Test Readiness Review

REcuperating Advanced Propulsion Engine Redesign

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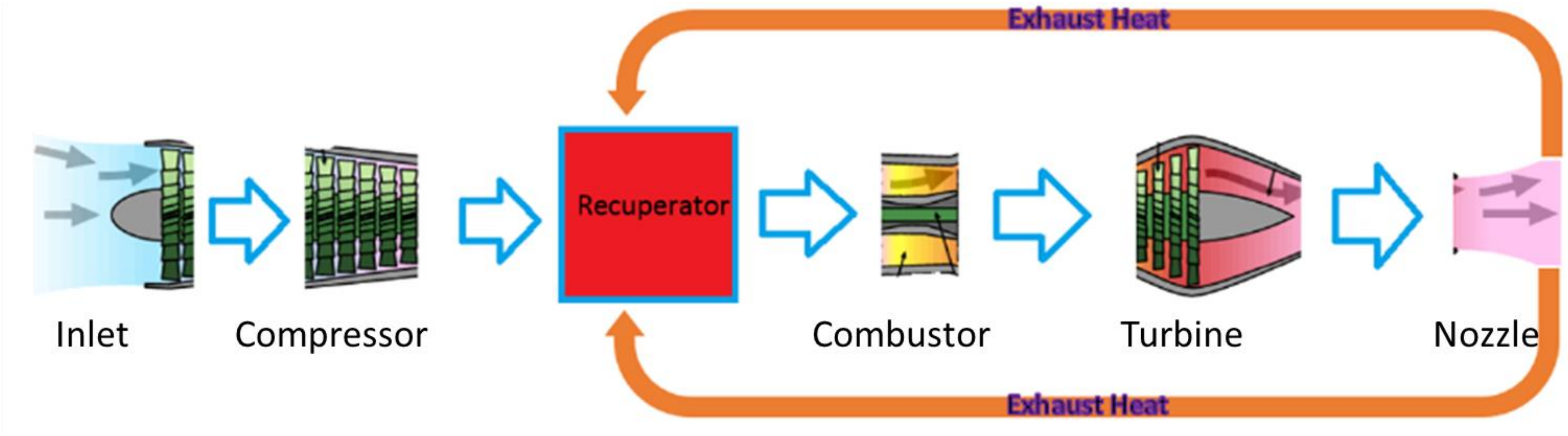
Presentation Agenda

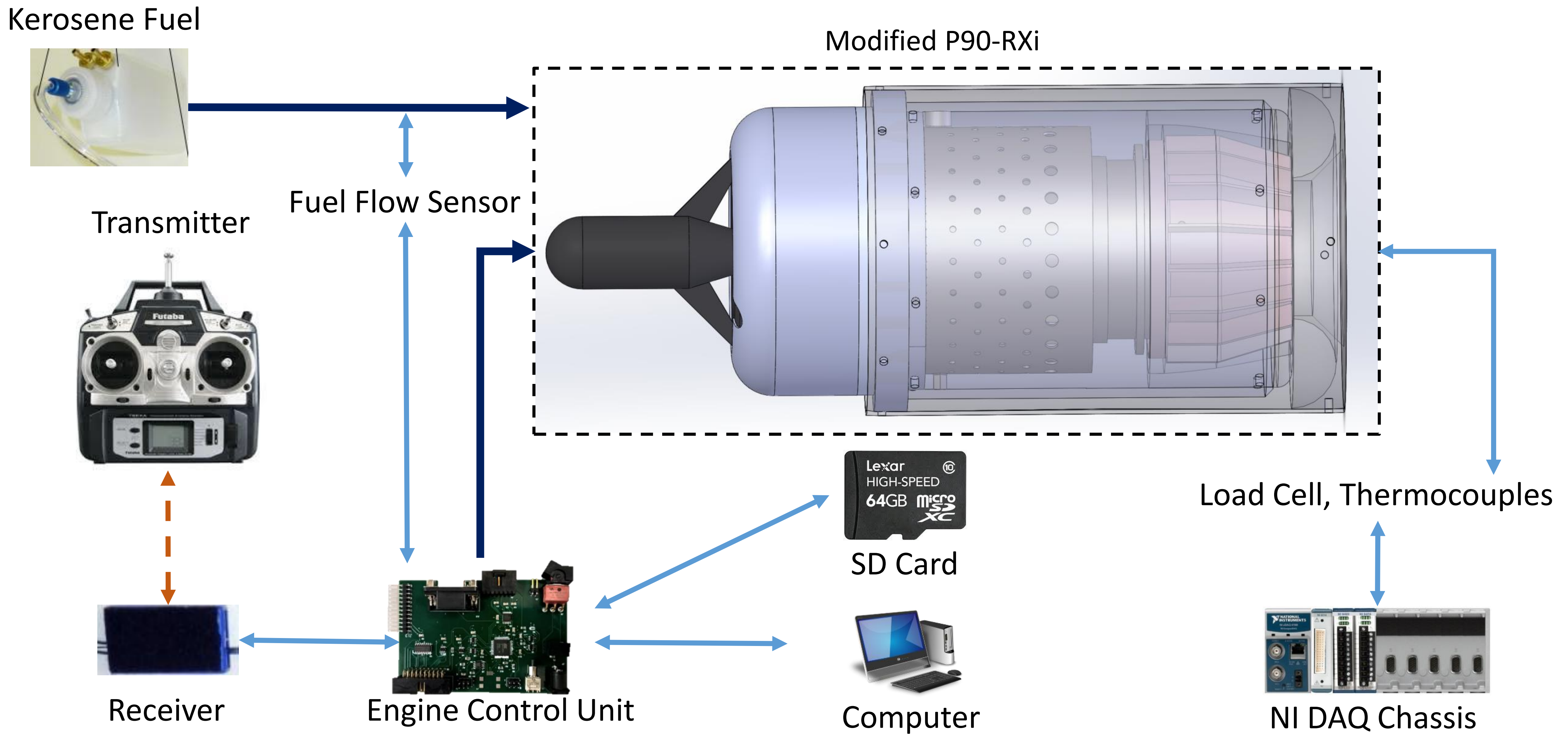
- Project Overview
- Schedule
- Testing
- Budget

Overview

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

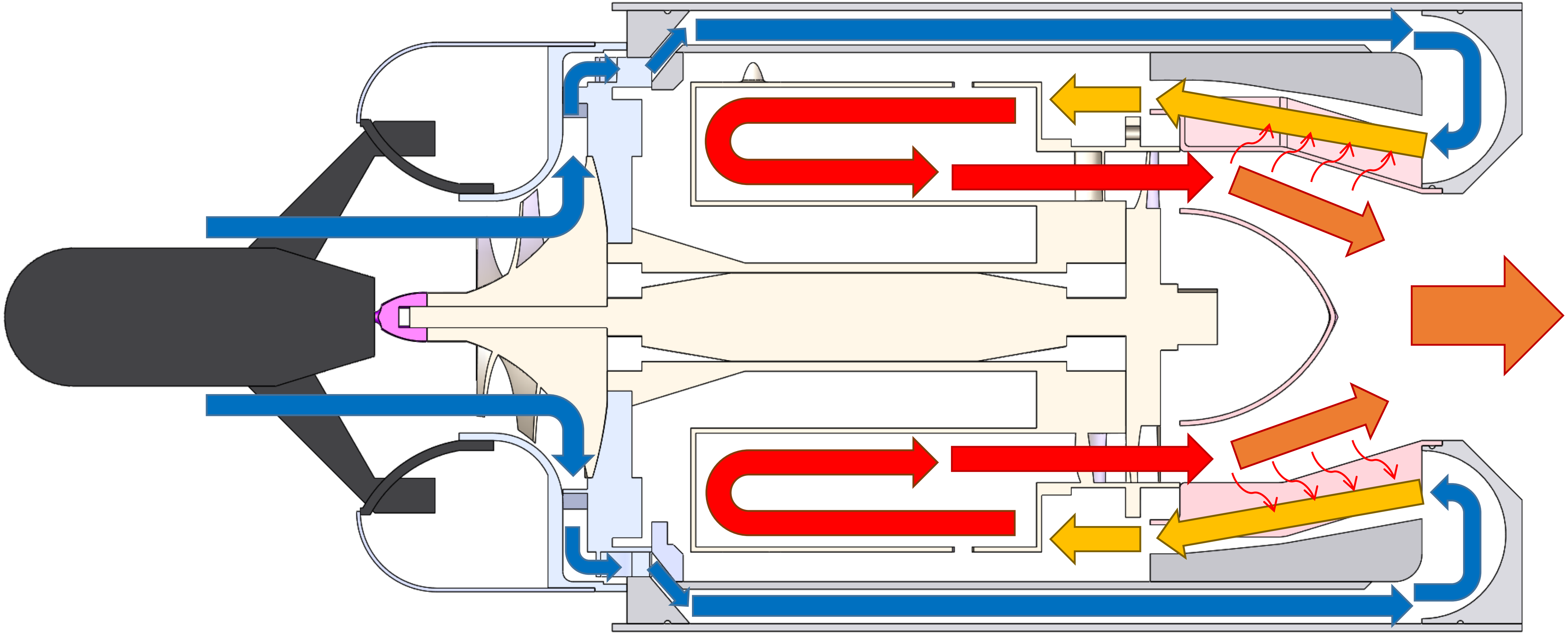


Concept of Operations

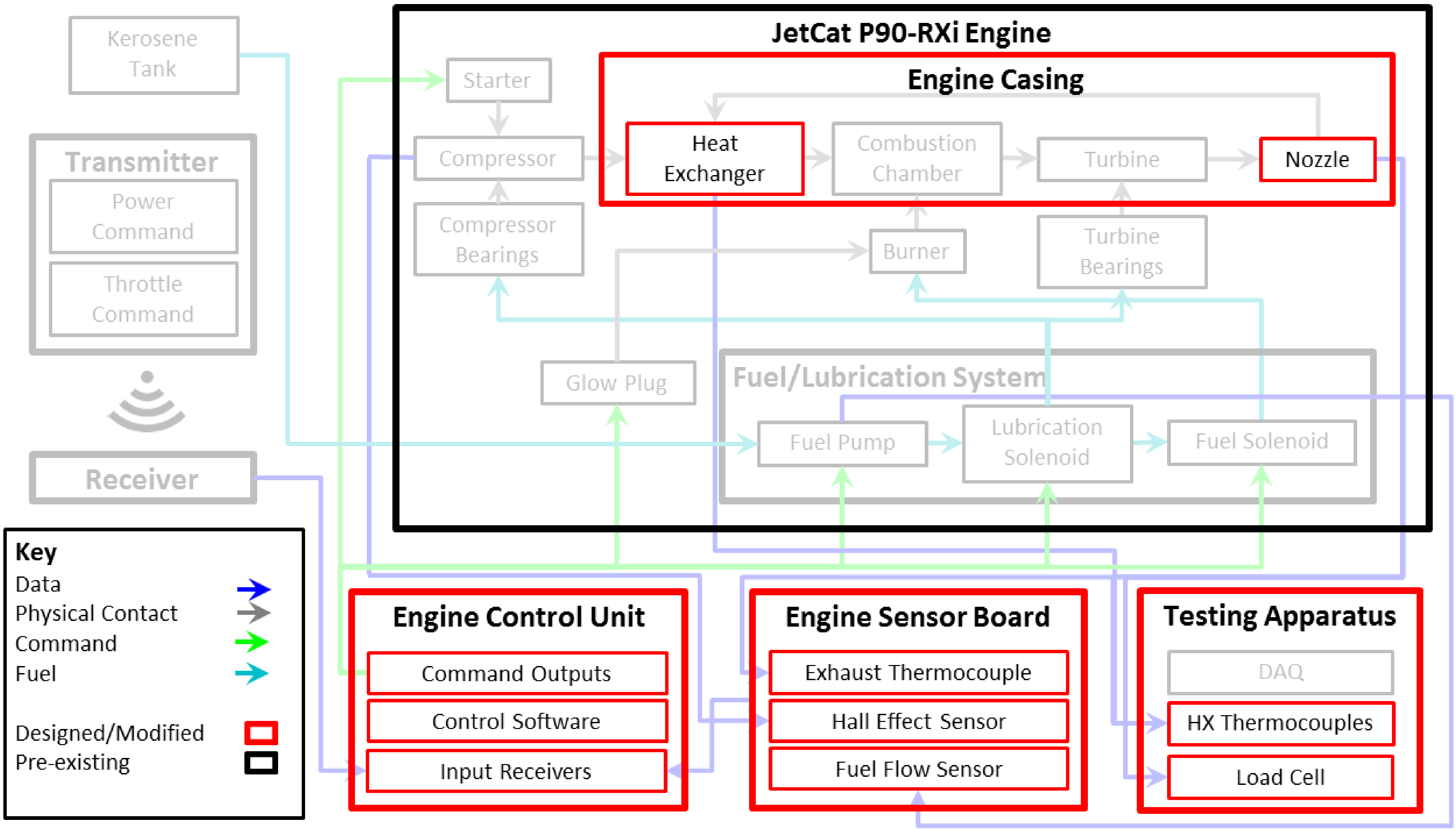


Baseline Design: Flow Path

1. Engine Starts Up
2. Air Enters Compressor
3. Air Passes Along Outside of Casing
4. Air Enters Recuperator
5. Recuperator Heats Passing Air
6. Air Enters Combustor
7. Exhaust Passes through Turbine
8. Exhaust heats Recuperator Manifold



Functional Block Diagram



Critical Project Elements

CPE 1: Thermal-Fluid Modeling

- System **Characterization**

CPE 2: Heat Exchanger

- **Manufacturing**, Cost, Integration

CPE 3: Engine Electronics

- **Control**, Safety, Sensors

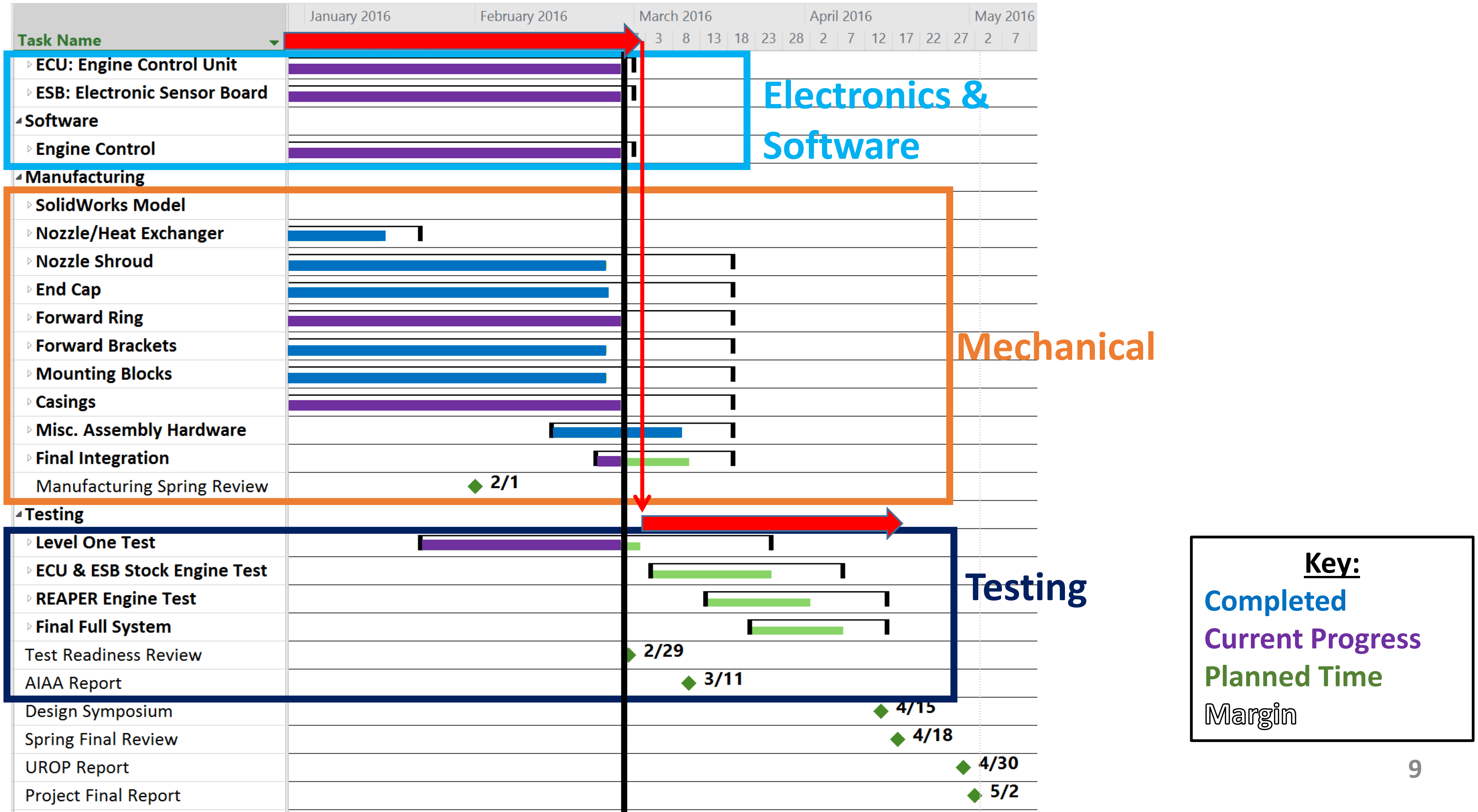
CPE 4: Testing

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

Levels of Success

	Simulation	Recuperator
Level 1	(CPE 1 - Model) -Develop first order, steady state model -Model heat exchanger effectiveness, specific fuel consumption and thrust ✓	(CPE 2 – Heat Exchanger) (CPE 4 – Testing) -Recuperator designed and manufactured -Recuperator verified with engine analog
Level 2	-Model transient characteristics ✓	(CPE 3 – Engine Electronics) -Recuperator is integrated onto engine -Integrated engine system starts and runs
Level 3	-Develop CFD model -Model is verified with test data ✓	-Engine system operates for throttle range -Engine system meets design requirements

Schedule



Task Name
January 2016
February 2016
March 2016
April 2016
May 2016
3 8 13 18 23 28 2 7 12 17 22 27 2 7
ECU: Engine Control Unit
ESB: Electronic Sensor Board
Software
Engine Control
Manufacturing
SolidWorks Model
Nozzle/Heat Exchanger
Nozzle Shroud
End Cap
Forward Ring
Forward Brackets
Mounting Blocks
Casings
Misc. Assembly Hardware
Final Integration
Manufacturing Spring Review
2/1
Testing
Level One Test
ECU & ESB Stock Engine Test
REAPER Engine Test
Final Full System
Test Readiness Review
2/29
AIAA Report
3/11
Design Symposium
4/15
Spring Final Review
4/18
UROP Report
4/30
Project Final Report
5/2
Electronics & Software
Mechanical
Testing
Key:
Completed
Current Progress
Planned Time
Margin

Testing

Testing Overview

Heat Exchanger Verification

Description: Concentric pipe flow with heat exchanger for measured recuperation (ΔT)

Take Away: Is our model correct?

Custom ECU & ESB Test

Description: System test with stock Jet Cat P90RXi engine and REAPER electronics

Take Away: Can our custom ECU/ESB run an engine safely?

Integrated Engine Test

Description: System test with REAPER recuperating engine and REAPER electronics

Take Away: Can our modified engine run?

Full System Test

Description: Full system test with REAPER electronics, recuperating engine, and sensors

Take Away: Did we improve the stock engine?

