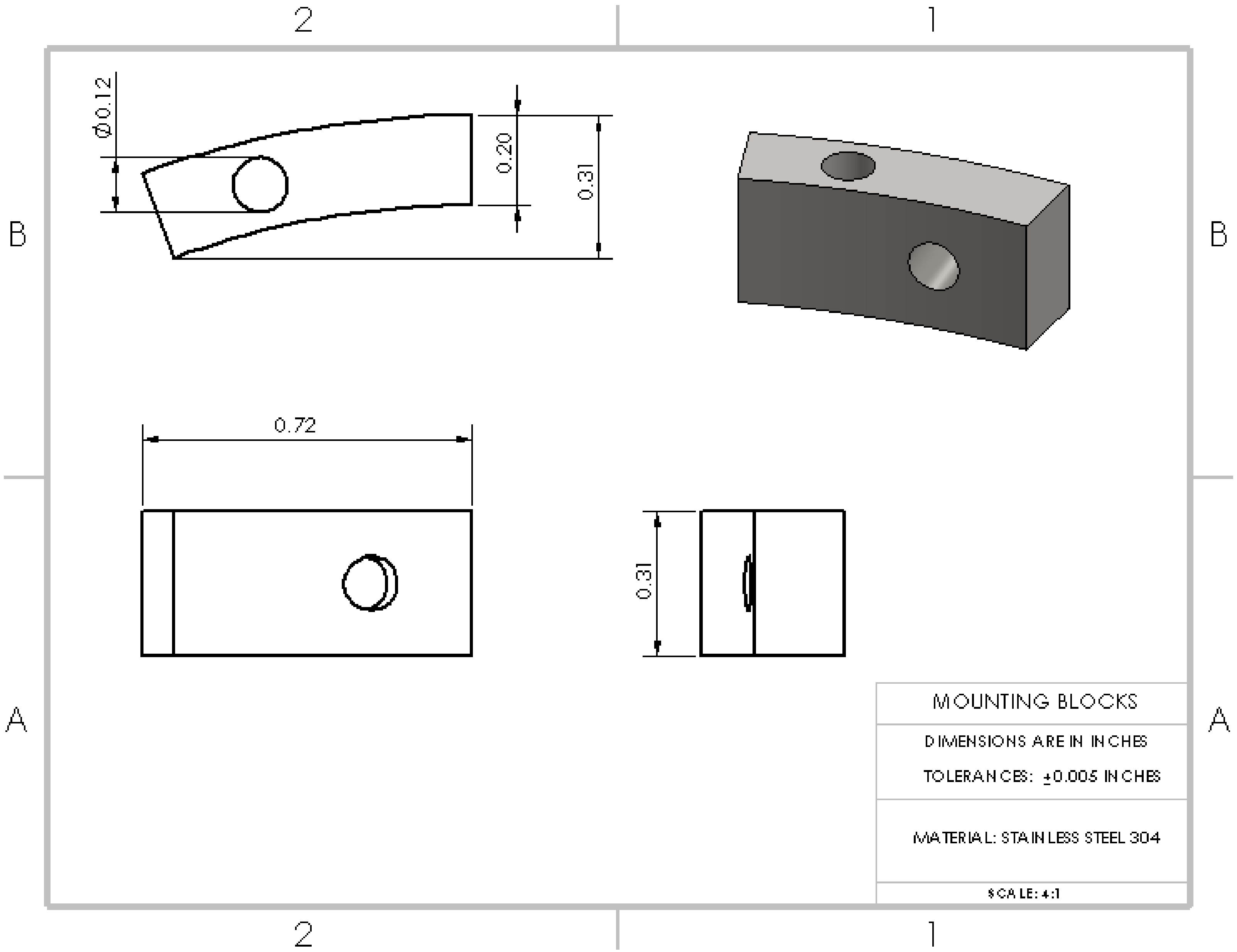
End Cap



Outer Casing

1.33 kg

Mounting Blocks: Dimensioned Drawing



MOUNTING BLOCKS

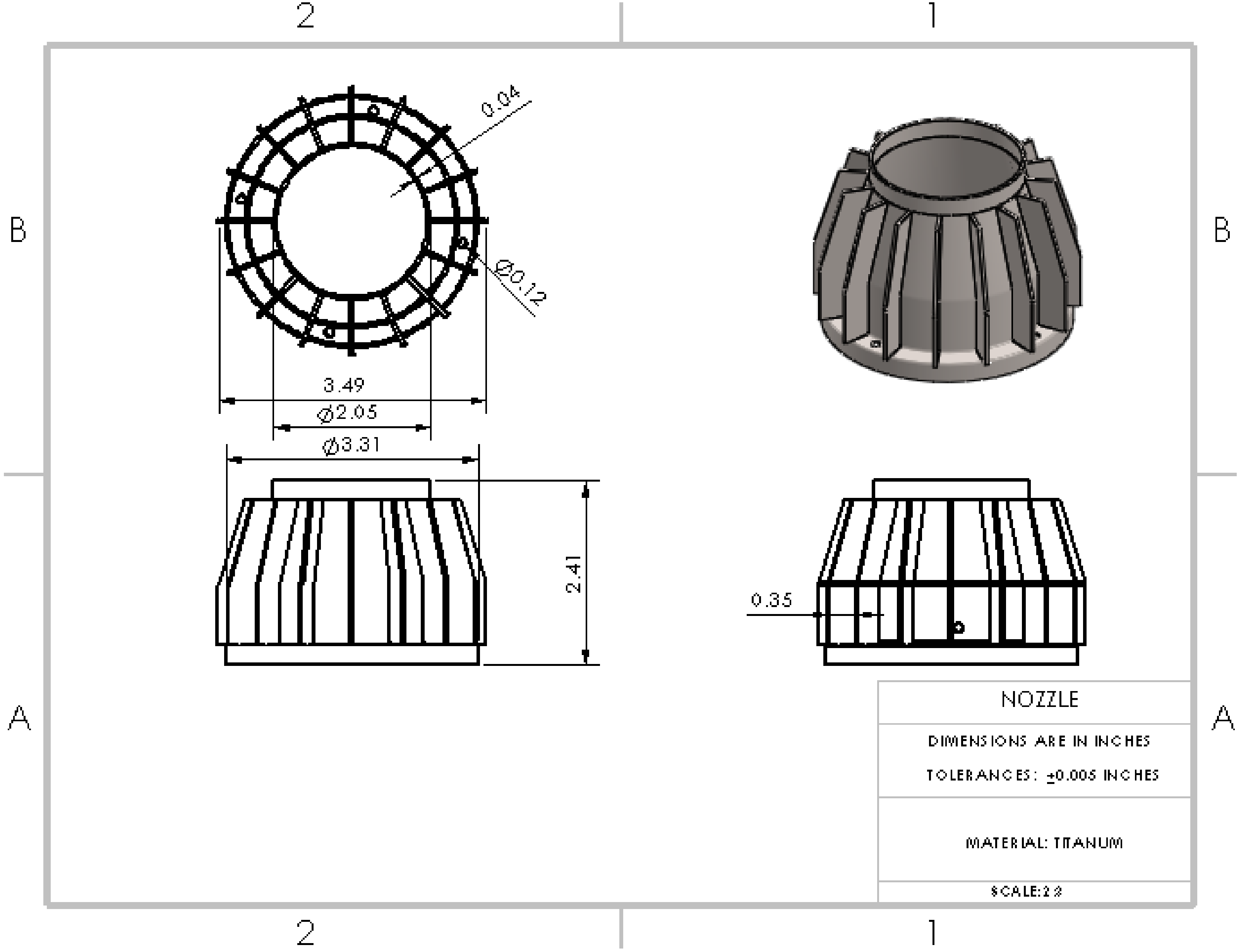
DIMENSIONS ARE IN INCHES

TOLERANCES: ±0.005 INCHES

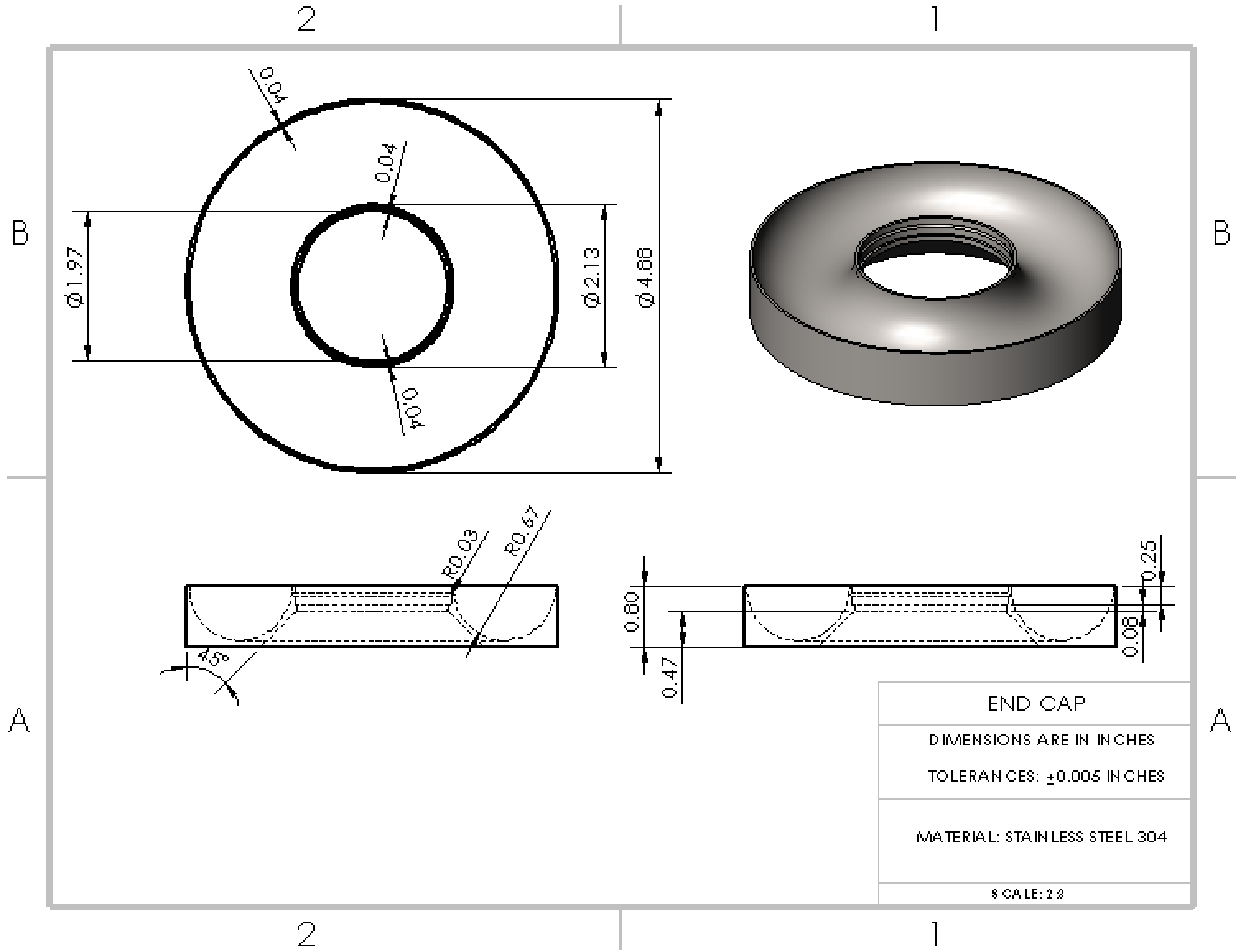
MATERIAL: STAINLESS STEEL 304

SCALE: 4:1

Nozzle/Heat Exchanger: Dimensioned Drawing



End Cap: Dimensioned Drawing



END CAP

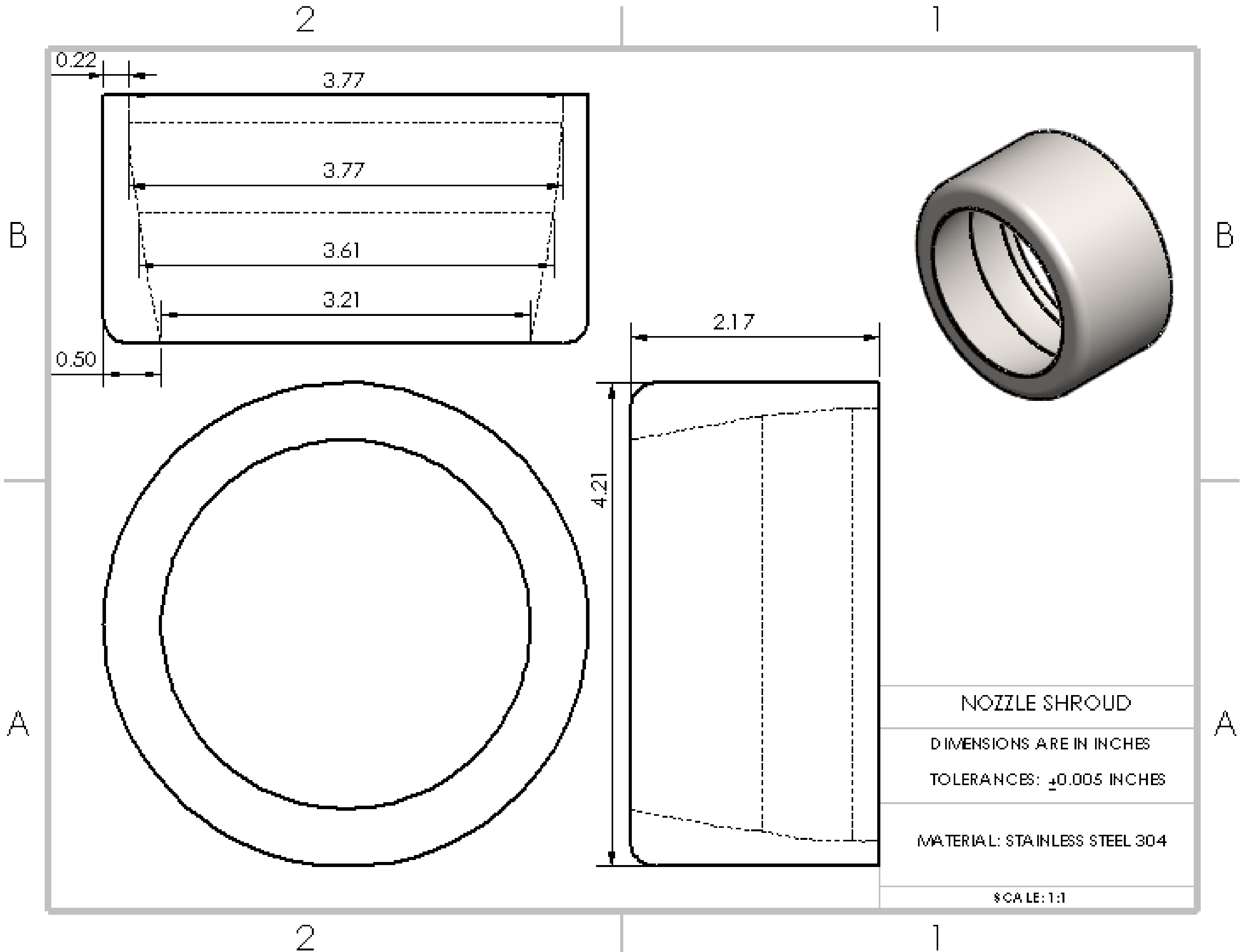
DIMENSIONS ARE IN INCHES

TOLERANCES: ±0.005 INCHES

MATERIAL: STAINLESS STEEL 304

SCALE: 1:2

Nozzle Shroud: Dimensioned Drawing



NOZZLE SHROUD

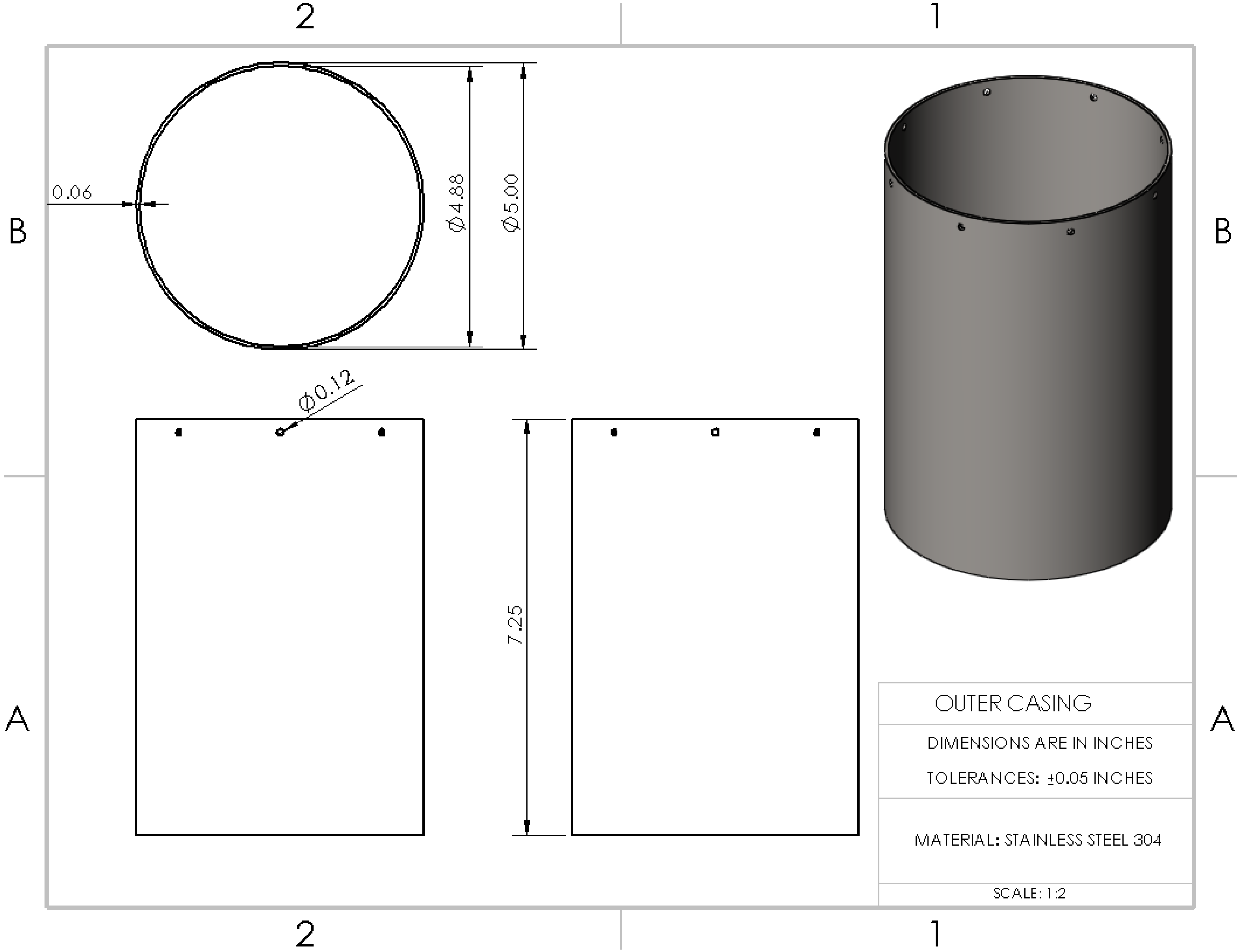
DIMENSIONS ARE IN INCHES

TOLERANCES: ±0.005 INCHES

MATERIAL: STAINLESS STEEL 304

SCALE: 1:1

Outer Casing: Dimensioned Drawing



OUTER CASING

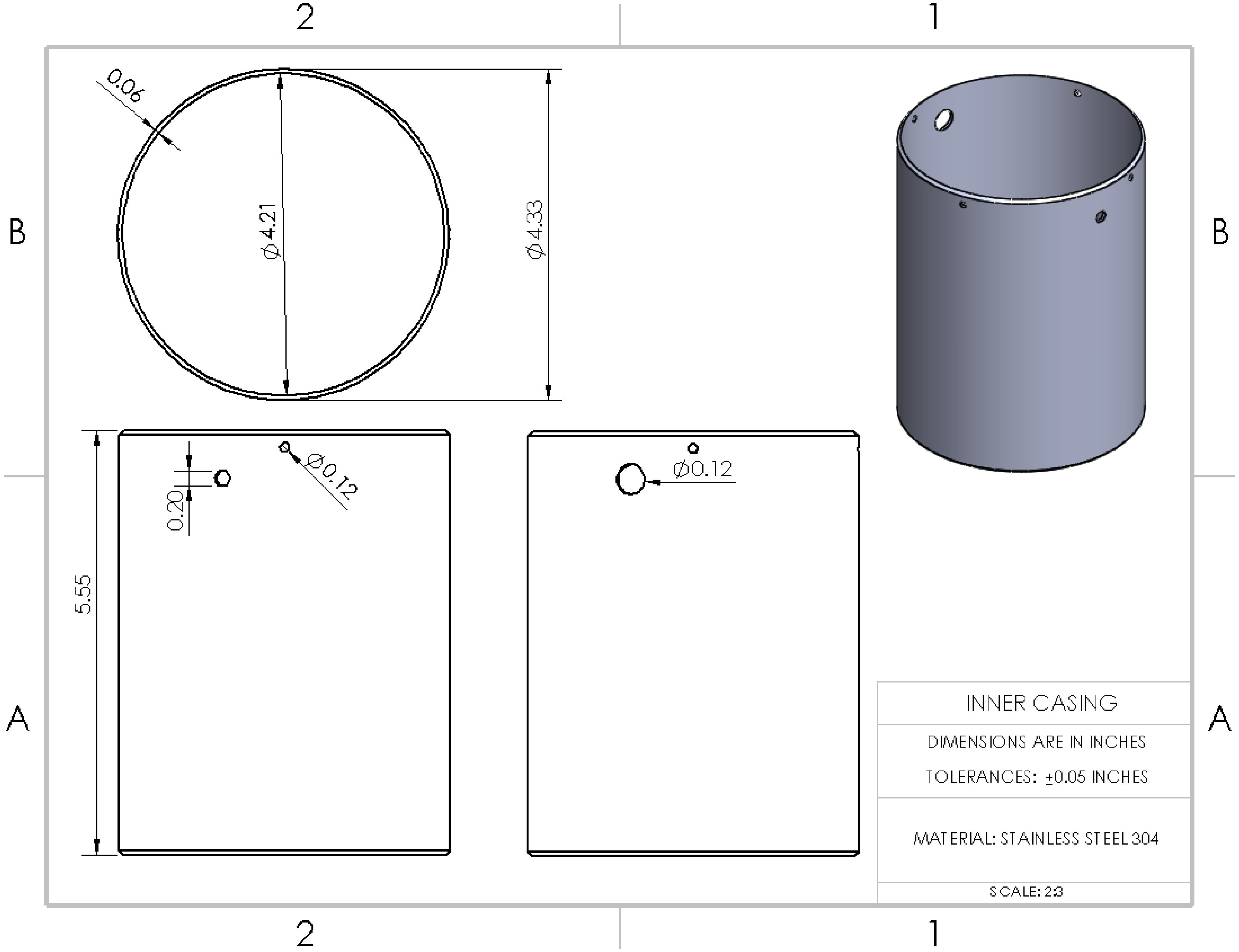
DIMENSIONS ARE IN INCHES

TOLERANCES: ±0.05 INCHES

MATERIAL: STAINLESS STEEL 304

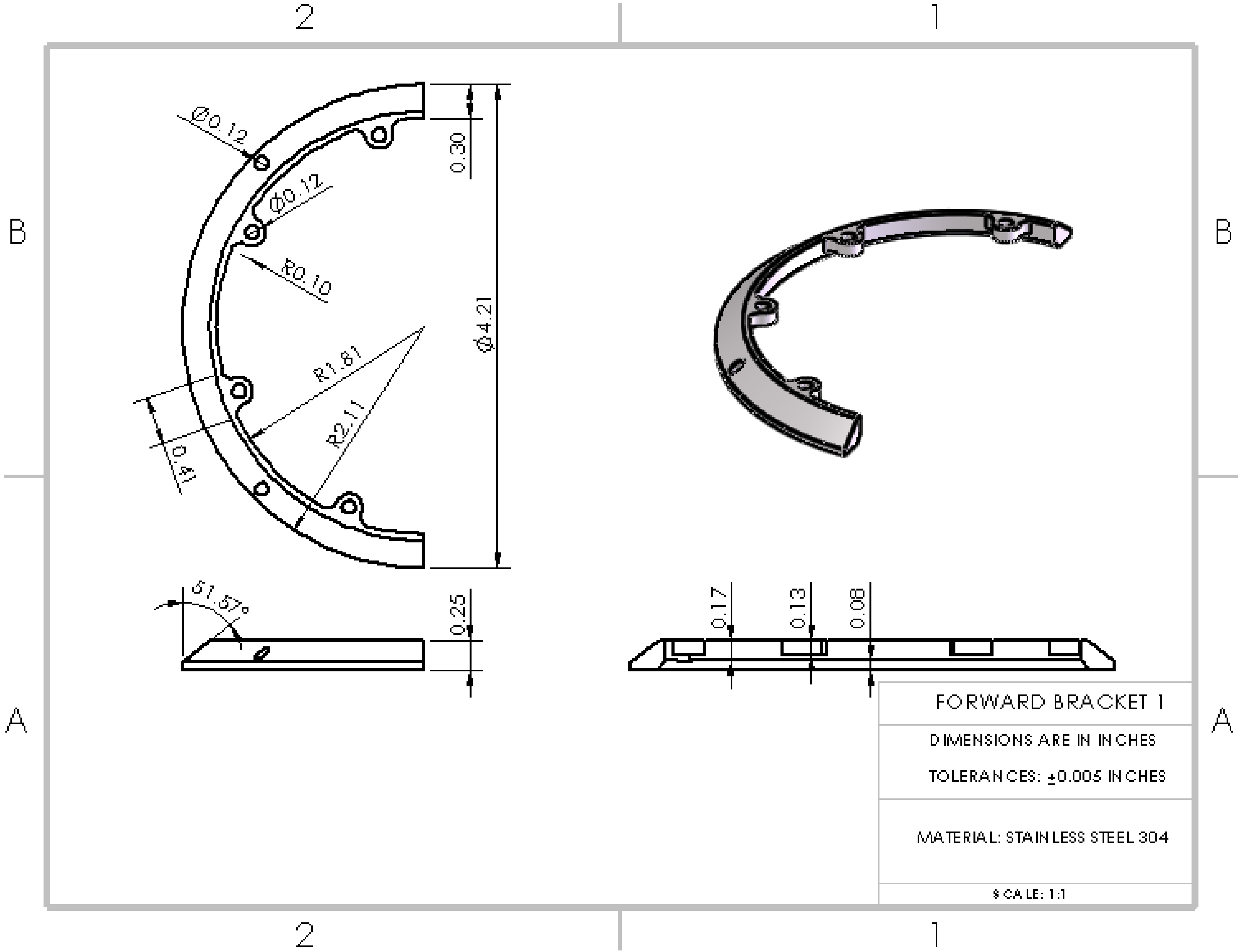
SCALE: 1:2

Inner Casing: Dimensioned Drawing



INNER CASING
DIMENSIONS ARE IN INCHES
TOLERANCES: ±0.05 INCHES
MATERIAL: STAINLESS STEEL 304
SCALE: 2:3

Forward Brackets: Dimensioned Drawing



FORWARD BRACKET 1

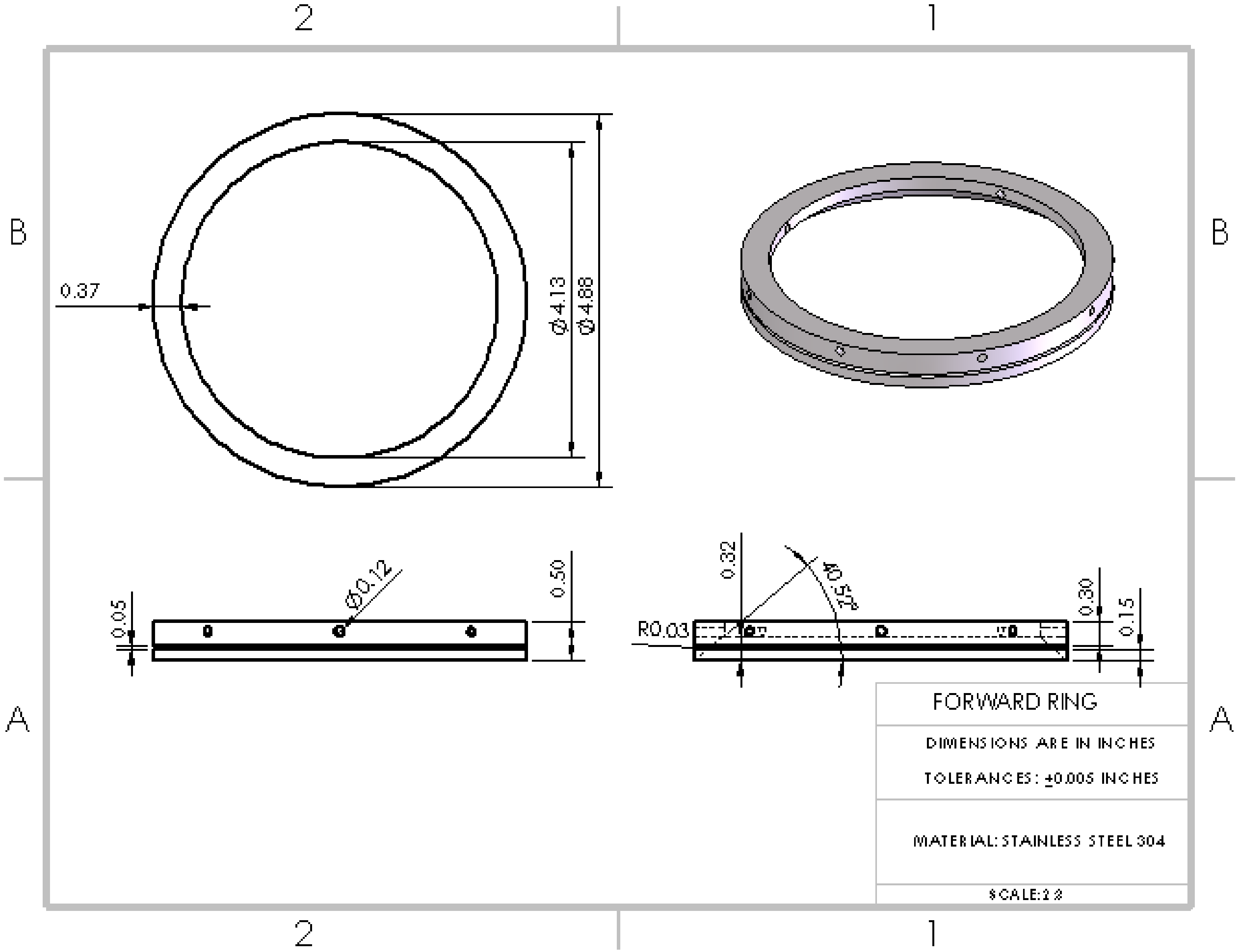
DIMENSIONS ARE IN INCHES

TOLERANCES: ±0.005 INCHES

MATERIAL: STAINLESS STEEL 304

SCALE: 1:1

