Preliminary **D**esign **R**eview

REcuperating Advanced Propulsion Engine Redesign

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

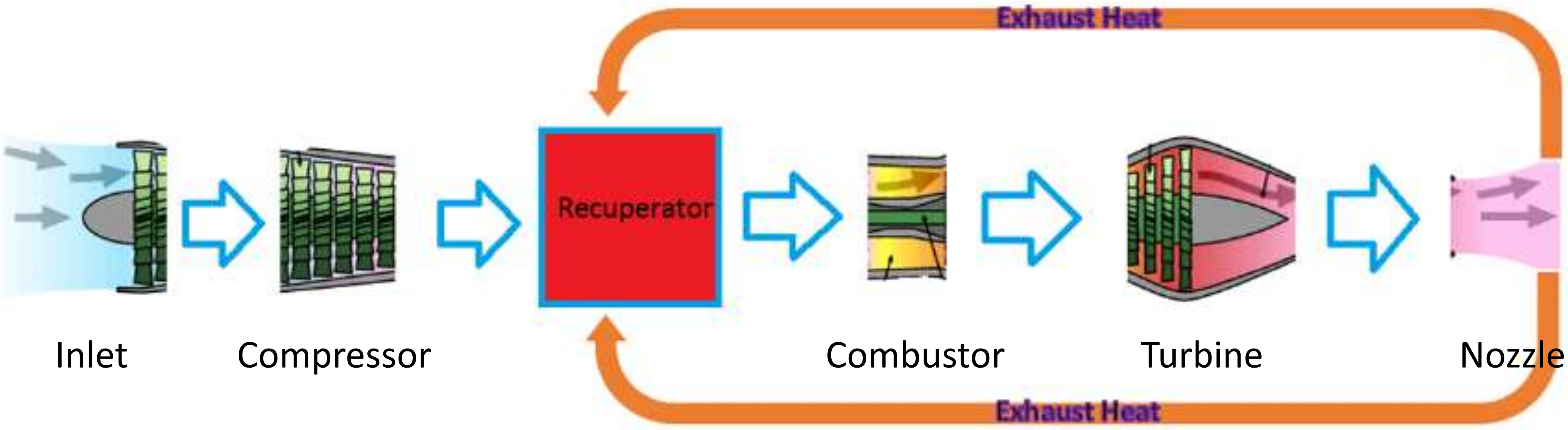
Outline

- Project Description
- Baseline Design
- Feasibility Analysis
- Project Summary

Project Description | Baseline Design | Feasibility Analysis | Project Summary

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.



Project Description | Baseline Design | Feasibility Analysis | Project Summary

What is a Recuperator?

- A recuperator is a form of energy recovery heat exchanger designed to recover waste heat from a system
- Our recuperator:
  - Recover heat energy from the exhaust
  - Preheated compressed air will decrease fuel consumption

$$Q_{required} = Q_{fuel\ burn} + Q_{heat\ transfer}$$

Novelty

- Most existing systems are ground based
  - Highly efficient (up to ~90%)
  - Add huge amounts of mass and volume to system
- Recuperators have not been used on turbojets of any size
  - This project is a proof of concept

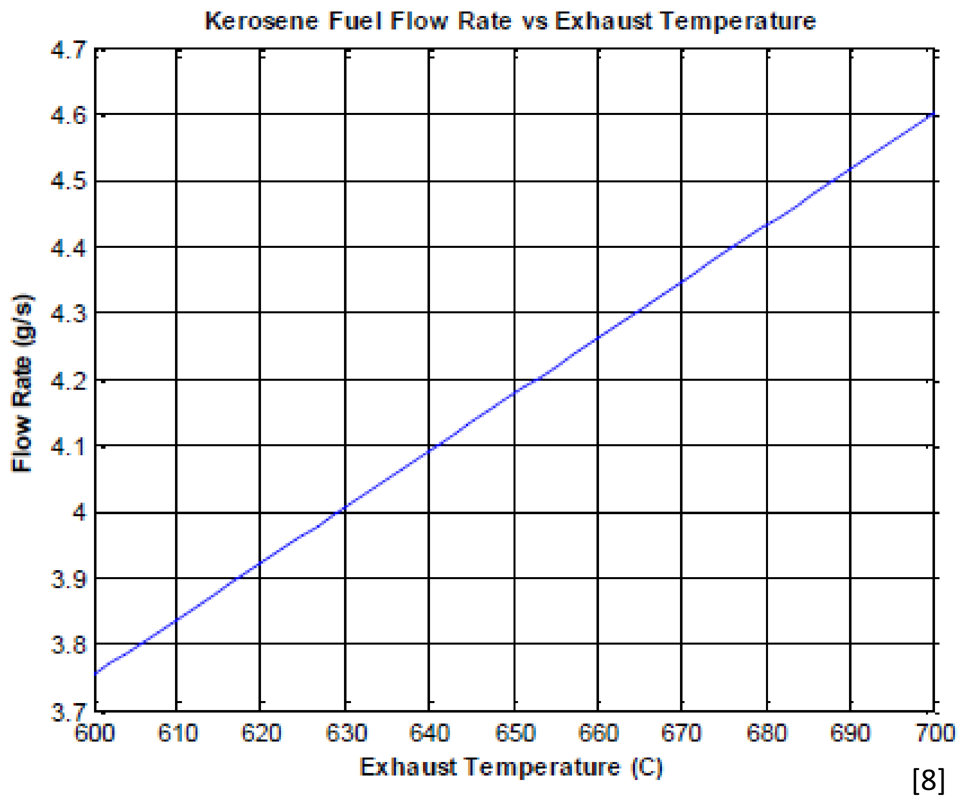
14

Engine: JetCat P90-RXi

- Hobbyist miniature jet engine
- Fuel: 19:1 Kerosene/Oil Mixture
- Specifications:
  - Max thrust: 105 N @ 130,000 RPM
  - Exhaust: 490-690 °C at 1454 km/h (403.9 m/s)
  - Fuel Flow Rate at Max RPM: 370 ml/min
  - Diameter: 112 mm
  - Mass: 1.435 kg

Heritage

- GoJett
  - Test Stand and Test Procedures
- 2013-2014 COMET
  - Generated turbine and compressor map
- 2014-2015 MEDUSA
  - Prototyped custom circuit boards for engine control
  - Characterized fuel and lubrication rates



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Project Description | Baseline Design | Feasibility Analysis | Project Summary

Requirements

Functional Requirements

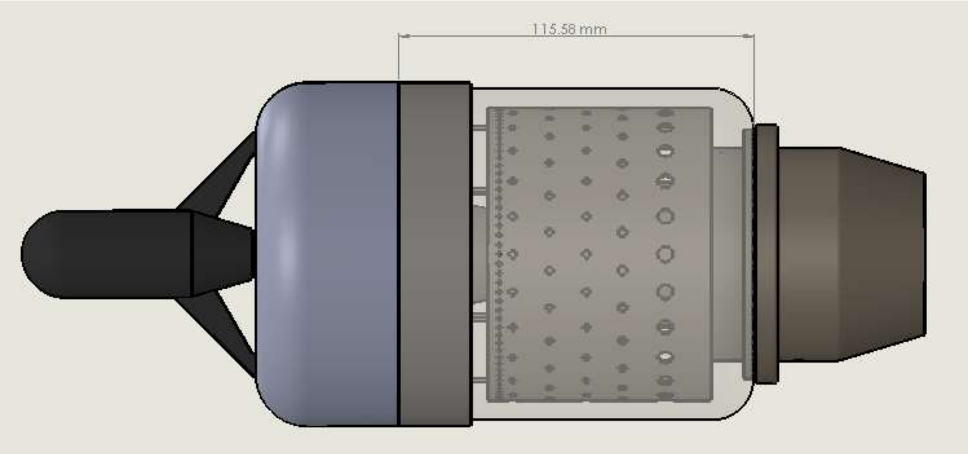
- **FR 1**: The engine shall operate with the heat exchanger system integrated.
- **FR 2**: The thrust specific fuel consumption (TSFC) of the engine with the heat exchanger system integrated shall decrease by at least 10%

  DR 2.4: Less than 100% increase in throttle response time between half and full thrust
  DR 2.5: Less than 10% thrust reduction
  DR 2.6: Less than 50% mass increase
  DR 2.7: Less than 100% volume increase

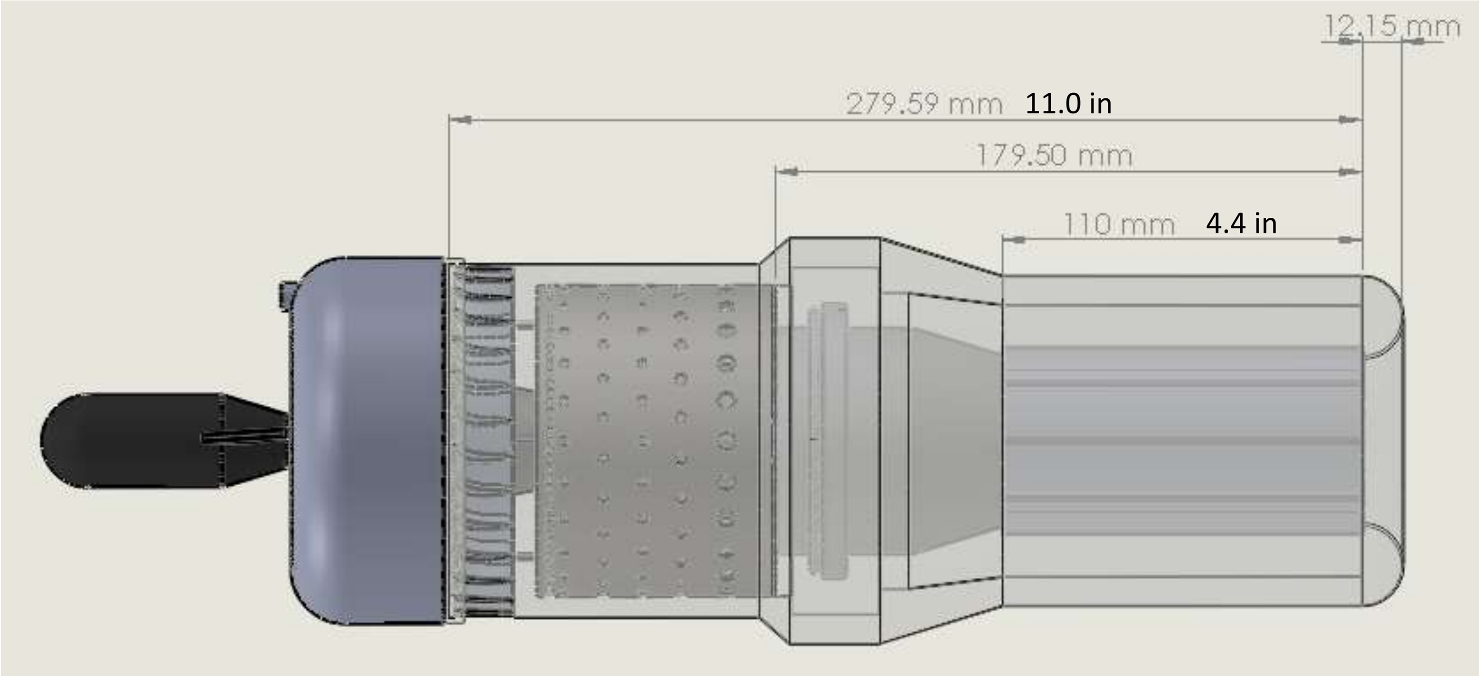
$$TSFC = \frac{Weight\ Flow\ Rate\ of\ Fuel}{Net\ Thrust}$$

- **FR 3**: The simulation shall model the thrust and efficiency of the engine with the integrated heat exchanger system.

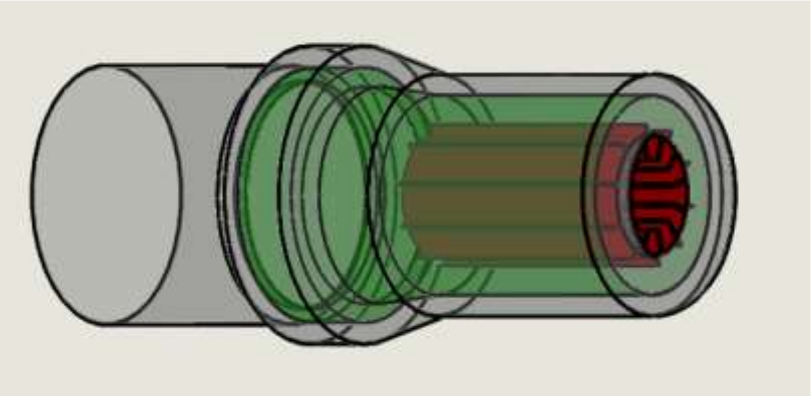
Baseline Design



Stock JetCat Engine

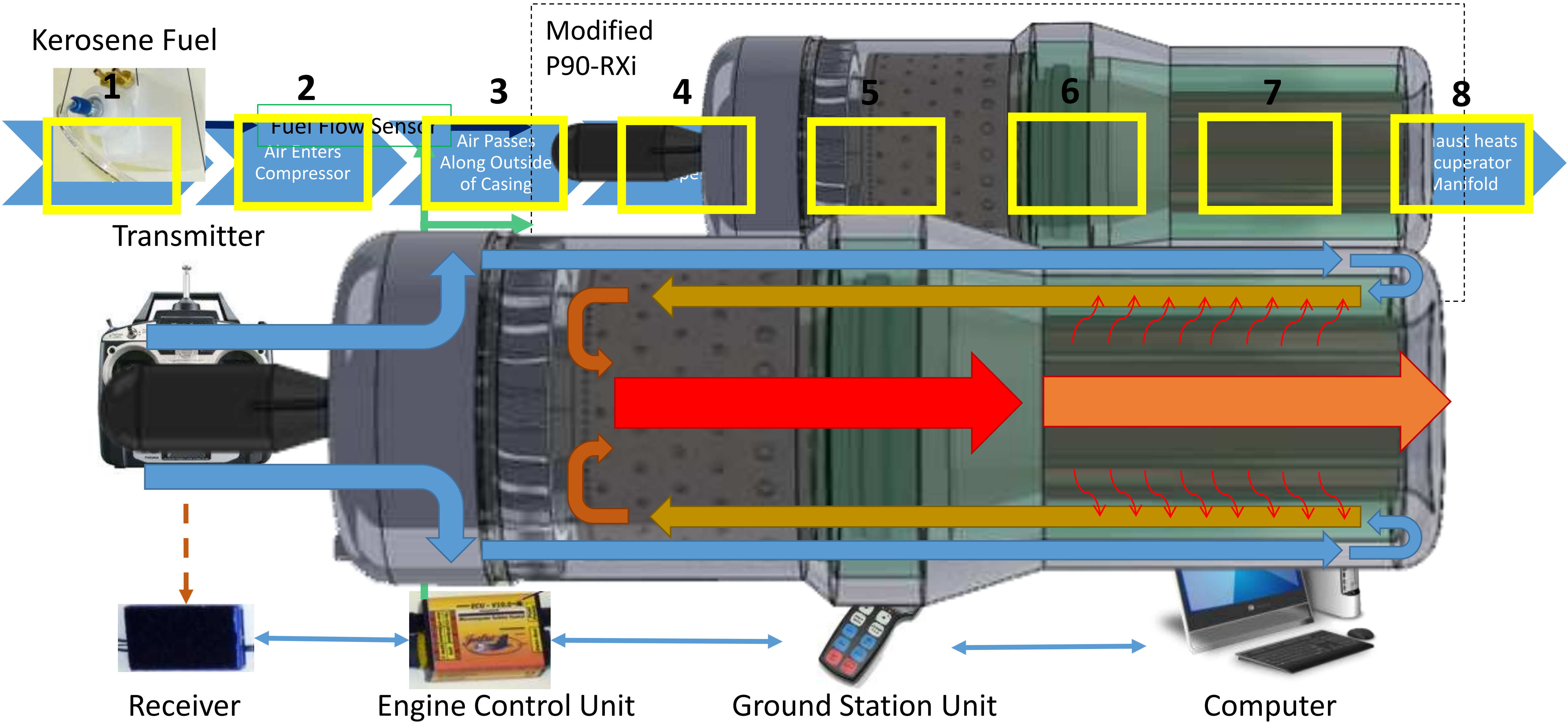


REAPER Recuperated Engine Design

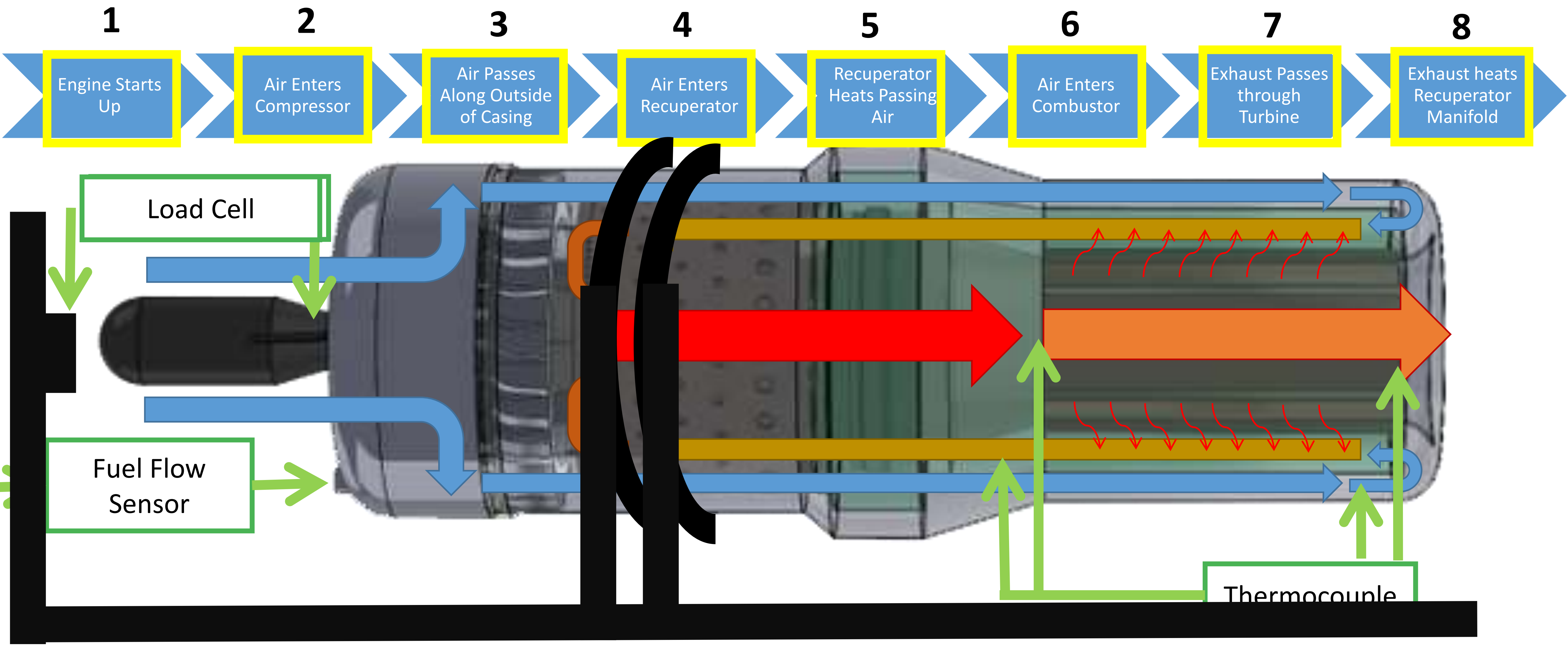

REAPER Recuperator Design

	Net Thrust [N]	Thrust Specific Fuel Consumption $[s^{-1}]$
Stock Engine	105	4.46×10^{-4}
REAPER Design	101	4.05×10^{-4}
Percent Reduction	4%	10%