Level 1 Success

Level 2 Success

Level 3 Success

Heat Exchanger Verification Overview

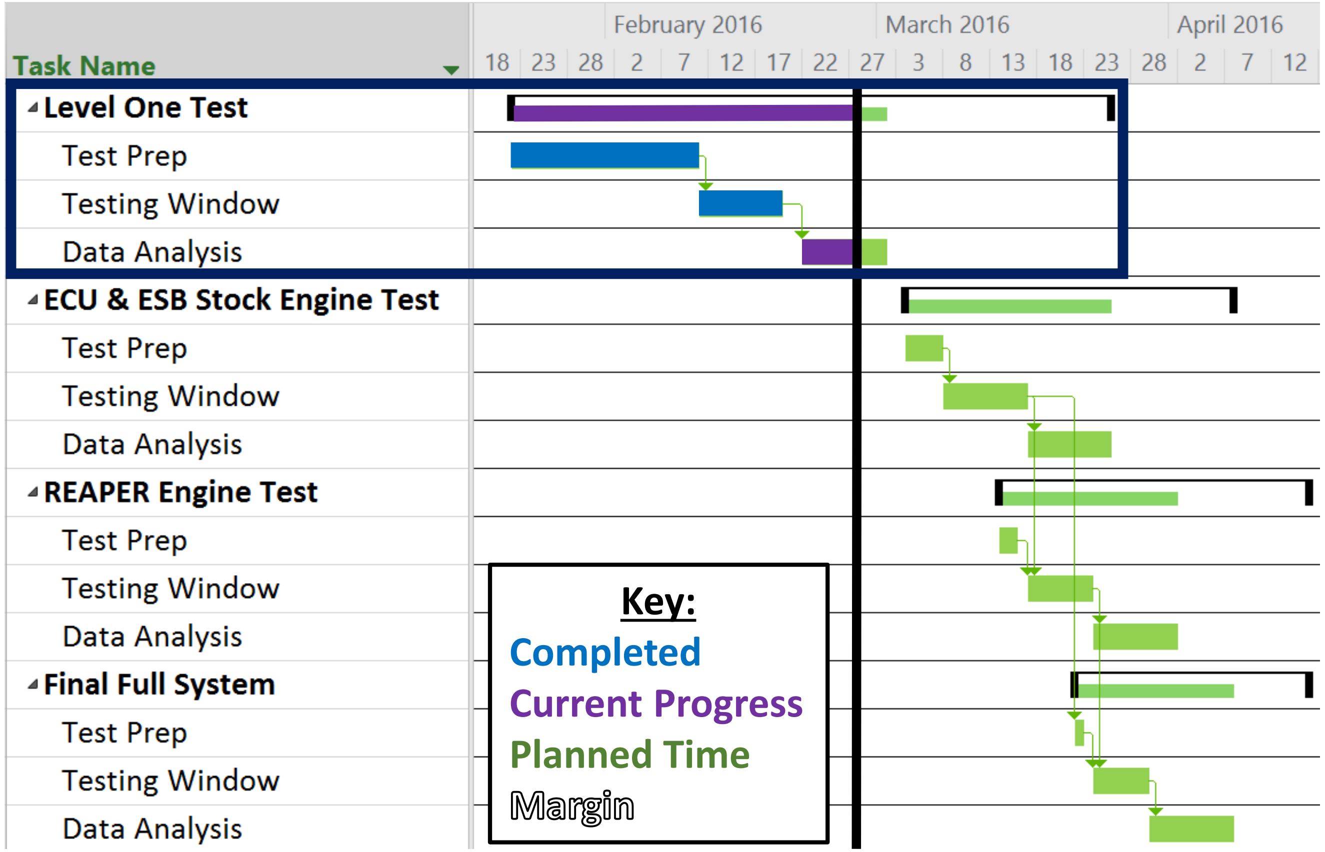
Test Dates: 2/11-2/19

Purpose:

- Measure temperature change across concentric flow heat exchanger to validate model

Main Test Equipment:

- REAPER Nozzle-Heat Exchanger
- Thermistors (Cold side)
- K-Type Thermocouples (Hot side)
- Pitot Tube/Manometer

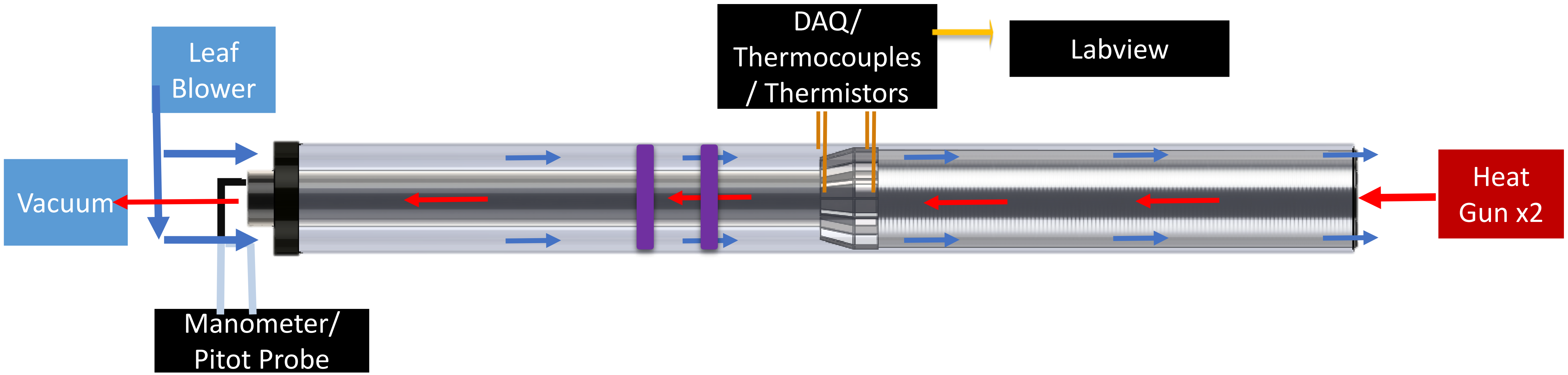


Estimated Hours Remaining: 10 hours

Workforce: 2

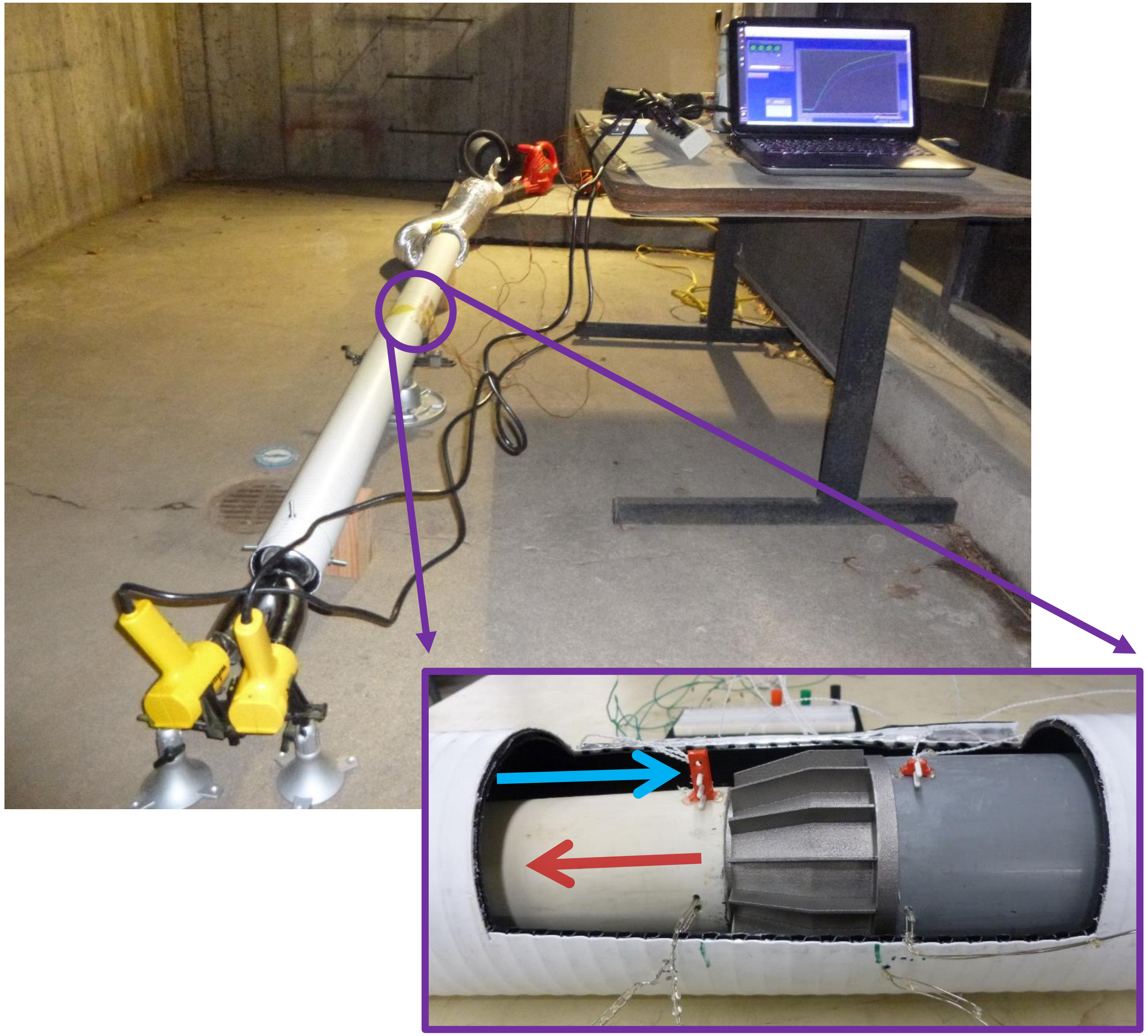
Scheduled Time after TRR: 15 hours

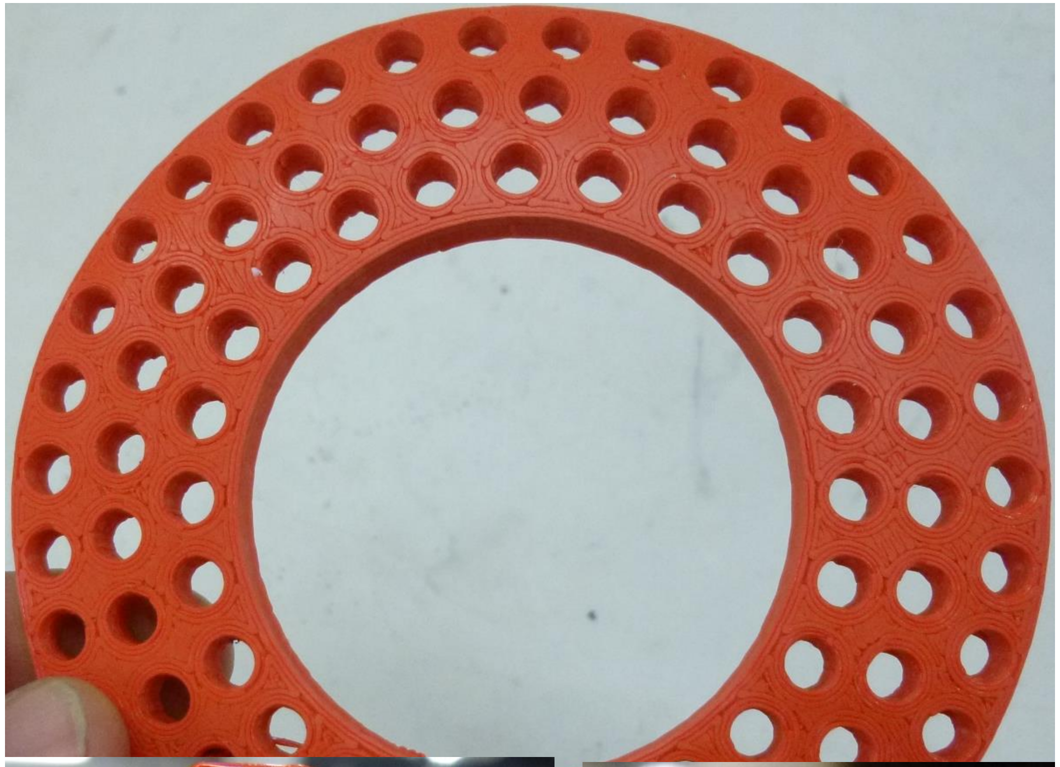
Heat Exchanger Verification

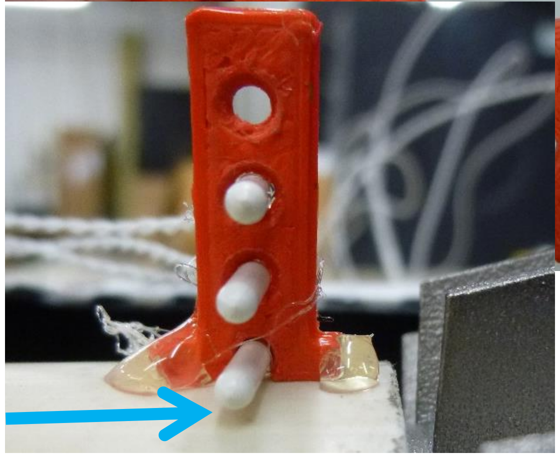


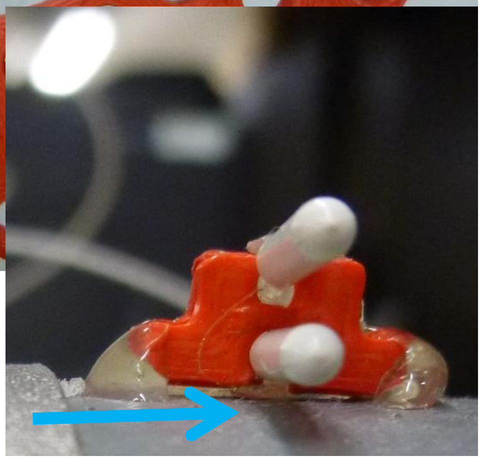
Sensor List	Error	Expected Sample Range	Sample Rate
Thermocouples	+/- 2°C	Hot Flow 100-300°C	1Hz
Thermistors	+/- 0.2°C	Cold Flow 10-40°C	1 Hz
Pitot Static Tube	+/- 1 m/s	5-40m/s	N/A

Heat Exchanger Verification



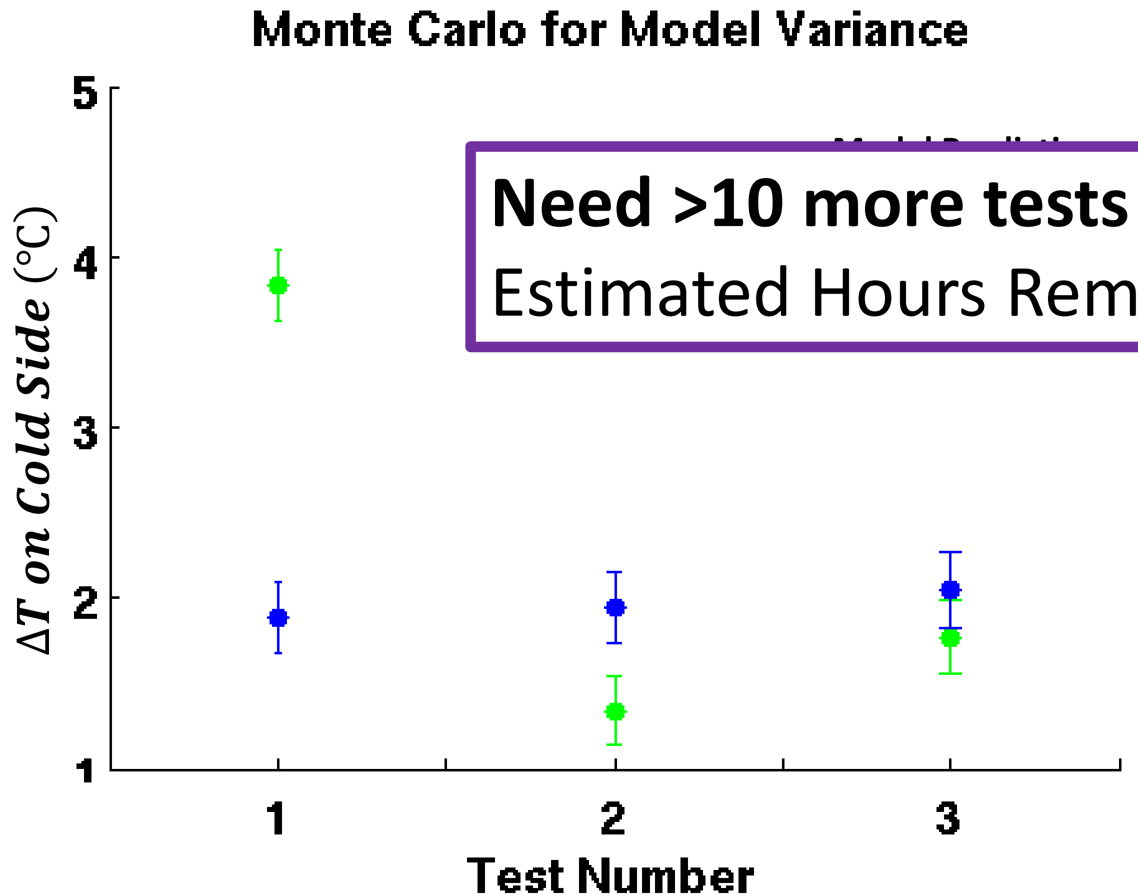






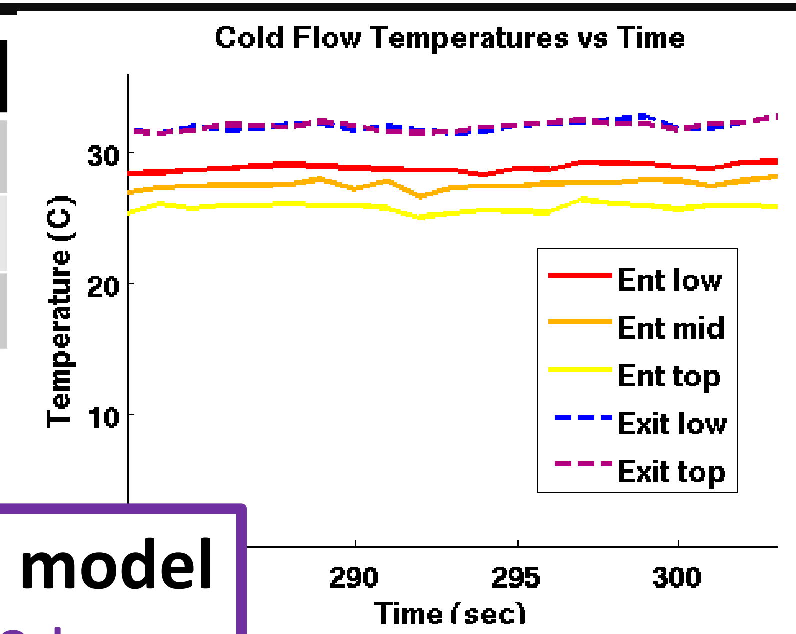
Heat Exchanger Verification

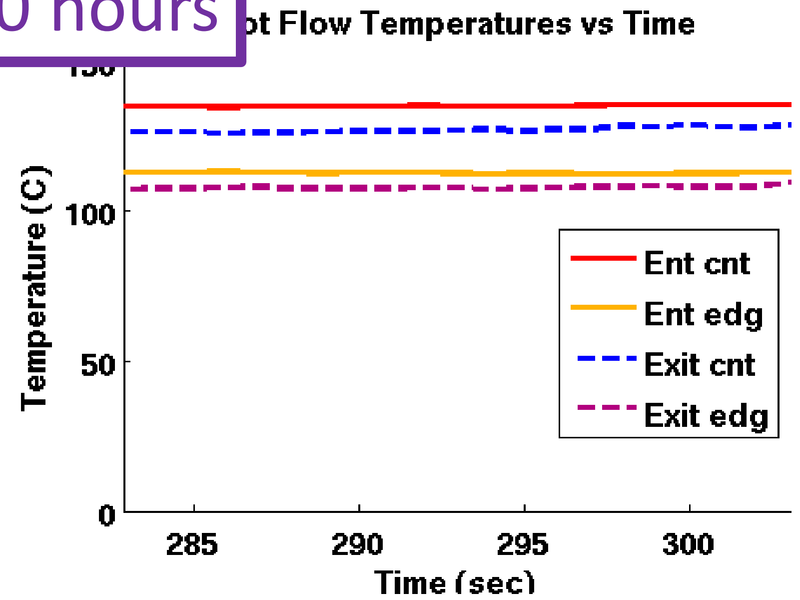
Test	Model	Experimental	Percent Difference
Test 1	1.9+/- 0.2 °C	3.83 +/-0.2°C	+102%
Test 2	2.0 +/-0.2 °C	1.34 +/-0.2°C	-32%
Test 3	1.8+/- 0.2 °C	1.77 +/-0.2°C	-14%