Forward Ring: Dimensioned Drawing



FORWARD RING

DIMENSIONS ARE IN INCHES

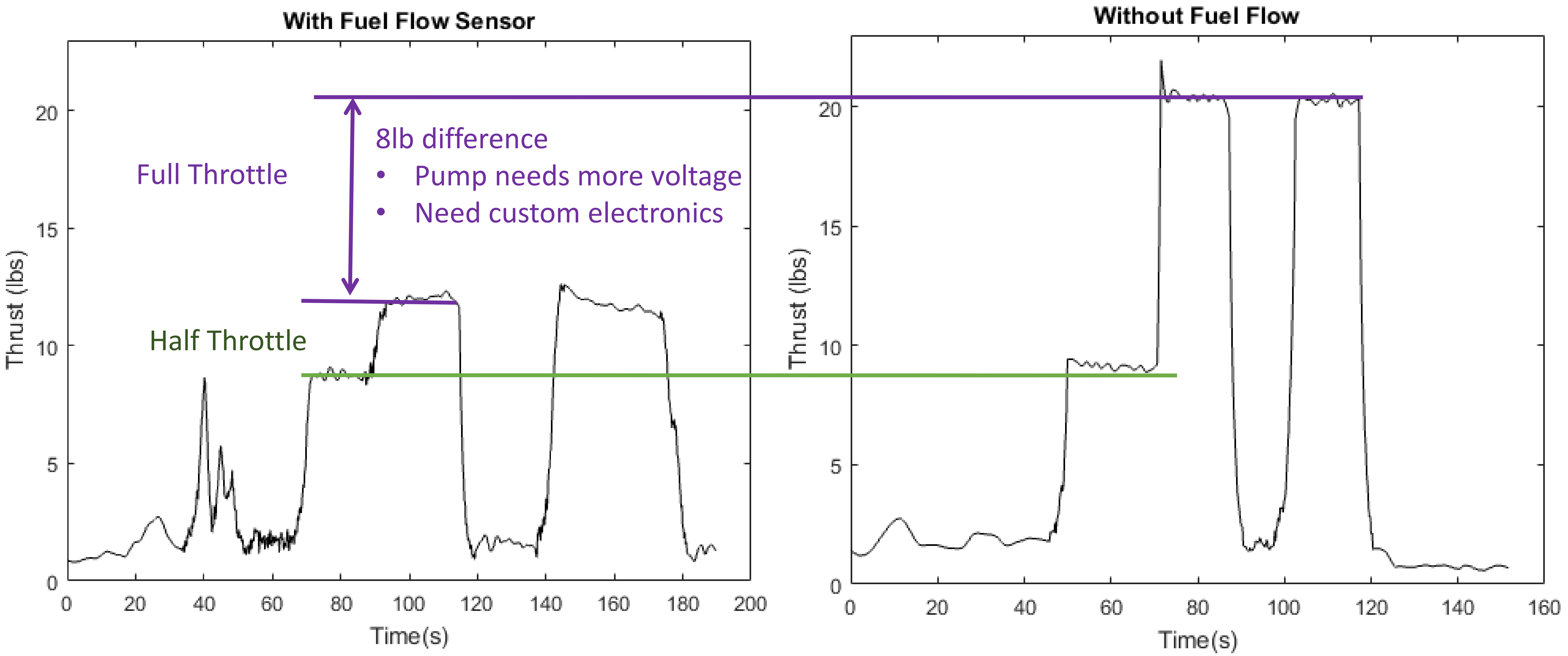
TOLERANCES: ±0.005 INCHES

MATERIAL: STAINLESS STEEL 304

SCALE:1:2

Electrical Backup Slides

Custom EE Motivation: Stock Engine Thrust Data



Full Throttle

8lb difference
- Pump needs more voltage
- Need custom electronics

Half Throttle

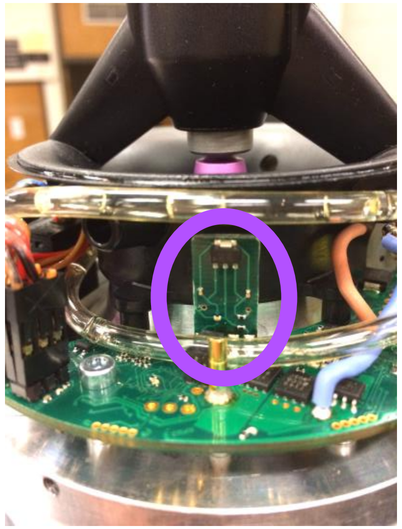
Max RPM = 109,500

Max RPM = 130,000

Major Sensors - Design

Sensor	Measures	Error	Use	Error Effect
Thermocouple	Exhaust Gas Temp	±3 °C	Engine Status during Test	Low
Hall Effect	Shaft RPM	±0.5%	Engine Stats during Test	Low
Load Cell	Engine Thrust	±3%	Thrust Data for Analysis	High
Fuel Flow	Fuel Flow	±1%	Fuel Flow Data for Analysis	Medium

Thermocouple



Hall Effect

Fuel Flow

Load Cell

Power Budget, Major Actuators

Actuator	Duty Cycle	PWM Frequency	Approx. Voltage	Current (approx.)**	Power	Time On (5 min test)	Energy Draw
Starter Motor	25%*	20 Hz	2.5 V	4.25 A	10.6 W	2 min	142 mAh
Glow Plug	27%*	20 Hz	2.7 V	5.5 A	14.9 W	0.50 min	46 mAh
Lubrication Solenoid	100%	20 Hz	9.9 V	0.3 A	3.0 W	5 min	25 mAh
Fuel Solenoid	100%	20 Hz	9.9 V	0.3 A	3.0 W	5 min	25 mAh
Fuel Pump	20%*	20 Hz	2.0 V	2.0 A	4.0 W	4 min	133 mAh

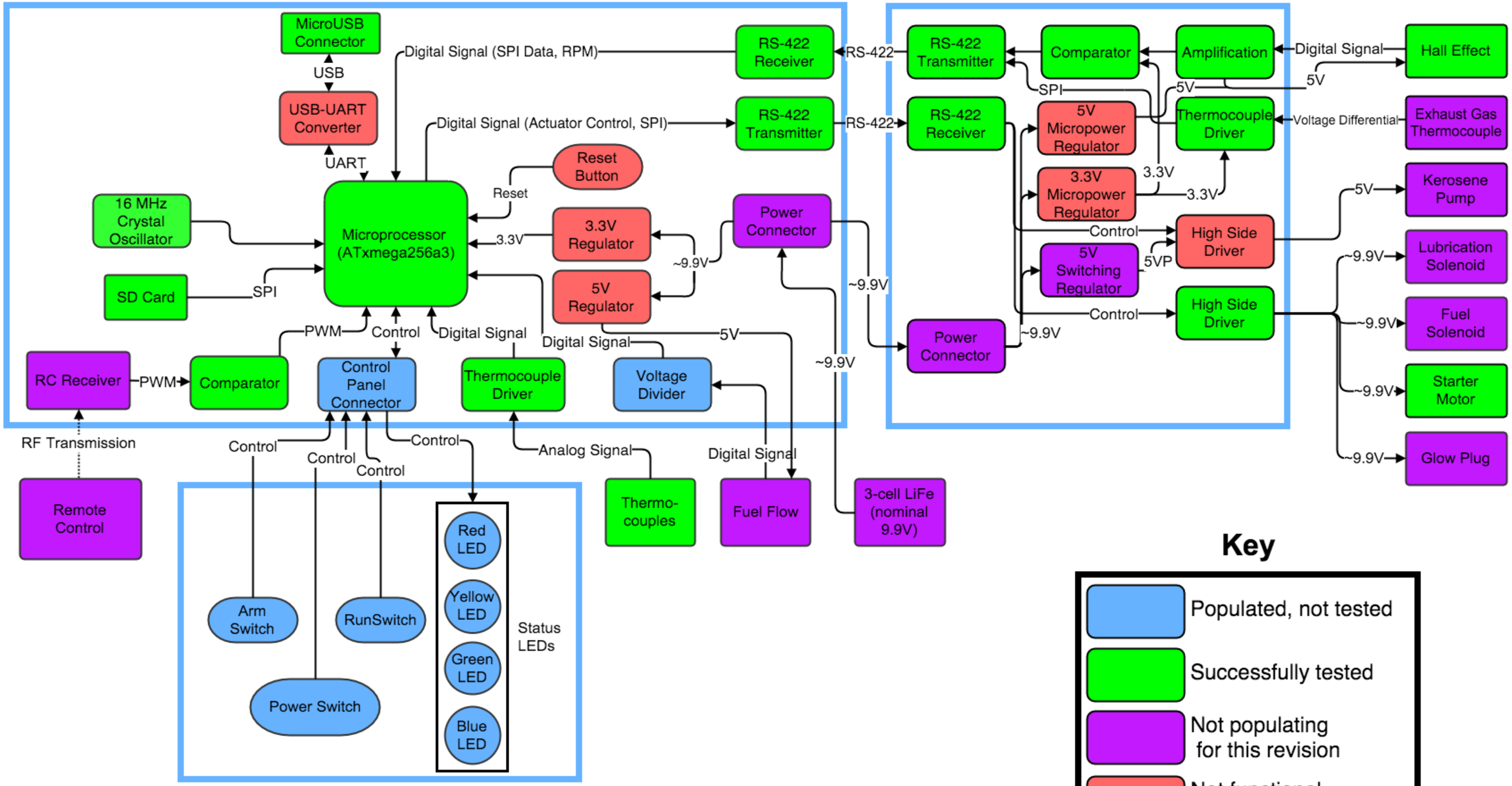
* Duty cycle changes during time on, so average listed