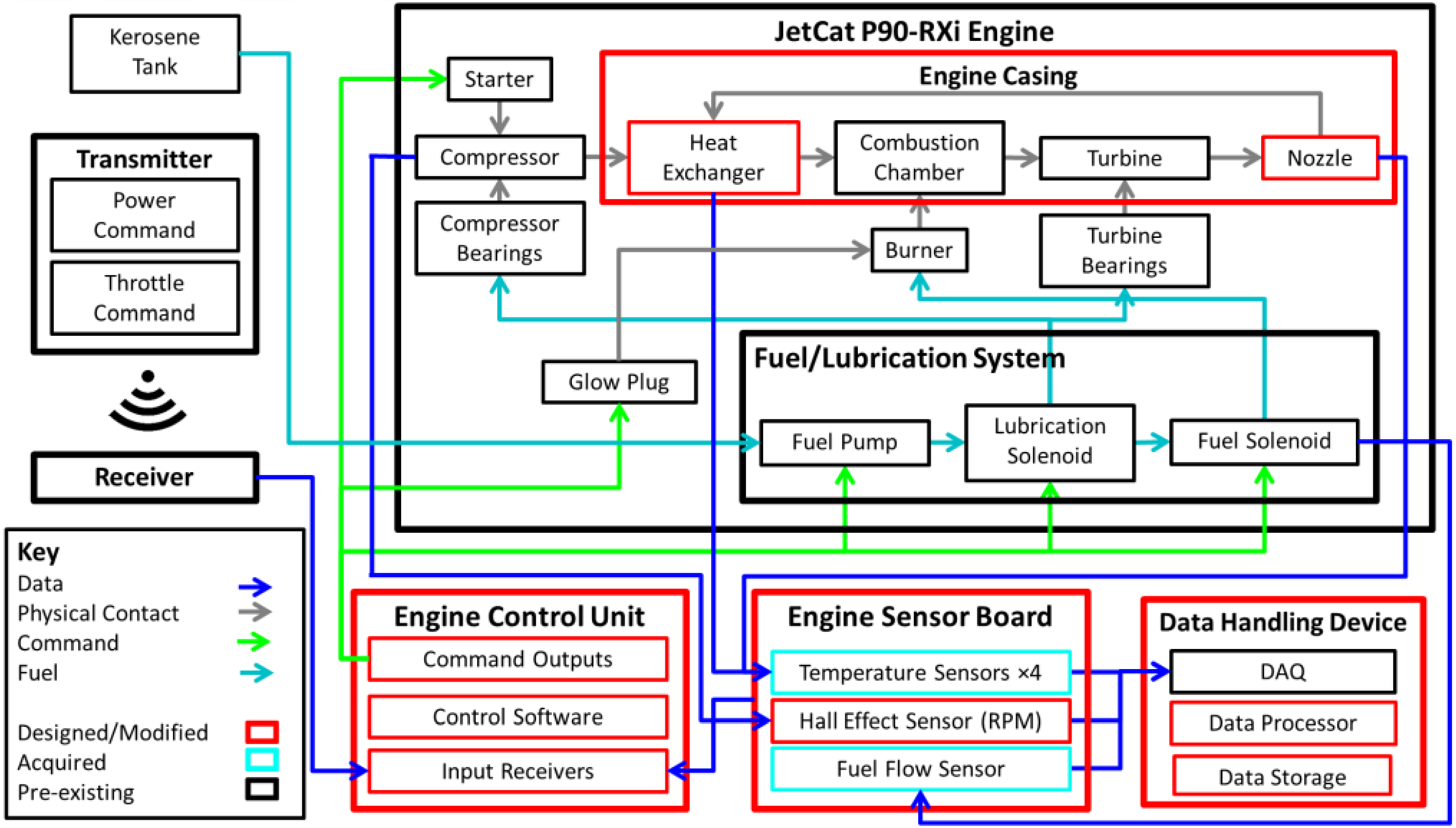
Concept of Operations



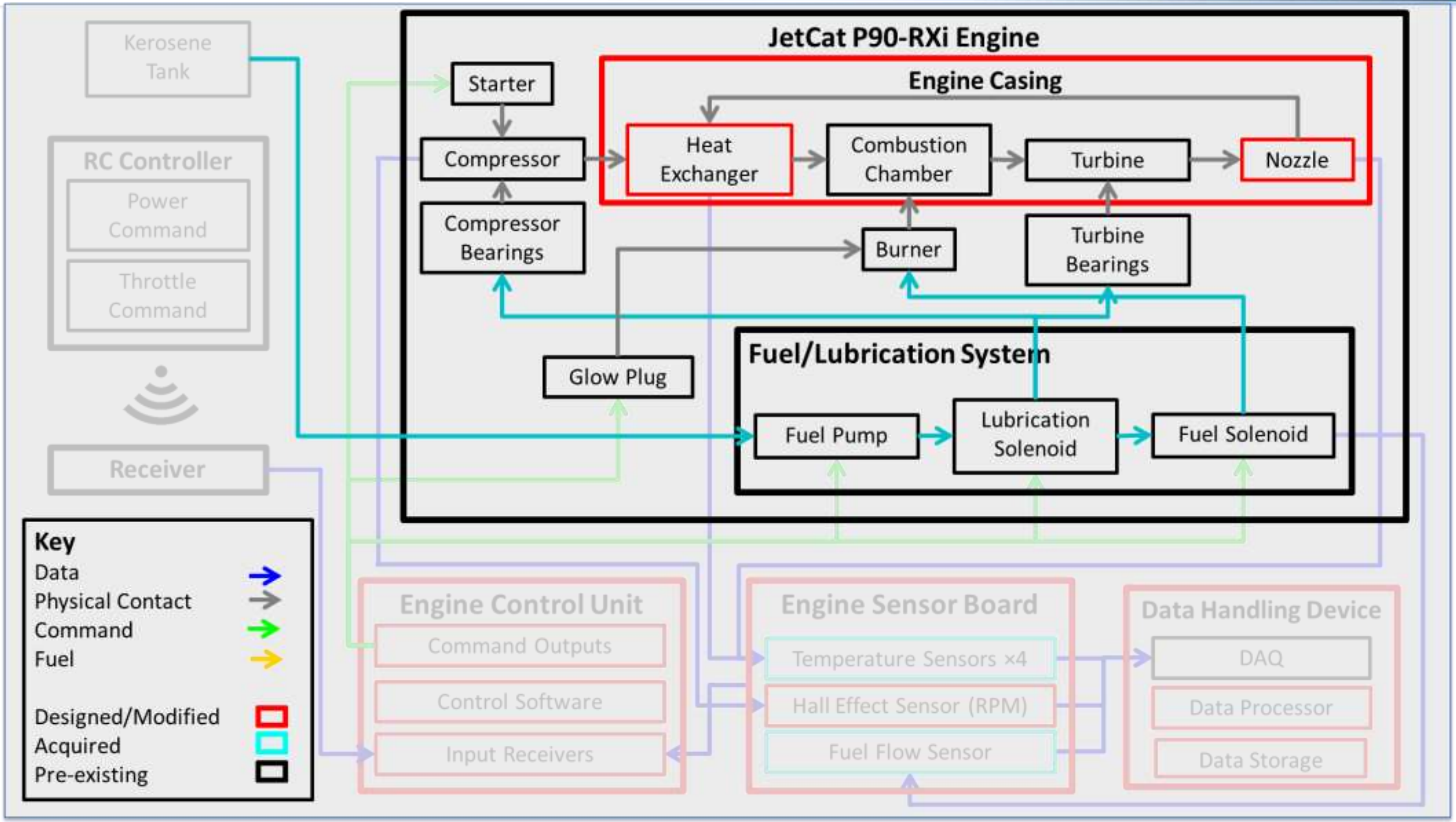
Concept of Operations



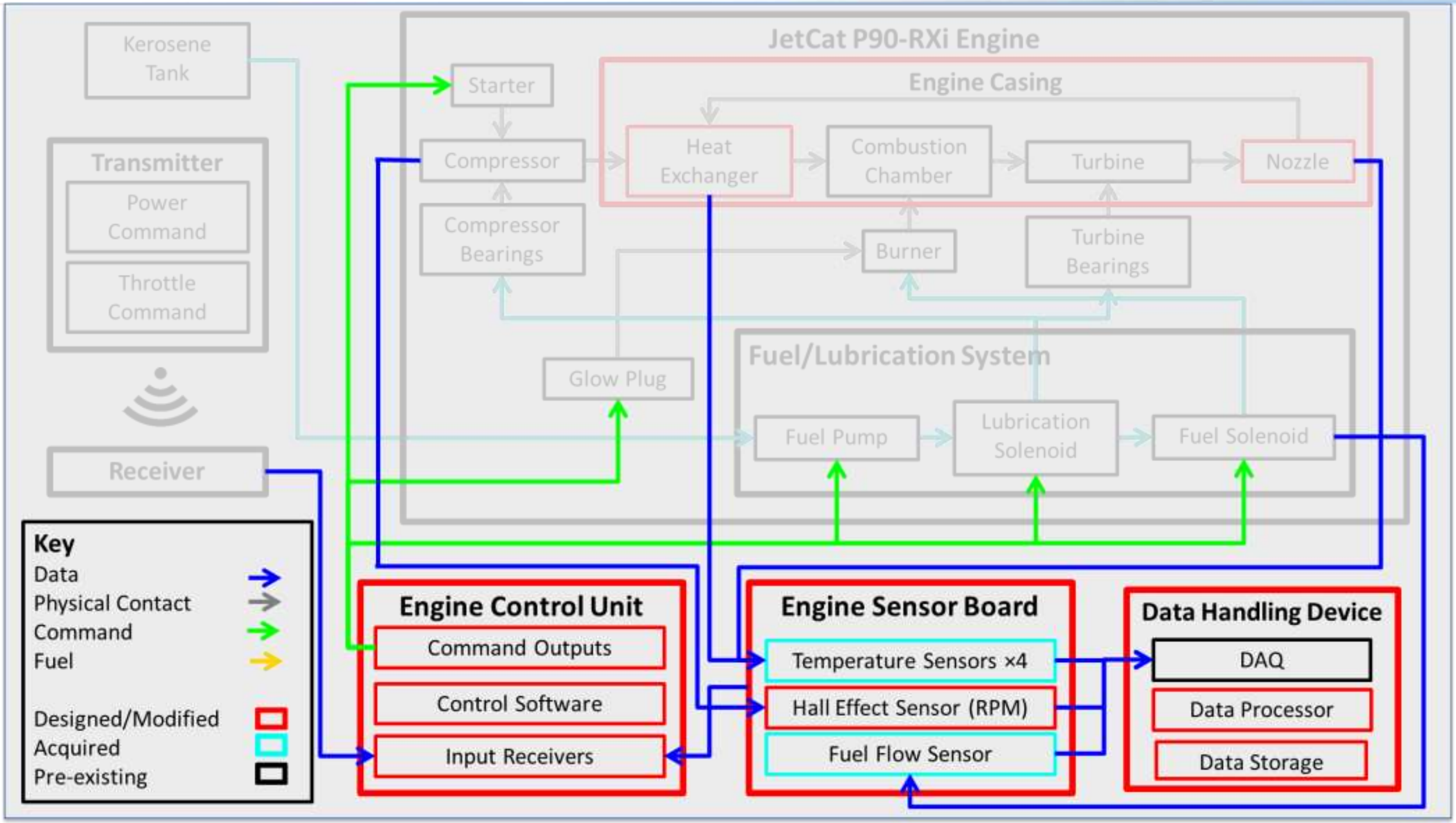
Functional Block Diagram



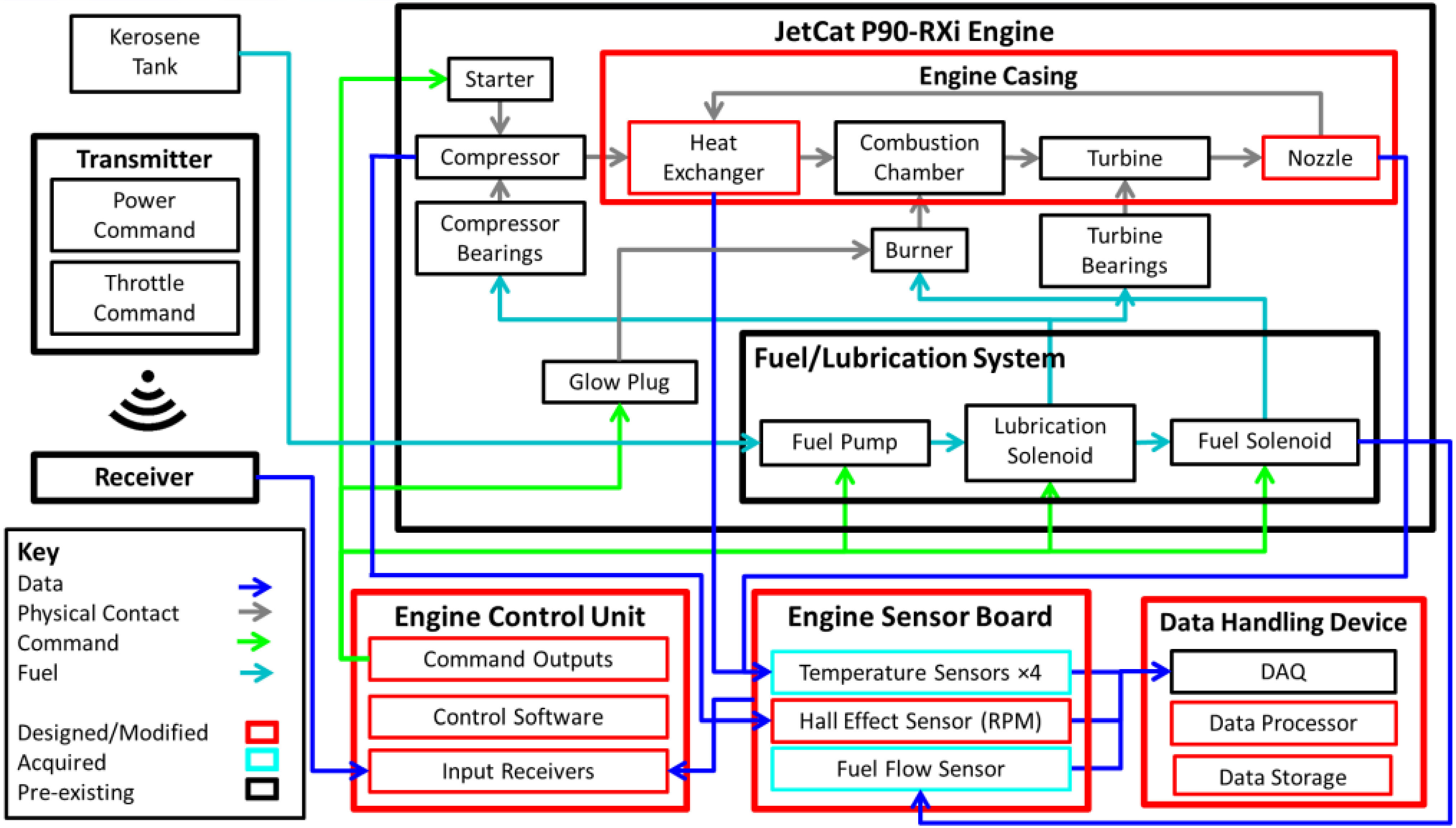
Recuperator System FBD



Electronics FBD

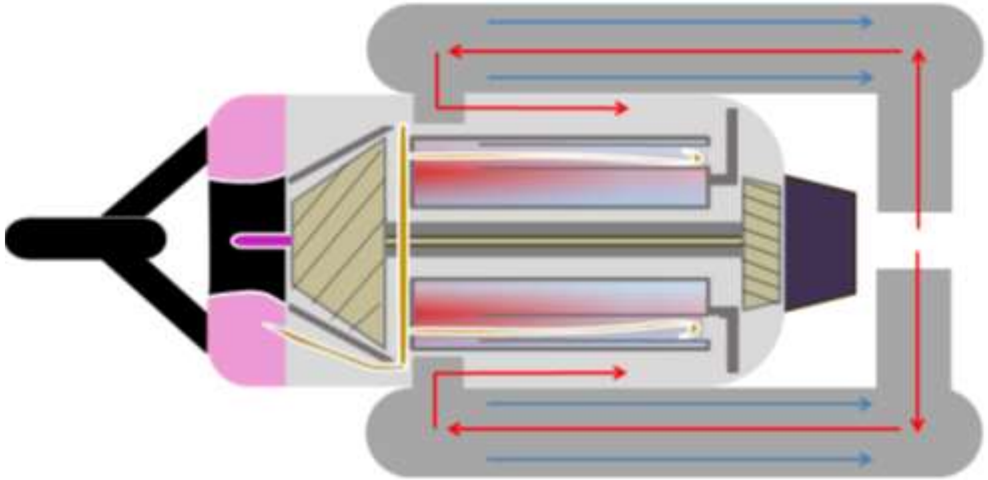


Functional Block Diagram

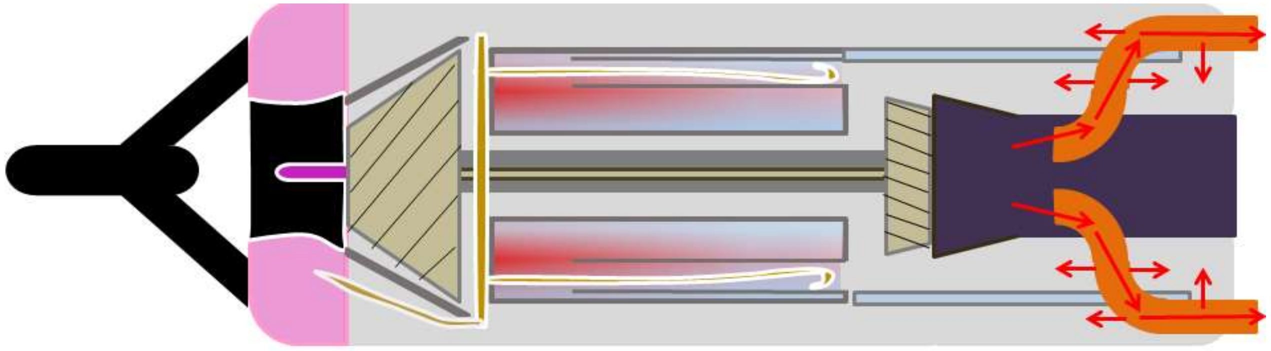


Heat Exchanger

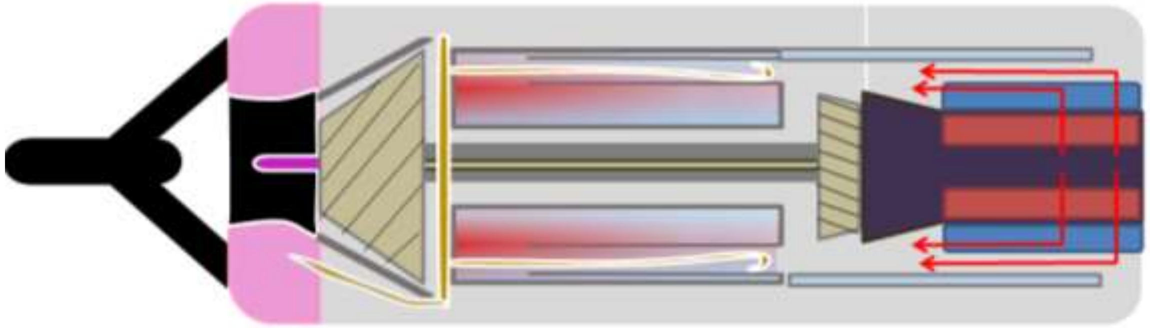
Heat Exchanger Options



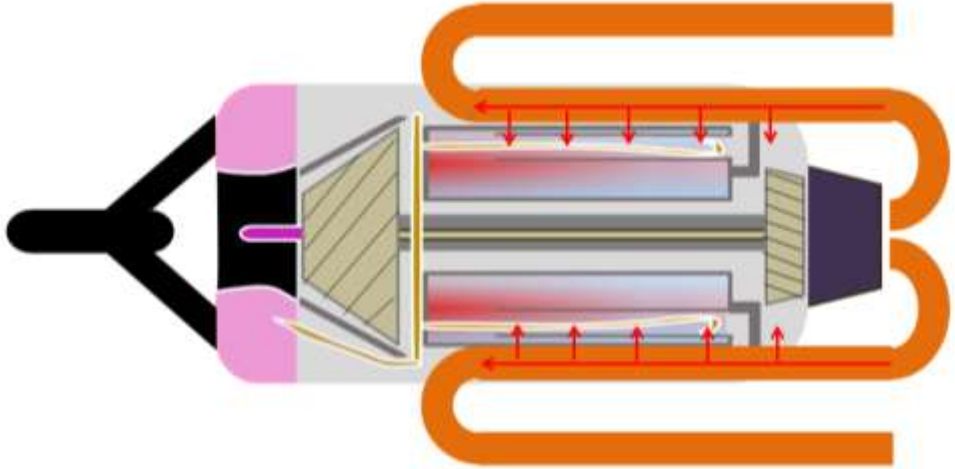
Heat Pipe



Rear Multi-Pass Gas-Gas



Rear Single-Pass Gas-Gas

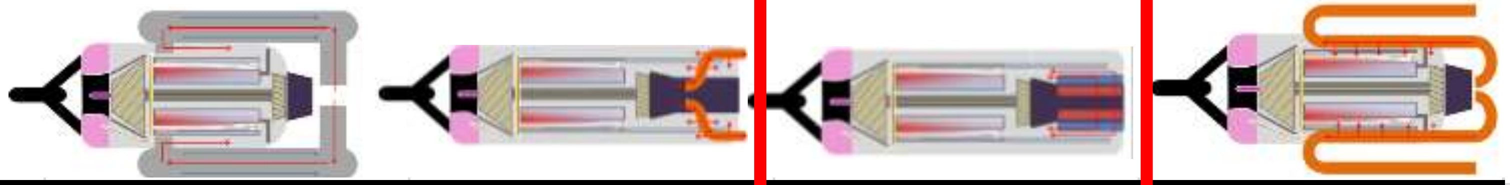


Forward Counter Flow Gas-Gas

Heat Exchanger Heuristic

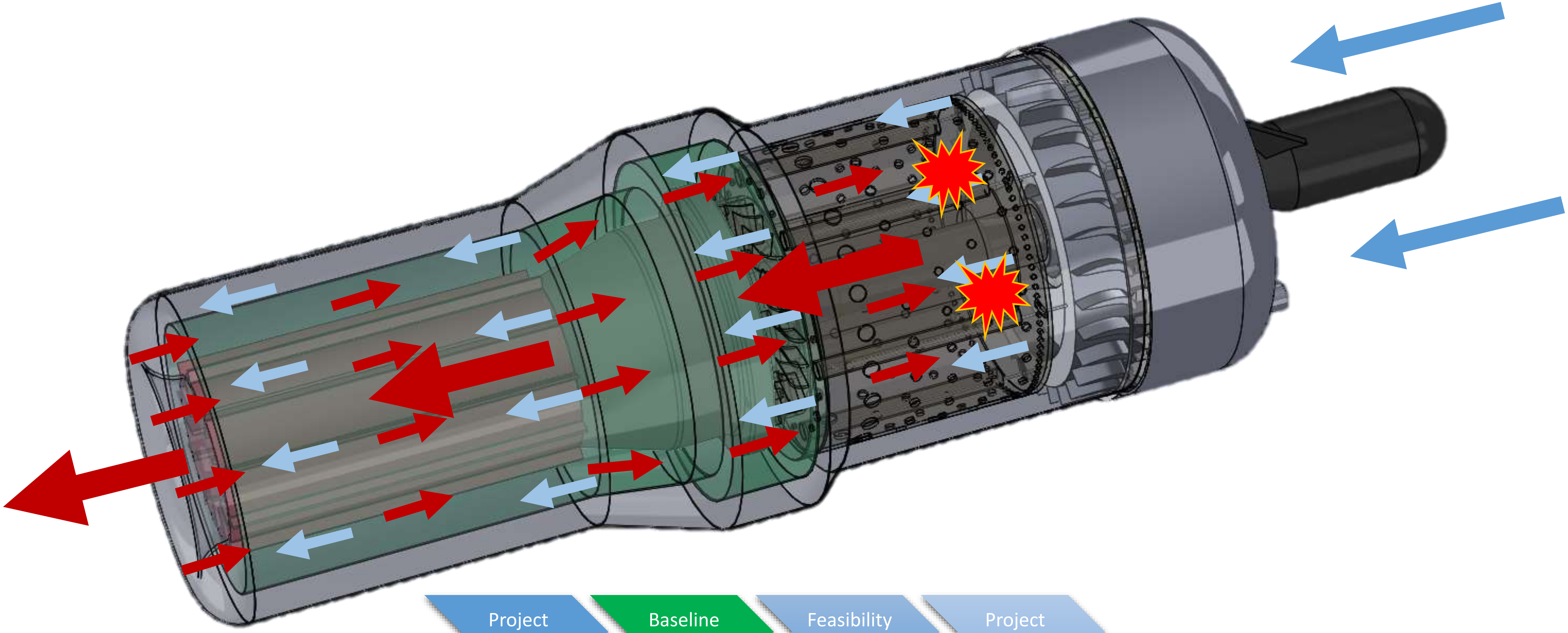
Category	Weight	1	2	3	4	5
Mass	10%					
Manufacturability/Cost	30%	Beyond team's skills/budget	Manufactured out of house for between $2000 and $3000	Manufactured in/out of house for less than $2000	Manufactured in house or purchased and modified for less than $1000	Purchasable and directly integrable for less than $1000
Integrability	30%	Complete redesign of > 2 engine components	Complete redesign of 1 component or modification of 3	Modification of 3 or less components	Modification of 1 component	No engine modifications
Outer Flow Impedance	20%	> 5% pressure drop at exit	4-5% pressure drop at exit	3-4% pressure drop at exit	2-3% pressure drop at exit	< 2% pressure drop at exit

