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PROPULSION

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REDEFINING LIMITS

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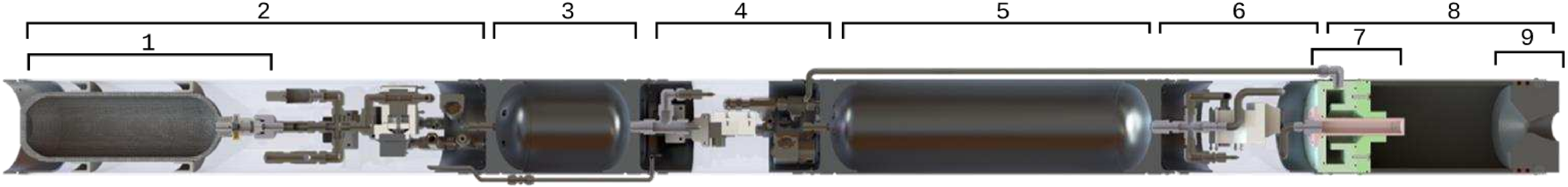
Contents

- Overview
- System simulation
- Routing & Plumbing
- Pressurization Control System
- Injector
- Engine
- Engine Cooling
- Conclusion

Subsystem Overview

- Responsible for the design and testing of Houbolt Jr's Liquid Bipropellant Propulsion System

1. Pressurant tank
2. Upper engineering bay
3. Fuel tank
4. Lower engineering bay
5. Oxidizer tank
6. Injector bay
7. Pintle injector
8. Combustion chamber
9. Nozzle

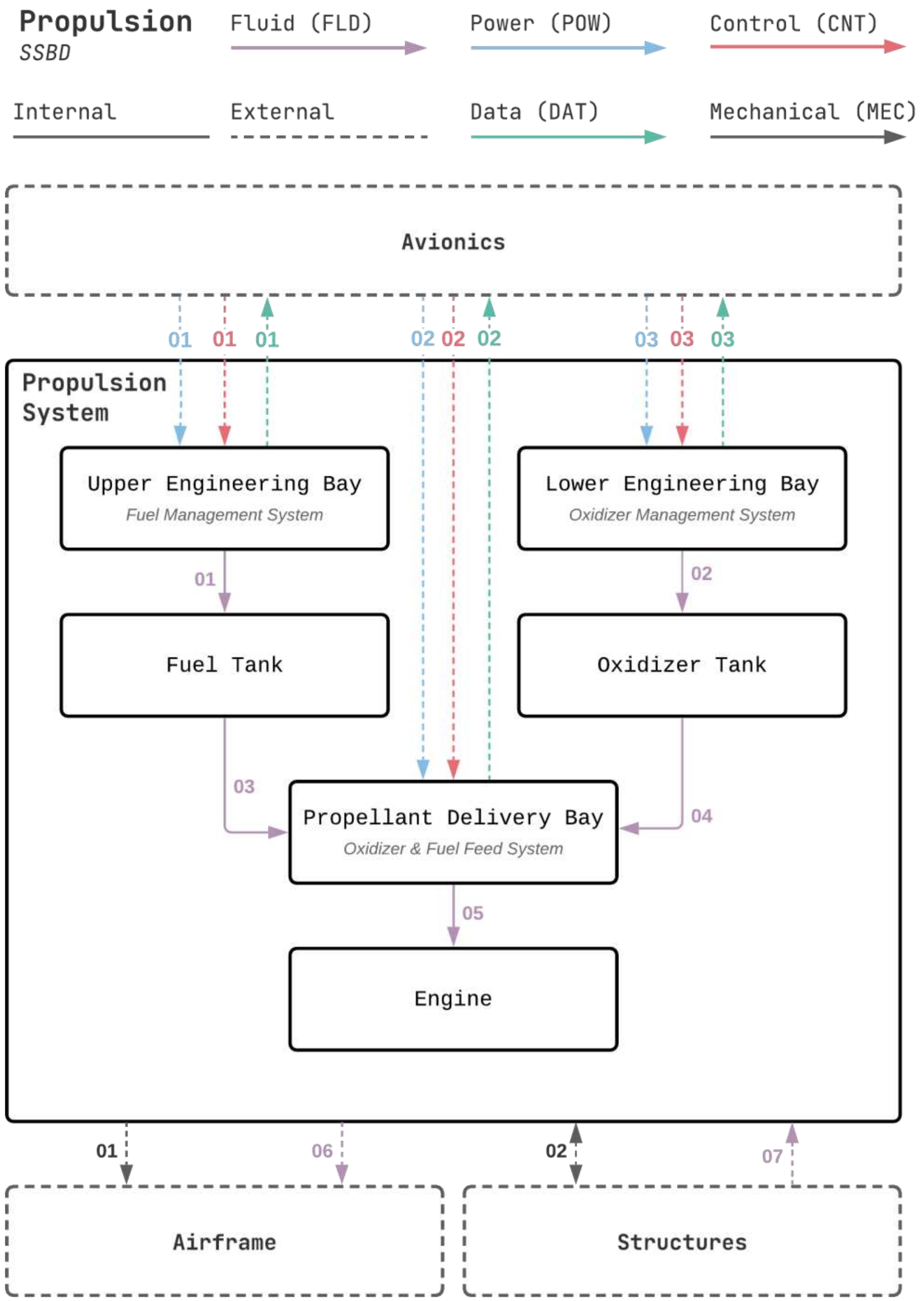


Driving Requirements

Req. ID	Requirement
PRO_F06	The propulsion subsystem shall be capable of remote propellant loading
PRO_F07	The propulsion subsystem shall be designed to load propellants from the bottom of the tanks
PRO_F08	The propulsion subsystem shall fail-safe/revert to an inactive and unarmed state.
PRO_F15	The propulsion subsystem shall have remote electronic pressure instrumentation for tank pressures
PRO_F20	The propulsion subsystem shall allow for safe ignition by intiating the sequence remotely.
PRO_F25	The propulsion subsystem shall provide pressure relief capability to all presure tanks onboad the rocket

Subsystem Block Diagram

- Main components:
  - Fluid system bays
  - Propellant tanks
  - Engine
- Fluid system bays connected to individual propellant tanks
- Avionics and Propulsion connections
  - Power, data, and control lines go to every fluid system bay



Propulsion
SSBD

Fluid (FLD)
Power (POW)
Control (CNT)
Internal
External
Data (DAT)
Mechanical (MEC)

Avionics

01 01 01
02 02 02
03 03 03

Propulsion System

Upper Engineering Bay
Fuel Management System

Lower Engineering Bay
Oxidizer Management System

01
02

Fuel Tank
Oxidizer Tank

03
04

Propellant Delivery Bay
Oxidizer & Fuel Feed System

05

Engine

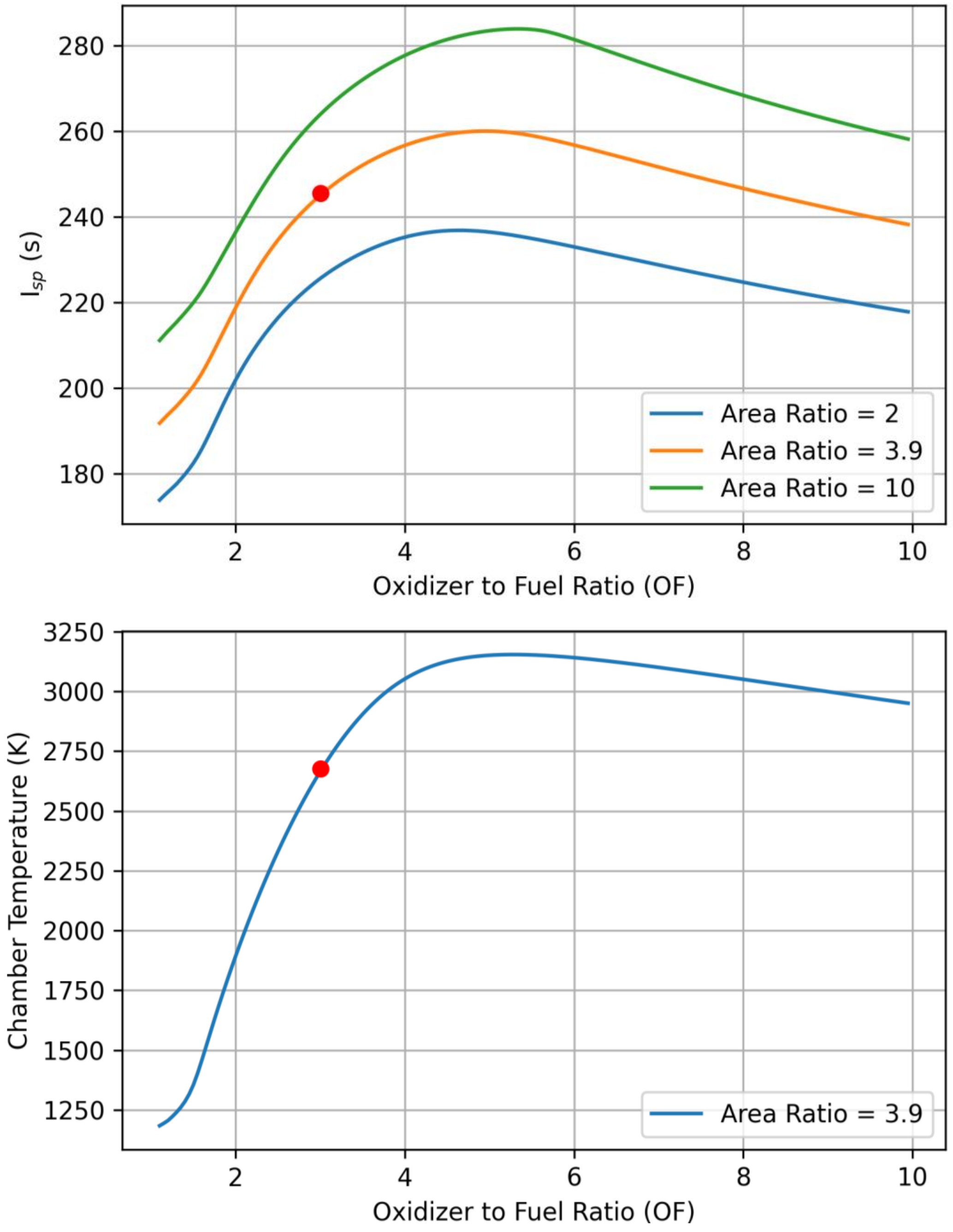
01
06
02
07

Airframe
Structures

SYSTEM SIMULATION

System Overview

Fuel	Ethanol
Oxidizer	Nitrous Oxide
Pressurant	Nitrogen
Chamber pressure (psi)	350
Thrust (N)	2120
Oxidizer to Fuel Ratio	3
Oxidizer Mass Flow Rate (kg/s)	0.8
Burn time (s)	8.4
Burnout Altitude (m)	1068
Apogee (m)	3370