** Approximation, not measured directly during testing

EE: Rev. 1 Final Status

Engine Control Unit

Engine Sensor Board



MicroUSB Connector
USB
USB-UART Converter
UART
Digital Signal (SPI Data, RPM)
Digital Signal (Actuator Control, SPI)
RS-422 Receiver
RS-422 Transmitter
RS-422
16 MHz Crystal Oscillator
Microprocessor (ATxmega256a3)
Reset Button
Reset
3.3V
3.3V Regulator
5V Regulator
~9.9V
Power Connector
SD Card
SPI
PWM
Control
Digital Signal
5V
RC Receiver
Comparator
Control Panel Connector
Thermocouple Driver
Voltage Divider
RF Transmission
Remote Control
Analog Signal
Thermo-couples
Fuel Flow
3-cell LiFe (nominal 9.9V)
Arm Switch
RunSwitch
Power Switch
Red LED
Yellow LED
Green LED
Blue LED
Status LEDs
RS-422 Transmitter
RS-422 Receiver
Comparator
Amplification
Hall Effect
5V Micropower Regulator
3.3V Micropower Regulator
5V Switching Regulator
5VP
Thermocouple Driver
Voltage Differential
Exhaust Gas Thermocouple
High Side Driver
High Side Driver
Power Connector
Kerosene Pump
Lubrication Solenoid
Fuel Solenoid
Starter Motor
Glow Plug

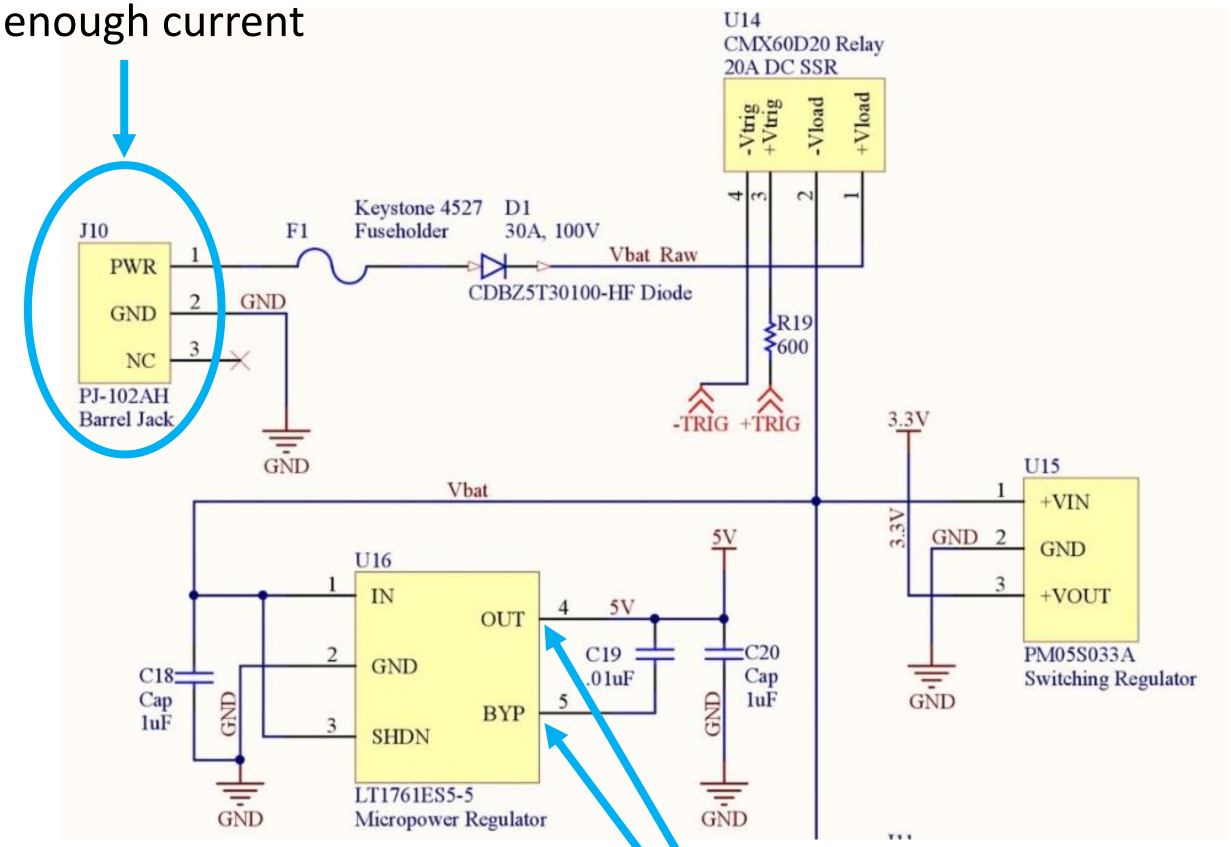
Control Panel

Key

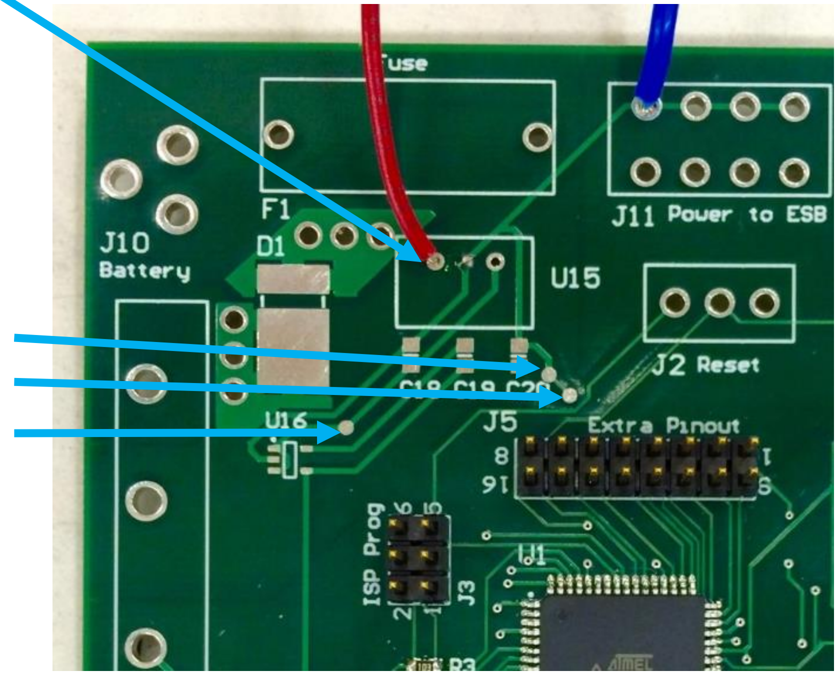
🟦	Populated, not tested
🟩	Successfully tested
🟪	Not populating for this revision
🟥	Not functional, needs fix

Engine Electronics: Power Issues Rev. 1

Can't source enough current



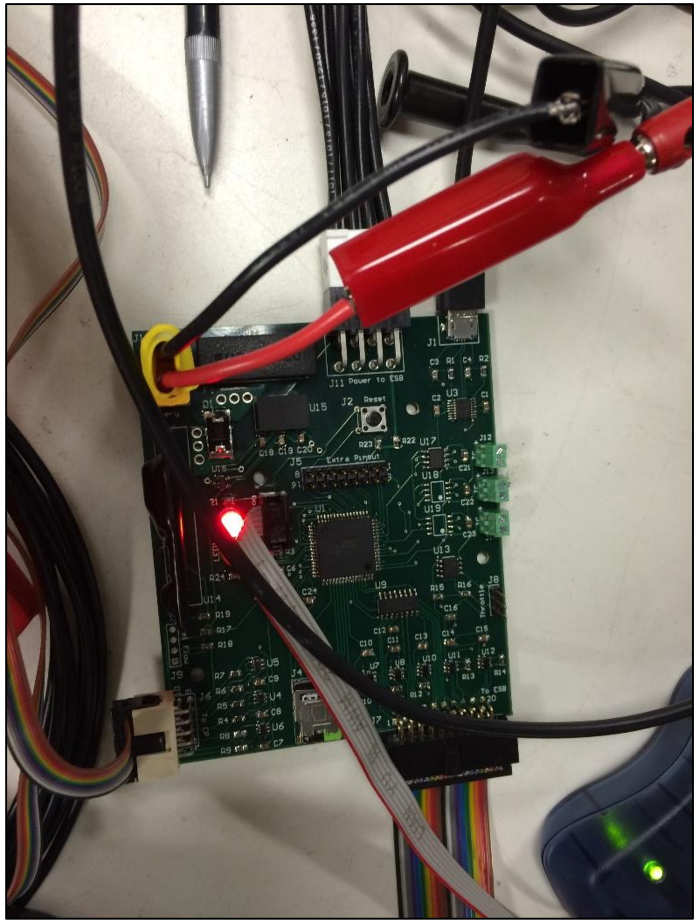
Power Plane Issue



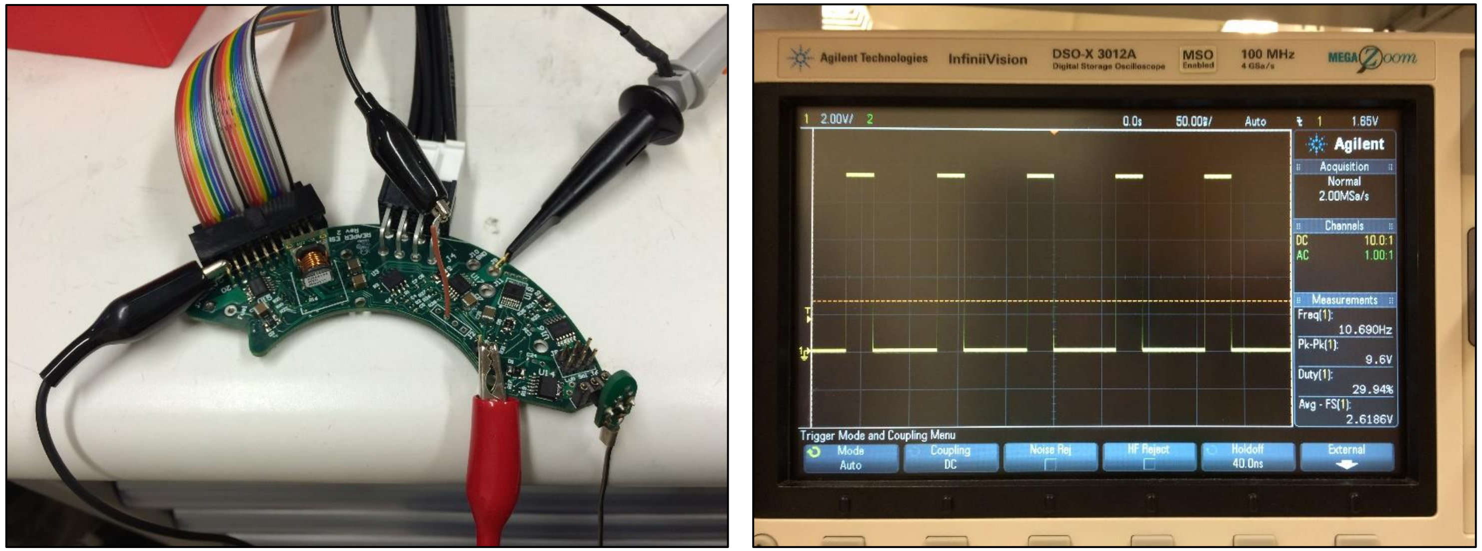
Incorrectly Designed Vias

Swapped pins on footprint

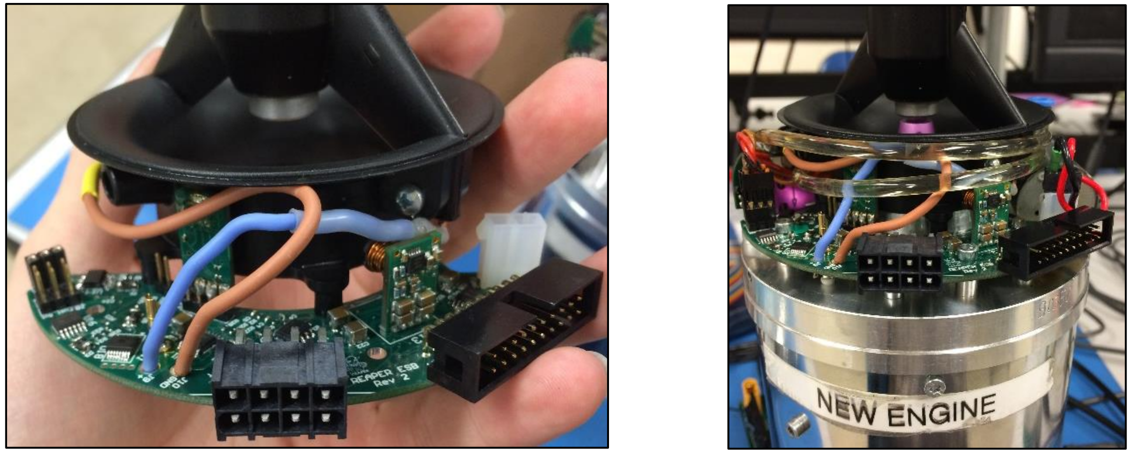
Engine Actuator Testing



Individual Components
Verification - Success

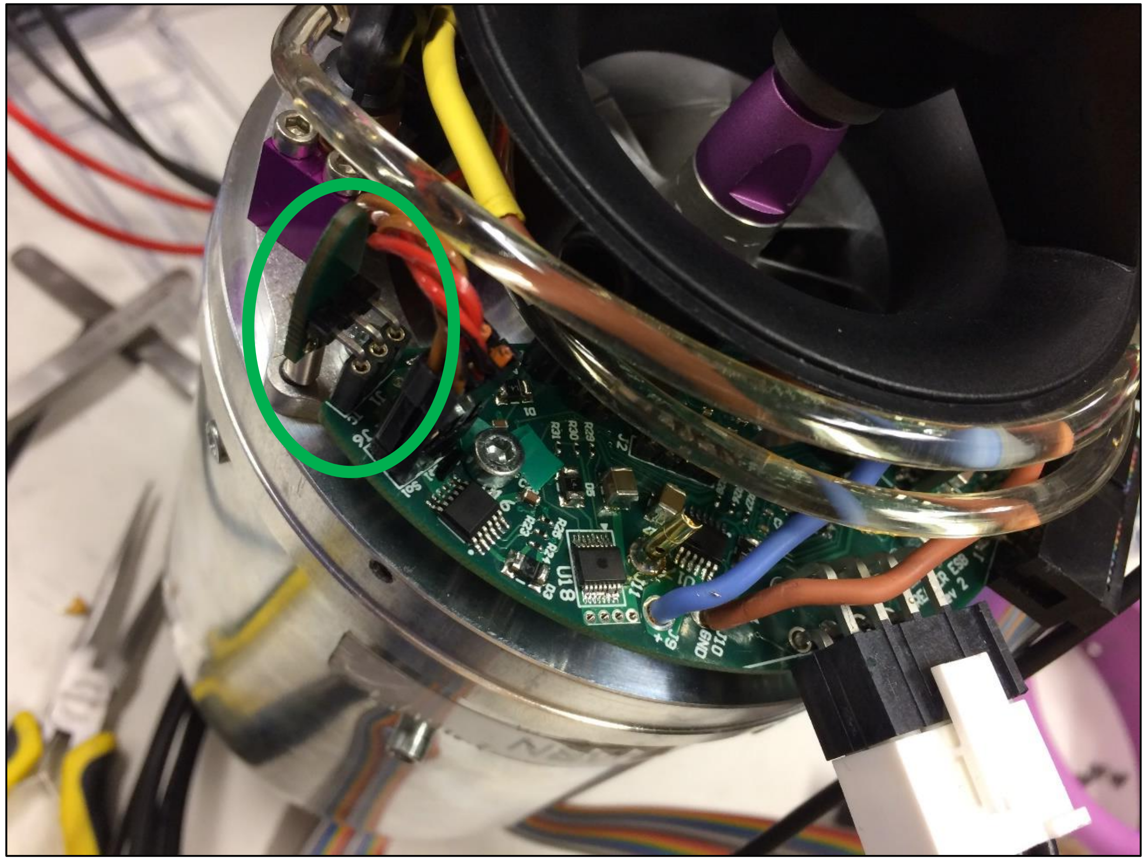


Actuator Signals Verification - Success

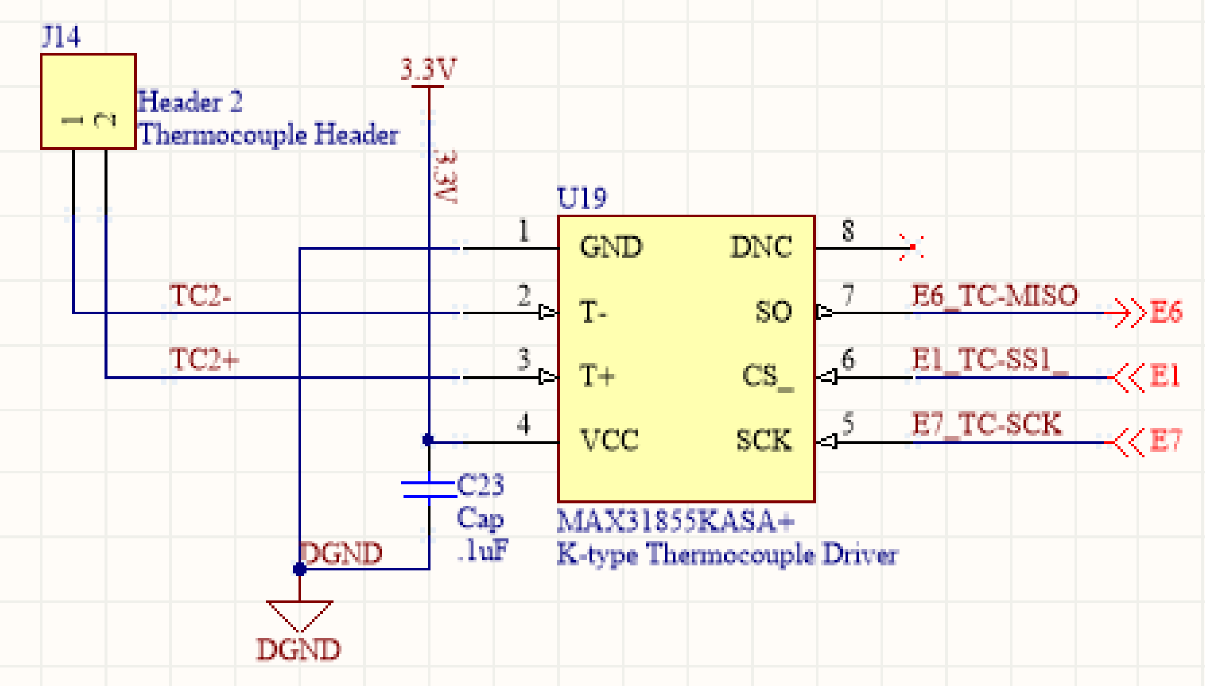


Actuators Integrated and Individually Tested - Success

Engine Sensor Testing - Thermocouple



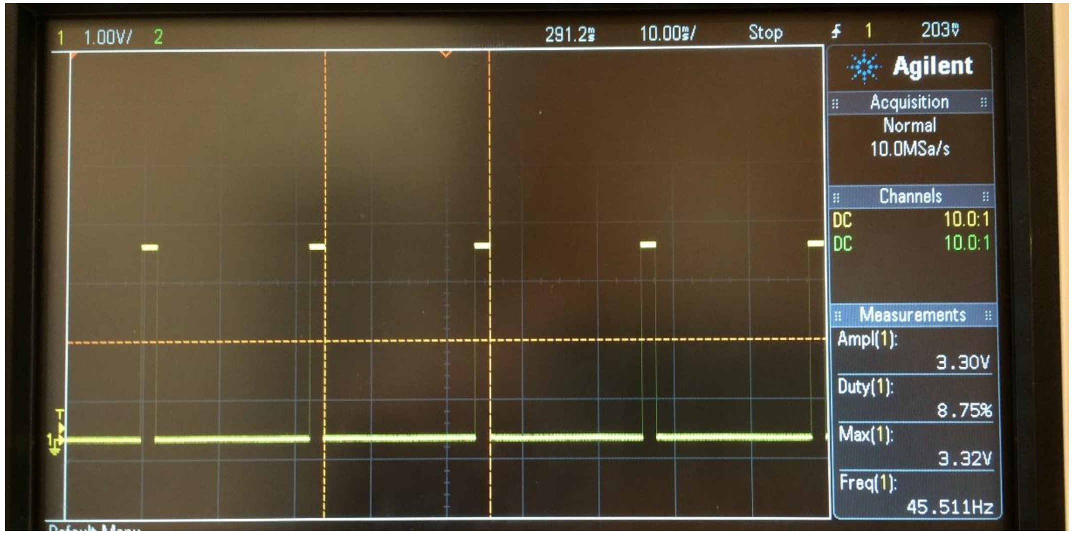
Thermocouple Integration and Testing - Success