Need >10 more tests to prove model

Estimated Hours Remaining: 10 hours





ECU & ESB Stock Engine Test Overview

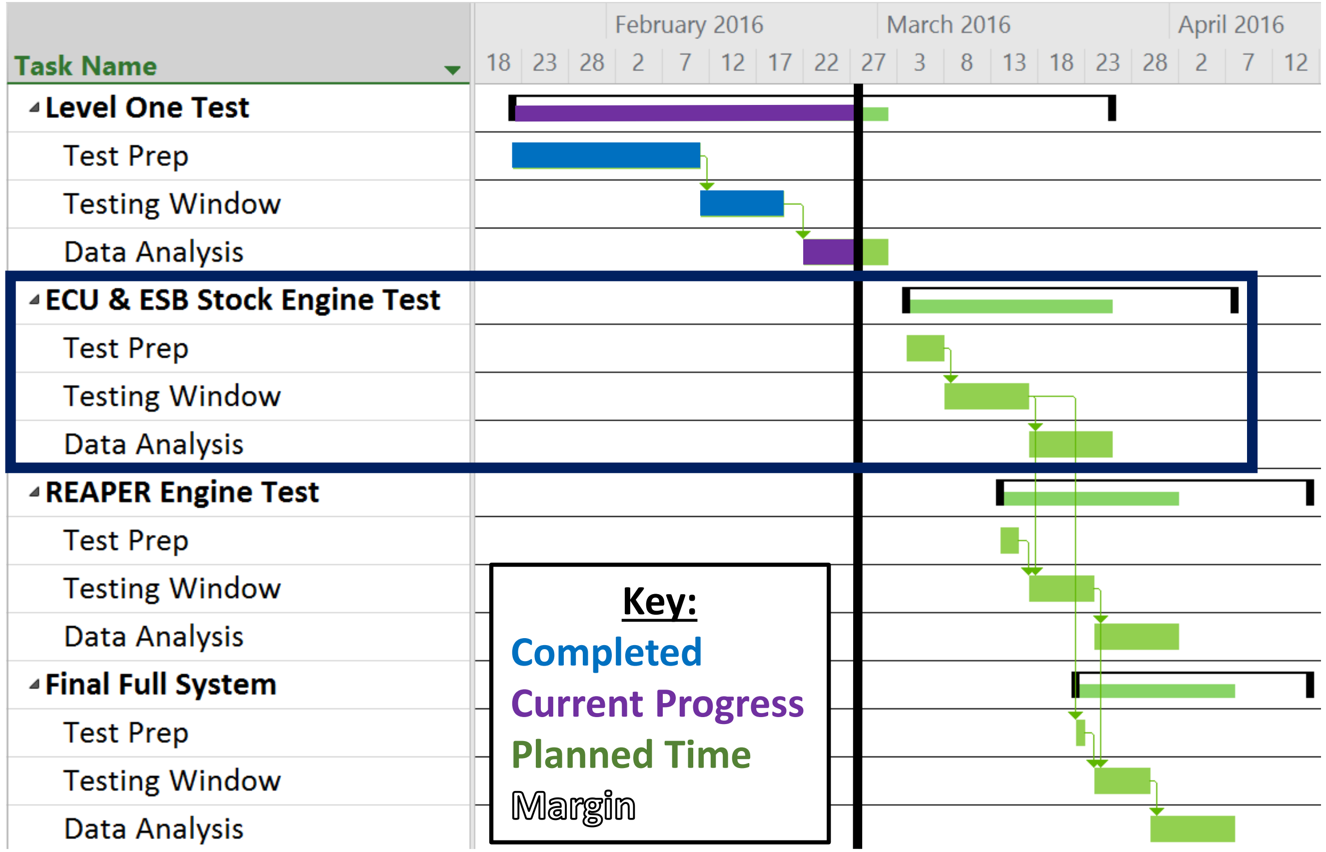
Test Dates: 3/8-3/16

Purpose

- Collect stock thrust and fuel consumption rate data
- Ensure custom ECU and ESB operates engine safety
- Partial Level 2 Success

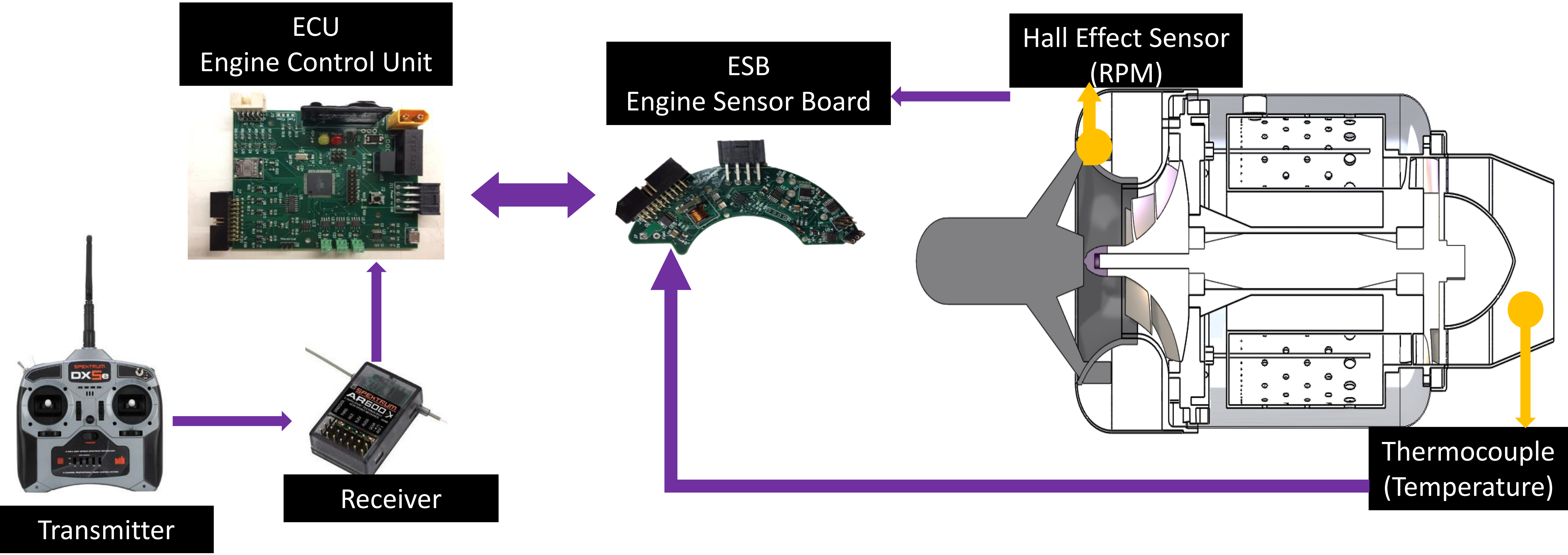
Main Test Equipment

- JetCat stock P-90RXi engine
- Custom Engine Control Unit and Electronic Sensor Board



Estimated Hours Remaining: 25 hours
Workforce: 4
Scheduled Time after TRR: 35 hours

ECU and ESB Verification

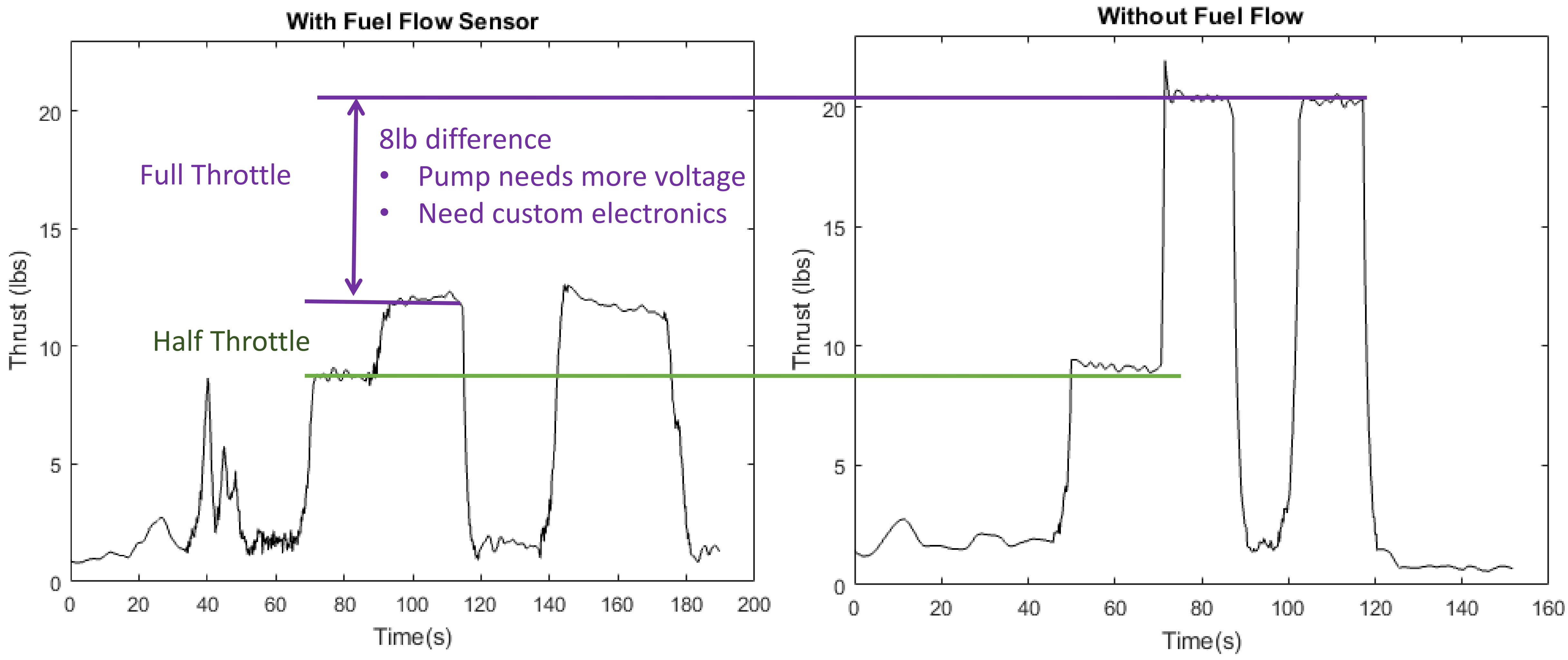


Sensor List	Error	Expected Range	Sample Rate
Thermocouple	±2.5 °C	0-900 °C	31 Hz
Hall Effect	±0.05%	0- 130,000 rpm	31 Hz

Preparation For Stock Engine Test

- Stock engine tests:
  - Show preparedness for ECU/ESB Engine Test
  - Show sensors used in TSFC are ready
- Progress
  - 2/26 full characterization of engine with fuel flow sensor and load cell
  - Efficient setup and trouble shooting issues
- Concerns
  - Weather- tests cut short due to wind and cold temperatures

Stock Engine Thrust Data



Max RPM = 109,500

Max RPM = 130,000

Engine Electronics

- Two Custom Printed Circuit Boards:
  - Engine Control Unit (ECU)

(back)

  - Engine Sensor Board (ESB)

(back)

EE: Testing Tree

Single Component Testing (complete)

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

Bench Top Testing (in progress)

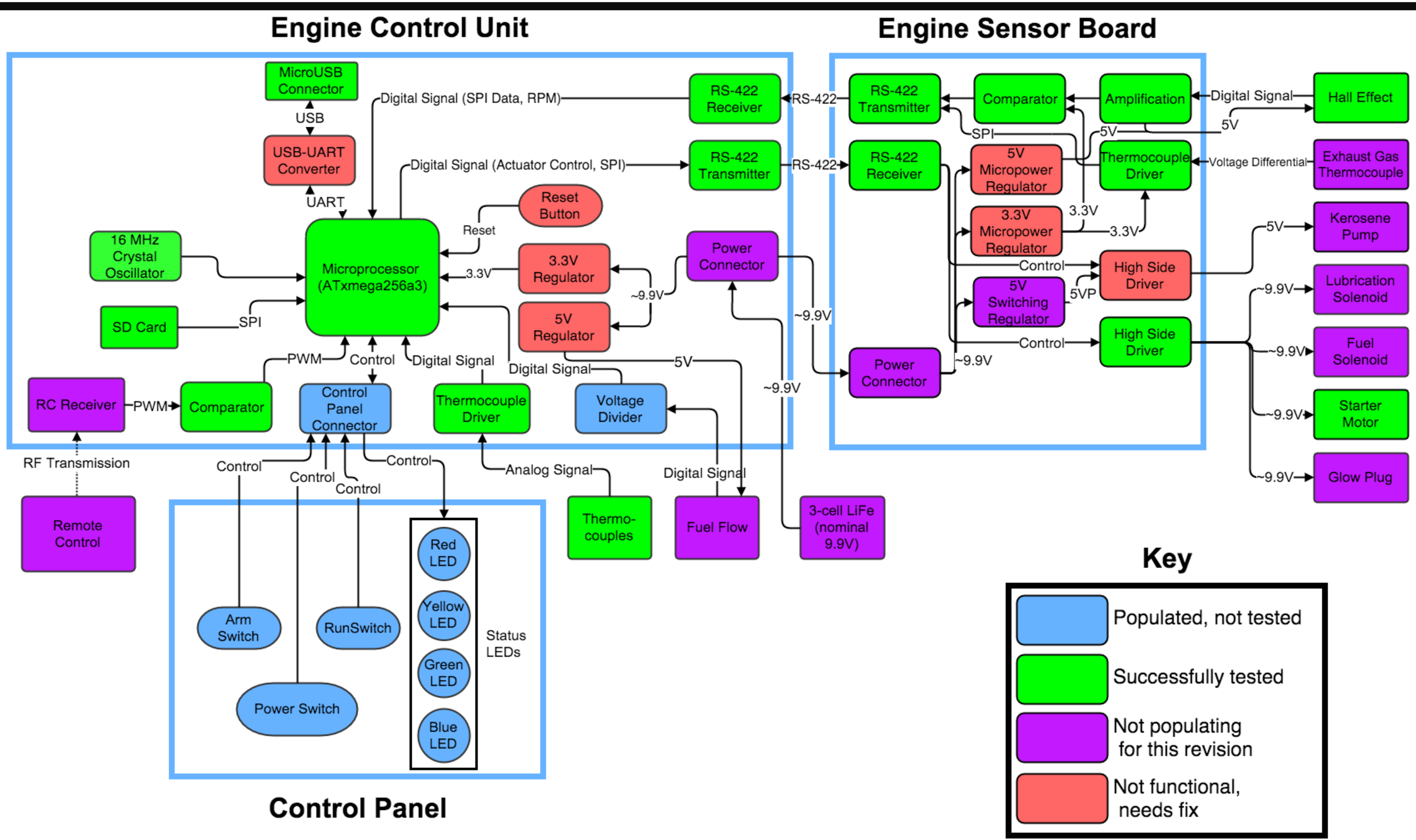
- Sensor integration (hall effect, thermocouple, fuel flow)
- Actuator integration
- Full "engine test" run without connecting to engine

Stock Engine Test (upcoming)

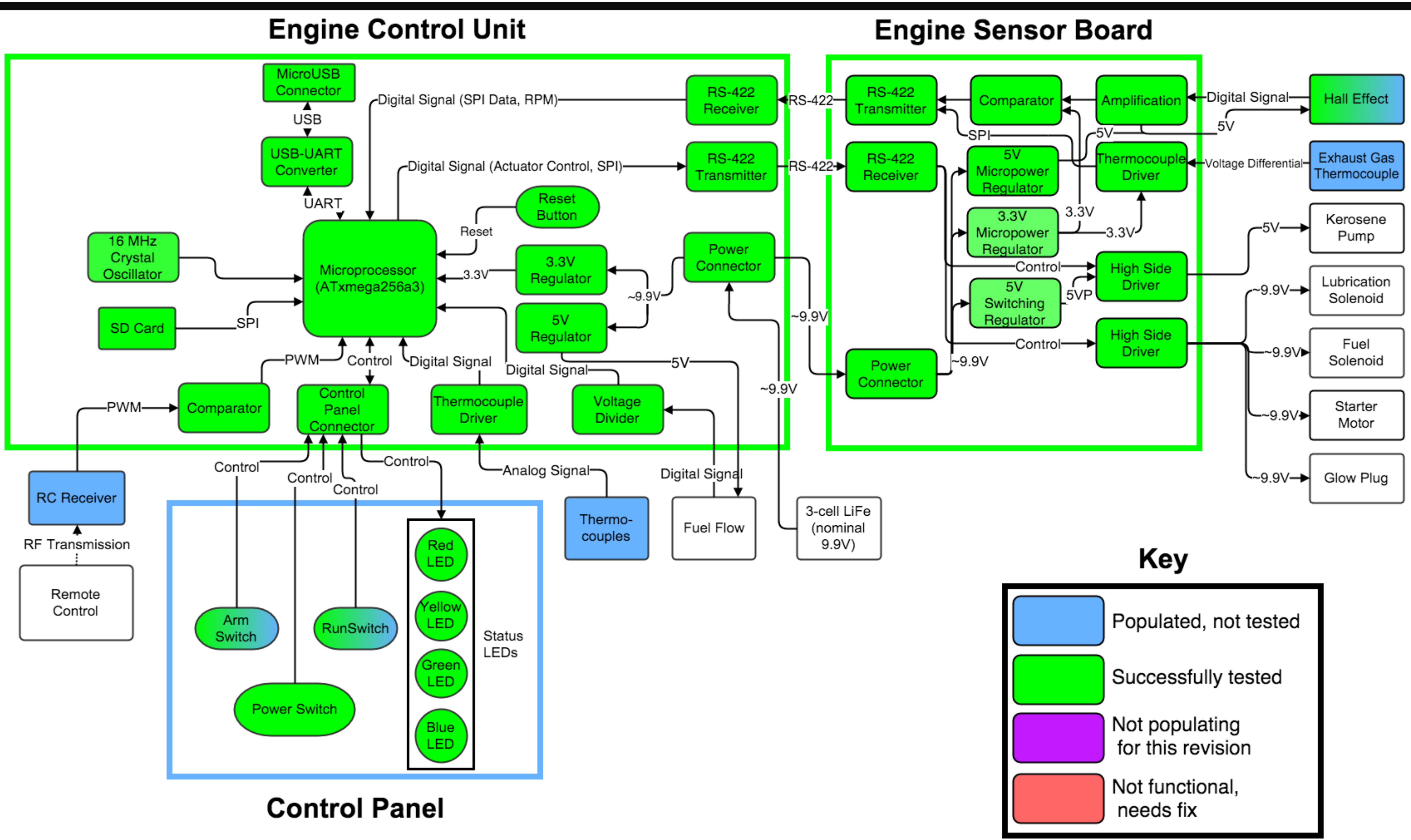
- Engine integration
- Full engine test

Estimated Hours Remaining: 15 hours
Workforce: 2
Scheduled Time after TRR: 20 hours