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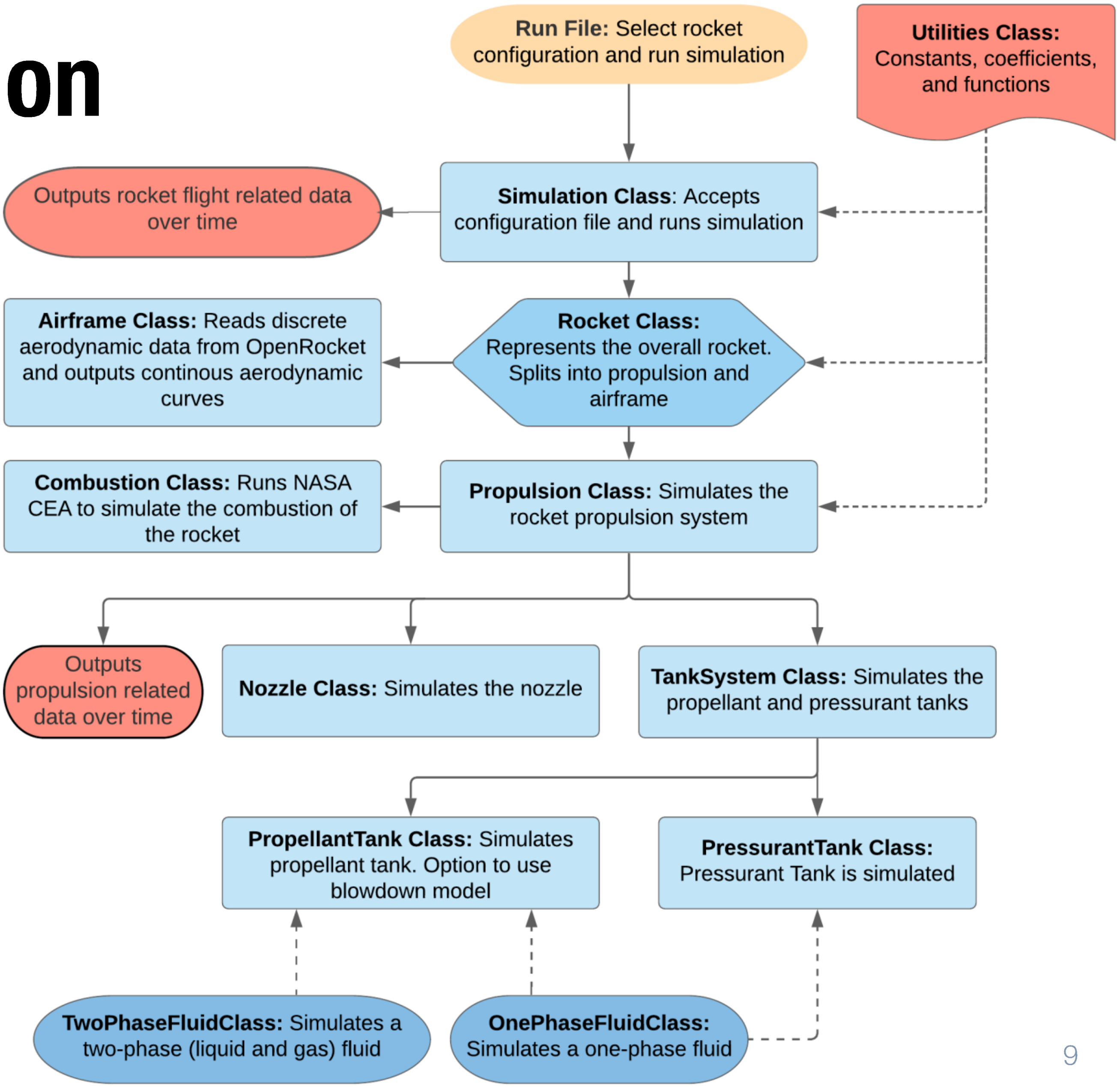
Liquid Rocket Simulation

- Easily model components of the rocket for quick design iteration
- Object-oriented Python simulation (previously MATLAB)
- Using a wrapped version of NASA CEA Fortran code
- Using a wrapped version of OpenRocket Java code
- Ultimate goal is optimization based design



Run File: Select rocket configuration and run simulation

Utilities Class: Constants, coefficients, and functions

Simulation Class: Accepts configuration file and runs simulation

Outputs rocket flight related data over time

Rocket Class: Represents the overall rocket. Splits into propulsion and airframe

Airframe Class: Reads discrete aerodynamic data from OpenRocket and outputs continous aerodynamic curves

Propulsion Class: Simulates the rocket propulsion system

Combustion Class: Runs NASA CEA to simulate the combustion of the rocket

Outputs propulsion related data over time

Nozzle Class: Simulates the nozzle

TankSystem Class: Simulates the propellant and pressurant tanks

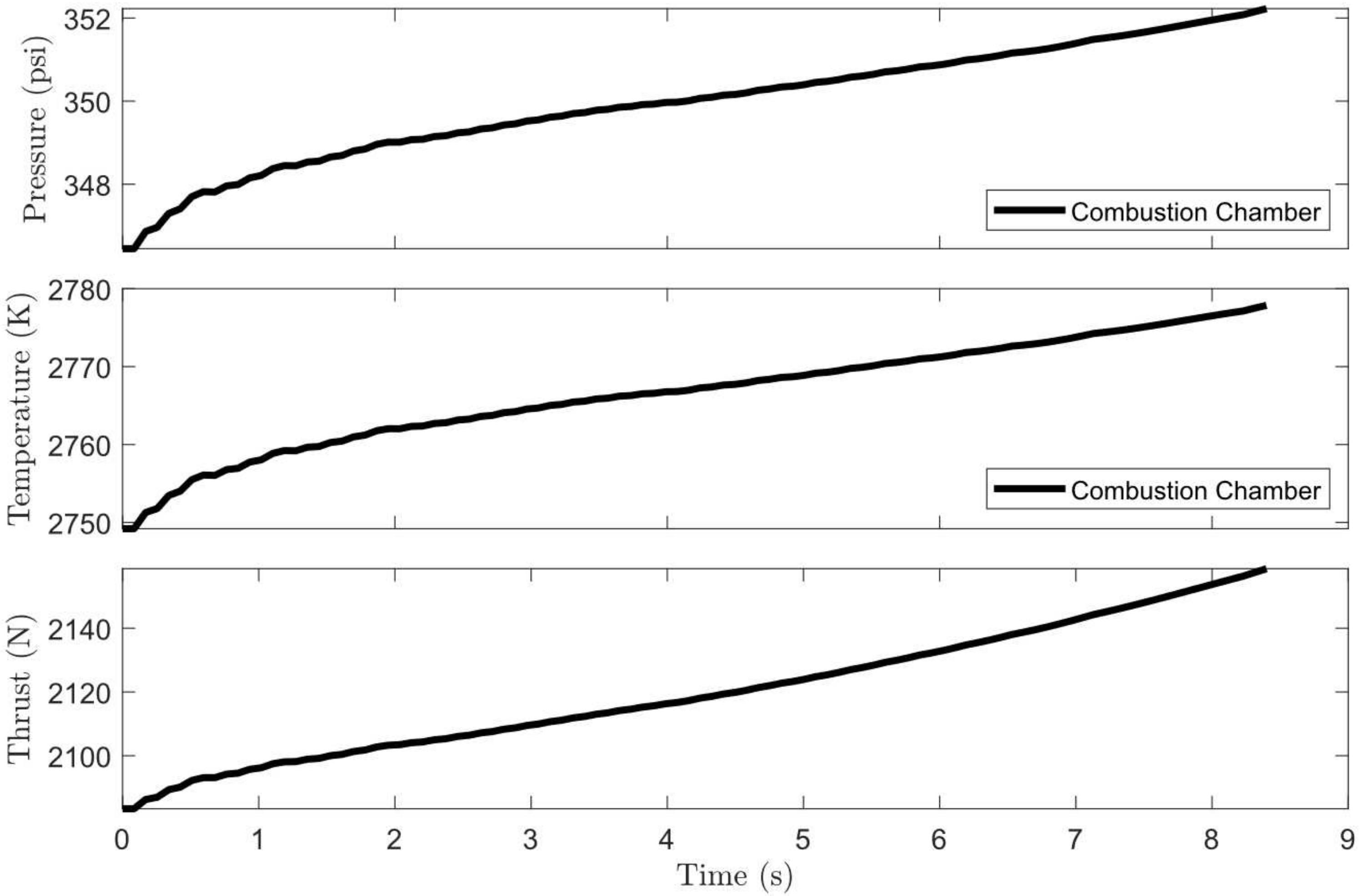
PropellantTank Class: Simulates propellant tank. Option to use blowdown model

PressurantTank Class: Pressurant Tank is simulated

TwoPhaseFluidClass: Simulates a two-phase (liquid and gas) fluid

OnePhaseFluidClass: Simulates a one-phase fluid

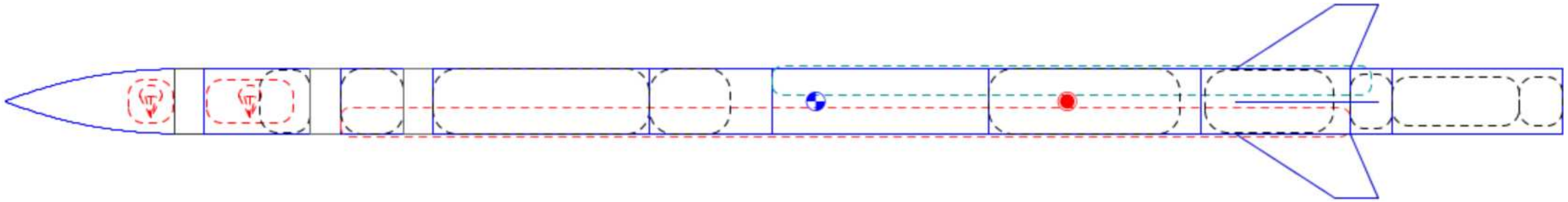
Outputs

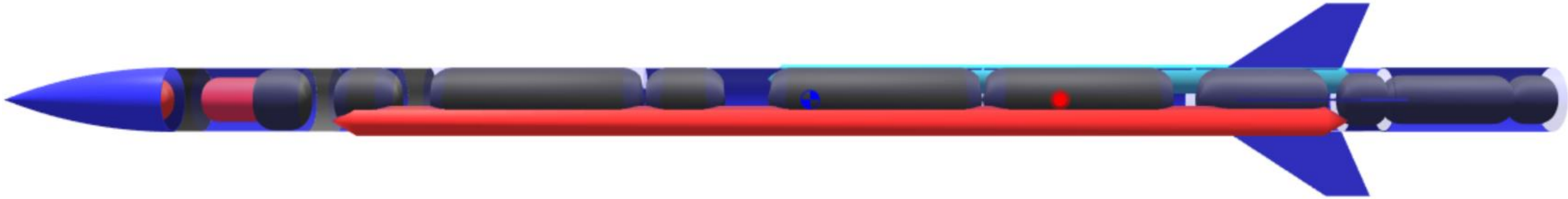


Pressure (psi)
352
350
348
Combustion Chamber
Temperature (K)
2780
2770
2760
2750
Combustion Chamber
Thrust (N)
2140
2120
2100
0
1
2
3
4
5
6
7
8
9
Time (s)

OpenRocket Model

- OpenRocket is used to calculate stability, aerodynamic coefficients, kinematic and dynamic variables
- Python simulation outputs motor file, then calls OpenRocket to simulate the rocket with the new motor file


Side View


3D Figure

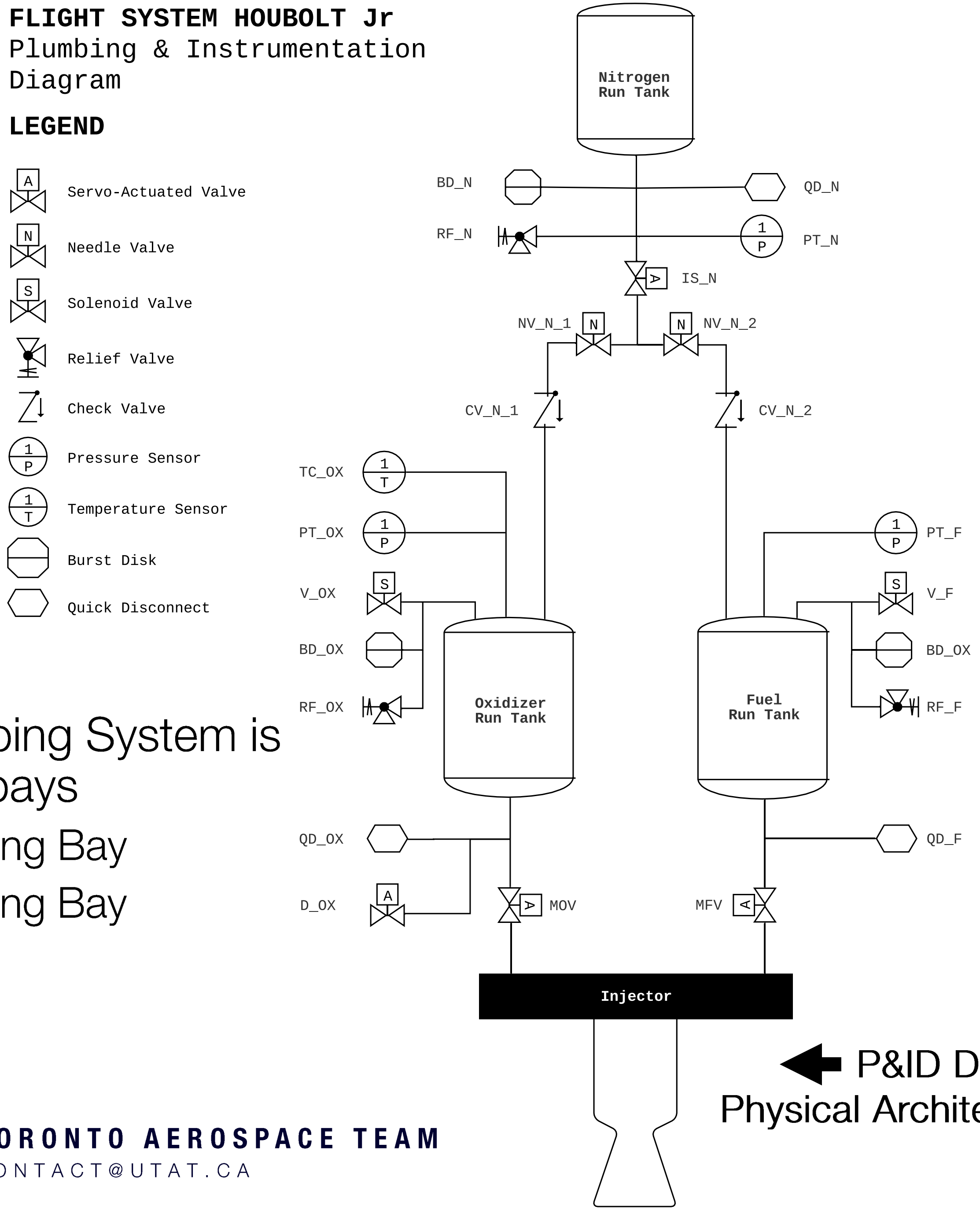
Next Steps

- Finish blowdown models for general liquids
  - So we can estimate blowdown of fuels, and required pressurization
  - Allows to finally use arbitrary tank arrangements
- Finish python simulation
- Use the simulator to drive preliminary rocket design