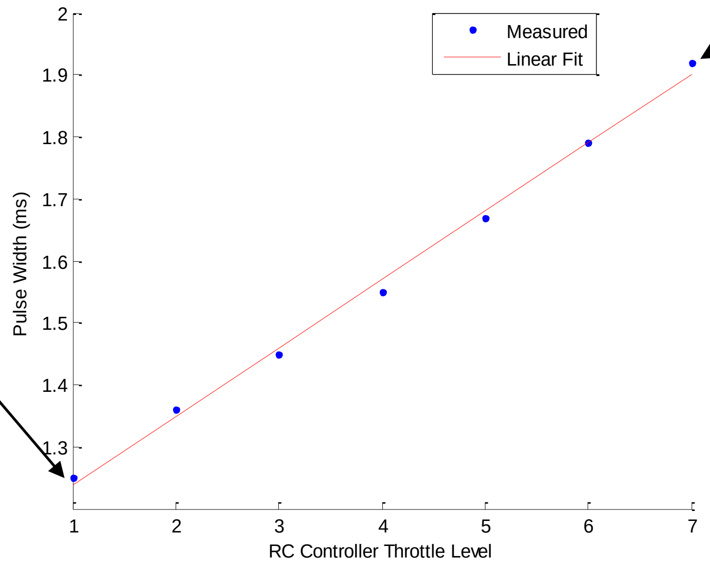
Schematic for Thermocouple circuit

Component Validation – RC Receiver

Low Throttle: 5.77% Duty Cycle (1.26 ms pulse)



Full Throttle: 8.75% Duty Cycle (1.92 ms pluse)



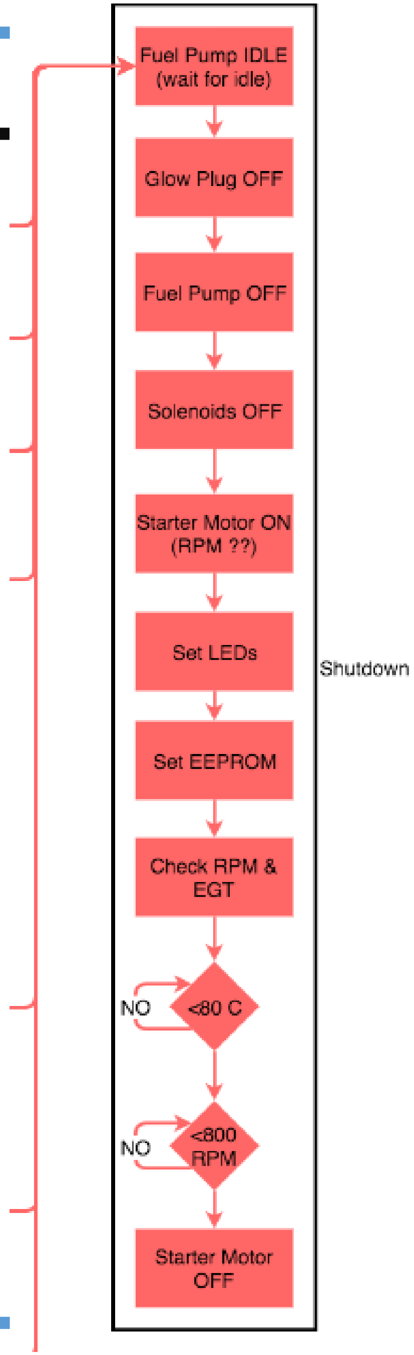
*Plot Credit: MEDUSA PFR

Very small difference – required more timers and interrupt for high fidelity, but did not have time to test after completion of software changes

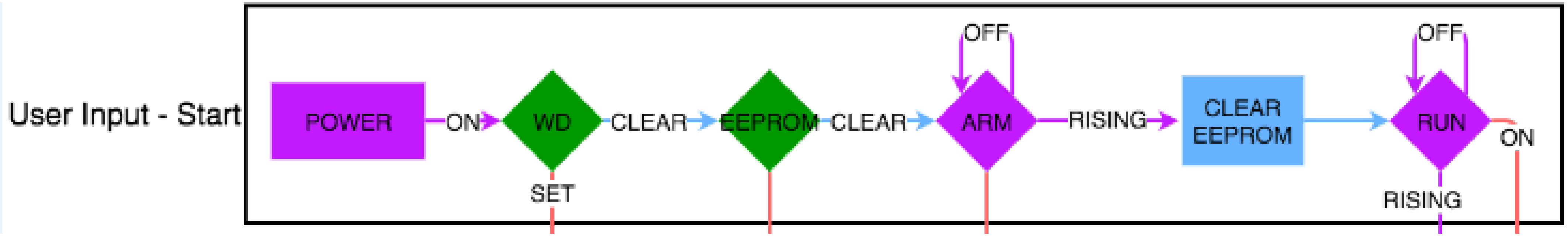
Software Backup Slides

Shutdown

Validated using simulated inputs and real world testing

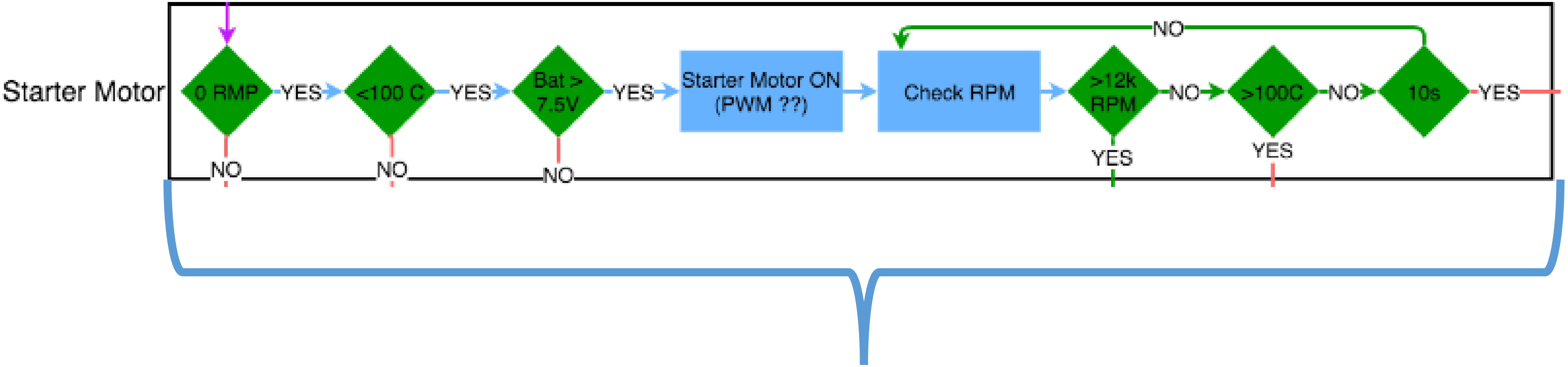


Startup Software



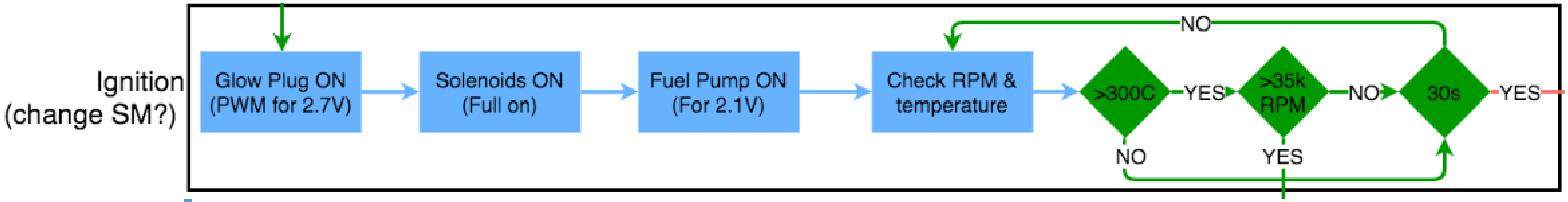
Validated using simulated inputs and real world testing

Warmup Software



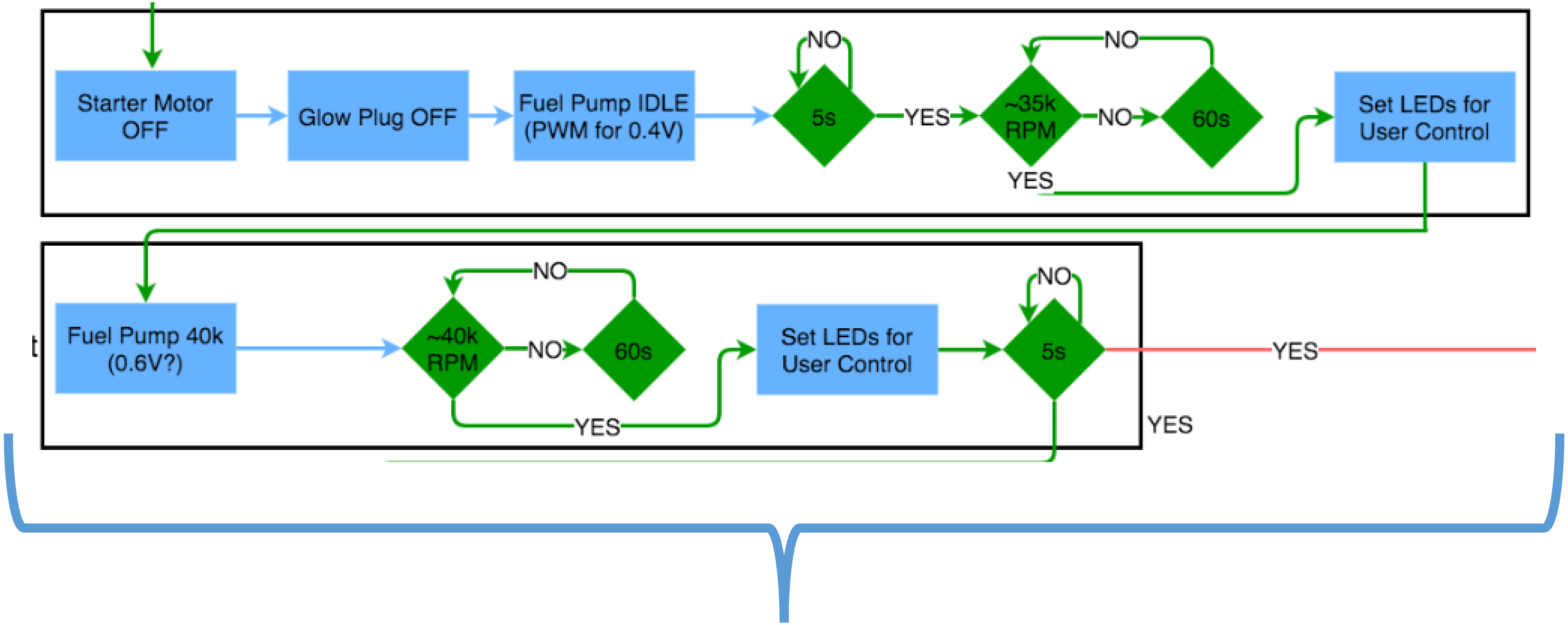
Validated using simulated inputs and real world testing

Ignition



Validated using simulated inputs

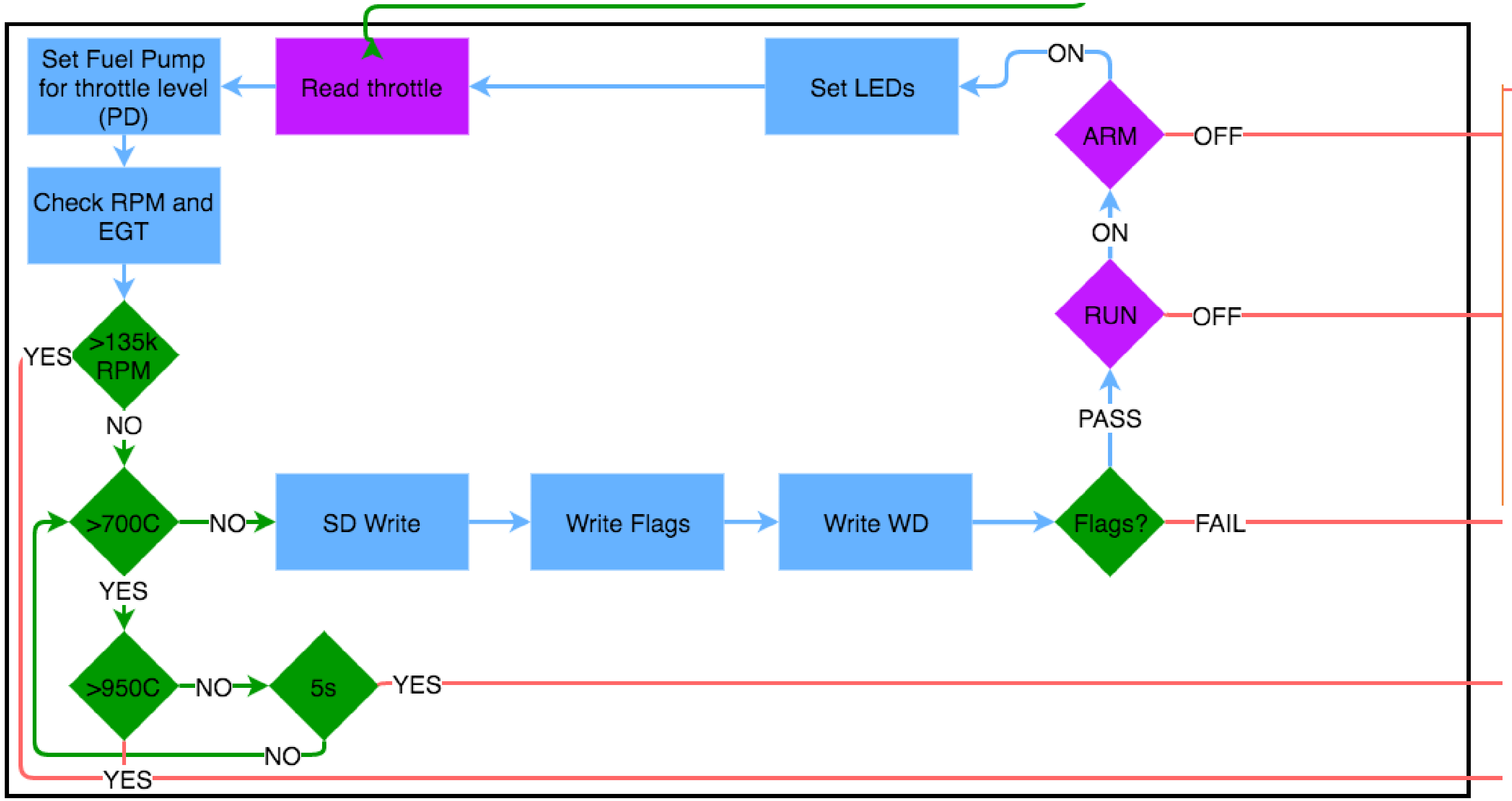
Control Testing

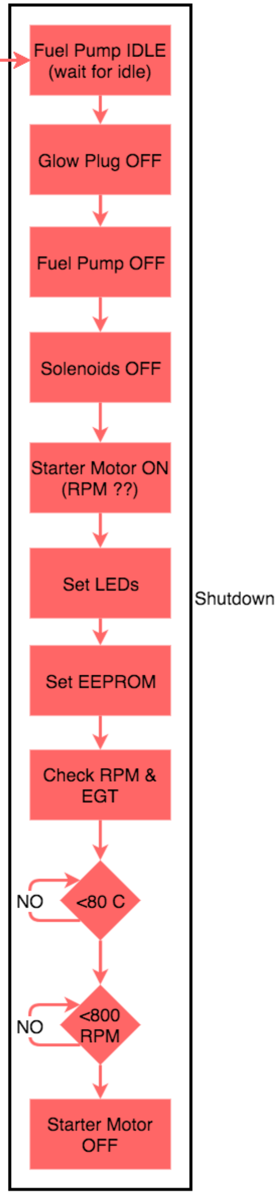


Validated using simulated Inputs

Software Flow

Start Signal	Wait for signals fr
Warmup	Spin star compres
Ignition	Heat glov temperat
Idle Test	Set fuel p until idle
Running Loop (Throttle Input)	Set fuel pump to reach RPM correlating with throttle level; check safeties and switches
Shutdown Sequence	Run starter motor until engine is below 80ºC





