Critical **D**esign **R**eview

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

Outline

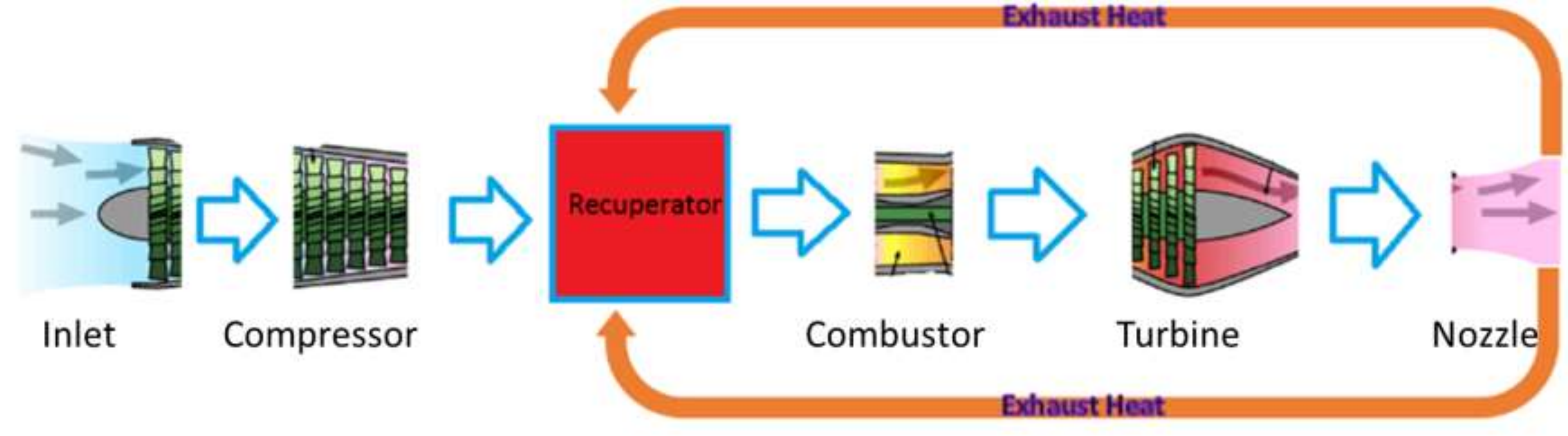
- Project Description
- Design Solution
- Critical Project Elements
- Design Requirement Satisfaction
- Risk Analysis
- Verification and Validation
- Project Planning

Project Statement

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

Engine Recuperation

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



Customer Requests

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

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

CR 3: Minimize thrust loss, weight, and volume additions

Functional Requirements

FR 1: Engine operates in modified state

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

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

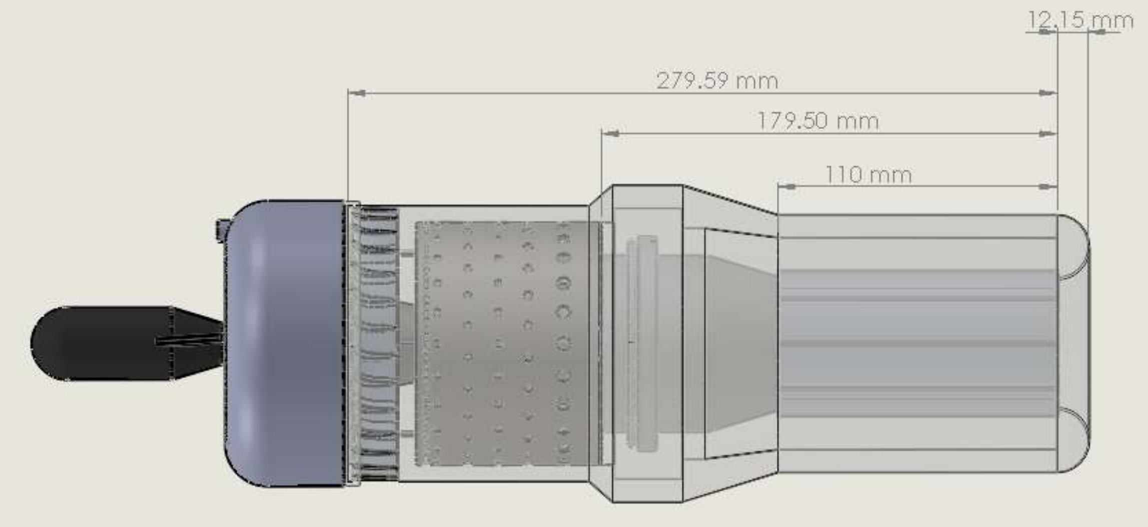
FR 4: Engine control electronics command the modified engine

Levels of Success

	Simulation	Recuperator
Level 1	-Develop first order, steady state model -Model heat exchanger effectiveness, specific fuel consumption and thrust	-Recuperator designed and manufactured -Recuperator verified with engine analog
Level 2	-Model transient characteristics	-Recuperator is integrated onto engine -Integrate 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

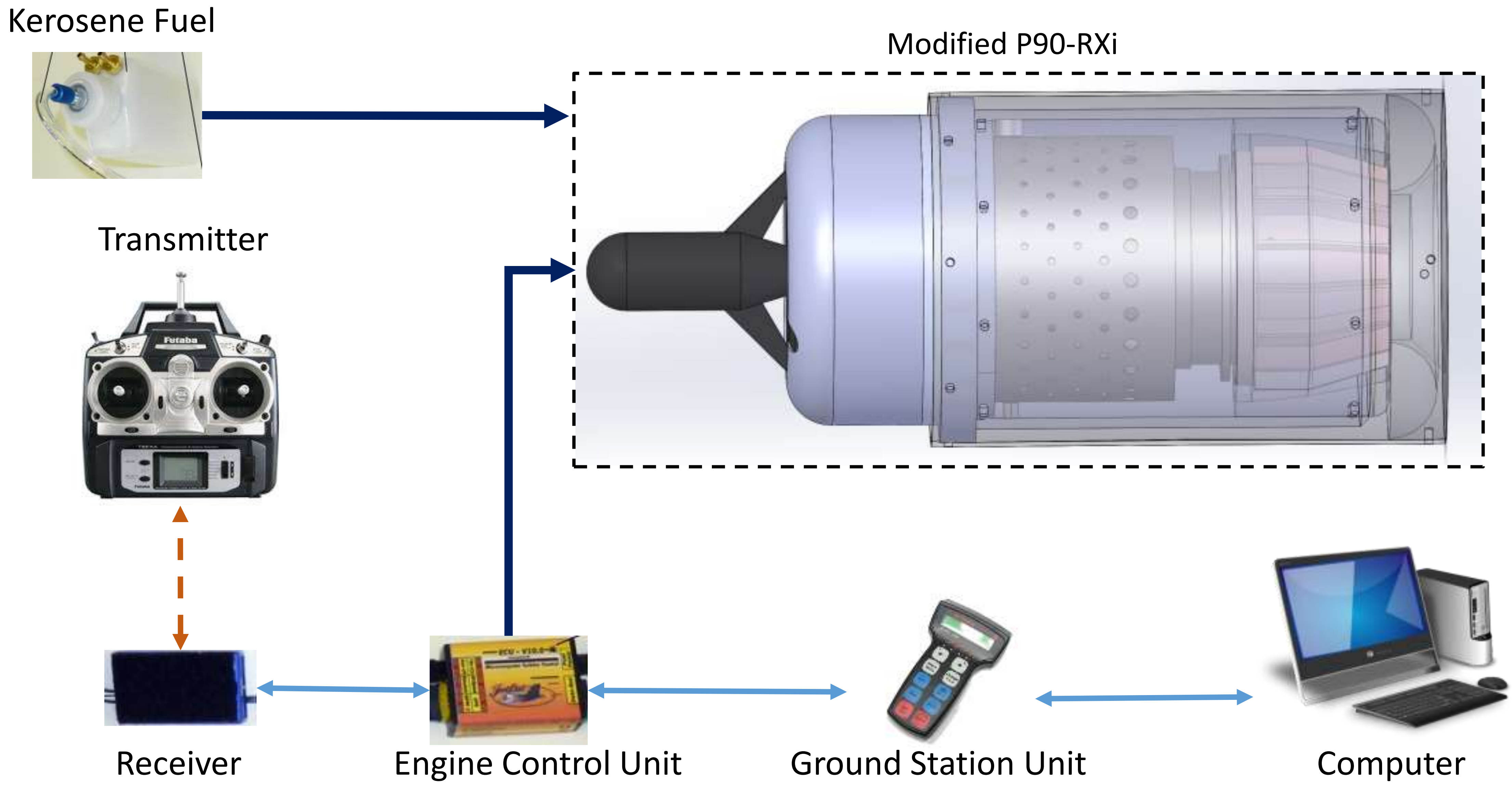
Design Overview: Differences from PDR Design

- Problems with PDR Design
  - Flow Impedance
  - Not enough mass flow through Heat Exchanger
- Problems found with improved models



Design Overview Animation

Concept of Operations



Kerosene Fuel

Modified P90-RXi

Transmitter

Receiver

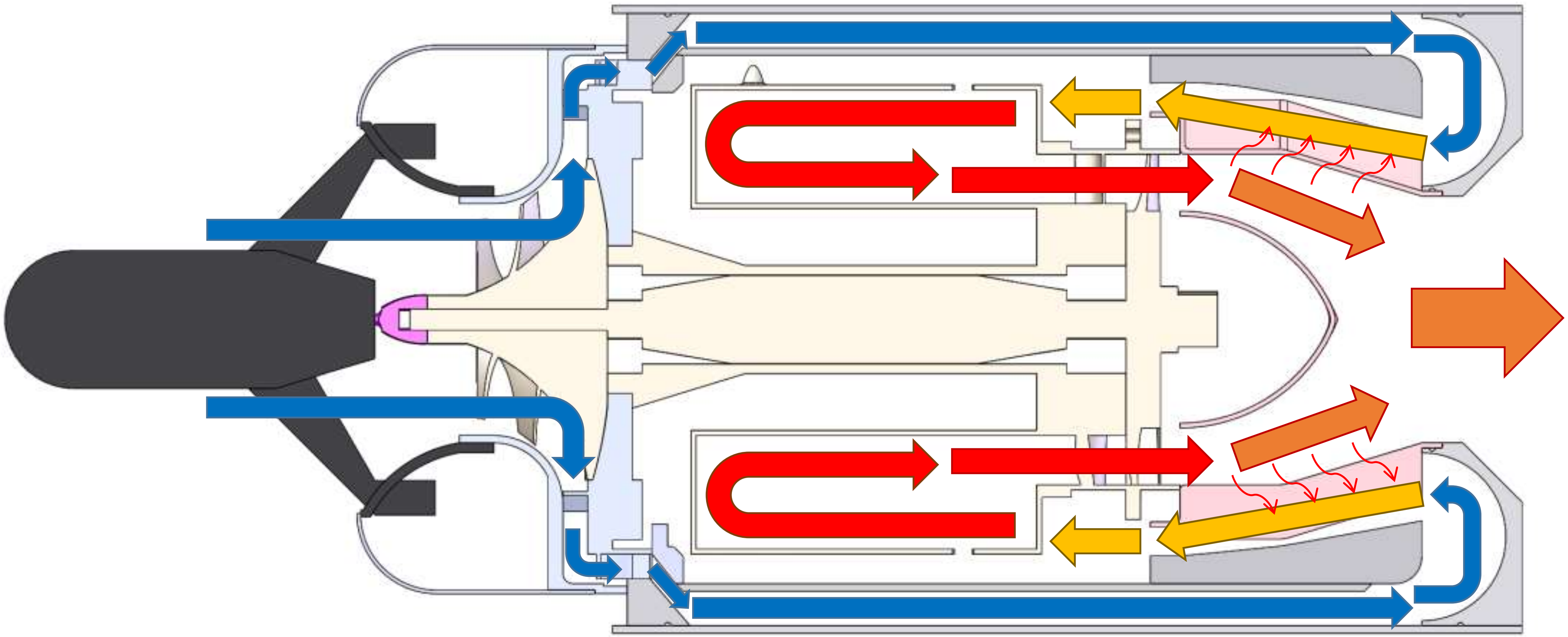
Engine Control Unit

Ground Station Unit

Computer

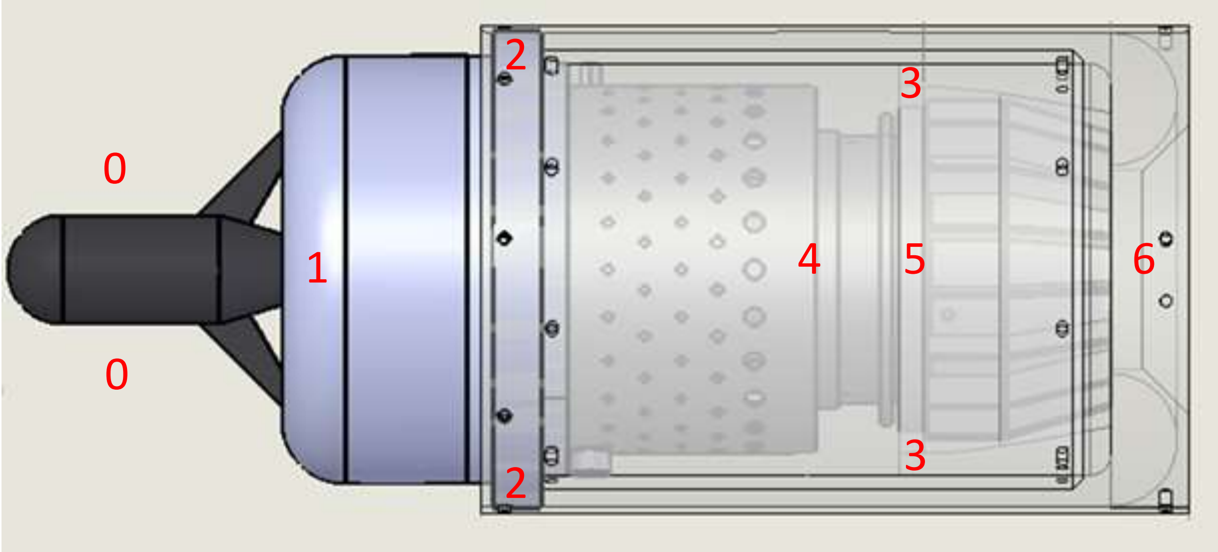
Concept of Operations

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



Flow Overview

Station	Total Pressure [Atm]	Total Temperature [K]
1	1.00	273.0
2	2.60 ± 0.01	403 ± 2
3	2.53 ± 0.01	408 ± 2
4	2.36 ± 0.02	1080 ± 3
5	1.33 ± 0.02	963 ± 3
6	1.33 ± 0.02	958 ± 4



Stock Thrust: 105 N

Stock TSFC: 4.46E-4 s^{-1}

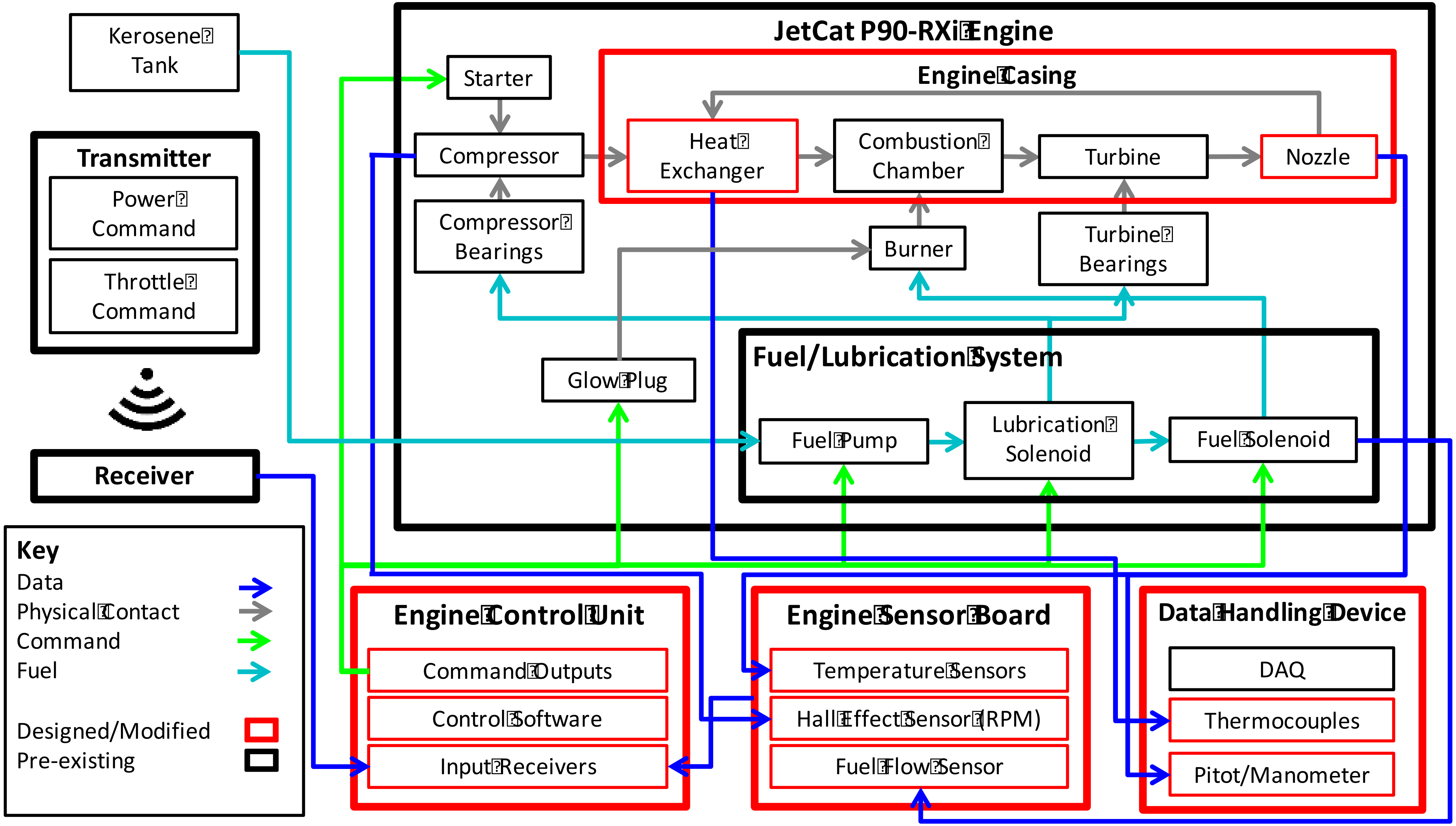
REAPER Thrust: 103.4±0.5 N

REAPER TSFC: 4.40 ±0.05E-4 s^{-1}

-1.6 %

-1.2 %

Functional Block Diagram



Kerosene Tank

Transmitter

Power Command

Throttle Command

Receiver

JetCat P90-RXi Engine

Starter

Compressor

Compressor Bearings

Glow Plug

Engine Casing

Heat Exchanger

Combustion Chamber

Turbine

Nozzle

Burner

Turbine Bearings

Fuel/Lubrication System

Fuel Pump

Lubrication Solenoid

Fuel Solenoid

Engine Control Unit

Command Outputs

Control Software

Input Receivers

Engine Sensor Board

Temperature Sensors

Hall Effect Sensor (RPM)

Fuel Flow Sensor

Data Handling Device

DAQ

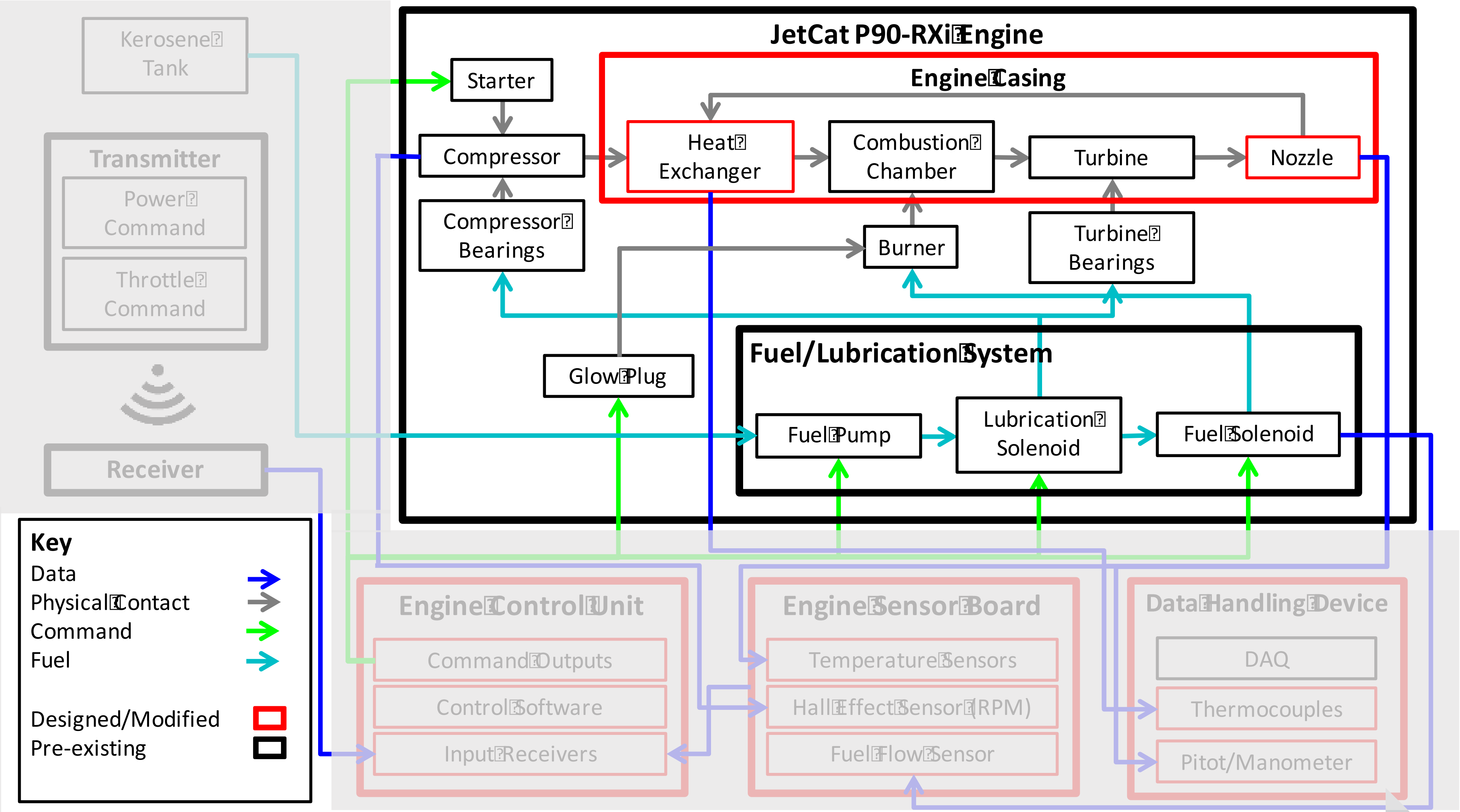
Thermocouples

Pitot/Manometer

Key

Data	→
Physical Contact	→
Command	→
Fuel	→
Designed/Modified	🟥
Pre-existing	☐

Engine FBD



Kerosene Tank

Transmitter
Power Command
Throttle Command

Receiver

JetCat P90-RXi Engine

Engine Casing

Starter
Compressor
Heat Exchanger
Combustion Chamber
Turbine
Nozzle
Compressor Bearings
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
Temperature Sensors
Hall Effect Sensor (RPM)
Fuel Flow Sensor

Data Handling Device
DAQ
Thermocouples
Pitot/Manometer

Key

Data	→
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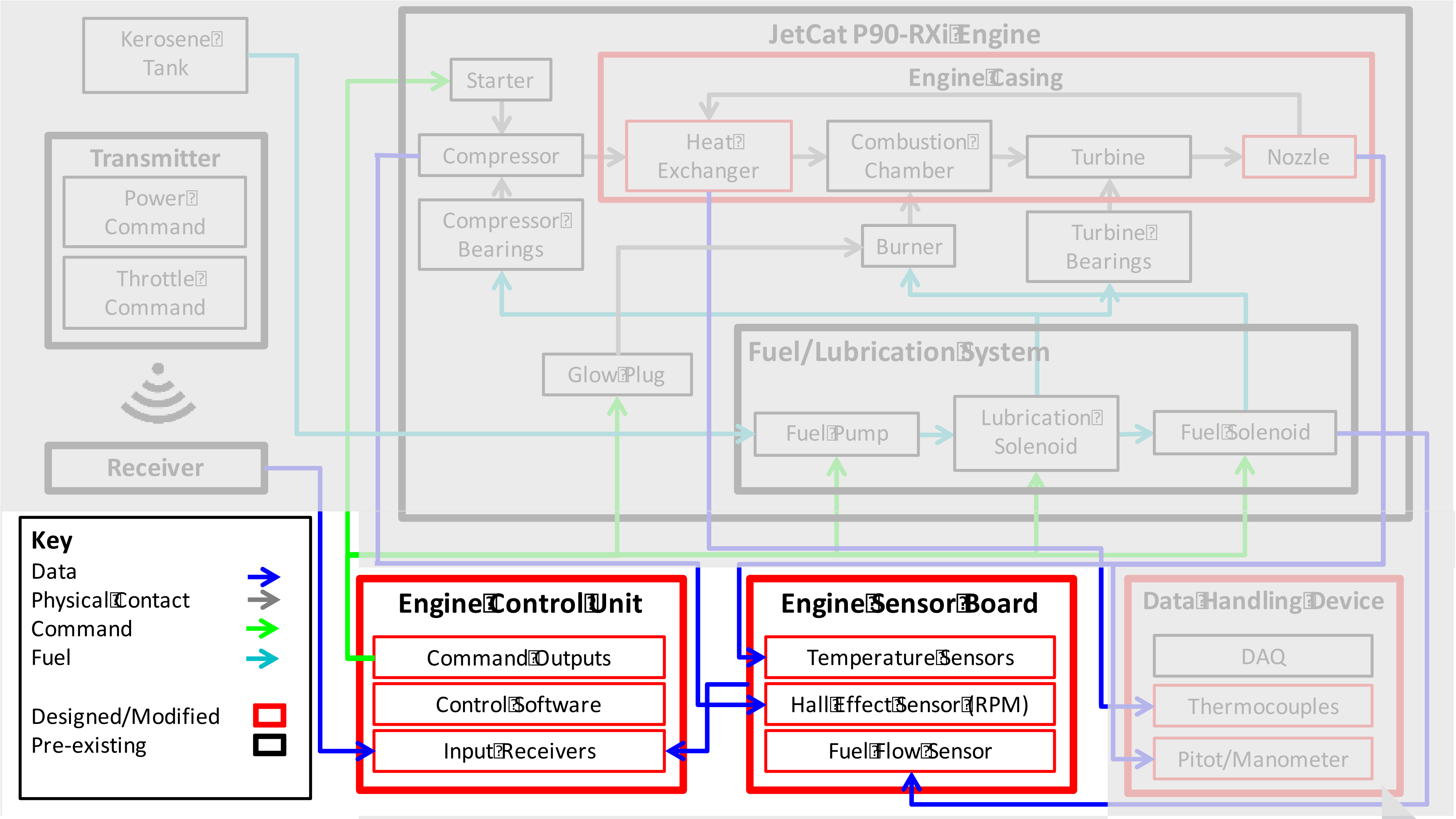
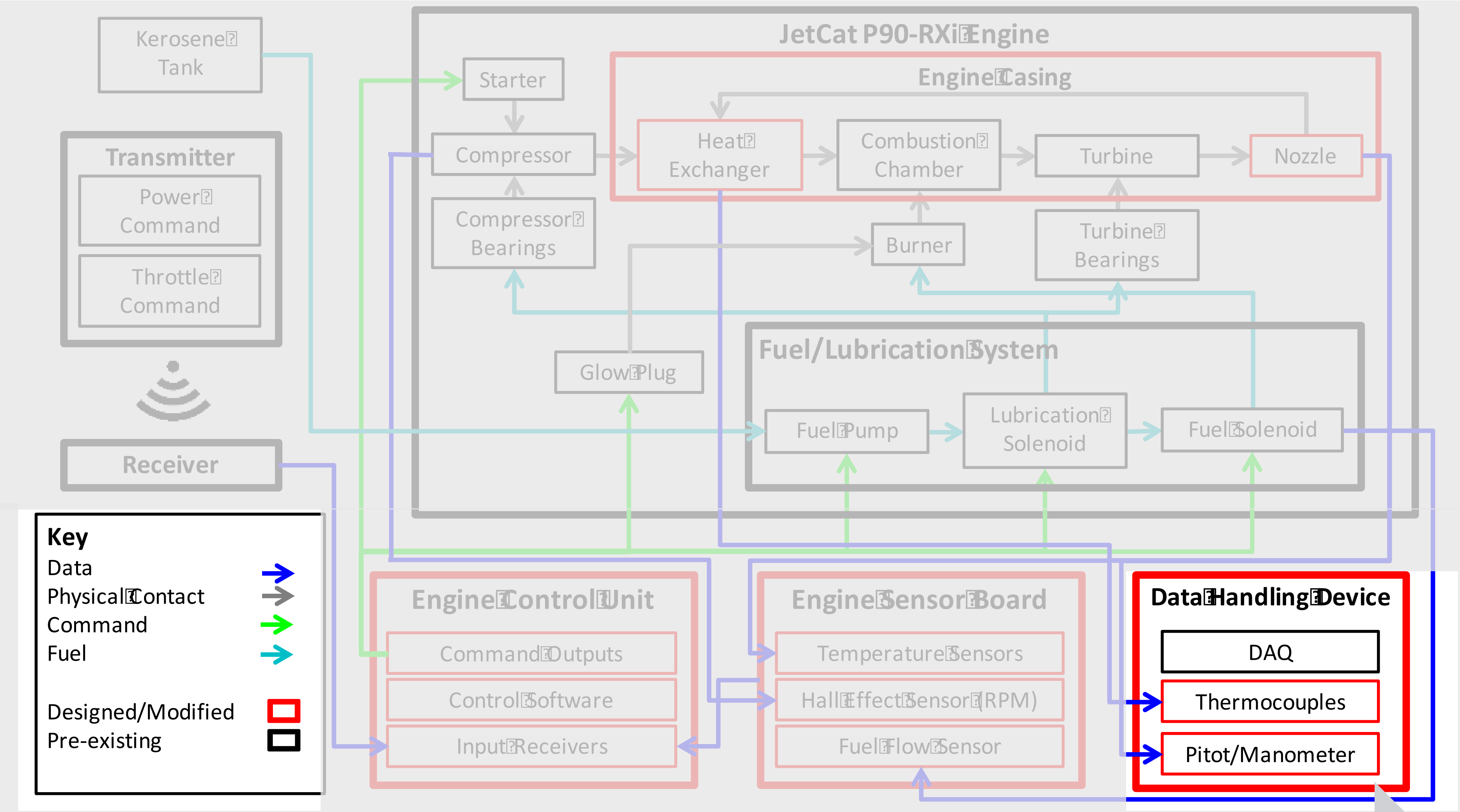
Engine Electronics FBD



Testing Electrical FBD



Critical Project Elements

CPE 1: Thermal-Fluid Modeling

- System **Characterization**

CPE 2: Heat Exchanger

- **Manufacturing**, Cost, Integration

CPE 3: Engine Electronics

- **Control**, Safety, Sensors

CPE 4: Testing

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

CPE 1: Thermal-Fluid Modeling

Goal: Characterize system to enable heat exchanger design and validation

Thermal Model Design Requirements

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

DR 3.1: Quantify changes in engine thrust

DR 3.2: Quantify changes in fuel consumption

DR 3.3: Quantify frictional and geometric losses

Thermal Model 1: Control Volume Analysis

Conservation Laws

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

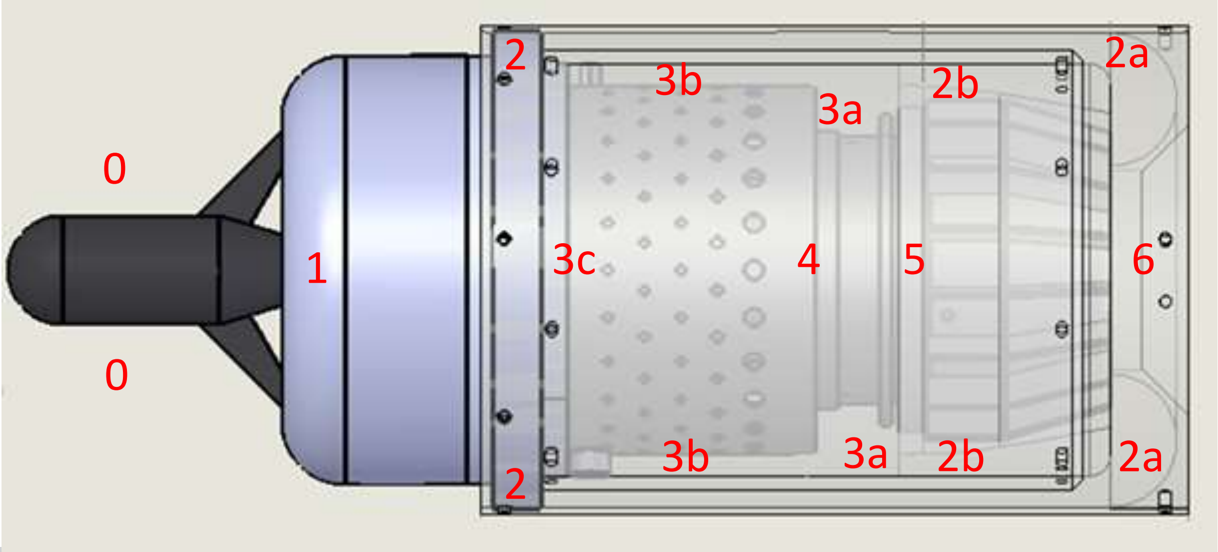
Momentum: $\rho_1 A_1 {V_1}^2 + p_1 A_1 = \rho_2 A_2 {V_2}^2 + p_2 A_2 + g h_L$

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

Constitutive: $p = \rho R T$

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



Thermal Model 2: Heat Exchanger CFD

Assumptions:

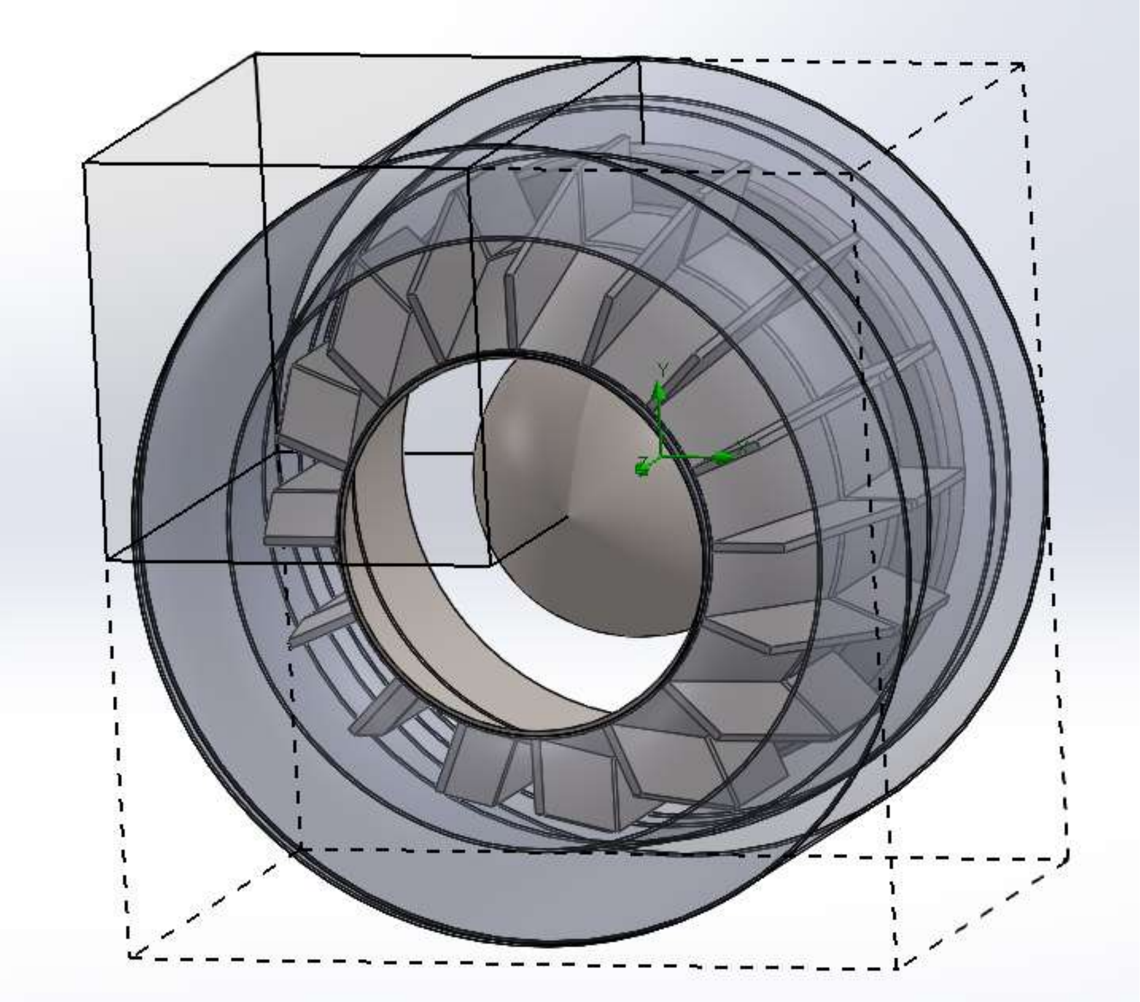
- 4x symmetry
- Boundary conditions independent of flow parameters
- K-ε turbulence model

Convergence:

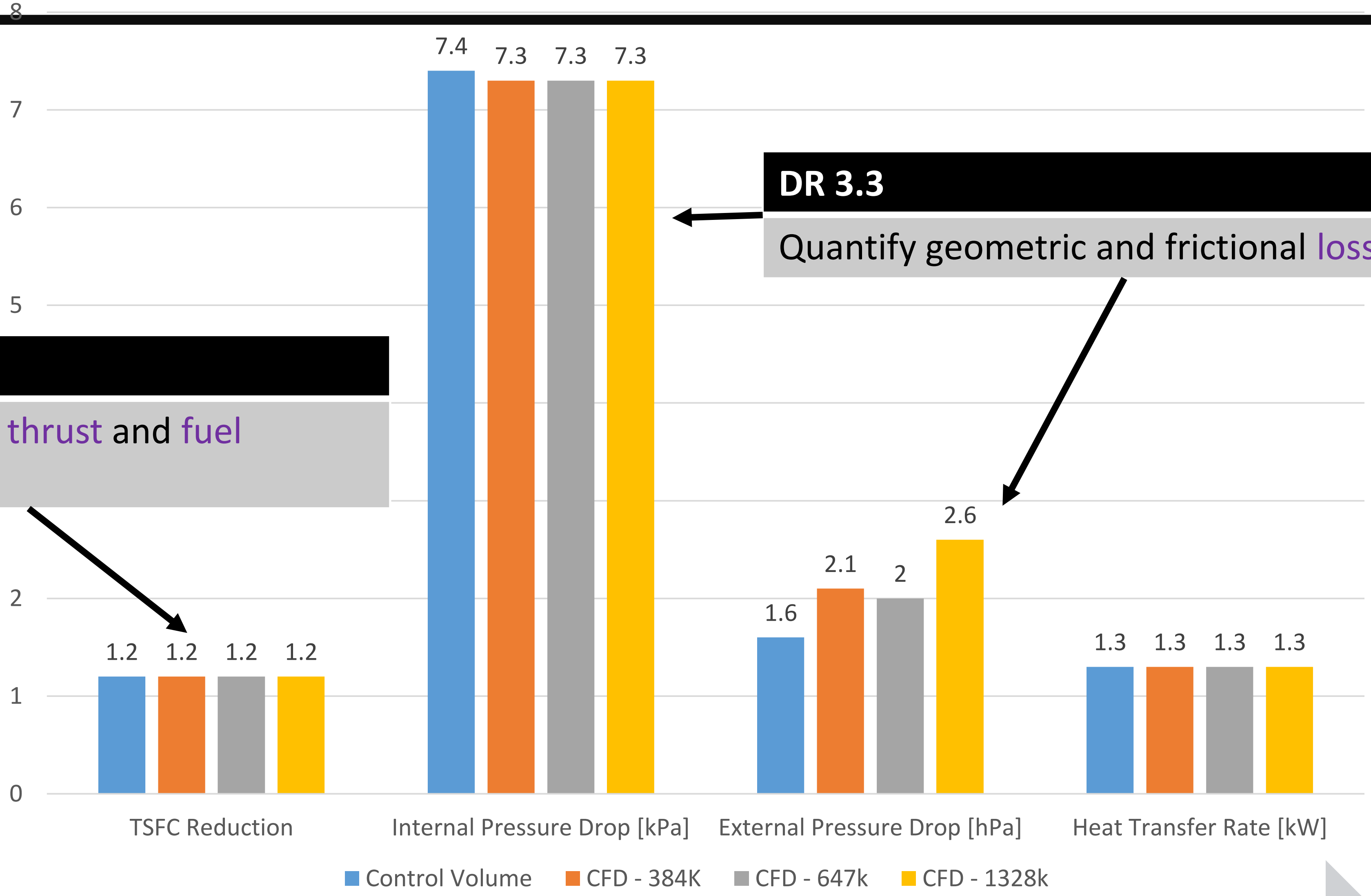
- All flow variables forced to converge within 0.5% across 3 travels

Mesh Independence

- 3 meshes (384k, 647k, 1328k fluid cells) showed similar results



Thermal Model: Results



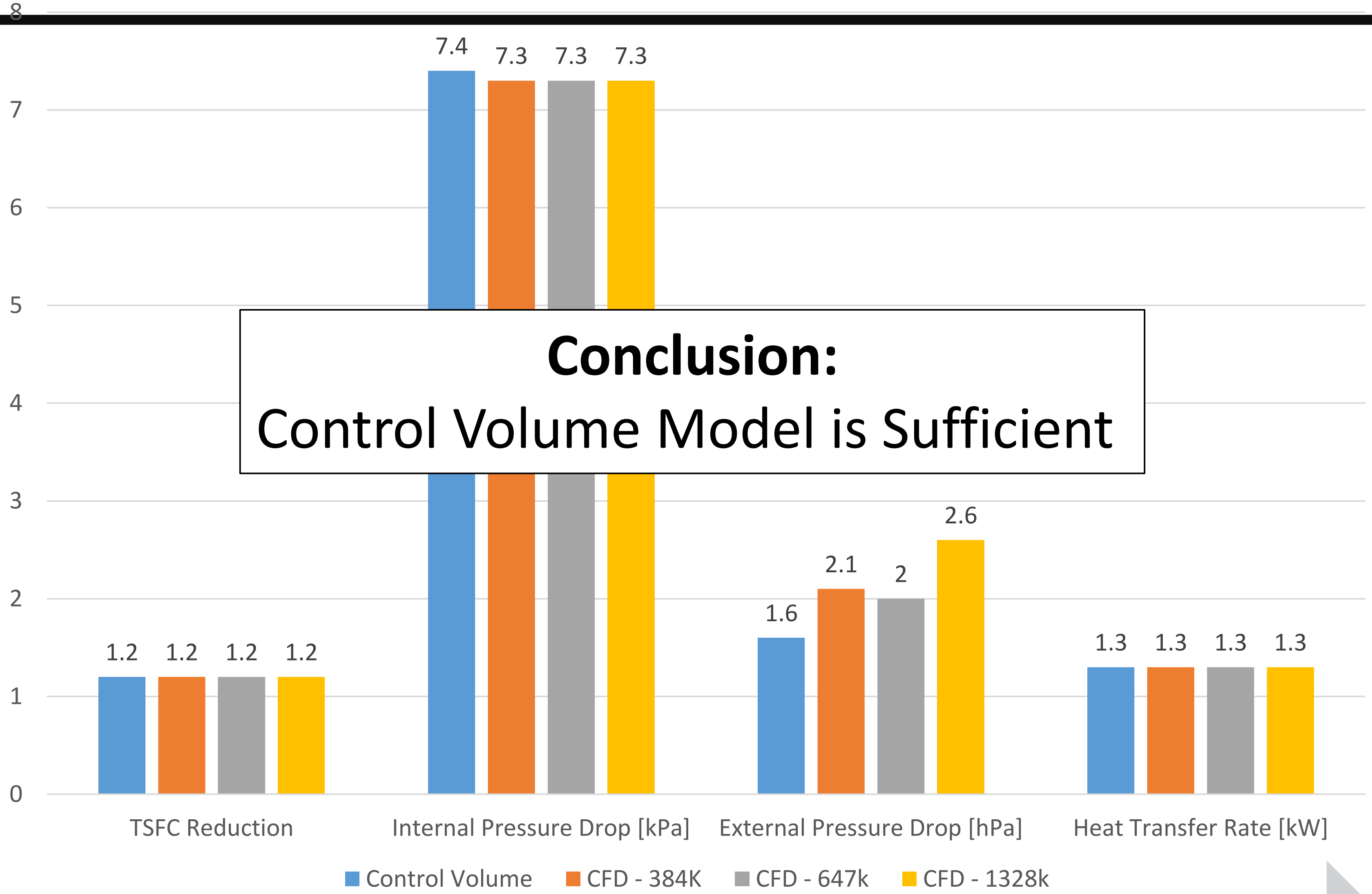
DR 3.3

Quantify geometric and frictional losses

DR 3.1/3.2

Quantify changes in thrust and fuel consumption

Thermal Model: Results



Conclusion:

Control Volume Model is Sufficient

CPE 2: Heat Exchanger

Goal: Transfer exhaust heat and integrate with engine

Heat Exchanger Design Requirements

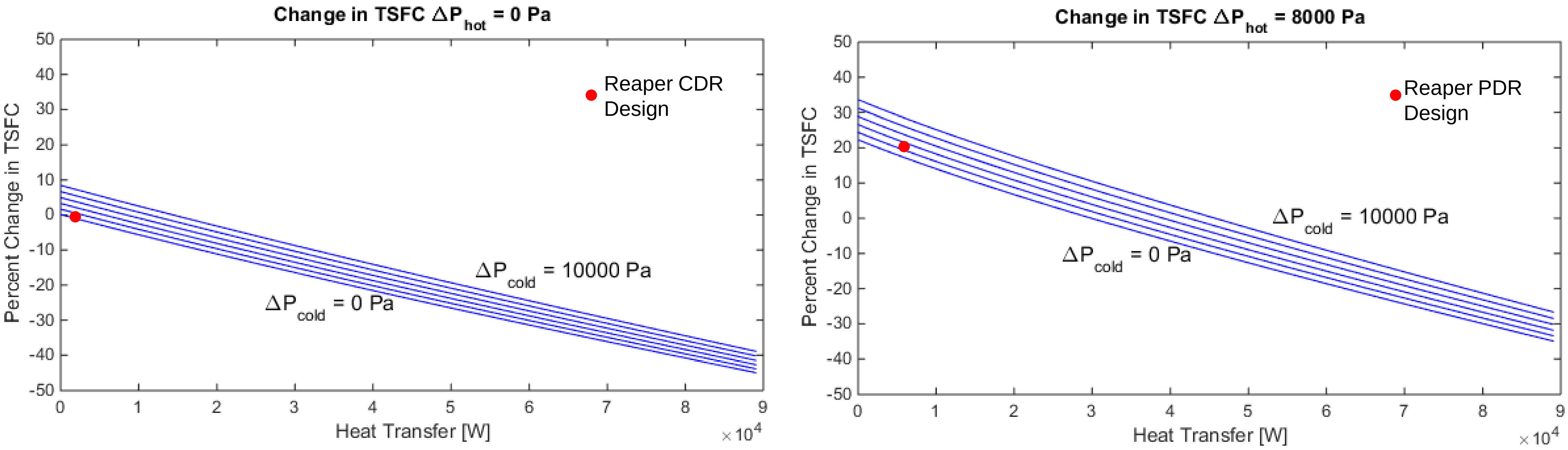
FR 2: Thrust specific fuel consumption decreases at least 10% at full throttle

DR 2.1: Effectiveness of at least 13%

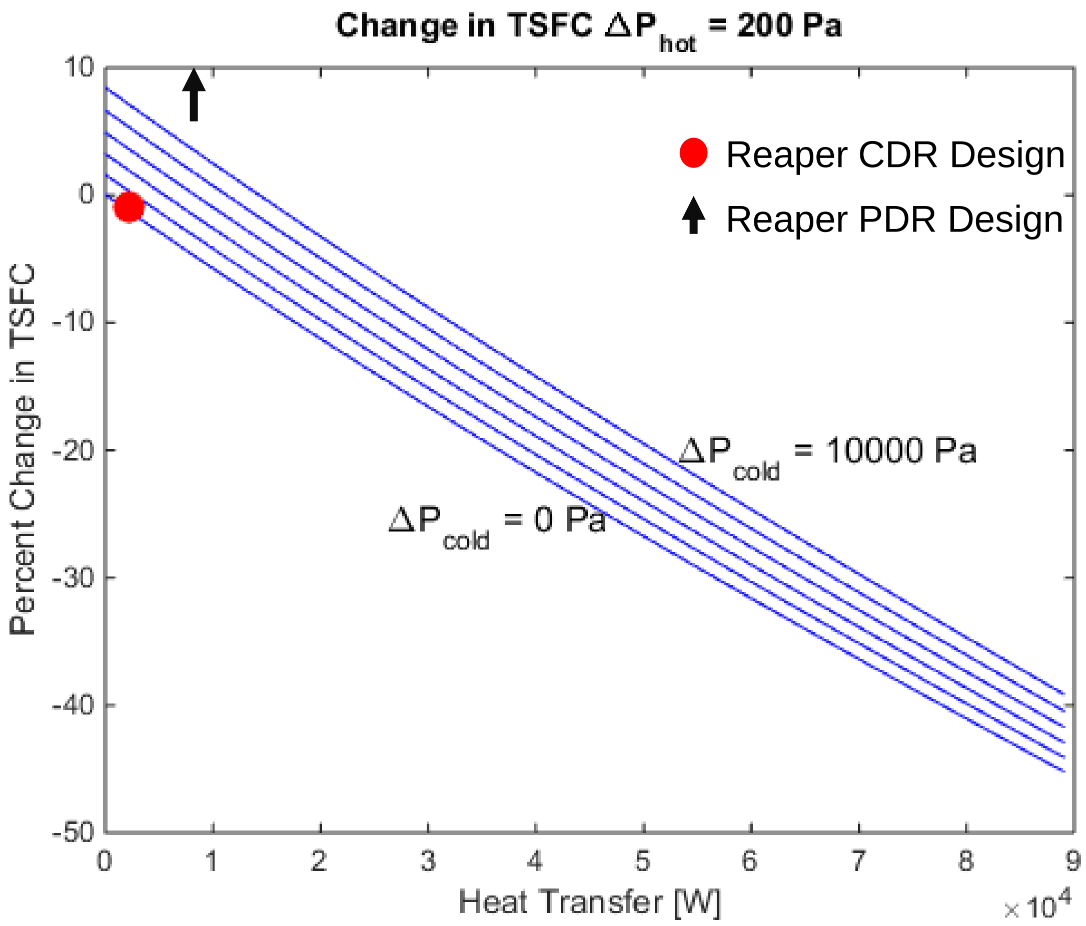
DR 2.3: Integrate with engine

DR 2.5: Less than 10% thrust decrease

Thrust Specific Fuel Consumption



Thrust Specific Fuel Consumption



Key Conclusions:

1. 10% reduction in TSFC requires ~20 kW of heat transfer with no losses
2. Exhaust pressure losses supersede internal pressure losses

Reaper Design:

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

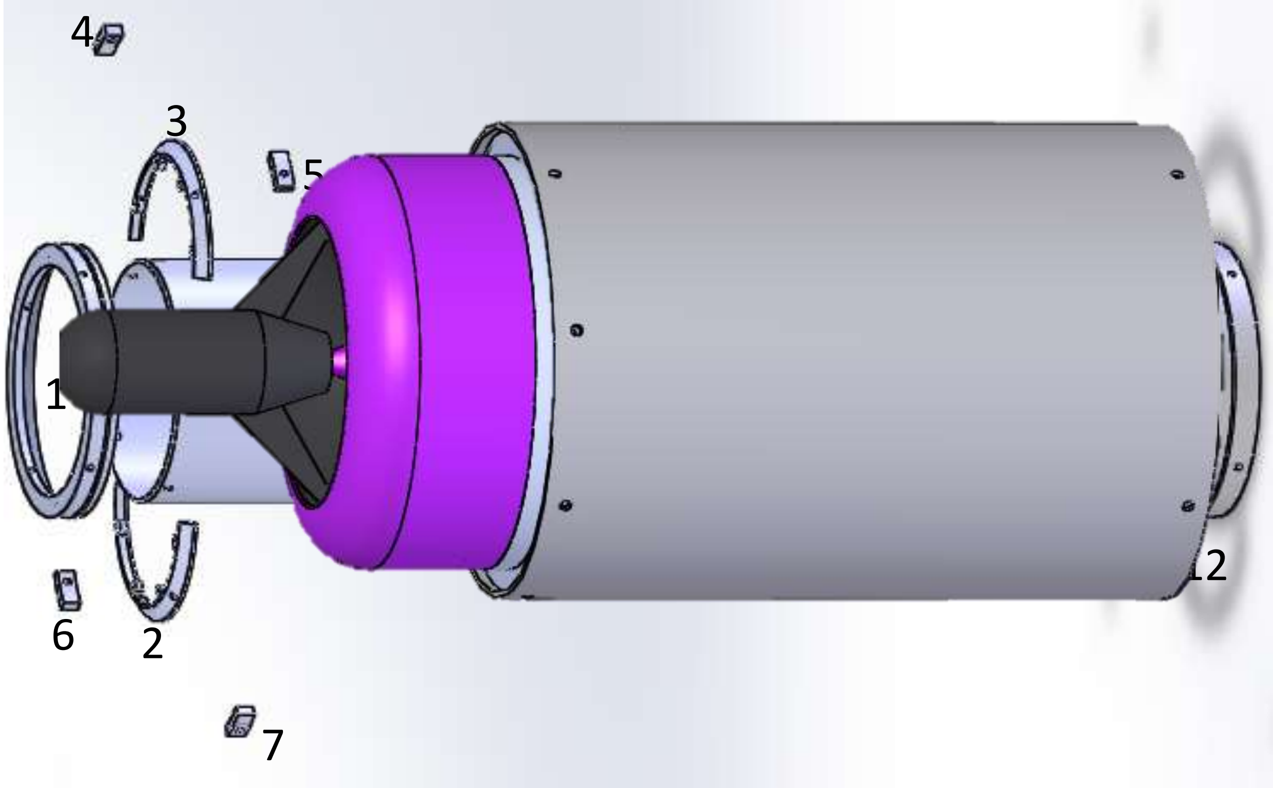
Heat Exchanger Performance

Requirement	Value	Reaper Design	Compliance
FR 2: Decrease in TSFC	10%	1.2%	**Do Not Comply**

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

Remaining Pieces

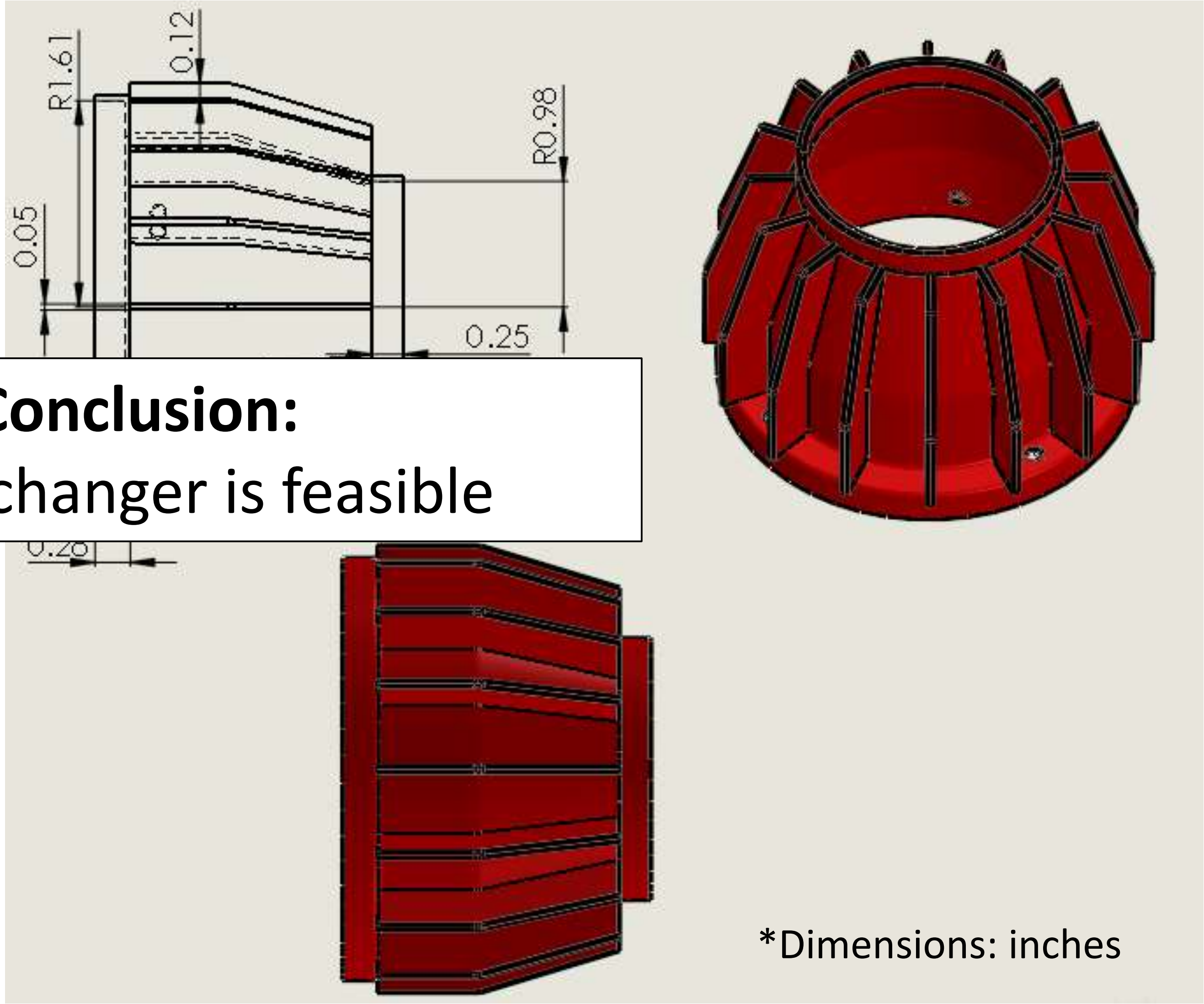
- Will be made in-house
  - Casings(8,9) - Rolled and welded
  - Ring(1), Brackets(2,3), Connectors(4-7), Nozzle Shroud(11), Endcap(12) - Milled



- Stainless Steel 304
  - Machinable
  - Weldable
  - Can withstand engine temperatures

Heat Exchanger: Finned Nozzle

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



Conclusion:
Heat exchanger is feasible

*Dimensions: inches

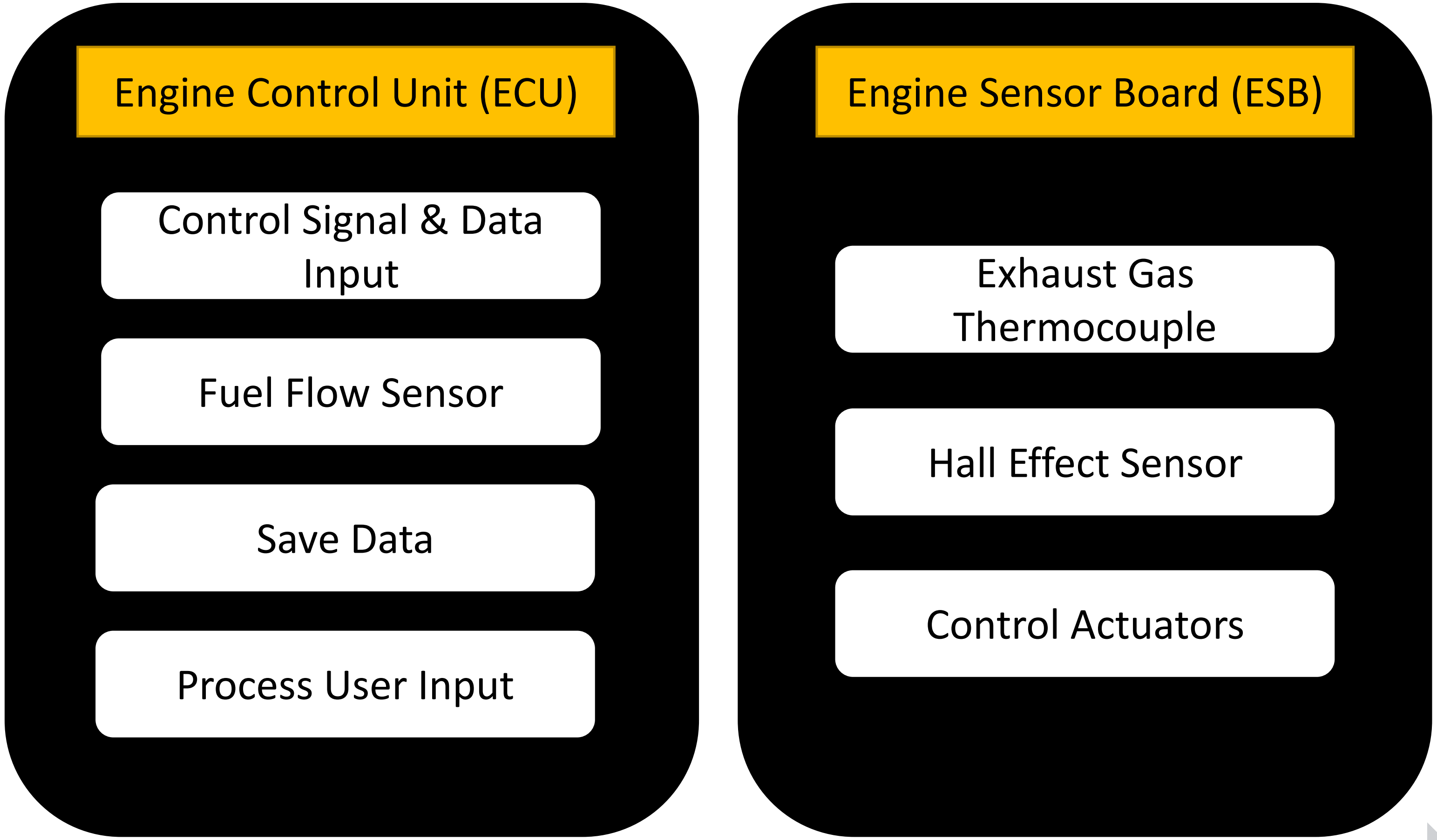
CPE 3: Engine Electronics

Goal: Safely control modified engine and save sensor data

Engine Electronics – Overview

Custom printed circuit boards – based off MEDUSA design

MEDUSA ECU



Engine Control Unit (ECU)

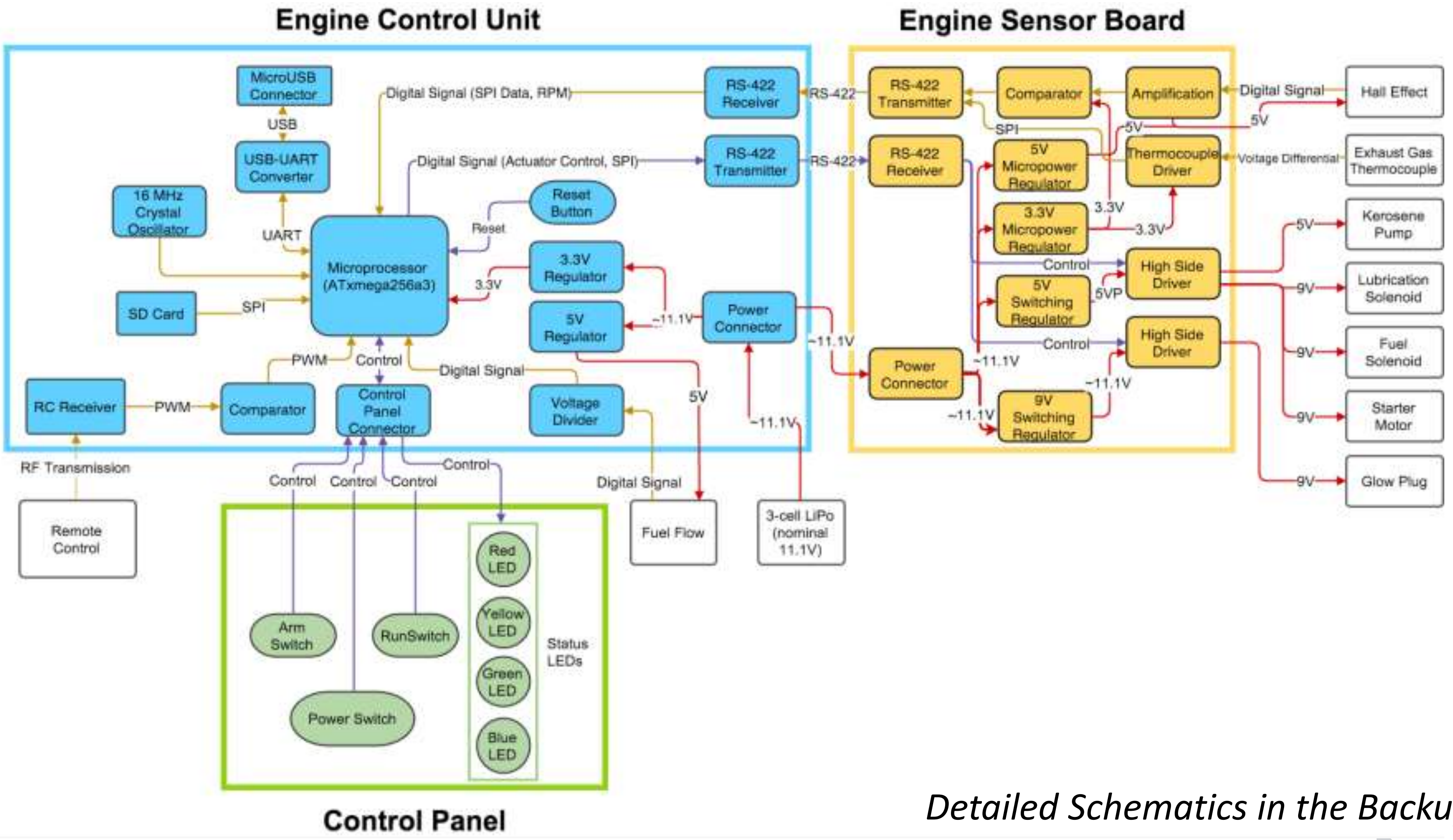
- Control Signal & Data Input
- Fuel Flow Sensor
- Save Data
- Process User Input

Engine Sensor Board (ESB)

- Exhaust Gas Thermocouple
- Hall Effect Sensor
- Control Actuators

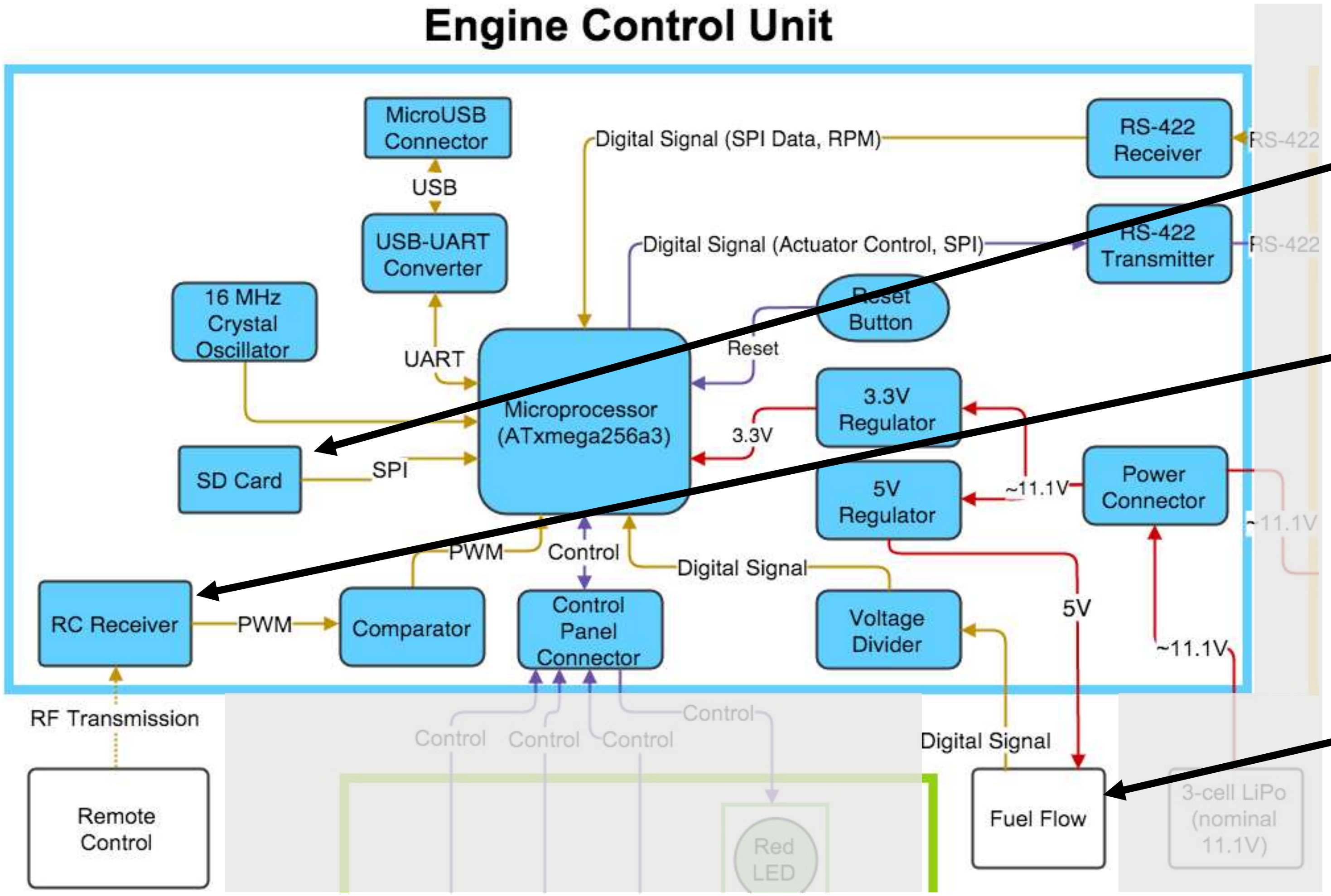
MEDUSA ESB

Engine Electronics– Overview



Detailed Schematics in the Backup Slides

Engine Electronics– ECU



DR 1.3

Save data at a rate of at least 5 Hz.

DR 1.9

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

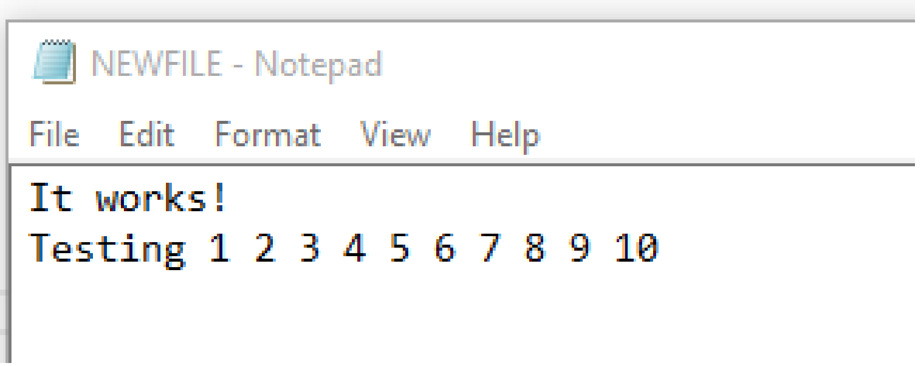
* Micro USB also included to send data and status to computer during testing

DR 1.4

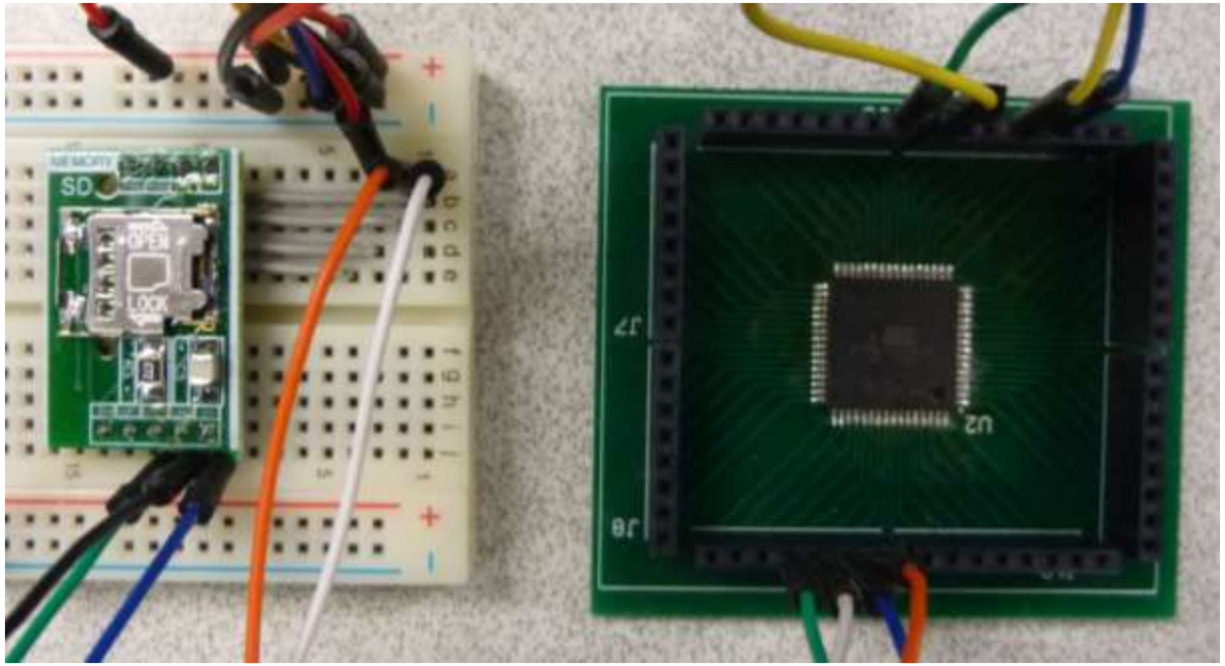
Measure and control the fuel flow rate to the engine.