ROUTING & PLUMBING

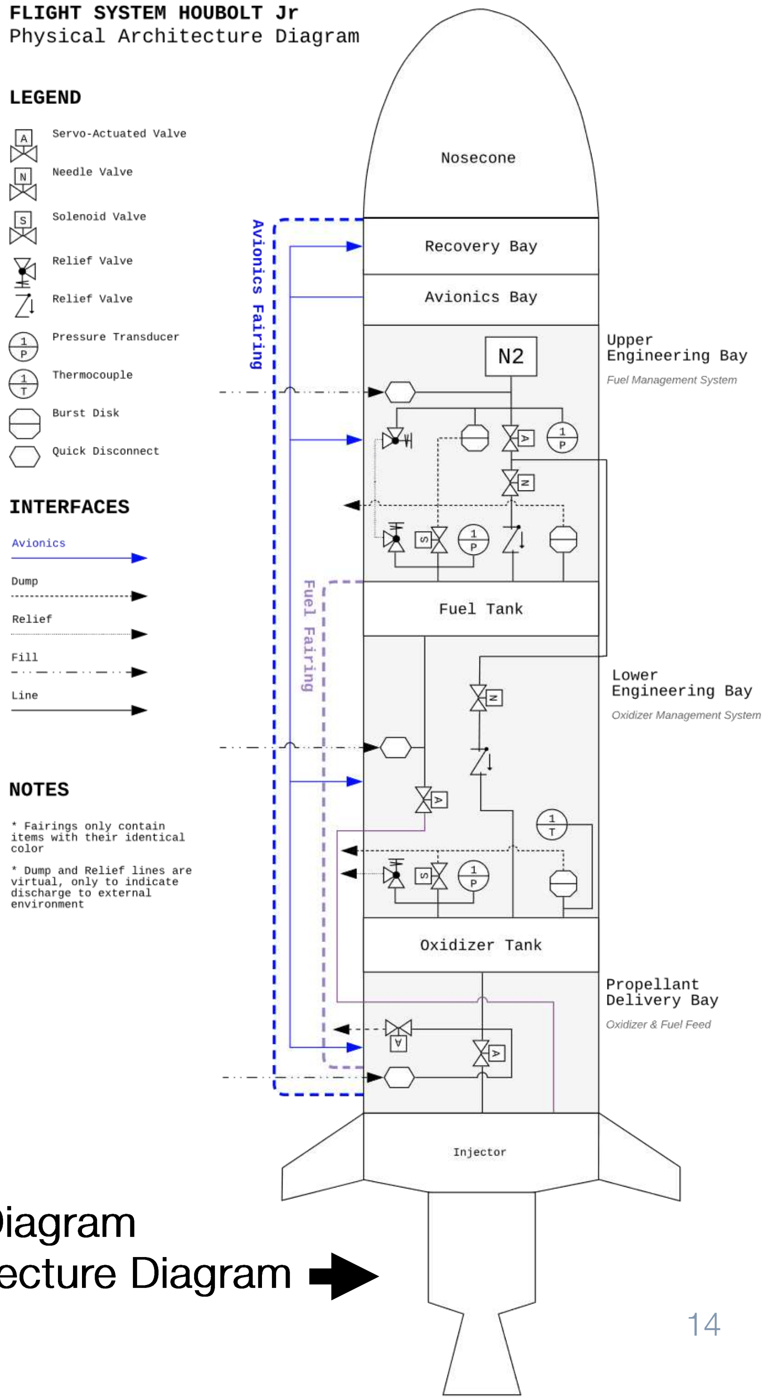
Diagrams

- Routing and Plumbing System is divided into three bays
  - Upper Engineering Bay
  - Lower Engineering Bay
  - Injector Bay



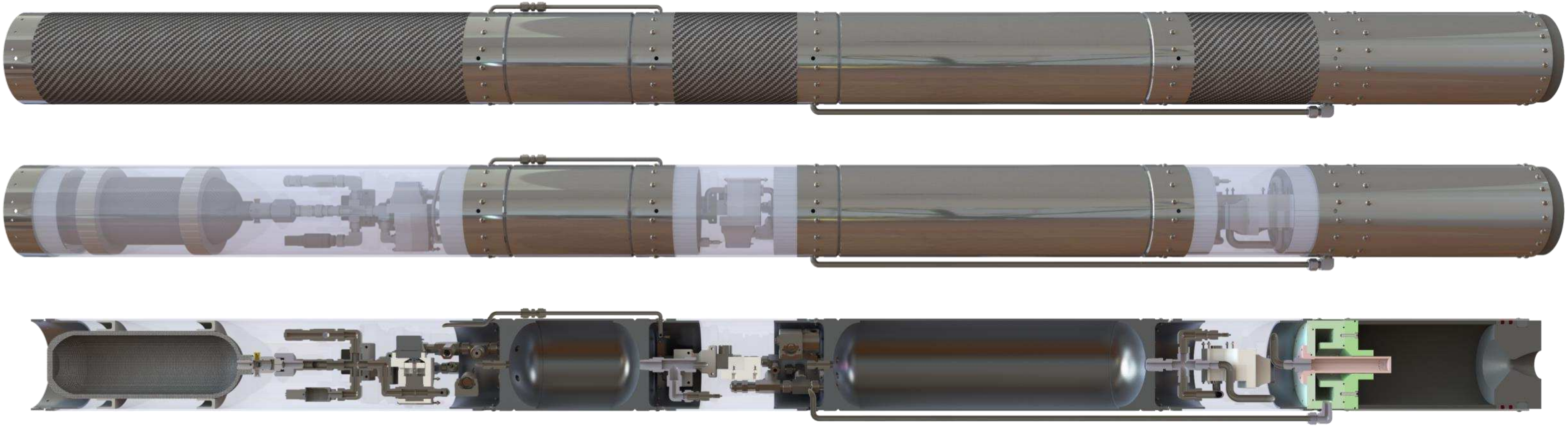
P&ID Diagram

Physical Architecture Diagram



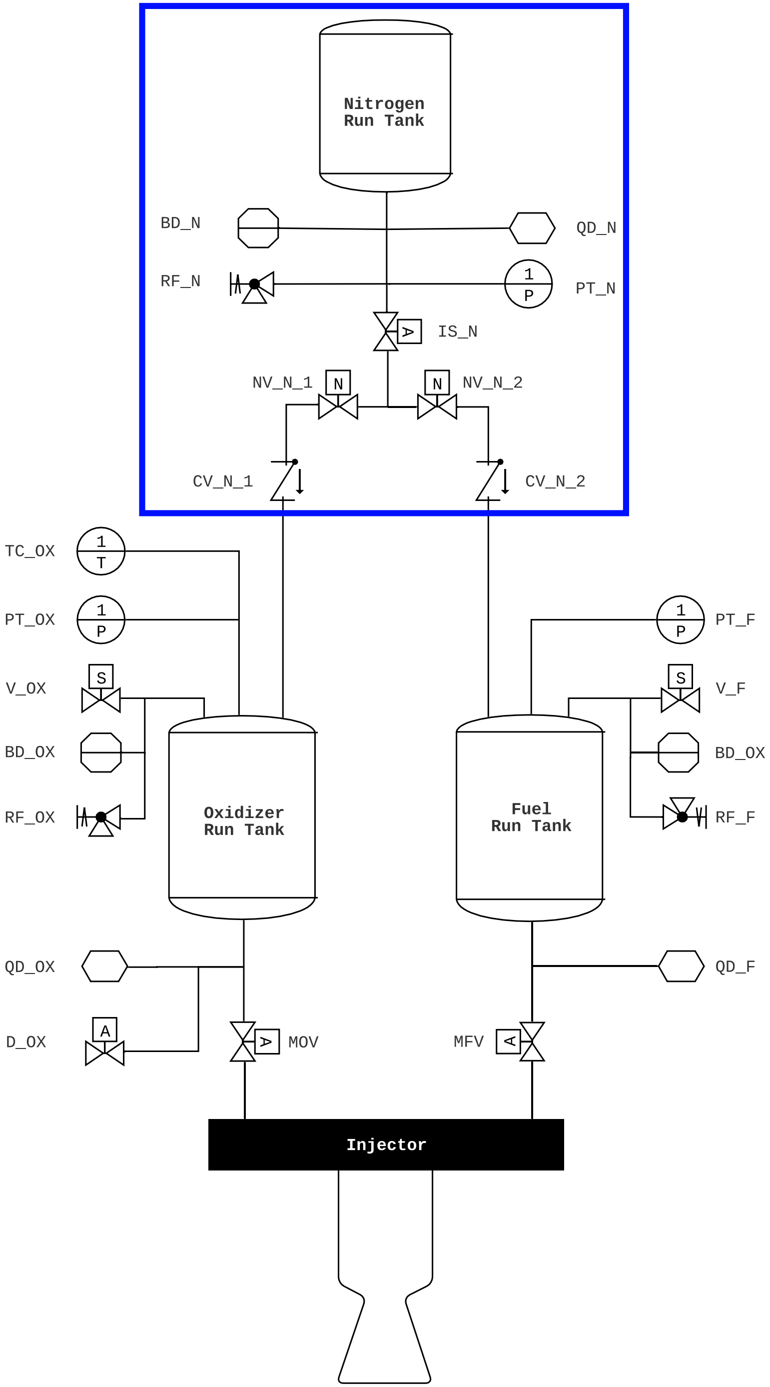
Propulsion System CAD

- All propulsion system components have been determined and are represented in the CAD model



Pressurant Delivery

- N_2 flow is controlled through Servo-Actuated Needle Valve to achieve varying output N_2 pressure
- N_2 flows through: isolation valve → needle valve → check valve → tank
- Quick disconnect used to fill pressurant tank with Nitrogen
- N_2 tank filled outside of rocket