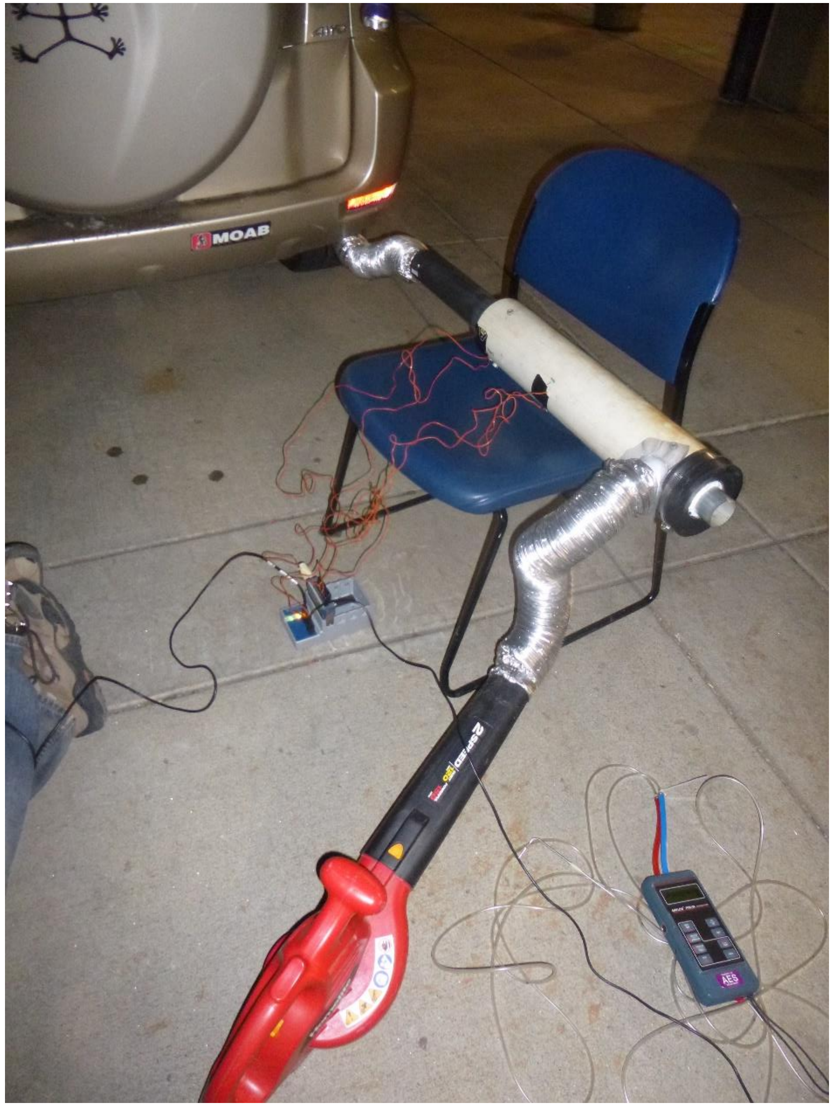
KEY

🟪	User Input
🟥	Shutdown
🟦	Processor Action
◆	Decision Point

Testing Backup Slides

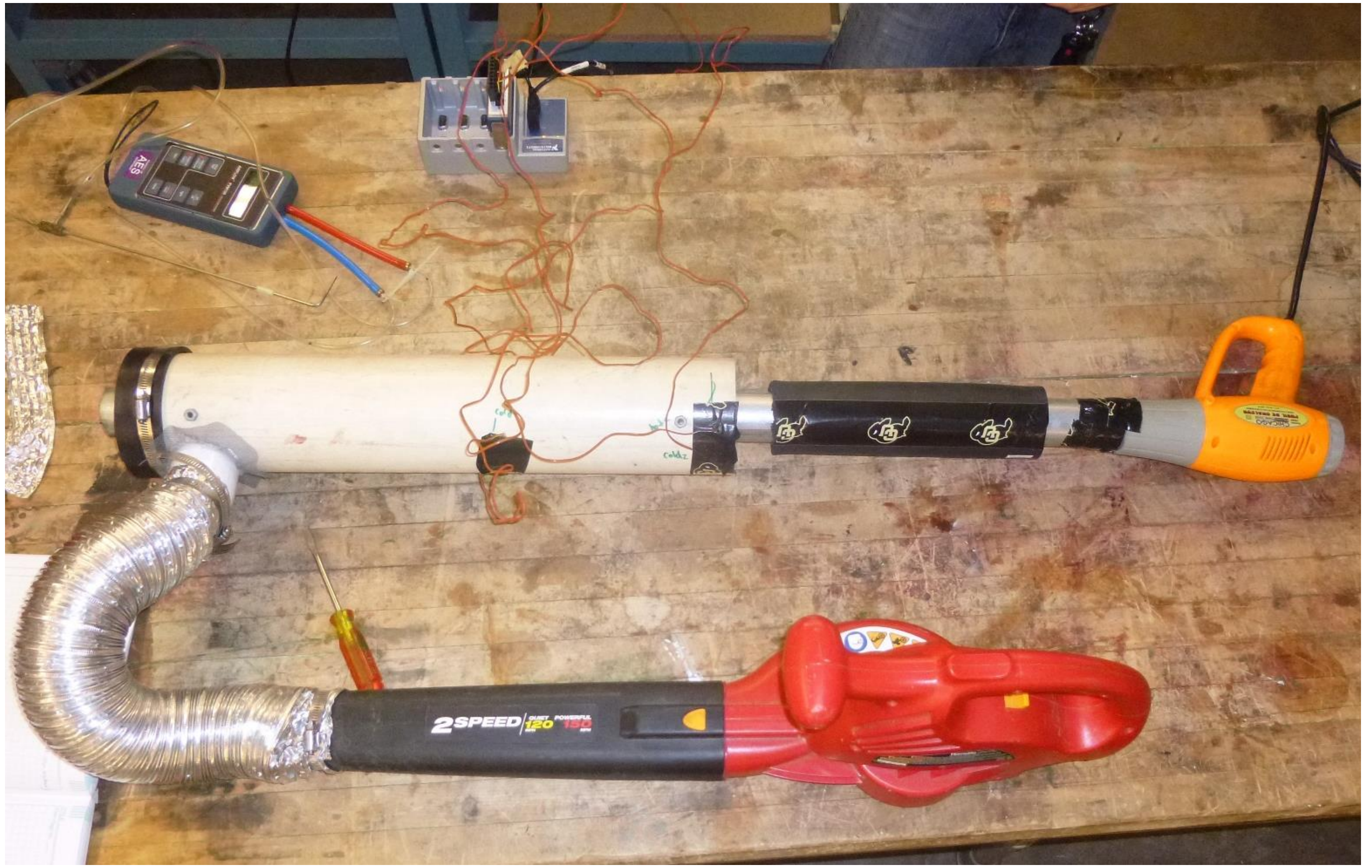
Iterations/ Lessons Learned: Level 0.0

- Description
  - Concentric pipe flow
  - Hot flow from car exhaust
- Lessons Learned
  - Car exhaust is not hot/ fast enough for turbulent flow
  - Not a sustainable test, takes too long to reach steady state
  - Difficult to set up and tear down



Iterations/ Lessons Learned: Level 0.1

- Description:
  - Concentric pipe flow
  - Single heat gun for hot flow
- Lessons Learned:
  - Flow is uneven in the cold flow since the leaf blower is coming in from the side
  - Test section not long enough for fully developed turbulent flow
  - Results are difficult to quantify since the heat exchange is small. Need more heat

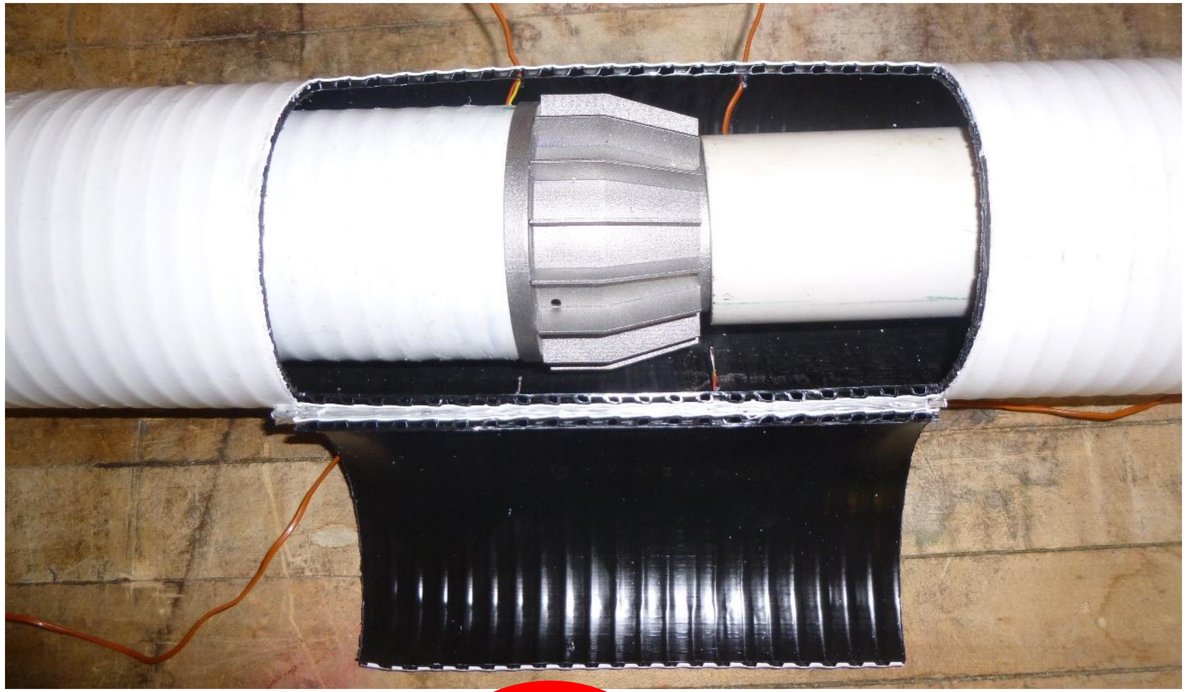


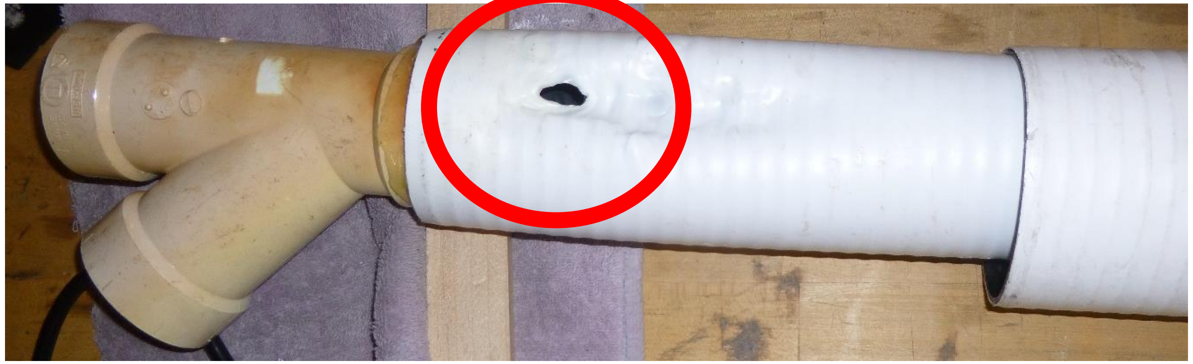
Iterations/ Lessons Learned: Level 0.2

- Description:
  - Concentric pipe flow
  - Cold flow straightened via flow diverter/ shroud
  - Cold flow has longer to develope
  - Two heat guns and additional flow for greater temperature
- Lessons Learned:
  - Heat guns over heated, because hot air was flowing back through them
  - Thermocouples difficult to integrate in flow since the pipe is closed

Iterations/ Lessons Learned: Level 1.0

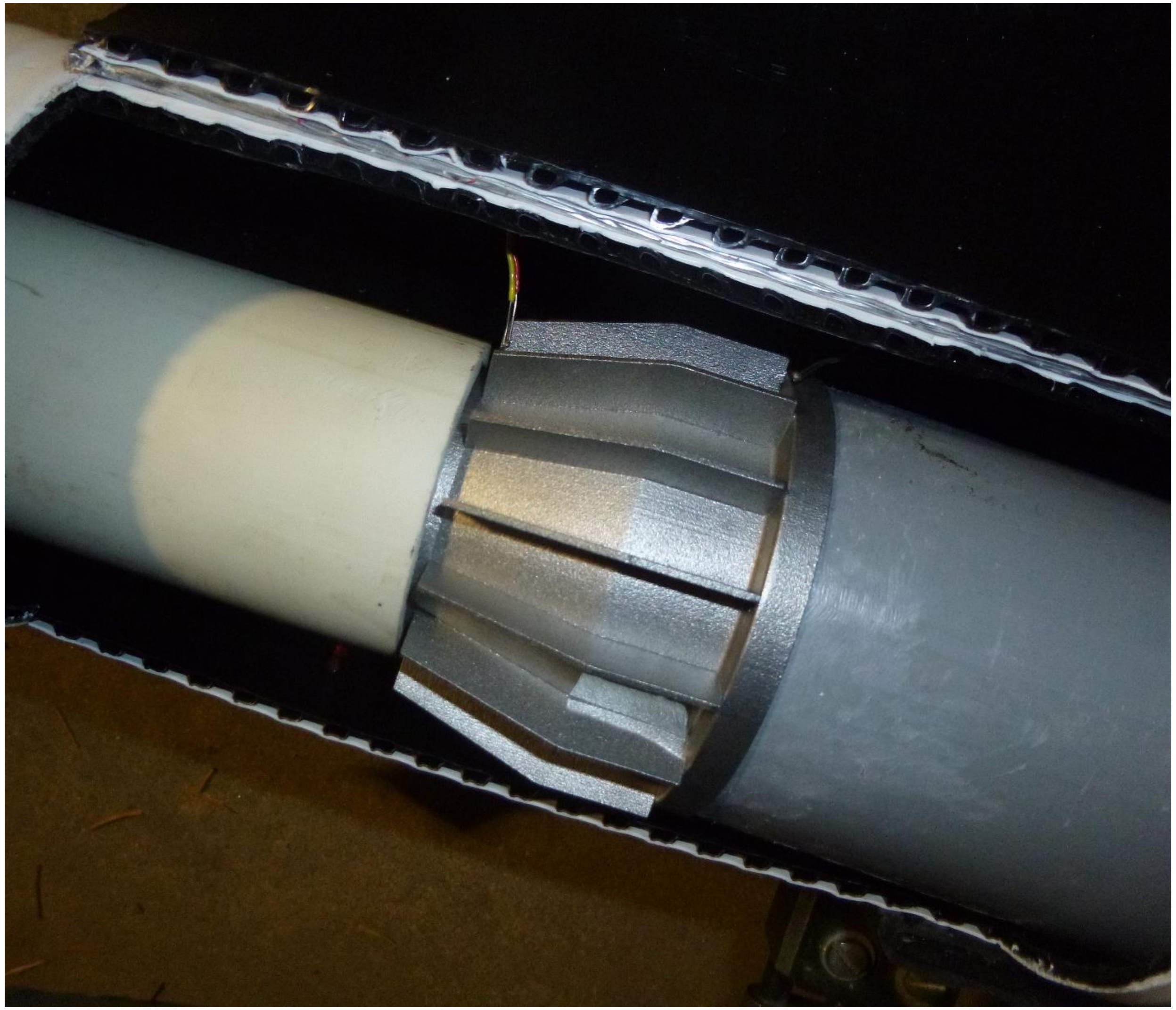
- Description:
  - Concentric pipe flow with heat exchanger
  - Longer heat pipes for developed flow
  - Door cut for easier access to heat exchanger and thermocouples
  - Hot flow pulled down the pipe using a sucking fan, allowing for higher Reynolds number, hotter flow, and less risk for the heat guns
- Lessons Learned:
  - Extra heat from heat guns caused severe melting and weird results from unknown melting sections





Iterations/ Lessons Learned: Level 1.1

- Description:
  - Concentric pipe flow with heat exchanger
  - New hot flow entrance pipe, with metal interior and pvc exterior to take the heat better, but still provide insulation to the flow
- Lessons Learned:
  - The new pipe held up, but the heat guns melted the Y-pipe so that it was unusable. Plastic is a bad idea



Iterations/ Lessons Learned: Level 1.2

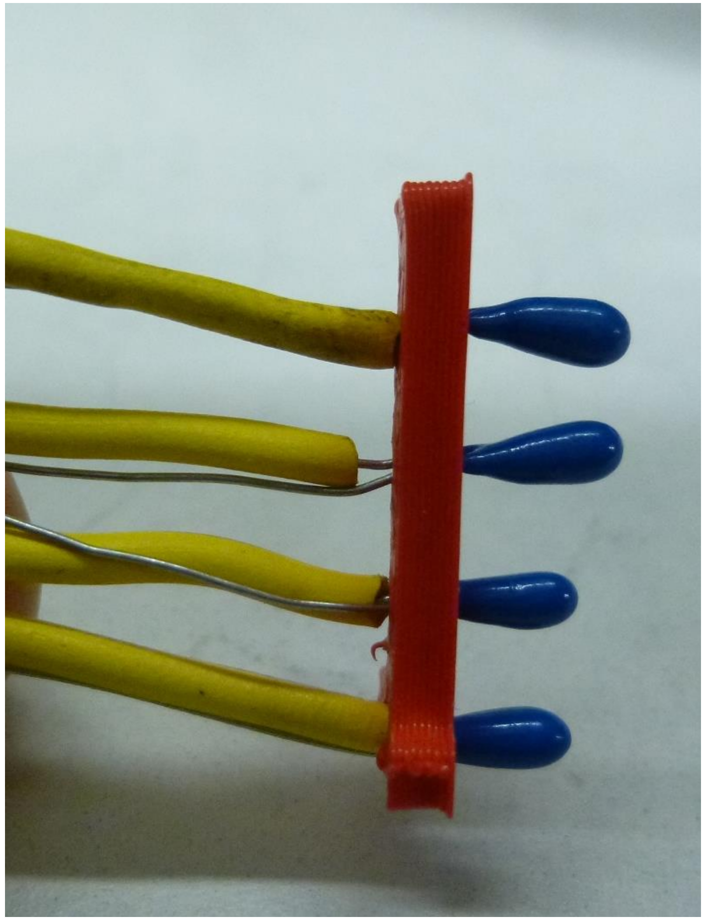
- Description:
  - Concentric pipe flow with heat exchanger
  - Replaced Y-pvc pipe with a Y-car exhaust pipe
- Lessons Learned:
  - A temperature profile is necessary for the cold flow because the thermocouples are very sensitive to placement

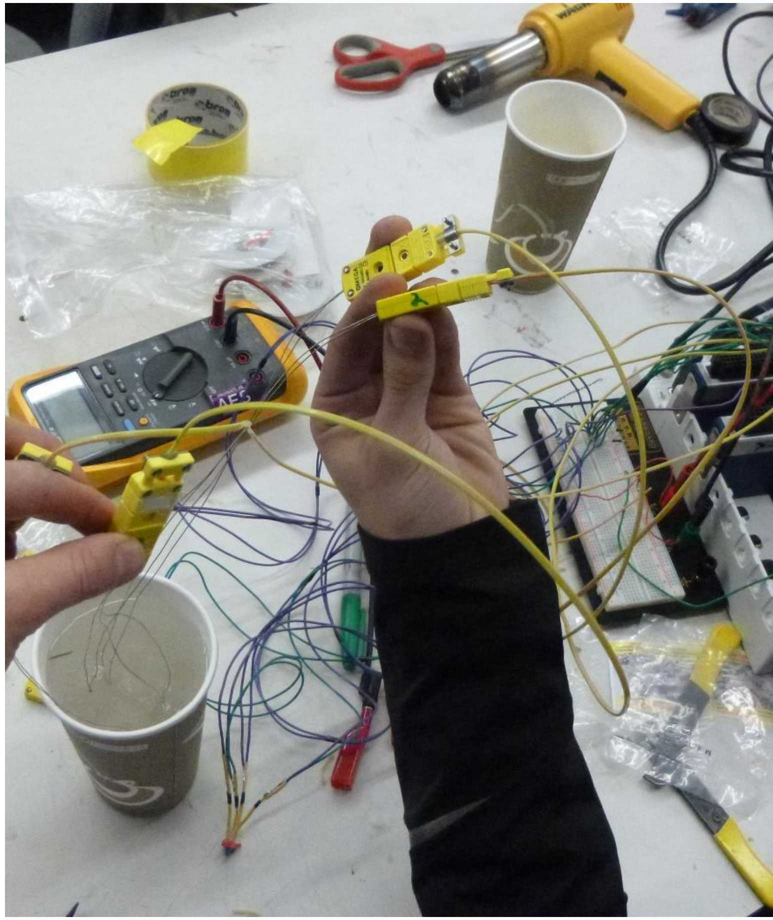
Iterations/ Lessons Learned: Mini test

- Description:
  - Used level 0 setup to get a temperature profile in concentric pipe flow
  - Found experimental profile for different leaf blower and sucker speeds
- Lessons Learned:
  - Leaf blower low, sucker low 0.37°/mm (radial)
  - Leaf blower high, sucker low 0.74°/mm (radial)
  - A temperature profile is needed for conclusive results
  - Thermistors should be used instead of thermocouples, because they have less error