Heat Exchanger Trade Study



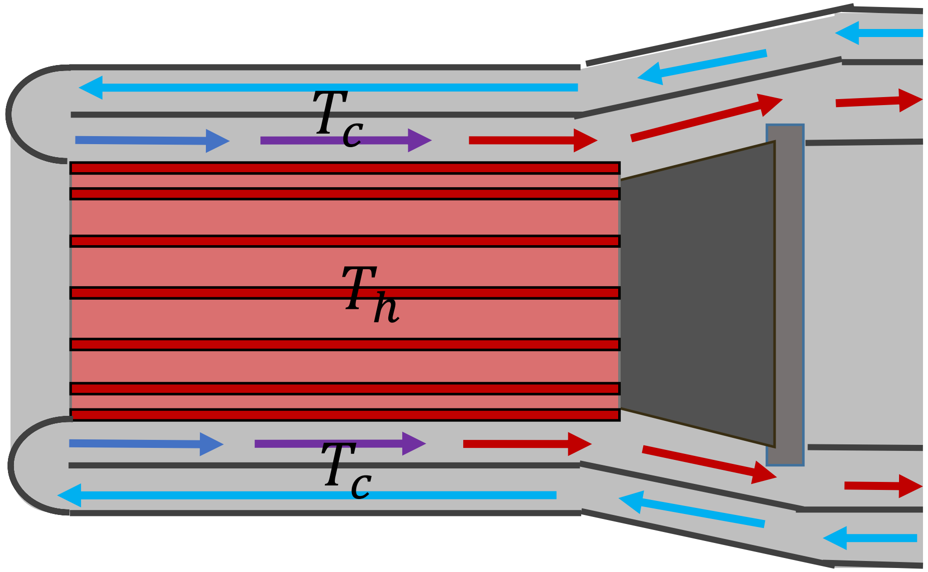
Exchanger type→ Category↓	Weight	Heat Pipe	Rear Multi-Pass Gas-Gas	Rear Single Pass Finned Gas-Gas	Forward Counterflow Gas-Gas
Mass	0.1	1	2	4	1
Volume	0.1	3	2	3	3
Manufacturability/Cost	0.3	1	3	4	3
Integrability	0.3	4	1	2	2
Outer Flow Impedance	0.2	5	4	5	1
Total	1	2.9	2.4	3.5	2.1

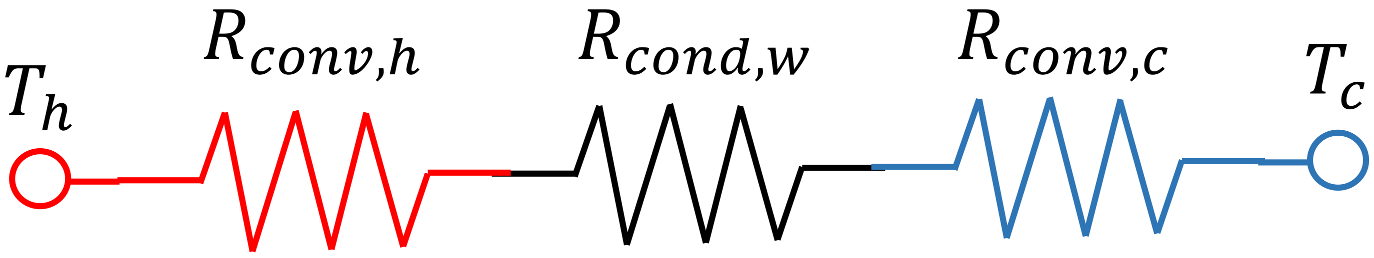
Baseline Design: Visualizing the Flow



How It works: Heat Exchanger

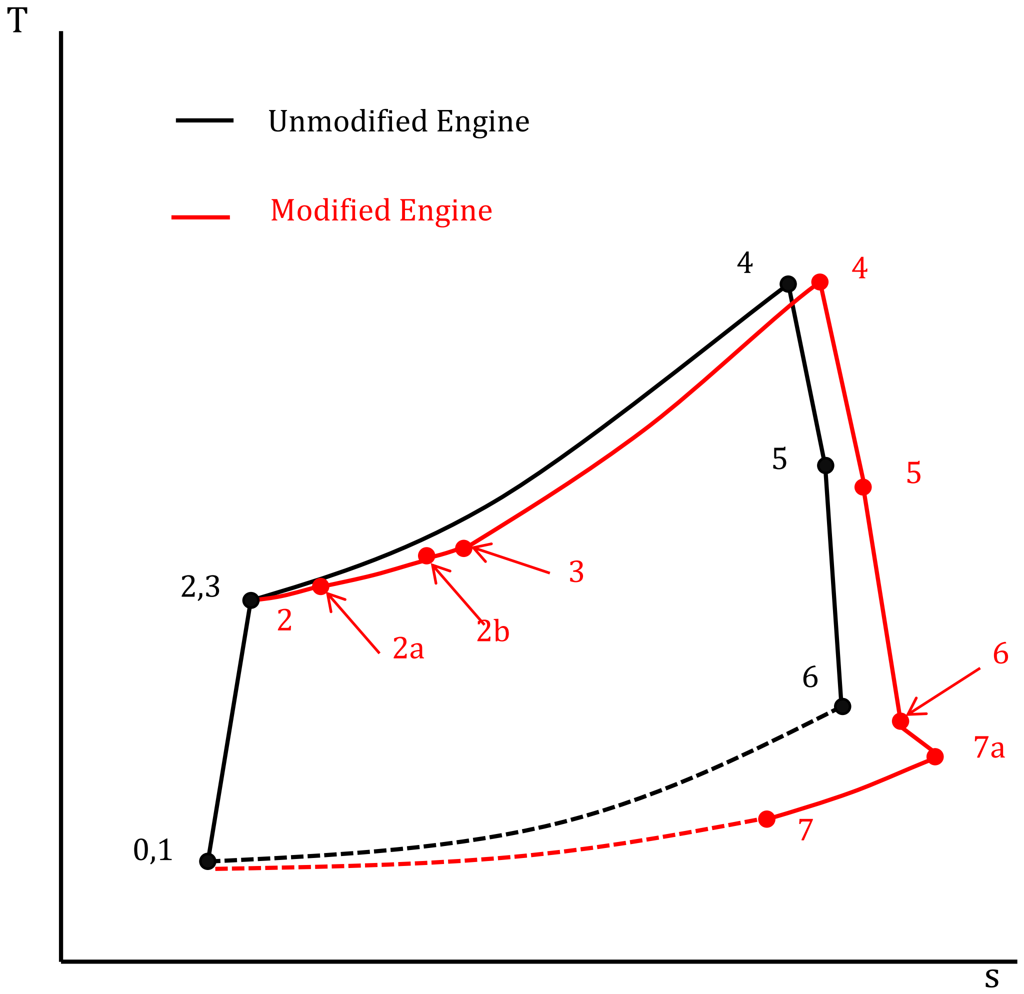
$$\dot{Q} = U_h A_h (T_h - T_c)$$

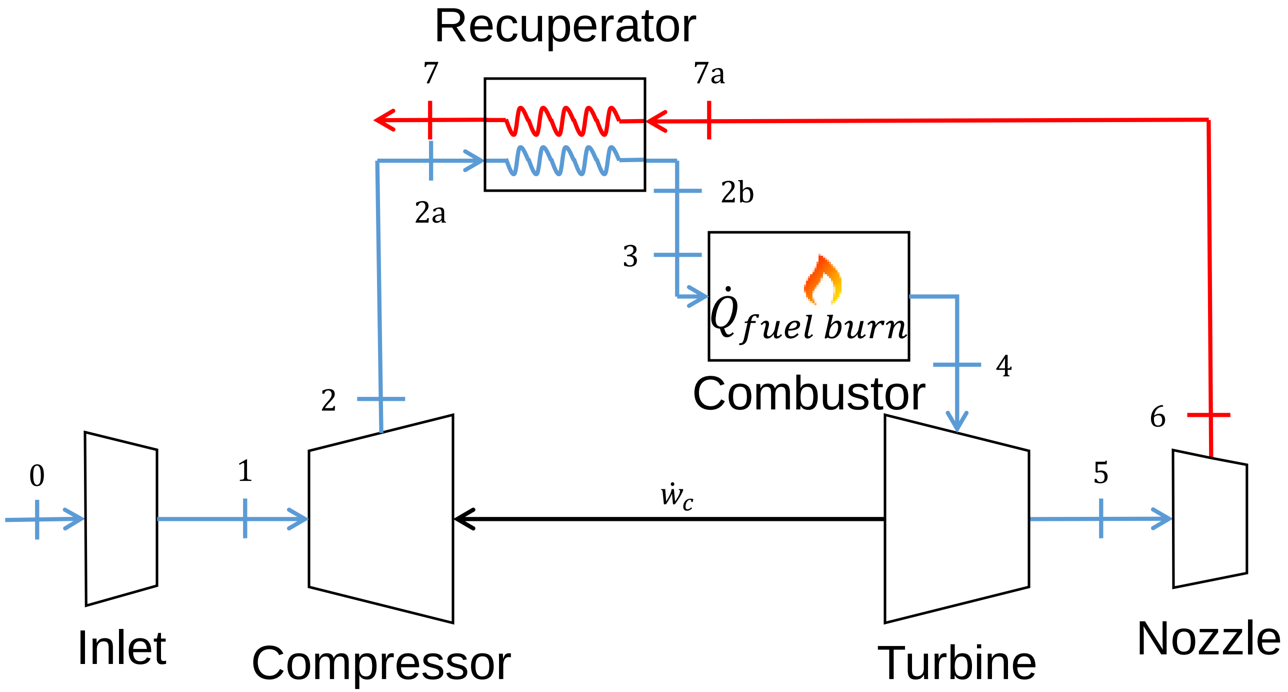




$$\frac{1}{U_h A_h} = \frac{1}{\eta_{0,h} A_h h_h} + \frac{t_w}{A_w k_w} + \frac{1}{\eta_{0,c} A_c h_c}$$

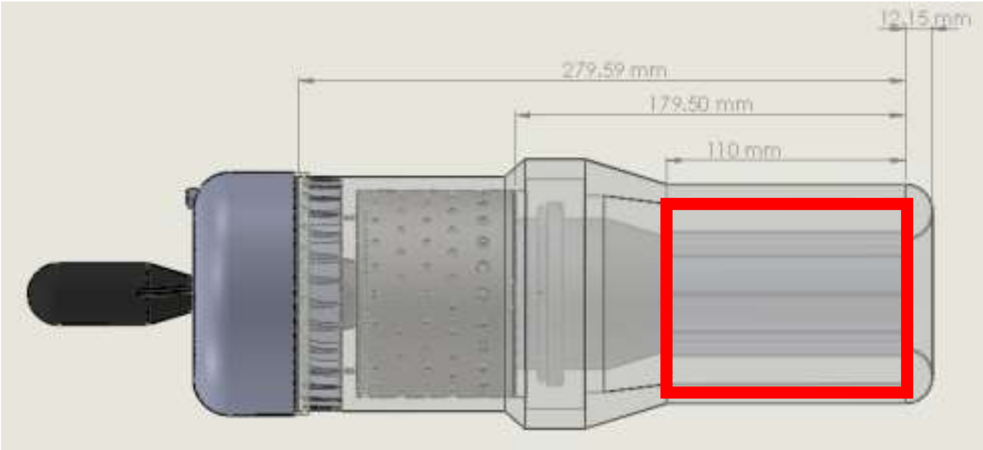
How It works: Cycle Analysis

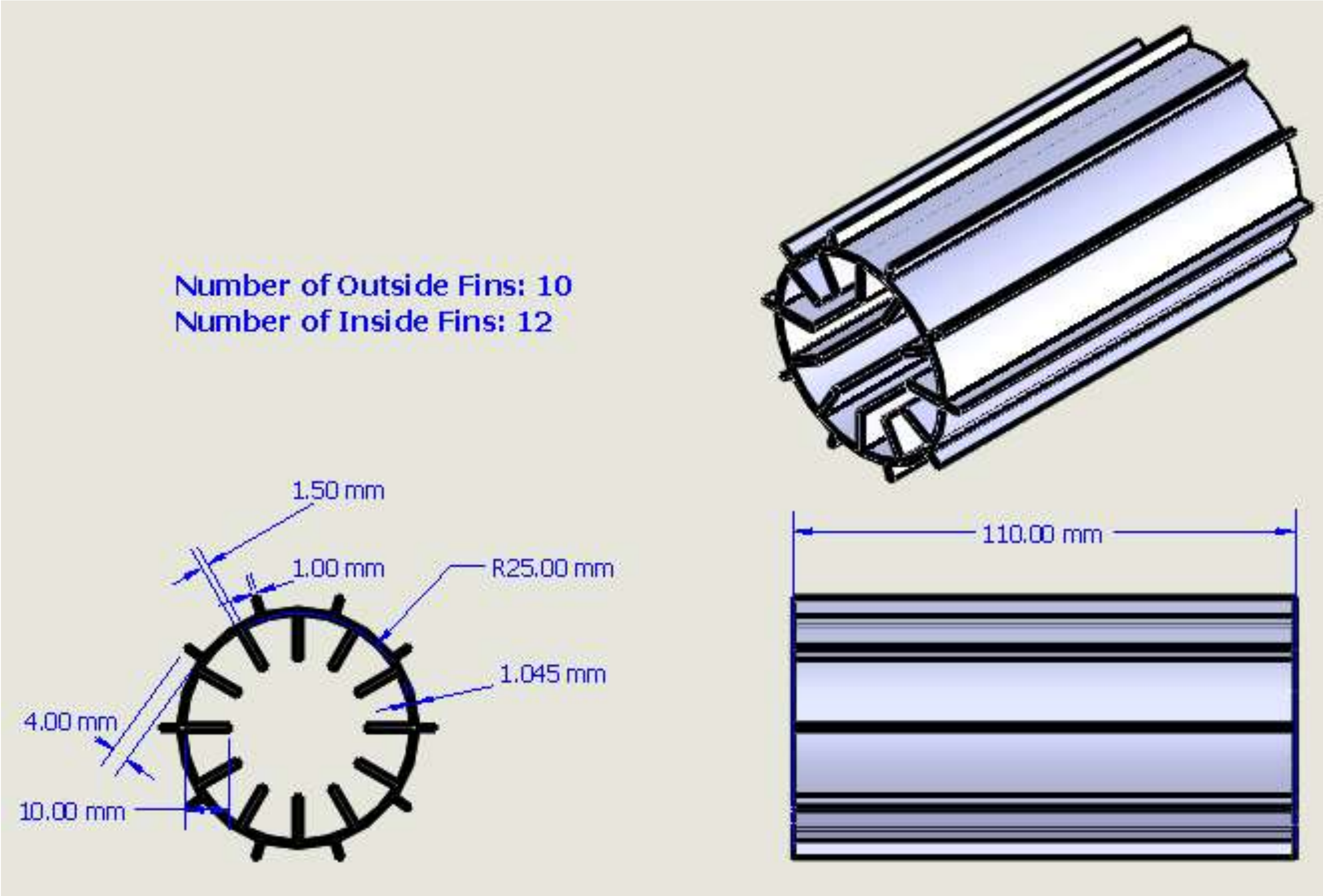




$$\frac{\dot{Q}_{fuel\ burn}}{\dot{m}} = h_{t4} - h_{t3}$$

Nozzle Extension Design





Project Description → Baseline Design → Feasibility Analysis → Project Summary

Nozzle Extension Manufacturability

- Direct Metal Laser Sintering (DMLS)
  - Additive manufacturing technique similar to 3D printing
  - Laser binds sinter powdered material together
- Electro Discharge Machining (EDM)
  - Start with solid metal item
  - Two electrodes discharge current to cut out desired shape
- In-house Machining
  - Clamp and weld method
  - Matt Rhode

	DMLS	EDM	In-House
Price*	$1,666	~$1000	$515
Tolerance	0.007 in (0.178 mm)	0.001 in (0.025 mm)	~0.05 in (1.27 mm)
Lead Time	3-5 days	TBD	1 month

*Including material (Titanium 6-4), no margin

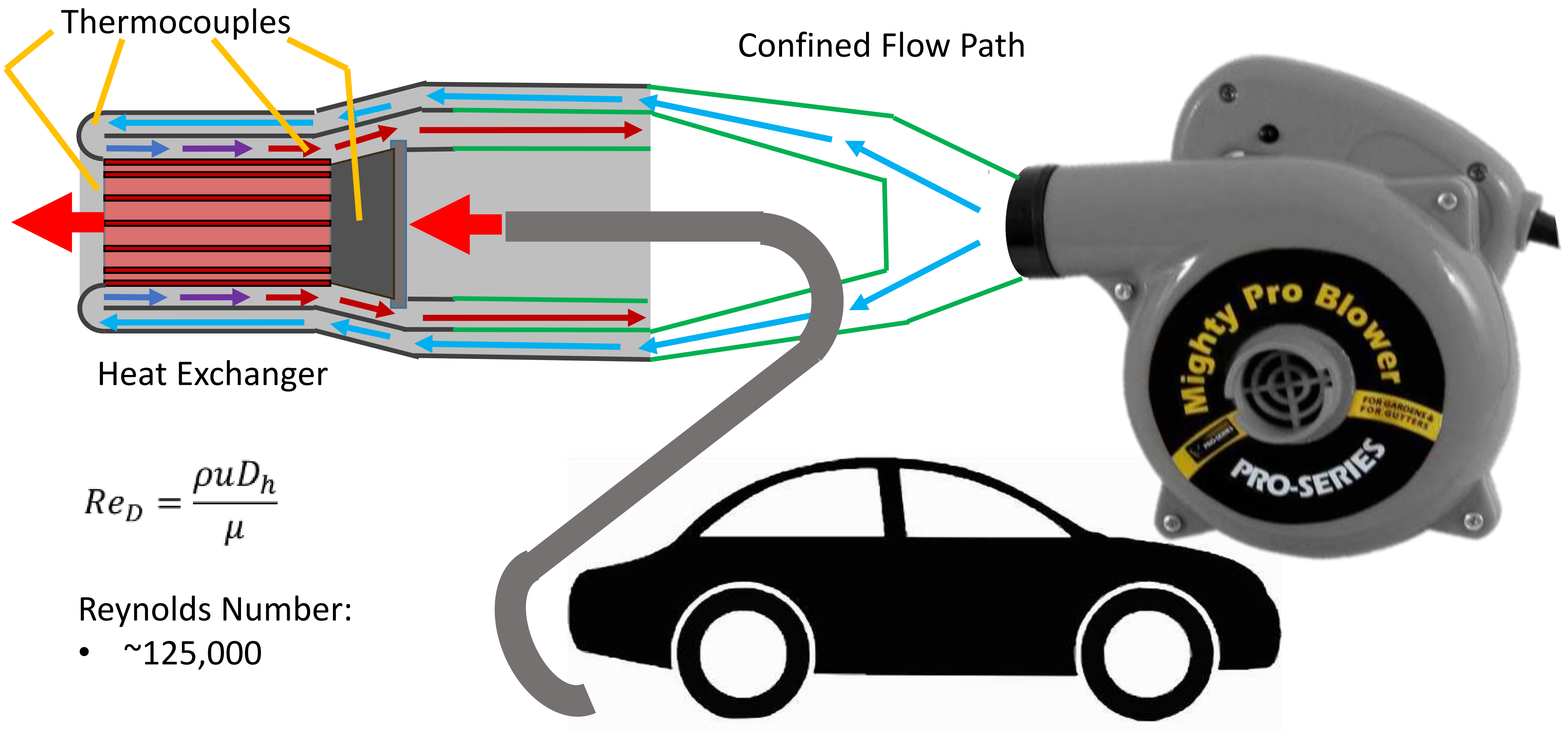
Materials

Data ↓ Metal →	Titanium Alloy (TI 4-6)	Stainless Steel 17-4	Inconel 718
Maximum Temperature (K)	1873	1373	1677
Thermal Conductivity (W/mK)	16.4	16	11.4
Mass (g)	484	849	889
Cost per (3"D x 8"L rod)	$428	$116	$232