EE: Rev. 1 Final Status



EE: Rev. 2 Current Status



Engine Electronics: Software Progress

High Level

Final Implementation

Hardware Interface Layer

SD Card

Hall Effect

Thermocouples

Fuel Flow

Glow Plug

Starter motor

Low Level Interface

SPI

Oscillator

Interrupts

USART

PWM

KEY

Validated

Written

Incomplete

Estimated Hours Remaining: 12 hours

Workforce: 1

Scheduled Time after TRR: 15 hours

Integrated Engine Test Overview

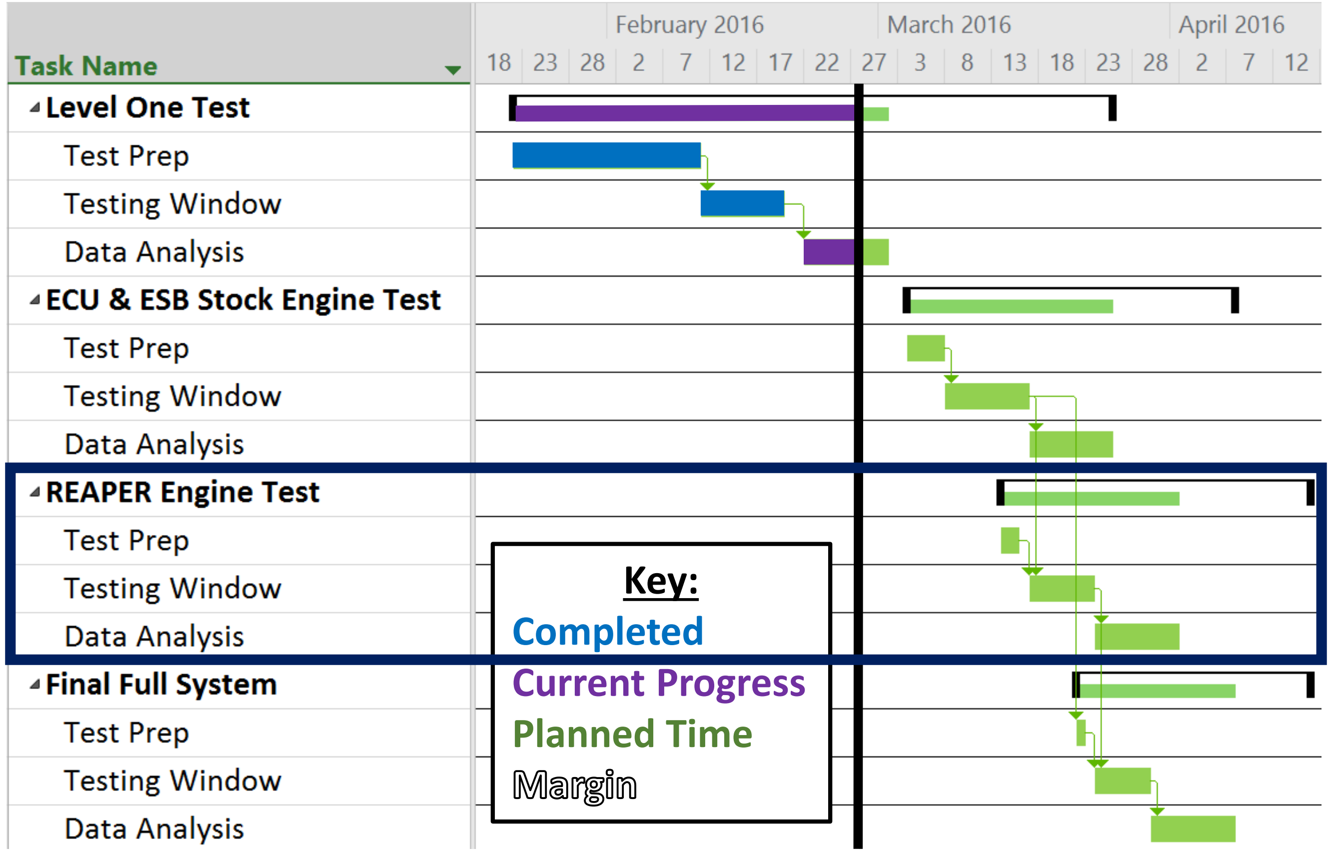
Test Dates: 3/17-3/23

Purpose

- Ensure REAPER engine starts
- Ensure custom ECU and ESB operates engine safety
- Reach Level 2 Success

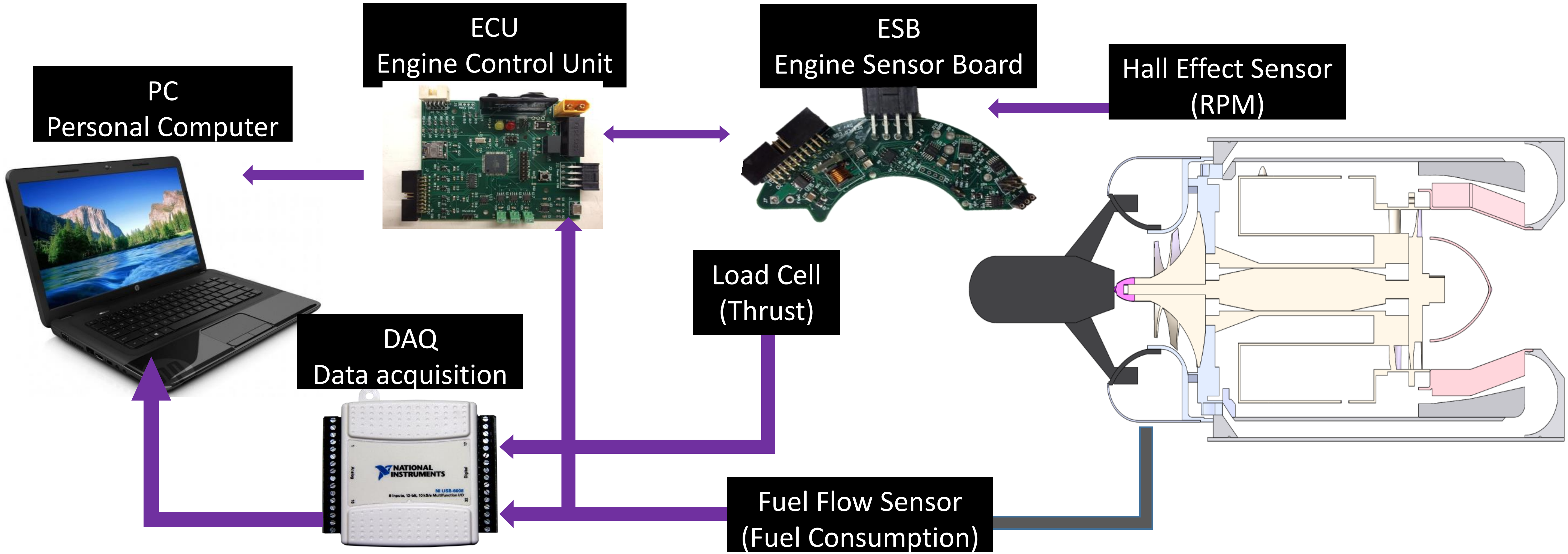
Main Test Equipment

- Modified P-90RXi engine
- Custom Engine Control Unit and Electronic Sensor Board



Estimated Hours Remaining: 25 hours
Workforce: 4
Scheduled Time after TRR: 35 hours

Integrated Engine Test Validation



Sensor List	Error	Expected Range	Sample Rate
Fuel Flow Sensor	±1%	0-5 mL/s	31 Hz
25lb Load Cell	±0.2%	0- 22 lbs	1 Hz
Hall Effect	±0.05%	0- 130,000 rpm	31 Hz

Full System Test Overview

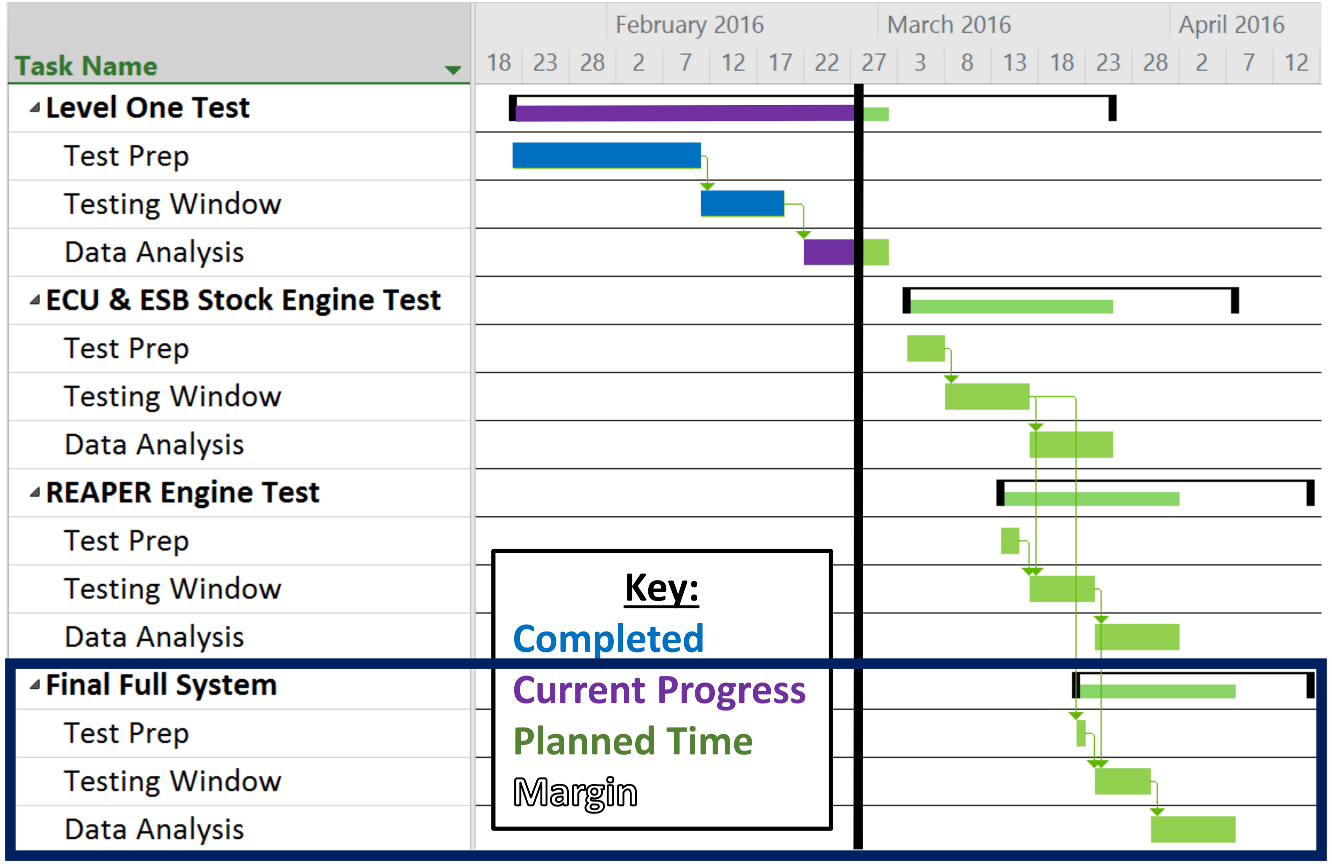
Test Dates: 3/24-3/29

Purpose

- Ensure REAPER engine starts
- Collect TSFC data
- Reach Level 3 Success

Main Test Equipment

- Modified P-90RXi engine
- Custom Engine Control Unit and Electronic Sensor Board
- Fuel Flow Sensor
- Load Cell

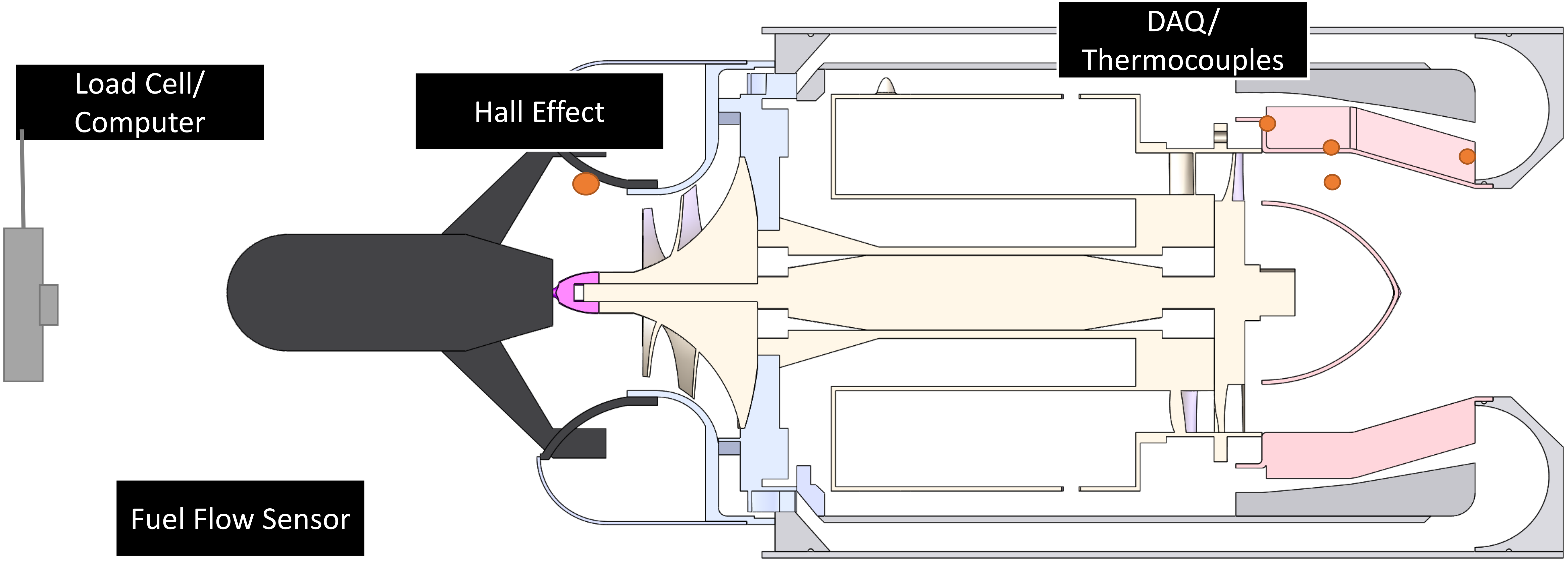


Estimated Hours Remaining: 25 hours

Workforce: 4

Scheduled Time after TRR: 35 hours

Full System Test: Additional Characterization



Sensor List	Error	Expected Range	Sample Rate
Fuel Flow Sensor	±1%	0-5 mL/s	31 Hz
25lb Load Cell	±0.2%	0-22 lbs	1 Hz
Hall Effect	±0.05%	0-130,000 rpm	31 Hz
Thermocouples	±2.5 °C	0-900 °C	31 Hz

Control Volume Model

Conservation Laws

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

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

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

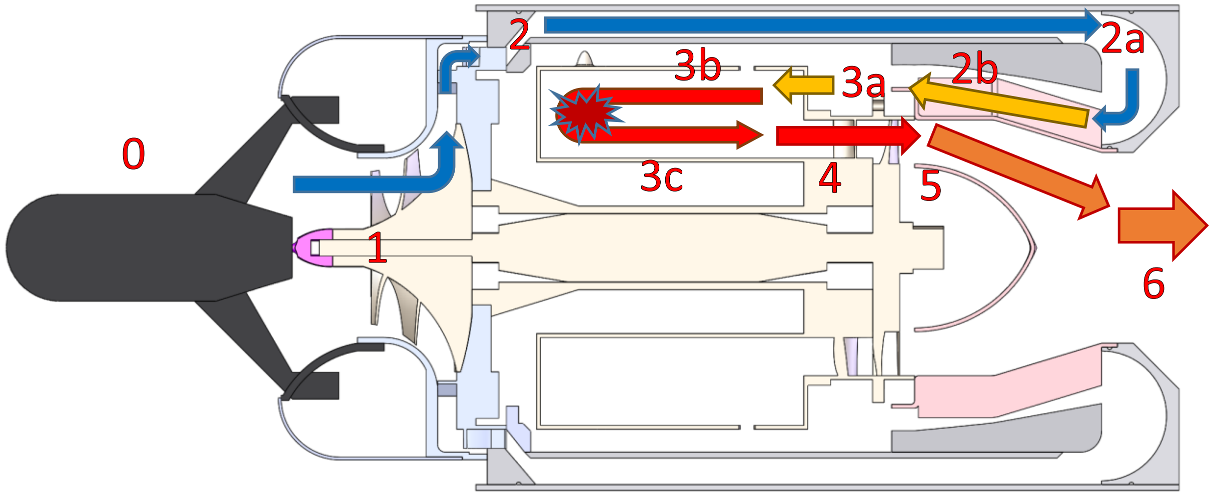
Constitutive: $p = \rho R T$

Loss Sources

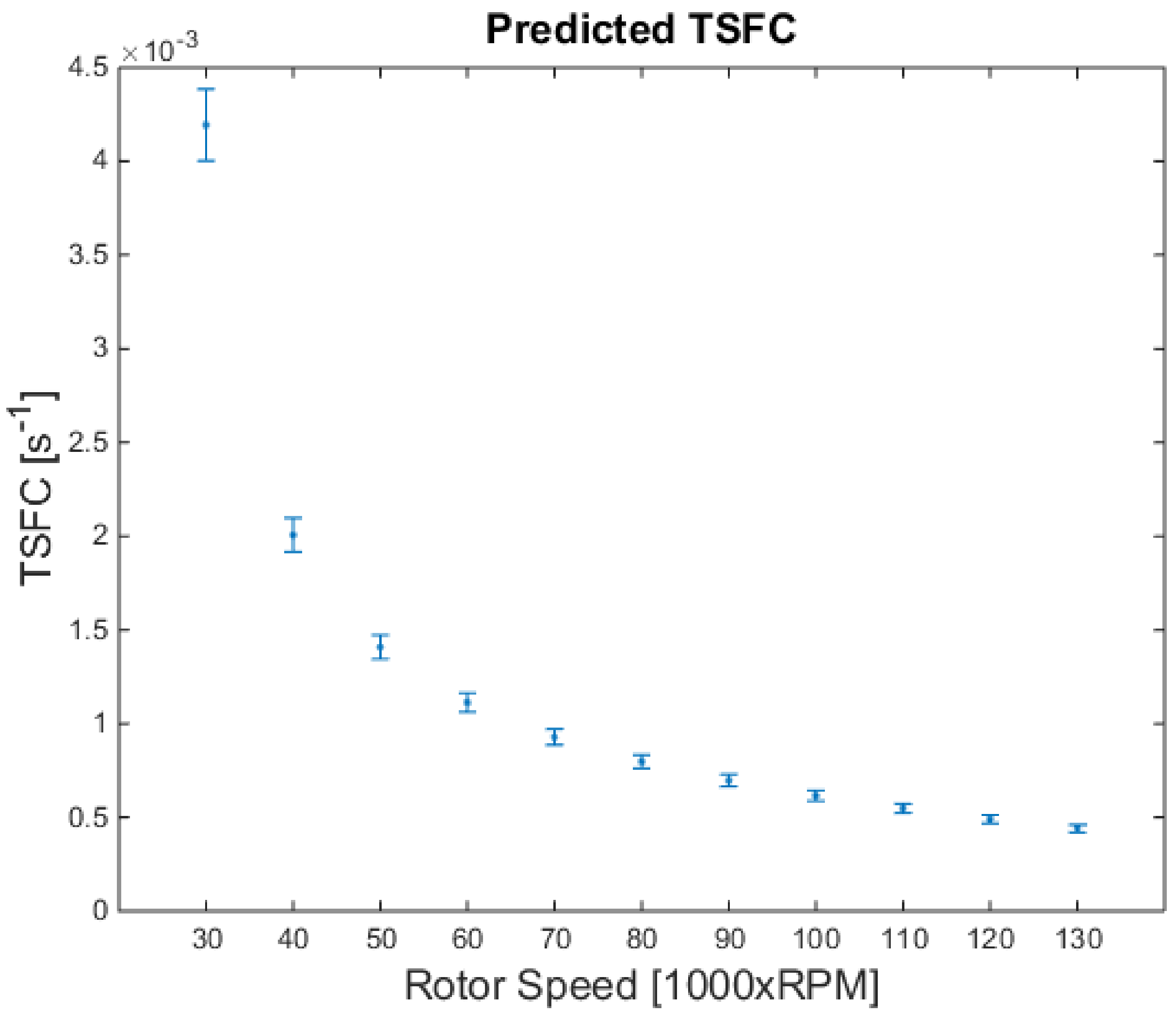
- Friction (Colebrook-White)
- Sudden expansion/contraction
- Gradual Expansion
- Turning the flow

Assumptions/Correlations

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



Control Volume Model – Final Test Prediction



Important Features:

- Fuel consumption increases linearly
- Thrust increase exponentially
- Error concentrated on fuel consumption prediction

Monte Carlo Simulation Sensitivity Variables

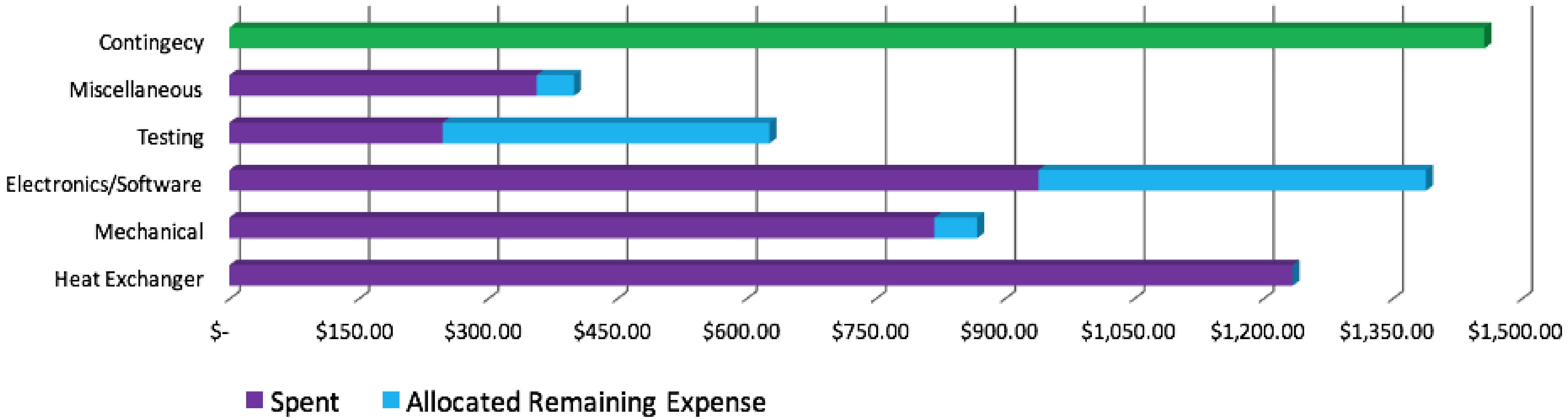
- Engine RPM
- Compressor Efficiency
- Turbine Efficiency
- Combustor Efficiency
- Heat Transfer Coefficients (x2)
- Friction Coefficients (x6)
- Expansion/Contraction Coefficients (x3)
- Flow Diversion Coefficients (x4)
- Environmental conditions

Assume Normal Distribution

$$x = \bar{x} + N(\bar{x}\,, \sigma)$$

Budget

Budget



Total Budget **$5,975**

Total Spent **$3,595**

Remaining Expenses **$880**

Contingency **$1,500**

Remaining Expected Expense	Total Cost
Fuel Flow Inserts	$330
Misc. Integration Hardware	$50
Misc. Electronics Components	$50
Spare Parts for Final Testing	$450
Total	$880

Questions?