Engine Electronics– Saving Data

- SD storage
  - Tested and fully functional
  - Up to 32 GB
  - Full File System
- Transfer rate of 16 Mbs write/read
  - 1 ms start up time per write
  - 512 byte buffer



```
It works!
Testing 1 2 3 4 5 6 7 8 9 10
```



SD Testing Configuration

Engine Electronics – Fuel Flow Sensor

- Equflow 0045
- Disposable insert (~$50)
  - Fuel pump too weak to include filter in line
- Flow Rate 0.1-2L/min with 110,000 pulses/L
  - Engine fuel flow rate: 0.370 L/min
  - Accurate to 1% of reading (±0.0001 L/min)
  - Predicted 580±5 pulses/s
- 34mA current at 5V

Disposable PFA flow meter

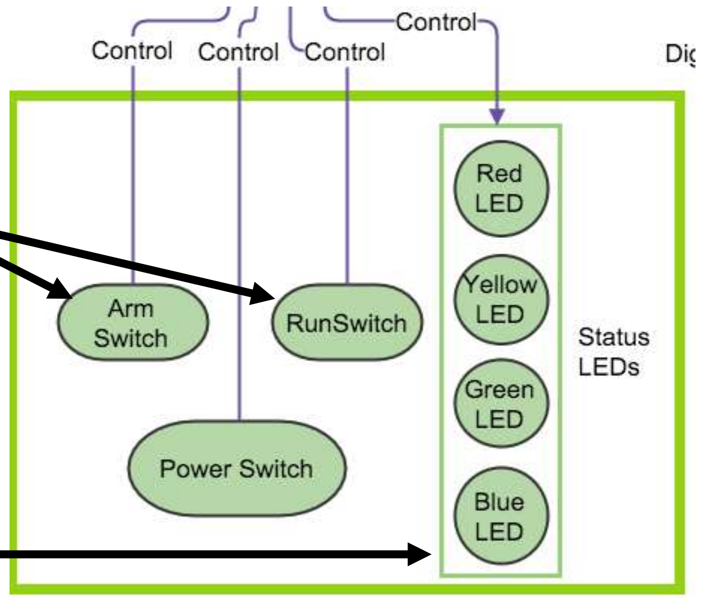
Engine Electronics– Control Panel

DR 1.9

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

DR 1.10

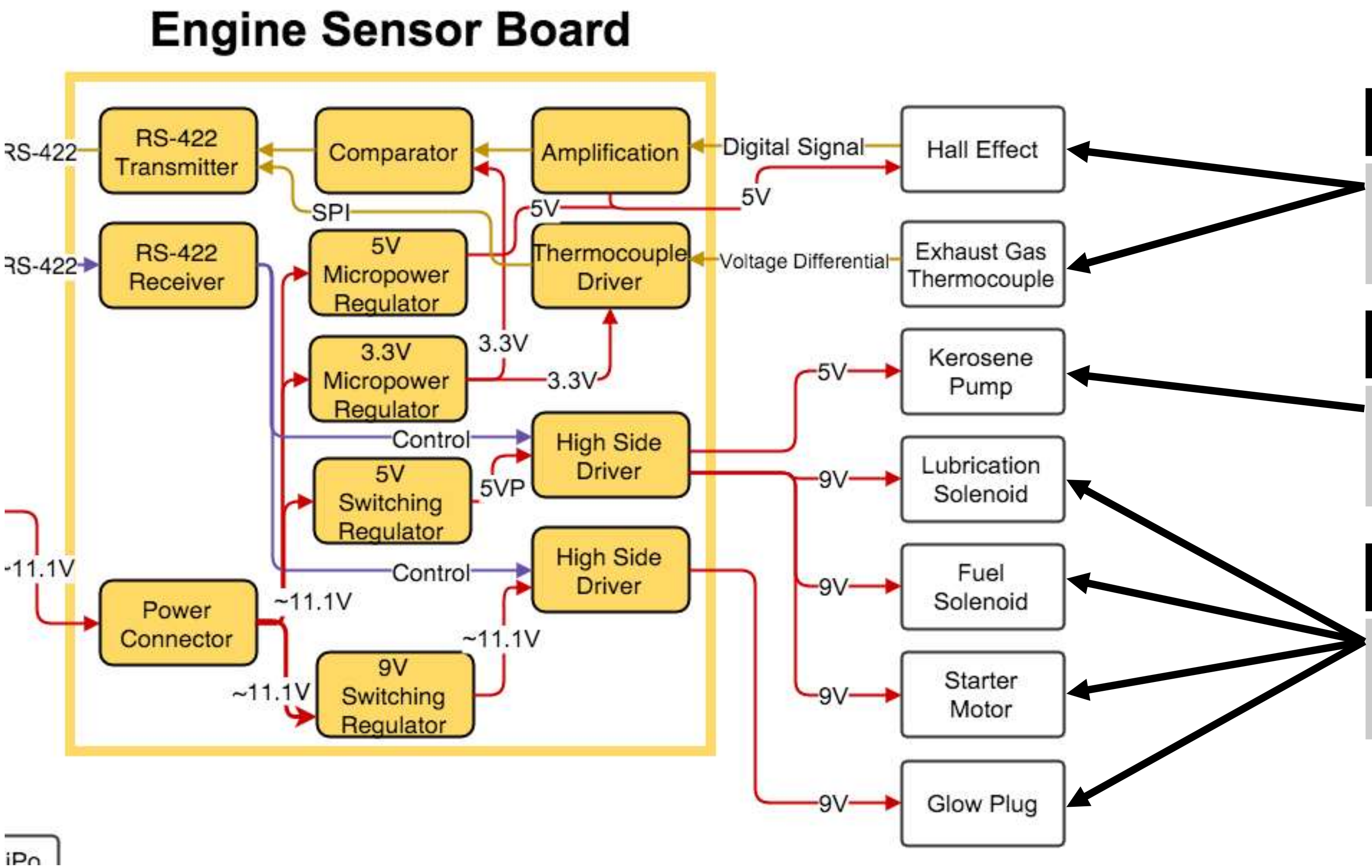
Display status with indicator LEDs.



Control Panel

- *Arm*: Indicates normal start procedure
    - For electronic reset safety
- *Run*: Begin start procedure

Engine Electronics– ESB



DR 1.1

Read the state of the engine at a rate of at least 113 Hz.

DR 1.4

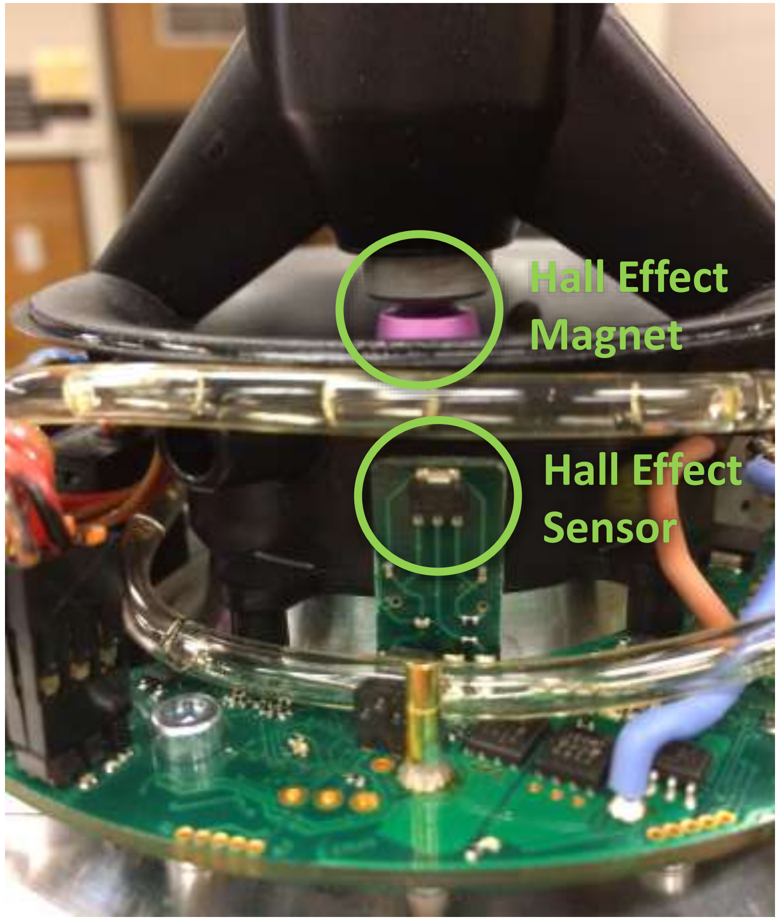
Measure and control the fuel flow rate to the engine.

DR 1.5-1.8

Control the existing engine starter motor, glow plug, fuel solenoid, and lubrication solenoid.

Engine Electronics – Hall-Effect

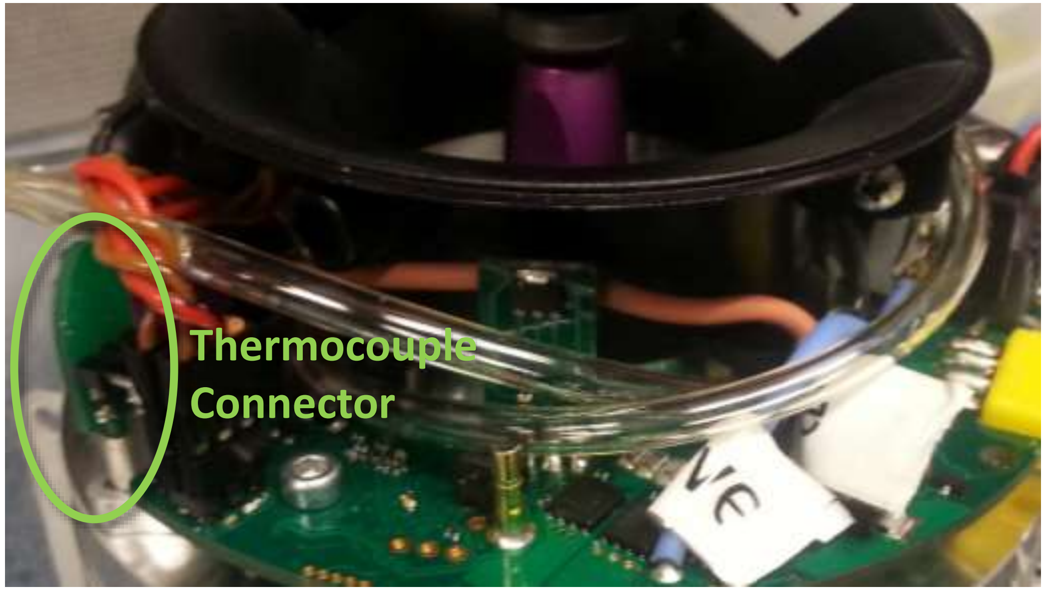
- Used to calculate RPM
  - Limit of 130,000 RPM
  - 2116 pulses per second
  - Pull rate of at least 31 Hz
    - Maximum error of 0.5% at any moment
- Best option: Stock part
  - Off ramp: SS56AT (Honeywell)



Stock Engine Sensor Board: Hall Effect Location

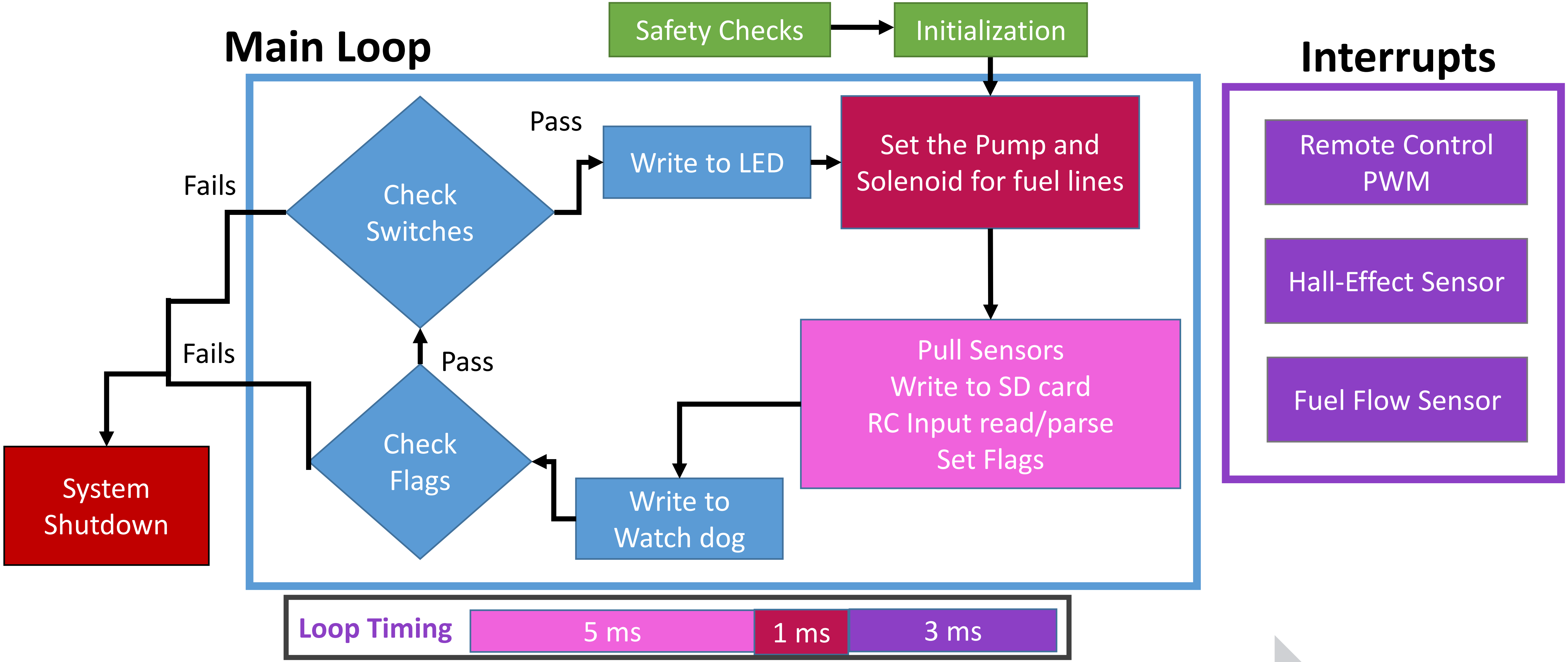
Engine Electronics – Thermocouple

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

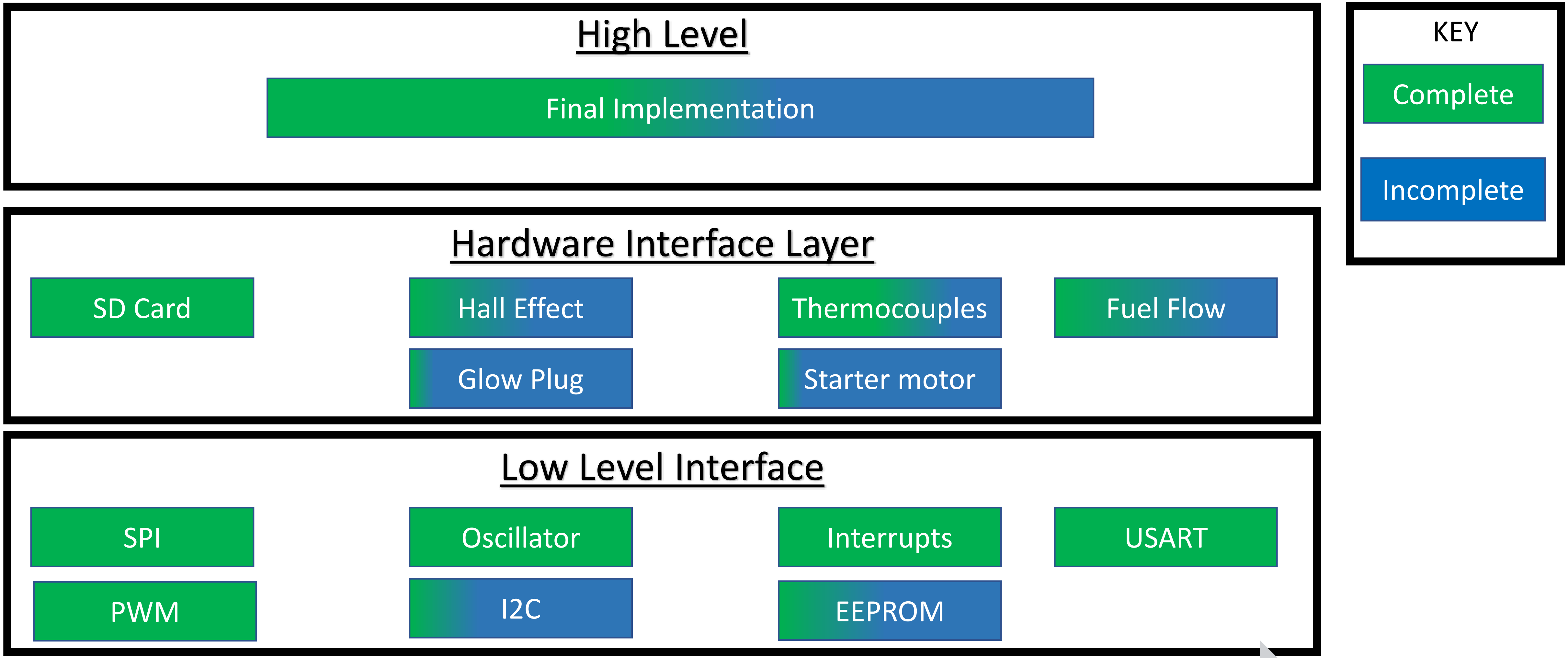


Stock Engine Sensor Board: Thermocouple Location

Engine Electronics– Software Main Loop



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

I2C

EEPROM

KEY

Complete

Incomplete

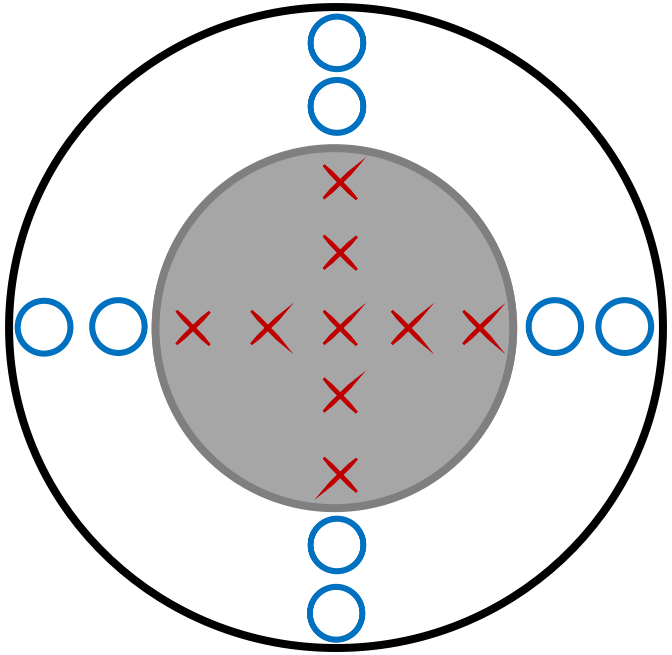
CPE 4: Testing

Goal: Validate model and verify requirements

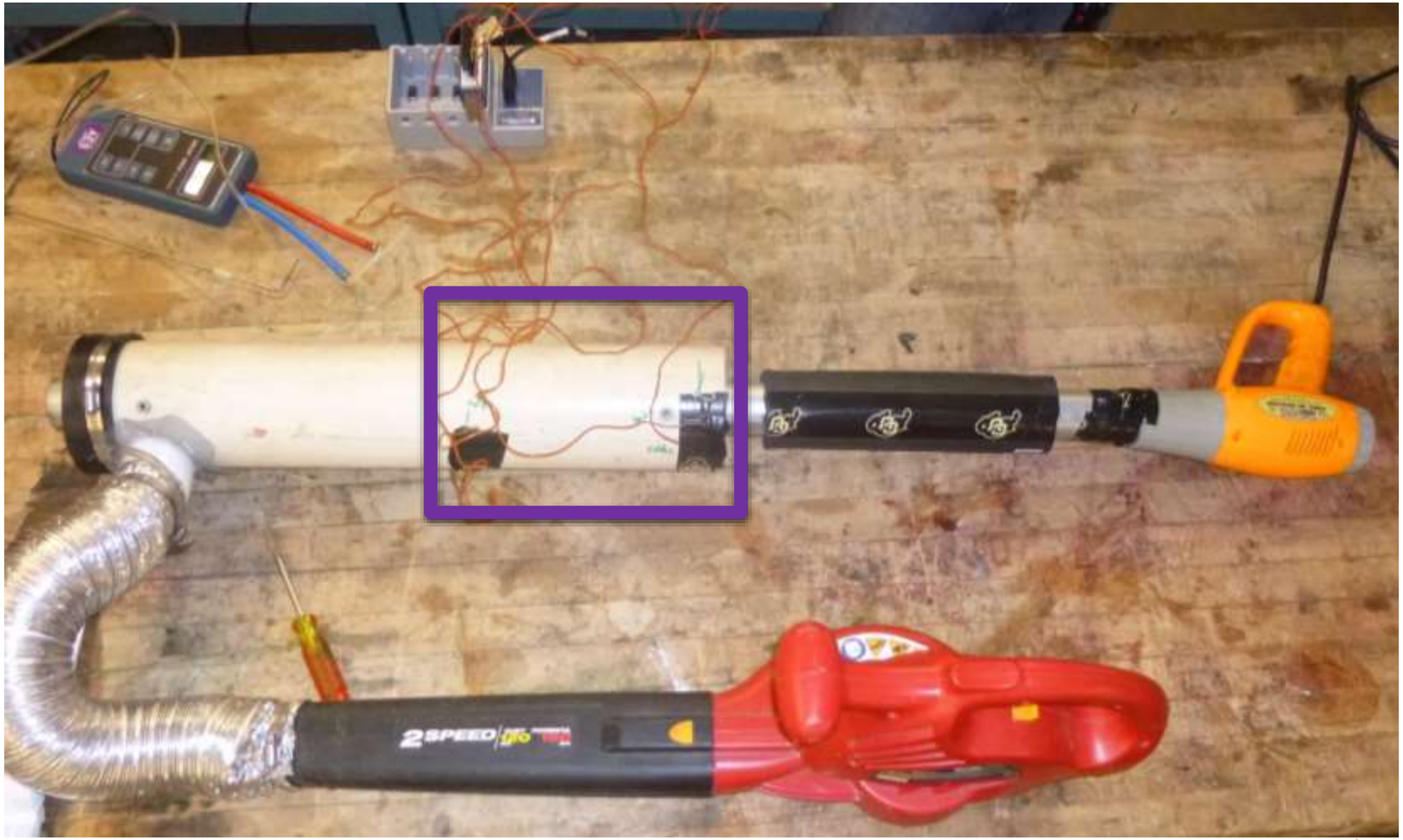
Model Validation Test

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

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



Model Validation Test



Model Validation Test: Takeaway

- ΔT within 0.36K (**12%**) of 1D model prediction
  - ΔTmodel = 2.9K ± 0.3K
  - ΔTanalog = 2.6K ± 0.2K
  - Between 2% a
- Decrease error
  - Take more me
  - Switch therm
  - Increase speed of hot flow for a turbulent Reynolds number

Conclusions:

Model is Feasible

Analog Test is Valid

Risk Analysis

Risks

1. Modified Engine

1.1 Modified engine does not start

1.2 Primary air flow extinguishing flame

1.3 Fuel flow rate cannot be precisely controlled

1.4 Pressure leaks degrade engine performance

2. Data Collection

2.1 Smalls changes in properties cannot be accurately measured

3. Engine Analog Tests

3.1 Sensor placement in flows to achieve correct readings

Risk Matrix

Likelihood	Minimal	Minor	Major	Serious	Catastrophic
Near Certainty		1.4			
Highly Likely				1.1 1.2	
Likely		3.1	1.3	2.1	
Low					
Extremely Unlikely					

Severity

[illegible]
3.1 Validation requires field measurements
➔ [illegible]
➔ Several sensors, vary locations

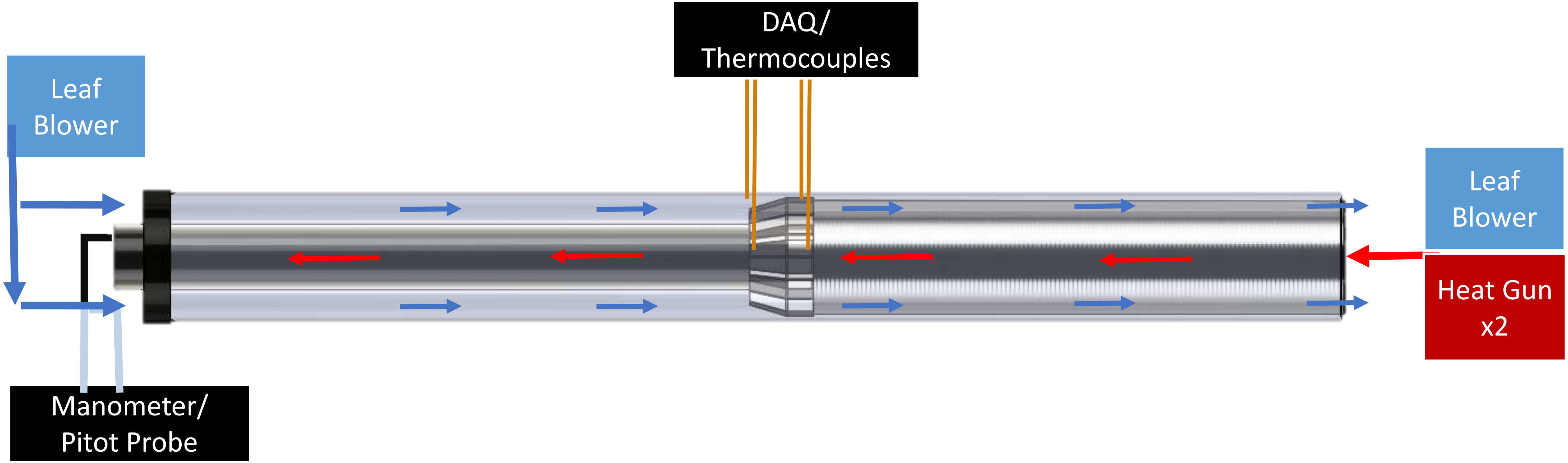
Verification and Validation

Verification

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

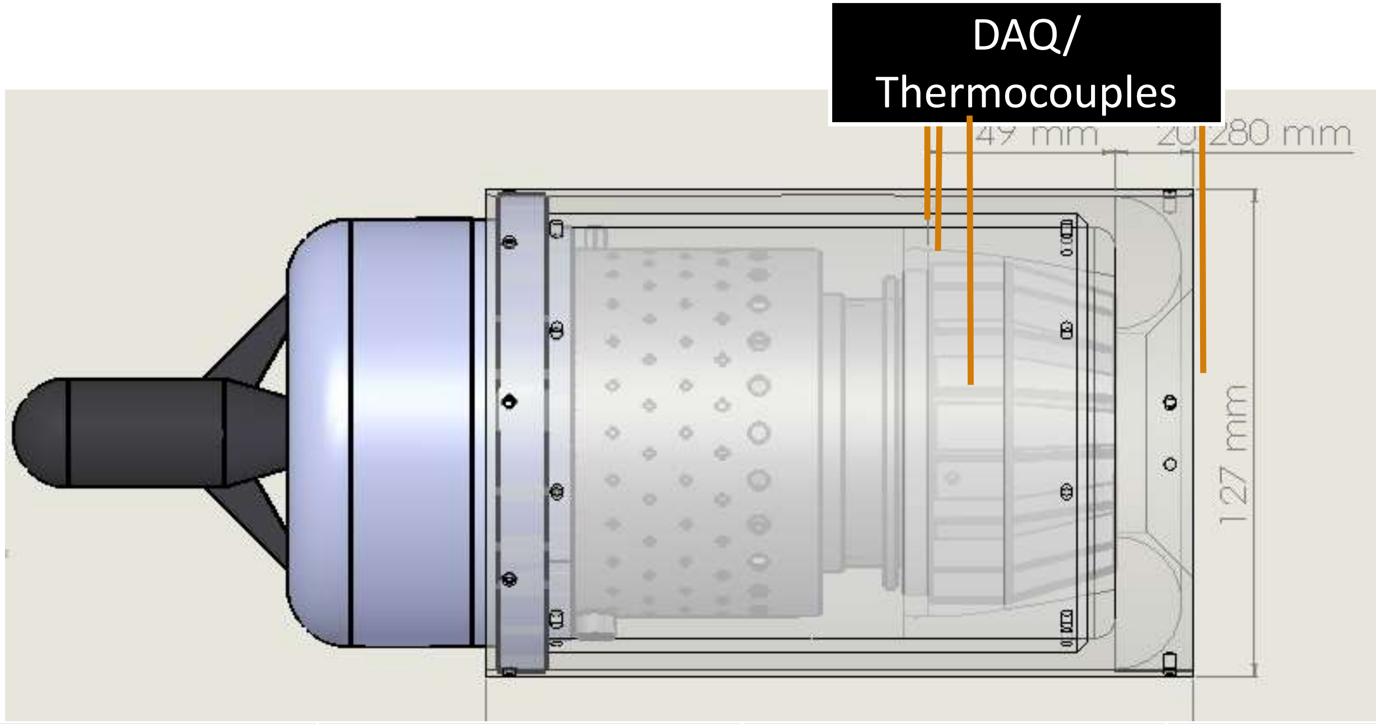
- Level 3:
    - Engine **runs with recuperator** attached
    - **Throttle time** met
    - Verifies **effectiveness**, Thrust Specific Fuel Consumption (**TSFC**), and **thrust reduction match 1D and CFD models**

Engine Analog Level 1 Verification



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

Engine Integration Level 3 Verification



Fuel Flow Sensor

Load Cell

Hall Effect

Sensor List	FR Validation	Error	Sample Rate	Acquired/ Tested
Fuel Flow Sensor	TSFC (FR 2)	±1%	31 Hz	No / No
Load Cell	Thrust (DR 2.5)	±0.2%	1 Hz	Yes / No
Hall Effect	RPM (DR 2.4)	±0.05%	31 Hz	No / No

Engine Integration Level 3 Verification

$$Throttle\ Time = \Delta t$$

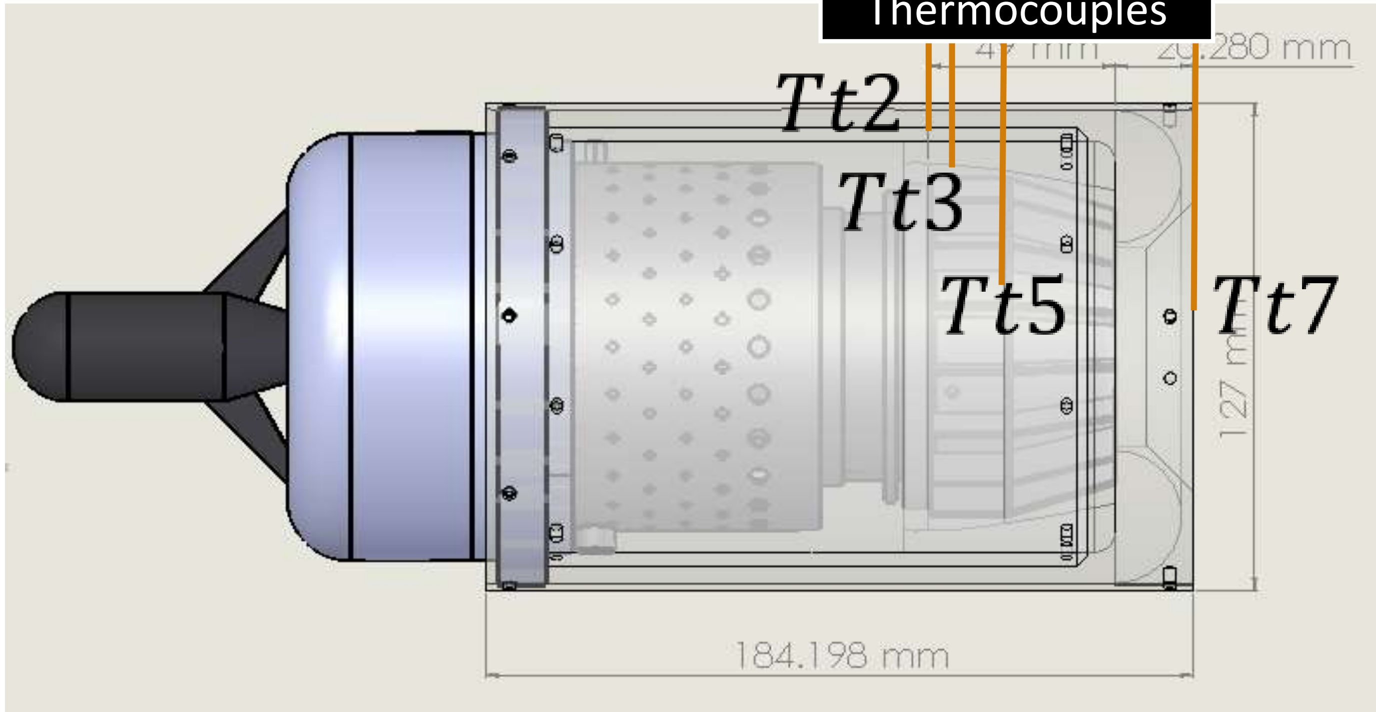
Hall Effect

$$TSFC = \dot{w}_f / F$$

Fuel Flow Sensor

Load Cell

Daq/
Thermocouples



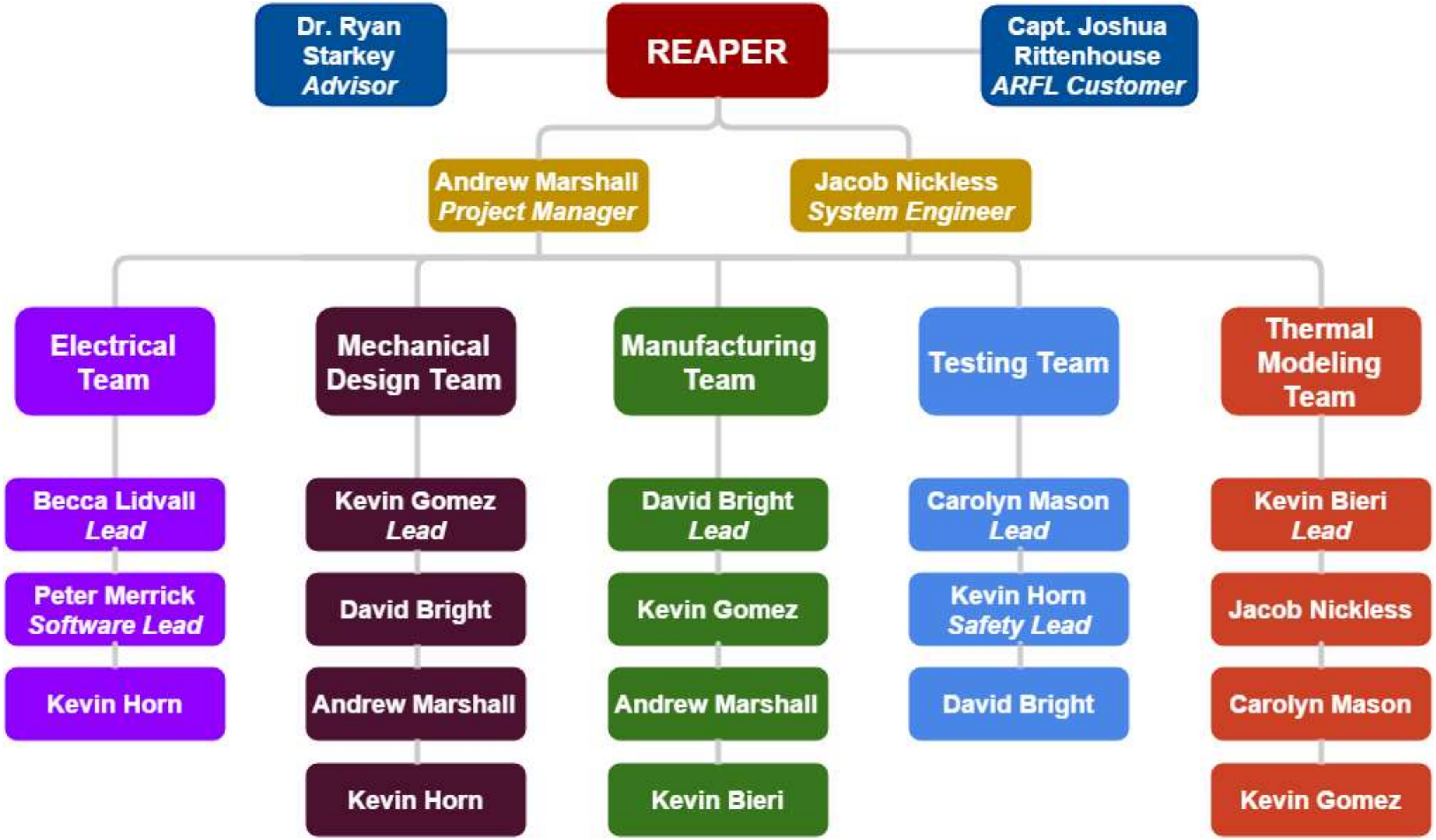
$$Effectiveness = \frac{Tt3 - Tt2}{Tt5 - Tt2}$$

Project Planning

Organizational Chart

Lead positions:

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



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**

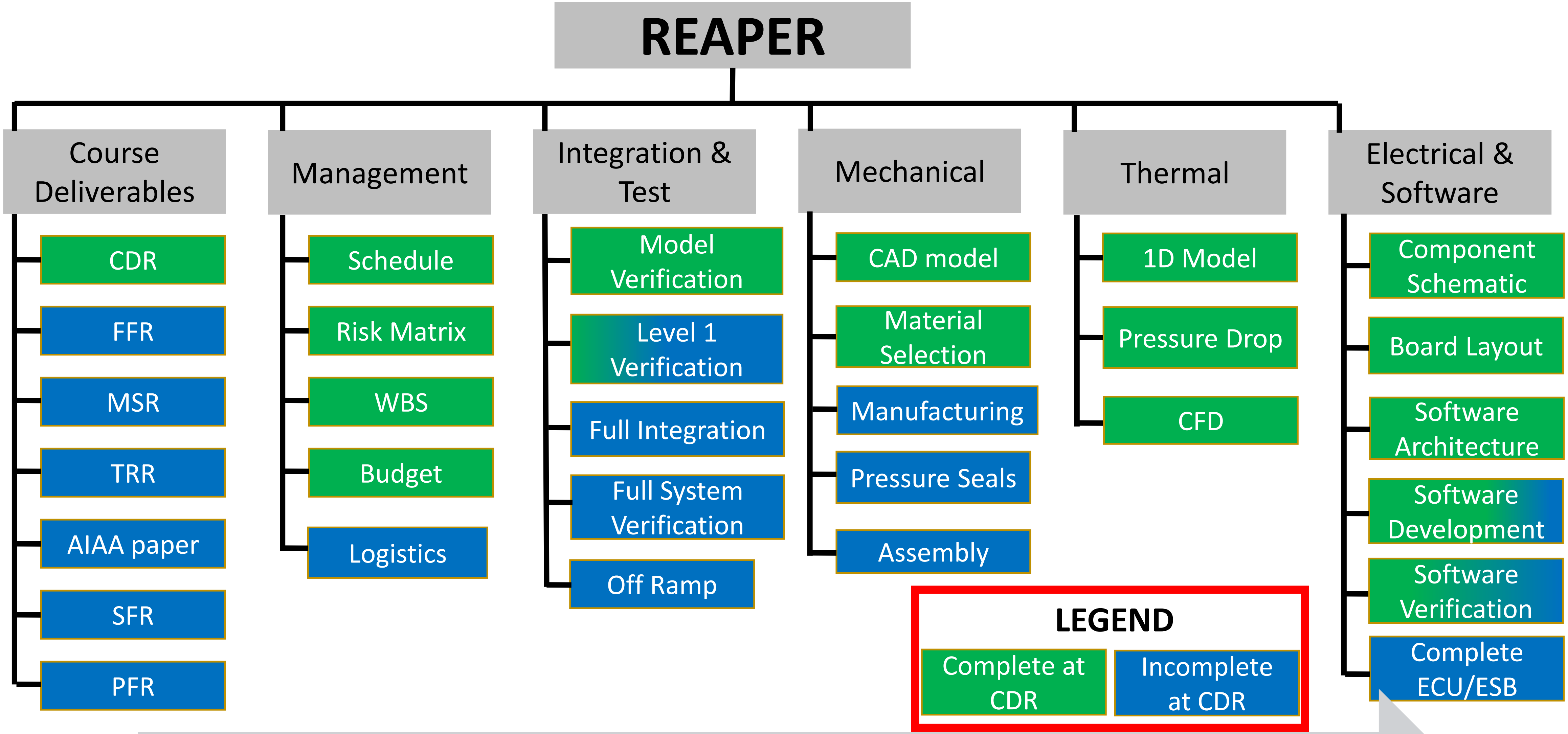
Mechanical Design Team
- **Kevin Gomez** ***Lead***
- **David Bright**
- **Andrew Marshall**
- **Kevin Horn**