Design Verification: Level 1

- Historically, engine has been challenging to run
  - Software is proprietary
  - Any modifications to the engine usually result in engine inoperability
- Testing with Engine Analog
  - Verify heat transfer model
  - Keep additional mass< 50% of stock engine
  - Keep additional volume increase < 100% of stock engine

Engine Analog Level 1



$$Re_D = \frac{\rho u D_h}{\mu}$$

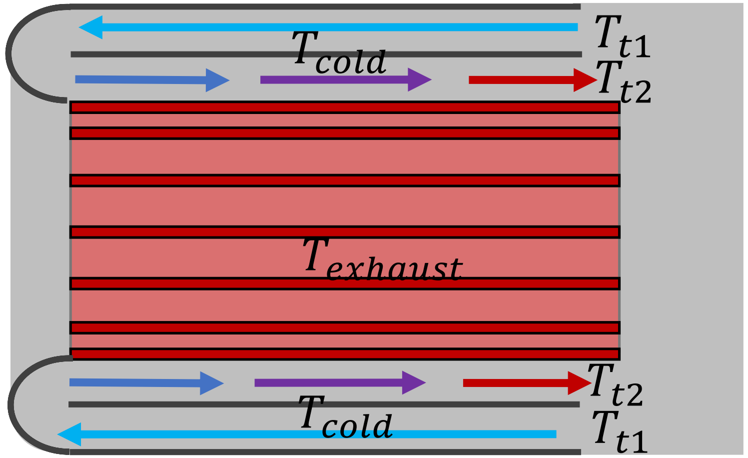
Reynolds Number:
- ~125,000

Engine Analog: Analysis

Requirements

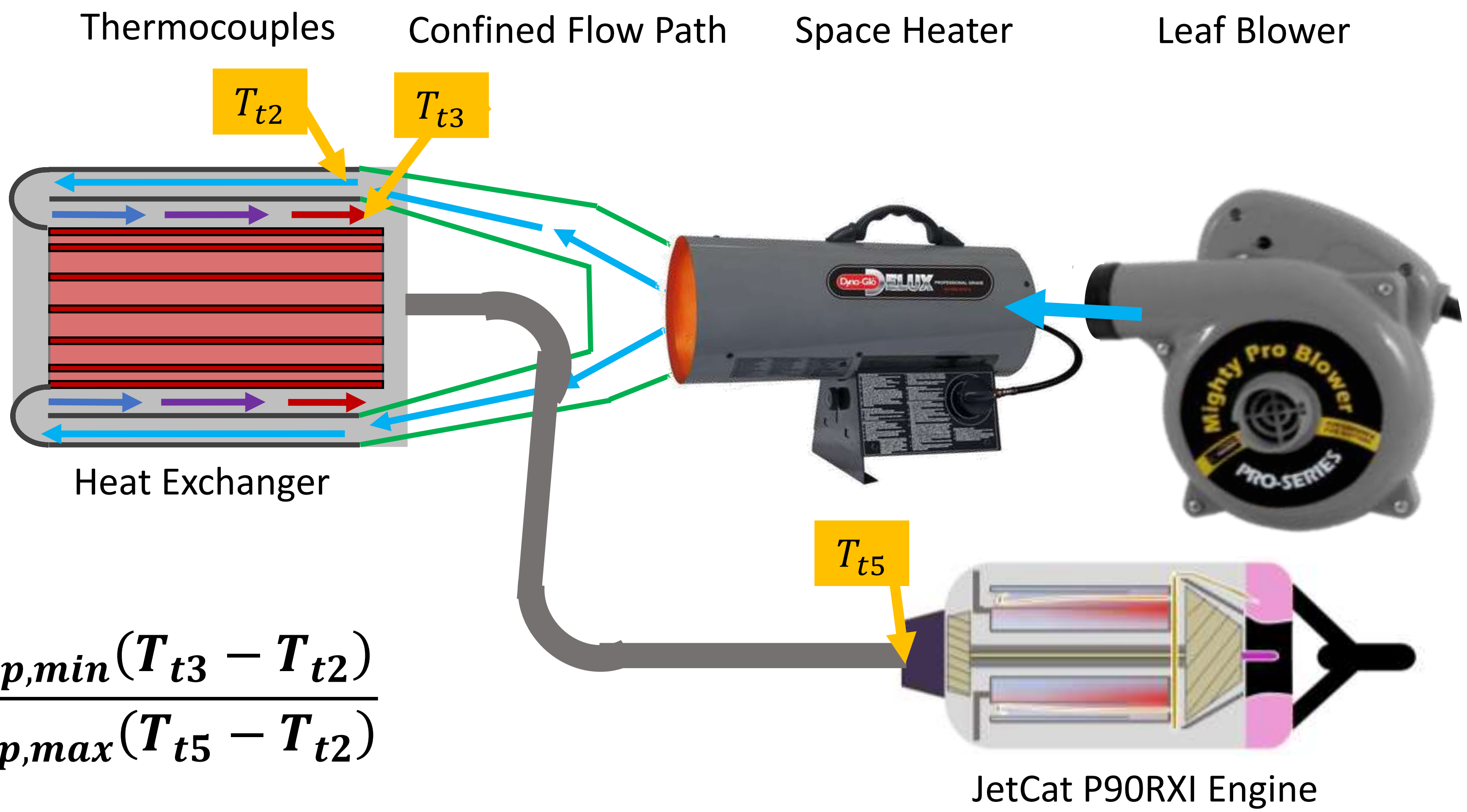
- Fully turbulent flow ($Re \geq 10000$)

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



$$C_p (T_{t2} - T_{t1}) = U_h A_h \left(T_{static,exhaust} - T_{static,cold} \right)$$

Engine Analog Level 2: Off Ramp

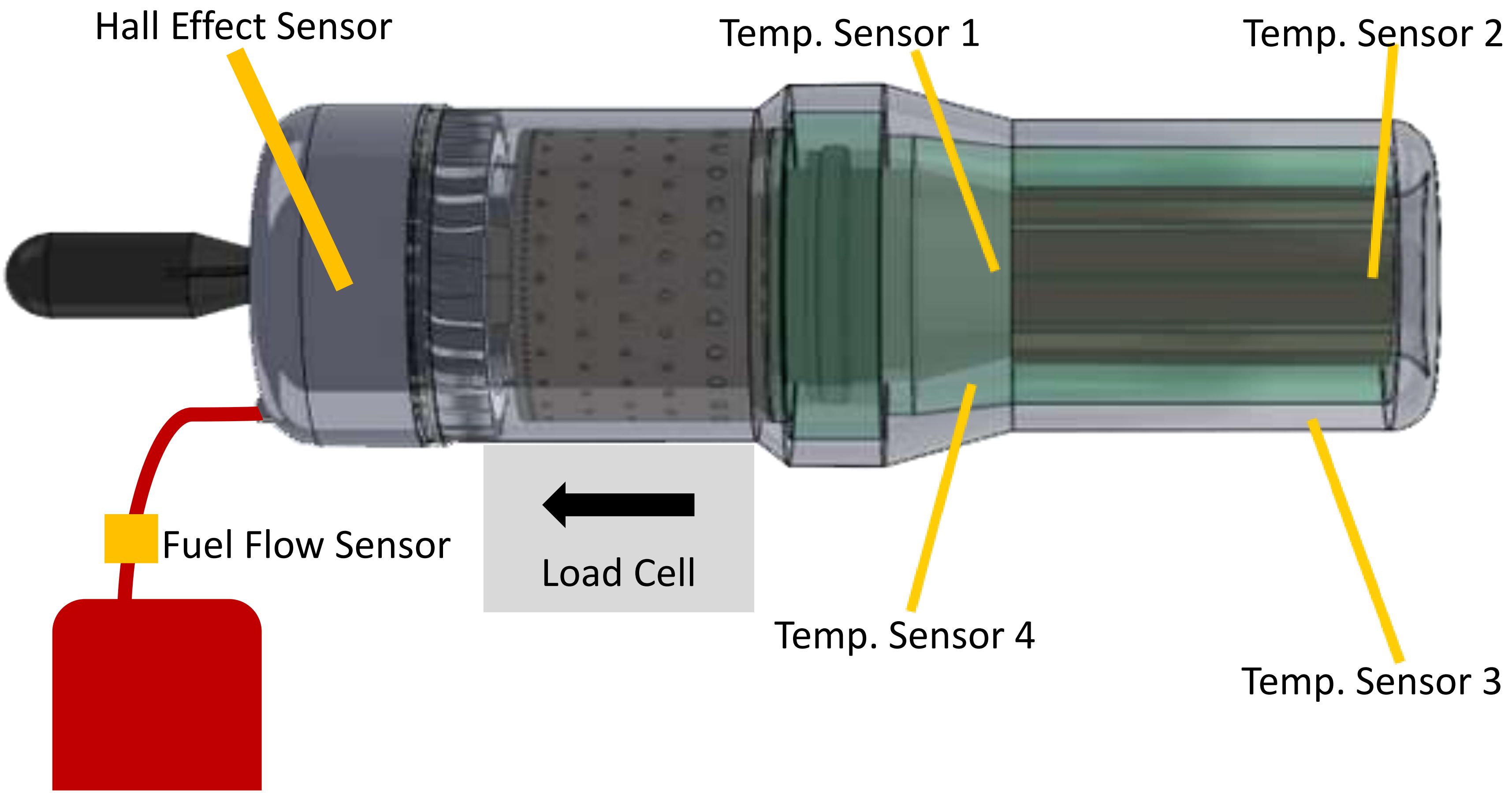


$$\epsilon_X = \frac{C_{p,min}(T_{t3} - T_{t2})}{C_{p,max}(T_{t5} - T_{t2})}$$

Design Verification: Level 3

- Recuperator Integrated with the Engine:
  - Effectiveness >13%
  - Thrust Specific Fuel Consumption Reduction > 10%
  - Thrust Reduction < 10%
  - Runs > 4 minutes
    - 2 minutes at full throttle
  - Engine throttle time from half to full throttle is within 100% of stock throttle response time

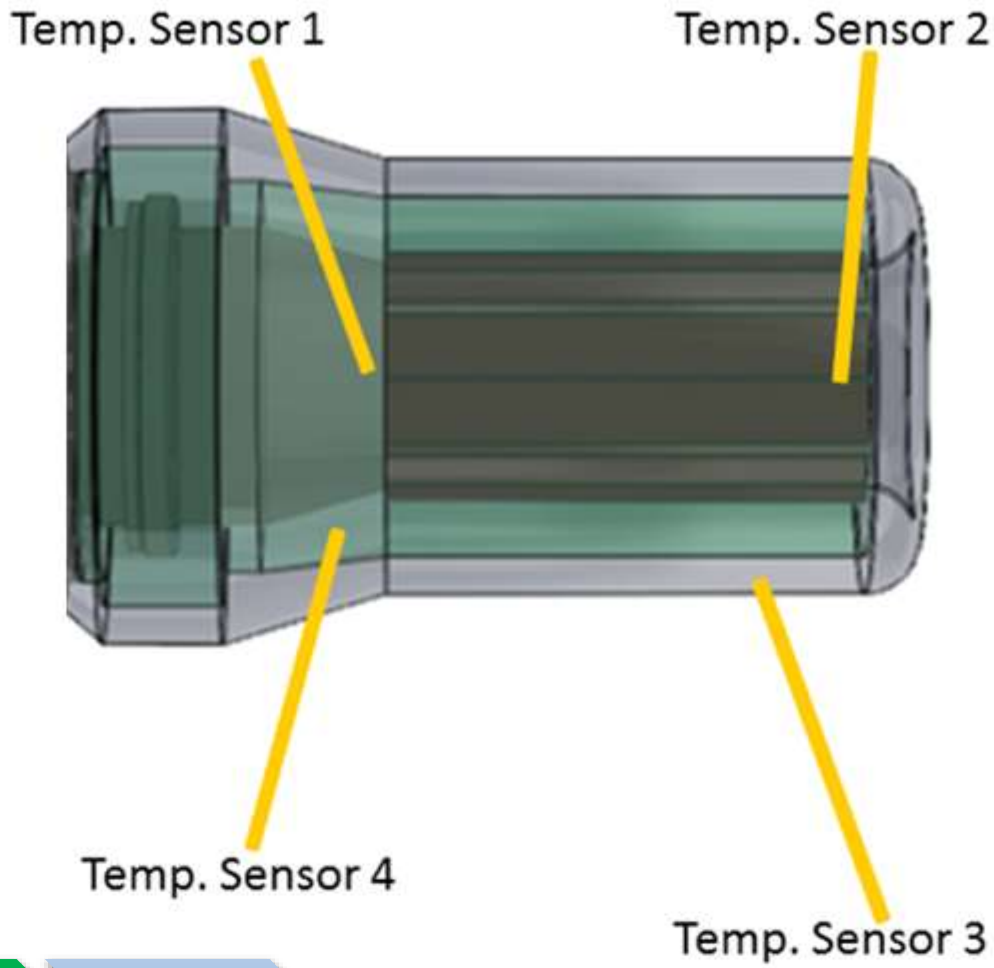
Full System: Test



Electronics

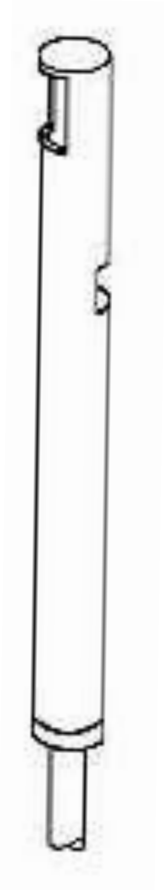
Electronics Verification: Level 1 & 2

- Total and static temperature will be sampled to verify model
- Achieved using an NI DAQ
- Saved to a CSV file
  - Data will then be processed



Total Temperature Probes

- Exhaust Gas (maximum)
  - Velocity: 404 m/s (1325 ft/s)*
  - Temperature: 700 C (1300 F)*
- Heat Exchanger Effectiveness:
  - Total temperature = static temperature + velocity
  - Pitot probe, with temperature
- United Sensor Corp.
  - For use near burners, K type thermocouple



*As specified by JetCat

Data Collection: Level 1 & 2

- National Instruments DAQ Options:
  - NI-9205
    - Available for purchase or rent from the ITLL
    - 16 high fidelity sensing ports 16-bit resolution and 250 kilo-samples/s aggregate sampling rate
  - NI-9263
    - Is available in lab for quick measurements
    - Only 4 inputs
- LabVIEW:
  - Thermocouple: amplified analog input
  - Saved to CSV file
- Without full recuperator integration:
  - Verifies model of recuperator
  - No specific fuel consumption or thrust change

Electronics: Level 3

- Operation of the engine in a modified configuration.
  - Requires custom engine control unit and sensor board to run engine in modified configuration
  - Fuel flow rate sensor, RPM sensor, and load cell
- Requires additional DAQ work to add extra sensors

Custom ESB (Engine Sensor Board)

Electronics: Engine Control Trade Study

- Main Components:
  - Engine Control Unit (ECU)
  - Engine Sensor Board (ESB)
- Options:
  - Stock
  - Custom PCB (Printed Circuit Board) - heritage
  - Programmable ECU
- Main Category: Feasibility
- Limiting Factor: Time & Budget

Stock ECU

Custom PCB ECU

Programmable ECU

Electronics: Engine Control Trade Study

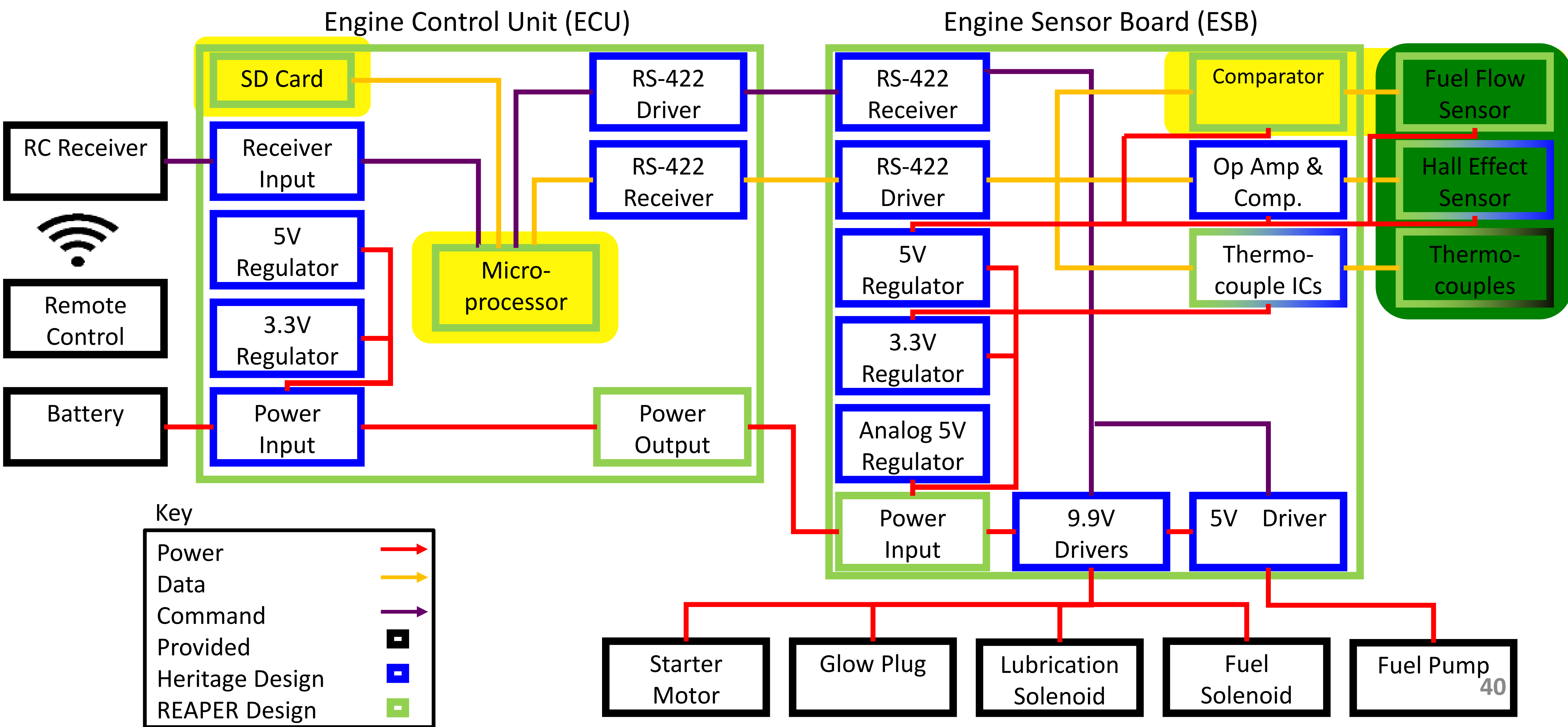
- Will develop custom PCB for ECU and ESB
- Stock ECU/ESB for preliminary testing
  - Provides success up to level 2
  - Without recuperator integration, get only effectiveness (no thrust or specific fuel consumption)
- Not enough time/money to try programmable ECU development

	Weight	Stock	Custom PCB	Programmable
Feasibility	30	-9	3	0
Safety	25	3	0	-3
Development Time	15	3	-3	-3
Data	15	0	3	0
Cost	10	-3	0	-3
Accuracy	5	-3	3	3
Total	**100**	**-1.95**	**1.8**	**-1.35**