Works Cited

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- [12] "Stainless Round 304/304L 4.25 inch." *OnlineMetals.com.* Web. Accessed 29 Nov. 2015. <https://www.onlinemetals.com/merchant.cfm?pid=124 &step=4&showunits=inches&id=6&top_cat=1#>
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Backup Slides

Testing Overview Backup Slides

Testing Tree

Level 1

- **1.a** Initial proof of concept test rig for correct flow
- **1.b** Test and calibrate sensors
  - **1.b.1** Pitot probe/ manometer in wind tunnel
  - **1.b.2** Thermistors and thermocouples/ DAQ in ambient, hot bath, and cold bath
- **1.c** Prove test rig
- **1.d** Sensor placement
  - **1.d.1** Temperature profile sensitivity to heat and flow speed
  - **1.d.2** Velocity profile in hot and cold flow
- **1.e** Iterate for statistical significance

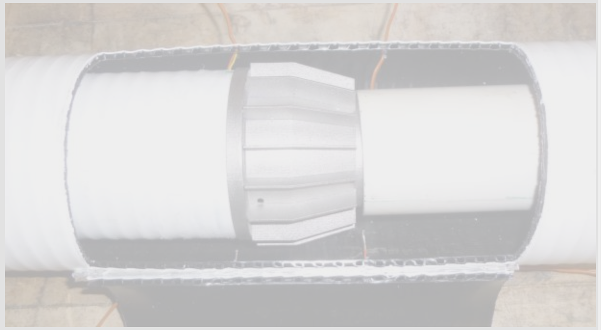
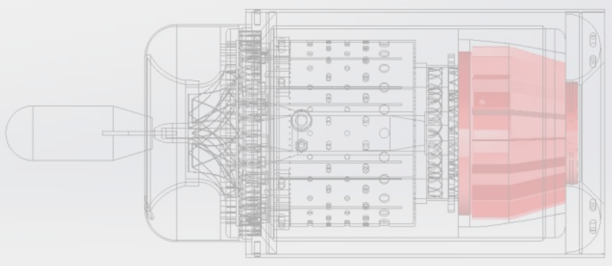
Level 2

- **2.a** Custom electronics/ software control the engine
  - **2.a.1** Unit test ECU and ESB on test bench
  - **2.a.2** Spool up the engine and test expected safeties and sensors
  - **2.a.3** Run engine and verify expected stock conditions are met
- **2.b** Mechanical components integrate with/run engine
  - **2.b.1** Bench fit and leak checks on engine
  - **2.b.2** Integrate and run on engine and verify expected stock conditions met

Level 3

- **3.a** Test and calibrate sensors
  - **3.a.1** Load cell/ Daq with known load values
  - **3.a.2** Fuel flow sensor/ Daq with known flow values
- **3.b** Characterize stock engine
  - **3.b.1** Run stock engine with load cell and fuel flow sensor with throttle range
- **3.c** Run full system test
  - **3.c.1** Fit altered engine with thermocouples
  - **3.c.2** Characterize altered engine with sensors using custom electronics

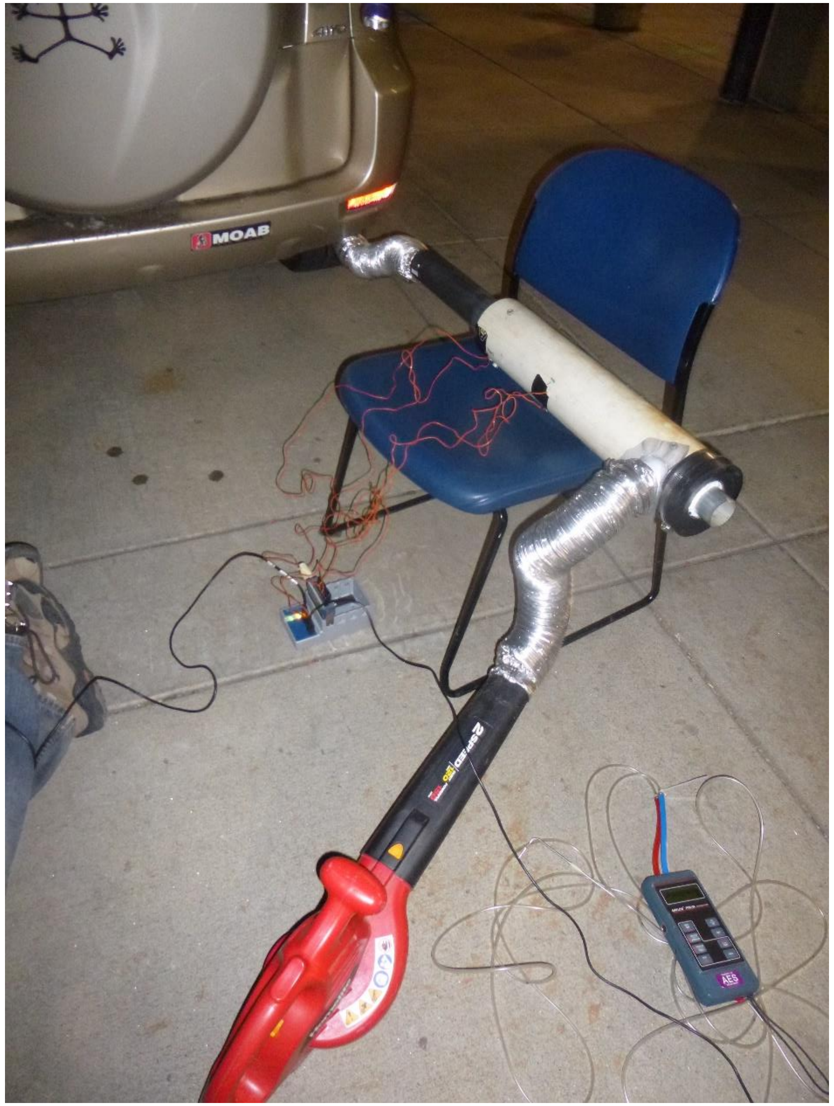
Planned Tests

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

Heat Exchanger Verification Backup Slides

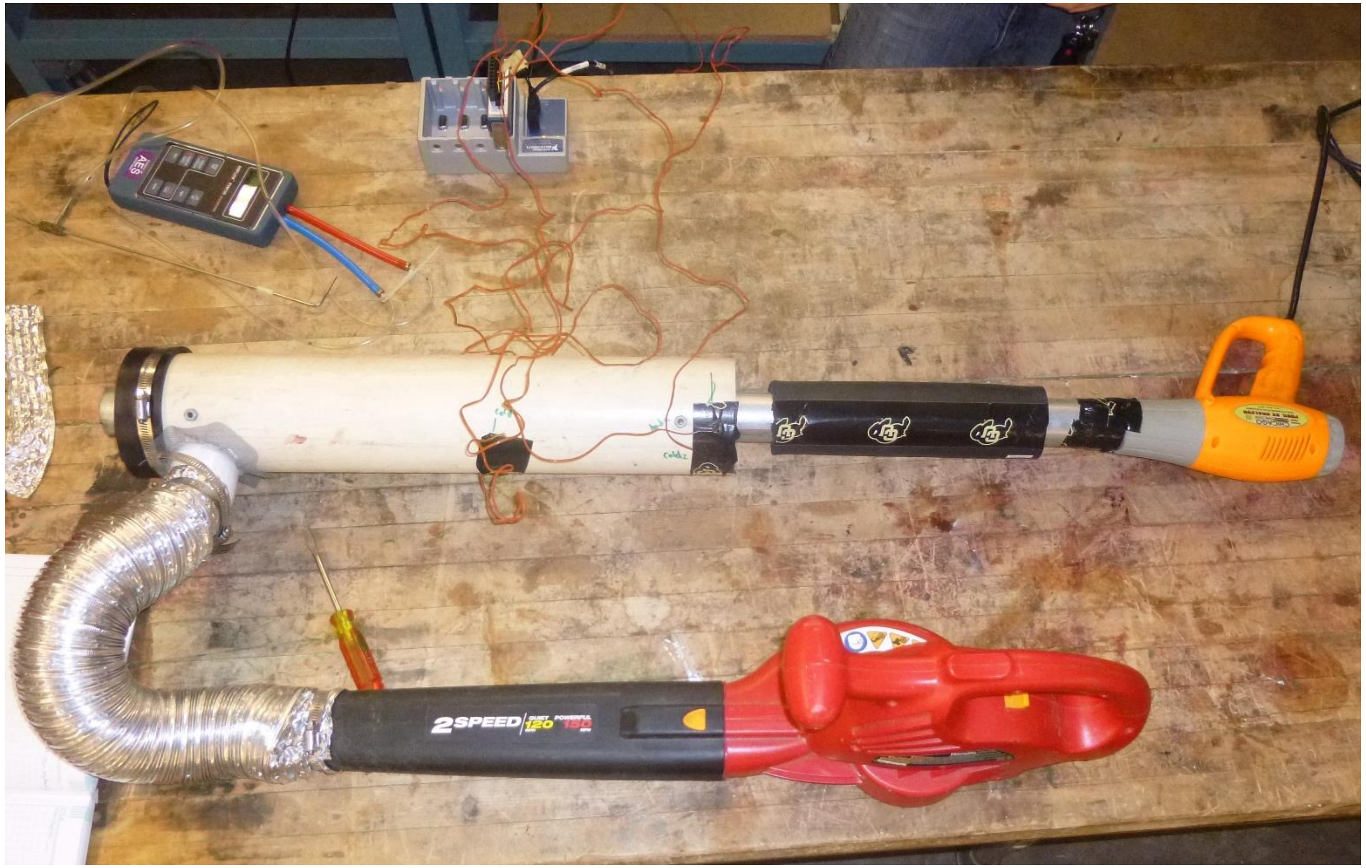
Iterations/ Lessons Learned: Level 0.0

- 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



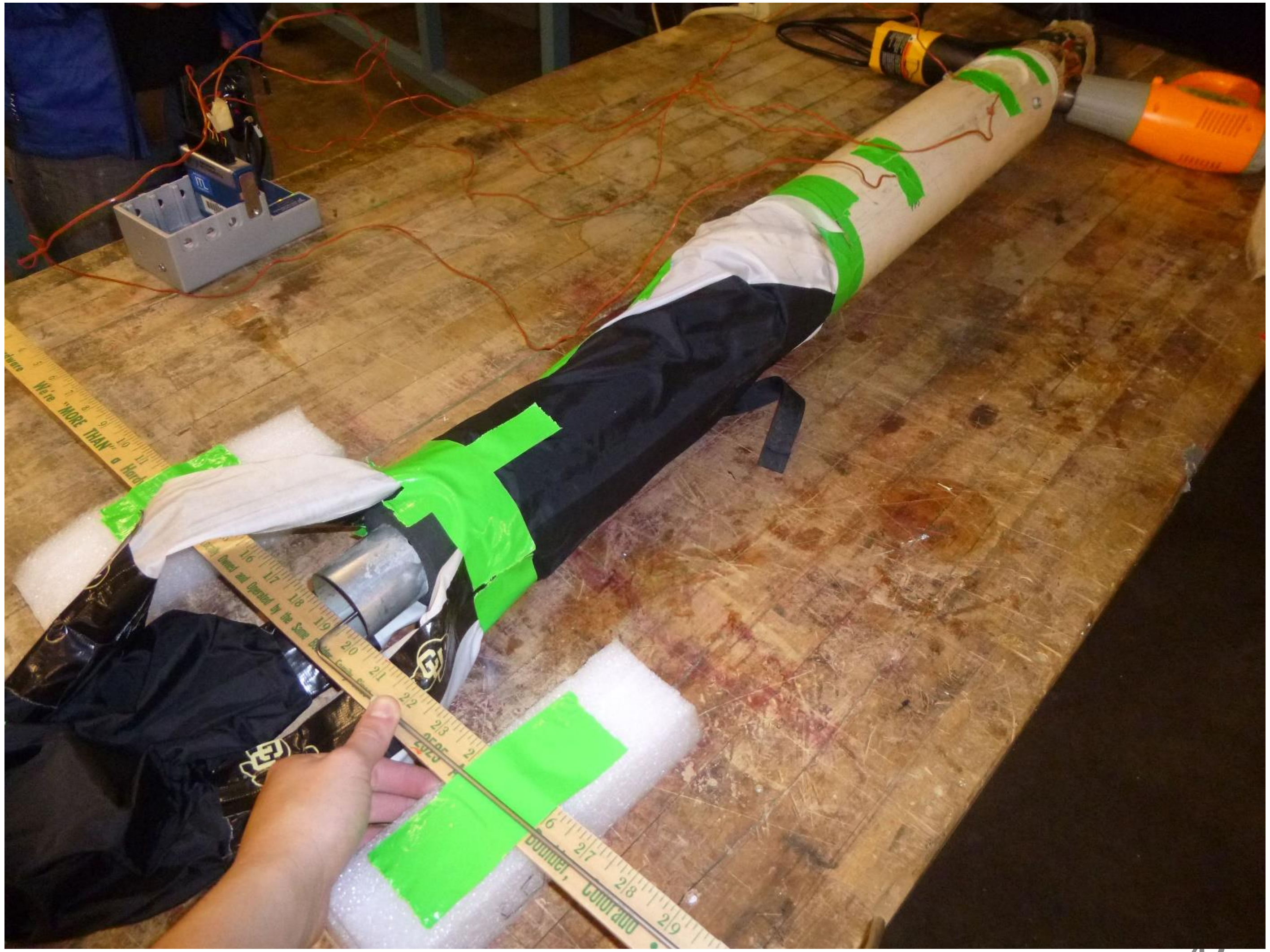
Iterations/ Lessons Learned: Level 0.1

- 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



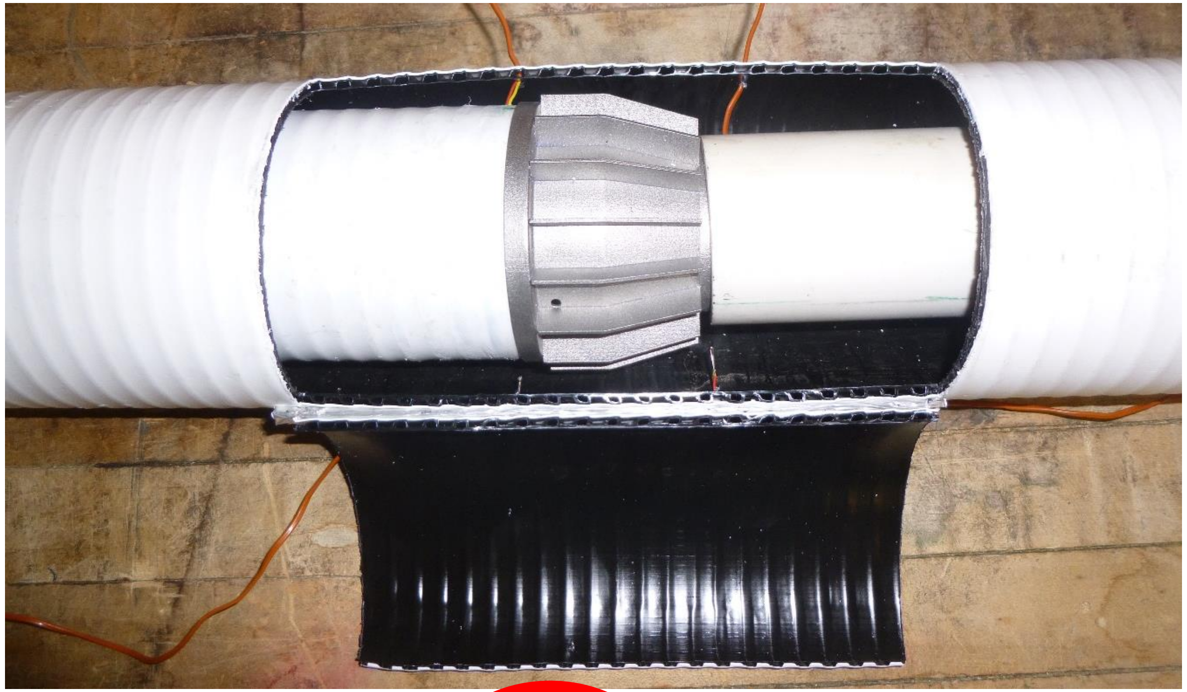
Iterations/ Lessons Learned: Level 0.2

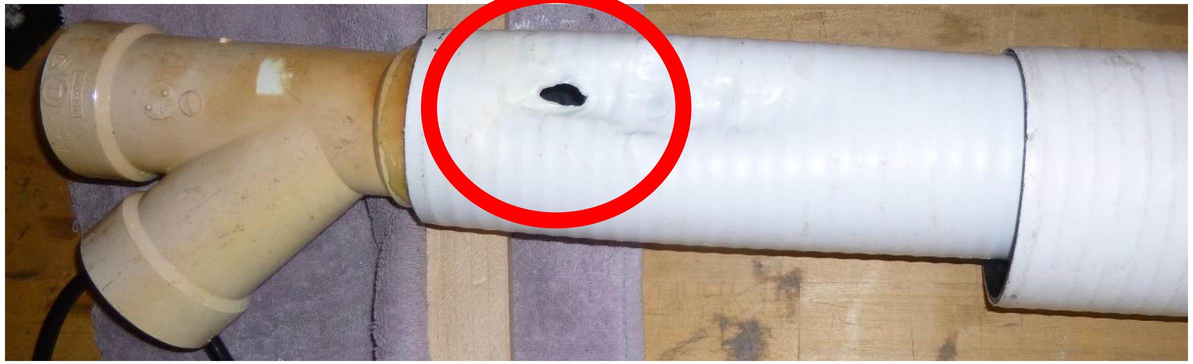
- Description:
  - Concentric pipe flow
  - Cold flow straightened via flow diverter/ shroud
  - Cold flow has longer to develope
  - Two heat guns and additional flow for greater temperature
- Lessons Learned:
  - Heat guns over heated, because hot air was flowing back through them
  - Thermocouples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