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**

Work Breakdown Structure



REAPER

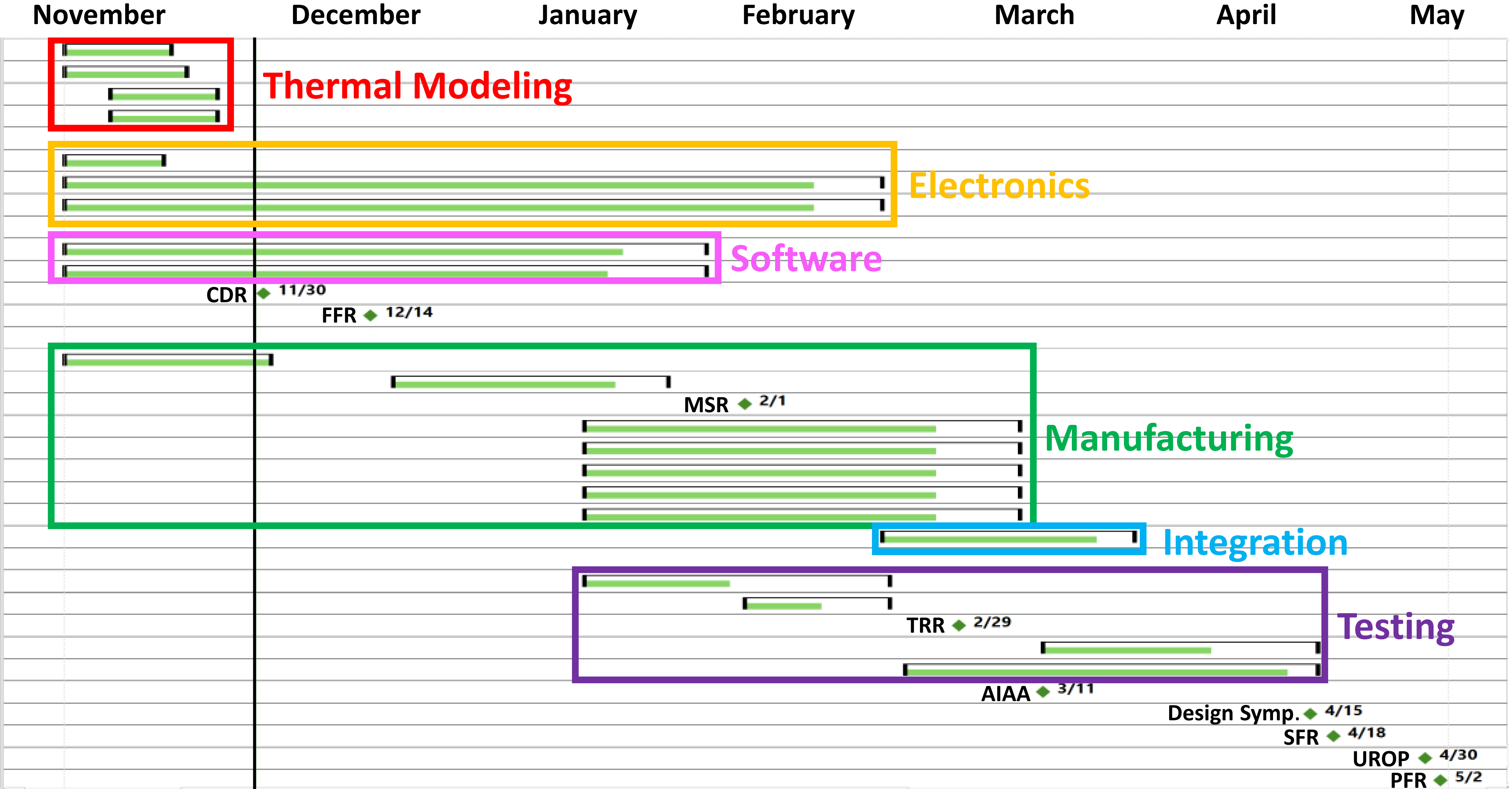
- Course Deliverables
  - 🟩 CDR
  - 🟦 FFR
  - 🟦 MSR
  - 🟦 TRR
  - 🟦 AIAA paper
  - 🟦 SFR
  - 🟦 PFR
- Management
  - 🟩 Schedule
  - 🟩 Risk Matrix
  - 🟩 WBS
  - 🟩 Budget
  - 🟦 Logistics
- Integration & Test
  - 🟩 Model Verification
  - 🟩🟦 Level 1 Verification
  - 🟦 Full Integration
  - 🟦 Full System Verification
  - 🟦 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 CDR

🟦 Incomplete at CDR

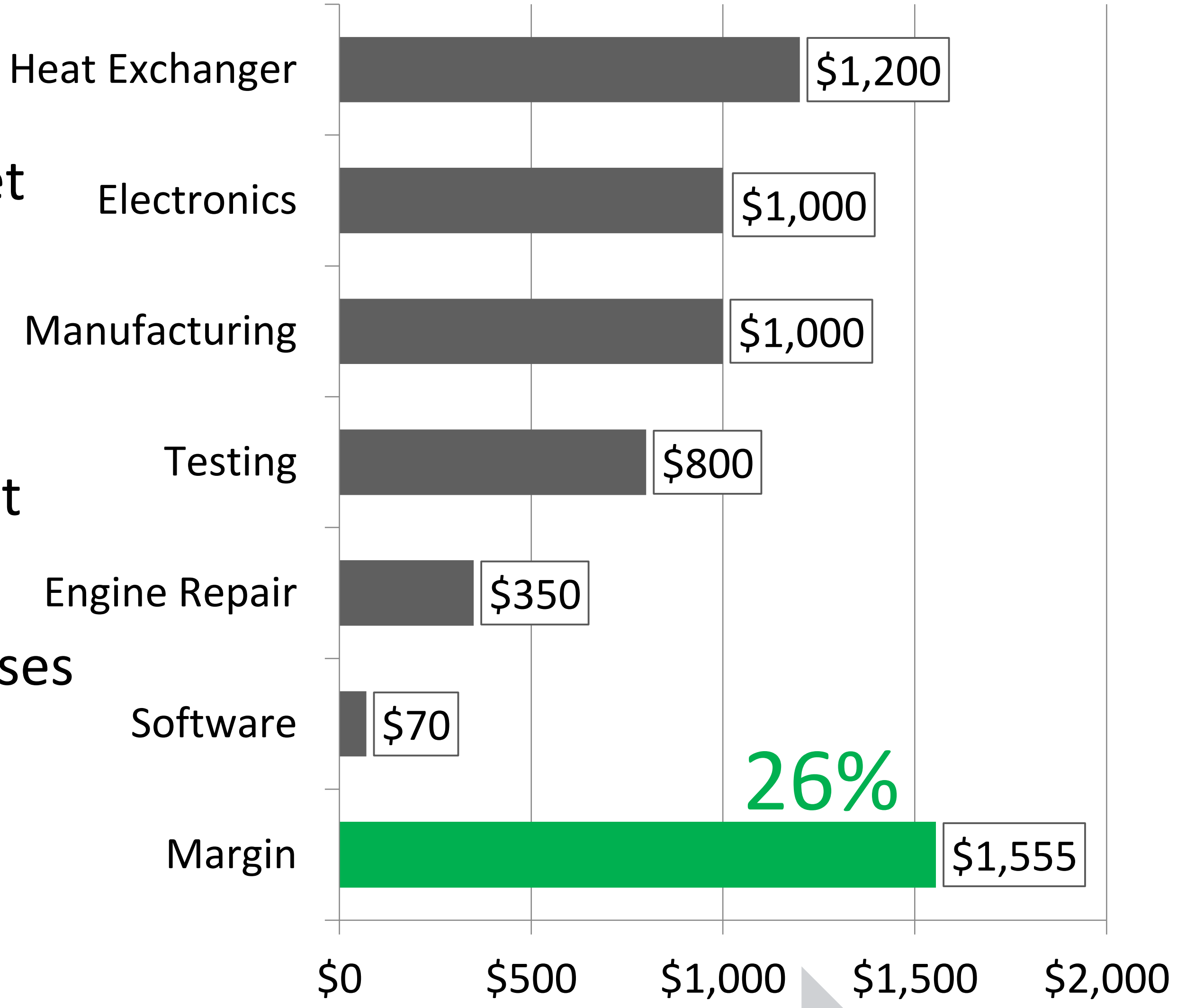
Work Plan


November
December
January
February
March
April
May
Thermal Modeling
Electronics
Software
CDR ◆ 11/30
FFR ◆ 12/14
MSR ◆ 2/1
Manufacturing
Integration
TRR ◆ 2/29
Testing
AIAA ◆ 3/11
Design Symp. ◆ 4/15
SFR ◆ 4/18
UROP ◆ 4/30
PFR ◆ 5/2

Cost Plan

Category	Major Components
Electronics	ECU Board (3 revs)
	ESB Board (3 revs)
Heat Exchanger	DMLS Manufacturing
	Shipping
Manufacturing	Outer Casing
	Inner Casing
	Endcap
	Pressure Sealing
Testing	Materials
	Sensors
Software	Testing PCB
Engine Repair	ESB damage

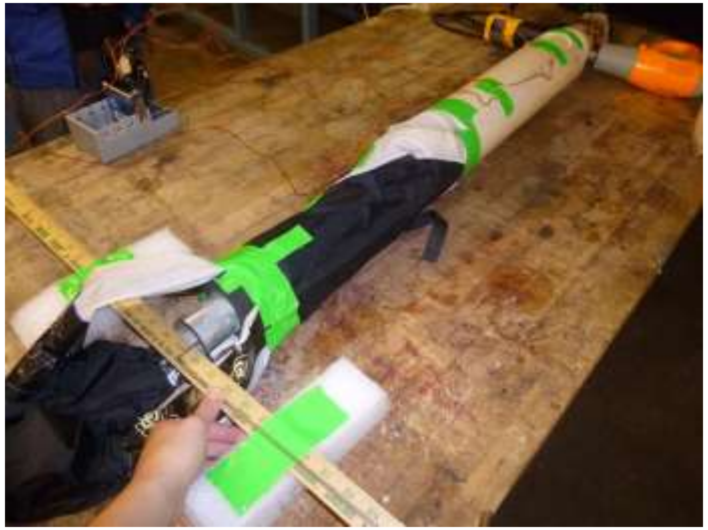
- Class Budget
  $5,000
- UROP
  + $975
- Total Budget
  $5,975
- Total Expenses
  $4,420



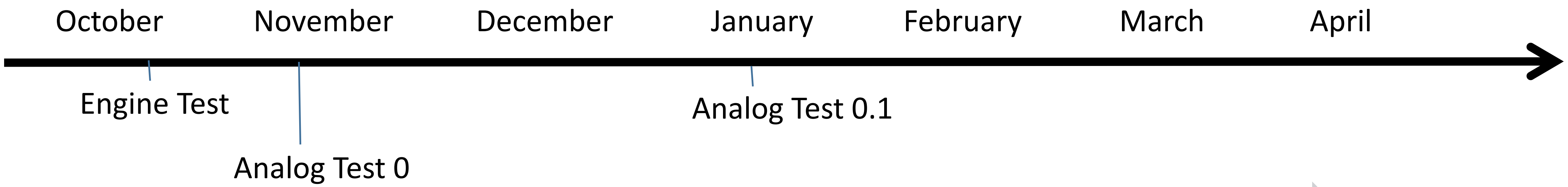
Test Plan

10/20 Engine Test

11/12 Analog Test 0



1/15 Analog Test 0.1



October

November

December

January

February

March

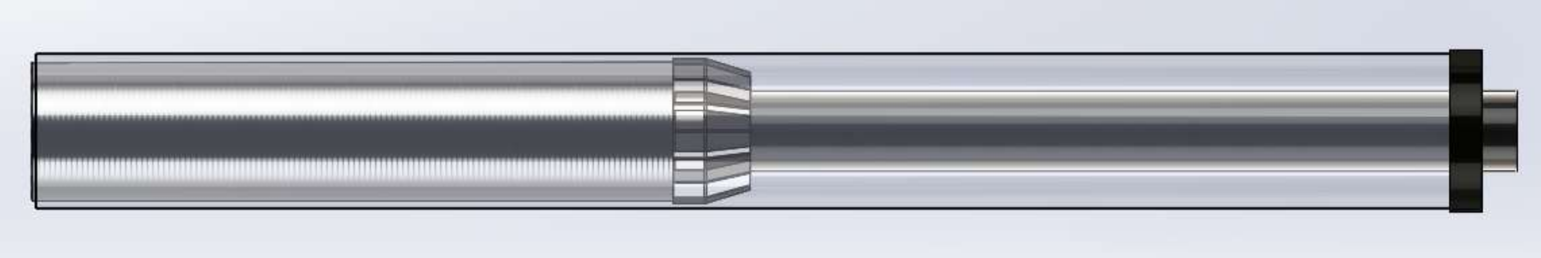
April

Engine Test

Analog Test 0

Analog Test 0.1

Test Plan



1/23 Engine Analog Level 1

2/8 Fully Characterize Stock Engine

October November December January February March April

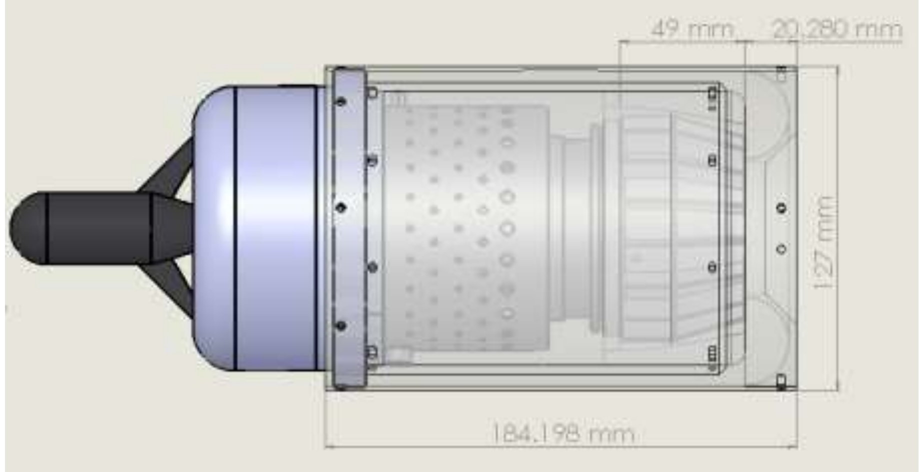
Engine Analog Level 1

Fully Characterize Stock Engine

Test Plan

Test Readiness Review

2/29 TRR



3/28 Final Full System Test

October November December January February March April

TRR

Final Full System Test

Conclusion

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

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

CR 3: Minimize thrust loss, weight, and volume additions ✓

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

On track for project success

Questions?

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- [13] “Stainless 2B Sheet 304 Annealed.” *OnlineMetals.com.* Web. Accessed 29 Nov. 2015. <http://www.onlinemetals.com/merchant.cfm?pid=6828&step=4 &showunits=inches&id=233&top_cat=1>
- [14] “Stainless Redtangle 304/304L.” *OnlineMetals.com.* Web. Accessed 29 Nov. 2015. <https://www.onlinemetals.com/merchant.cfm?pid=4420&step=4&showunits=inches &id=25&top_cat=1>

Backup Slides

Heat Exchanger Design Requirements

FR 1: Engine operates in modified state

DR 1.1: Integrate with engine

DR 1.2: Throttle response characterization

DR 1.3: Less than 10% thrust decrease

Heat Exchanger Design Requirements

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

DR 2.1: Effectiveness of at least 13%

DR 2.2: Thermal survivability

DR 2.3: Integrate with engine

DR 2.4: Throttle response characterization

DR 2.5: Less than 10% thrust decrease

Thermal Model Design Requirements

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

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

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

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

DR 3.4: Limited required **sensors** to validate model

Engine Control Design Requirements

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

DR 1.1: Know the state of the engine.

DR 1.2: Ability to shut down engine with greater than with 31 Hz response time.

DR 1.3: Save data at a rate of at least 5 Hz.

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

DR 1.5: Control the existing engine starter motor.

DR 1.6: Control the existing engine glow plug.

DR 1.7: Control the existing engine fuel solenoid.

DR 1.8: Control the existing engine lubrication solenoid.

DR 1.9: Engine shall start, shutdown, and be throttle-able according to user input.

DR 1.10: Display status with indicator LEDs.

Model Backup Slides

Correlations and Loss Coefficients

Colebrook-White Equation

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

Gnielinski Correlations

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

Frictional Drag

$$D = \frac{1}{2}\rho V^2 A_w C_f$$

$$C_f = f/4$$

Loss	Equation
Friction	$h_L = f\frac{l}{D}\frac{V^2}{2g}$
Expansion	$h_L = \frac{V_1^2\rho_1}{2g\rho_2}(K_C + 1 - \sigma^2)$
Contraction	$h_L = \frac{V_1^2\rho_1}{2g\rho_2}(K_e + 1 - \sigma^2)$
Turn (0-45 degrees)	$h_L = 0.3\frac{V^2}{2g}(\alpha/45)$
Sharp 90 degree turn	$h_L = 0.9\frac{V^2}{2g}$
180 degree smooth bend	$h_L = 0.7\frac{V^2}{2g}$

$$H_L = \sum \rho g h_L$$

CFD: Boundary Conditions/Assumptions

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

Surface Roughness:

$\epsilon = 4.8E-5\ m$

Turbulence Intensity:

$$I = 0.16 Re_D{}^{-1/8}$$

→Cold Side Inlet: 3%

→Hot Side Inlet: 8%

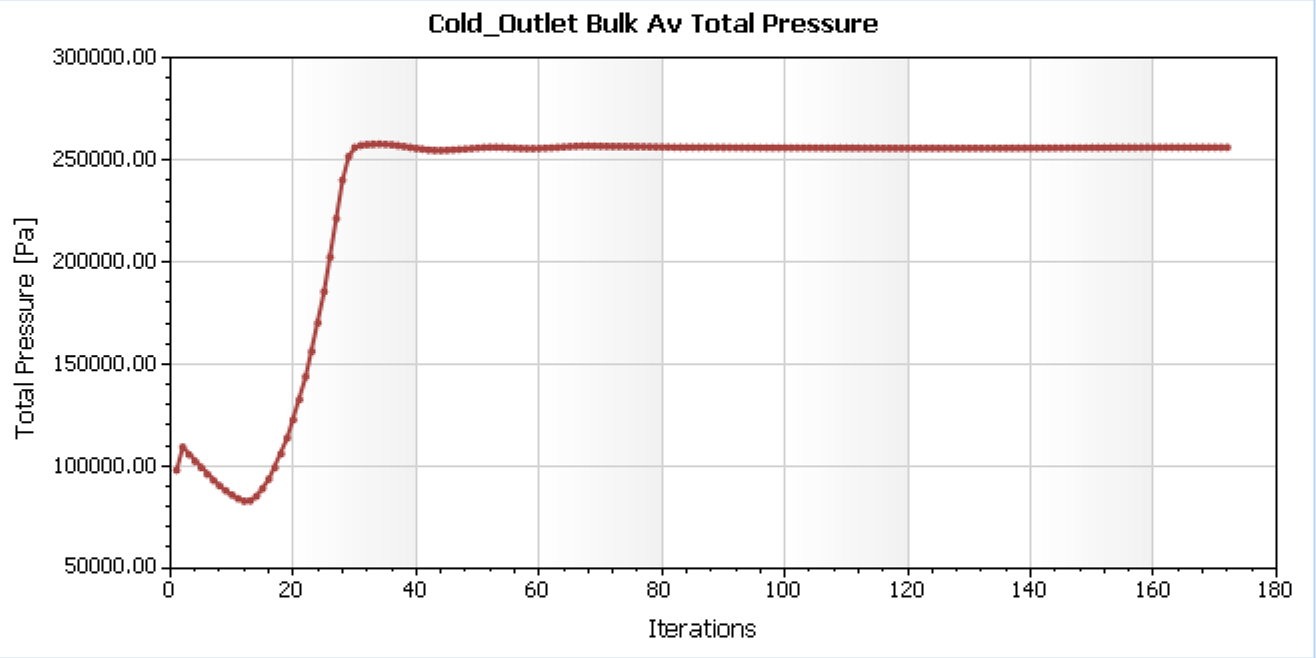
Fluid:

- Air
- Ideal gas
- Thermally perfect

CFD: Solidworks Flow Simulation Convergence

Method:

- Propagates calculation forward from initial conditions
- Tracks change between each iteration
- Once change drops below specified goals for all goals end of 1 “travel”
- Averages results across several (3) travels to give final steady-state solution

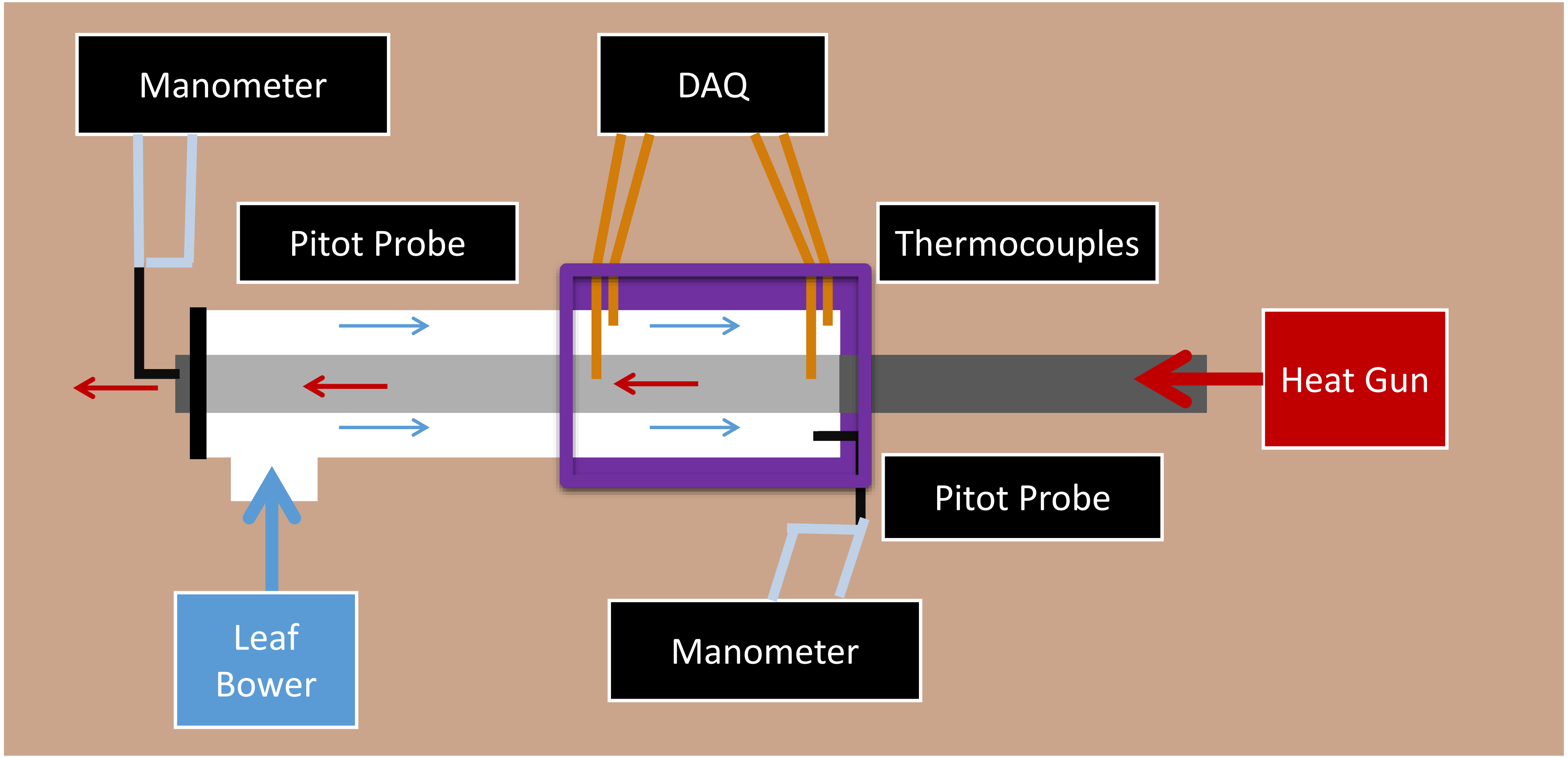


Thermal Model: Results

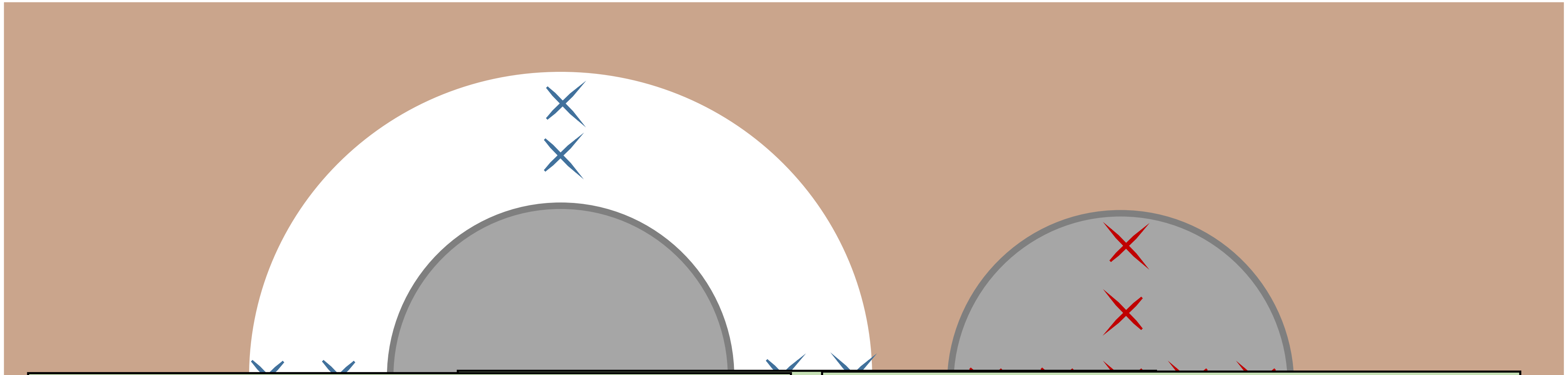
Model	Internal Total Pressure Loss [Pa]	External Total Pressure Drop [Pa]	Heat Addition [W]	Fuel Consumption Rate [kg/s]	Thrust [N]	TSFC $\left[s^{-1}\right]$
Control Volume	7403	158	1321	4.70E-2	104.8	4.40E-4
CFD – 384k	7281	207	1278	4.69E-2	104.6	4.41E-4
CFD – 647k	7261	194	1265	4.70E-2	104.7	4.41E-4
CFD – 1328k	7279	235	1309	4.68E-2	104.7	4.39E-4
Mean	7306	204	1286	4.69E-2	104.7	4.40E-4
Standard Deviation	65	40	75	0.00E-2	0.1	0.01E-4

Testing Backup Slides

Model Validation Test



Model Validation Test



Model

$$\frac{1}{U_h A_h} = \frac{1}{\eta_{0,h} A_h h_h} + \frac{t_w}{A_w k_w} + \frac{1}{\eta_{0,c} A_c h_c}$$

$$\dot{Q} = UA(Th - Tc)$$

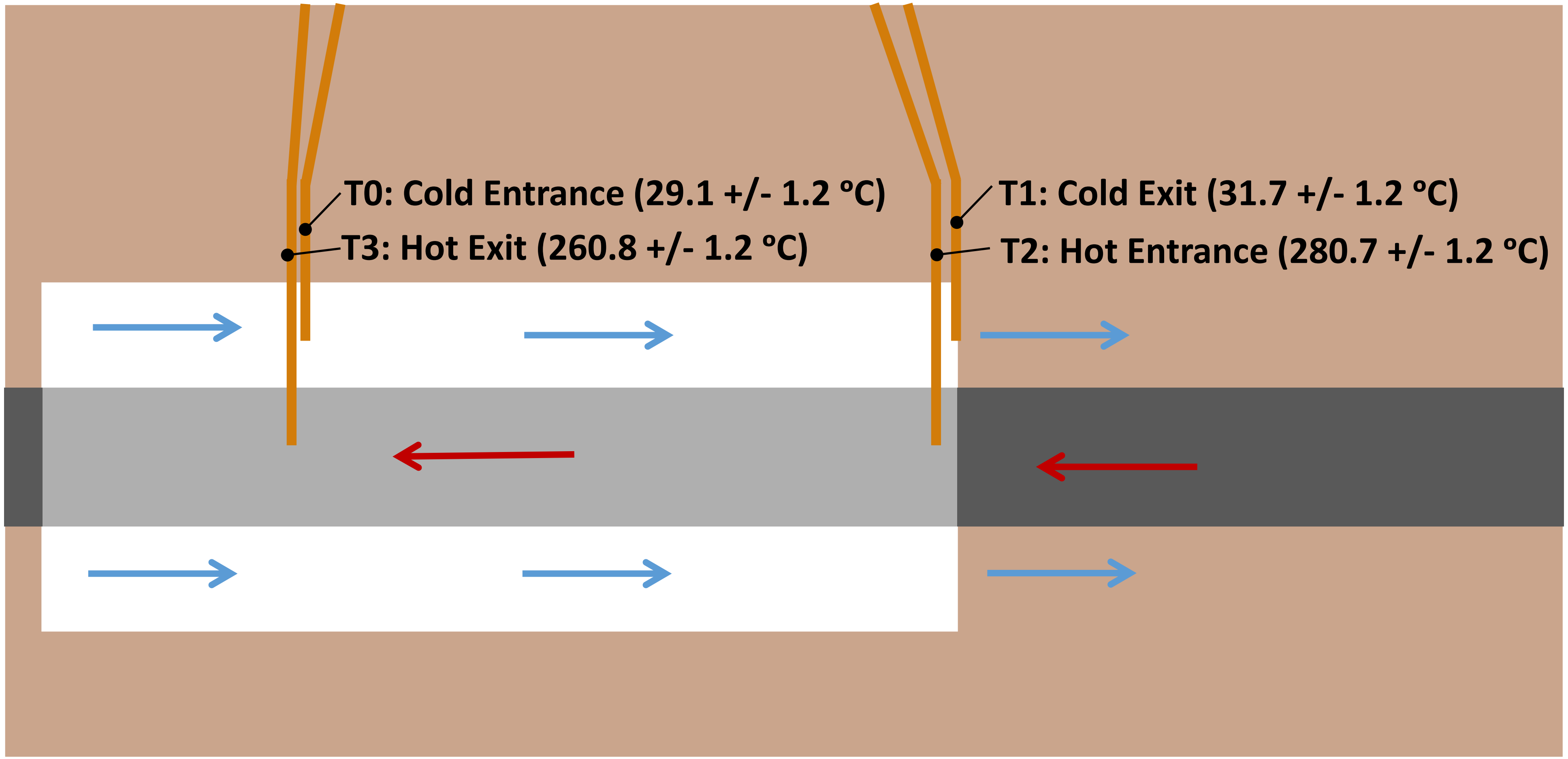
$$\dot{m} = \rho_c V_c A$$

$$\Delta T_{model} = \dot{Q}/(\dot{m} c_p)$$

Analog Test

$$\Delta T_{analog} = \Delta T_c$$

Model Verification



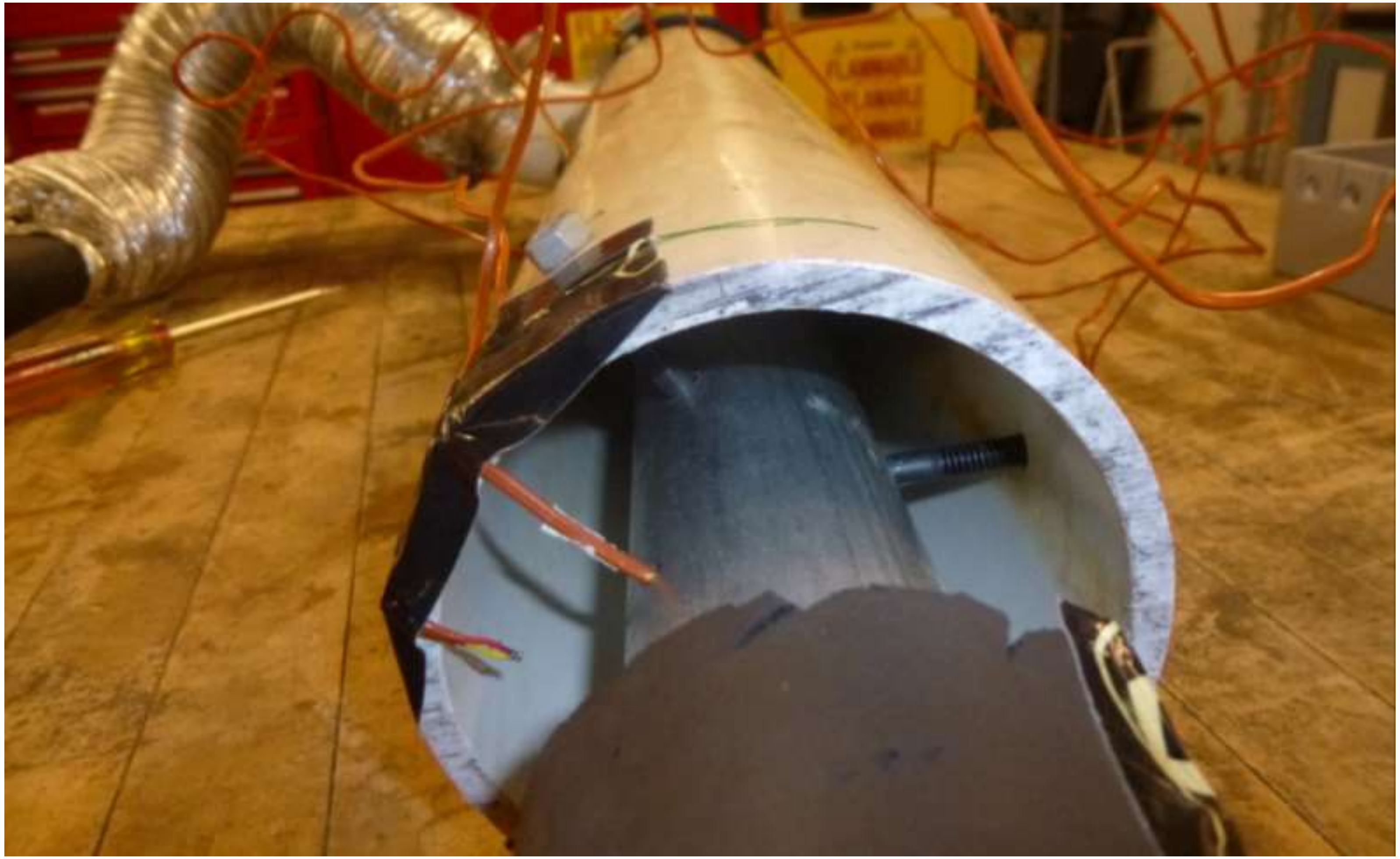
T0: Cold Entrance (29.1 +/- 1.2 °C)

T3: Hot Exit (260.8 +/- 1.2 °C)

T1: Cold Exit (31.7 +/- 1.2 °C)

T2: Hot Entrance (280.7 +/- 1.2 °C)

Model Verification



Model Verification

Model Verification: Results

- Percent difference: -12% +/- 10%
  - ∆Tmodel = 2.9 K+/- 0.3K
  - ∆Tanalog = 2.6 K+/- 0.2K