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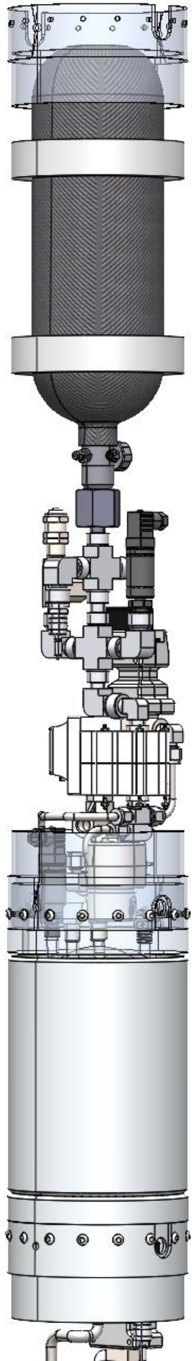
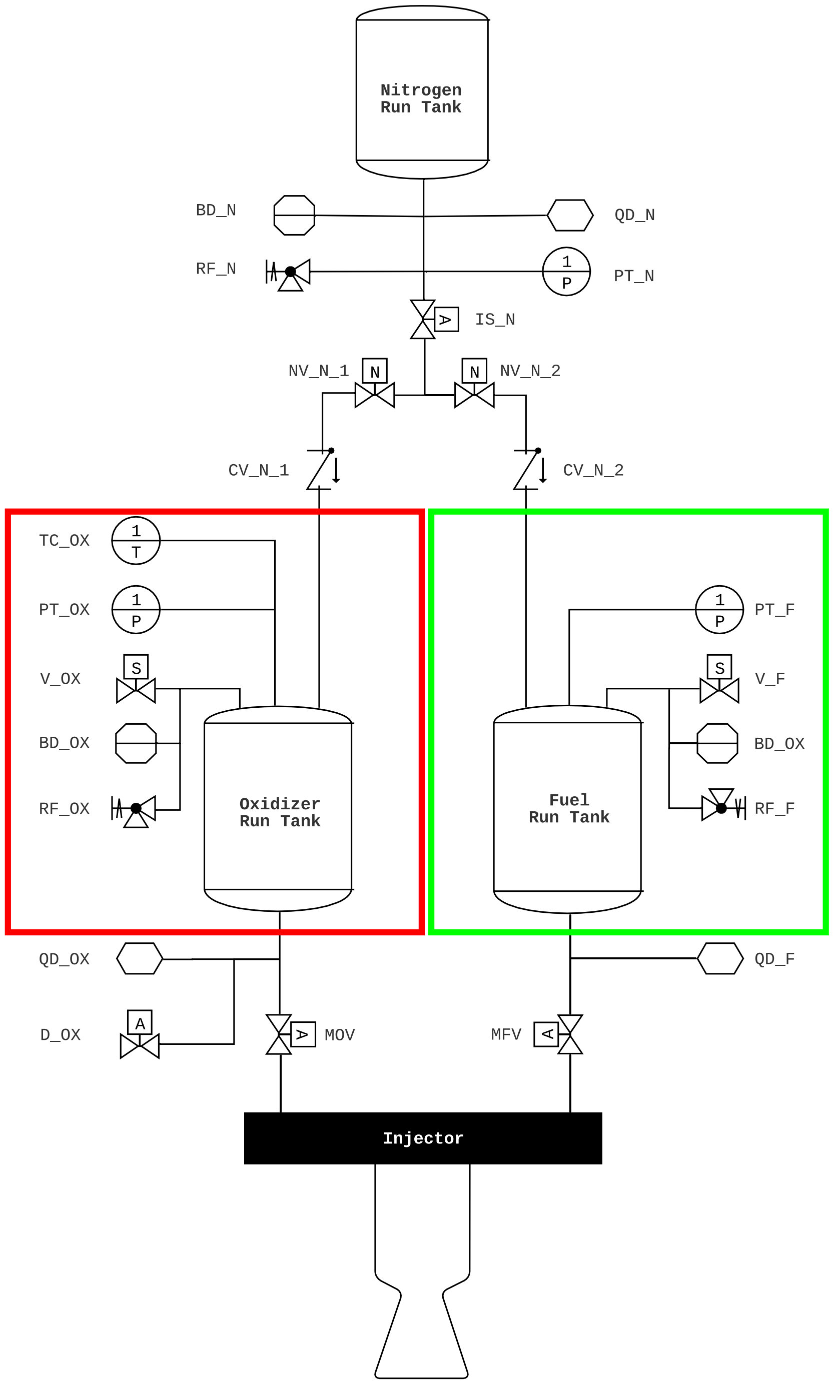
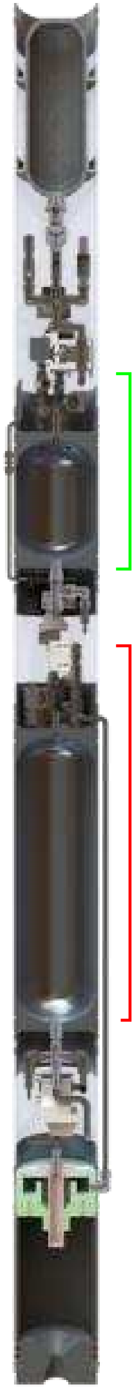


Propellant Management

- Ox Fuel Relief Valve and Burst Disk act as primary and secondary pressure relief components, respectively
- Ox Fuel Solenoid Valve acts as vent for gas during fill
- Ox Fuel Pressure Transducer measures pressure inside propellant tank
- Ox Thermocouple measures temperature inside propellant tank





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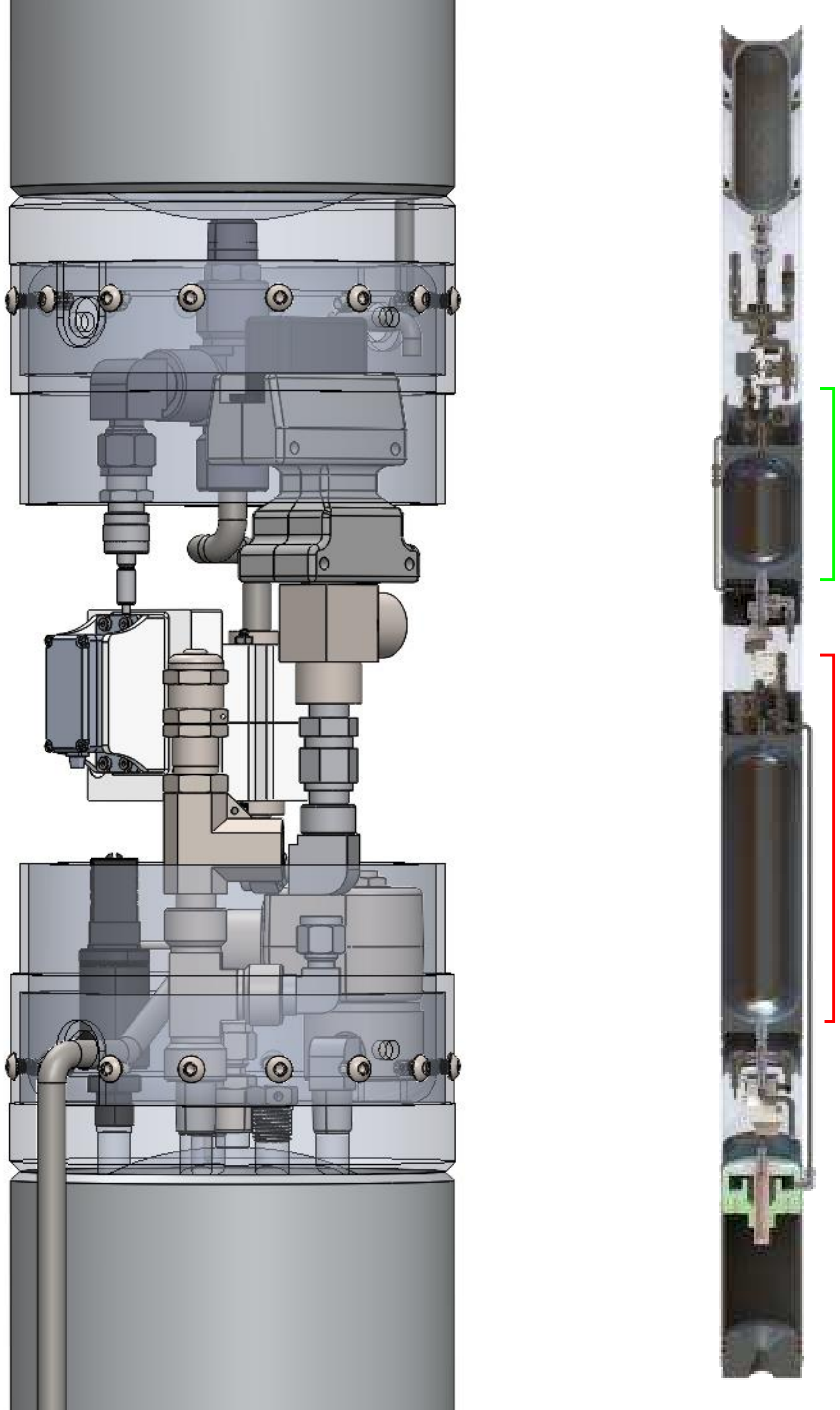
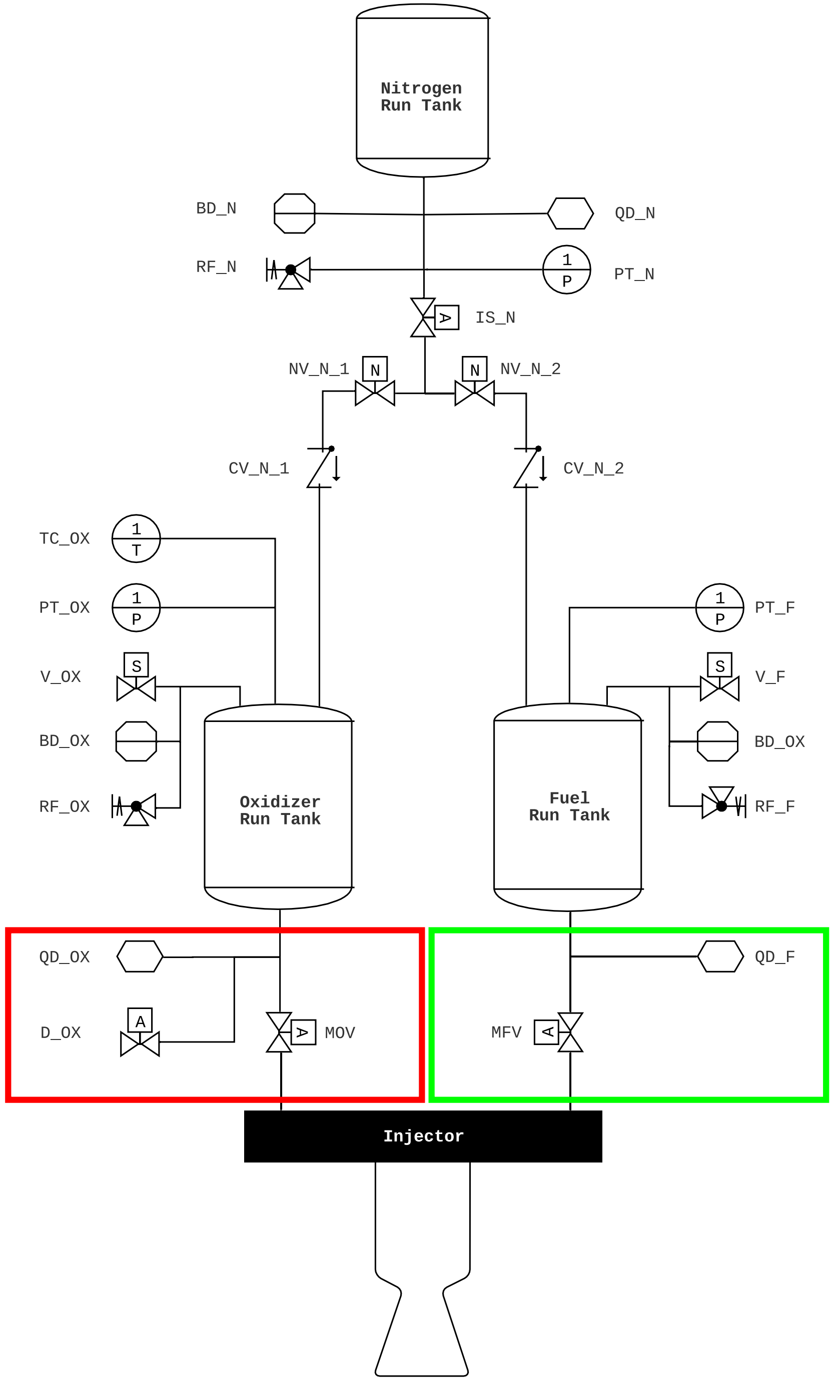
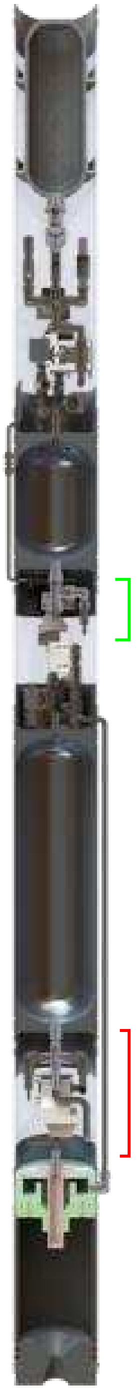