Iterations/ Lessons Learned: Level 1.0

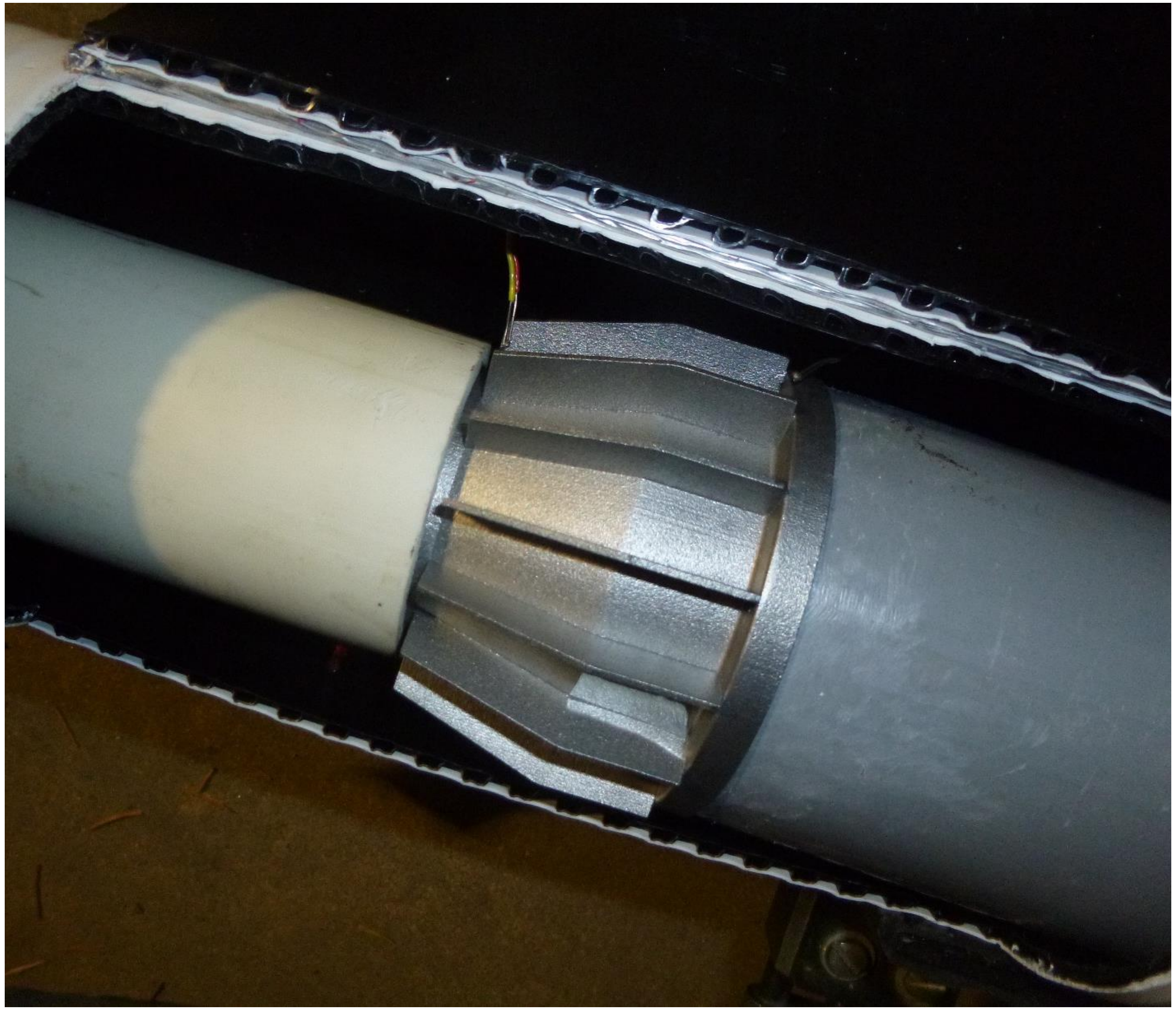
- Description:
  - Concentric pipe flow with heat exchanger
  - Longer heat pipes for developed flow
  - Door cut for easier access to heat exchanger and thermocouples
  - Hot flow pulled down the pipe using a sucking fan, allowing for higher Reynolds number, hotter flow, and less risk for the heat guns
- 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

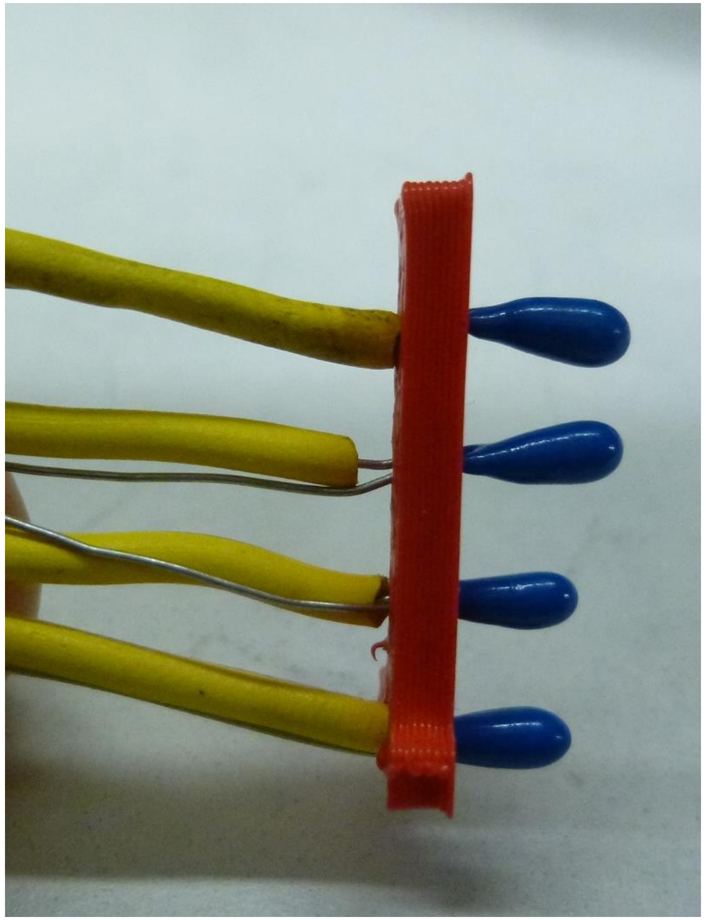
- Description:
  - Concentric pipe flow with heat exchanger
  - Replaced Y-pvc pipe with a Y-car exhaust pipe
- Lessons Learned:
  - A temperature profile is necessary for the cold flow because the thermocouples are very sensitive to placement

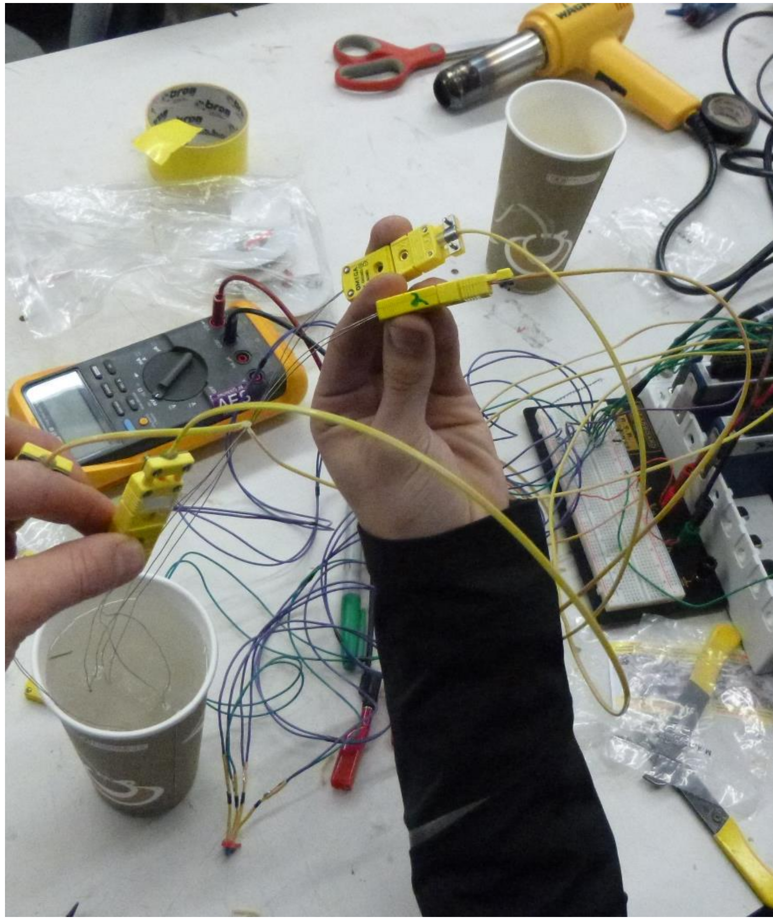
Iterations/ Lessons Learned: Mini test

- 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

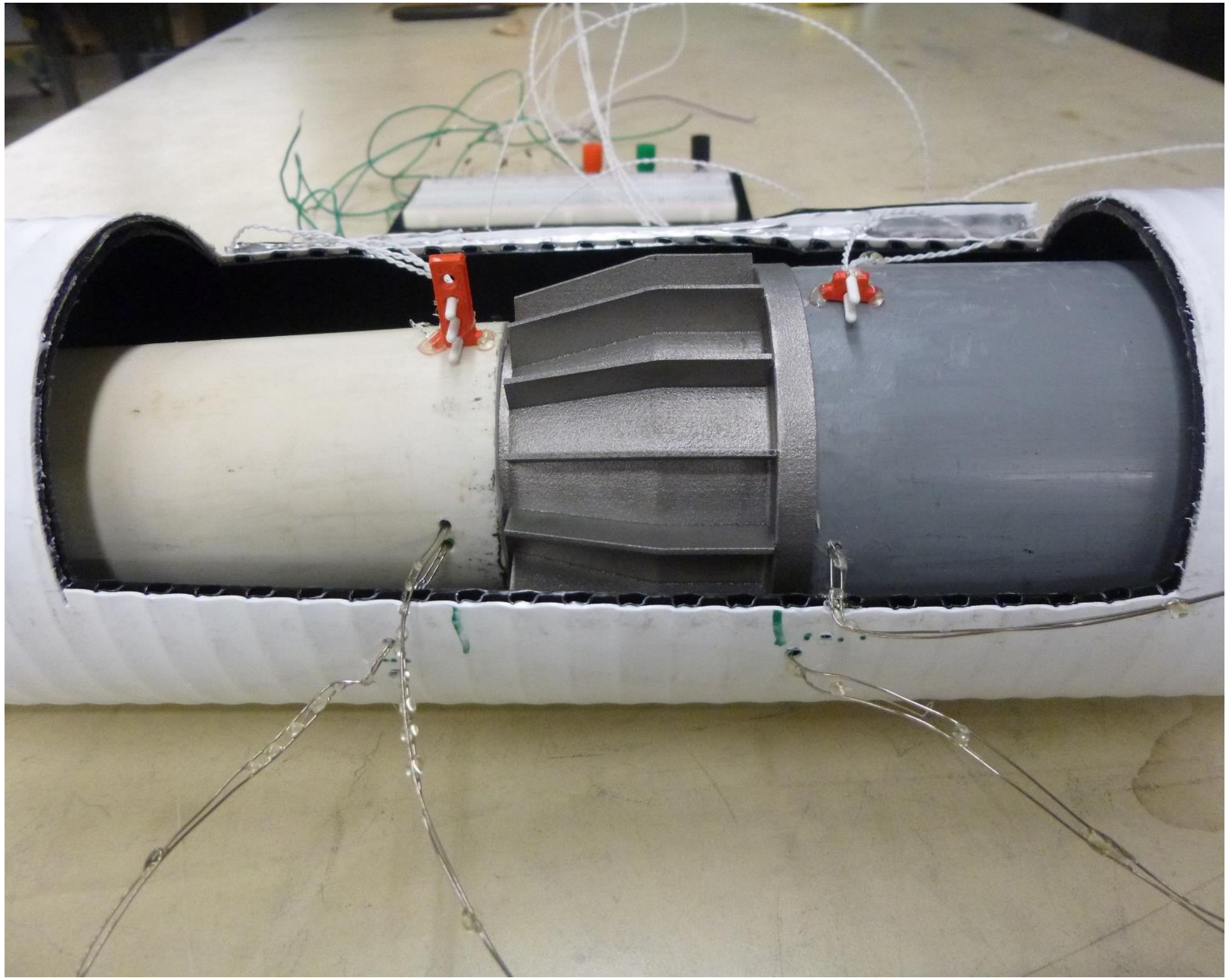
- Description:
  - Concentric pipe flow with heat exchanger
  - 3D printed profile insert for thermistors
  - Made in-house thermocouples with bare wire for easier integration and testing with the Daq
- Lessons Learned:
  - Bare wires are difficult to work with and created poor data when test was run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





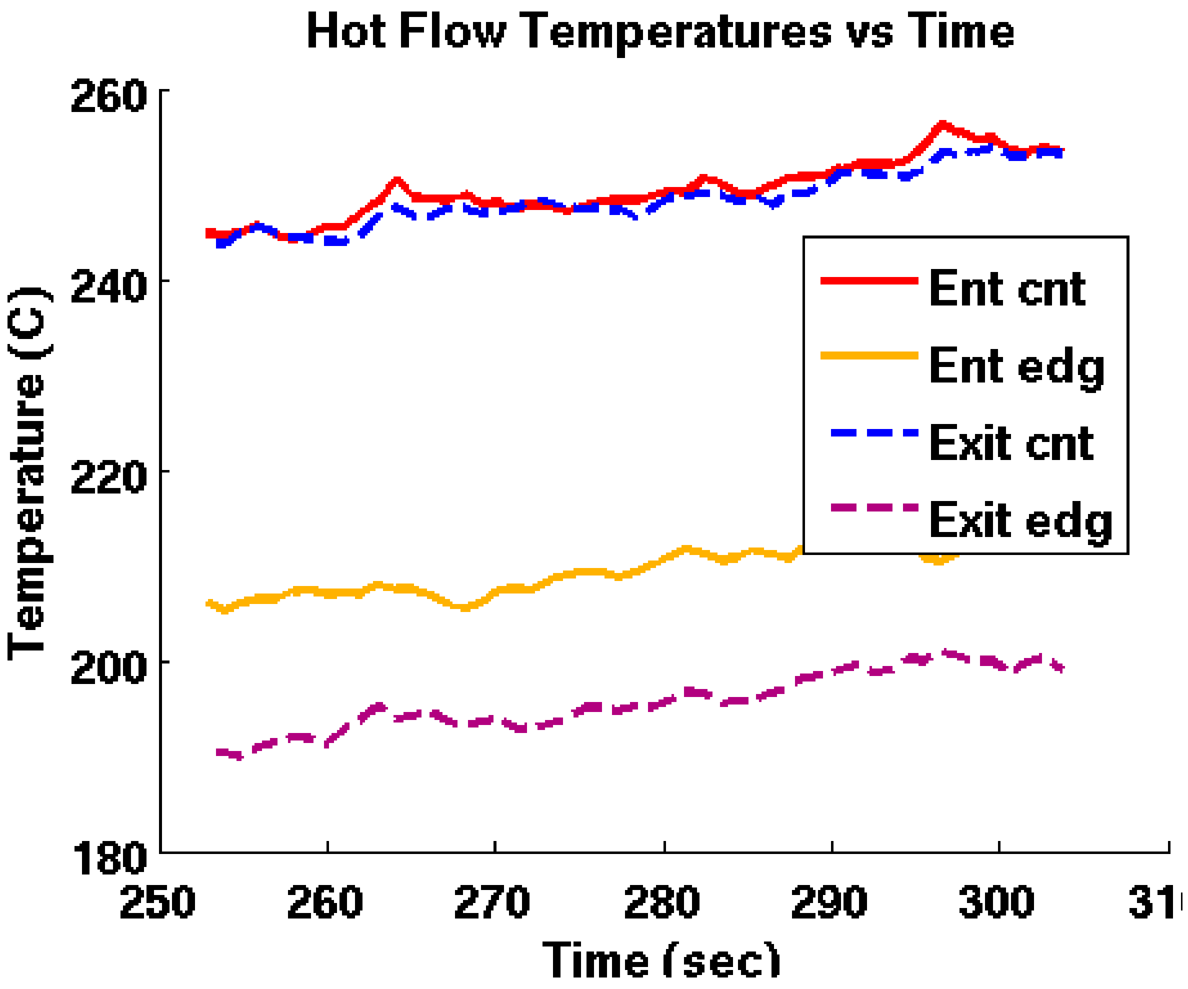
Iterations/ Lessons Learned: Level 1.4

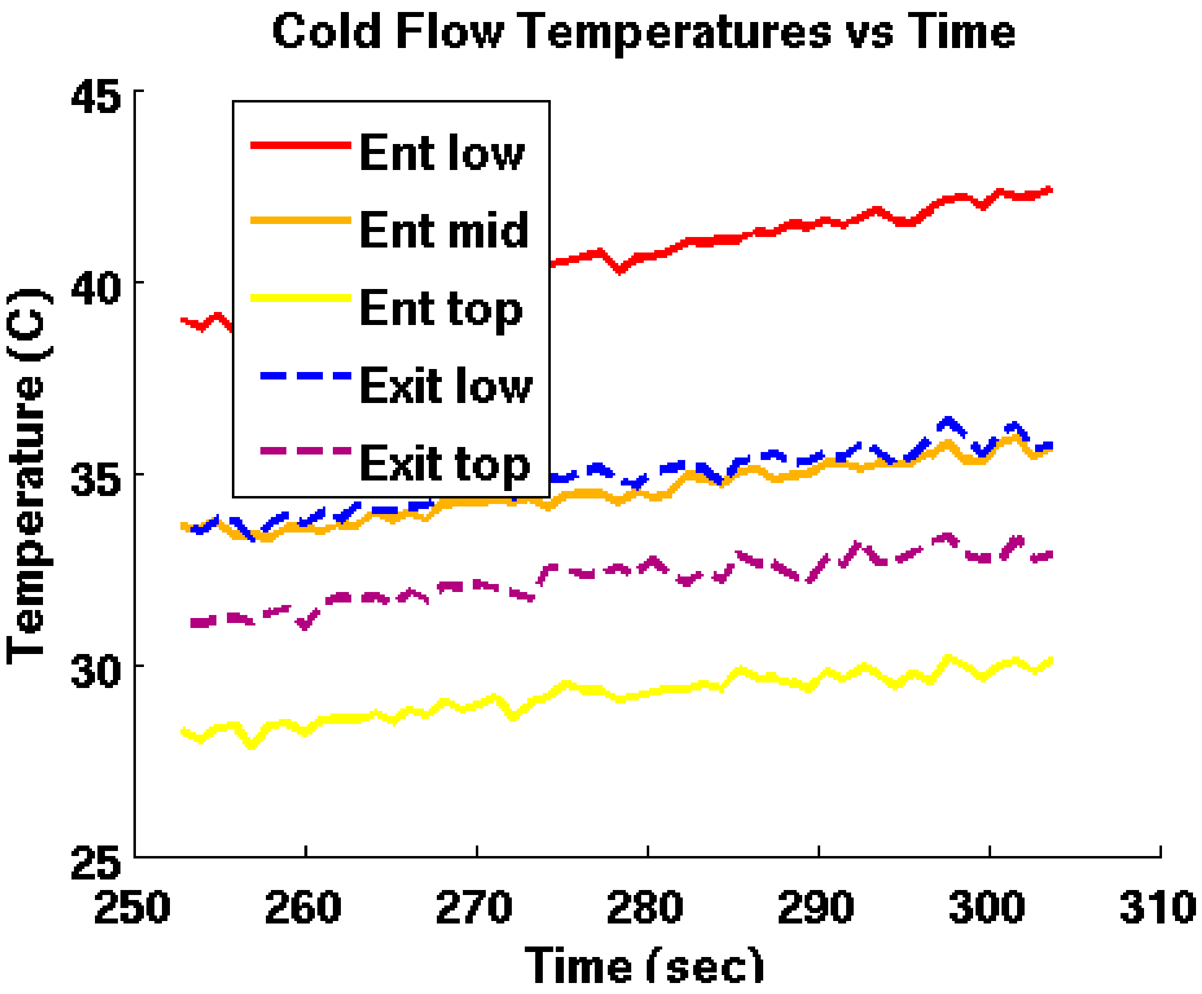
- Description:
  - Concentric pipe flow with heat exchanger
  - Using covered thermistors to prevent wires touching
  - Beaded in-house thermocouples with hot glue to prevent wires touching
- Lessons Learned:
  - Results inconclusive due to: spiraling flow (unexpected stream lines), pressure drops/ unintentional 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