Iterations/ Lessons Learned: Level 1.3

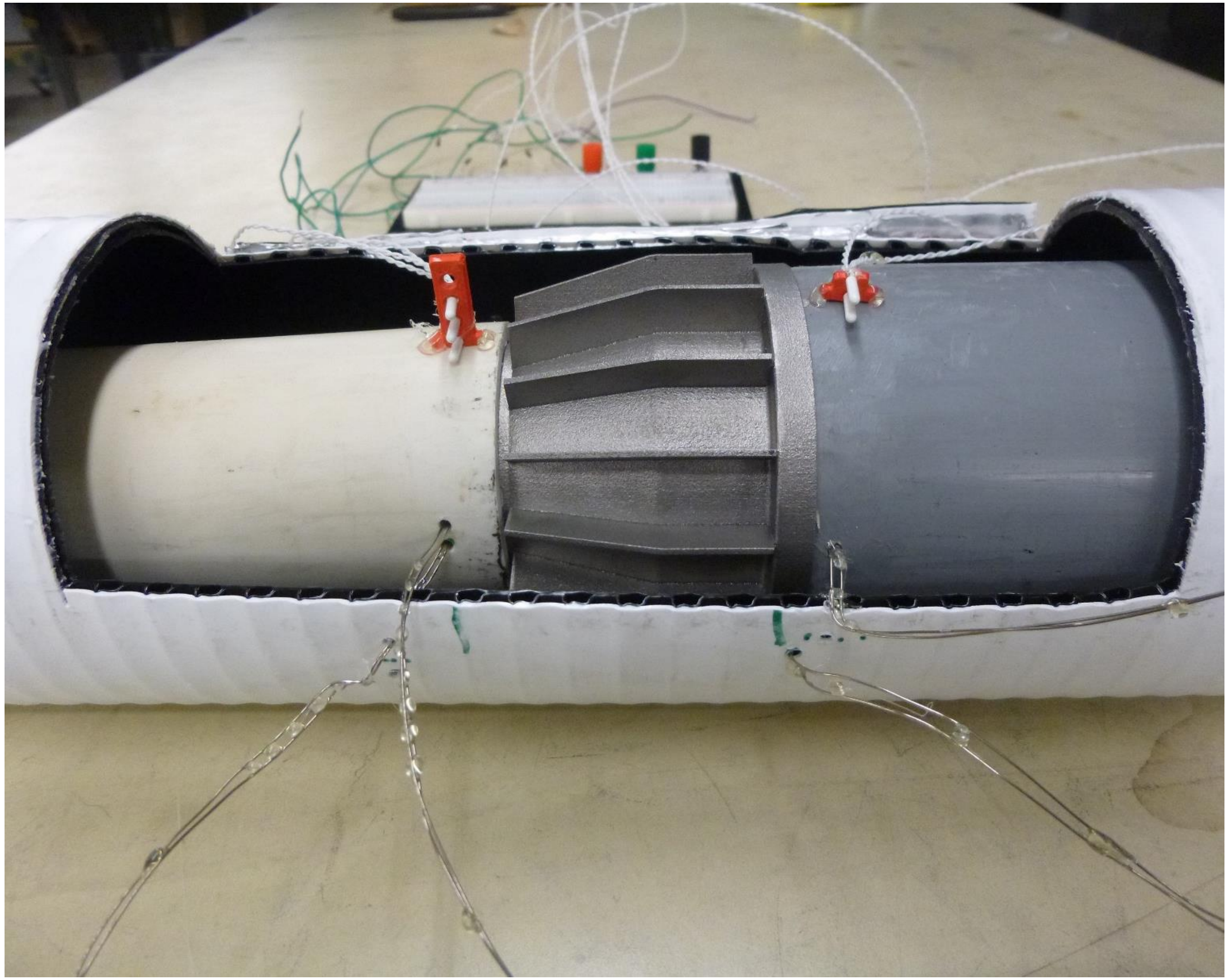
- Description:
  - Concentric pipe flow with heat exchanger
  - 3D printed profile insert for thermistors
  - Made in-house thermocouples with bare wire for easier integration and testing with the Daq
- Lessons Learned:
  - Bare wires are difficult to work with and created poor data when test was run since wires kept touching in flow





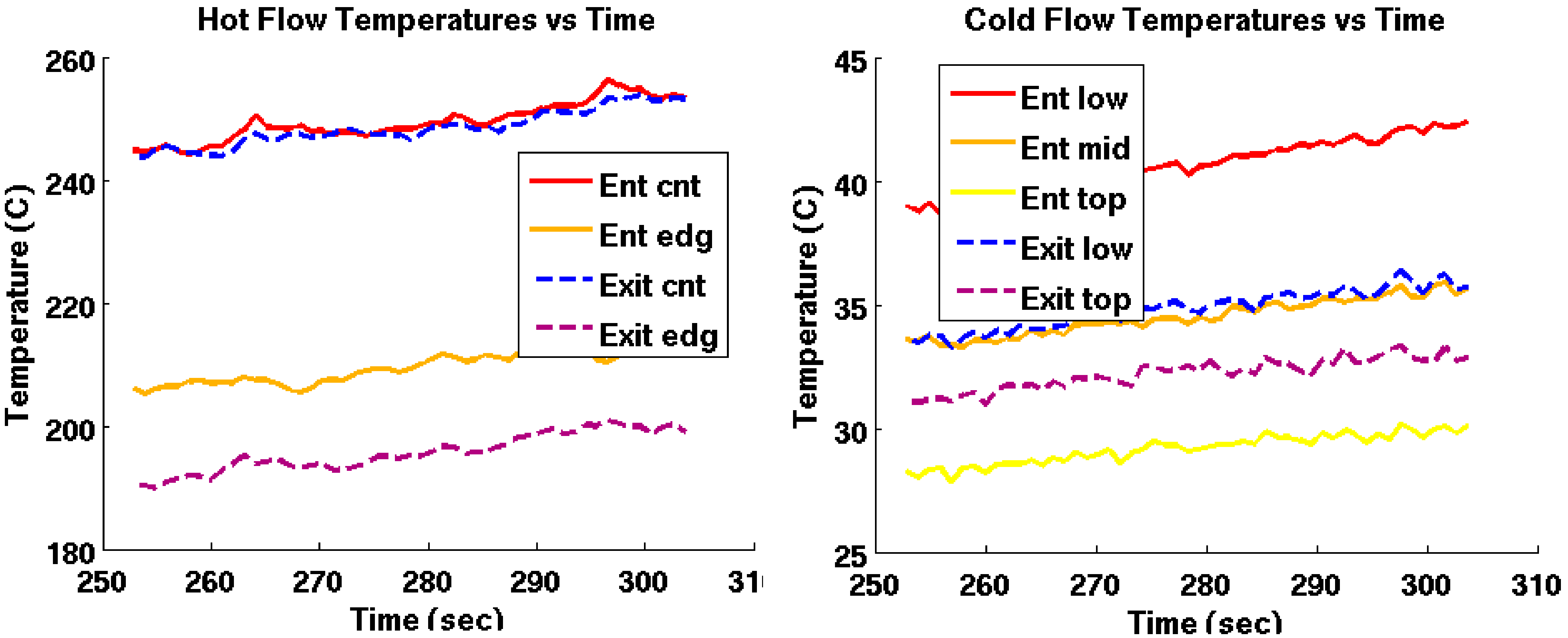
Iterations/ Lessons Learned: Level 1.4

- Description:
  - Concentric pipe flow with heat exchanger
  - Using covered thermistors to prevent wires touching
  - Beaded in-house thermocouples with hot glue to prevent wires touching
- Lessons Learned:
  - Results inconclusive due to: spiraling flow (unexpected stream lines), pressure drops/ unintentional mixing due to leaks, wrongly assumed resistors all have the same resistance
  - Important to take bulk temperatures and velocities in Matlab analysis
  - Need to wait longer between tests to prevent melting



Iterations/ Lessons Learned: Level 1.4

Result: -5 °C across heat exchanger

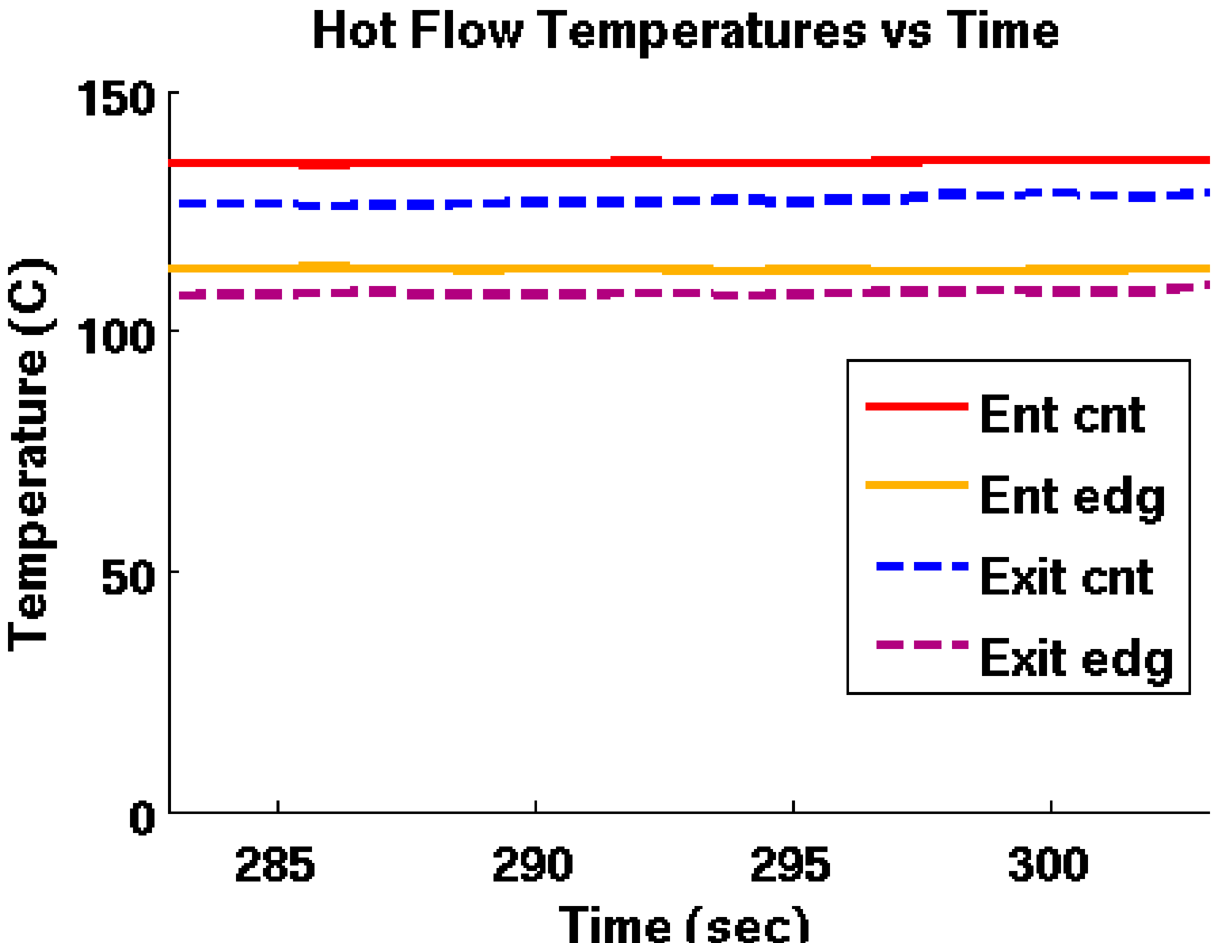


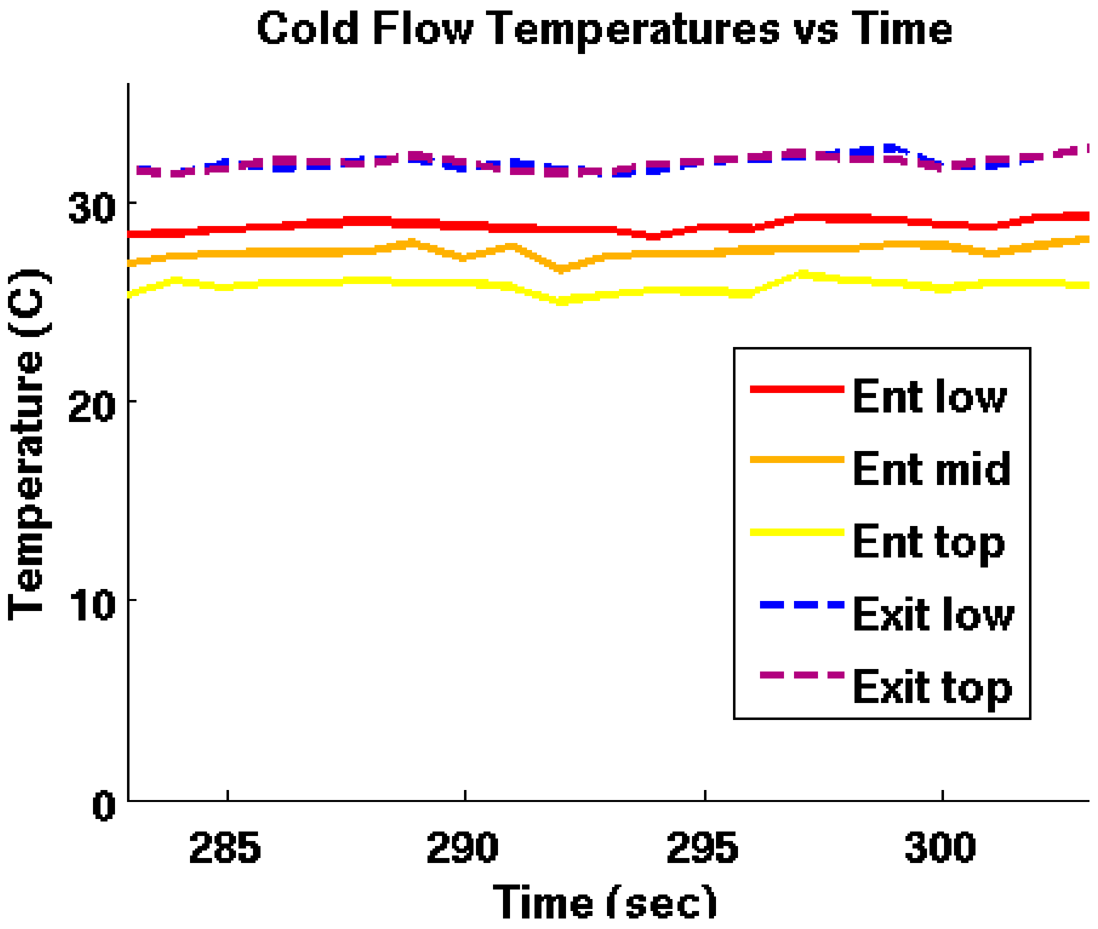
Iterations/ Lessons Learned: Level 1.5

- Description:
  - Concentric pipe flow with heat exchanger
  - Created flow straightener inserts to place in cold incoming flow
  - Secured ducting around the leaf blower to prevent uneven flow and unnecessary pressure drops
  - Place temperature profile inserts with thermistors in different streamlines
- Lessons Learned:
  - Ran 3 tests and found similar data. Need to run more tests for statistical assurance

Iterations/ Lessons Learned: Level 1.5

Result: +3.83 °C across heat exchanger





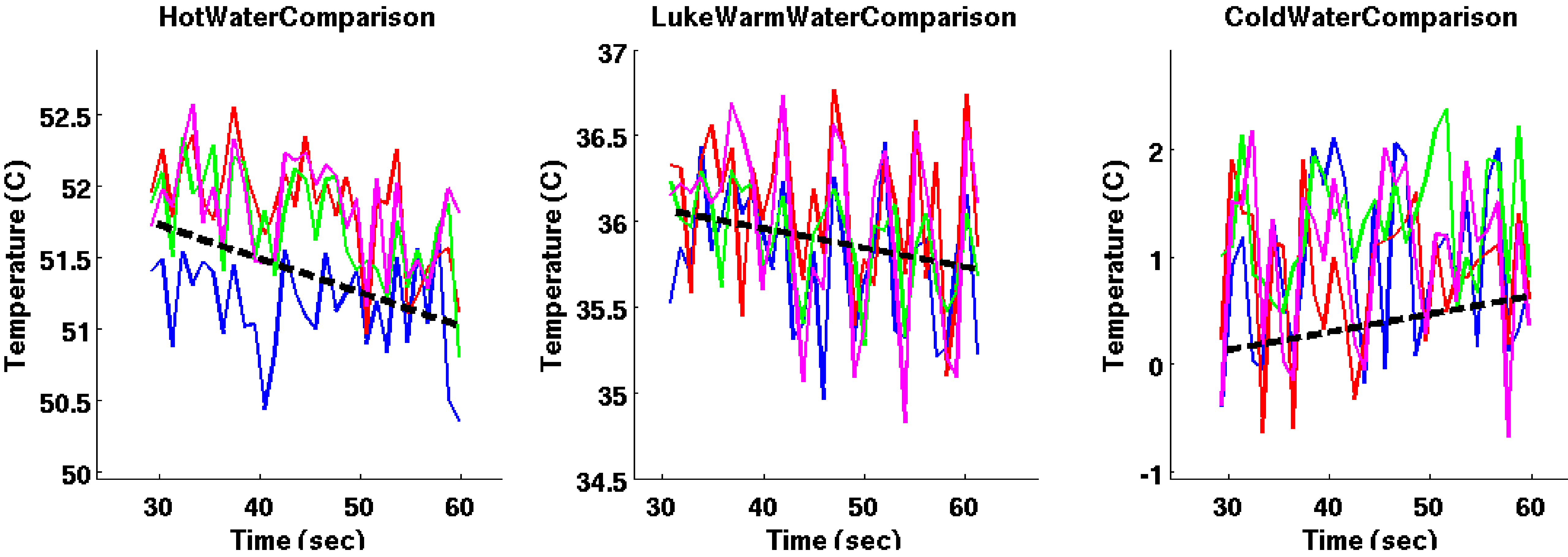
Heat Exchanger Model: Performance Prediction

Monte Carlo Simulation Sensitivity Variables

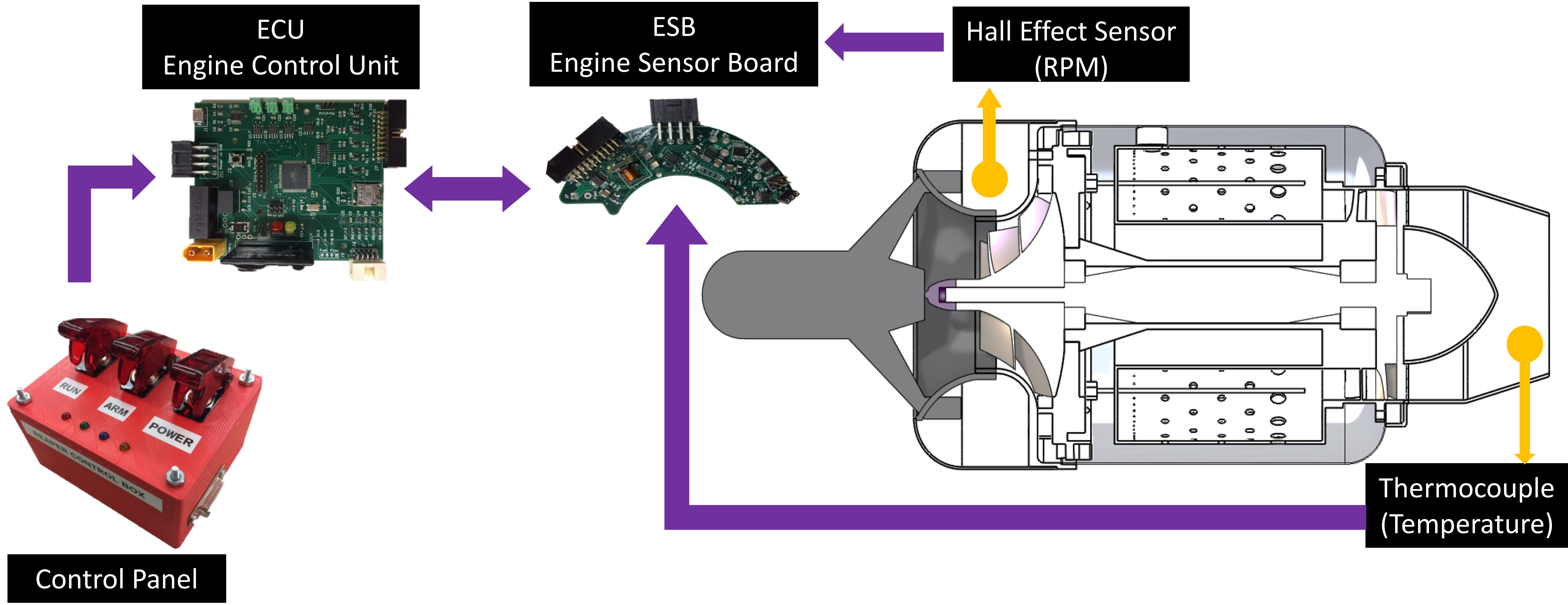
- Temperature
  - Cold flow in
  - Hot flow in
  - Hot flow out
- Velocity
  - Hot
  - Cold

Test	Model	Experimental	Percent Difference
1	1.94±0.2°C	1.29±0.4°C	33.5%
2	2.06±0.2°C	1.59±0.4°C	22.8%
3	1.93±0.2°C	1.72±0.4°C	11.0%
4	2.03±0.2°C	2.37±0.4°C	-17.4%
5	1.99±0.2°C	2.27±0.4°C	-13.9%
6	2.02±0.2°C	2.56±0.4°C	-26.6%
7	1.95±0.2°C	2.16±0.4°C	-10.8%
8	2.17±0.2°C	1.95±0.4°C	10.2%
9	1.09±0.1	0.82±0.4°C	24.4%
10	2.27±0.2°C	1.88±0.4°C	17.0%
Average	**1.95±0.2°C**	**1.86±0.4°C**	**5.0%**