Propellant Delivery

- Feed lines were sized to the smallest diameter that would prevent excessive pressure losses and minimize ignition risk due to flow contaminants
  - Fuel Feed line is 3/8” diameter
  - Ox Feed line is 1/2” diameter
- Ox Fuel Main Propellant Valves are servo-actuated ball valves
- Ox Fuel Propellants are loaded from the tank base through quick disconnect fittings
- Fuel Propellant dump occurs through the engine
- Ox Propellant dump occurs through a wall opening in the injector bay





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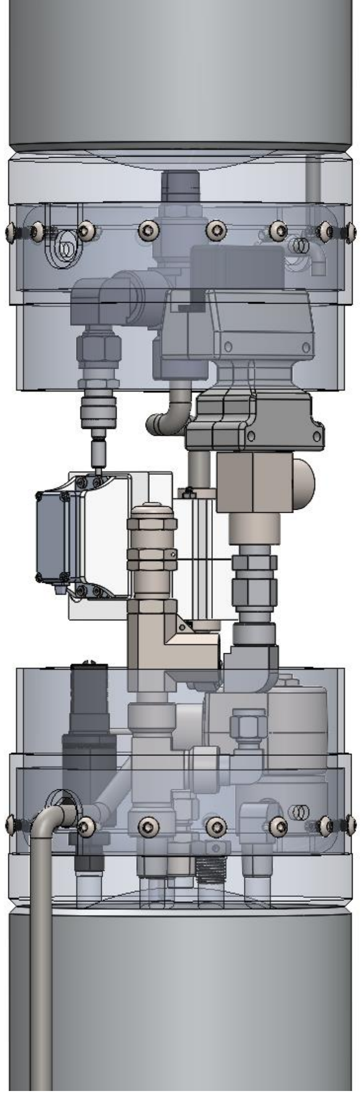
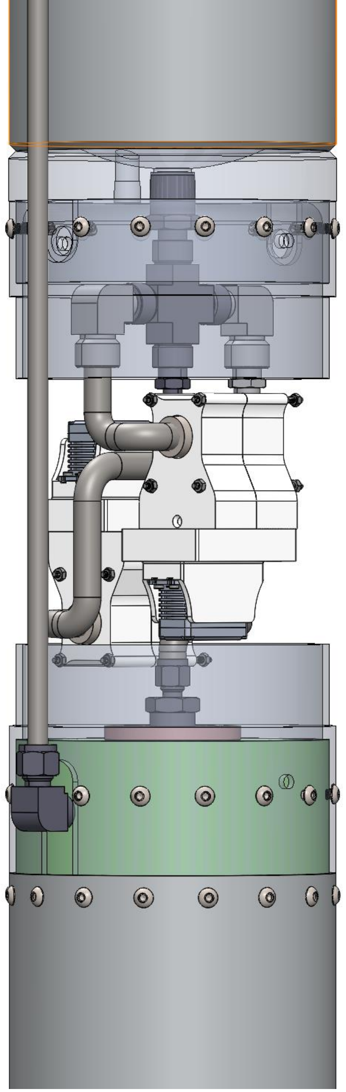
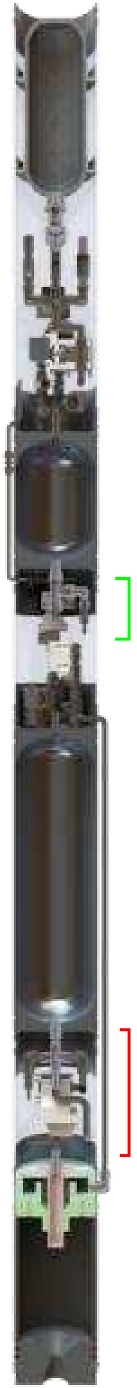


Fuel



Oxidizer

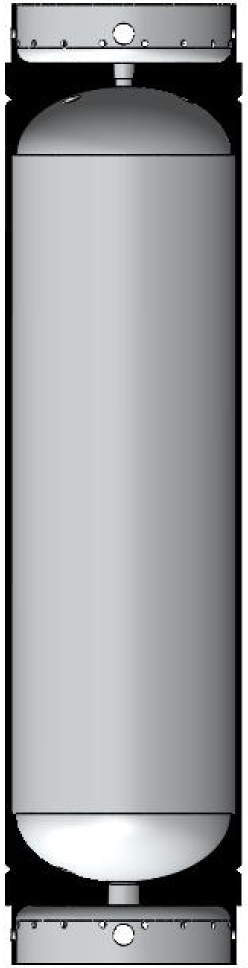


Pressurant and Propellant Tanks

- Oxidizer and Fuel tank bodies are COTS Tubes
  - 6061-T6 Aluminum Round Tube
  - 6 O.D x 0.125 wall
- Elliptical end caps
- Nitrogen tank is a COTS COPV

Nitrogen Tank – 1 L

Fuel Tank – 4.5 L



Oxidizer Tank – 13.5 L

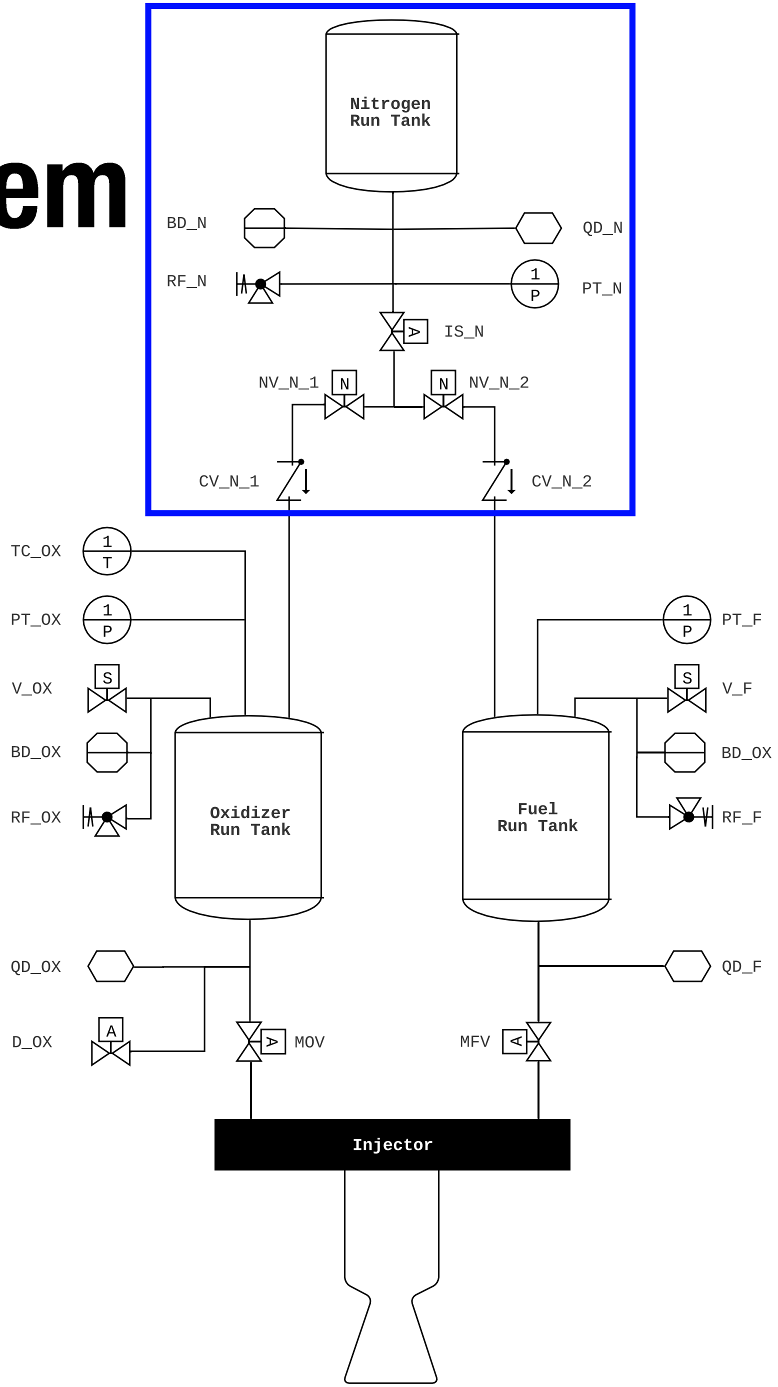
Next Steps

- Confirm sizing of valves, fittings, and tubing
- Optimize Layout in Rocket
- Redesign Needle Valve and Ball Valve enclosures to decrease volume / mass as well as to improve functionality
- Redesign Oxidizer and Fuel tank Caps
- Bolt Calculations for Tanks

PRESSURIZATION CONTROL SYSTEM

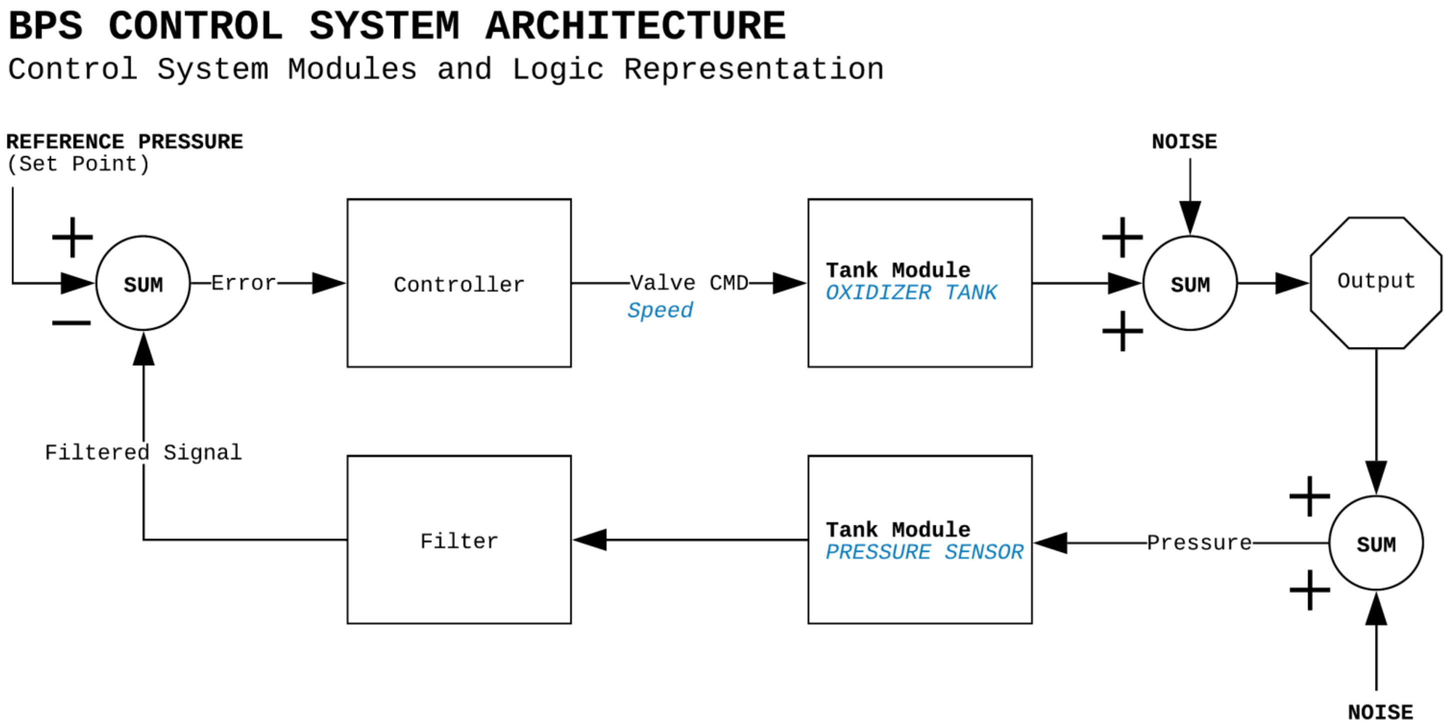
Pressurization Control System

- Motivation
  - Feeding high pressure propellants into the engine, at precise quantities, will maximize system performance
- Functions
  - Stores high pressure Nitrogen pressurant
  - Supplies regulated pressurant to propellant tanks
  - Monitor the state and conditions of all fluids in the system