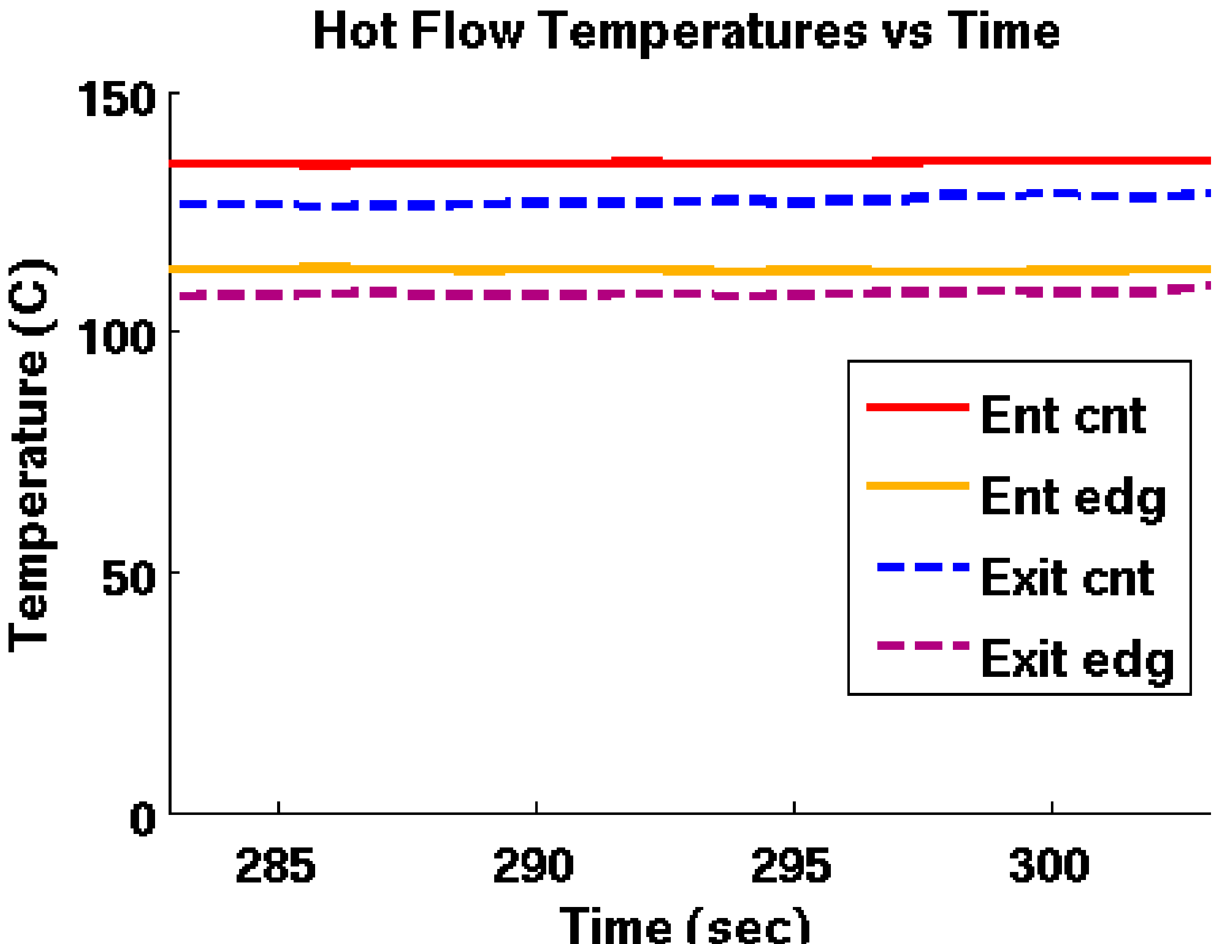


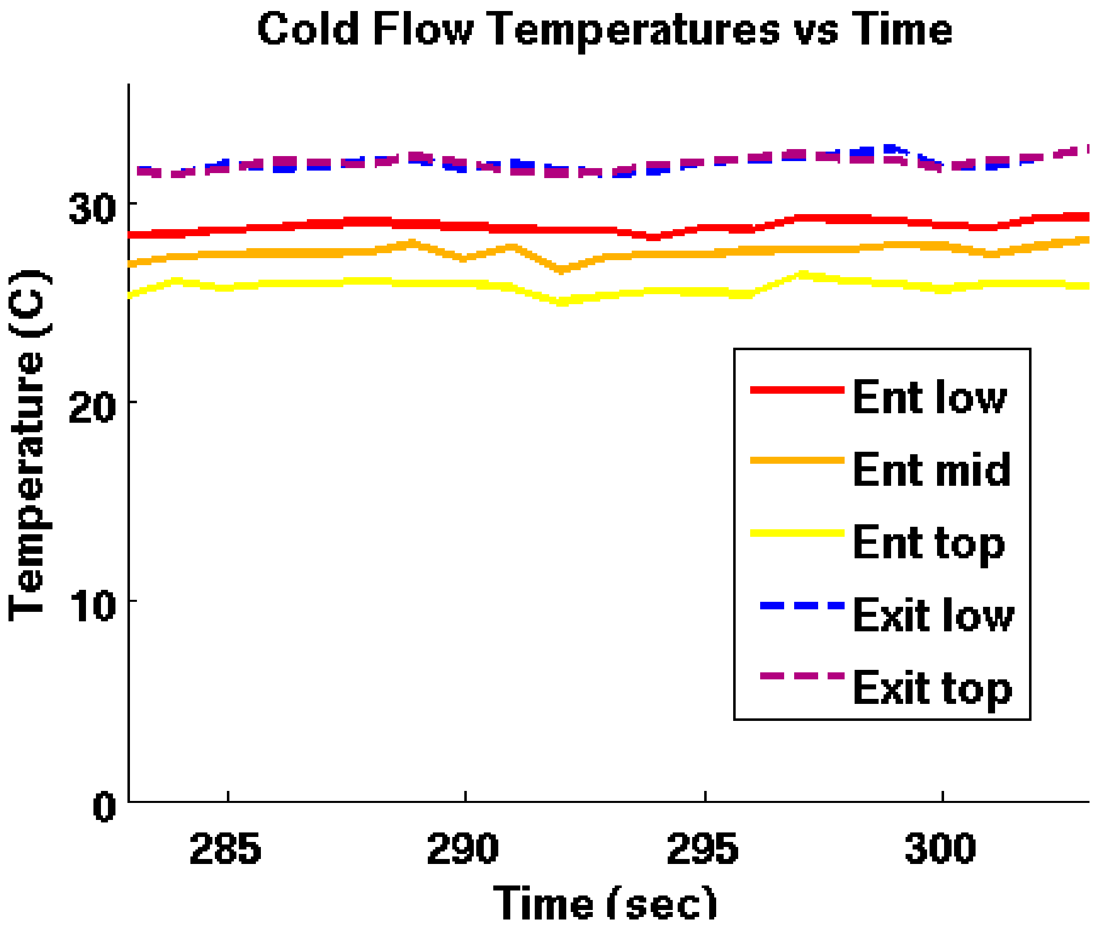
Iterations/ Lessons Learned: Level 1.5

- 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

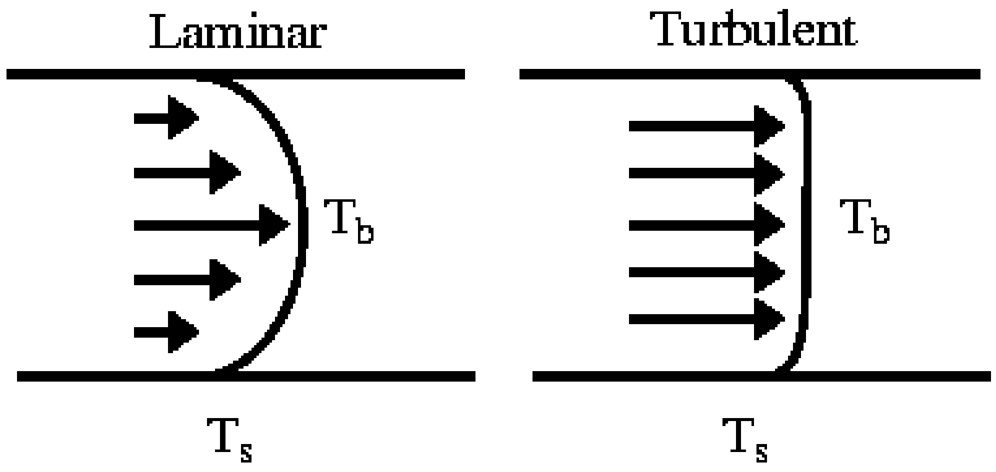
Result: +3.83 °C across heat exchanger





Heat Exchanger Verification

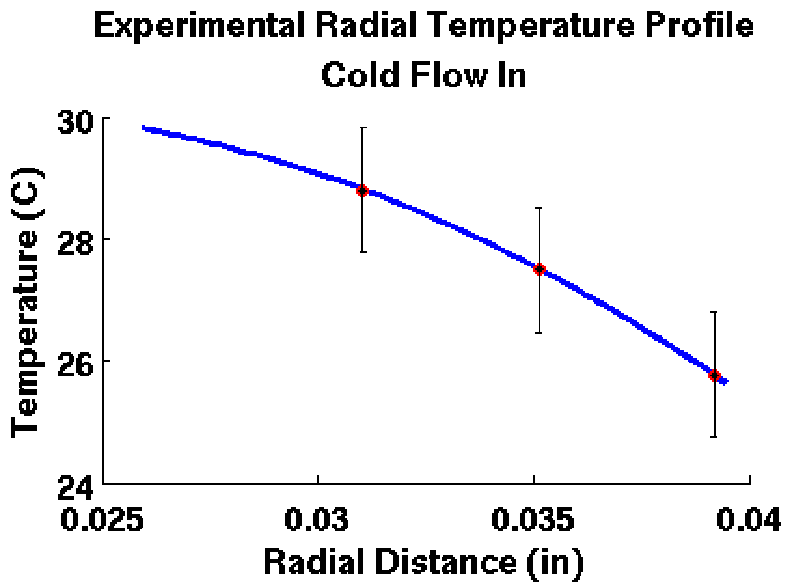
- Expected Results and Considerations:
  - Velocityprofiles [1]

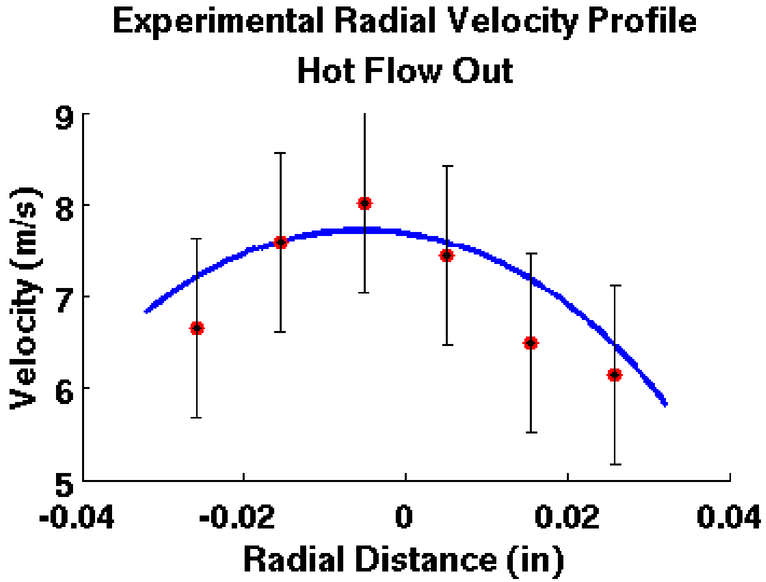


  - Take bulk velocity and temperature

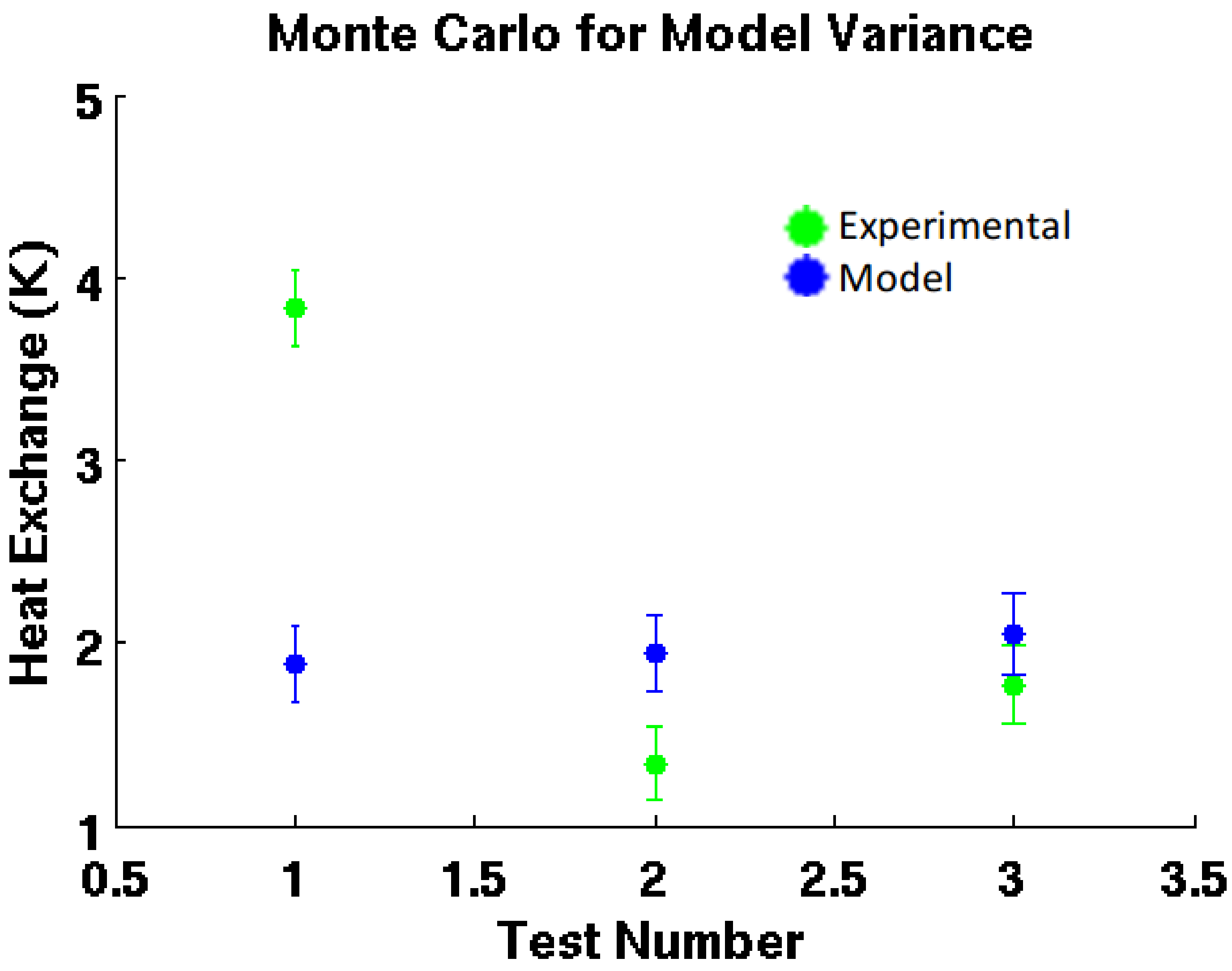
$$Tb = \frac{2}{U_m r_o^2} \int_0^{r_o} uTr\, dr$$

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





Heat Exchanger Model: Performance Prediction



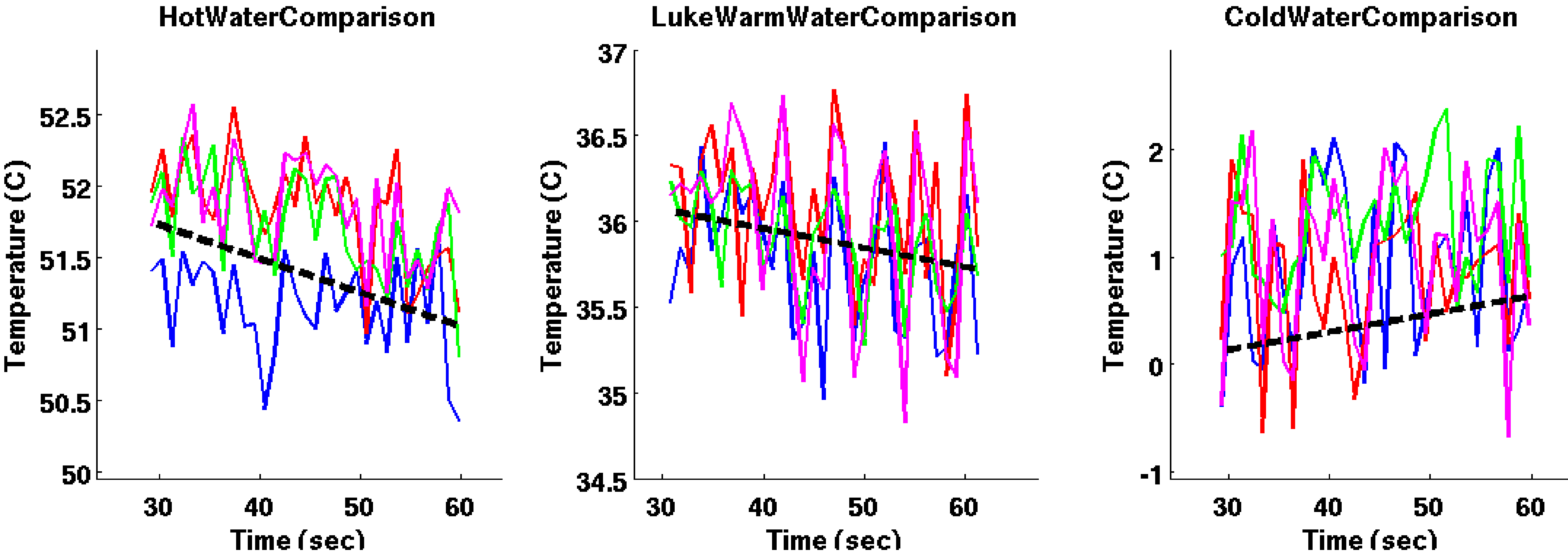
Monte Carlo Simulation Sensitivity Variables

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

Need to run at least ten tests to prove model

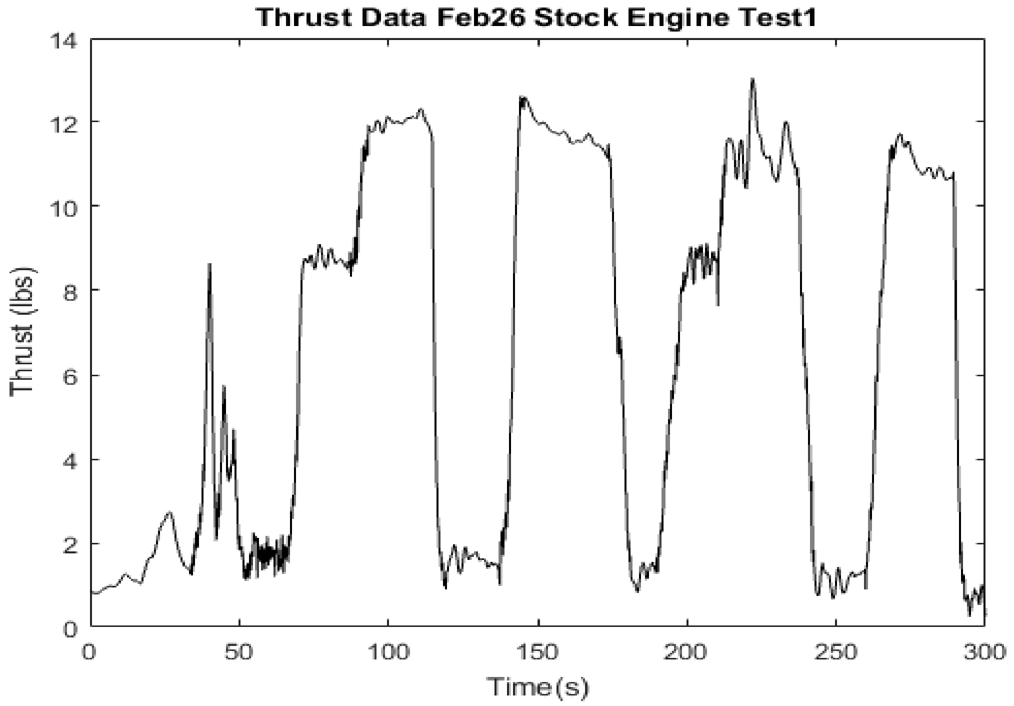
Estimated Hours Remaining: 10 hours

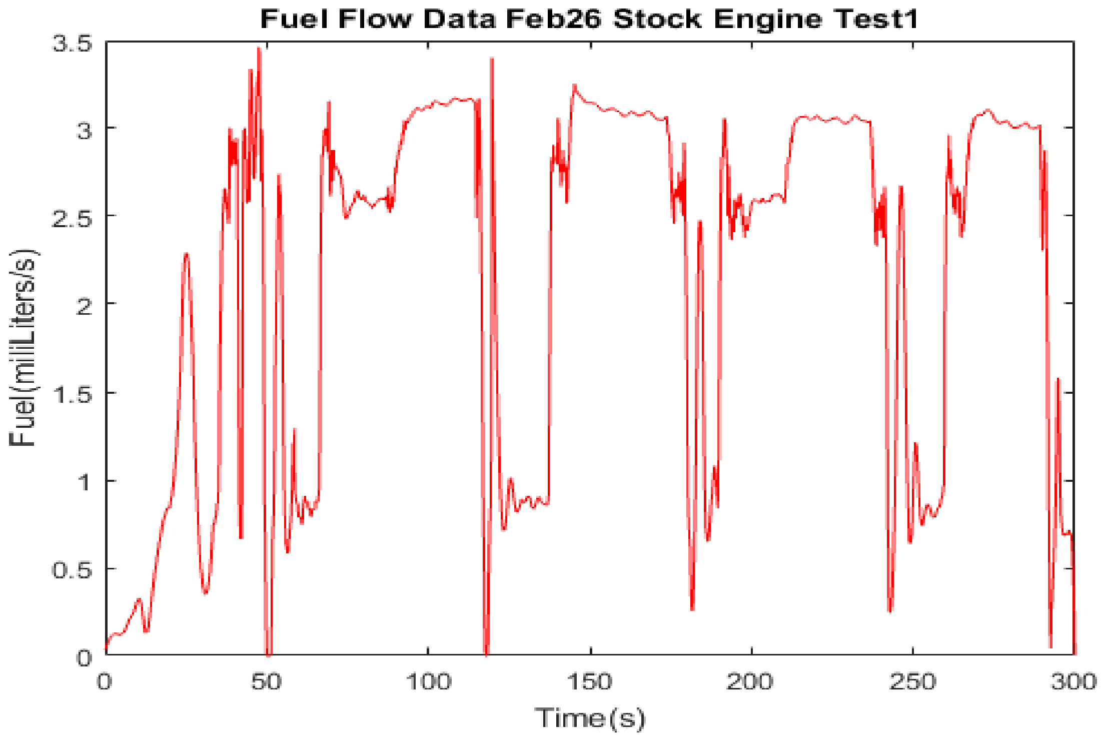
Sensor Calibration



ECU & ESB Stock Engine Test Backup Slides

Stock Engine Characterization (TSFC)