Data Collection: Level 3

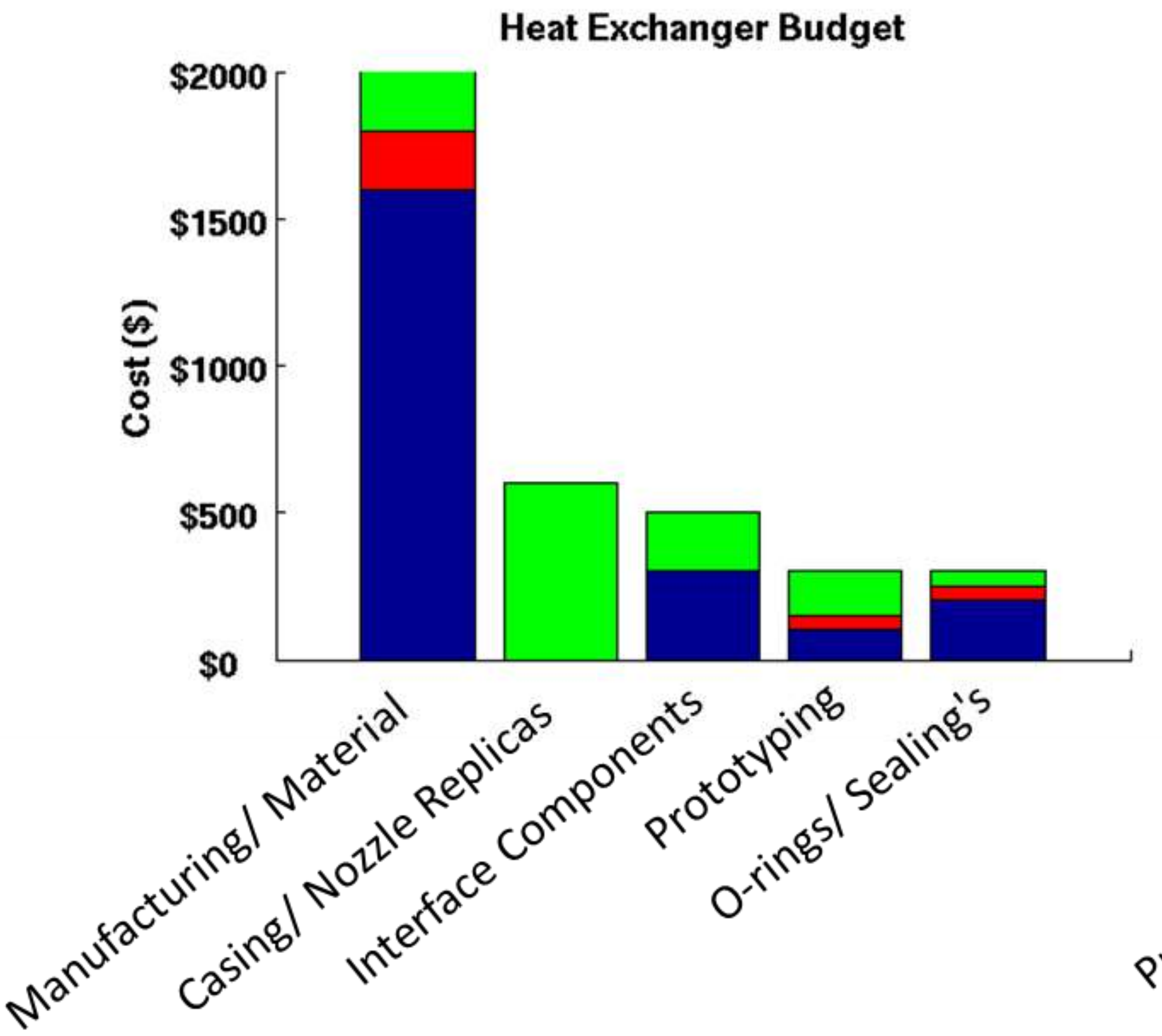
- Recorded through ECU/ESB
  - RPM, fuel flow, and temperature
- Redundantly collected through the NI DAQ
  - Sample rate of 250 KS/s (NI-9205)
- LabVIEW:
  - Thermocouples & Load cell - amplified analog readings
  - Flow sensor & Hall-effect (RPM) - similar to an encoder with pulses per second
- All data is saved to a CSV file

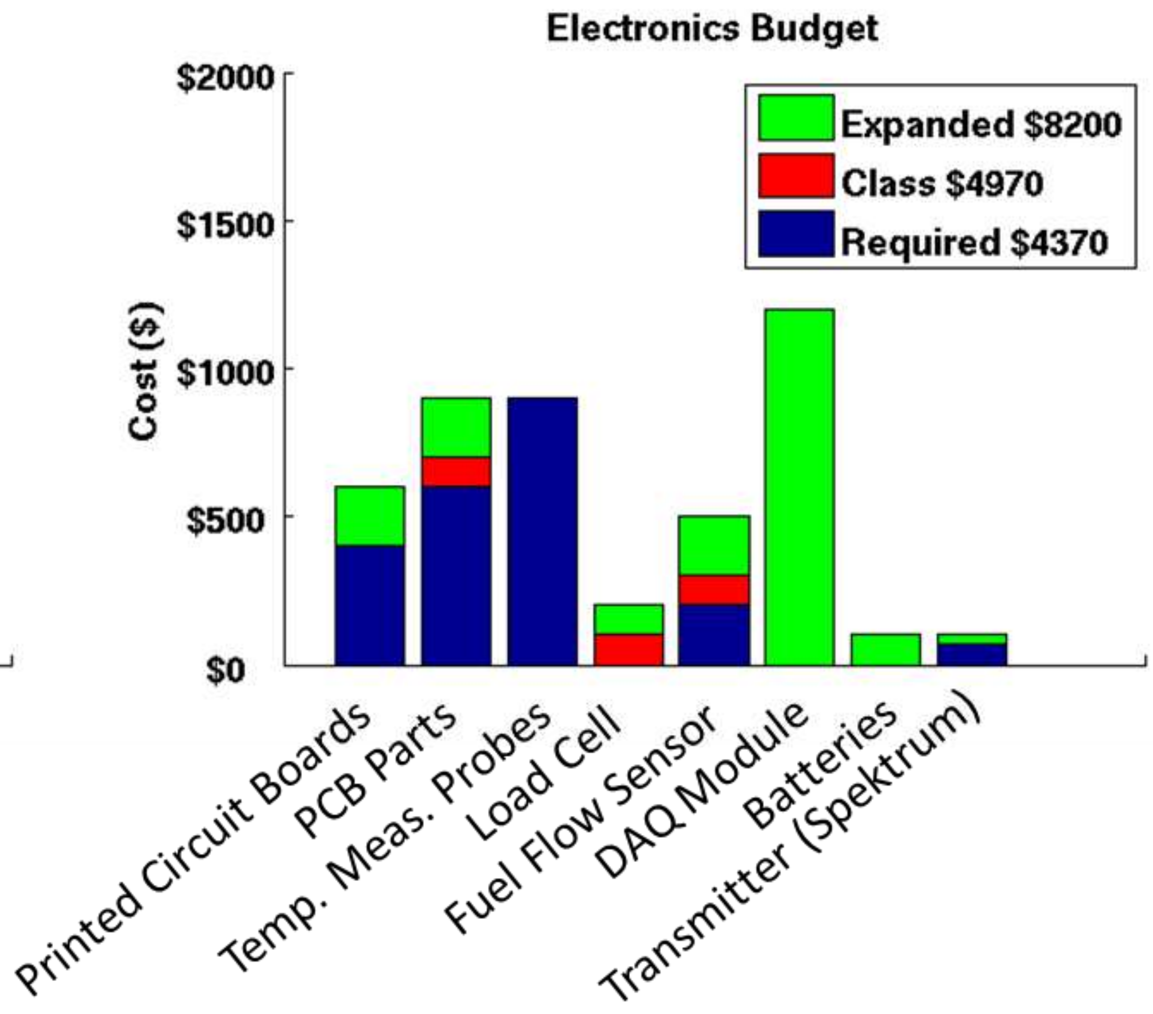
Electronics: Custom PCB Design (FBD)



Project Summary

Budget

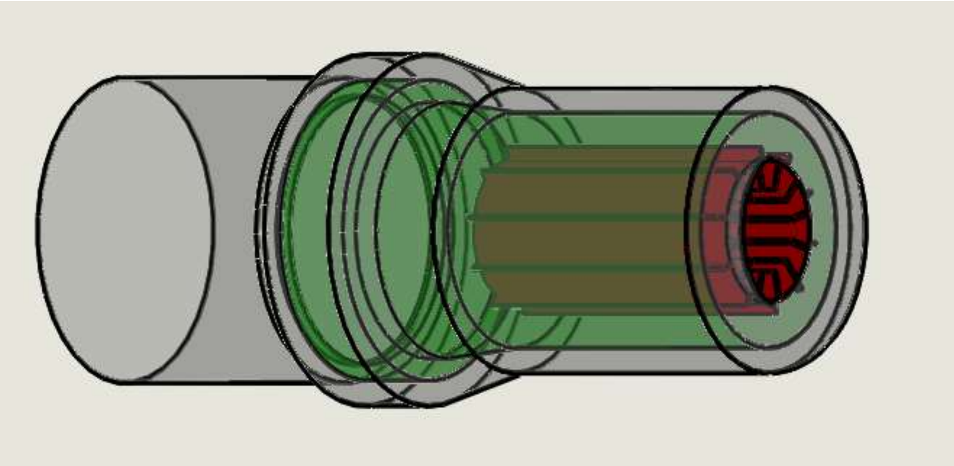


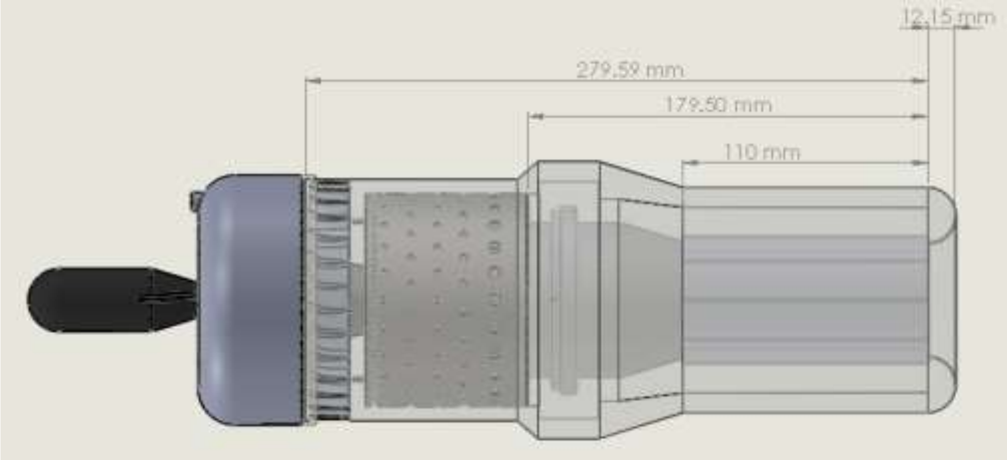


Project Description | Baseline Design | Feasibility Analysis | Project Summary

Feasibility Overview

- Recuperator Design
  - Materials: **FEASIBLE**
    - 3 material options meet heat transfer requirement and temperature limitations
  - Manufacturing: **FEASIBLE**
    - 3 methods beneath lead time and cost maximums
  - Testing: **FEASIBLE**
    - 3 test methods that validate the thermal model and levels of success

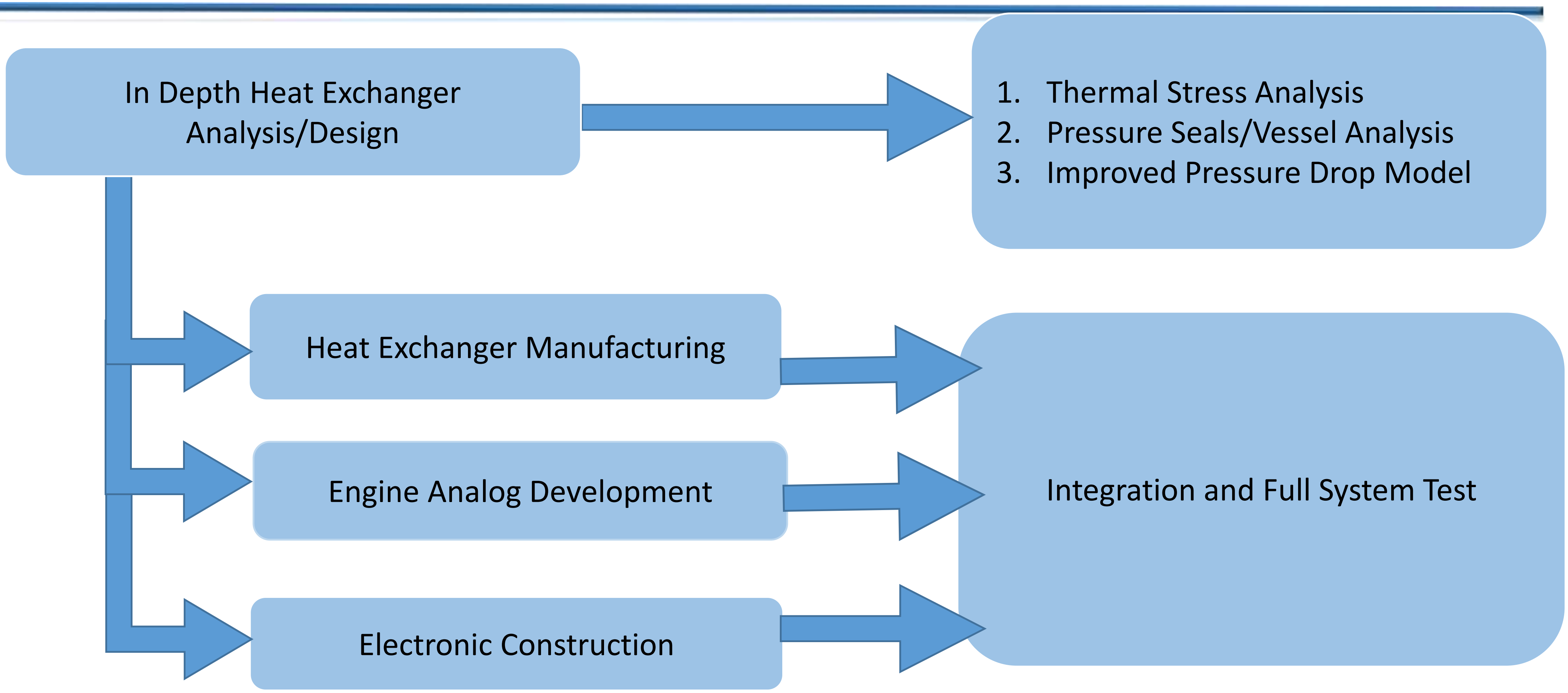




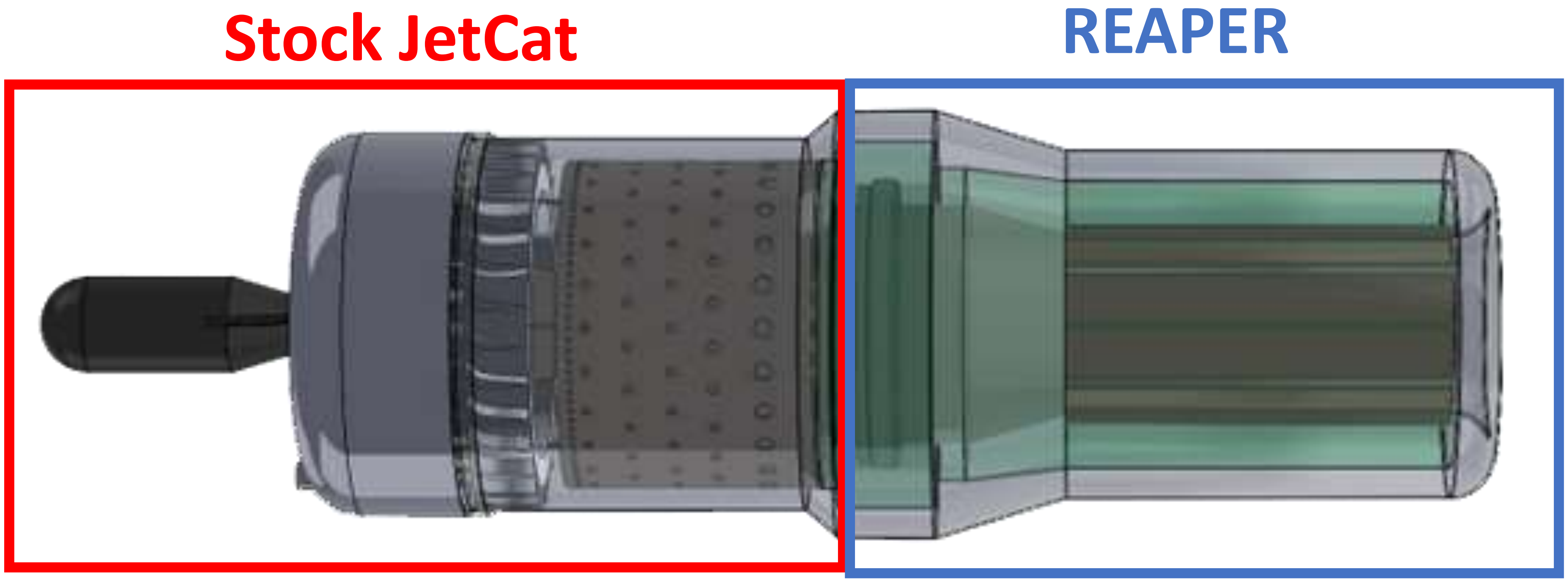
Feasibility Overview

- Electronic Design
  - Components: **FEASIBLE**
    - Sensor and electronic component options are within budget limitations
  - Data Acquisition: **FEASIBLE**
    - DAQ options are within budget limitations
  - PCB Manufacturing: **FEASIBLE**
    - Team experience and in-house resources

Critical Path



Questions?



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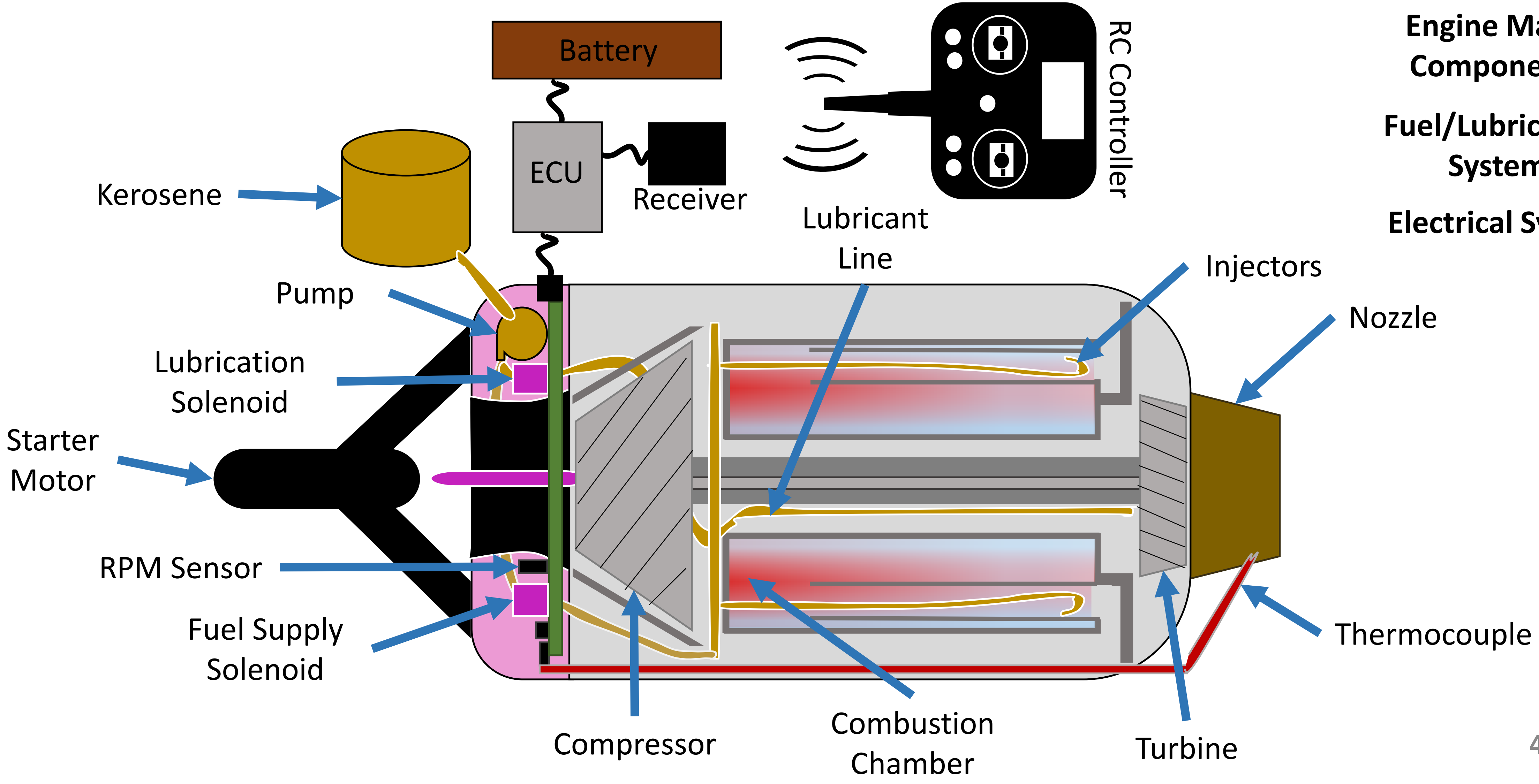
Backup Slides