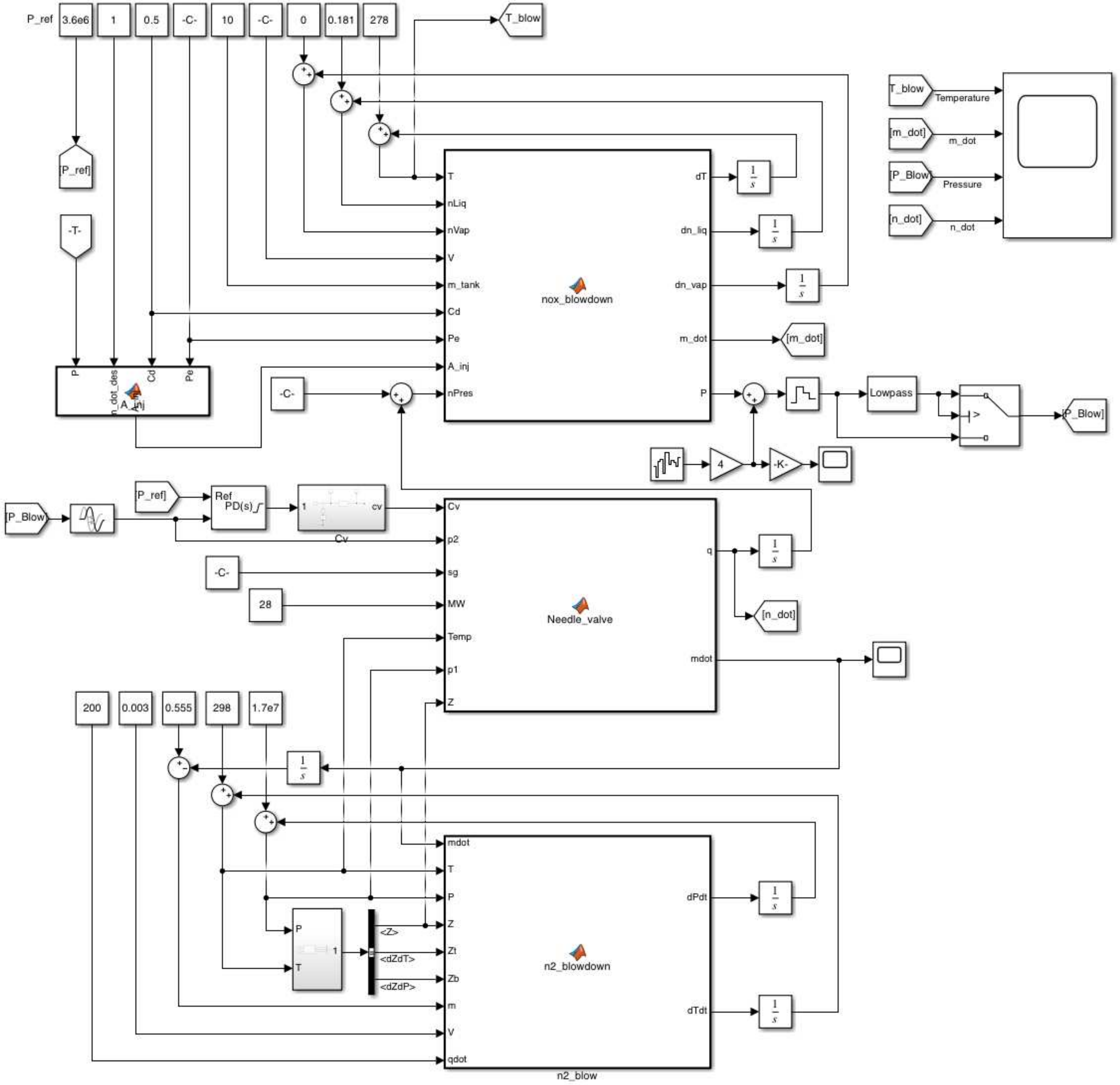
Pressurization Control System

- Controlling pressurant flow into propellant tanks using servo driven needle valve

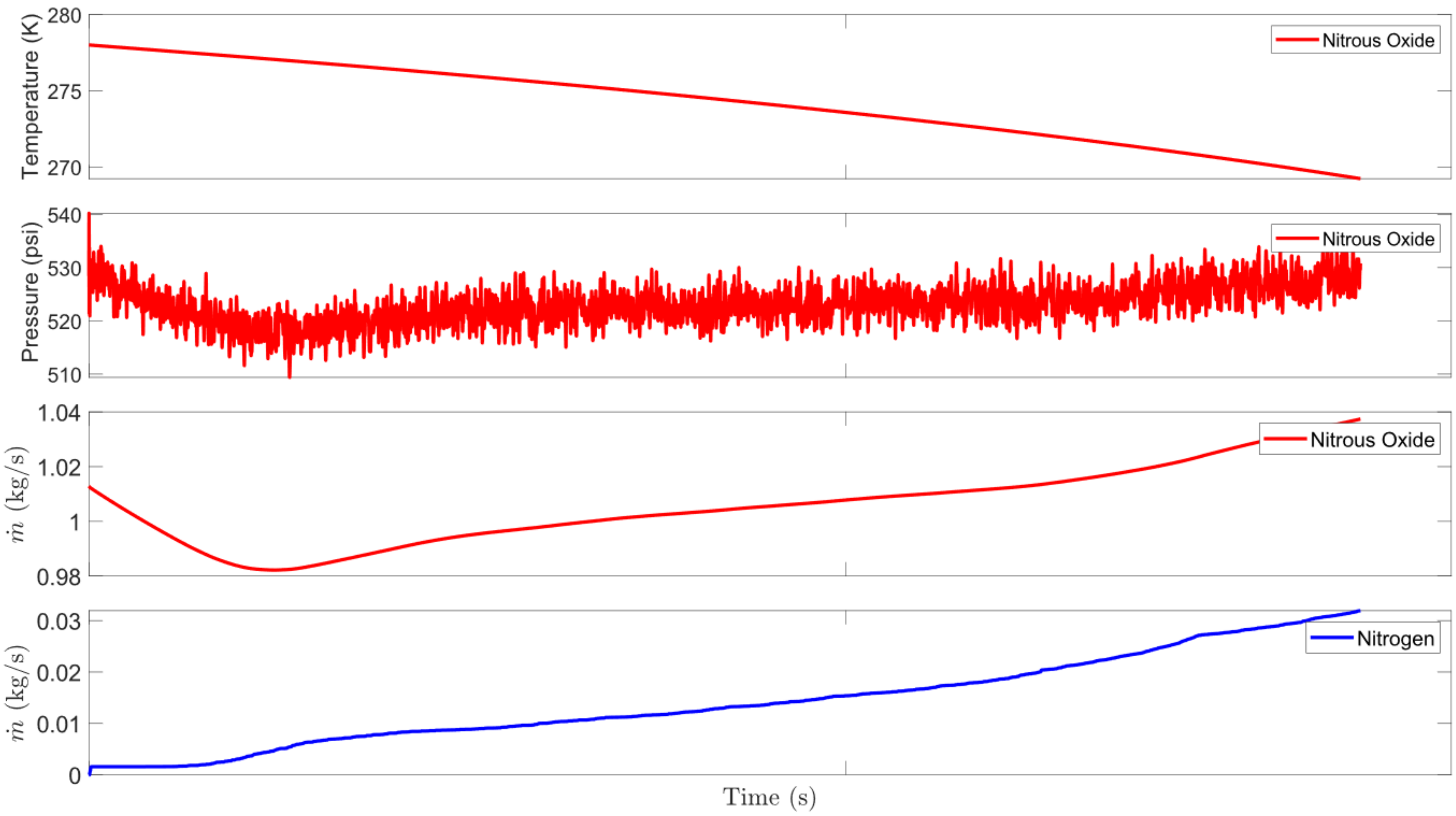


Simulink Model

- Created Simulink model of the pressurization system
- Controlling pressurant flow into propellant tanks using servo driven needle valve
- A Swagelok Needle Valve is being modeled by approximating its C_v value
- Manually tuned PD controller is used to control servo position



Outputs


Temperature (K)
280
275
270
Nitrous Oxide
Pressure (psi)
540
530
520
510
Nitrous Oxide
$\dot{m}$ (kg/s)
1.04
1.02
1
0.98
Nitrous Oxide
$\dot{m}$ (kg/s)
0.03
0.02
0.01
0
Nitrogen
Time (s)

Next Steps

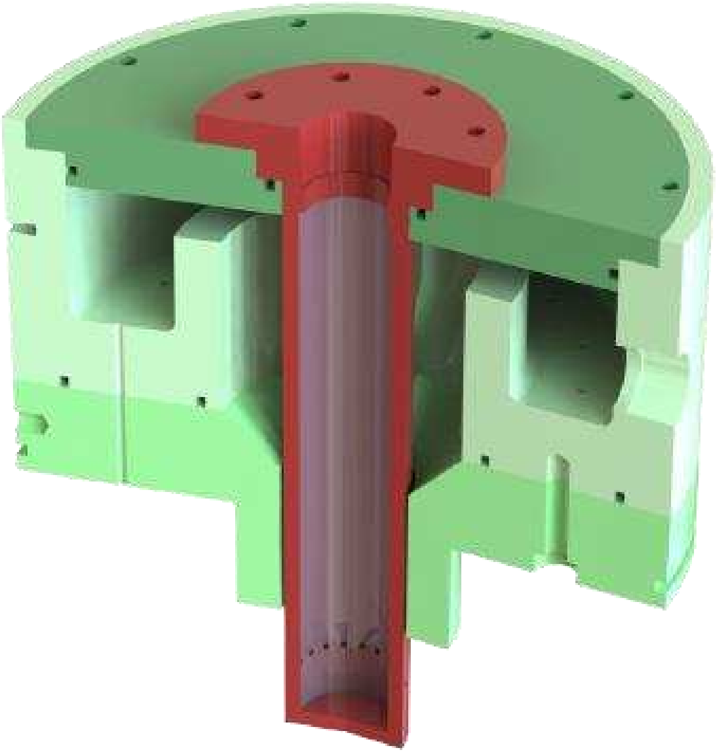
- Tuning control for new rocket parameters
- Implementation of needle valve for ethanol tank
- Validate results against the complete python simulation
- Validate results against Hybrid rocket Nitrogen tank tests

INJECTOR

Pintle Injector Overview

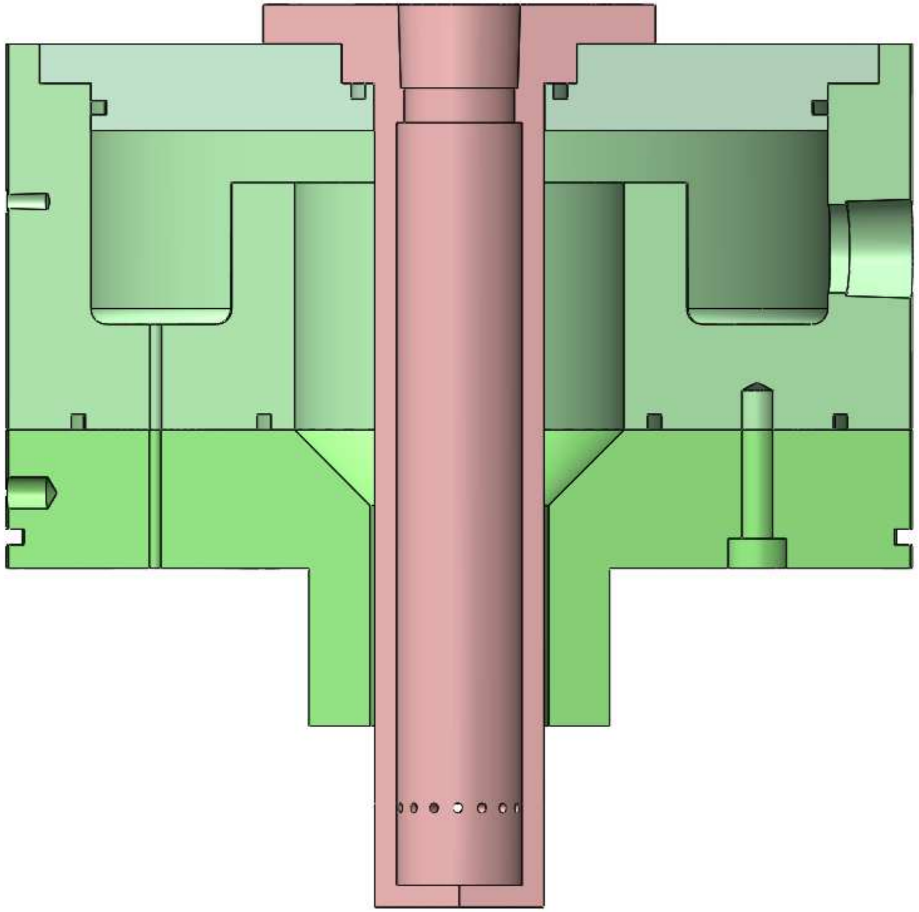
- Type of coaxial injector
- Oxidizer is injected in an inner tube, fuel from an outer tube. The streams impinge and atomize in the engine