Sensor Calibration



ECU and ESB Stock Engine Test



ECU
Engine Control Unit

ESB
Engine Sensor Board

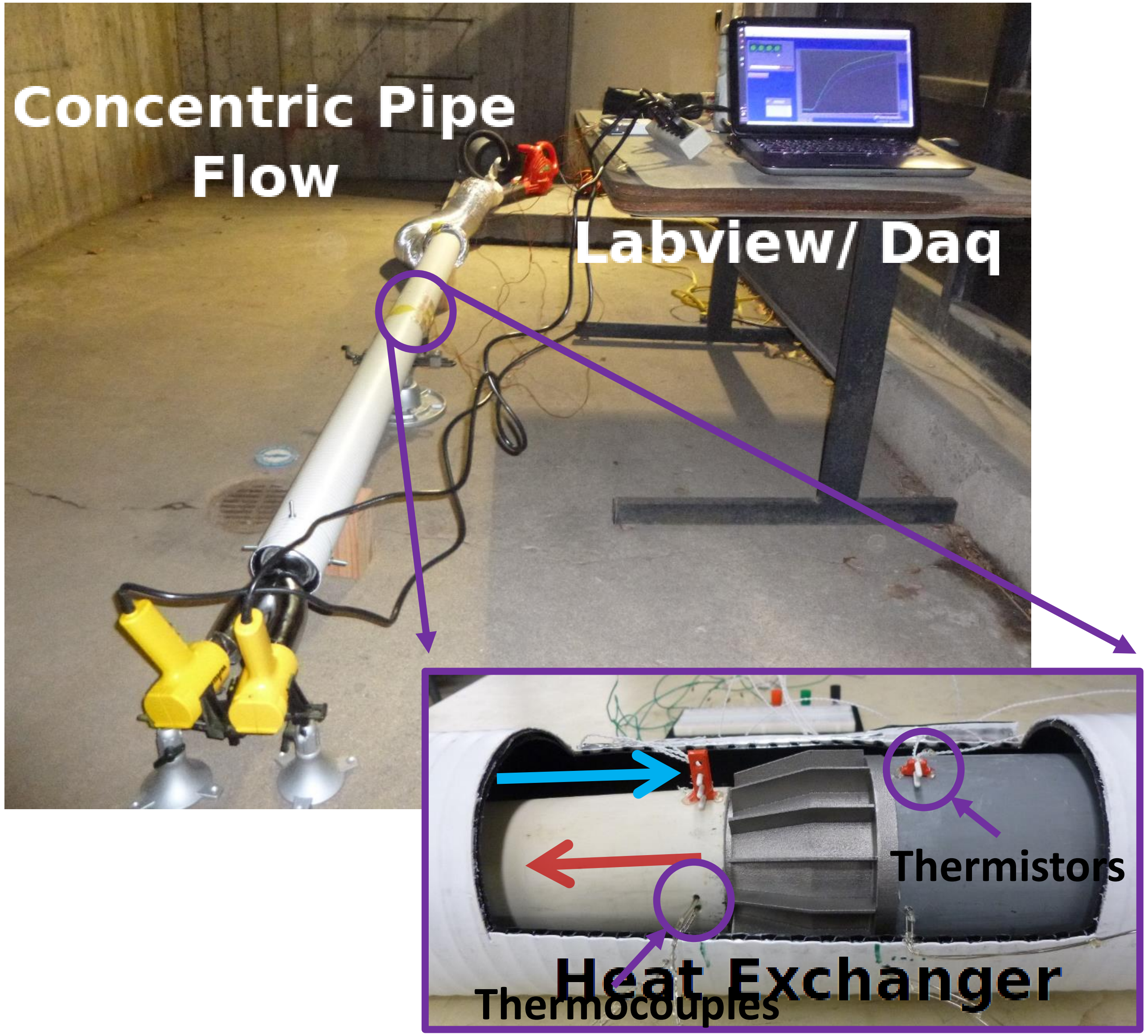
Hall Effect Sensor
(RPM)

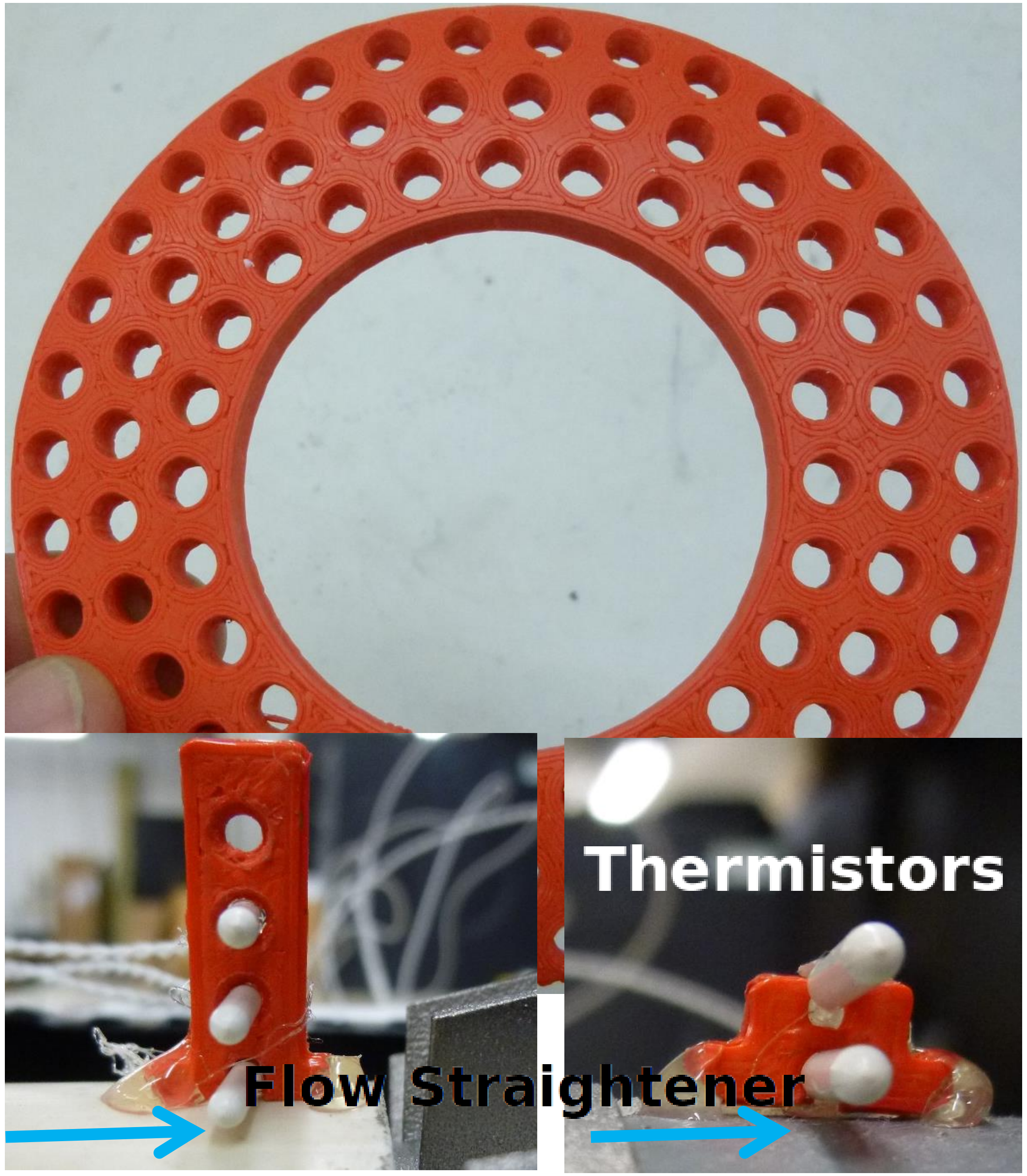
Thermocouple
(Temperature)

Control Panel

Sensor List	**Sensor Error**	**Expected Range**	**Minimum Sample Rate**
Thermocouple	±3 °C	0-900 °C	113 Hz
Hall Effect	±0.5%	0- 130,000 rpm	31 Hz

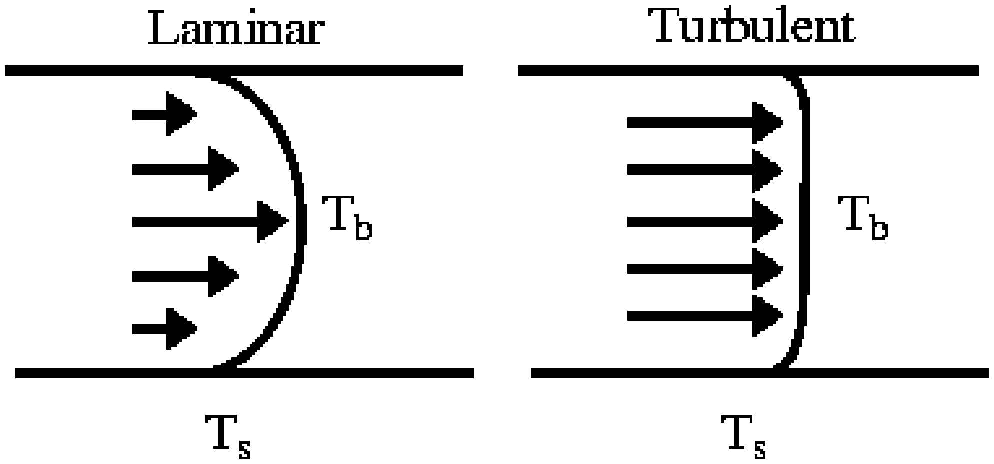
Heat Exchanger Verification





Heat Exchanger Verification

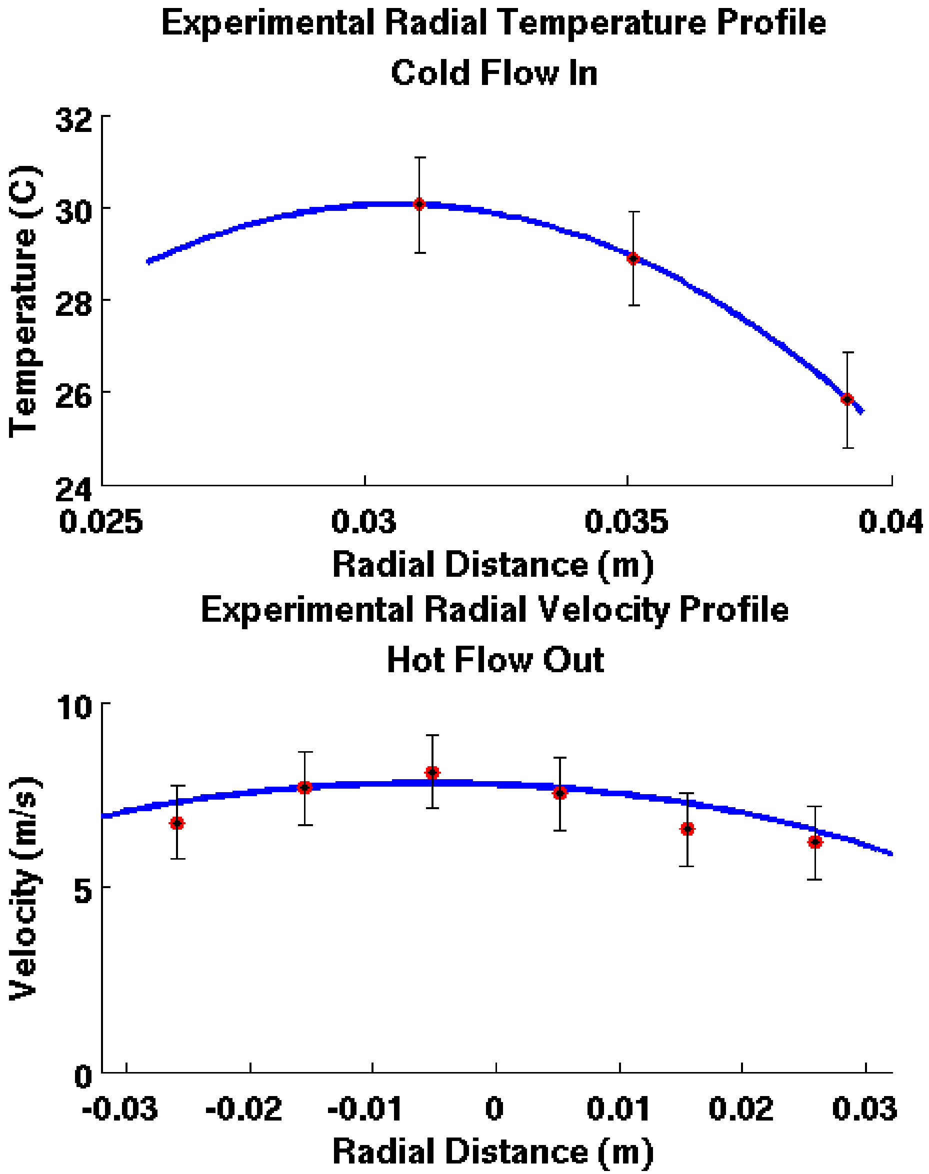
- Expected Results and Considerations:
  - Velocity Profiles



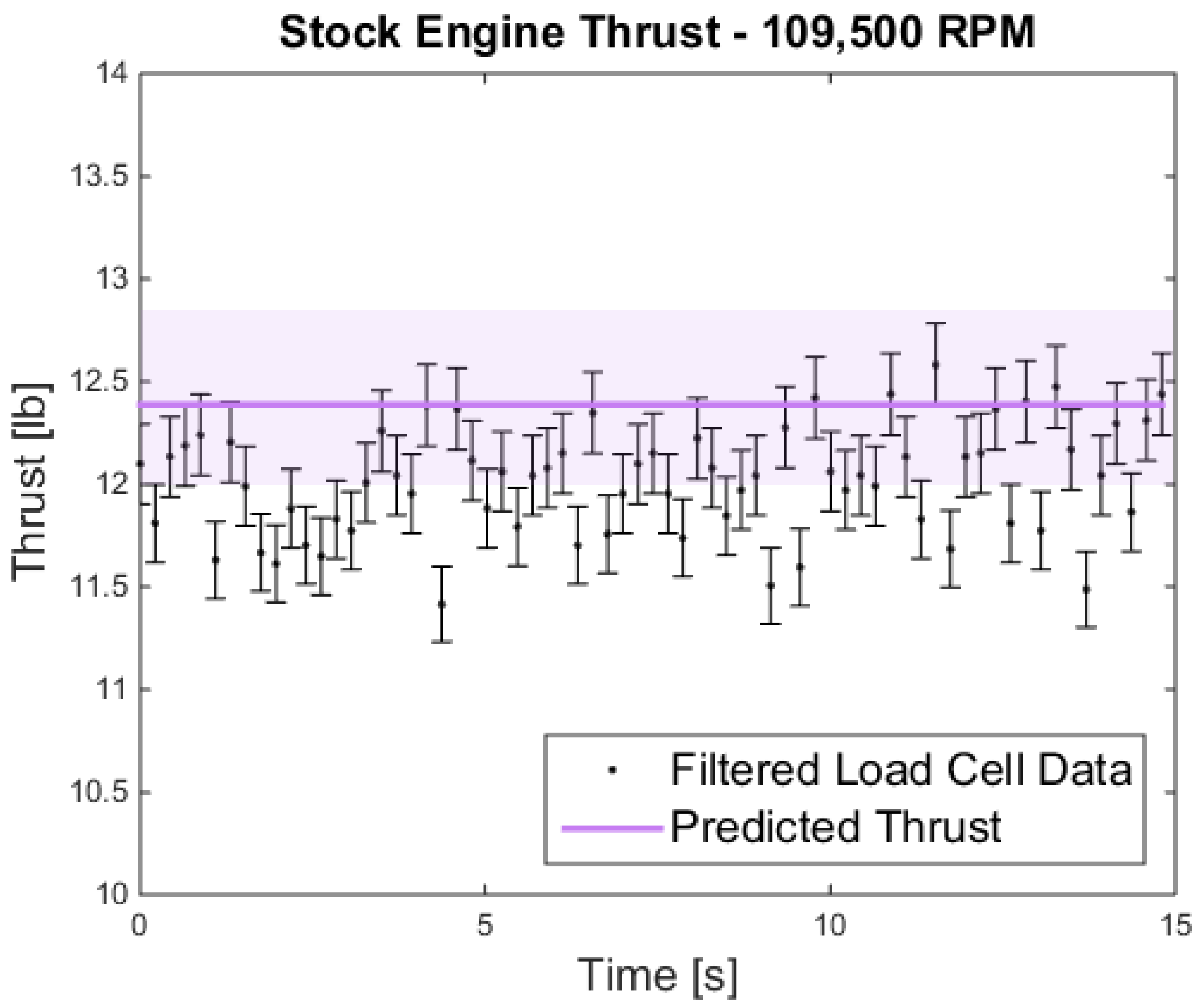
  - Take bulk velocity and temperature

$$Tb = \frac{2}{U_m r_o^2} \int_0^{r_o} uTr\, dr$$

$$U_m = \frac{2}{r_o^2} \int_0^{r_o} ur\, dr$$



Control Volume Model Validation: Thrust



Predicted Thrust: $12.4 \pm 0.4\ lbs$

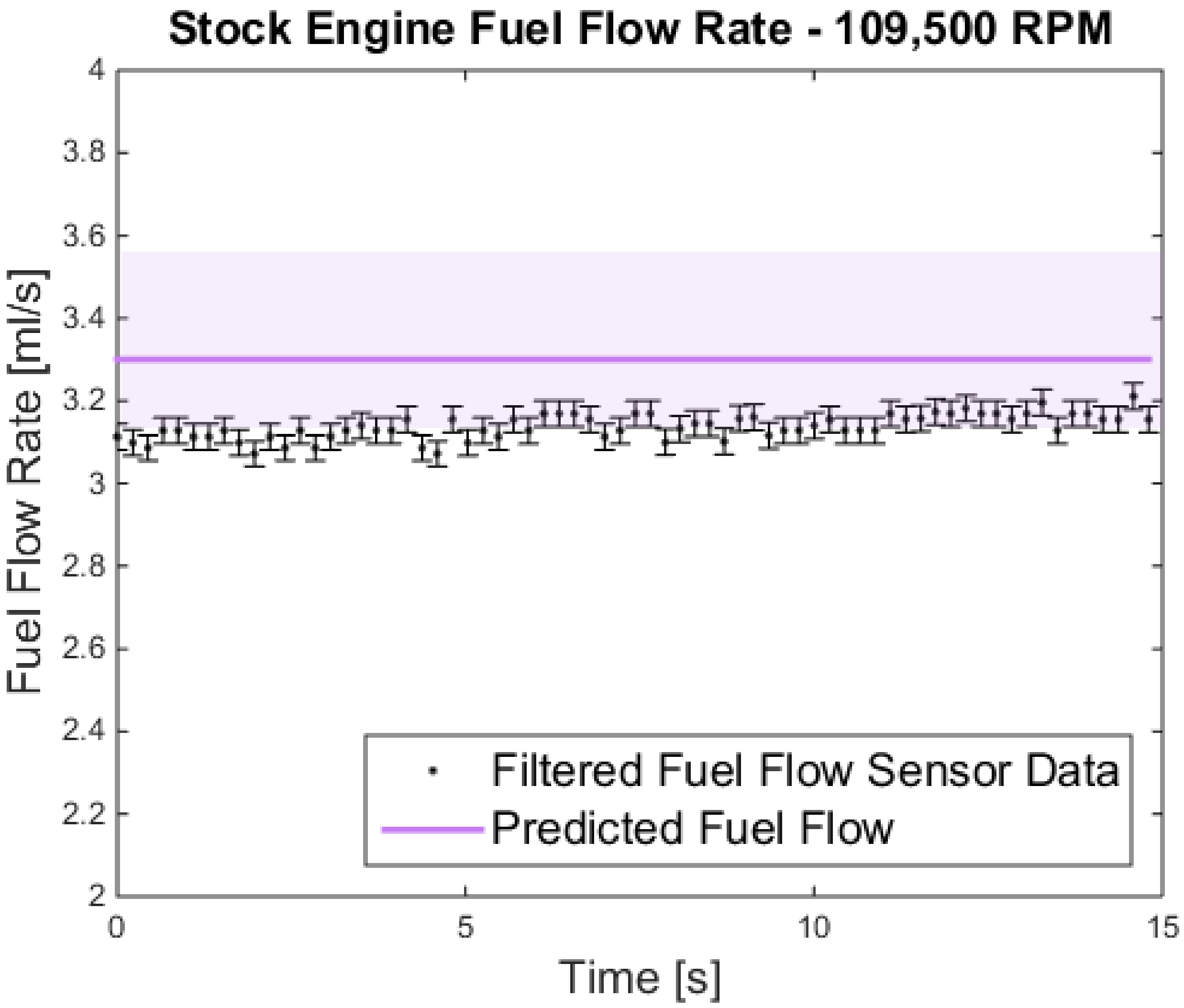
Measured Average Thrust: $12.0\ \pm 0.2\ lbs$