JetCat P90-RXi Overview



Engine Major Components

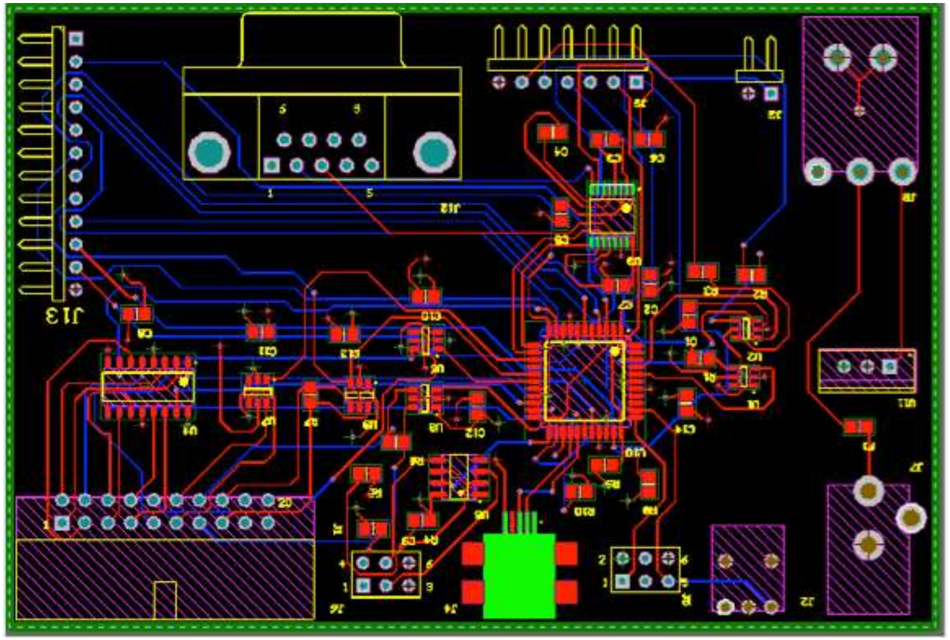
Fuel/Lubrication System

Electrical System

Backup Slides: Electronics

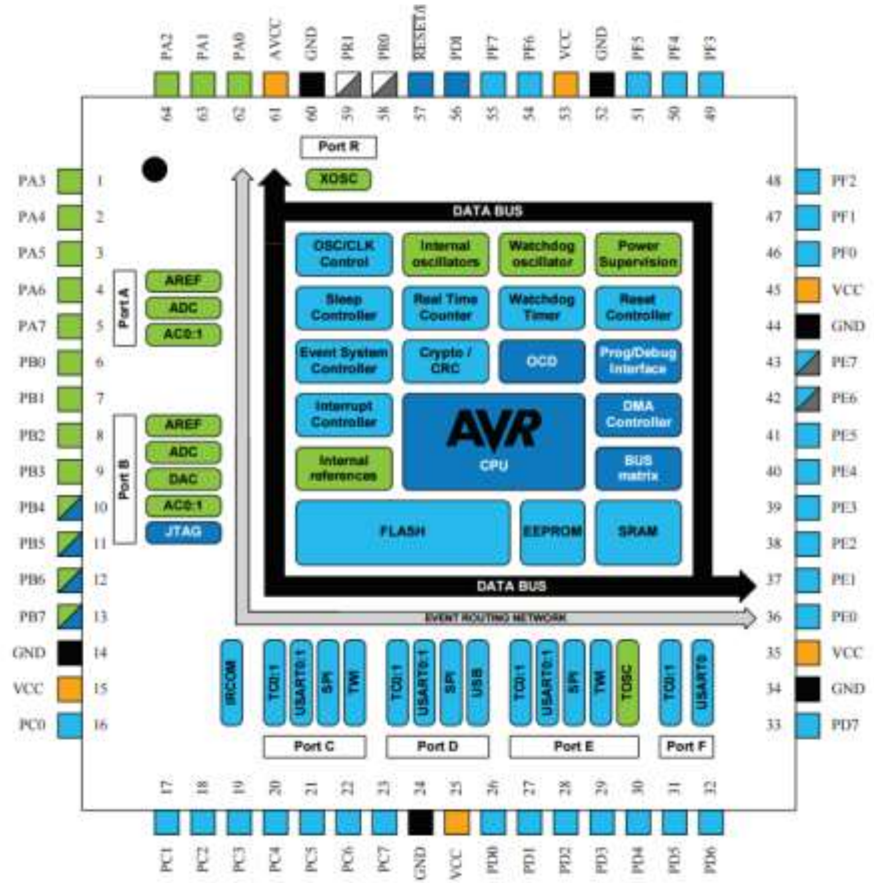
Electronics: Heritage

- MEDUSA printed circuit boards (PCB)
- Manufactured
  - No full system integration test
- Component Selection



Critical Component: Processor

- Atxmega128a3u
  - 64 pins - 50 IO
    - Need over 34
    - Correct number of communication Busses
    - Sufficient program memory and RAM
  - 32 MHz Clock Speed
    - External or Internal
  - Easily Available
    - ~$8.00 –Digikey
    - Large quantity in stock



Critical Component: Fuel Flow Sensor

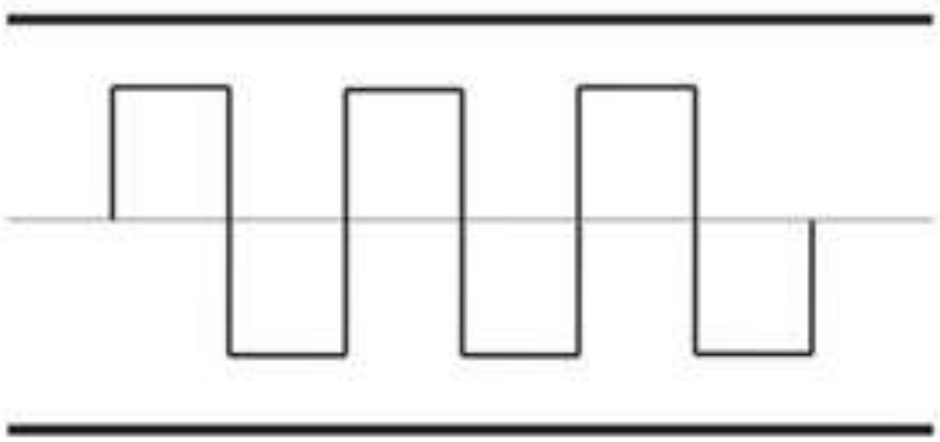
- Equflow 0045
- Disposable insert (~$50)
- Flow Rate 0.1-2L/min with 110,000 pulses/L
  - Engine fuel flow rate: 0.370 L/min
  - Accurate to 1% of reading (±0.0001 L/min)
  - Predicted 580±5 pulses/s
- 34mA current at 5V

Disposable PFA flow meter

Project Description | Baseline Design | Feasibility Analysis | Project Summary

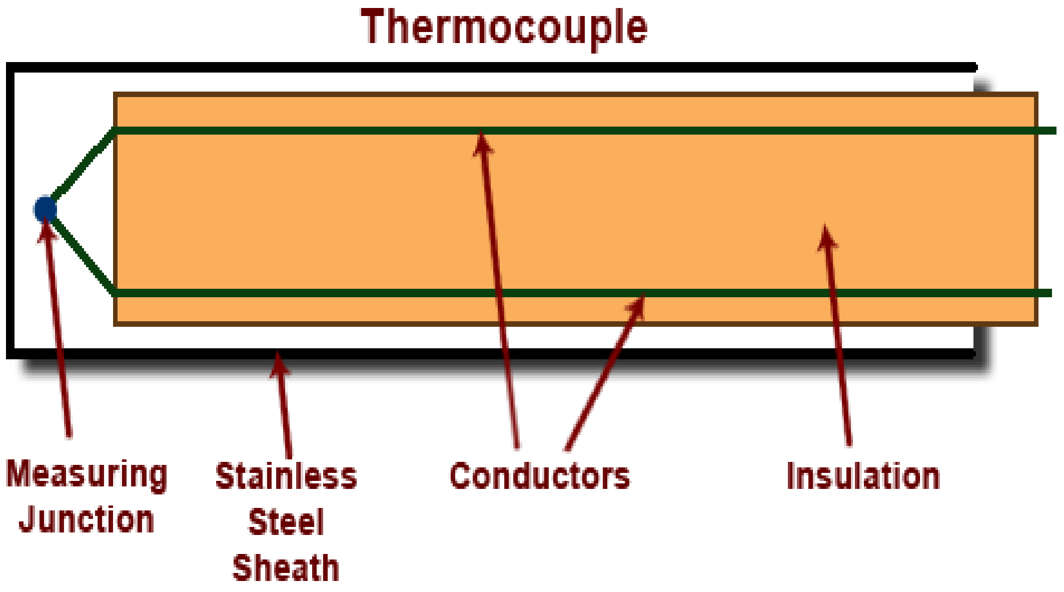
Critical Component: Hall-Effect and Comparator

- Used to calculate RPM
  - Reads magnetic changes
  - Must be sent through comparator circuit
- Cheap and Available
  - Thousand of different options
  - Under $10.00
- Circuit will be interrupt driven

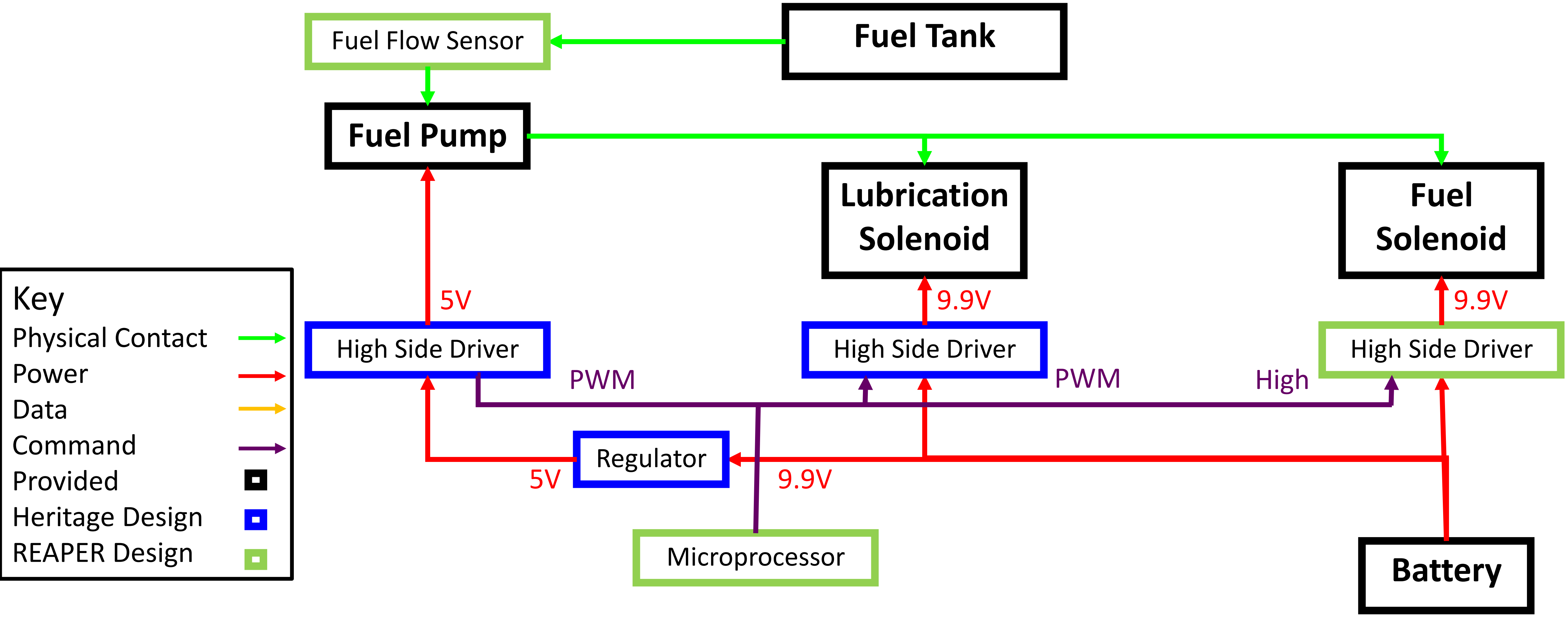


Thermocouple Sampling Rate

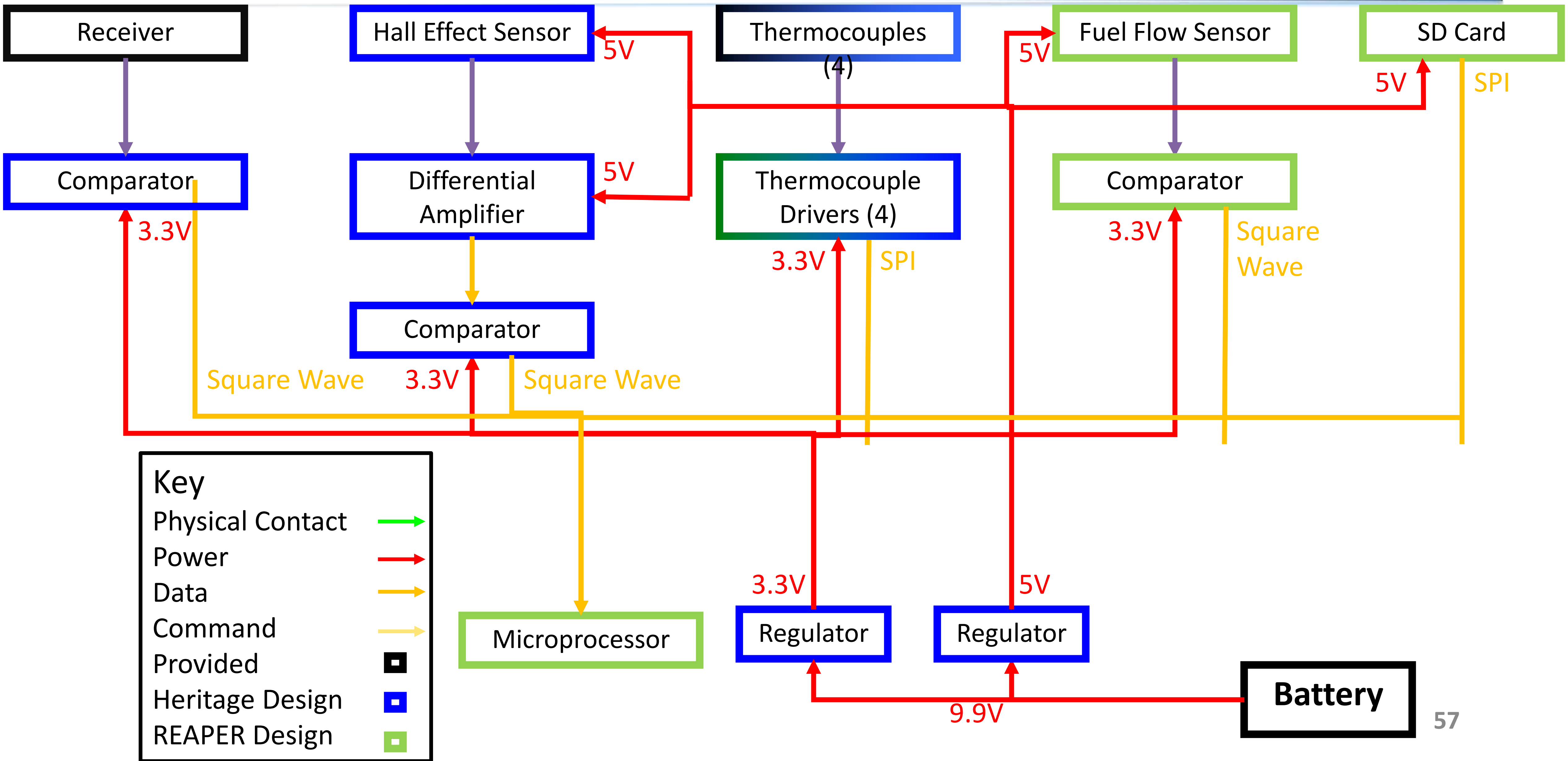
- K type Thermos couple
  - SPI interface
  - Engine temperature range
  - 0 – 700 ˚C
  - ±2˚C Accuracy
  - Maximum rate of change = 113.7 ˚C /s
  - ±3˚C Maximum Tolerance
    - Minimum sample rate 113.7 Hz