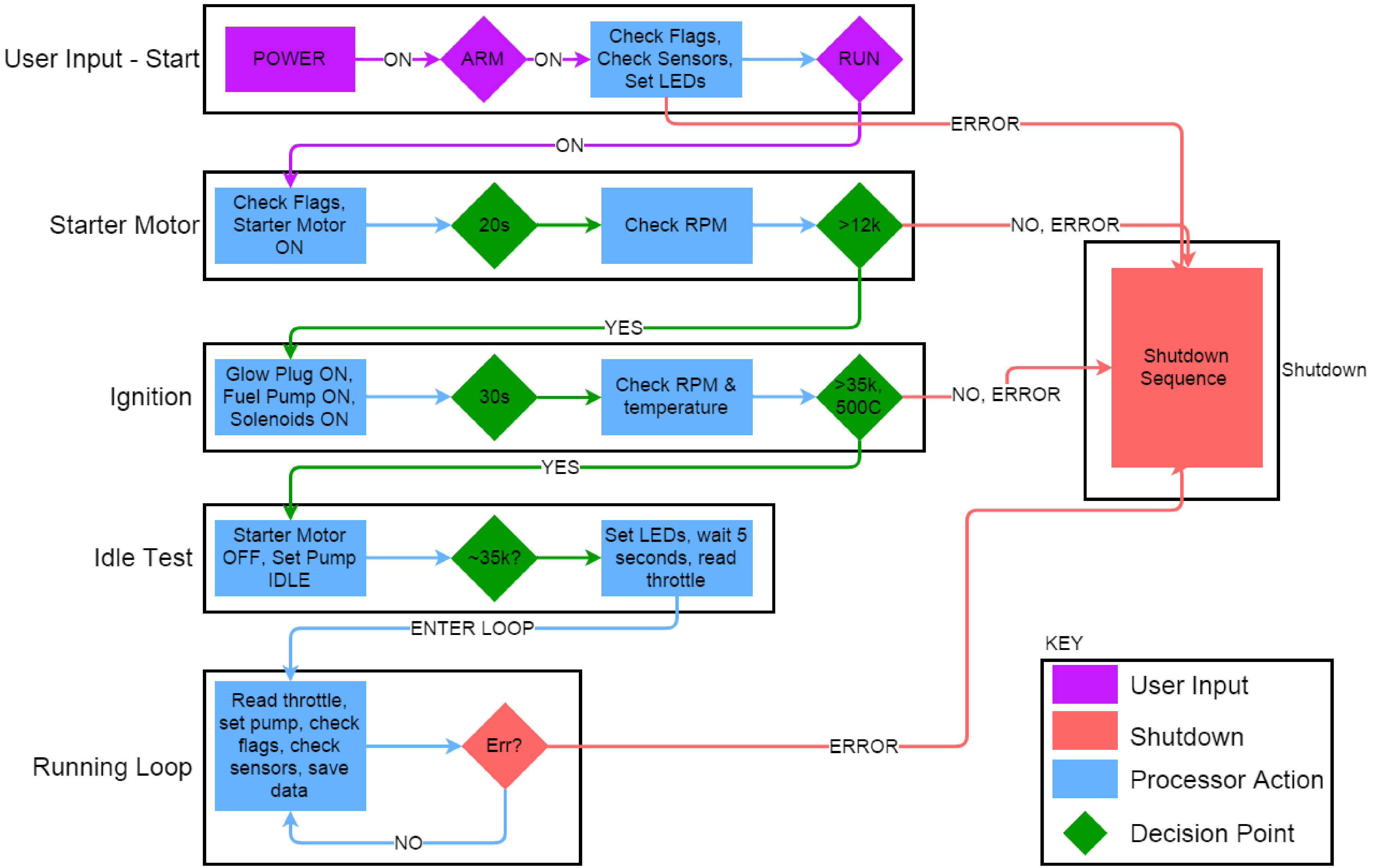




TSFC (1/s) *1E-4			
	Idle	**Half**	**Full**
Test 1*	14.4 ± 0.9	5.2 ± 0.3	4.7± 0.3

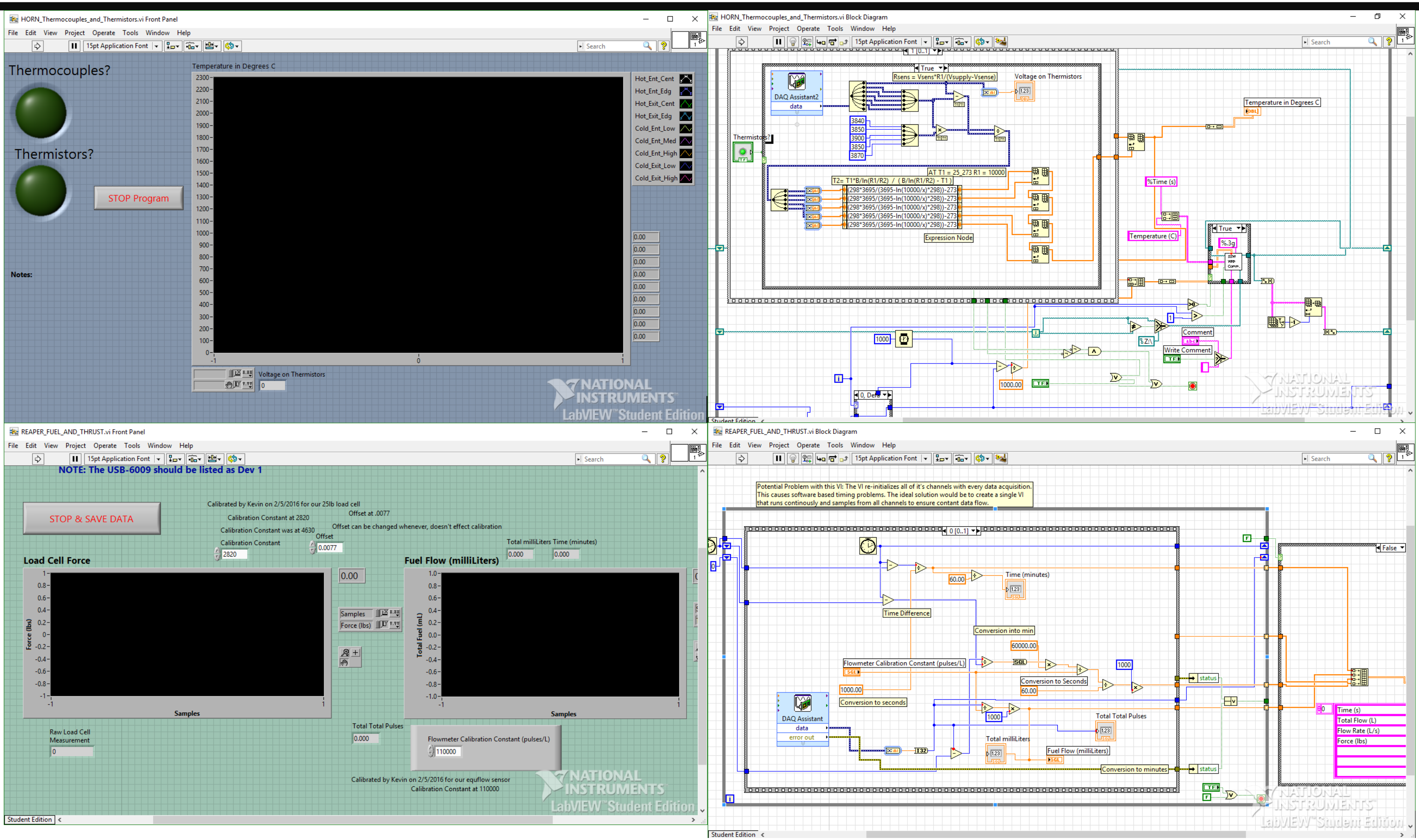
*During Test 1 Throttle max = 109,500 RPM (Should be ~130,000)

EE: Engine Test Flow Chart



Integrated/Full System Test Backup Slides

Labview VI's



HORN_Thermocouples_and_Thermistors.vi Front Panel
Thermocouples?
Thermistors?
STOP Program
Notes:
Temperature in Degrees C
Hot_Ent_Cent
Hot_Ent_Edg
Hot_Exit_Cent
Hot_Exit_Edg
Cold_Ent_Low
Cold_Ent_Med
Cold_Ent_High
Cold_Exit_Low
Cold_Exit_High
Voltage on Thermistors
HORN_Thermocouples_and_Thermistors.vi Block Diagram
DAQ Assistant2
Rsens = Vsens*R1/(Vsupply-Vsense)
AT T1 = 25,273 R1 = 10000
T2= T1*B/ln(R1/R2) / (B/ln(R1/R2) - T1)
Expression Node
%Time (s)
Temperature (C)
Comment
Write Comment
REAPER_FUEL_AND_THRUST.vi Front Panel
NOTE: The USB-6009 should be listed as Dev 1
STOP & SAVE DATA
Calibrated by Kevin on 2/5/2016 for our 25lb load cell
Calibration Constant at 2820
Offset at .0077
Calibration Constant was at 4630
Offset can be changed whenever, doesn't effect calibration
Calibration Constant
Offset
Total milliLiters
Time (minutes)
Load Cell Force
Fuel Flow (milliLiters)
Force (lbs)
Total Fuel (mL)
Samples
Raw Load Cell Measurement
Total Total Pulses
Flowmeter Calibration Constant (pulses/L)
Calibrated by Kevin on 2/5/2016 for our equflow sensor
Calibration Constant at 110000
REAPER_FUEL_AND_THRUST.vi Block Diagram
Potential Problem with this VI: The VI re-initializes all of it's channels with every data acquisition. This causes software based timing problems. The ideal solution would be to create a single VI that runs continously and samples from all channels to ensure contant data flow.
Time (minutes)
Time Difference
Conversion into min
Conversion to Seconds
Conversion to seconds
DAQ Assistant
Total Total Pulses
Total milliLiters
Fuel Flow (milliLiters)
Conversion to minutes
Time (s)
Total Flow (L)
Flow Rate (L/s)
Force (lbs)
NATIONAL INSTRUMENTS
LabVIEW Student Edition

Engine Run Test: Manufacturing Progress

To Be Completed

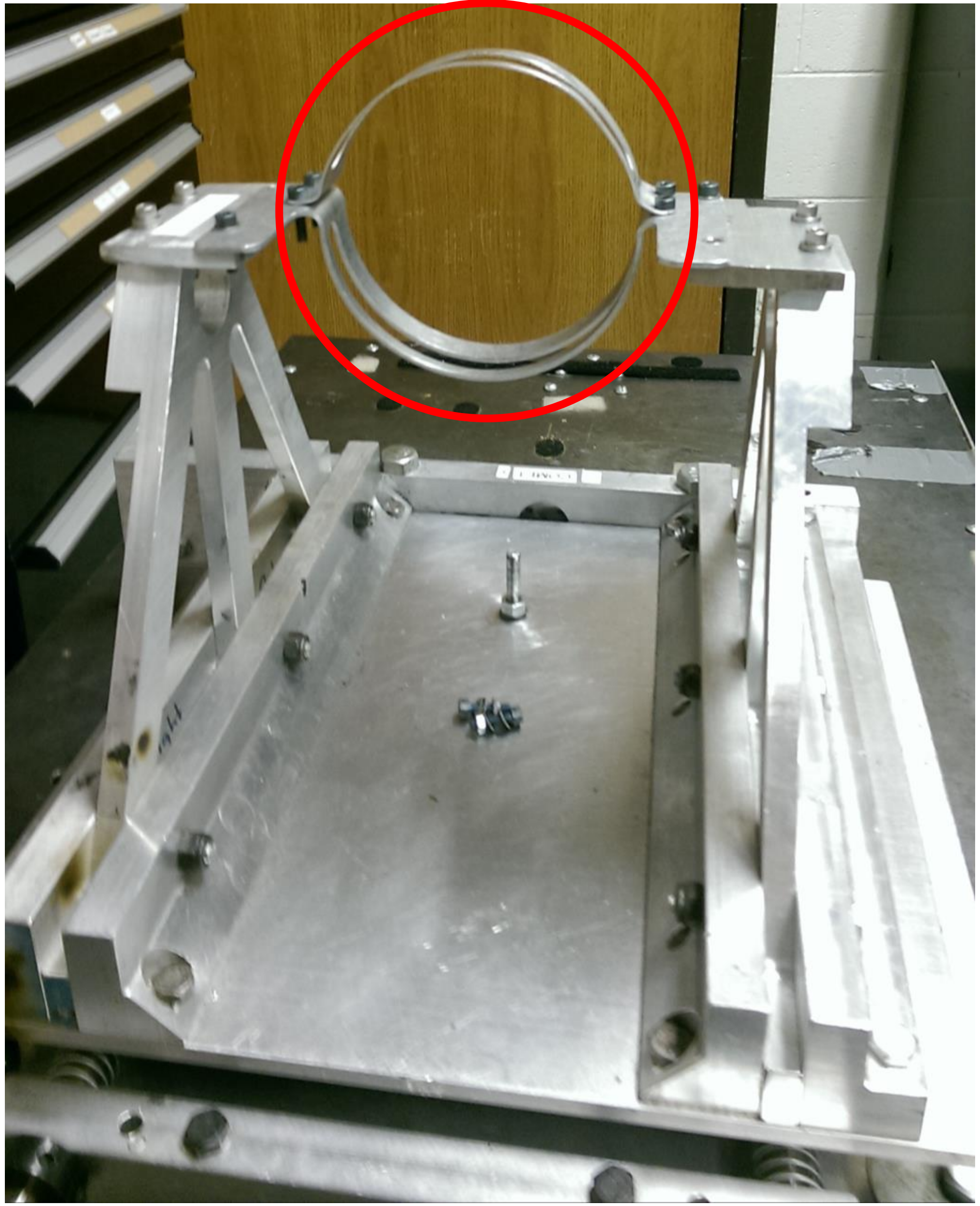
Part	Remaining Hours
Forward Ring	1
Outer Casing	2
Inner Casing	3
Nozzle	0.5

To Be Started

Part	Remaining Hours
Component Integration	4
Test Stand Alteration	6

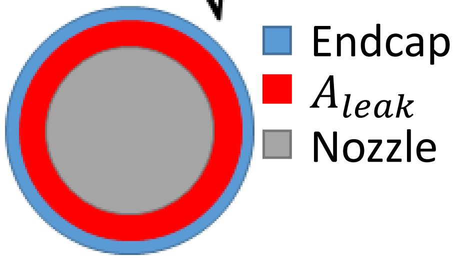
Total Remaining Hours: **16.5**

Engine Run Test: Test Stand Alteration



Pressure Leak: Magnitude

- Most likely to occur at joint of Endcap and Nozzle
- $\dot{m} = C * A_{leak}\sqrt{2\rho_{engine}(P_{engine} - P_{atm})}$
- $A_{leak} \rightarrow$

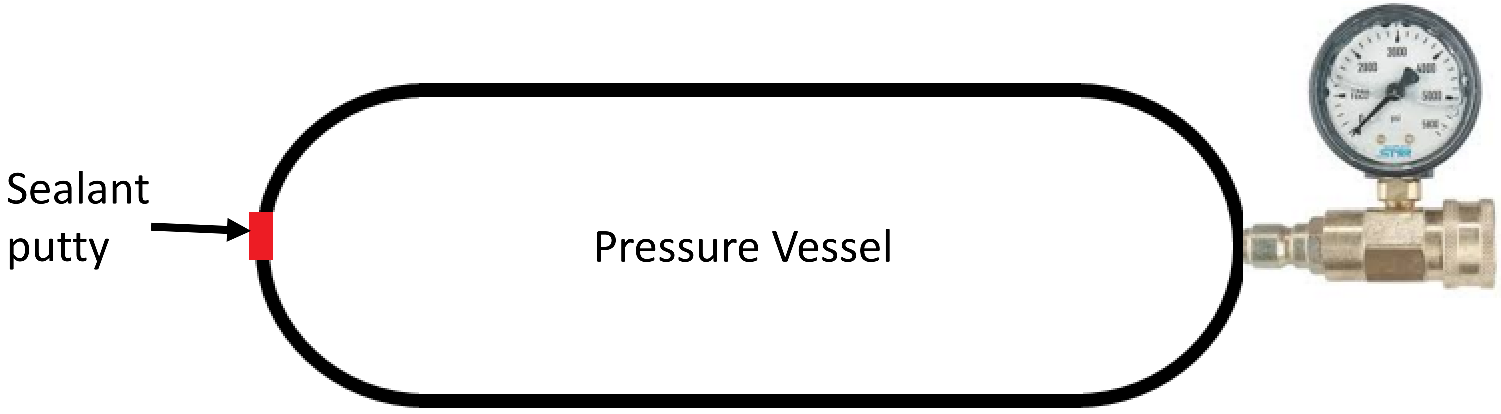


$$A_{leak} = \pi((r_{Nozzle} + gap)^2 - r_{Nozzle}^2)$$

$$A_{leak} = 2E^{-5}\ m^2$$

- $\rho_{engine} = 2.3\ \frac{kg}{m^3}$
- $P_{engine} = 2.6\ atm = 263445\ Pa, P_{atm} = 1\ atm = 101325\ Pa$
- $C = .625 \rightarrow$ hole flow coefficient, between .6 and .65
- $\dot{m} = 0.011\ \frac{kg}{s}$

Leak Analysis – Test Setup



Assume Ideal Gas → $\rho = \dfrac{P}{RT}$

$$\dot{m} = V\frac{\partial \rho}{\partial t} = V\left(\frac{\partial \rho}{\partial P}\frac{\partial P}{\partial t} + \frac{\partial \rho}{\partial R}\cancel{\frac{\partial R}{\partial t}} + \frac{\partial \rho}{\partial T}\cancel{\frac{\partial T}{\partial t}}\right)$$

$$\dot{m} = \mathrm{V}\left(\frac{1}{RT}\frac{\partial P}{\partial t}\right)$$

Pressure Leak: Performance Impact