Percent Difference: 3.3%

Conclusions:

- Model can predict P-90RXi thrust (DR 3.1)
- Model can predict losses in engine (DR 3.3)

Control Volume Model Validation: Fuel Rate



Predicted Fuel Rate: $3.3 \pm 0.2\ ml/s$

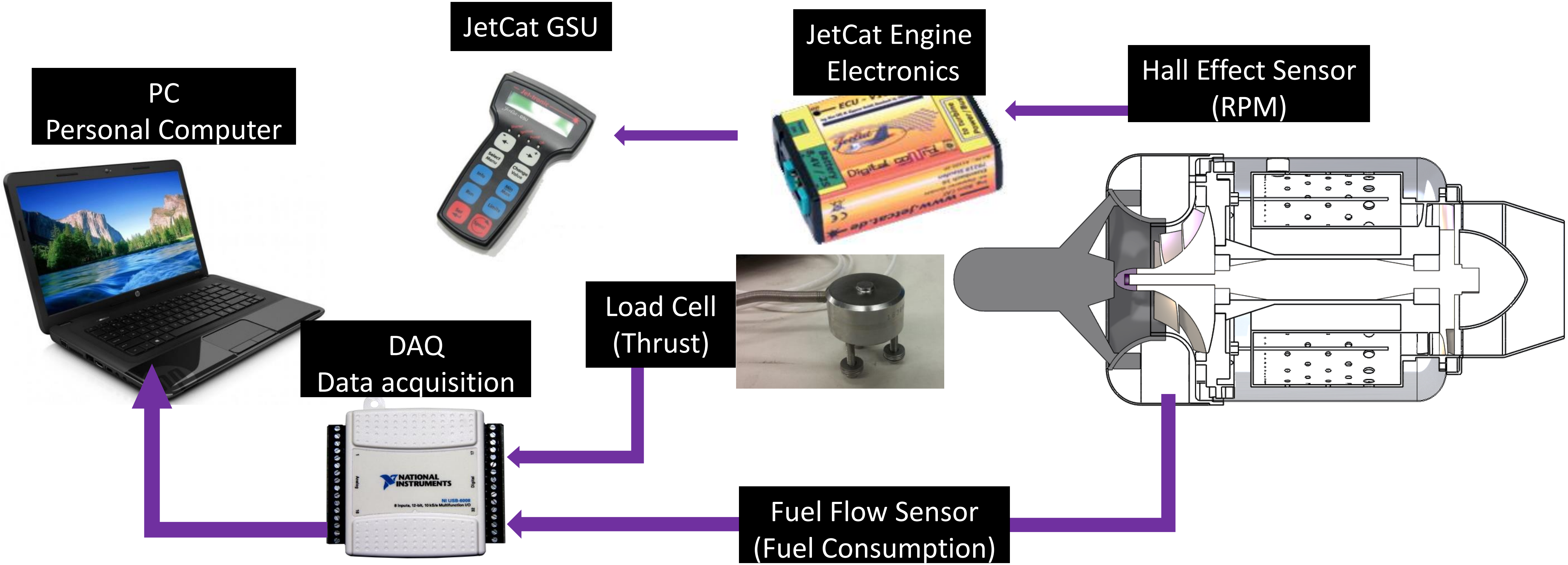
Measured Average Fuel Consumption: $3.13\ \pm 0.03\ ml/s$

Percent Difference: 6.5%

Conclusion:

- Model can predict P-90RXi fuel consumption rate (DR 3.2)

Stock Engine Test Setup



PC
Personal Computer

JetCat GSU

JetCat Engine
Electronics

Hall Effect Sensor
(RPM)

Load Cell
(Thrust)

DAQ
Data acquisition

Fuel Flow Sensor
(Fuel Consumption)

Sensor List	Error	Expected Range	Sample Rate
Fuel Flow Sensor	±1.2%	0-5 mL/s	1 Hz
25lb Load Cell	±1.9%	0- 22 lbs	1 Hz
Hall Effect	±100 RPM	0- 130,000 RPM	31 Hz

Project Management/Systems Engineering Backup Slides

Functional Requirements

FR 1: Engine control electronics command the modified engine

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

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

Systems: V Approach

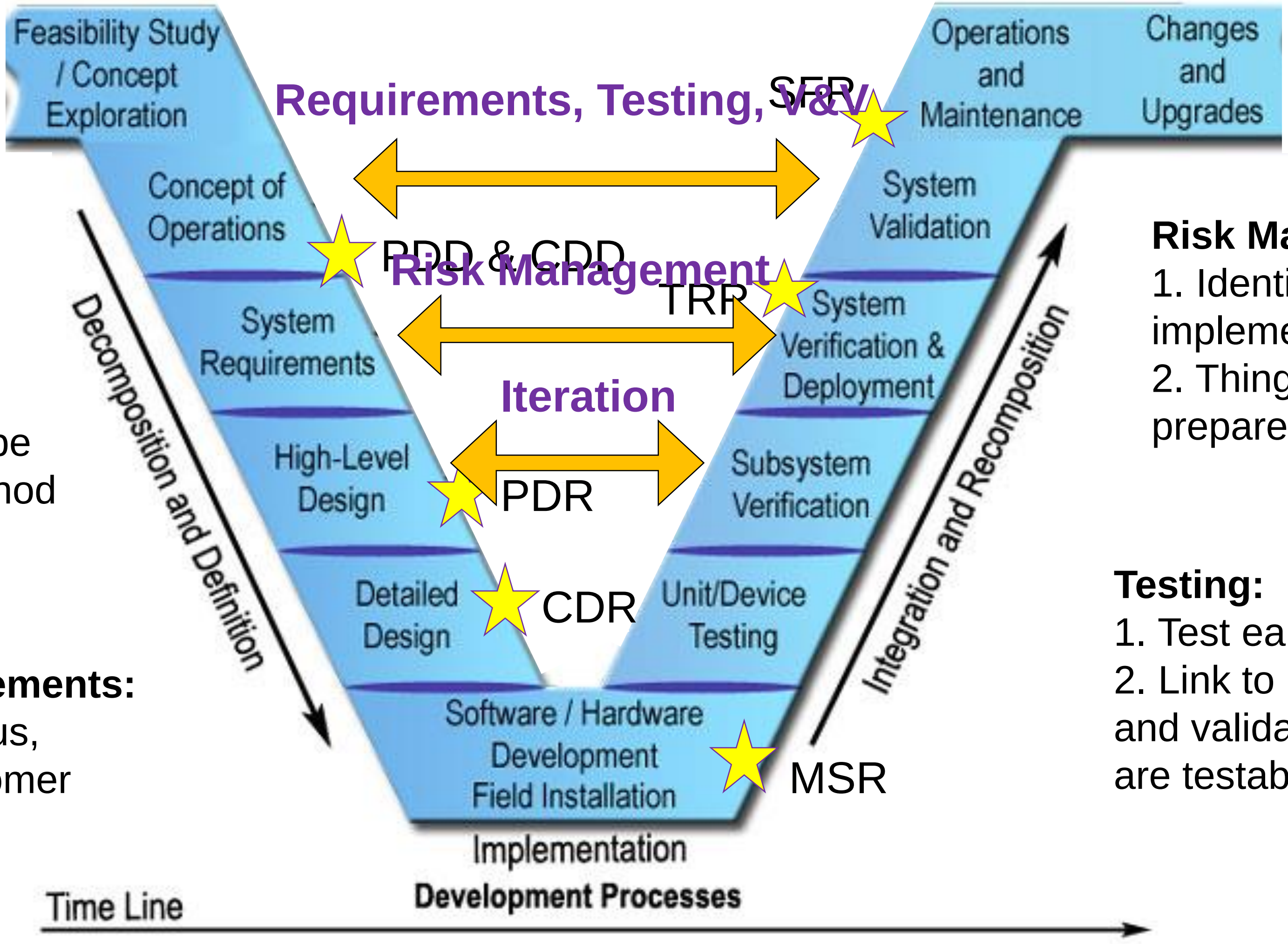
Defining Scope:

1. Proof of concept
2. Not for flight

Trade Studies:

1. Heat Exchanger Type
2. Engine Control Method

Functional Requirements:
Clear & unambiguous, testable, meet customer requests



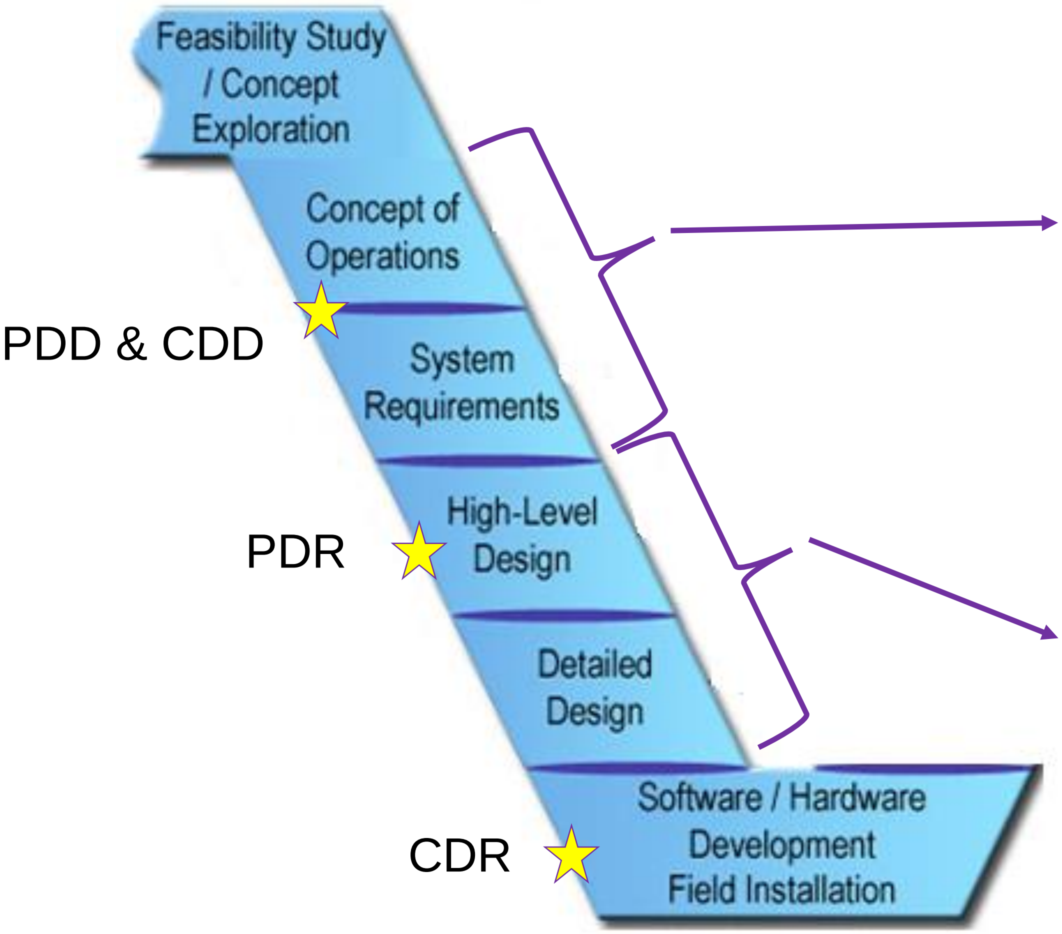
Risk Management:

1. Identify potential threats and implement mitigation plans **early**
2. Things will go wrong so be prepared

Testing:

1. Test early and often
2. Link to requirements for verification and validation – make sure requirements are testable!

Systems - Fall Semester



Key tasks:

- Identifying project objectives
- Defining concise requirements

Difficulties:

- Identifying project scope early
- Organizing team to best cover all design needs

Key tasks:

- Integrate and share design updates with CAD model
- Facilitate inter-system communication
- Risk analysis and assessment

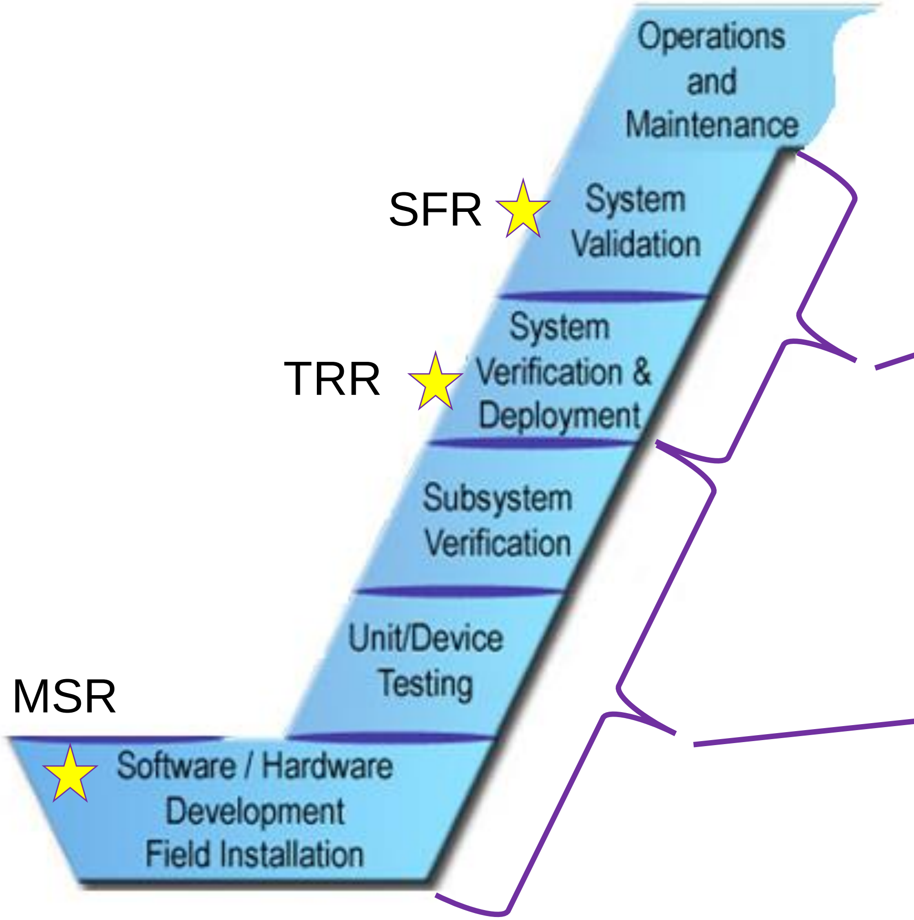
Difficulties:

- Keeping all subsystems communicating and updated with one another

Lessons Learned:

- Identify design milestones early
- Set design limits

Systems - Spring Semester



Key tasks:
- Identifying procedures for satisfying design and functional requirements
- Relating accomplishments to project success

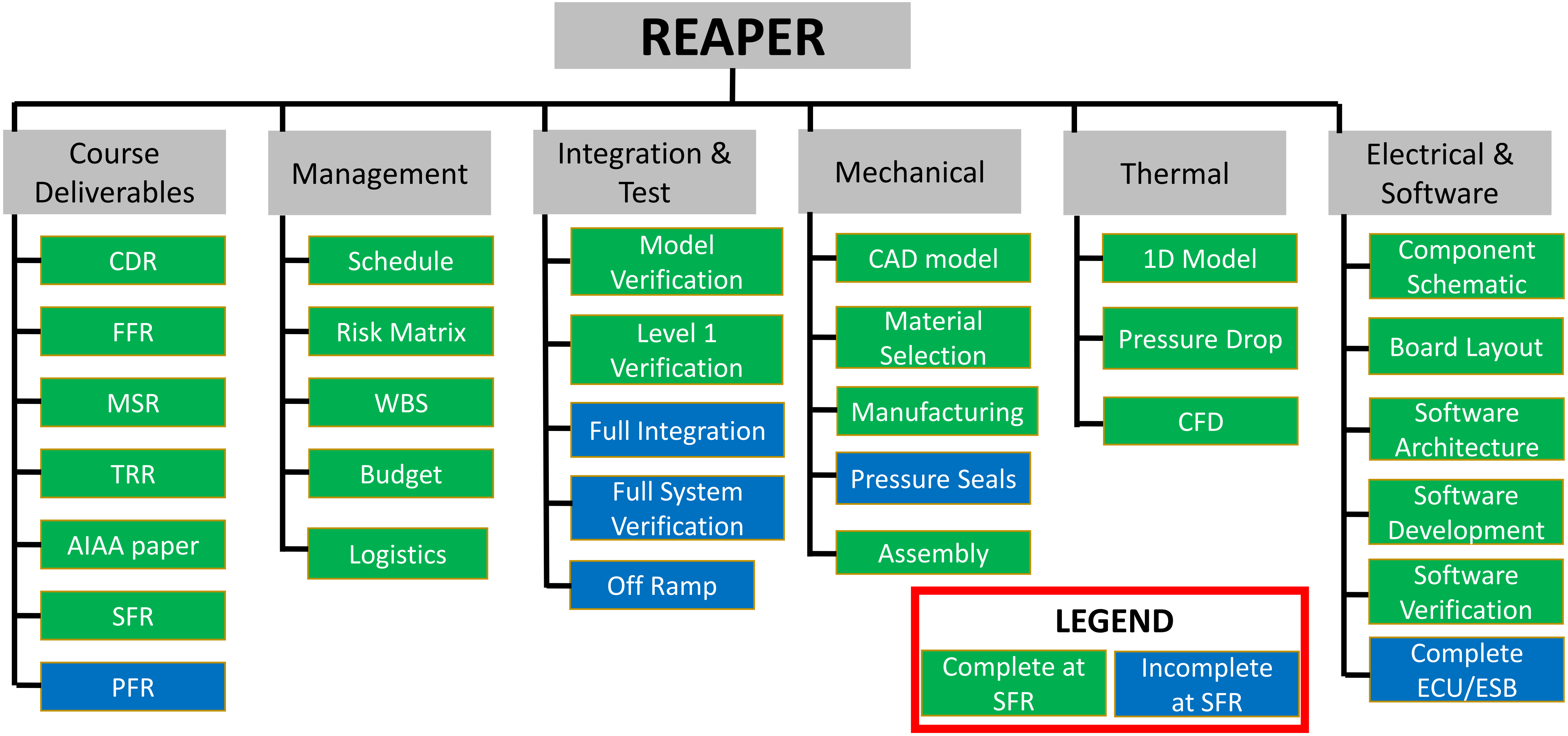
Difficulties:
- Finding the most efficient way to V&V all requirements
- Dealing with risks when they become realities

Key tasks:
- Relate hardware performance to design specifications
- Monitor risks and develop mitigation strategies

Difficulties:
- Balancing resources between design/analysis and manufacturing
- Maintaining a dynamically changing schedule

Lessons Learned:
- Make requirements and levels of success the purpose of actions
- Communication is **essential**

Work Breakdown Structure



REAPER

- Course Deliverables
  - CDR
  - FFR
  - MSR
  - TRR
  - AIAA paper
  - SFR
  - PFR
- Management
  - Schedule
  - Risk Matrix
  - WBS
  - Budget
  - Logistics
- Integration & Test
  - Model Verification
  - Level 1 Verification
  - Full Integration
  - Full System Verification
  - Off Ramp
- Mechanical
  - CAD model
  - Material Selection
  - Manufacturing
  - Pressure Seals
  - Assembly
- Thermal
  - 1D Model
  - Pressure Drop
  - CFD
- Electrical & Software
  - Component Schematic
  - Board Layout
  - Software Architecture
  - Software Development
  - Software Verification
  - Complete ECU/ESB

LEGEND

Complete at SFR

Incomplete at SFR