- Measurement Errors:
  - Thermocouples +/- 1.2 K
  - Pitot Probe+/- 2.8 m/s

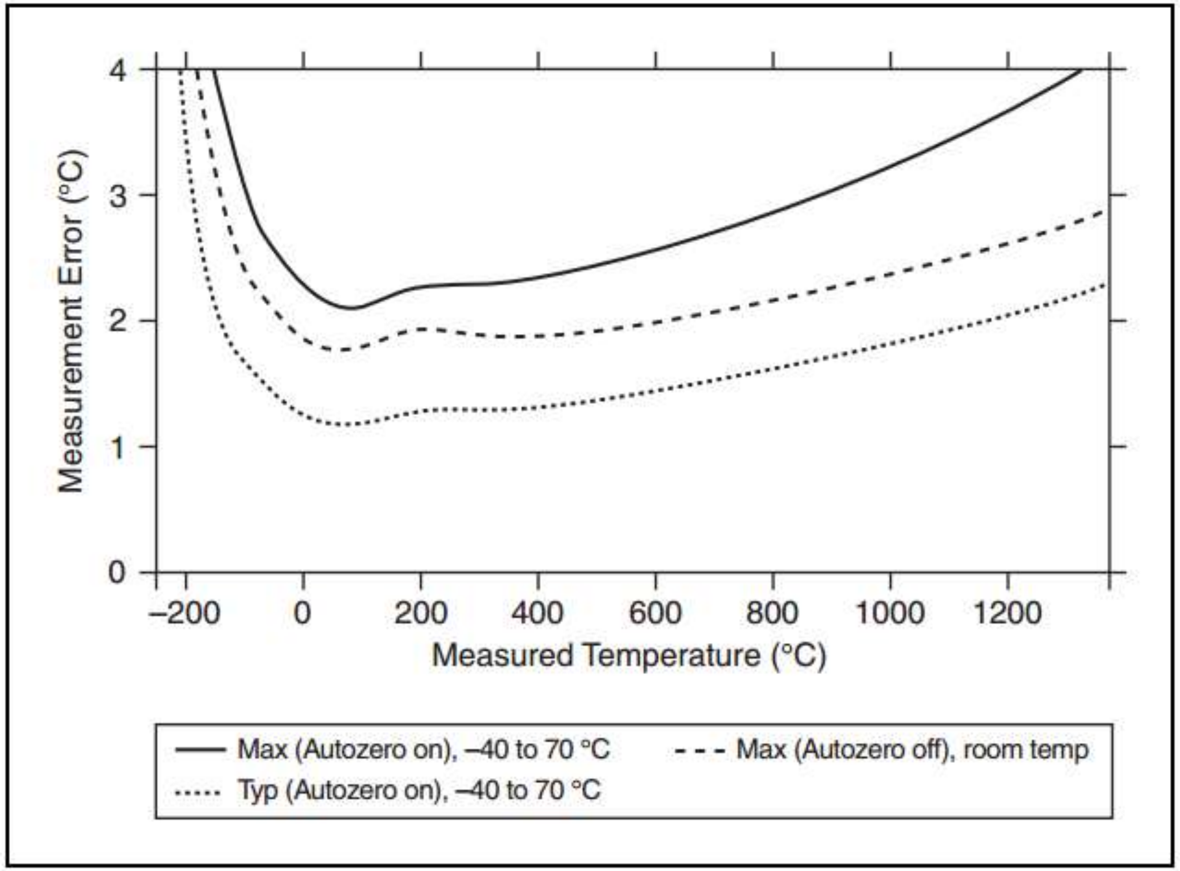
Model Verification: Results

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

Model Verification Error: DAQ + Thermocouple

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

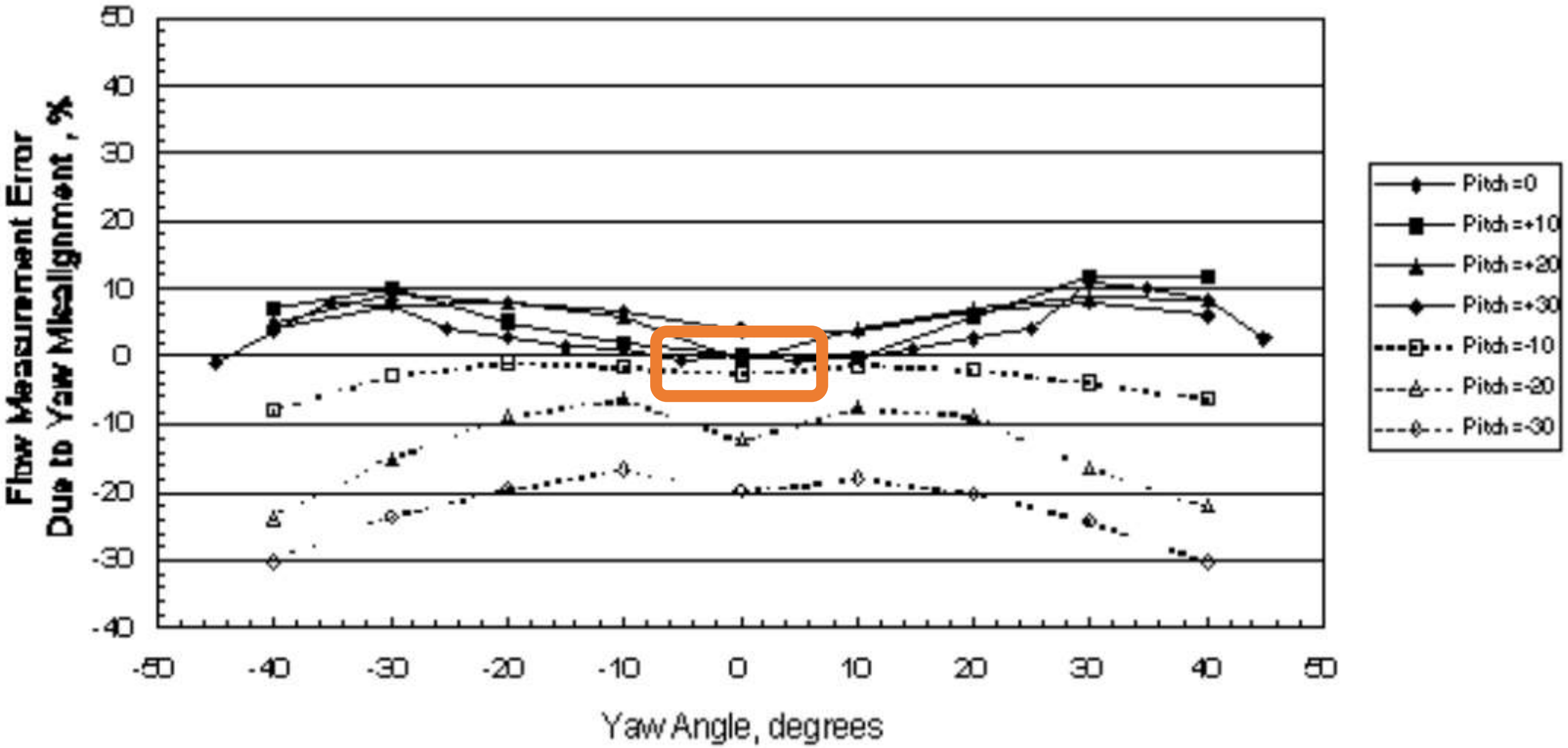
- Temperature Error:
  - +/- 2.2C or +/- 0.75%



Model Verification Error: Pitot

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

- Pitot Positioning Error:
  - +/- 3%



Model Verification Error: Load Cell

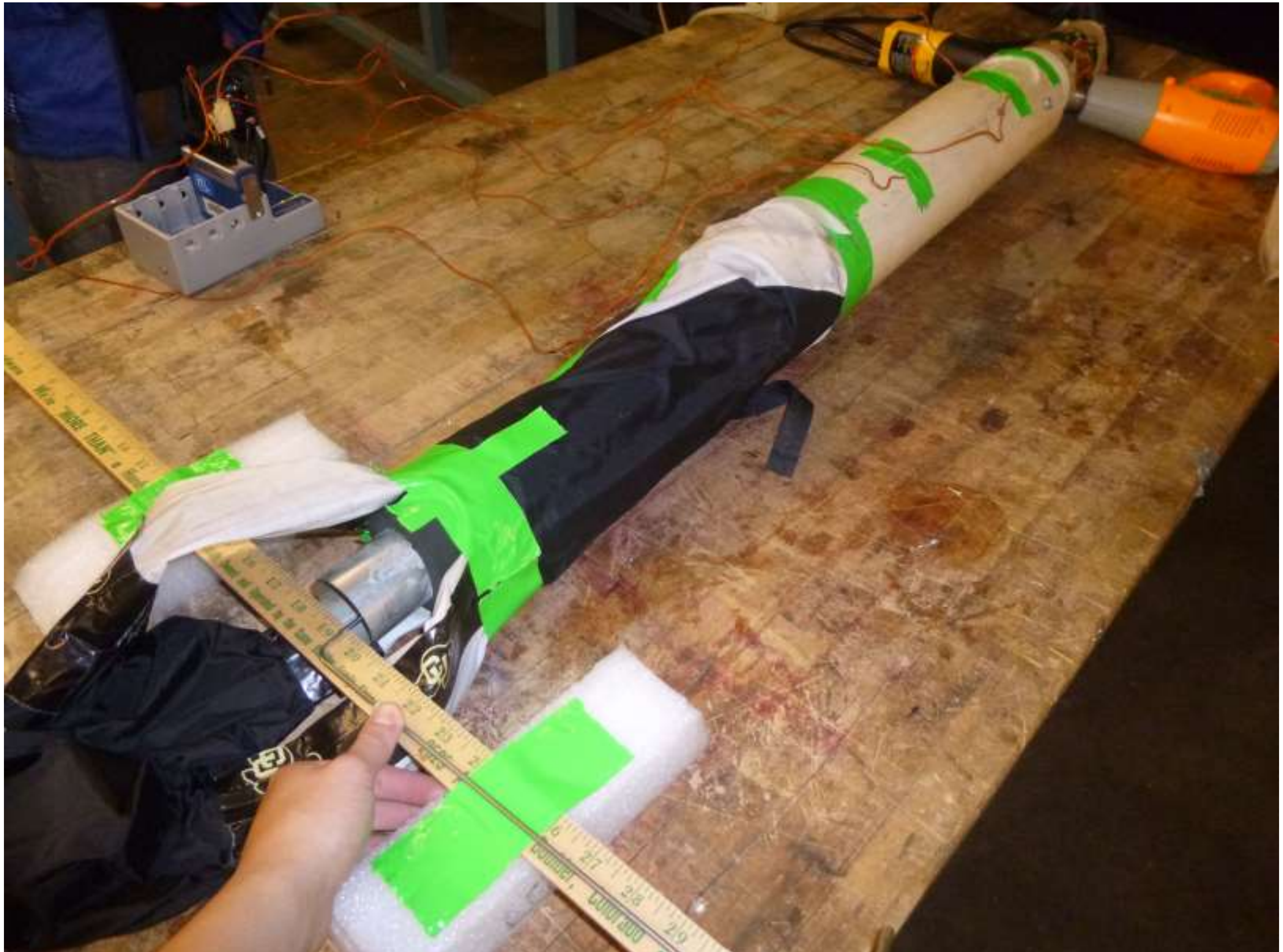
- National Instruments Daq USB-6009
  - Analog Input:
    - +/-10V, accuracy 7.73mV
    - +/-1V, accuracy 1.53mV
- Load Cell: LCGD-100
  - Range 0-100lbs
  - Repeatability +/-0.10% Full Scale Output

Heat Gun and Leaf Blower

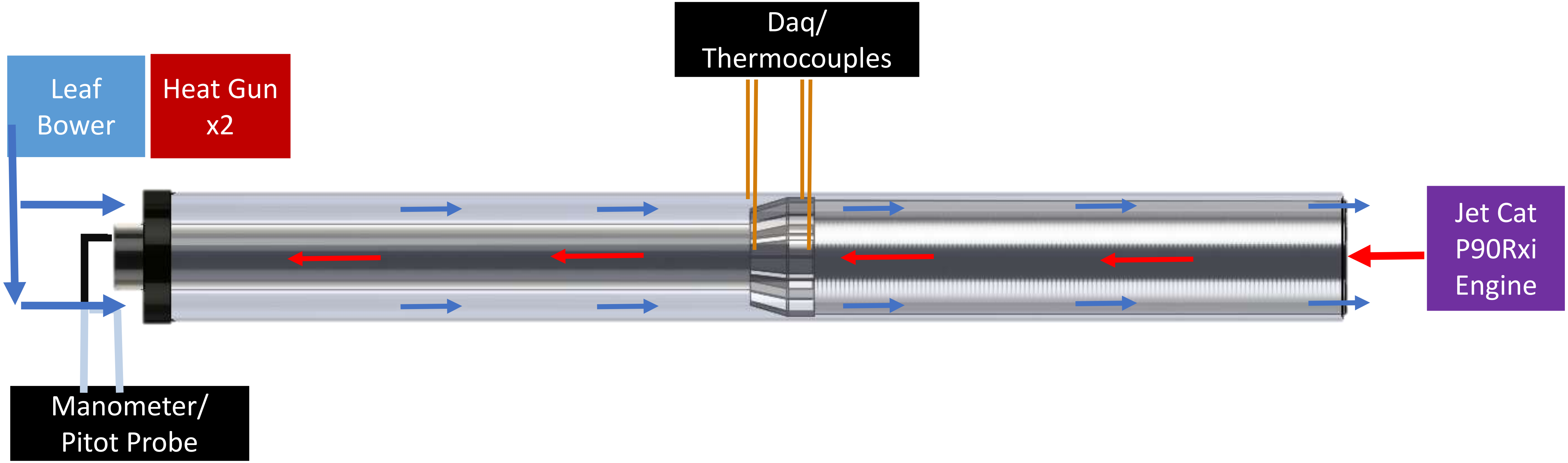
- Heat Gun:
  - Amperage (amps) 6.6, 12.1
  - Temperature range (deg F): 572°/1112°
  - Wattage (watts): 1500

- Leaf Blower:
  - Dual speed: 120 and 150mph

Next Test



Engine Analog Level 2 Verification- Off Ramp



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

Heat Exchanger & Manufacturing Backup Slides

Design Overview: Specifications

	Stock JetCat Engine	REAPER Design
Net Thrust (N)	105	103
Thrust Specific Fuel Consumption (s^{-1})	4.46×10^{-4}	4.40×10^{-4}
Mass (kg)	1.435	4.871
Volume (cm^3)	~2614	~3894

Thermal Survivability– Outer Casing

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

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

$$\sigma_{\theta\theta} = \frac{p_g R}{t} = \frac{(0.26 - 0.101)MPa \ * 0.054m}{0.0015m} = 5.7\ MPa$$

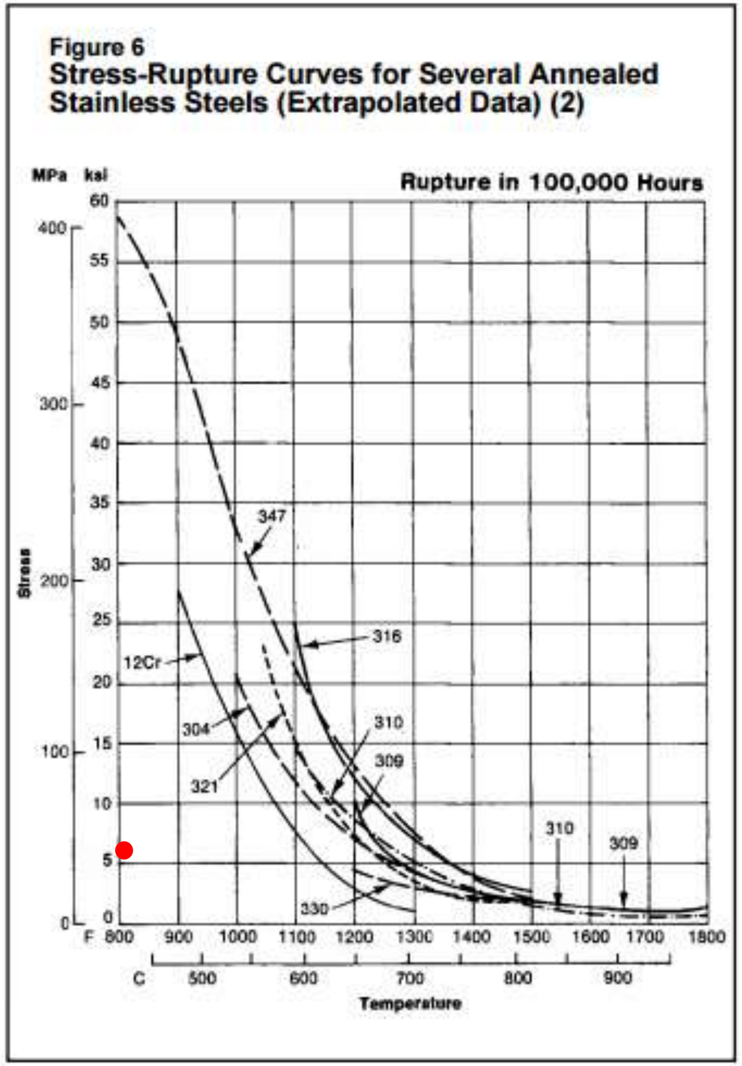


Figure 6
Stress-Rupture Curves for Several Annealed Stainless Steels (Extrapolated Data) (2)

Thermal Survivability– End Cap

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

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

$$\sigma_{\theta\theta} = \frac{p_g R}{t} = \frac{(0.26 - 0.101)MPa \; * 0.018m}{0.001m} = 2.9MPa$$

Safety Factor: 2.4

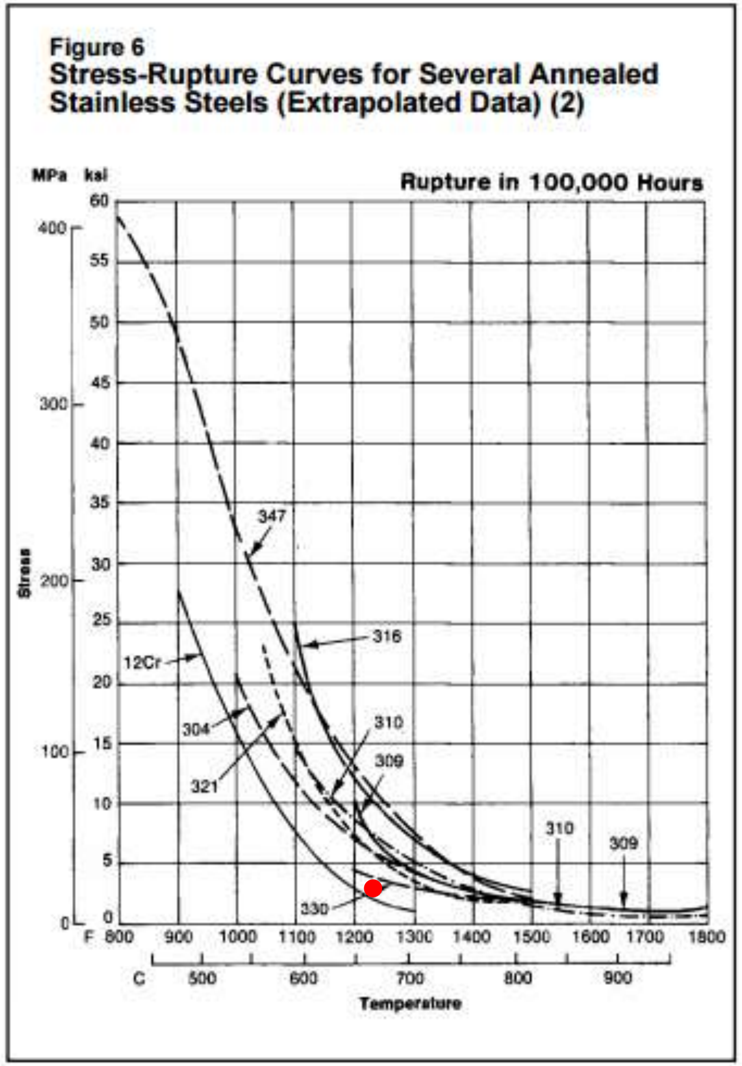


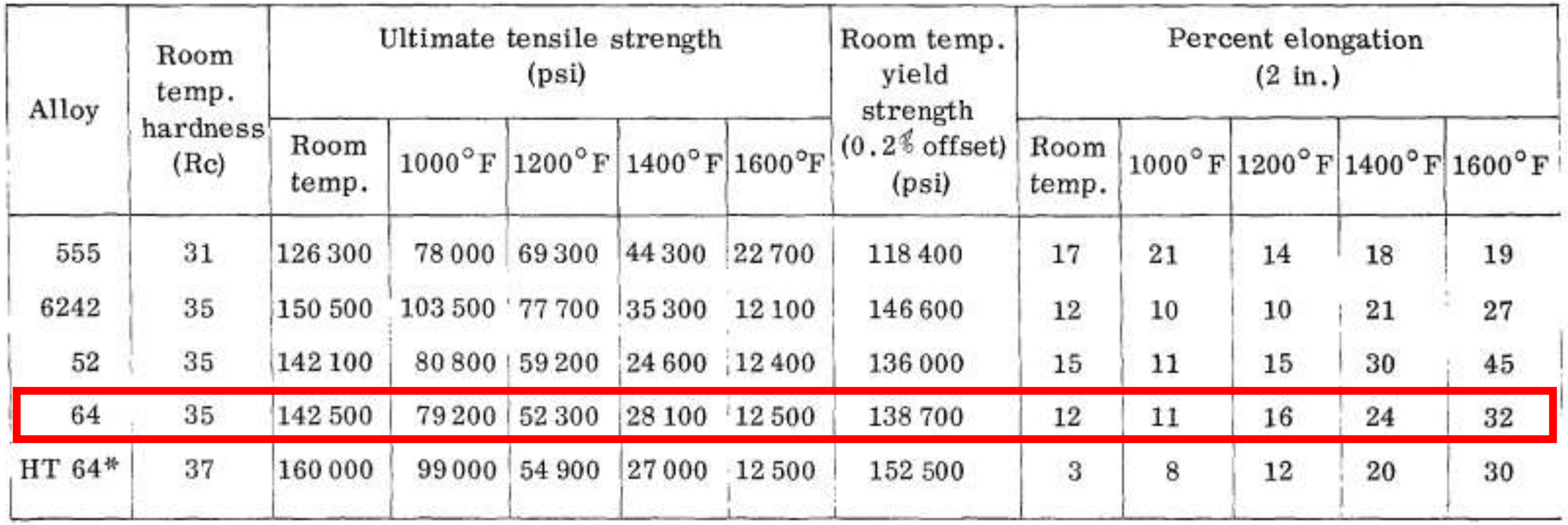
Figure 6
Stress-Rupture Curves for Several Annealed Stainless Steels (Extrapolated Data) (2)

Thermal Survivability– Heat Exchanger

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

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

$$\sigma_{\theta\theta} = \frac{p_g R}{t} = \frac{(0.26-0.101)MPa * 0.0335m}{0.0012m} = 4.4MPa \text{ (638 psi)}$$



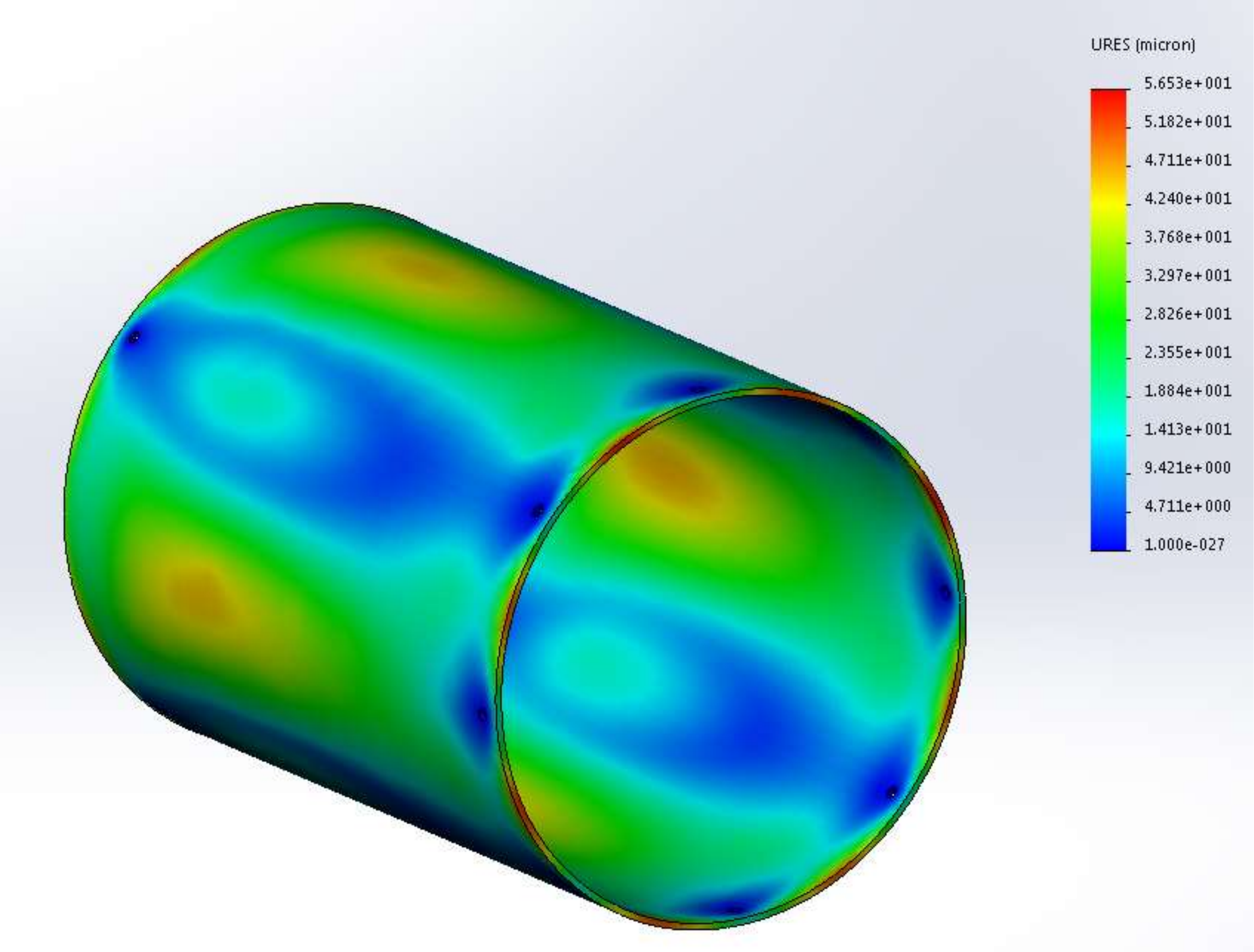
Alloy	Room temp. hardness (Rc)	Ultimate tensile strength (psi)					Room temp. yield strength (0.2% offset) (psi)	Percent elongation (2 in.)				
		Room temp.	1000°F	1200°F	1400°F	1600°F		Room temp.	1000°F	1200°F	1400°F	1600°F
555	31	126 300	78 000	69 300	44 300	22 700	118 400	17	21	14	18	19
6242	35	150 500	103 500	77 700	35 300	12 100	146 600	12	10	10	21	27
52	35	142 100	80 800	59 200	24 600	12 400	136 000	15	11	15	30	45
64	35	142 500	79 200	52 300	28 100	12 500	138 700	12	11	16	24	32
HT 64*	37	160 000	99 000	54 900	27 000	12 500	152 500	3	8	12	20	30

Thermal Expansion - Analysis Setup

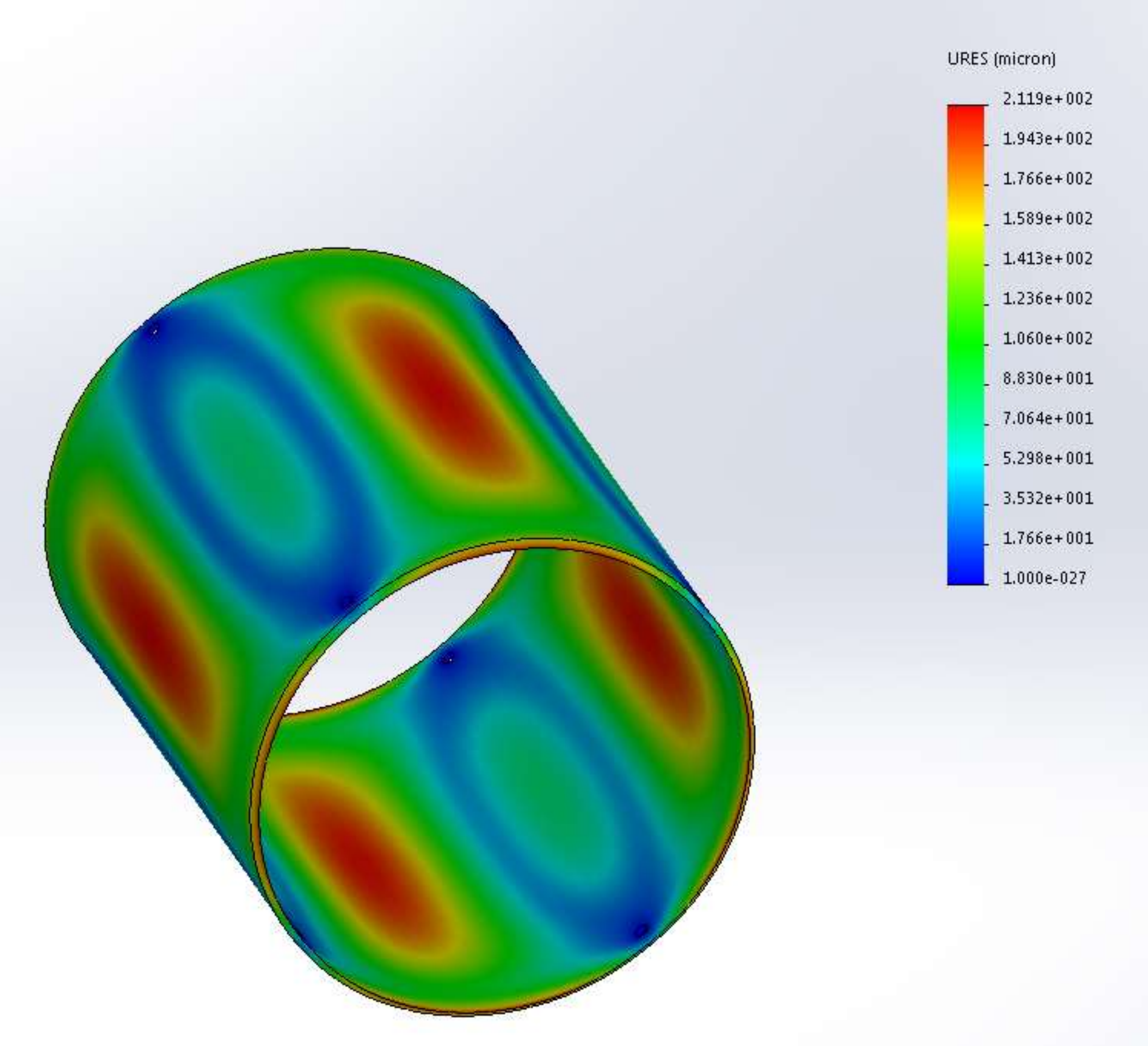
- Materials
  - Titanium 6Al-4V ELI
  - Stainless Steel 304

- Mean Coefficient of Thermal Expansion (µm/m*K)
  - Ti 6Al-4V ELI: $10.6*10^{-6}$
  - SS 304: $10*10^{-6}$