- We are focusing on Design for Manufacturing and minimizing mass
- Ability to quickly re-machine parts changing flow characteristics



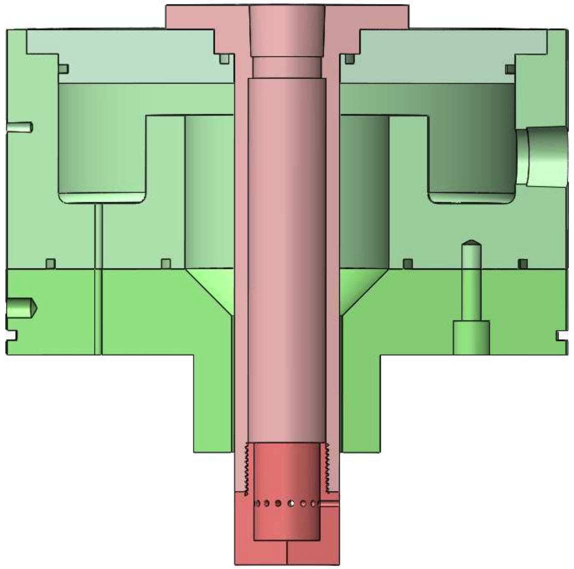
Current Design

- Number of parts and angled cuts decreased
- General locations of helicoils, through holes, and O-ring grooves determined
- Test Stand version and Rocket version have been designed
- Film-cooling incorporated in design

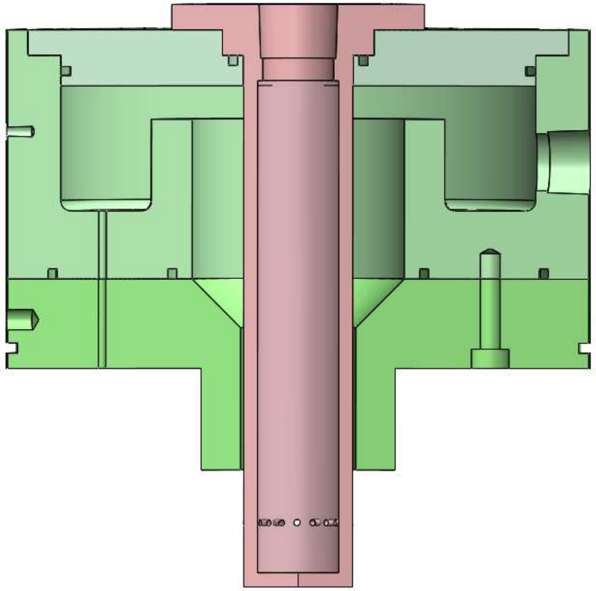


Design Variations

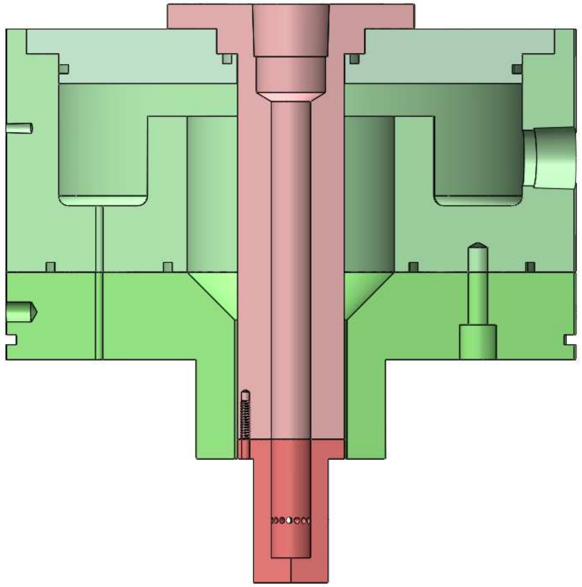
- Best pintle design balances design for manufacturing, ability to modify flow components and excellent sealing



Version 4.0 – Screw Design



Version 4.1 – Combined Design



Version 4.2 – Flange Design

Next Steps

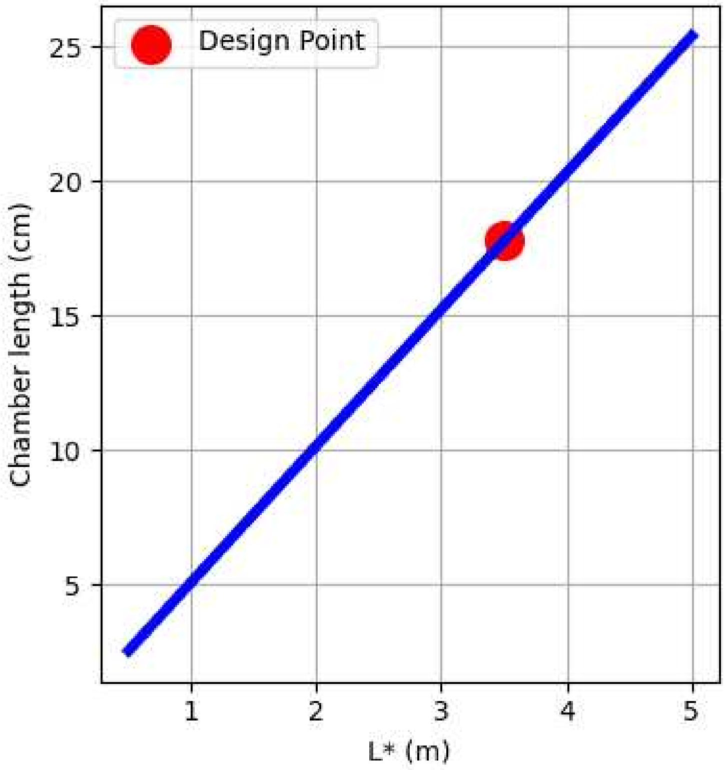
- Continue analysis on Pintle Design options
- Determine bolt dimensions according to force calculations
- Determine O-ring dimensions and materials
- Modify pintle dimensions according to design code

ENGINE

Engine Geometry

- Tokudome et al. determine an L* = 1 m for N_2O+Ethanol at a similar chamber pressure, using optimized impinging injectors
- Recirculation areas formed by the pintle can result in dead zones leading to poor mixing, this requires a longer chamber length
- To account for this inefficiency we select L* = 3.5 m
- Hot spots at the chamber wall can occur due to the pintle injector. We reduce these by maximizing chamber inner diameter, D = 5.25”
- Assuming a fixed chamber diameter, our design L* value results in a chamber length that is about 7” long (~ 17.5 cm)

Chamber length as a function of L* for an inner chamber diameter of 5.25"



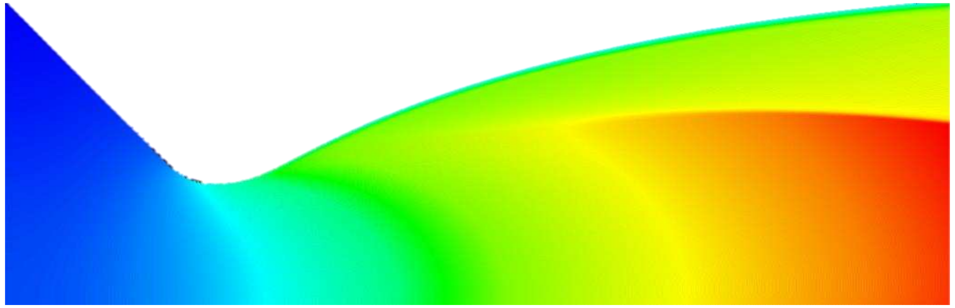
$$L^* = \frac{V_c}{A_t}$$

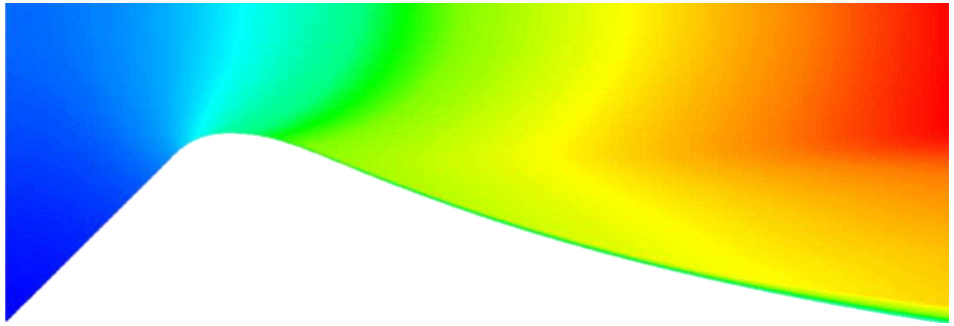
Propellant	***L* (m)***
LOX-kerosene	**1.5-2.5**
LOX-ethanol	**2.5-3**
HNO_3-UDMH	**1.5-2**

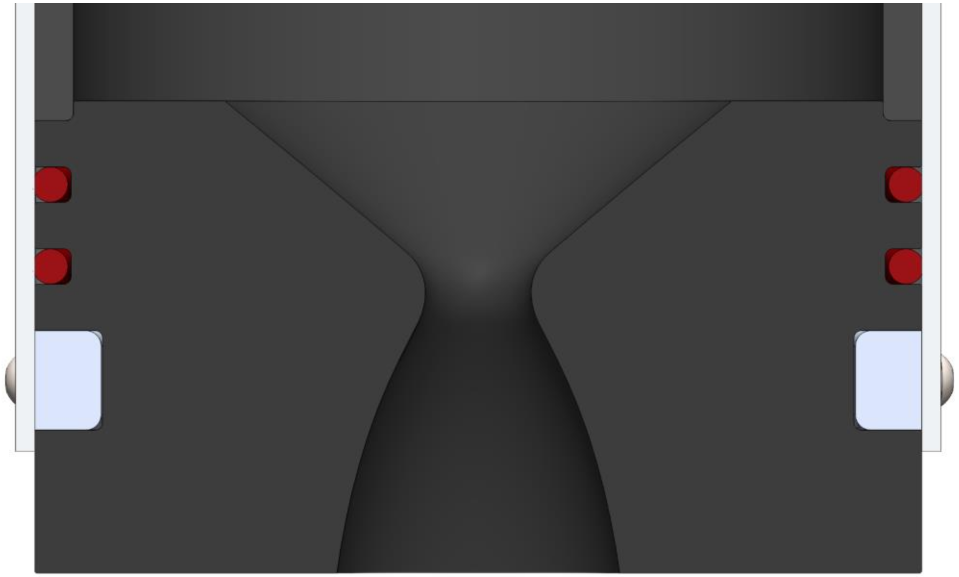
Nozzle

- TICTOP Bell Nozzle
    - Combination of Truncated ideal contour (TIC) and thrust-optimized parabola (TOP) curves
    - CFD required to tune TIC, TOP curve combination