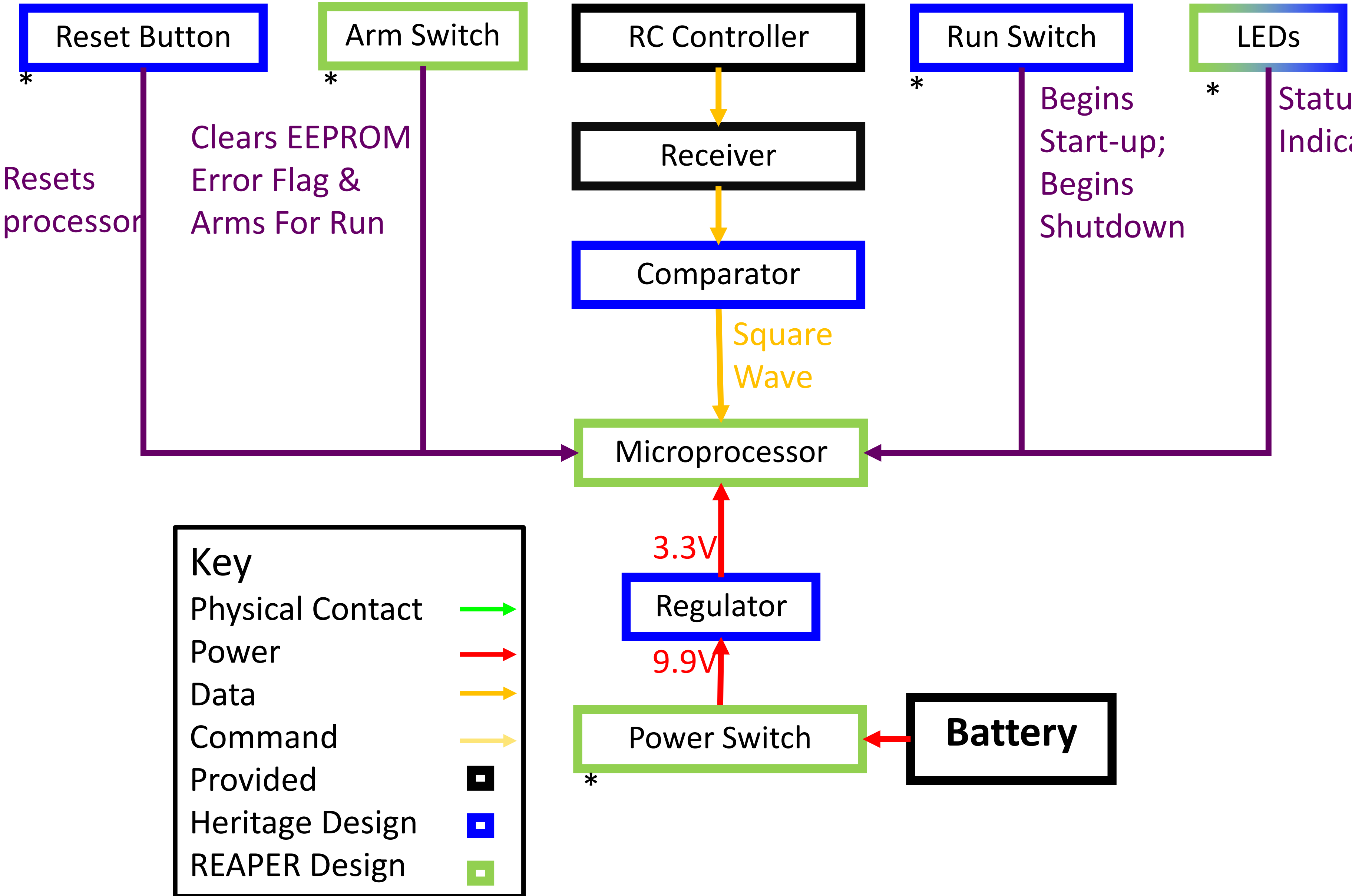
Fuel Delivery & Lubrication FBD



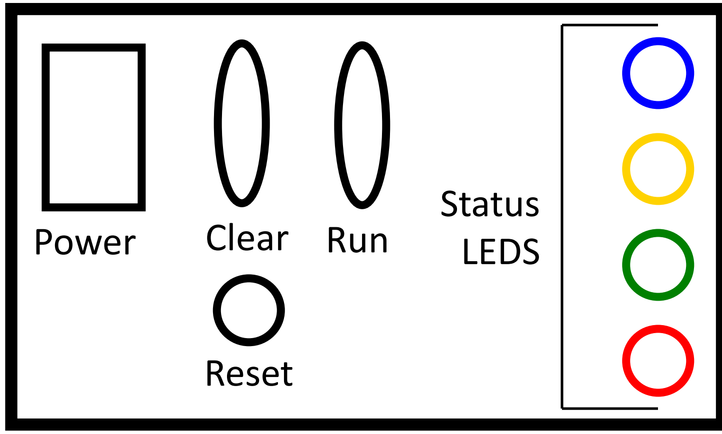
Electronics Sensors FBD



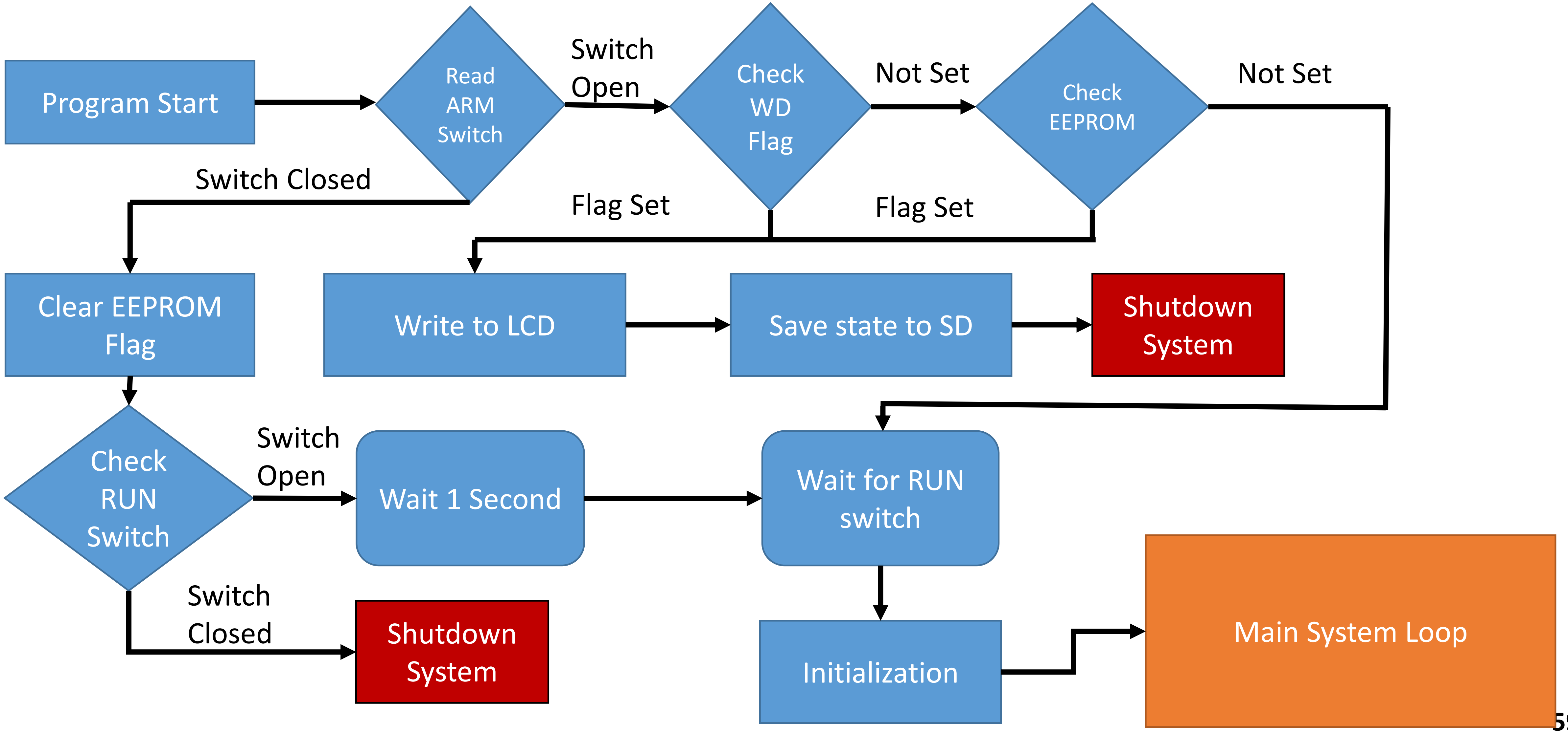
User Control Inputs FBD



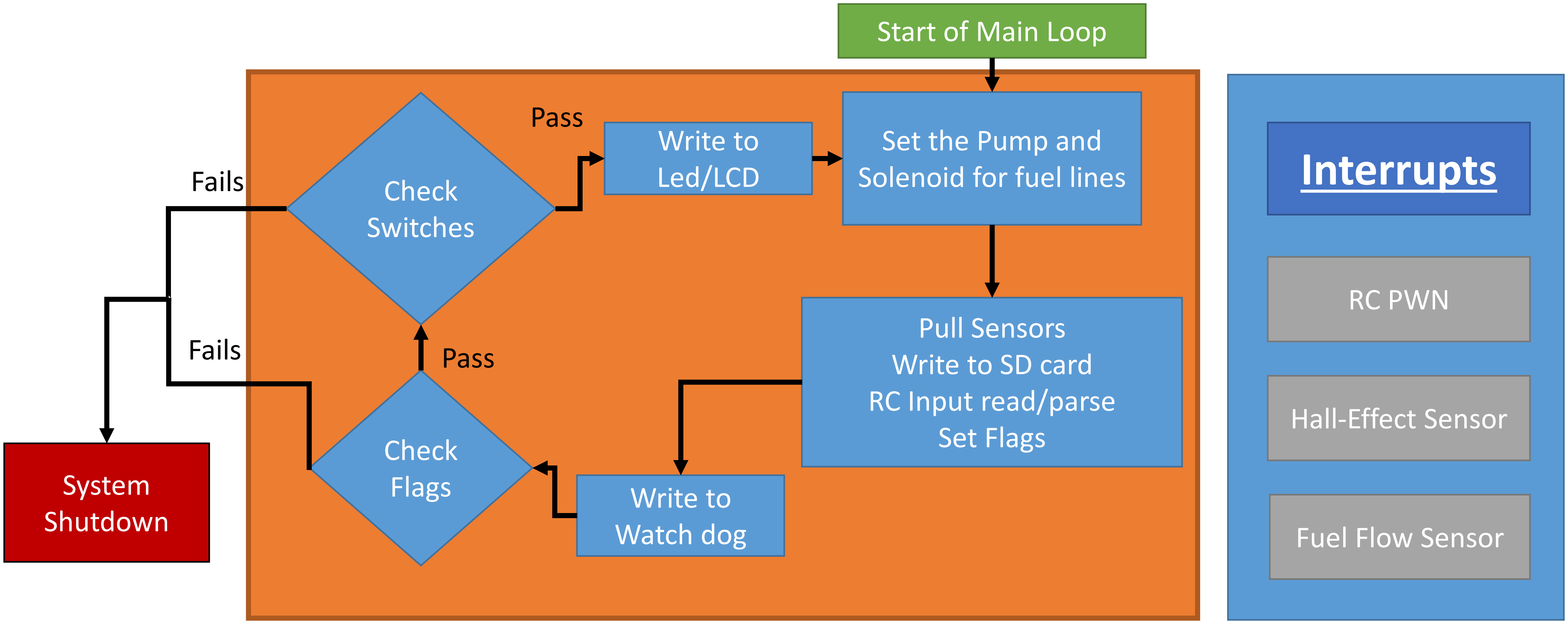
* Indicates Component is located on control panel:



Critical Component: Software Startup/Safety

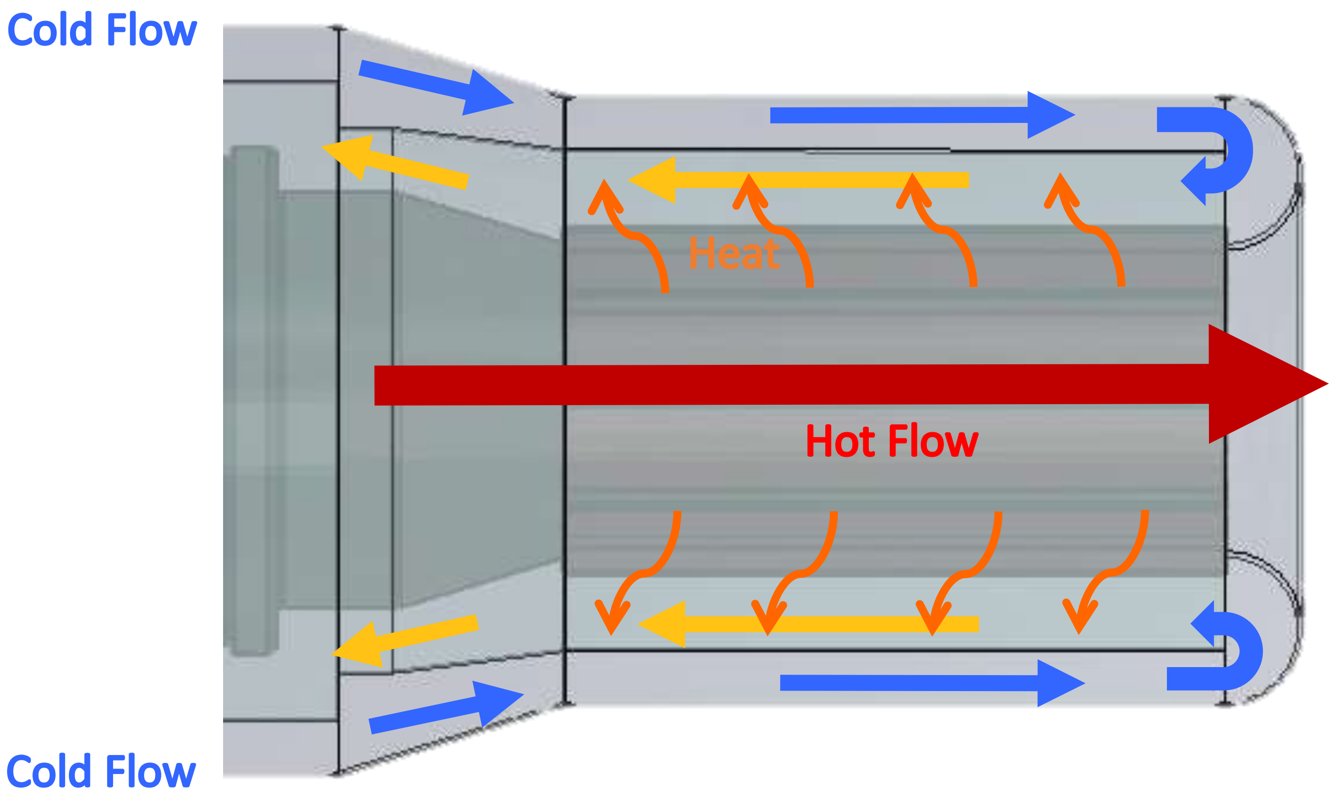


Critical Component: Software Main Loop



Backup Slides: Recuperator

Recuperator ConOps



Engine Testing

- Attended Graduate Engine Test (9/16):
  - Learned general test procedures
- REAPER Test (10/6)
  - Created own test procedures and cleaned up test environment
  - At test trouble shot errors: Thermocouple detached and ‘Wrong Pump’
  - Working with JetCat on ‘No Fuel’ error

Cycle Analysis: Methodology

1. Use JetCat manufacturer specifications and work from previous years to calculate engine component efficiencies

$\eta_b = 0.95$ $\quad P_{\mathrm{loss}} = 0.065$ $\quad \eta_{\mathrm{t}} = 0.82$ $\quad \eta_{\mathrm{n}} = 0.92$

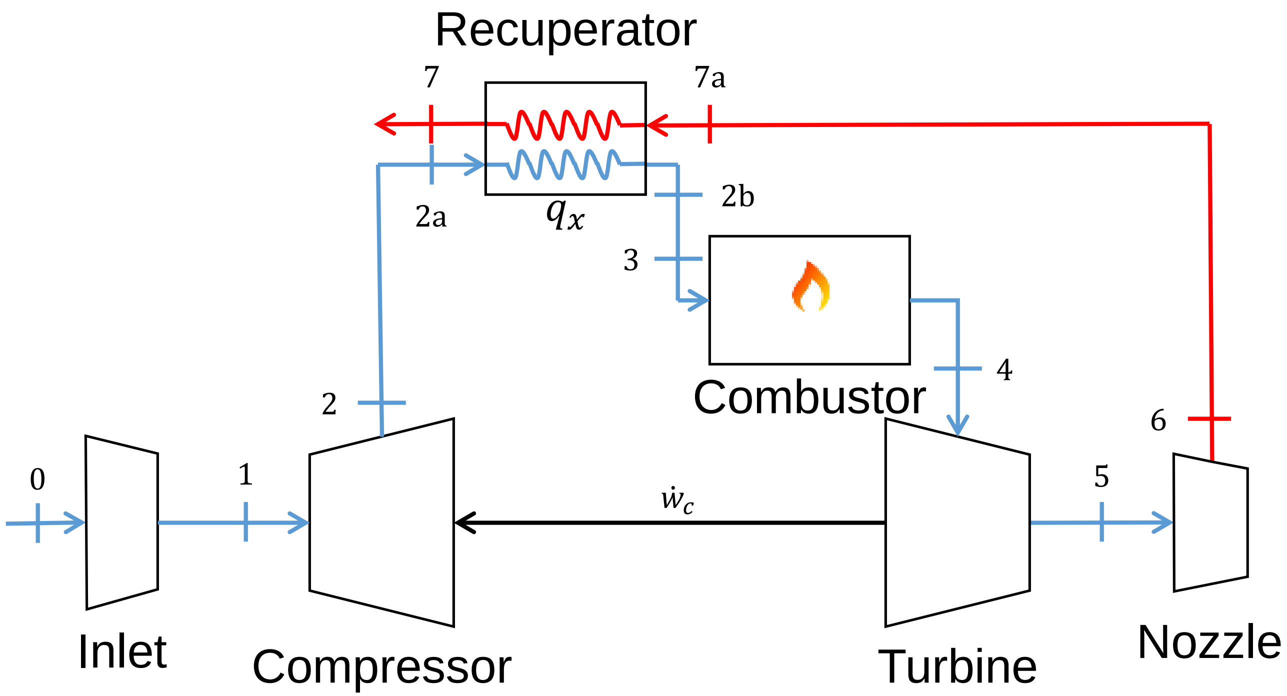
2. Calculate stock engine performance using efficiencies

$F_{\mathrm{n}} = 105\ \mathrm{N}$ $\quad \mathrm{TSFC} = 4.46 \times 10^{-4}\ s^{-1}$ $\quad V_{\mathrm{exit}} = 403\ \mathrm{m}/s$ $\quad T_{\mathrm{t4}} = 1079\ \mathrm{K}$

3. Calculate REAPER engine performance using efficiencies and same turbine inlet total temperature

$F_{\mathrm{n}} = 101\ \mathrm{N}$ $\quad \mathrm{TSFC} = 4.05 \times 10^{-4}\ s^{-1}$ $\quad V_{\mathrm{exit}} = 382\ \mathrm{m}/s$ $\quad T_{\mathrm{t4}} = 1079\ \mathrm{K}$

Cycle Analysis: Equations



[illegible]

$$T_6 = T_{t6} - \frac{V_6^2}{2C_p}$$

$$M_6 = \frac{V_6}{\sqrt{\gamma R T_6}}$$

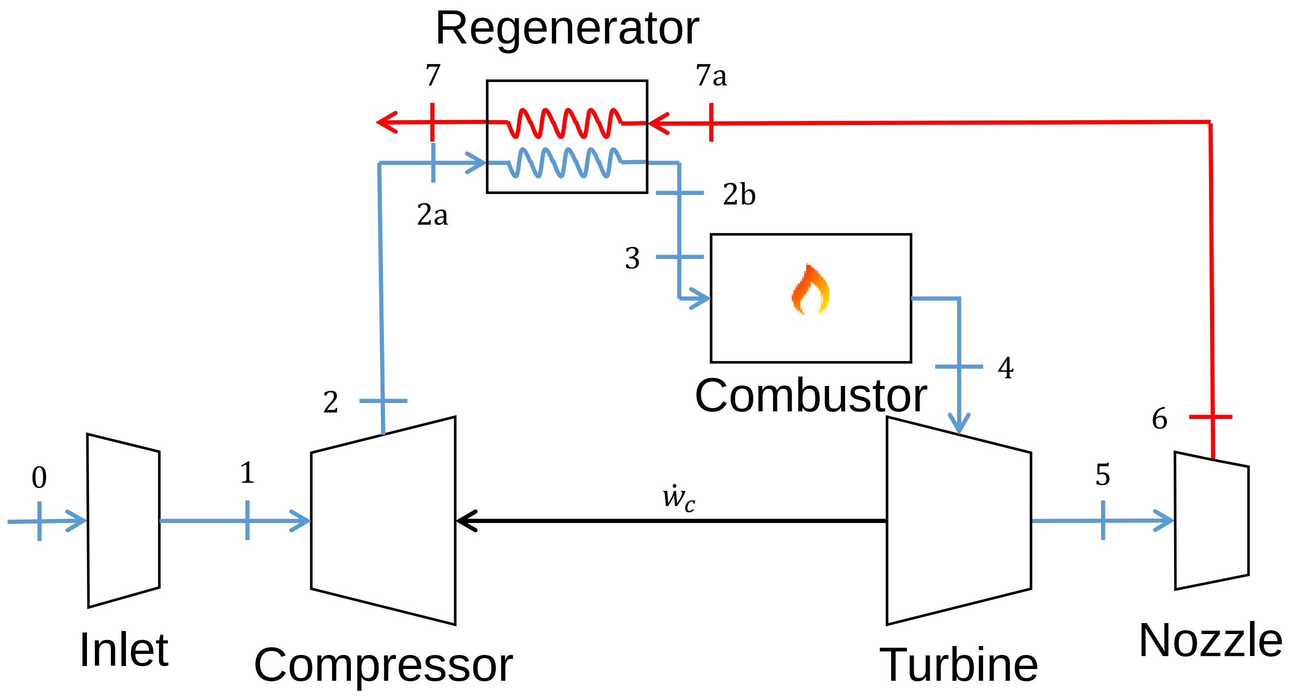
$$F_n = \dot{m}_0\left(1 + \frac{f}{a}\right)(V_{exit} - V_0) + A_{exit}(P_{exit} - P_0)$$

$$P_6 = P_{t5}\left(\frac{\eta_n - 1 + \left(1 + \frac{\gamma - 1}{2}M_6^2\right)^{-1}}{\eta_n}\right)^{\frac{\gamma}{\gamma-1}}$$

$$TSFC = \frac{g\dot{m}_0\frac{f}{a}}{F_n}$$

Cycle Analysis: Results

Measurement	Stock Engine	Modified Engine
$T_{t0} = T_{t1}$	101.3 kPa	101.3 kPa
$P_{t0} = P_{t1}$	288 K	288 K
T_{t2}	402.8 K	402.8 K
P_{t2}	263.4 kPa	263.4 kPa
T_{t3}	488.9 K	402.8 K
P_{t3}	263.2 kPa	263.4 kPa
T_{t4}	1079 K	1079 K
P_{t4}	139.0 kPa	139.3 kPa
T_{t5}	962.7 K	963.0 K
P_{t5}	139.0 kPa	139.3 kPa
T_{t6}	962.7 K	963.0 K
P_{t6}	135.2 kPa	135.5 kPa
T_{t7}	891.2 K	N/A
P_{t7}	135.0 kPa	N/A
V_{exit}	381.6 m/s	403.0 m/s
Fuel:Air Ratio	0.0183	0.0160



Heat Exchanger Sizing: Ideal Cycle Analysis

$$\epsilon_x = \frac{h_{o,3} - h_{o,2}}{h_{o,5} - h_{o,2}}$$

$$h_{o,3} = h_{o,2} + \epsilon_x(h_{o,5} - h_{o,2})$$

$$h_{o,5} = c_p \times T_{o,5}$$

$$h_{o,2} = c_p \times T_{o,2}$$

$$\dot{Q}_x = \dot{m}_0(h_{o,3} - h_{o,2})$$

$$\dot{Q}_x = \dot{m}_0\left(\epsilon_x(h_{o,5} - h_{o,2})\right)$$

Heat transfer needed

$$\dot{Q}_x = 22500\ W$$

Nomenclature

ϵ_x = effectiveness
h_o = total enthalpy
$\dot{Q}_x$= heat transfer rate
$\dot{m}$= mass flow rate
T_o = total temperature
c_p = constant pressure specific heat

Assumptions

1. c_p is constant
2. Ideal cycle
3. Isentropic

Data

$T_{o,2} = 318K$
$T_{o,5} = 973K$
$\dot{m}_0 = 0.26\ kg/s$

Heat Exchanger - Heat Transfer Model

$$Nu_{wall} = 0.027Re_D^{4/5}Pr^{1/3}\left(\frac{\mu}{\mu_s}\right)^{0.14}$$

$$Re_D = \frac{\rho u D_h}{\mu}$$

$$Nu_{fin} = 0.0296Re_L^{4/5}Pr^{1/3}$$

$$Re_l = \frac{\rho u l}{\mu}$$

$$N_{tu} = \frac{U_c A_c}{c_p \dot{m}}$$

$$\frac{1}{U_c} = \frac{1}{\eta_{o,c}h_c} + \frac{t_w}{{A_w}/{A_c}\,\kappa_w} + \frac{1}{\eta_{o,h}\,{A_h}/{A_c}\,h_h}$$

$$\mathcal{E} = \frac{1}{1 + N_{tu}}$$

$$\eta_o = 1 - \frac{A_f}{A_w}(1 - \eta_f)$$

$$m = \sqrt{\frac{2h}{\kappa_f \delta}}$$

$$\eta_f = \frac{tanh(m\ell)}{m\ell}$$

$$A_c = A_w + n_{f,c}A_{c,f}$$

Nomenclature

Nu= Nusselt Number

Re = Reynolds number

μ = dynamic velocity

u = velocity

$\dot{m}$ = mass flow rate

D = Hydraulic diameter

L= Fin length

c_p = constant pressure specific heat

η_0 = area efficiency

η_f = fin efficiency

ℓ = fin height

Assumptions

1. c_p is constant

2. Velocity is constant

3. Use film temperature

4. Turbulent flow ($Re \geq 10000$)

Heat Exchanger: Sizing Results

	Cold Side	Hot Side
Convective Heat Transfer Coefficient $\left[\frac{W}{m^2 K}\right]$	548	528
Area $[m^2]$	0.149	0.151
Area Effectiveness	0.99	0.97

$$U_{overall} = 263.4\ \frac{W}{m^2 K}$$

Heat Exchanger: Pressure Drop

Flow	Pressure Drop from Wall [Pa]	Pressure Drop from Fins [Pa]	Total Pressure Drop [Pa]
Internal	167	63	230
External	146	110	256