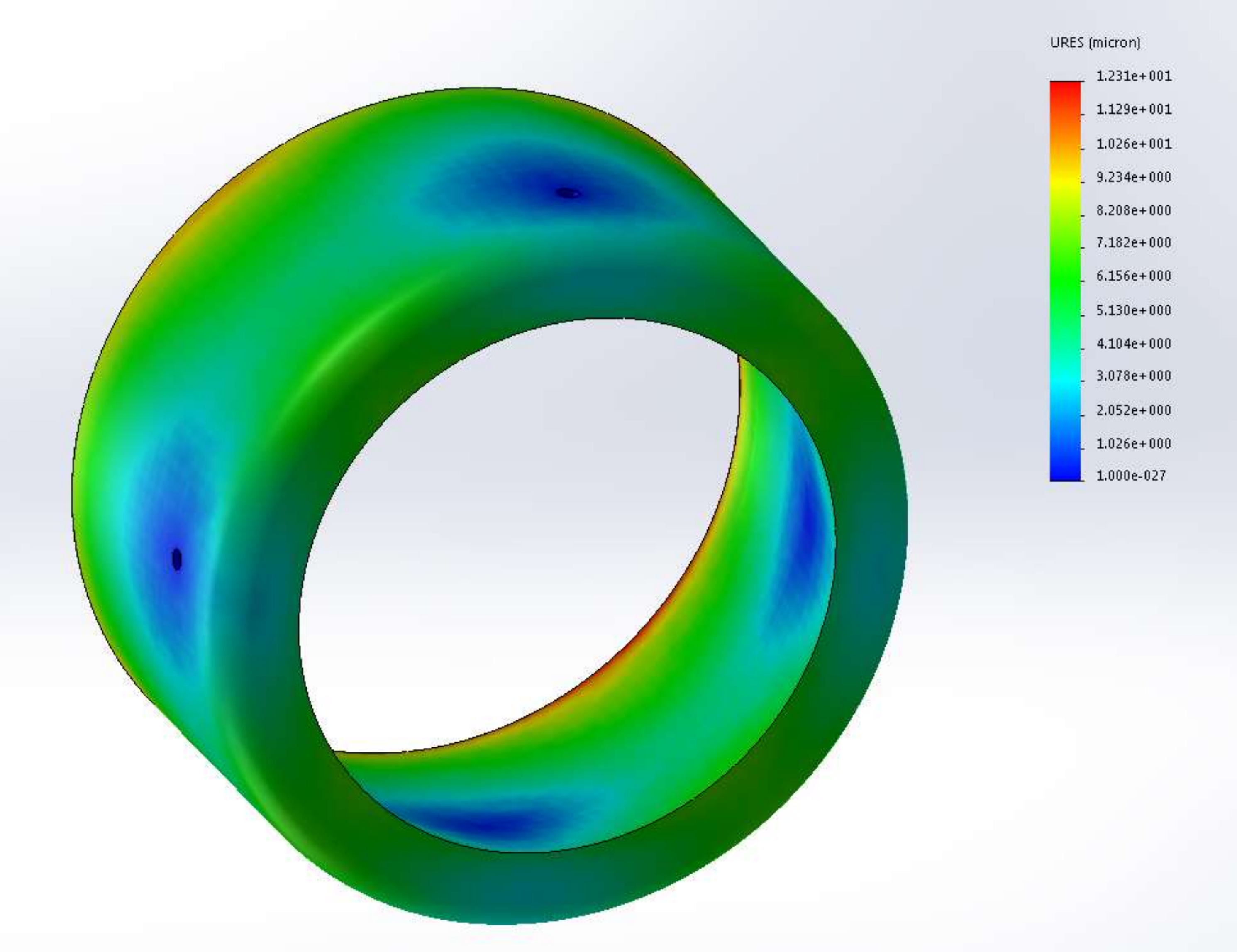
Thermal Expansion – Outer Casing



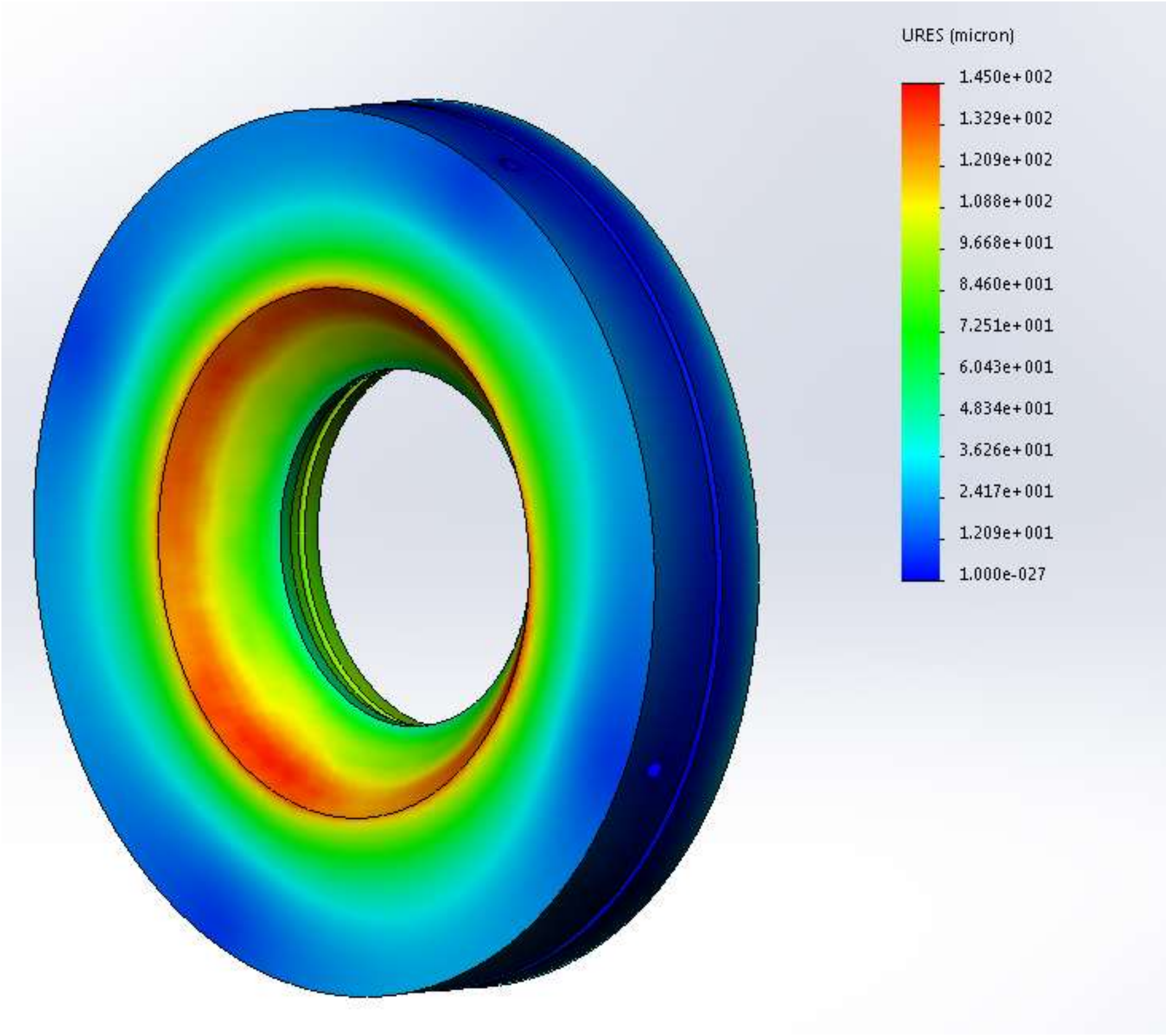
Thermal Expansion – Inner Casing

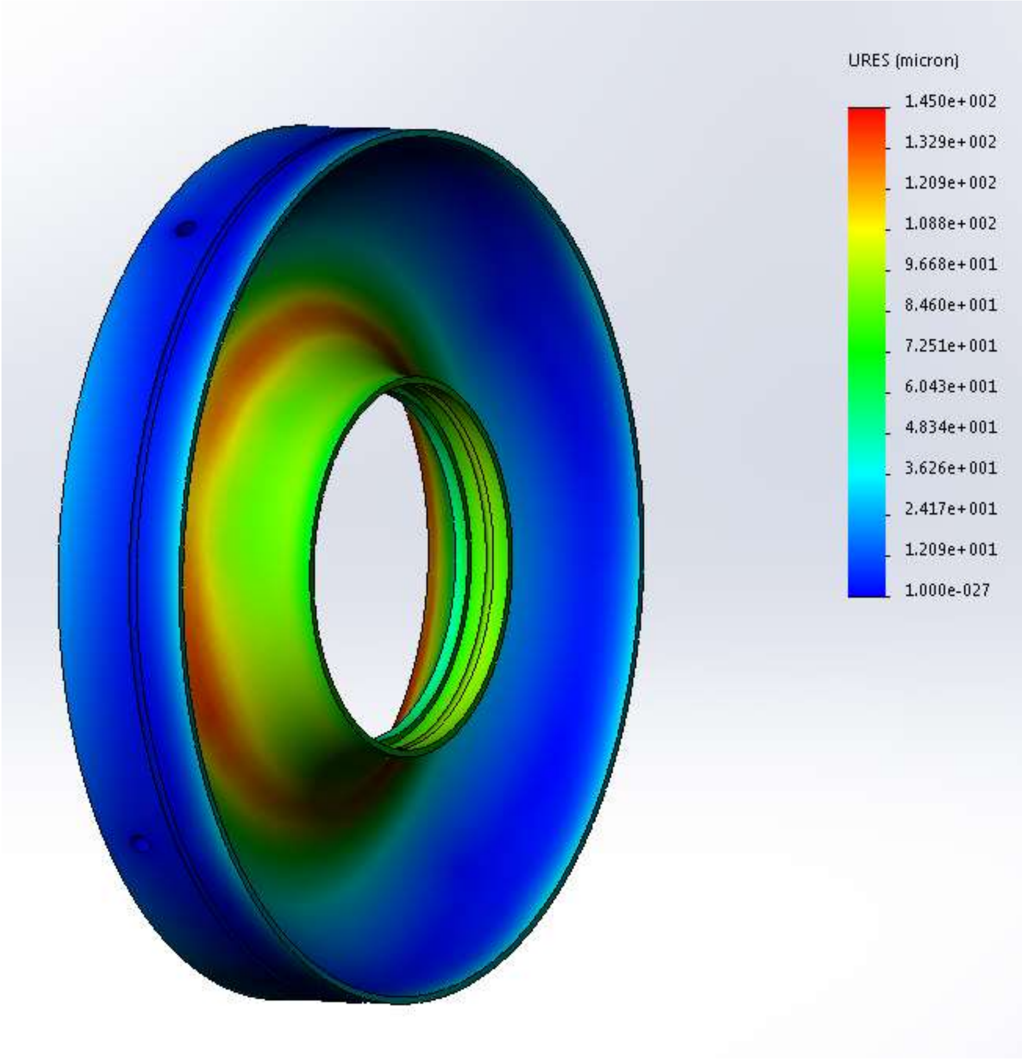


Thermal Expansion – Nozzle Shroud

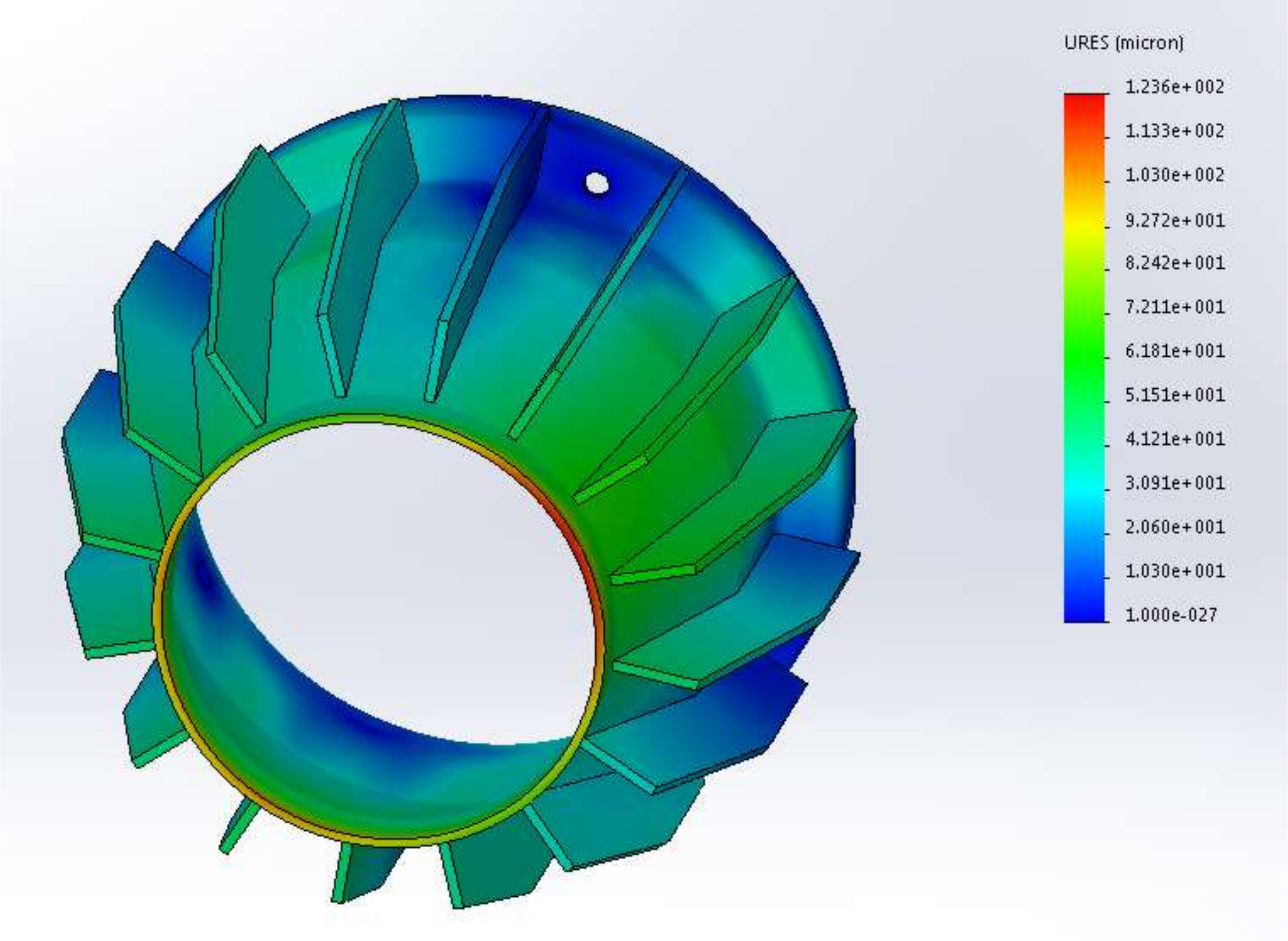


Thermal Expansion - Endcap

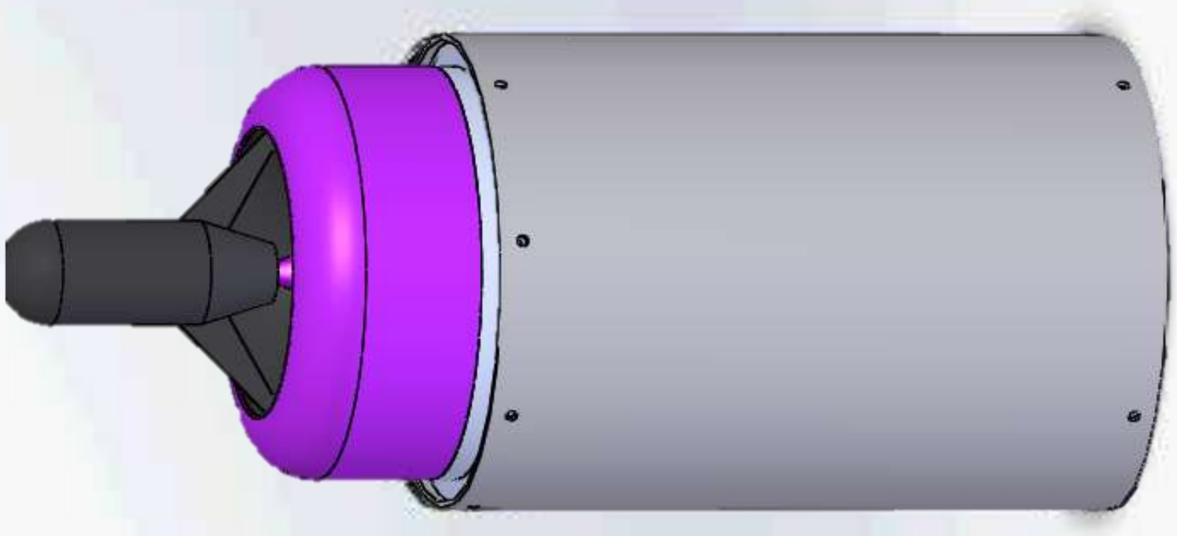




Thermal Expansion - Nozzle

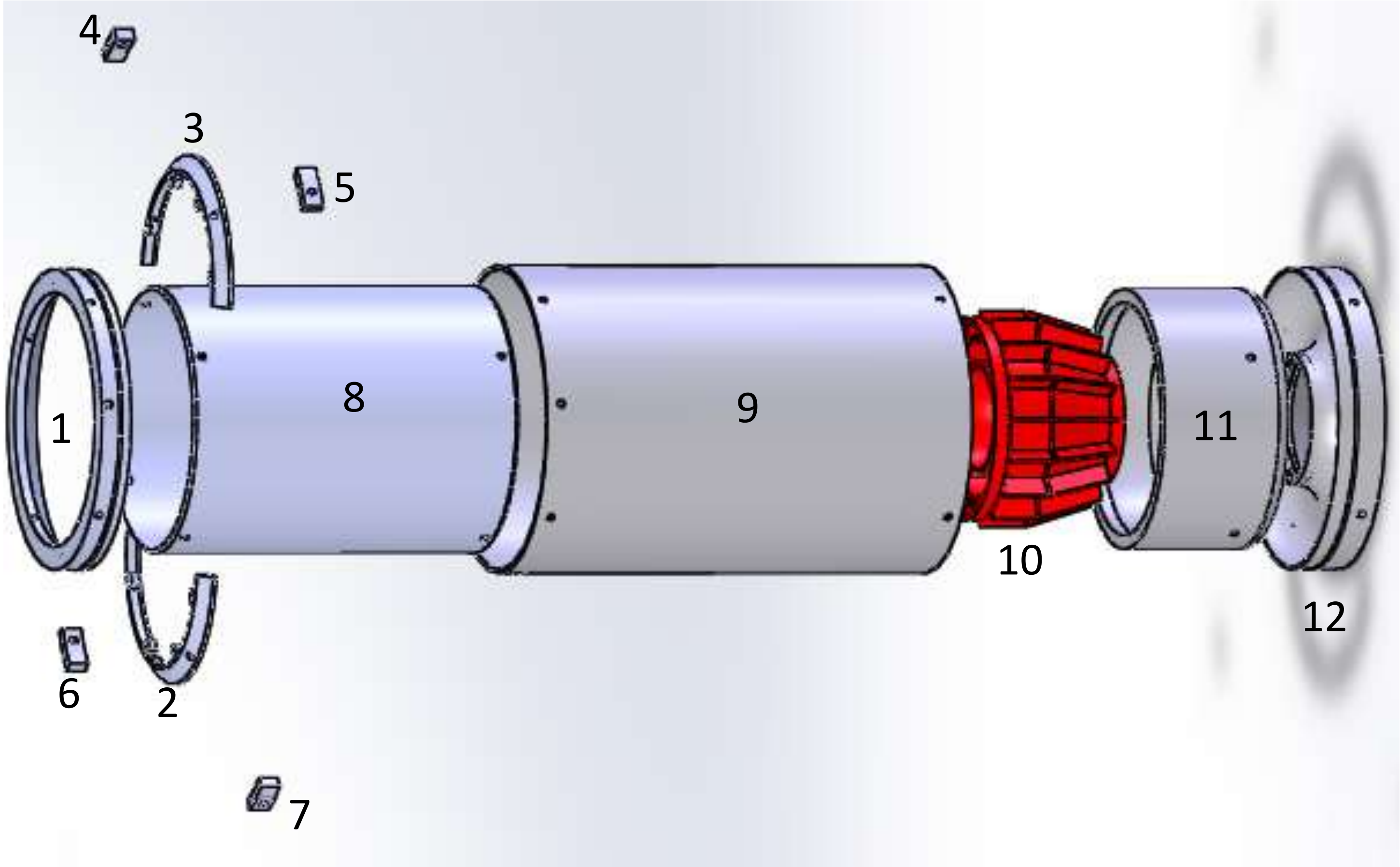


Manufacturing Parts



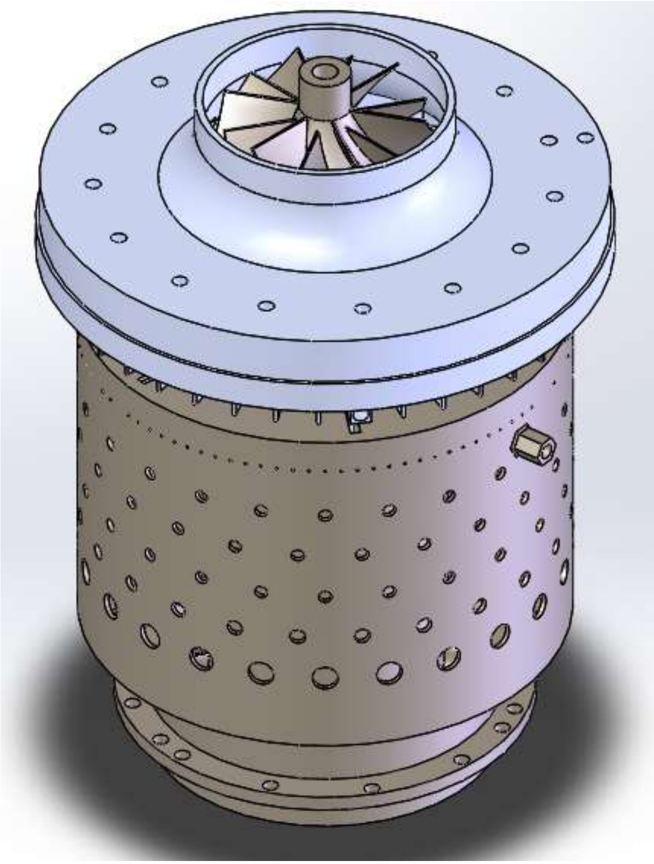
Manufacturing Overview

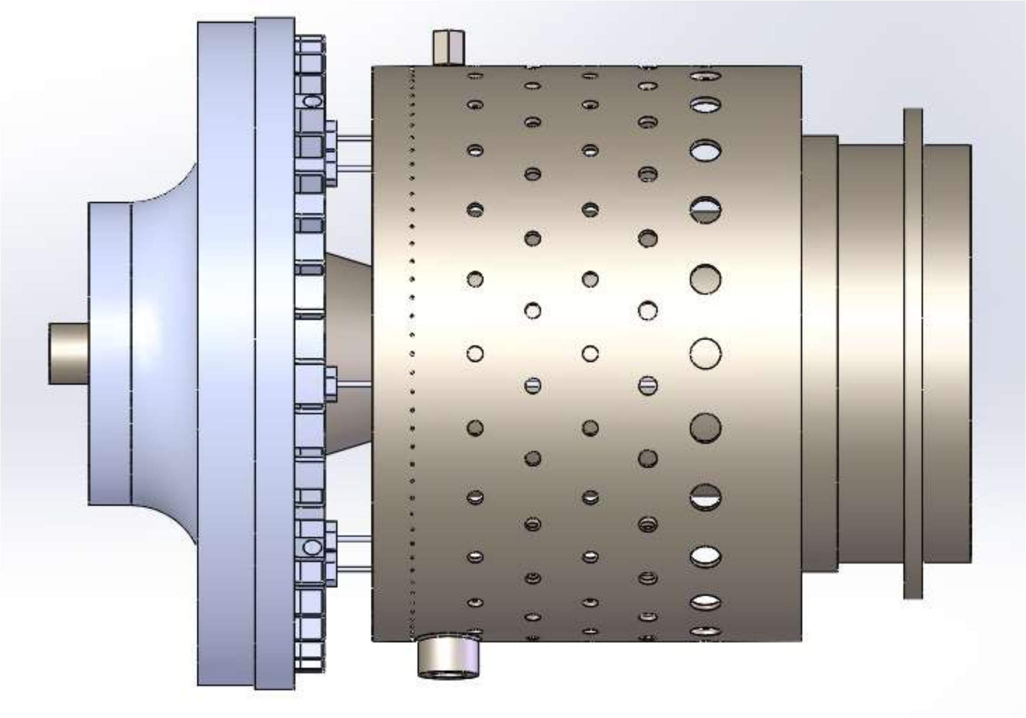
- 12 Total Parts
  1) Forward Ring
  2,3) Brackets (2 halves)
  4,5,6,7) Case Connectors (x4)
  8) Inner Casing
  9) Outer Casing
  10) Nozzle
  11) Nozzle Shroud
  12) Endcap



Design Overview: Assembly: Start

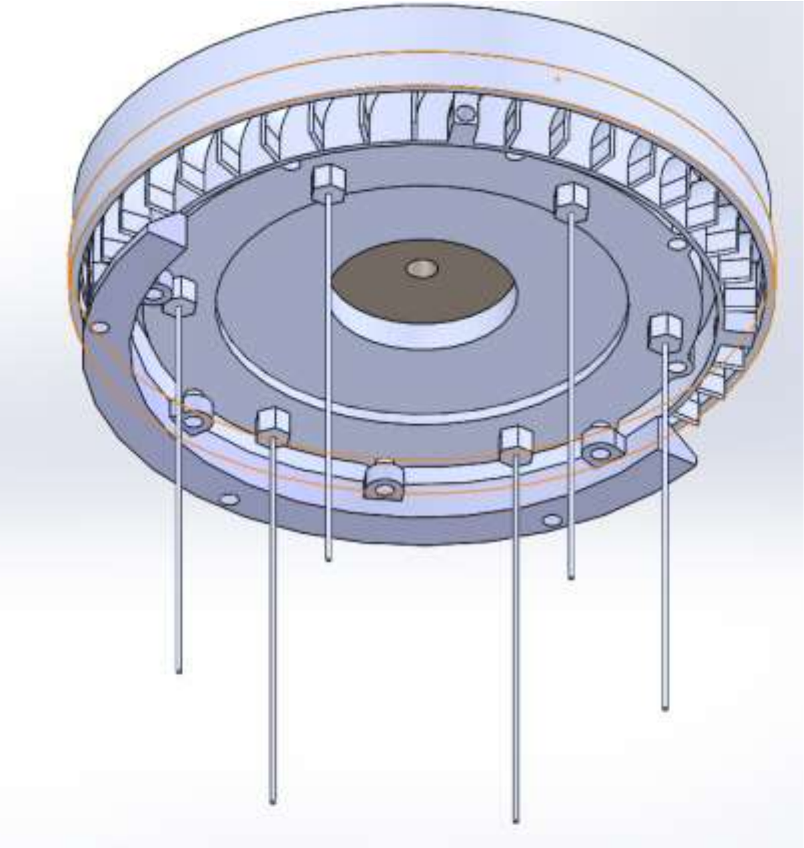
- Stock Components

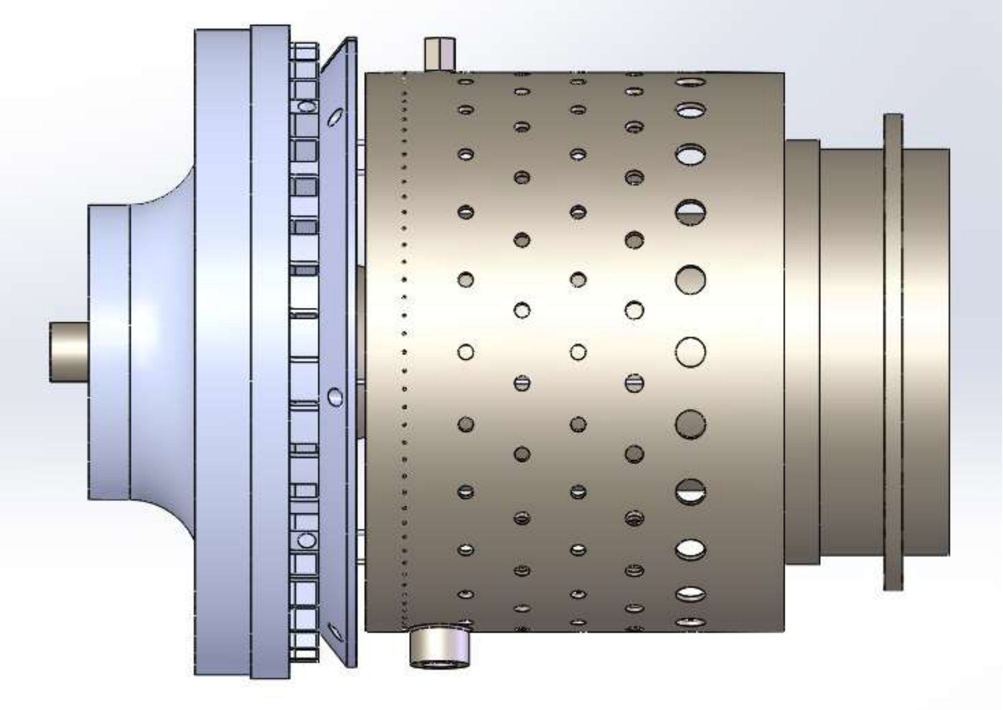




Design Overview: Assembly: Part 1

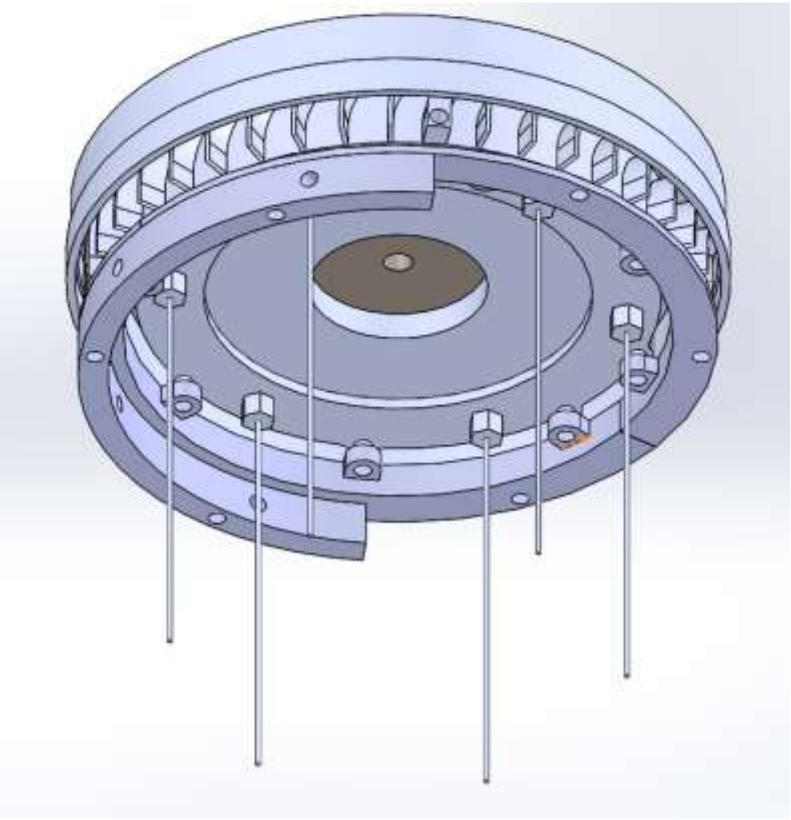
- Connection of two forward brackets to stator

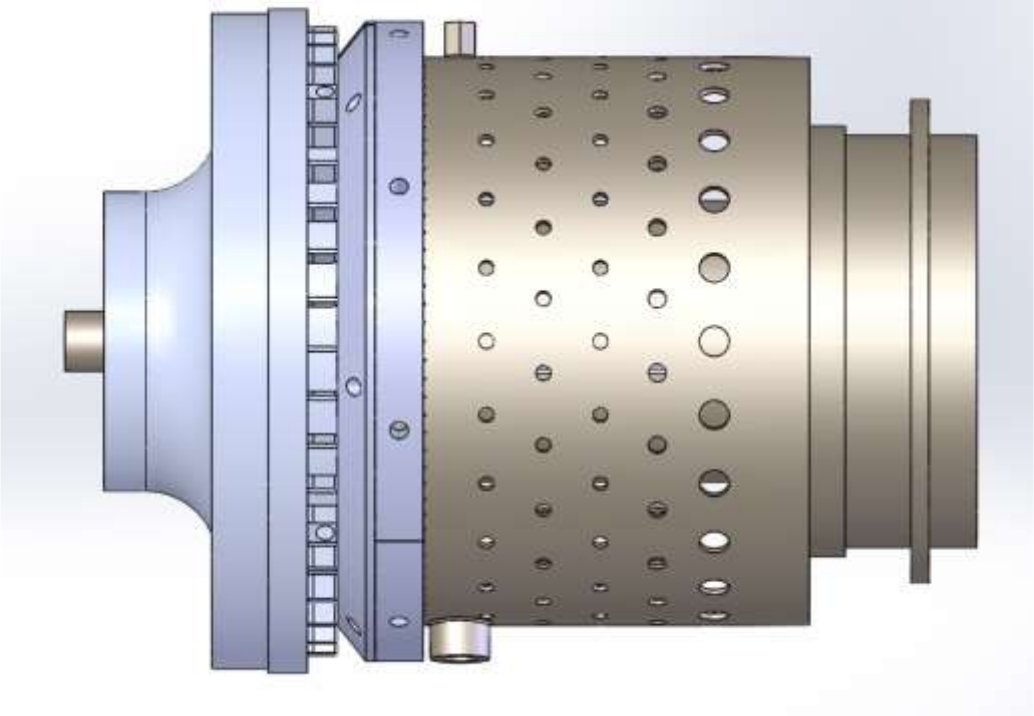




Design Overview: Assembly: Part 2

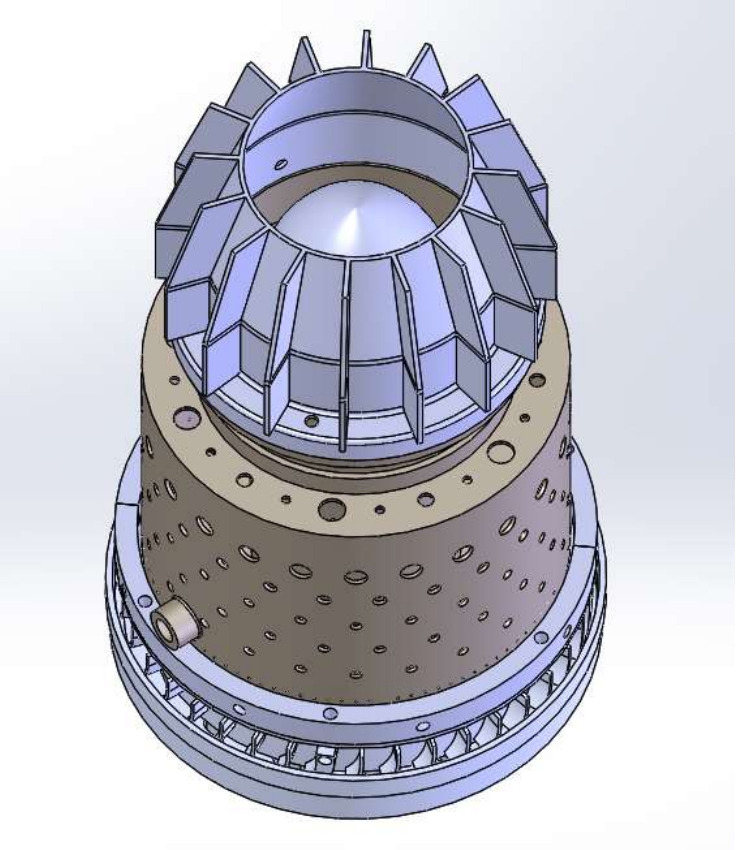
- Connection of secondary bracket rings to first set of brackets

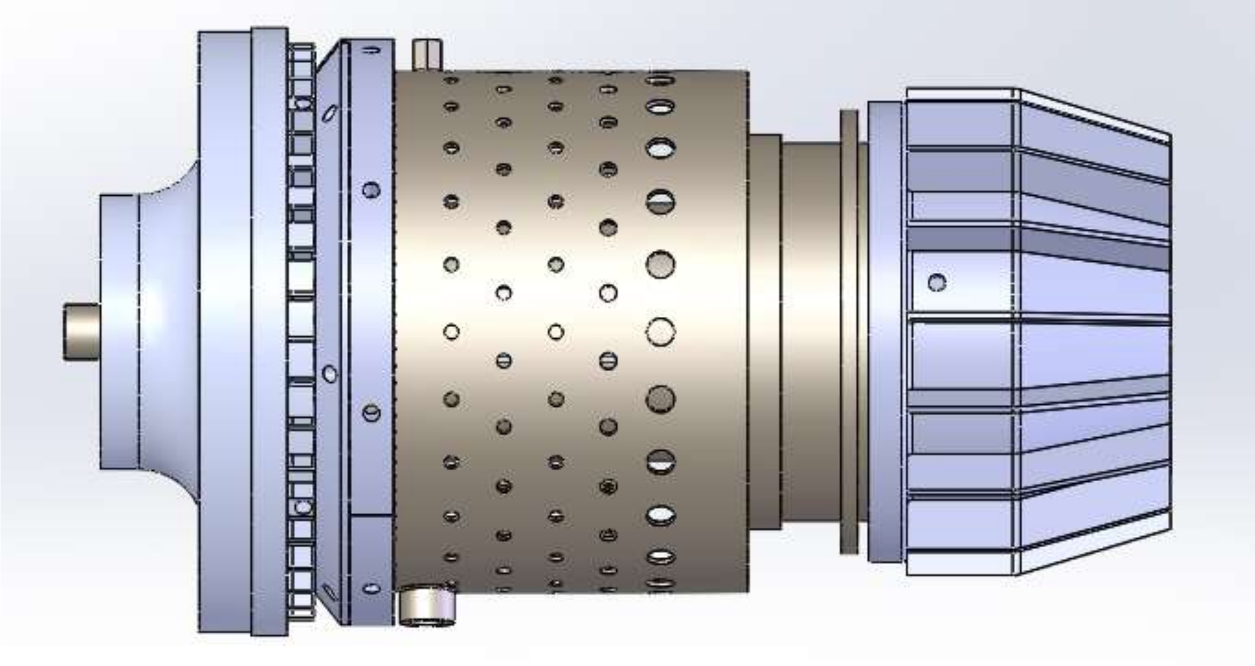




Design Overview: Assembly: Part 3

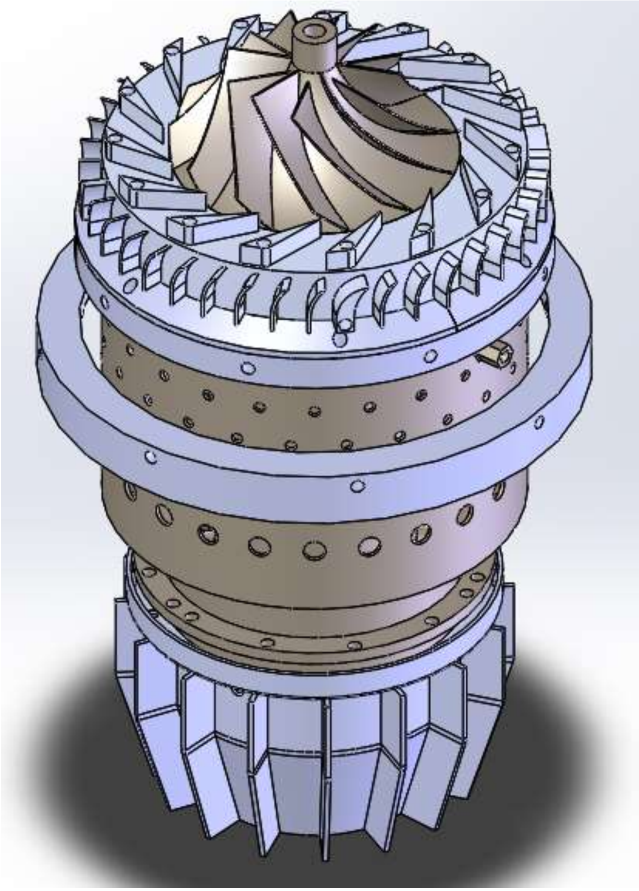
- Connection of nozzle to turbine

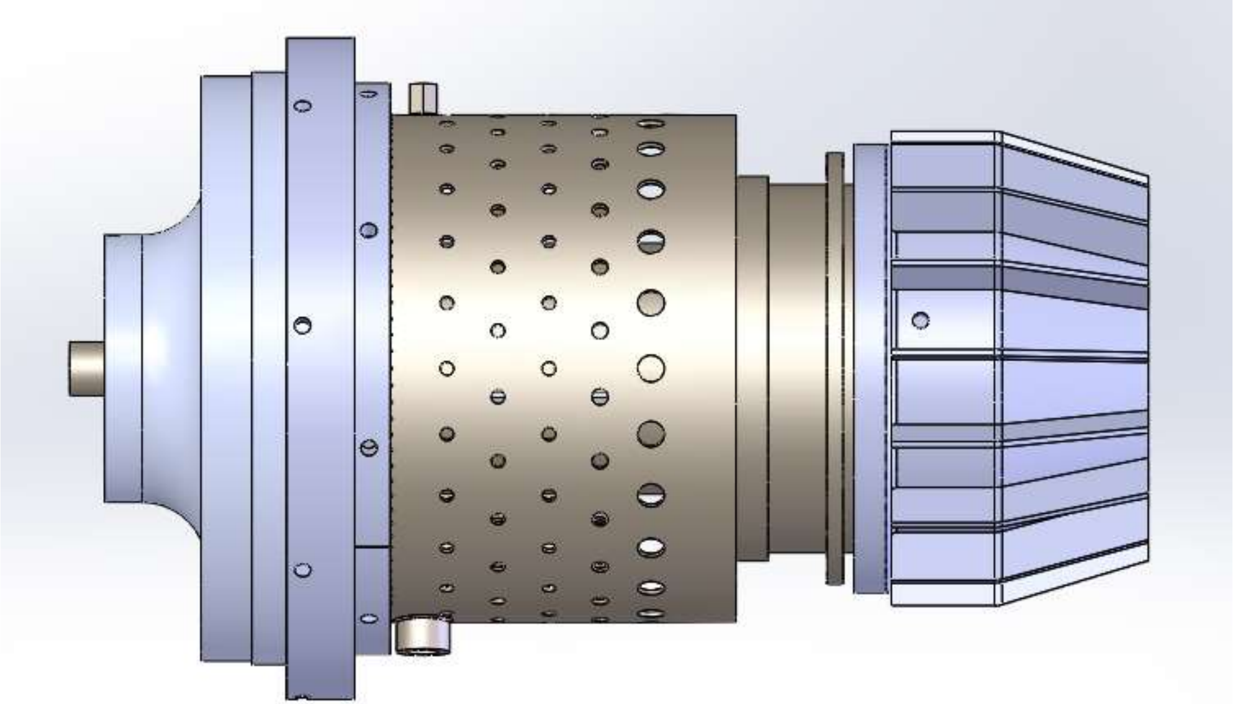




Design Overview: Assembly: Part 4

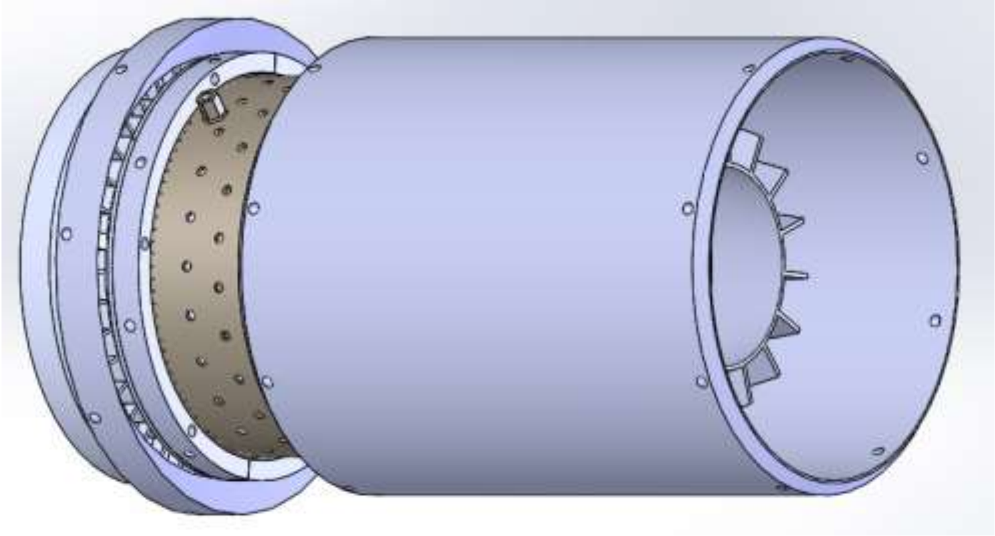
- Connection of casing ring

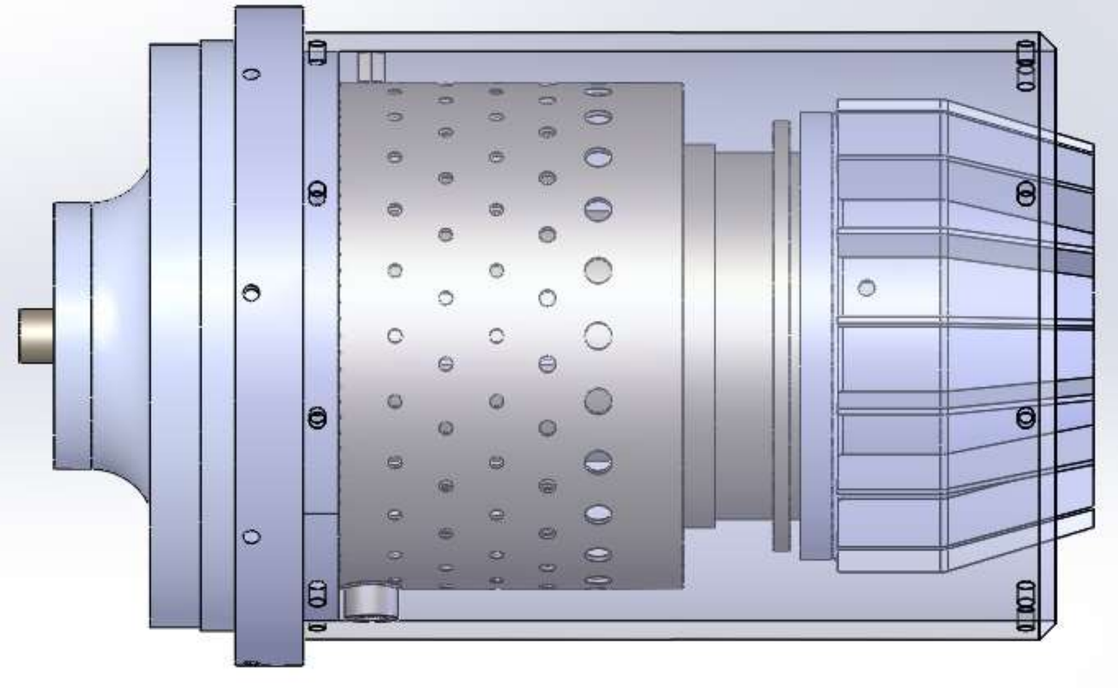




Design Overview: Assembly: Part 5

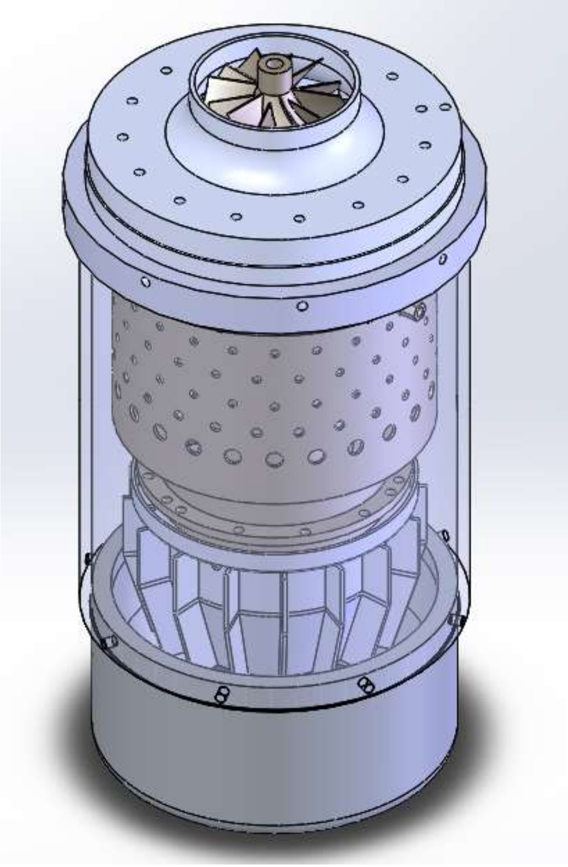
- Connection of inside case

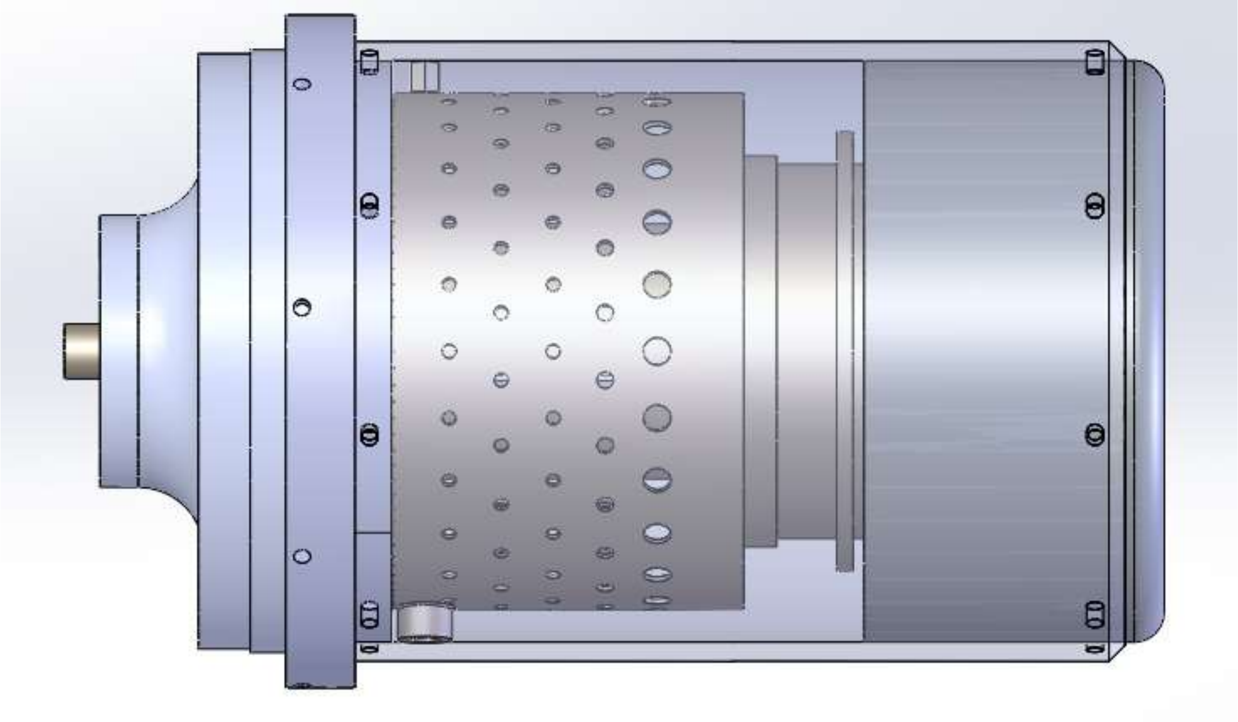




Design Overview: Assembly: Part 6

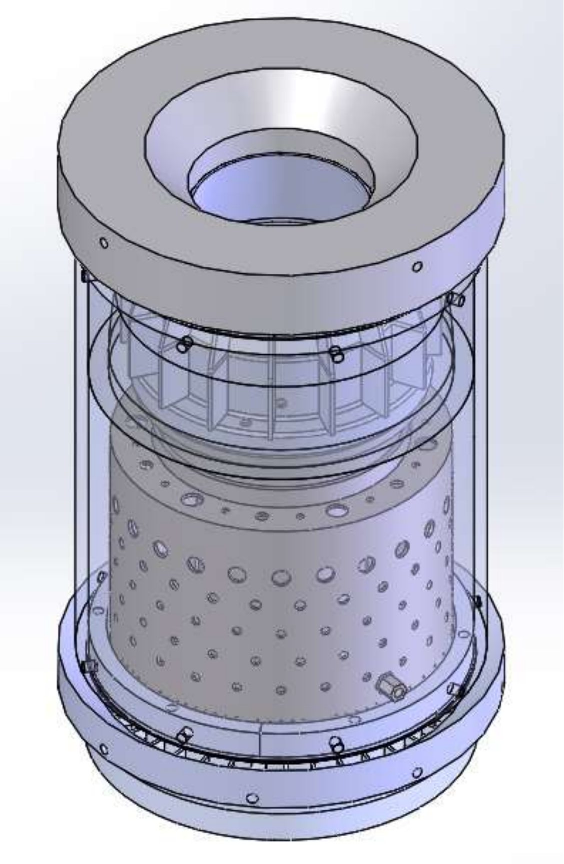
- Case over Nozzle

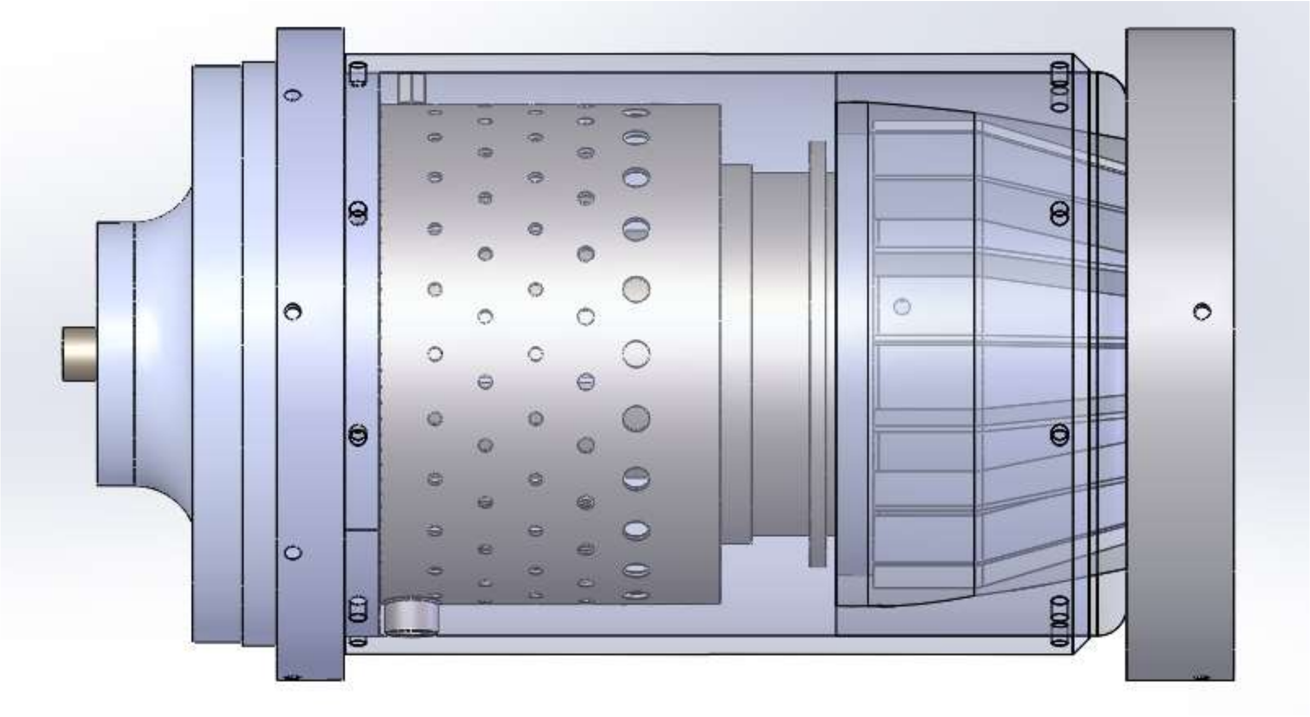




Design Overview: Assembly: Part 7

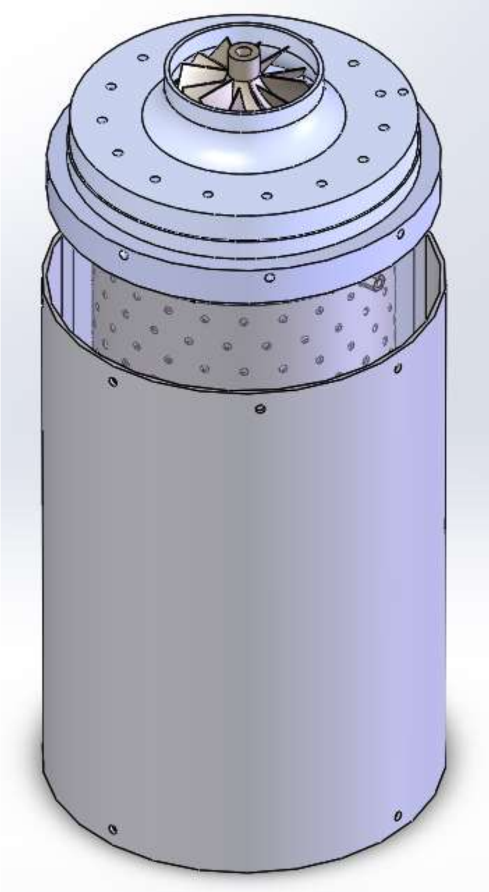
- Connection of endcap to nozzle

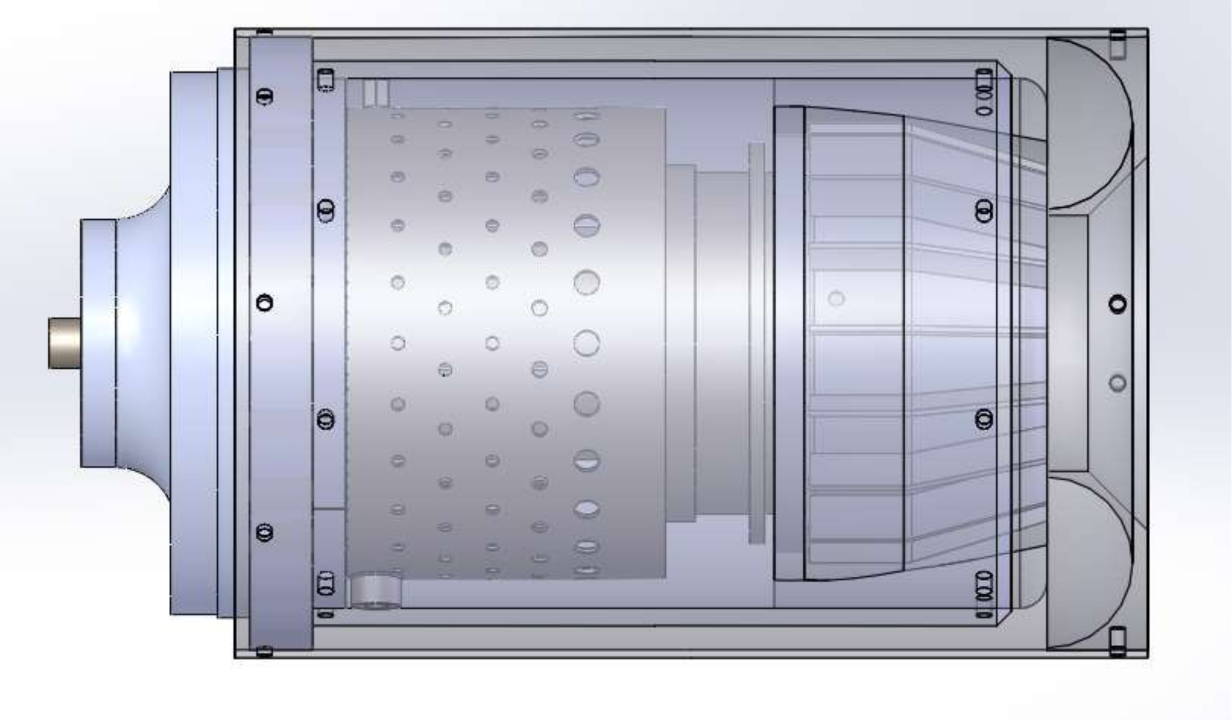




Design Overview: Assembly: Part 8

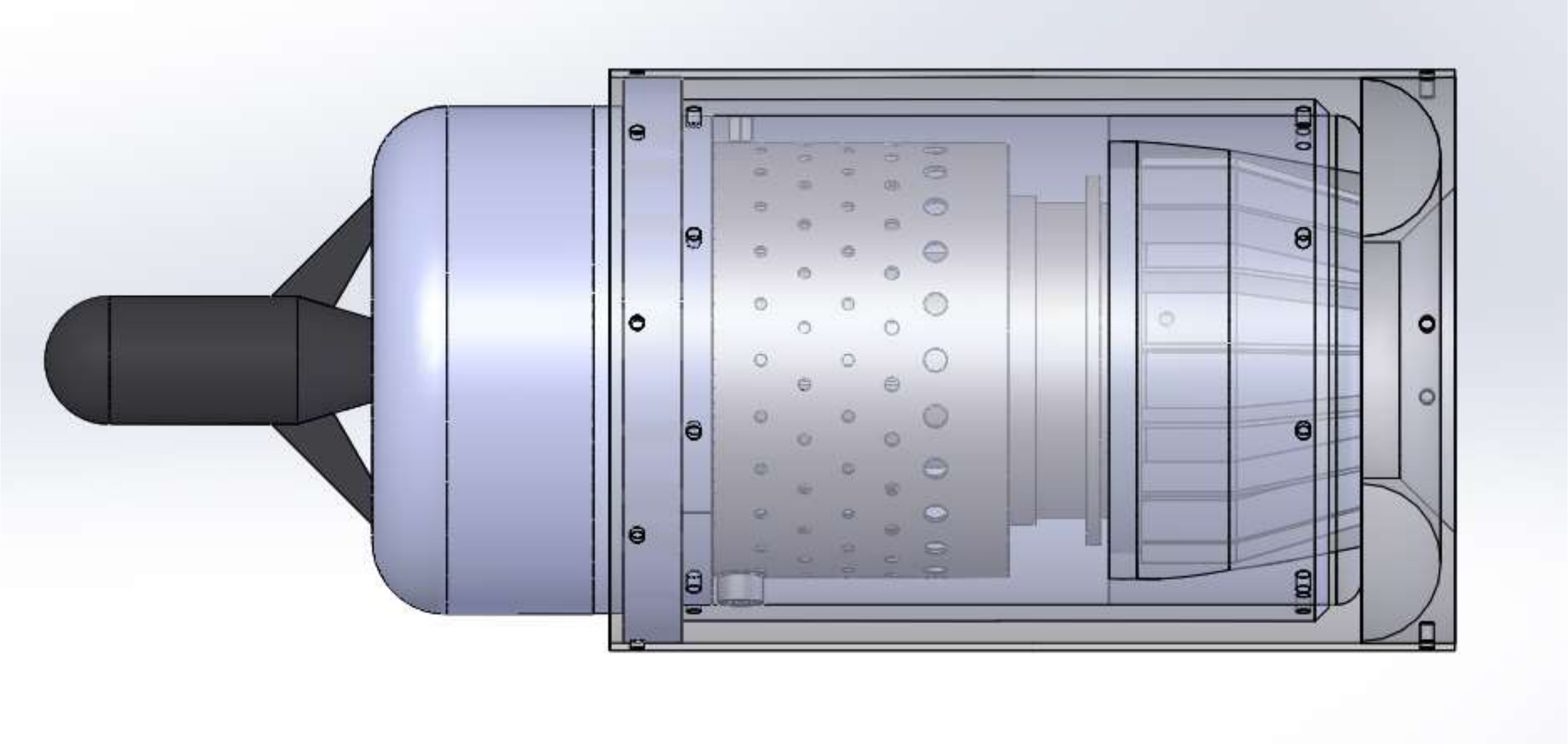
- Connection of Outer Casing





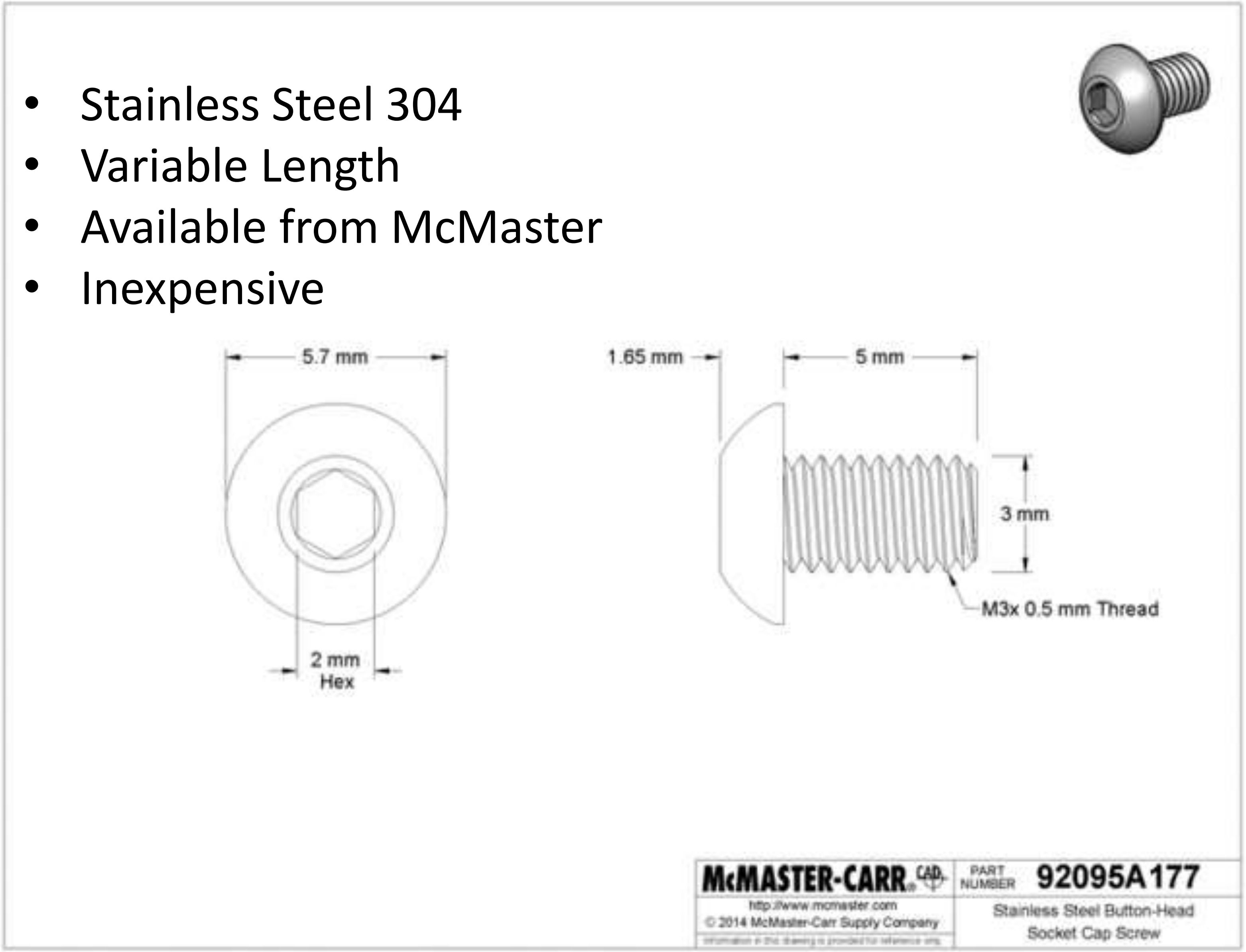
Design Overview: Assembly - Final

- Complete Assembly



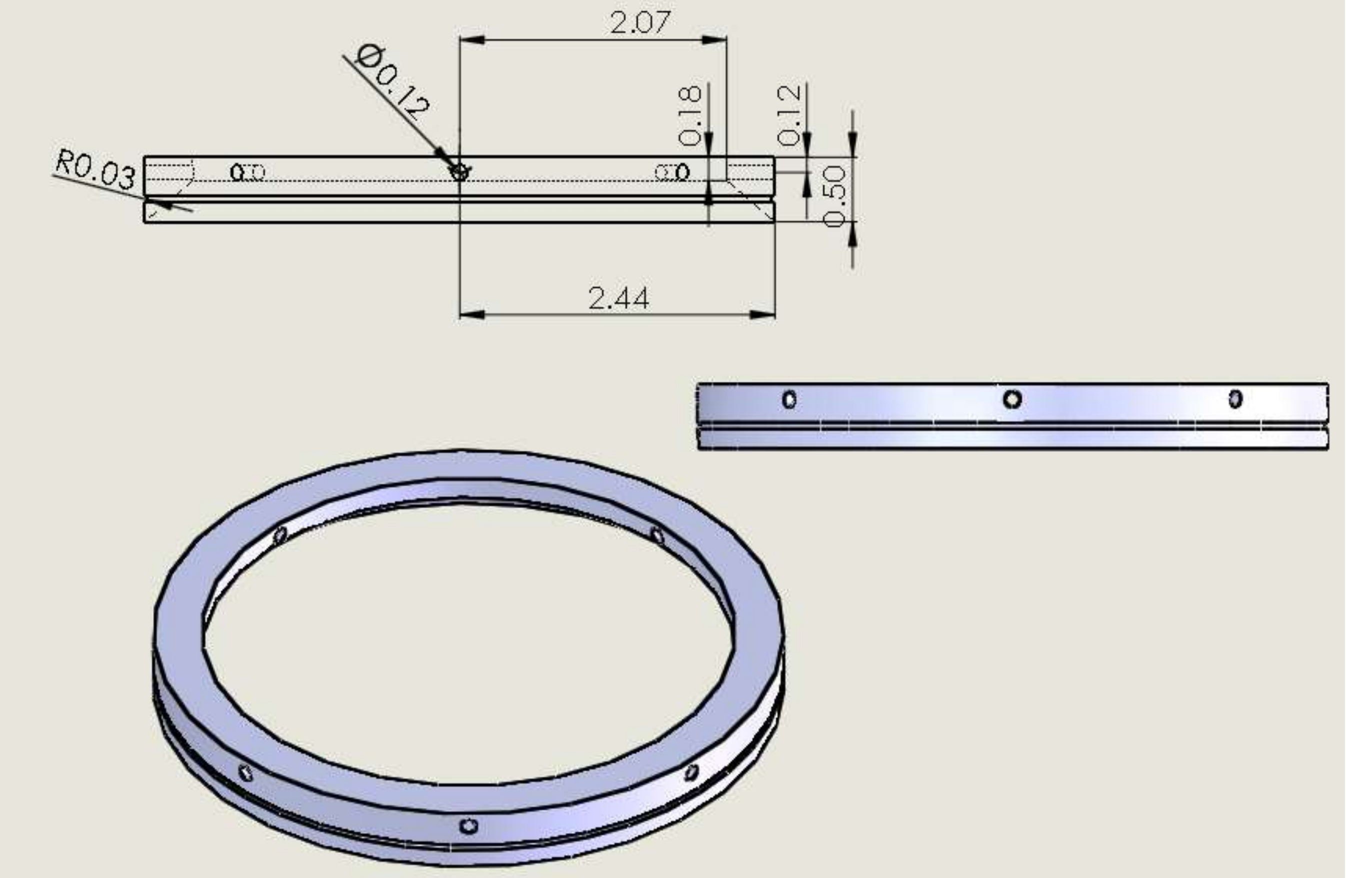
Manufacturing: Bolts

- Stainless Steel 304
- Variable Length
- Available from McMaster
- Inexpensive



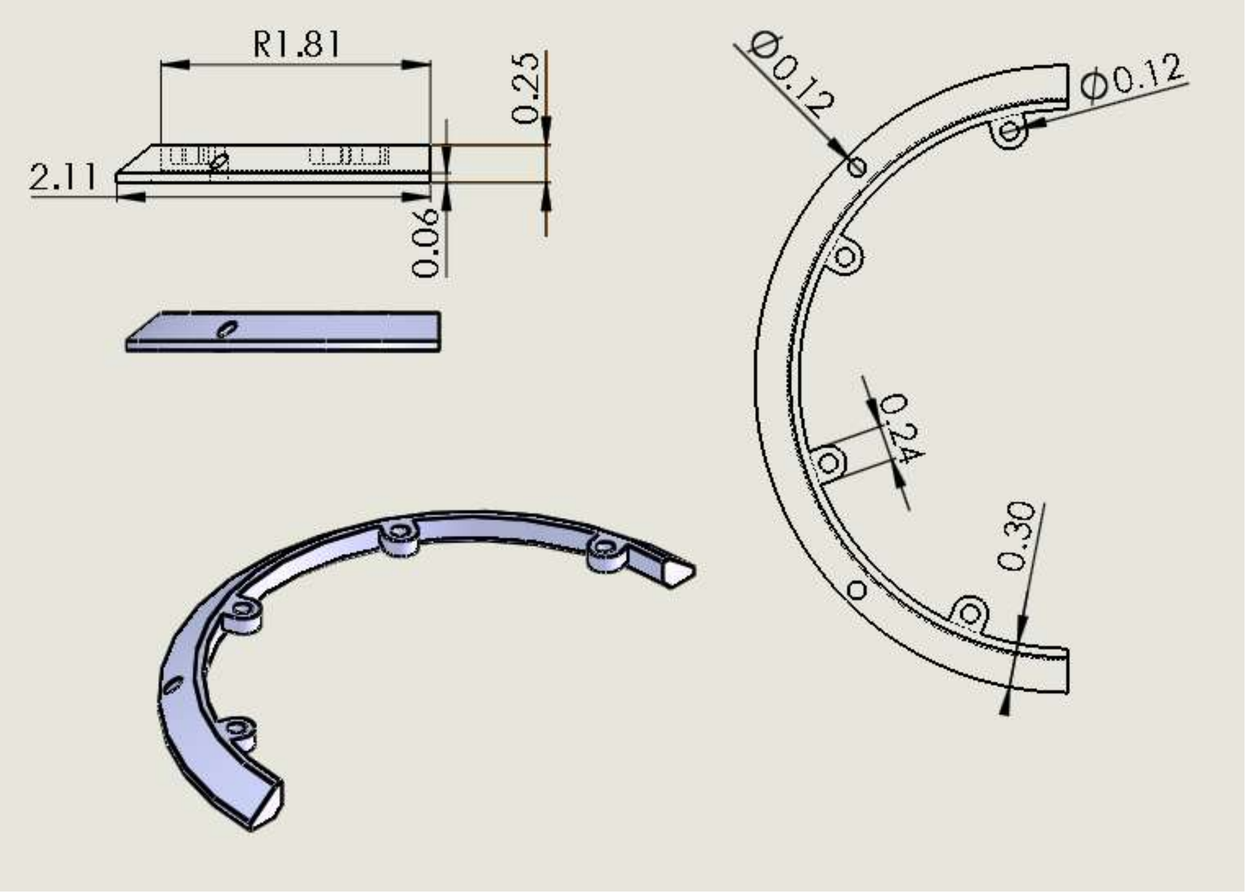
Manufacturing: Forward Ring

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



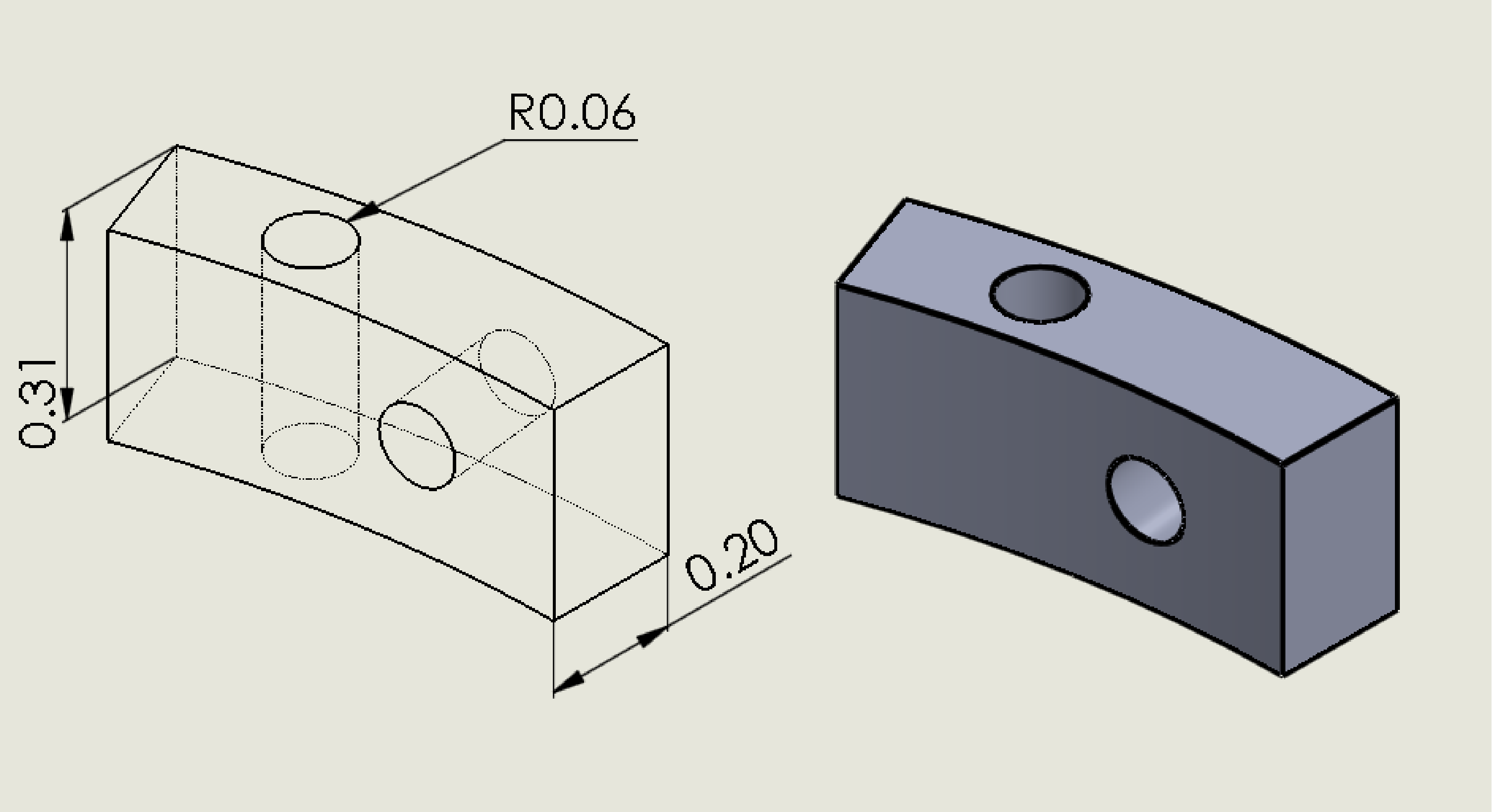
Manufacturing: Brackets

- Milled from solid bar
- Will need 2 “pucks” - 1 for each bracket
- Material: 4.25" diameter, 1" length bar = $20.34[3]



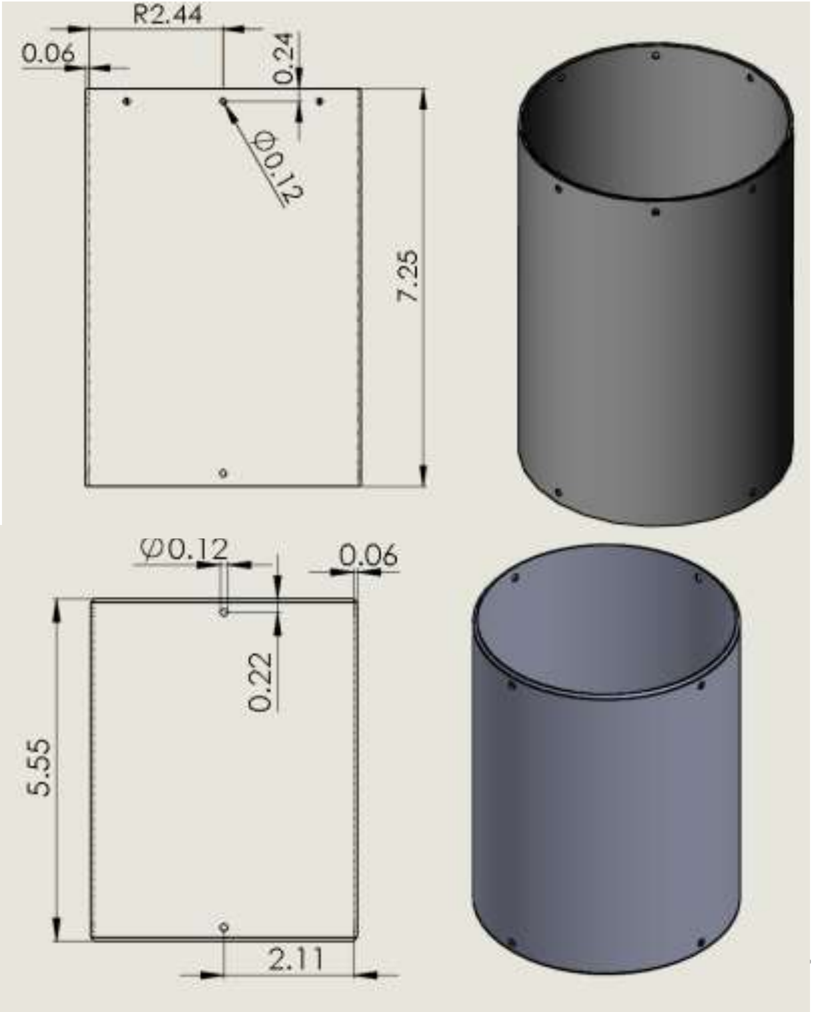
Manufacturing: Casing Connectors

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



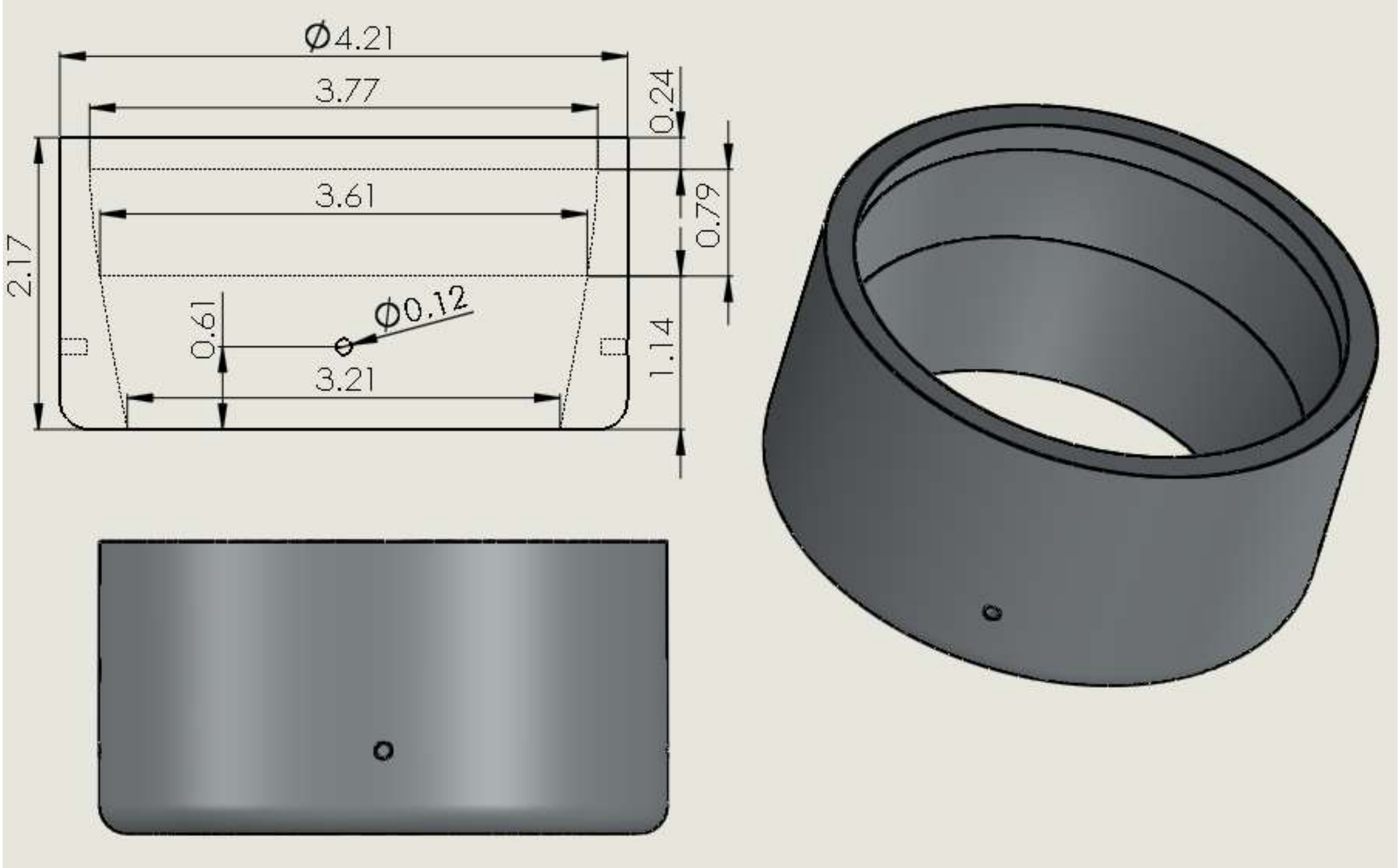
Manufacturing: Casings

- Roll 1/16" stainless steel sheets and weld seam
- Heat, then shrink onto "puck" and anneal to ensure roundness at ends
- Outer Casing
  - Needs to seal to Forward Ring and End Cap
  - 2.44" inner radius -> 15.33" circumference
  - 7.19" length
  - 16"x7.5" = $14.40[5]
- Inner Casing
  - 2.11" inner radius -> 13.26" circumference
  - 5.95" length
  - OnlineMetals.com - 14"x6" = $10.08[5]