Colebrook formula

$$\frac{1}{\sqrt{f}} = -2.0 log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re_D\sqrt{f}}\right)$$

1/7th Power Law

$$C_f = 0.0725 Re_L^{1/5}$$

Frictional Losses: Wall

$$\Delta P = \rho f \frac{\ell}{D}\frac{V^2}{2}$$

Frictional Losses: Fins

$$\Delta P = n_{fin} C_f A_{exposed} \rho \frac{V^2}{2}$$

Nomenclature

f= Wall friction factor
ε = Wall roughness
D = Hydraulic diameter
ℓ = effective length
V = Flow velocity
ρ = Fluid density
Re_D = Reynold's number in a pipe
Re_L = Reynold's number on a flat surface
C_f = Skin friction coefficient for a flat plate

Assumptions

1. Velocity is constant
2. Use film temperature
3. Turbulent flow ($Re \geq 10000$)

Engine Analog: Components

Portable Heater[16]

- Available from Home Depot ($100)
- Three levels of heat

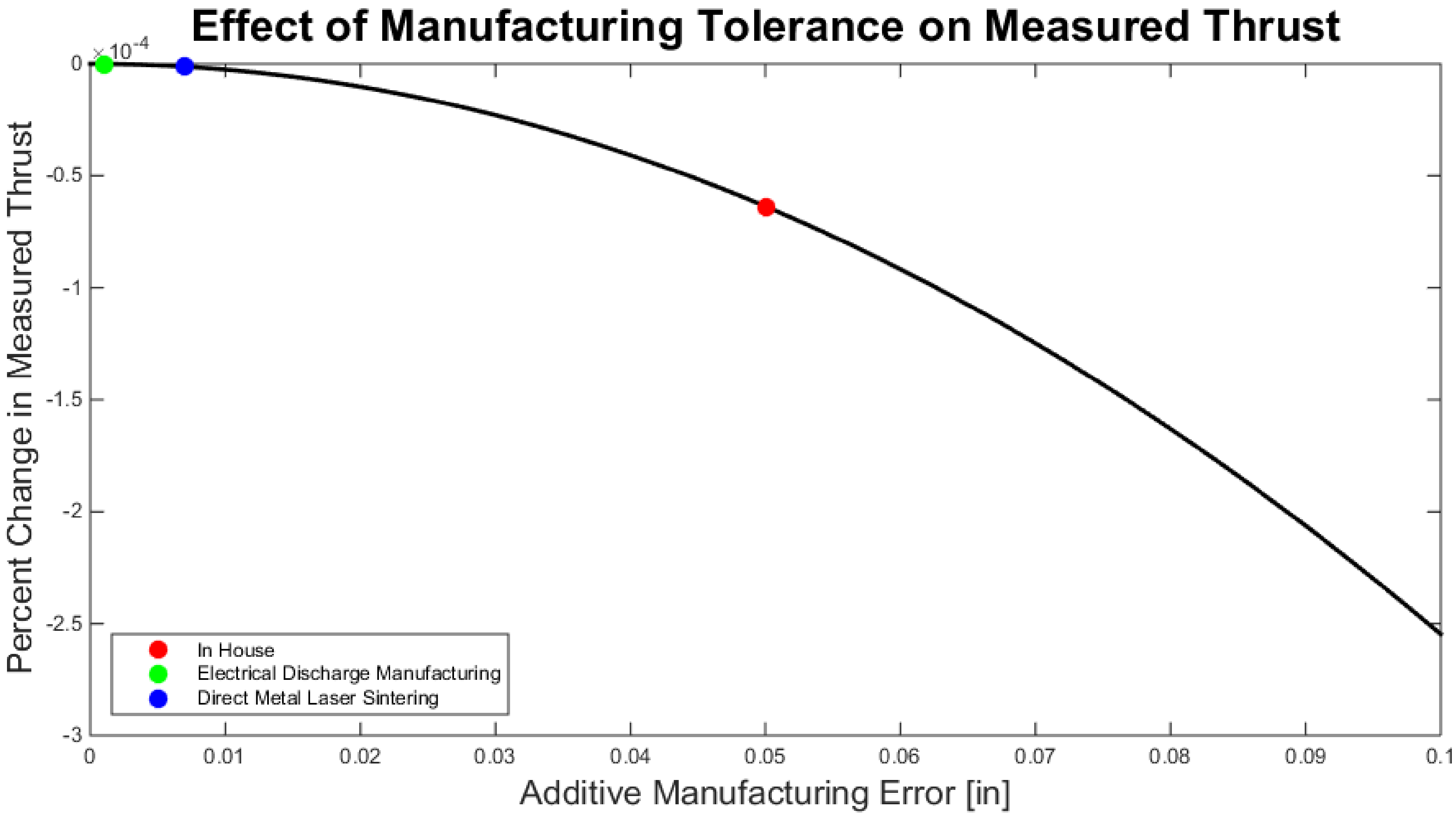
Mighty Pro Blower[15]

- Available from Home Depot ($20)
- 0.0635 kg/s mass flow rate
- 51 m/s max speed

Car Exhaust

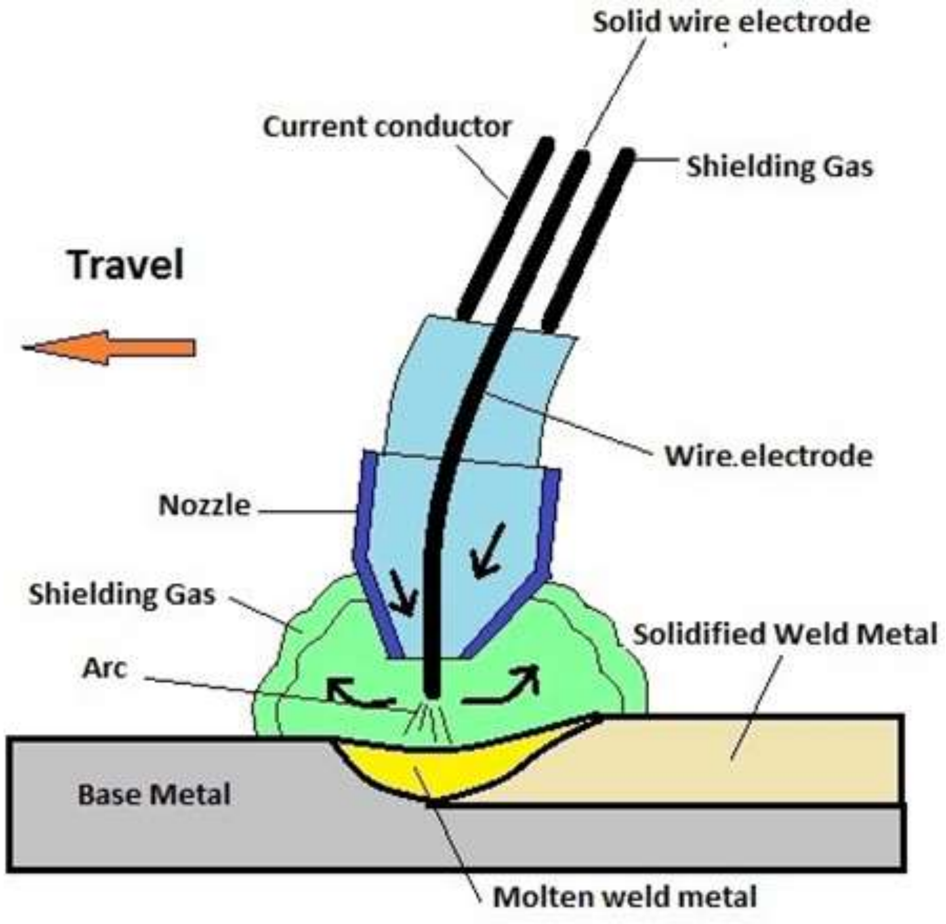
- High flow velocity and mass flow rate, lower temperature .
- Typical temperatures: 366-422 K
- Toyota RAV4 V6
    - 0.0245 kg/s mass flow rate (idle)
    - 17.54 m/s speed (idle)
    - 50 m/s at 2750 rpm

Nozzle Extension: Manufacturing Tolerance



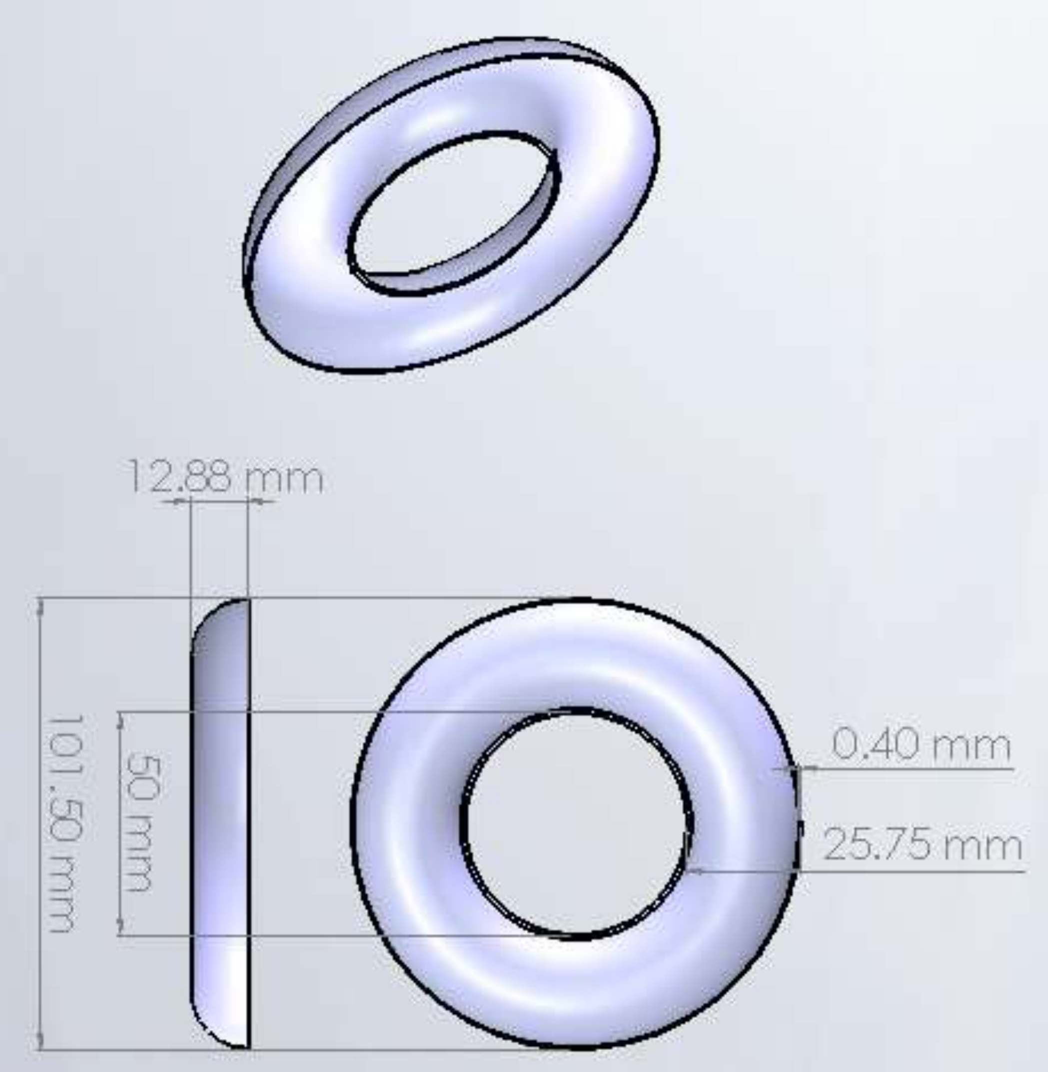
Material Selection – Titanium Alloy 6Al-4V

- **Weldability**: Vital for ability to integrate recuperator into engine
  - Inert gas shielding techniques must be employed to prevent oxygen pick up
  - Plasma and spot welding have been used successfully



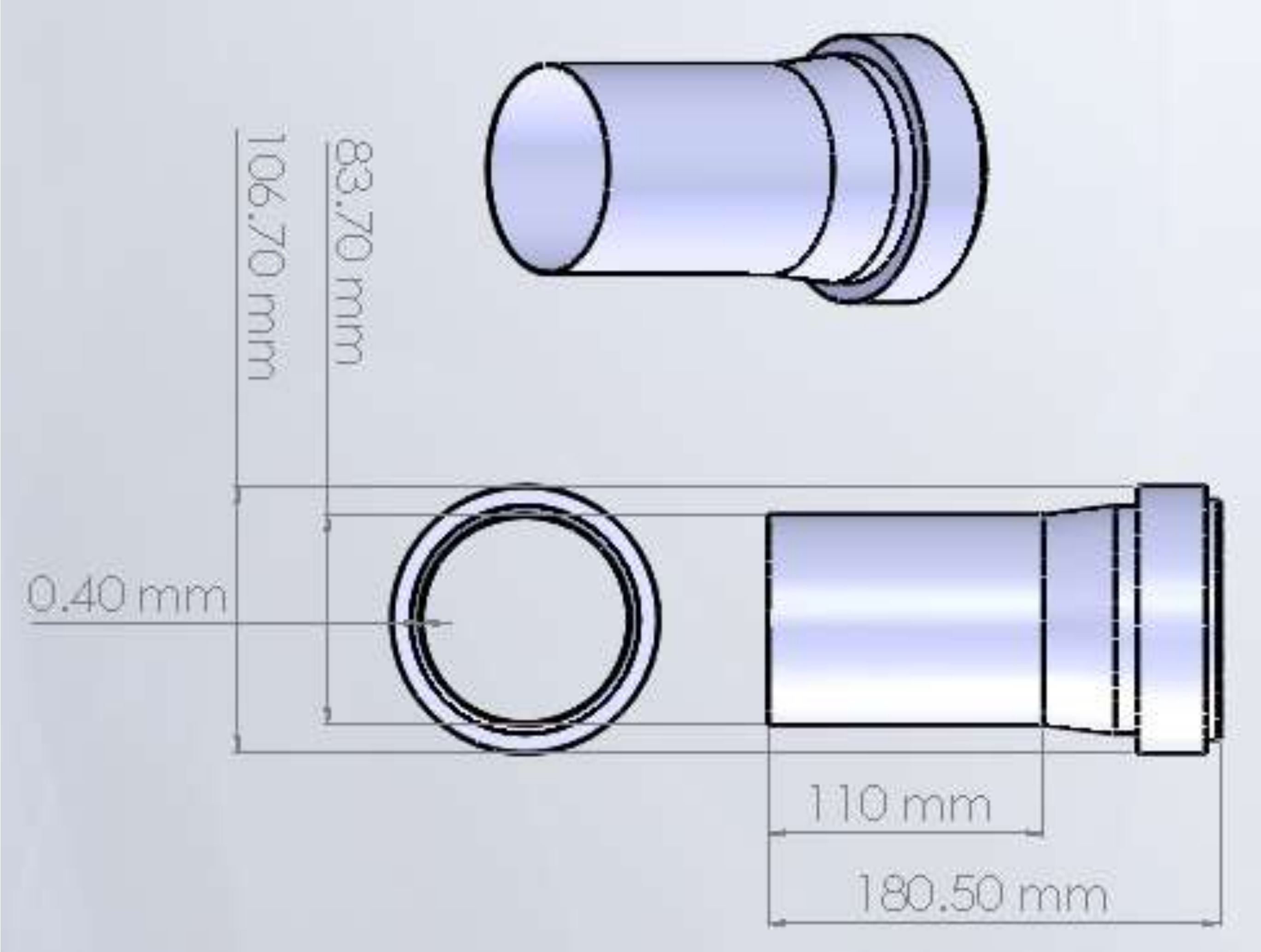
Parts: Endcap

Material: Inconel



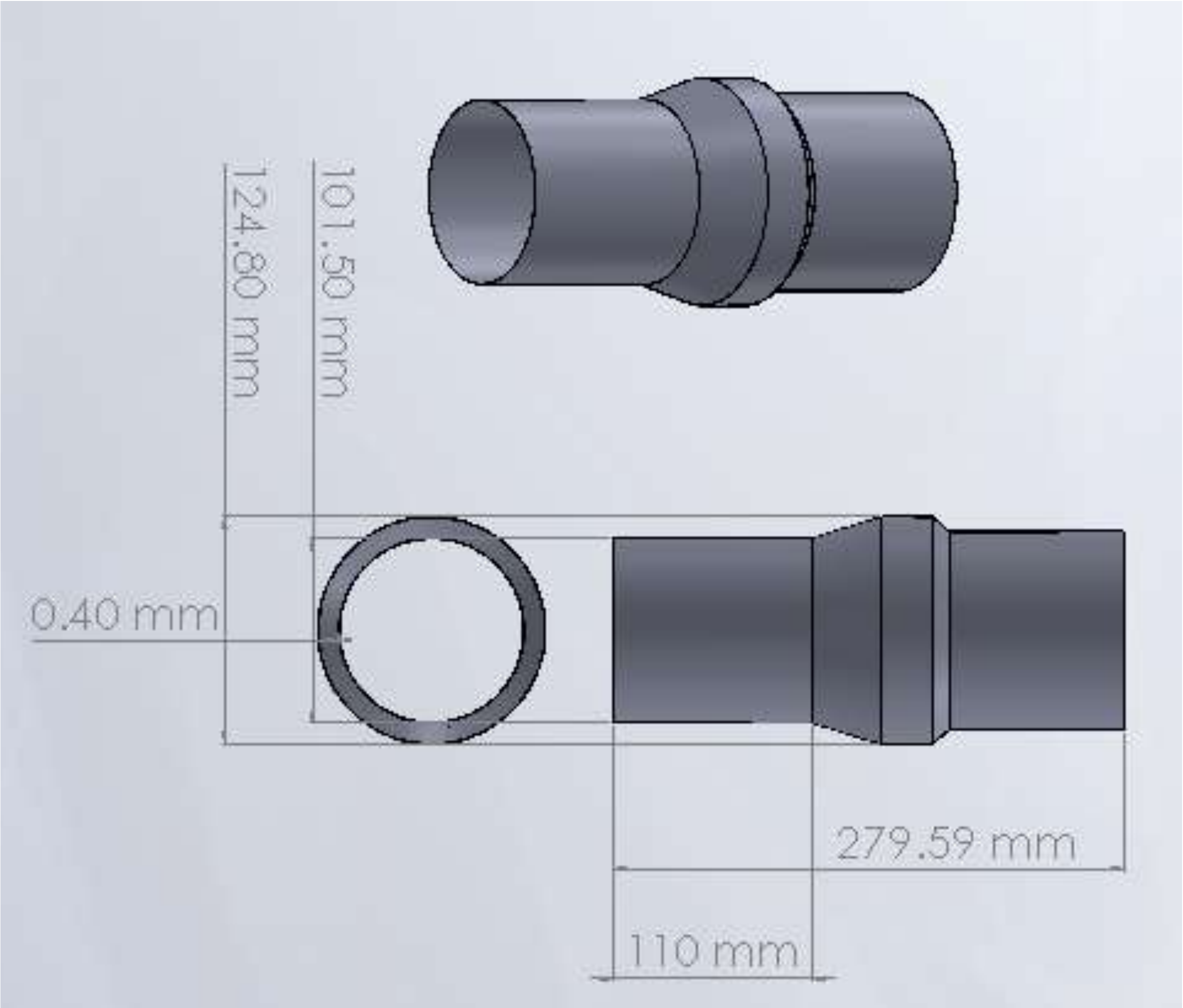
Parts: Combustor Can Extension

Material: Titanium



Parts: Housing

Material: Stainless Steel



Backup Slides: Budget

Expanded Budget: Electronics

Item	Unit Price	Quantity	Total
Printed Circuit Boards (PCB)	$100/board	6	$600
PCB Parts	$150/board	6	$900
Temperature Measurement Probes	$300	3	$900
Load Cell	$100	2	$200
Fuel Flow Sensor	$100 + $50 (inserts)	1, 10 inserts	$500
DAQ Module	$1,200	1	$1,200
Batteries	$100	--	$100
Transmitter	$100	1	$100
Total	-	-	$4,500

Expanded Budget: Heat Exchanger

Item	Unit Price	Quantity	Total
Manufacturing/Material	$2,000	1	$2,000
Engine Casing/Nozzle Replicas	$300	2	$600
Interface Components	$500	-	$500
Prototyping Materials	$300	-	$300
O-ring/Sealing	$300	-	$300
Total	-	-	$3,700