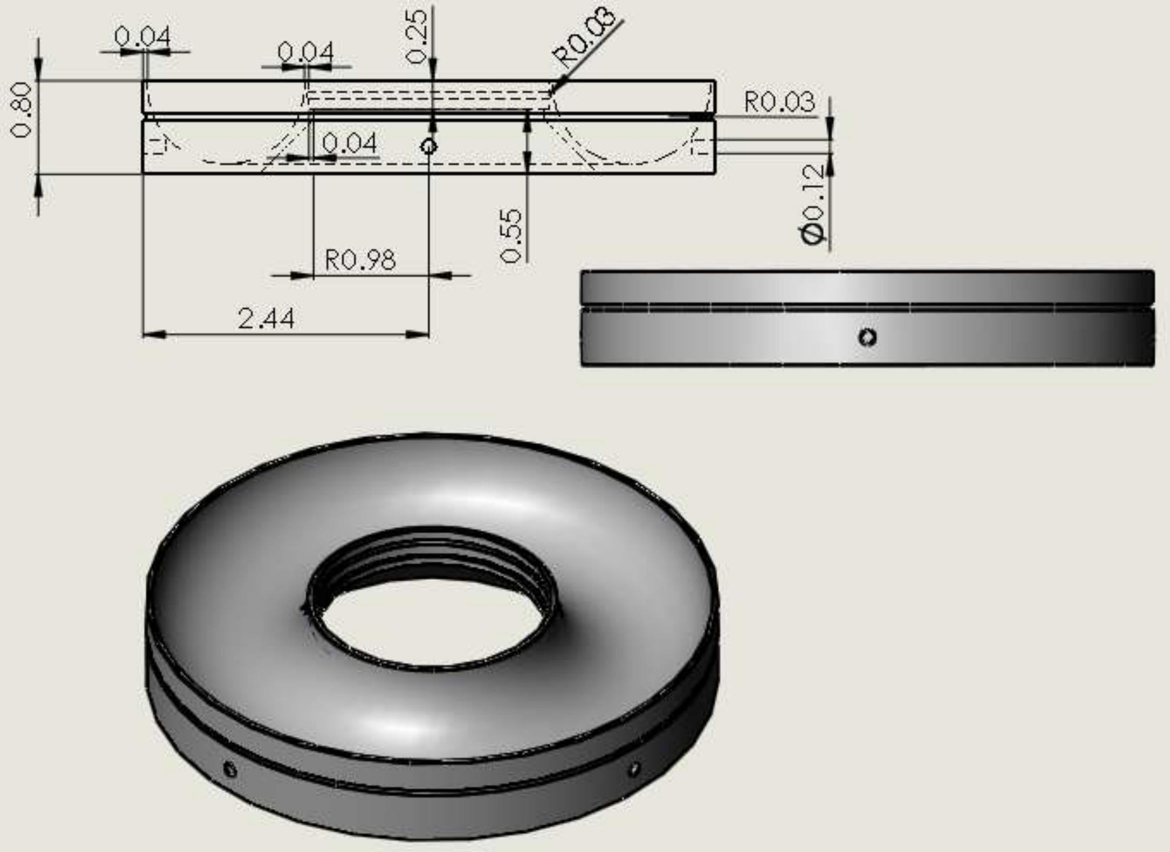
Manufacturing: Nozzle Shroud

- Machined from solid rod of stainless steel
- 4.25" diameter, 2.2" length = $44.75[3]



Manufacturing: End Cap

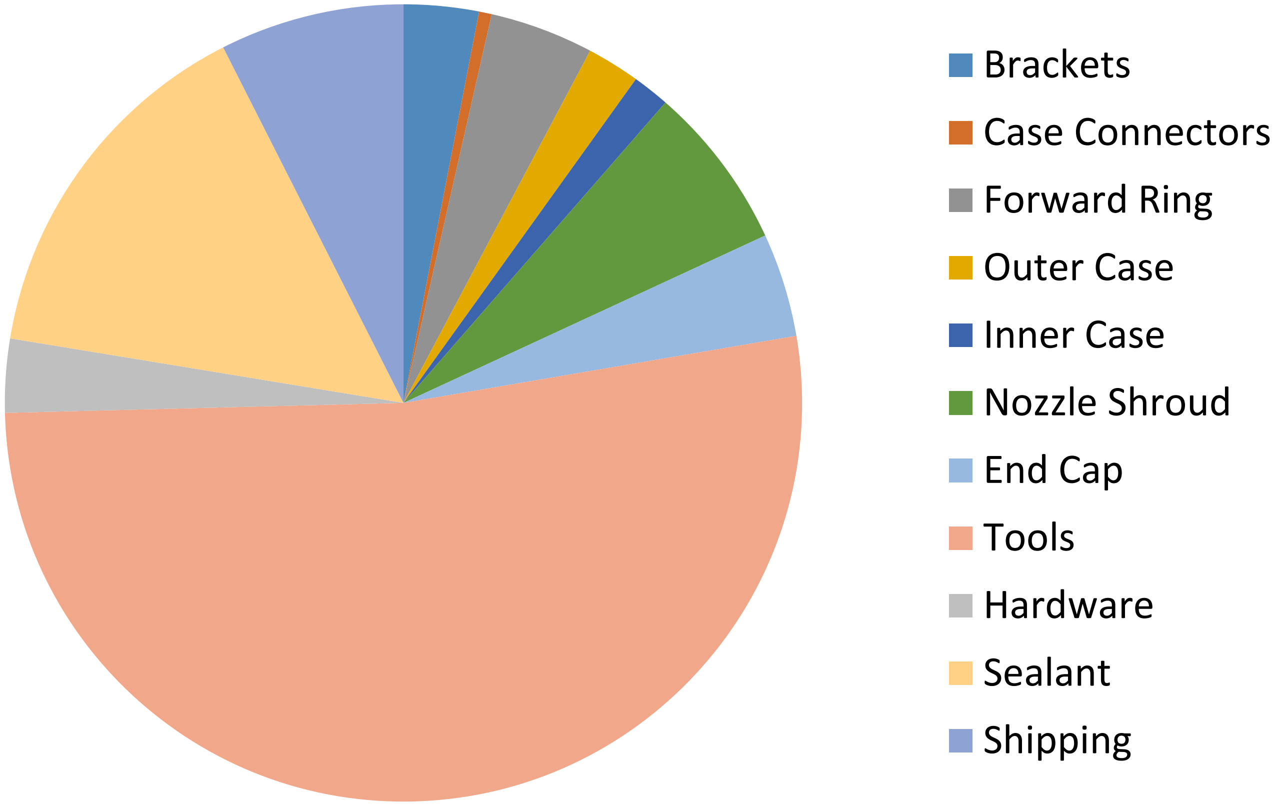
- Machined from solid disk of stainless steel
- 5" diameter rod, 1" length = \$28.15[2]
- Needs to seal with outer casing and end of nozzle



Manufacturing: Other Costs

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

Manufacturing: Cost Breakdown



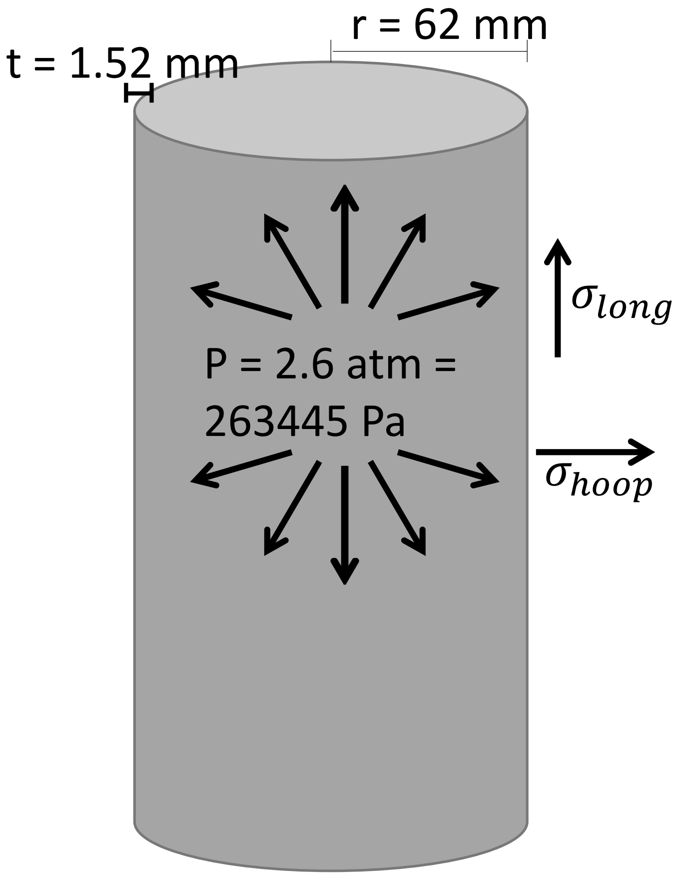
Total: $670

Pressure Vessel Analysis

- Outer Casing
- Thin Walled?
  - $\frac{r}{t} \geq 10? \rightarrow \frac{62\ mm}{1.52\ mm} = 40.8\ \geq 10$ ✓
- Longitudinal Stress
  - $\sigma_{long} = \frac{Pr}{2t} \rightarrow \sigma_{long} = \frac{(263445\ Pa)(.062\ m)}{2(.00152\ m)}$

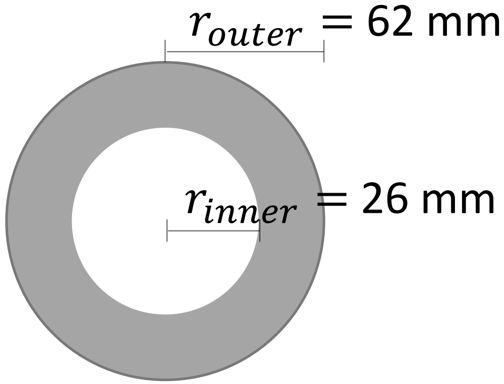
    $\sigma_{long} = 5372891.45\ Pa = \boxed{5.4\ MPa}$
- Hoop Stress
  - $\sigma_{hoop} = \frac{Pr}{t} \rightarrow \sigma_{hoop} = \frac{(263445\ Pa)(.062\ m)}{.00152\ m}$

    $\sigma_{hoop} = 10745782.89\ Pa = \boxed{10.7\ MPa}$
- Stainless Steel 304 Yield Strength = $\sigma_{yield} = 205\ MPa$
- $\boxed{\sigma_{long} \text{ and } \sigma_{hoop} \leq \sigma_{yield}}$ ✓



Casing Strength Analysis

- Shear Out of Casing?
  - Force on Endcap →



$$F_{case} = P * A$$

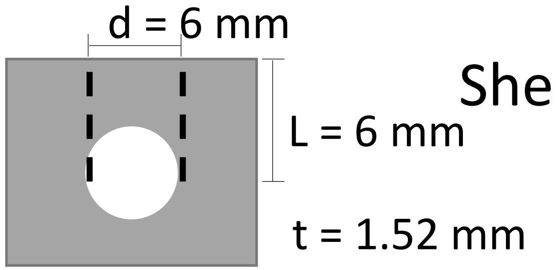
$$A = \pi\left(r_{outer}^2 - r_{inner}^2\right)$$

$$A = \pi(62^2 - 26^2) = 9952.57\ mm^2 = 9.95E^{-3}\ m\hat{}2$$

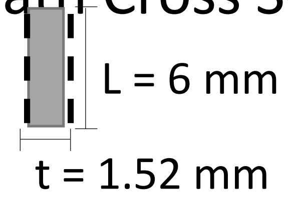
$$P = 2.6\ atm = 263445\ Pa$$

$$F_{case} = 263445\ Pa\ *\ 9.95E^{-3}\ m^2 = \boxed{2621\ N = F_{case}}$$

- Bolt hole shear path →



Shear Path Cross Section



Stainless 304 yield strength: 205 Mpa

Yield force = $F_{yield} = \sigma_{yield} * A$

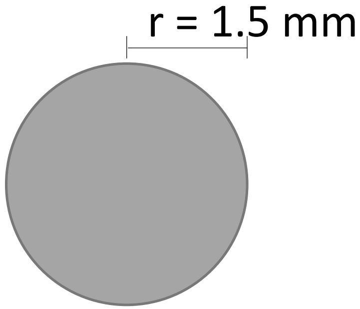
$$F_{yield} = 205E^6\ Pa\ * 2(.006 * .00152) = \boxed{3767N = F_{yield}}$$

$$\boxed{F_{case} \leq F_{yield}\ ✓}$$

Bolt Strength Analysis

$$F_{case} = \boxed{F_{bolt} = 2621\ N}$$

Bolt Cross Section



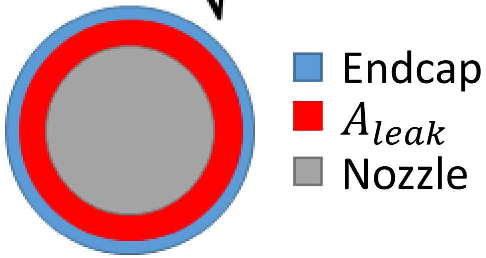
$$F_{yield} = \sigma_{yield} * A$$
$$\sigma_{yield} = 205\ MPa$$
$$A = \pi\, r^2 = \pi(.0015\ m)^2 = 7.07E^{-6}\ m^2$$
$$F_{yield} = 205E^6\ Pa\ * 7.07E^{-6}\ m^2 = 1449\ N$$

Need 2 bolts to hold case $\left(2 * 1449\ N = 2898\ N = F_{yield}\ \leq F_{bolt}\right)$

Using 4 bolts → $\boxed{F_{bolt} \leq F_{yield}\ ✓}$

Pressure Leak: Magnitude

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

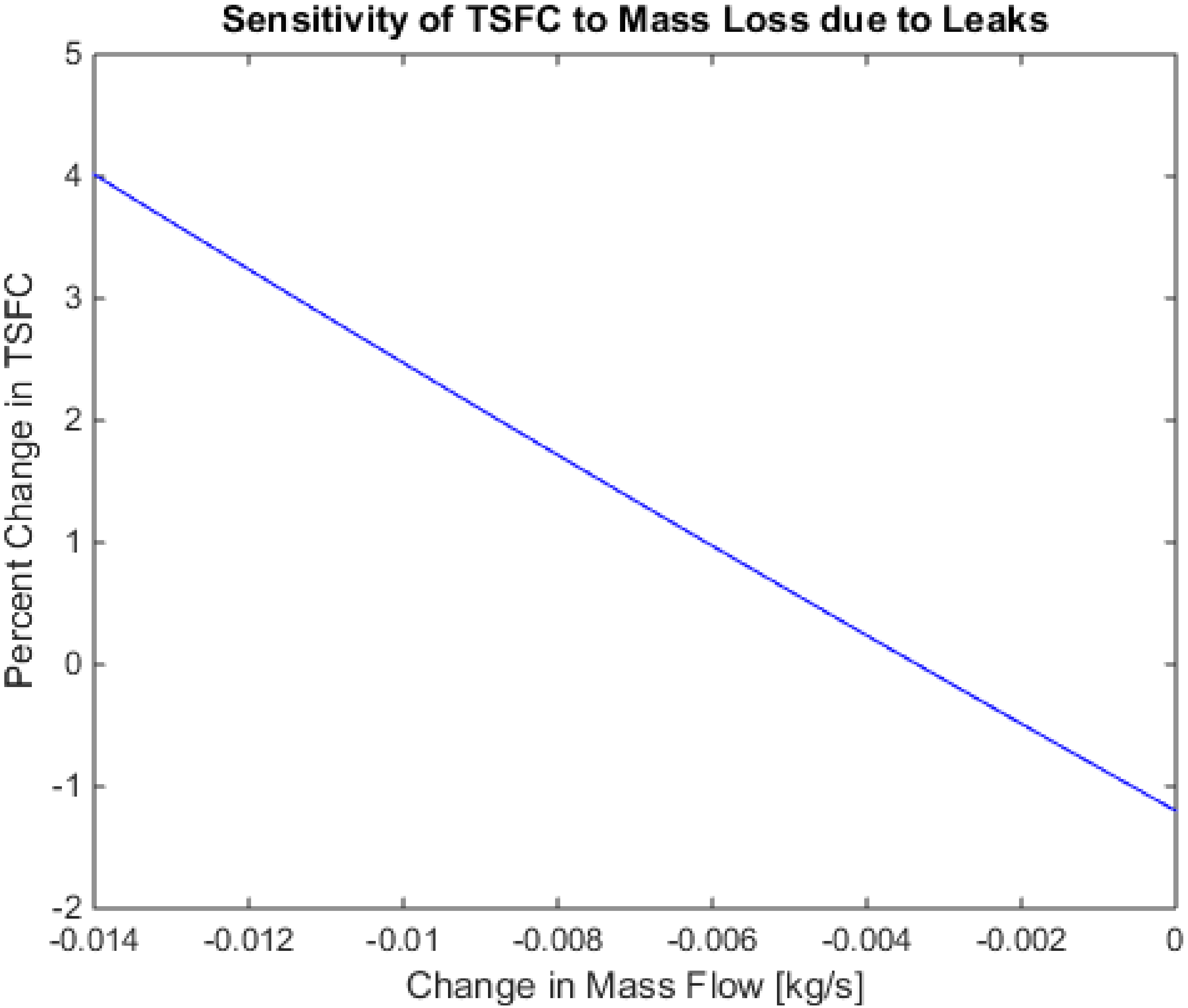


$$A_{leak} = \pi((r_{Nozzle} + gap)^2 - r_{Nozzle}^2)$$

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

- $\rho_{engine} = 3.6\frac{kg}{m^3}$
- $P_{engine} = 2.6\ atm = 263445\ Pa, P_{atm} = 1\ atm = 101325\ Pa$
- $C = .625 \rightarrow \text{hole flow coefficient, between .6 and .65}$
- $\boxed{\dot{m} = .014\frac{kg}{s}}$

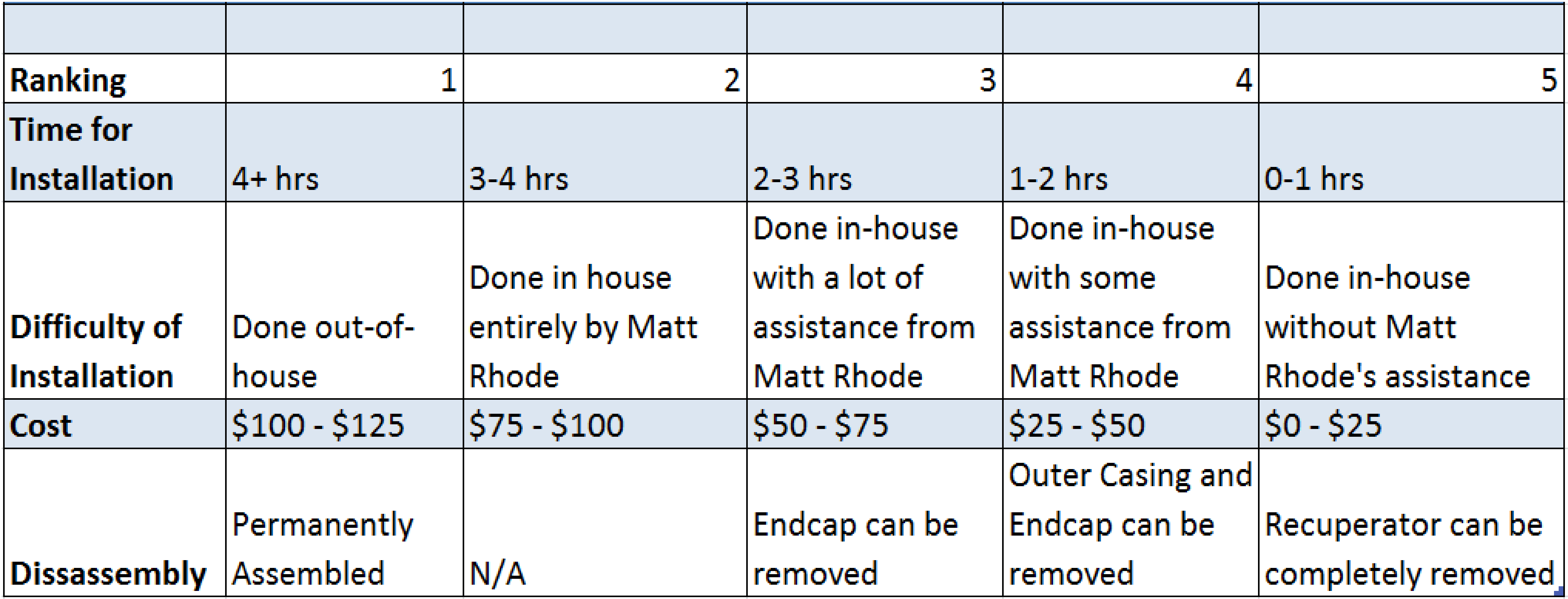
Pressure Leak: Effect on Efficiency



Sealant Trade Study

Metric	**Weighting**	**Welding**	**Putty**	**O-Ring**
Time for Installation	0.2	1	4	4
Difficulty of Installation	0.25	2	4	3
Cost	0.2	5	1	2
Dissassembly	0.35	1	5	5
Totals	1	2.05	3.75	3.7

Sealant Trade Heuristic

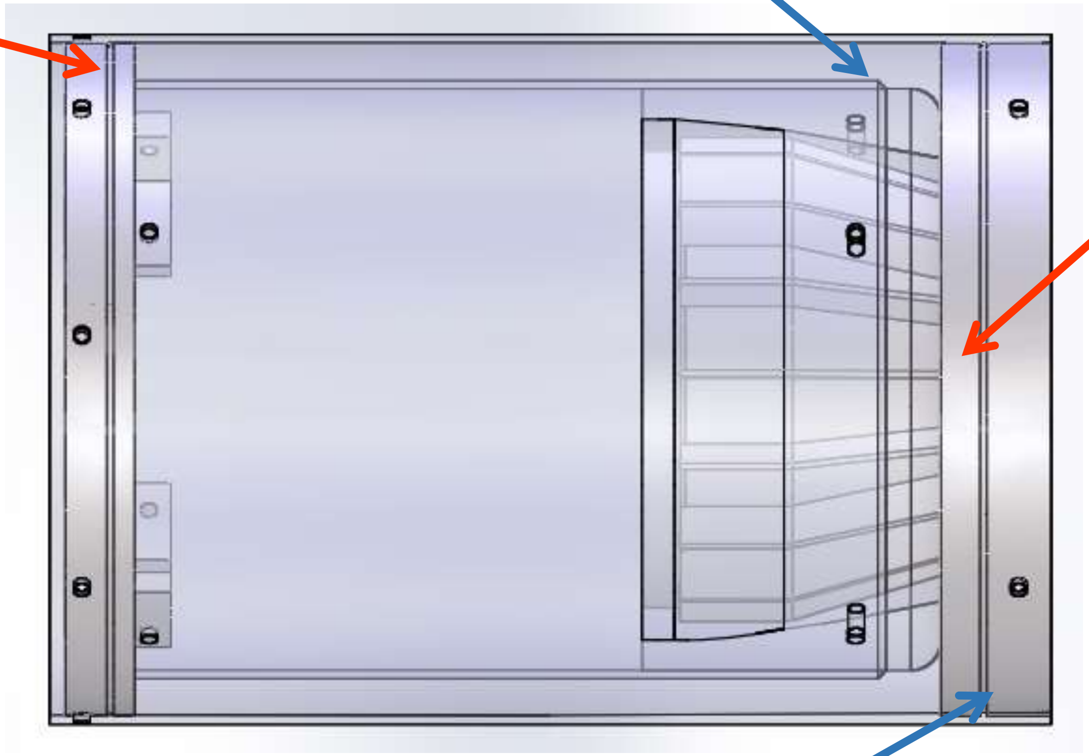


Ranking	1	2	3	4	5
Time for Installation	4+ hrs	3-4 hrs	2-3 hrs	1-2 hrs	0-1 hrs
Difficulty of Installation	Done out-of-house	Done in house entirely by Matt Rhode	Done in-house with a lot of assistance from Matt Rhode	Done in-house with some assistance from Matt Rhode	Done in-house without Matt Rhode's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

Pressure Sealing

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

Pressure Seal Locations



Outer Casing to Forward Ring (Gasket Compound)

Inner Casing to Nozzle Shroud (Weld)

Endcap to Nozzle (Gasket Compound)

Outer Casing to Endcap (Weld)

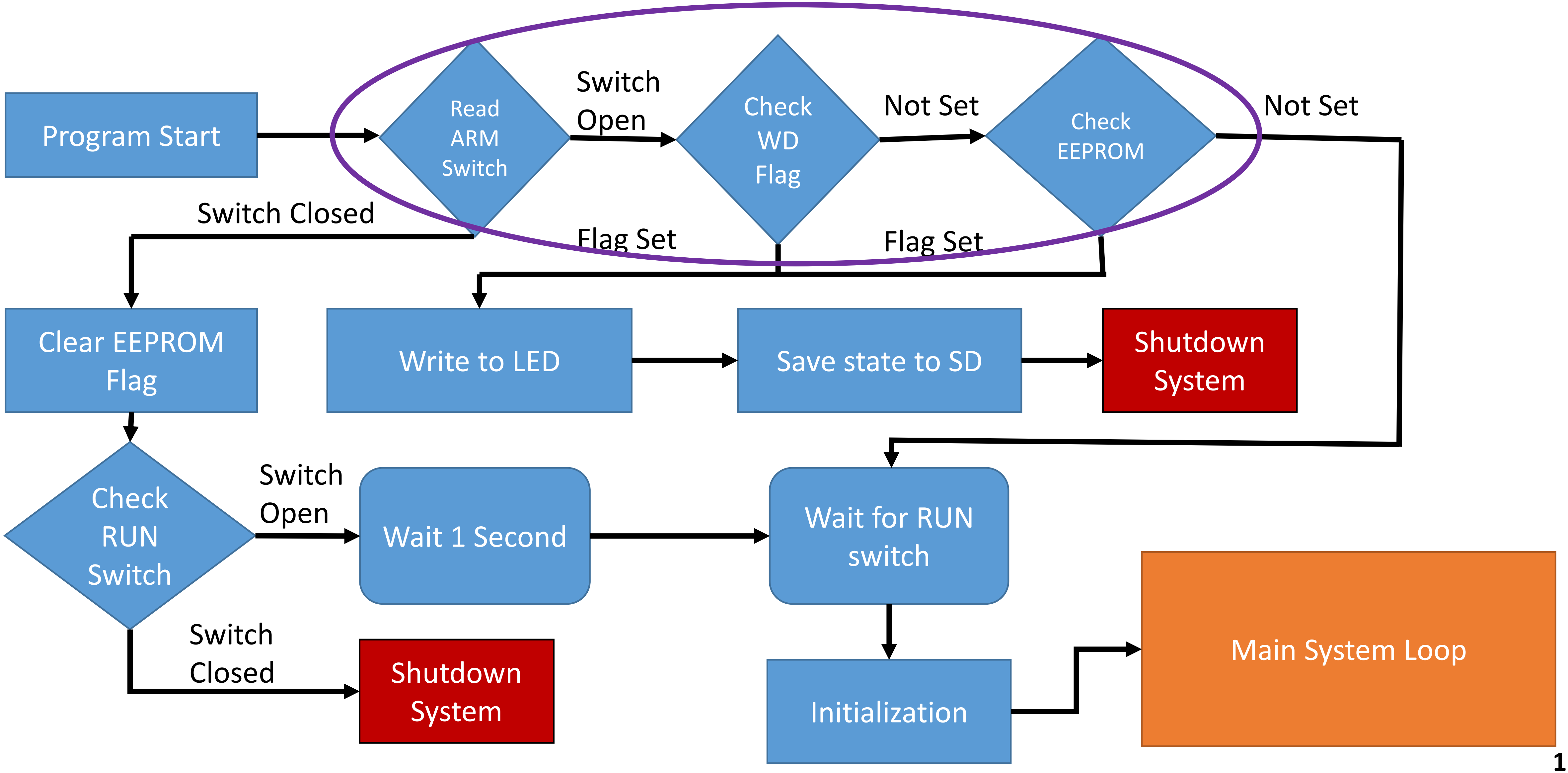
Engine Electronics Backup Slides

SD card Initialization

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

- All functionality complete

Engine Control Electronics – Software



System Shutdown

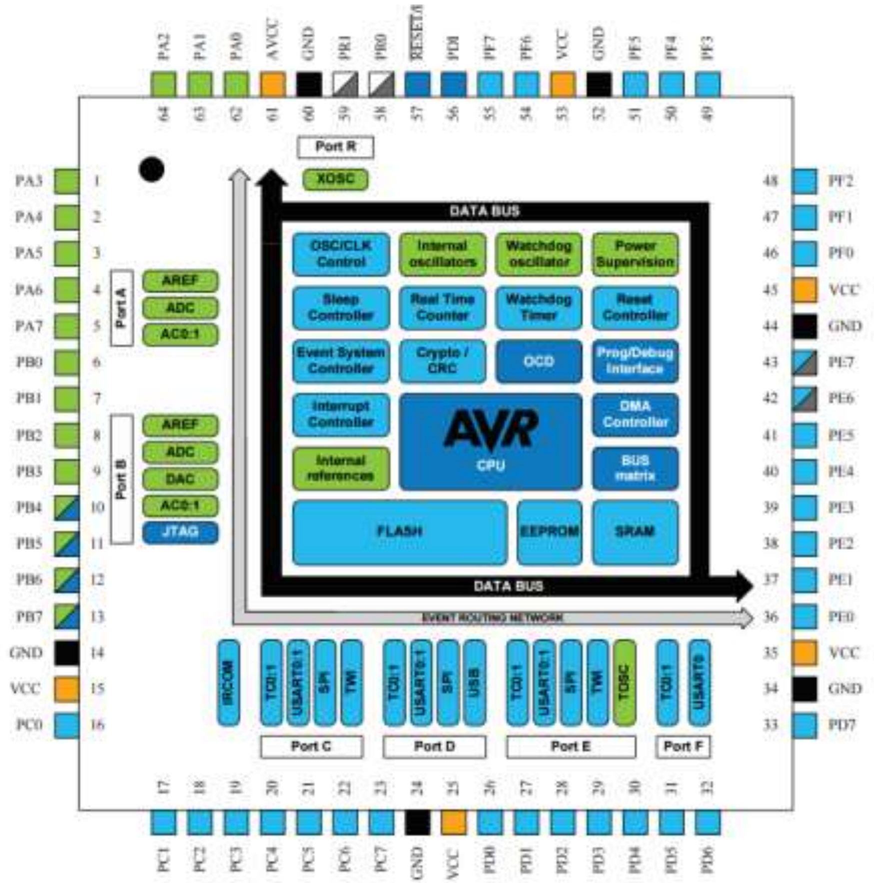
- Close Fuel Valves
- Leave lube solenoid open during shutdown
- Kill all power going to pump.
- Once stopped, close solenoid
  - Stop based on hall effect rpm
- Finalize all data
  - Flush buffers
- Reset flags

Watchdog

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

Critical Component: Processor

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



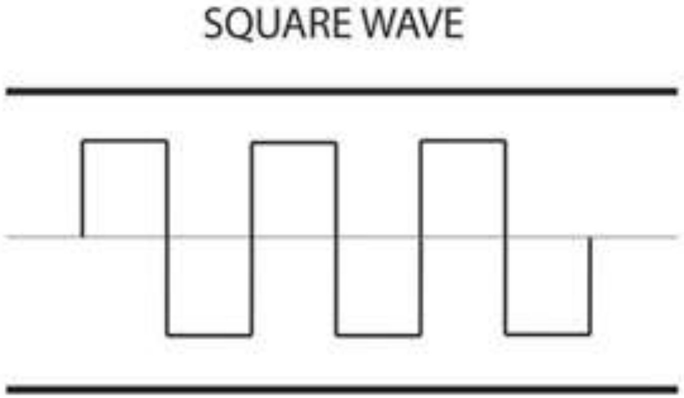
Fuel Flow Sensor

- Equflow 0045
- Disposable insert (~$50)
- Flow Rate 0.1-2L/min with 110,000 pulses/L
    - Engine fuel flow rate: 0.370 L/min
    - Accurate to 1% of reading (±0.0001 L/min)
    - Predicted 580±5 pulses/s
- 34mA current at 5V
    - Not using filters
    - Replace as needed
- Store pulses in buffer collect at every read cycle

Disposable PFA flow meter

Critical Component: Hall-Effect and Comparator

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



Hall Effect Sensor SNR

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

$$B \propto \frac{1}{r^3} \qquad \frac{B(r+\Delta r)}{B(r)} = \frac{37^3}{37.2^3} = 0.984 = 98.4\%\ \text{field} \qquad 20\log 0.984 = -.14\ dB$$

- Field: 15mT
- Sensitivity: 50mV/mT
- Sensor noise: 10μT

$$50\frac{mV}{mT} \times .15mT = 7.5\ mV$$

$$50\frac{mV}{mT} \times 10\mu T = 0.5\ mV$$

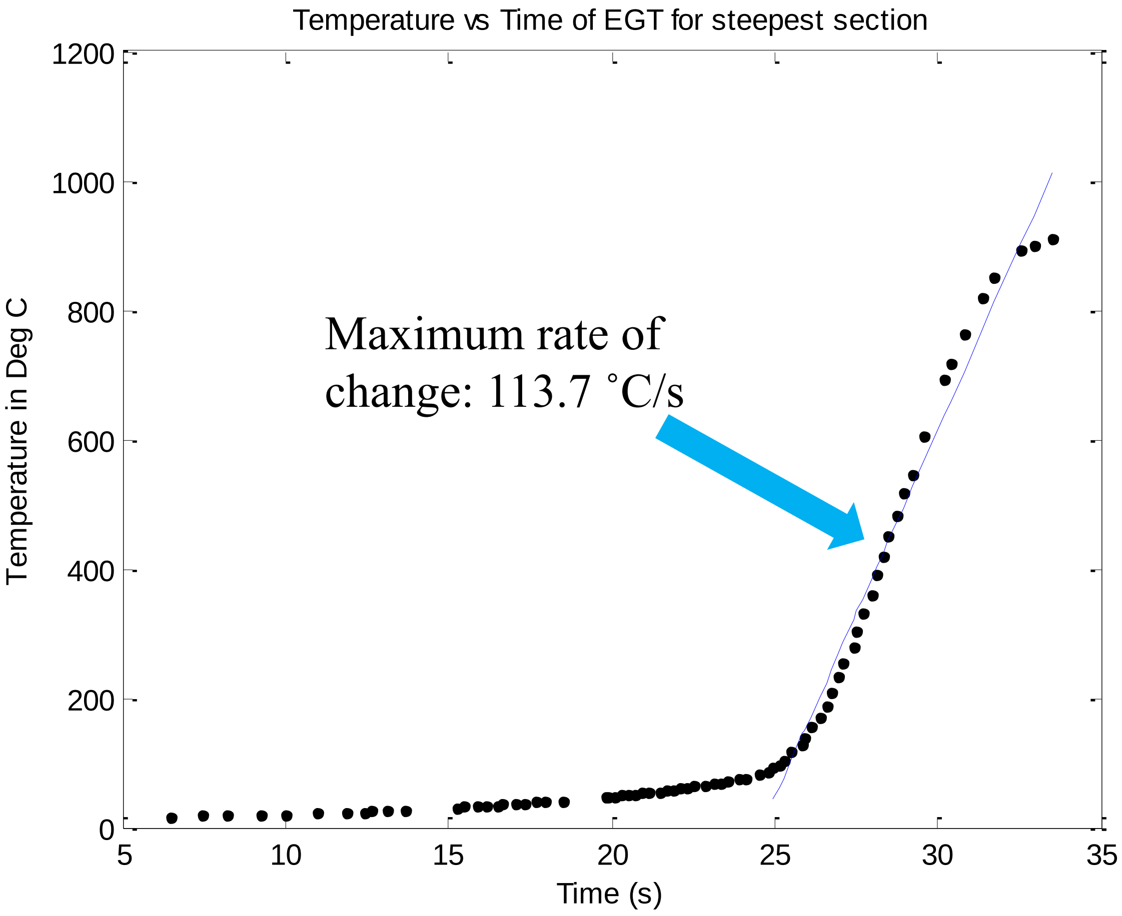
- Signal to noise ratio:

$$SNR = 20\log\frac{7.5}{0.5} = \ 23.5\ dB$$

Thermocouple Sample Rate

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

$$\text{Min sampling Rate} = \frac{113.7\frac{℃}{s}}{1℃} = \mathbf{113.7\ Hz}$$

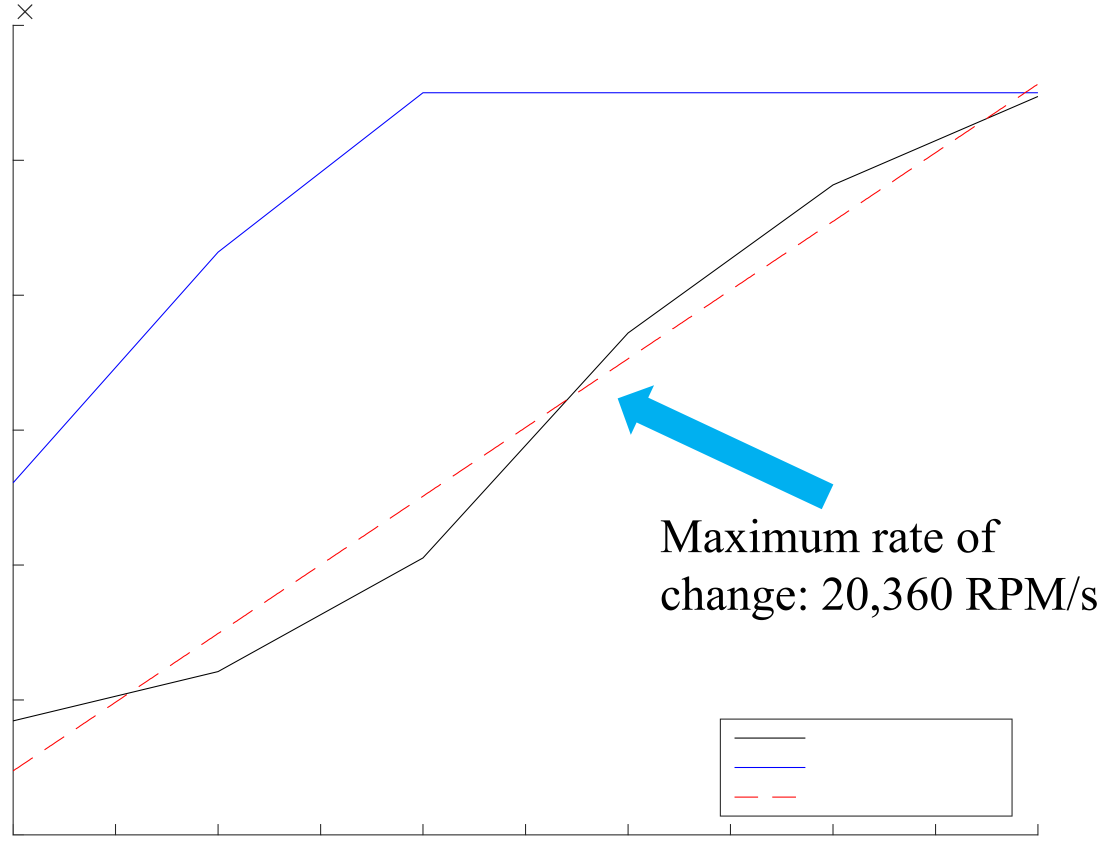


Maximum rate of change: 113.7 ˚C/s

Hall Effect Sample Rate

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

Min sampling Rate = $\dfrac{20{,}360\frac{RPM}{s}}{650\ RPM}$ **= 31 Hz**



Maximum rate of change: 20,360 RPM/s