Expansion Ratio (-)	3.9
Exit Mach number (-)	2.7
Convergence angle (°)	40

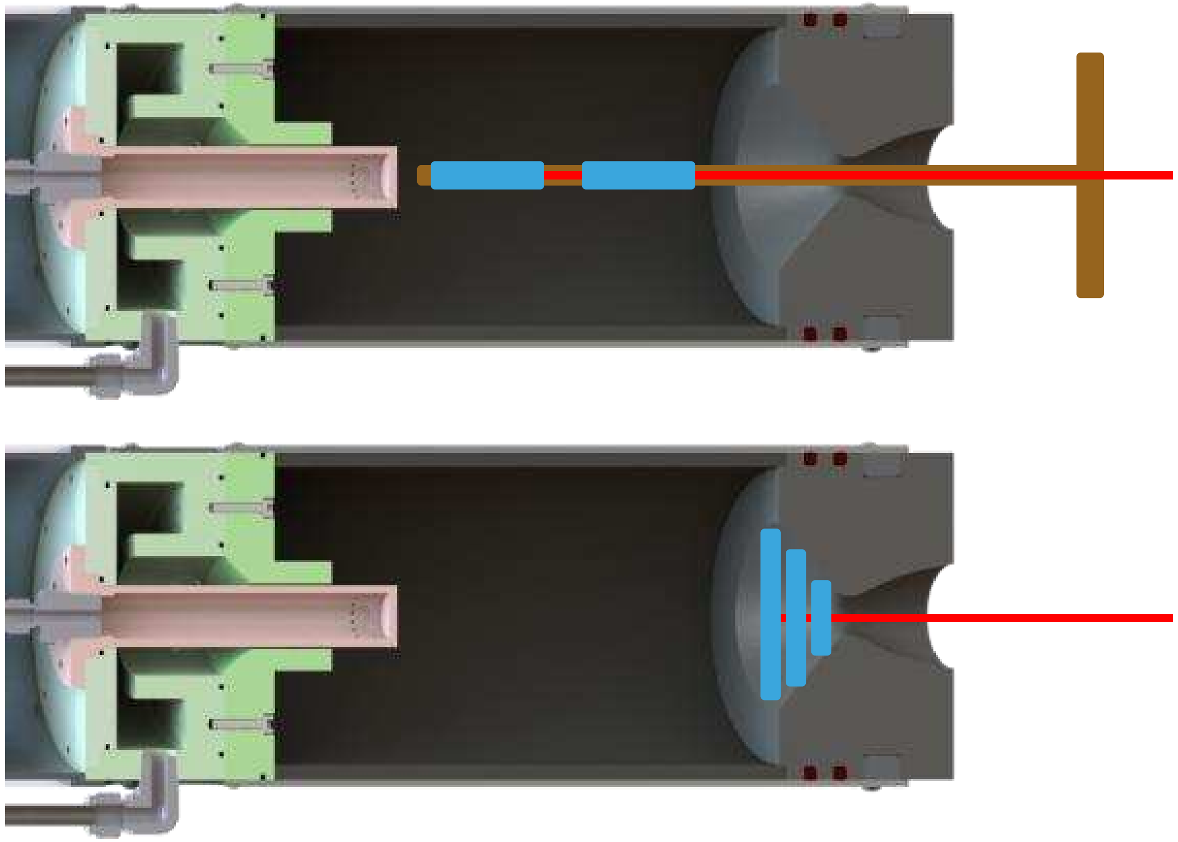

Initial


Optimal



Ignition System

- Same nitrocellulose-pyrodex pyrotechnic design as Defiance hybrid rocket
- Option A: Russian Torch
  - Cylindrical pyrotechnic igniters inserted through throat on wooden stick
- Option B: Hanging pyrotechnic
  - Pyrotechnic dowels hung inside nozzle converging area



LEGEND
🟦 = Nitrocellulose-Pyrodex Igniters
🟫 = Wooden Dowel
🟥 = Electrical Connection

Ignition Sequence

- For N_2O+Ethanol, similar chamber pressures and OF ratio, the literature shows the following operating sequence is viable
  - Ethanol injected 200 ms prior to N_2O
  - Igniter is activated along N_2O injection

- **Note:** The proposed pyrotechnic igniters cannot be deactivated

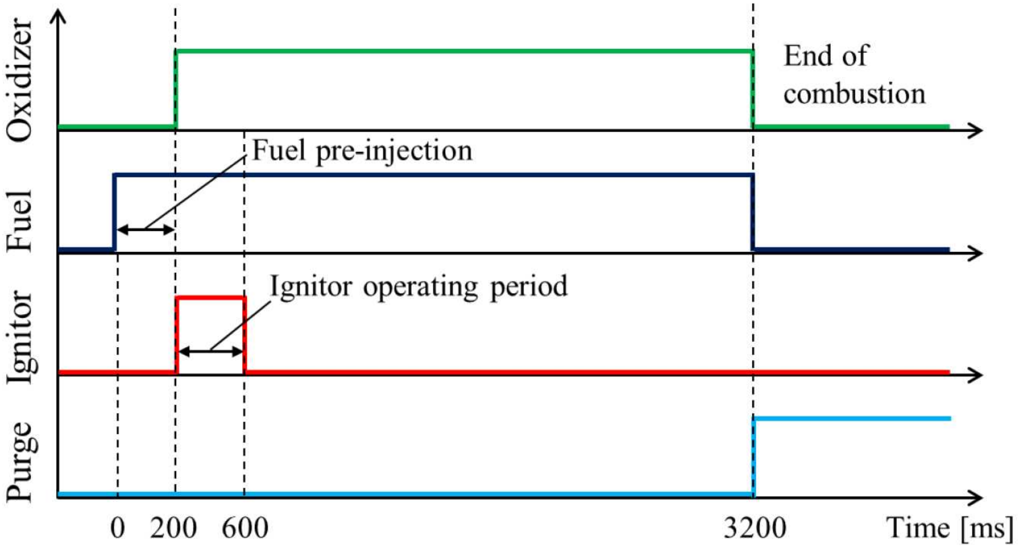


Fig. 3 Ignition sequence cyclogram

Source: Kim, D., Koo, J. (2015)

Next Steps

- FEA analysis of Nozzle to verify structural integrity
- Determine feasible actuation speeds of servo driven ball valves in order to characterize transient ignition behavior
- Determine actuation time for main fuel and oxidizer valves
- Choose and develop ignition system

ENGINE COOLING

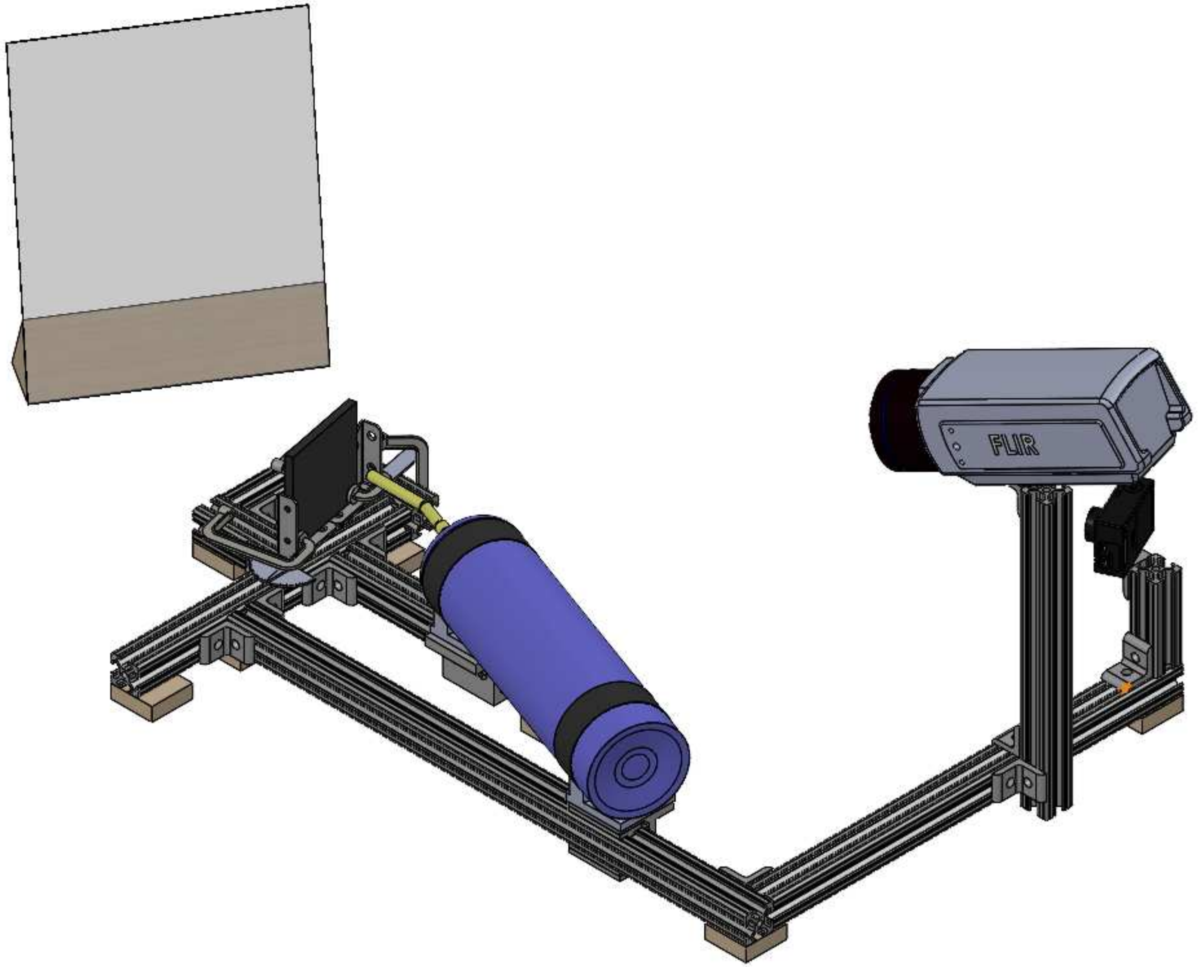
Ablative Materials

- Using proven ablative liners: rubber-based materials with fibrous fillers.
- Material is readily available in the form of gasket sheets.
- Fibers help retain charred rubber layer in place thereby reducing ablation rate
- Have sourced local vendors for liner sheets. We have secured free testing samples of a variety of sheets

Material	Cost/Sheet ($ CAD)	Dimensions (inch)
Durlon 8500 Aramid Fiber NBR	300	60 x 60 x 1/8
Donit Tesnit Doniflex Aramid Fiber NBR	329	59 x 58 x 1/8
Durlon 8400 Phenolic NBR	402	60 x 63 x 1/8
Garlock Blue-Gard 3000 Aramid Fibers NBR	412	60 x 60 x 1/8

Ablative Material Testing

- **Goal:** Compare relative ablation rates of various materials using fast, small scale testing
- Butane torch will be held to sample
- Variable flame angle and distance
- FLIR Camera and GoPro used to analyse test



Film Cooling

- Film cooling acts secondary to ablative cooling
- Coolant is injected parallel to direction of core flow
- In liquid film cooling, heat transfer directed to chamber walls evaporates the film coolant, reducing film thickness and producing a cooling effect
- NASA B model provides the necessary equations and information to calculate the film coolant length
- **Goal:** size orifices such that liquid phase reaches entire chamber length

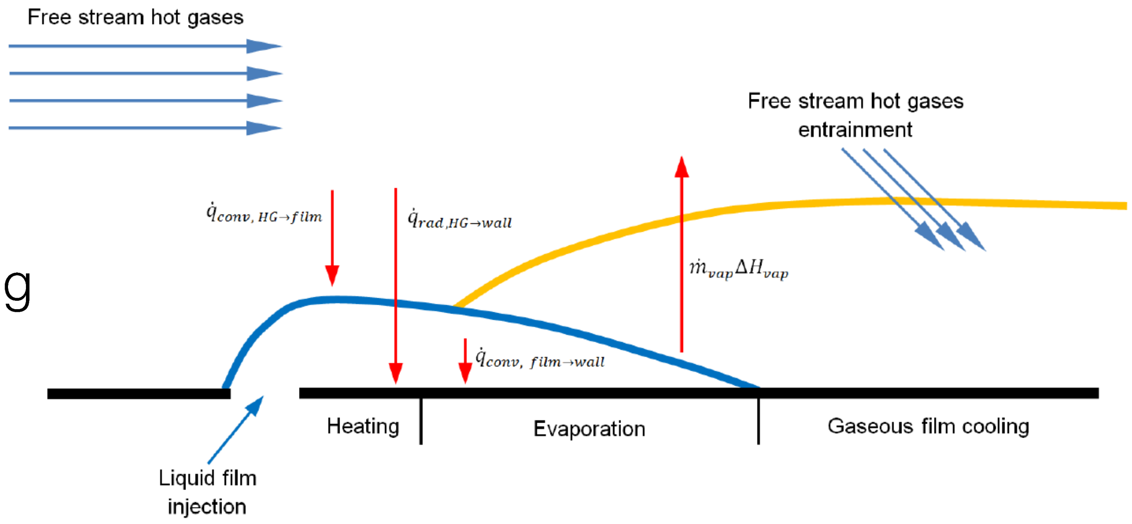
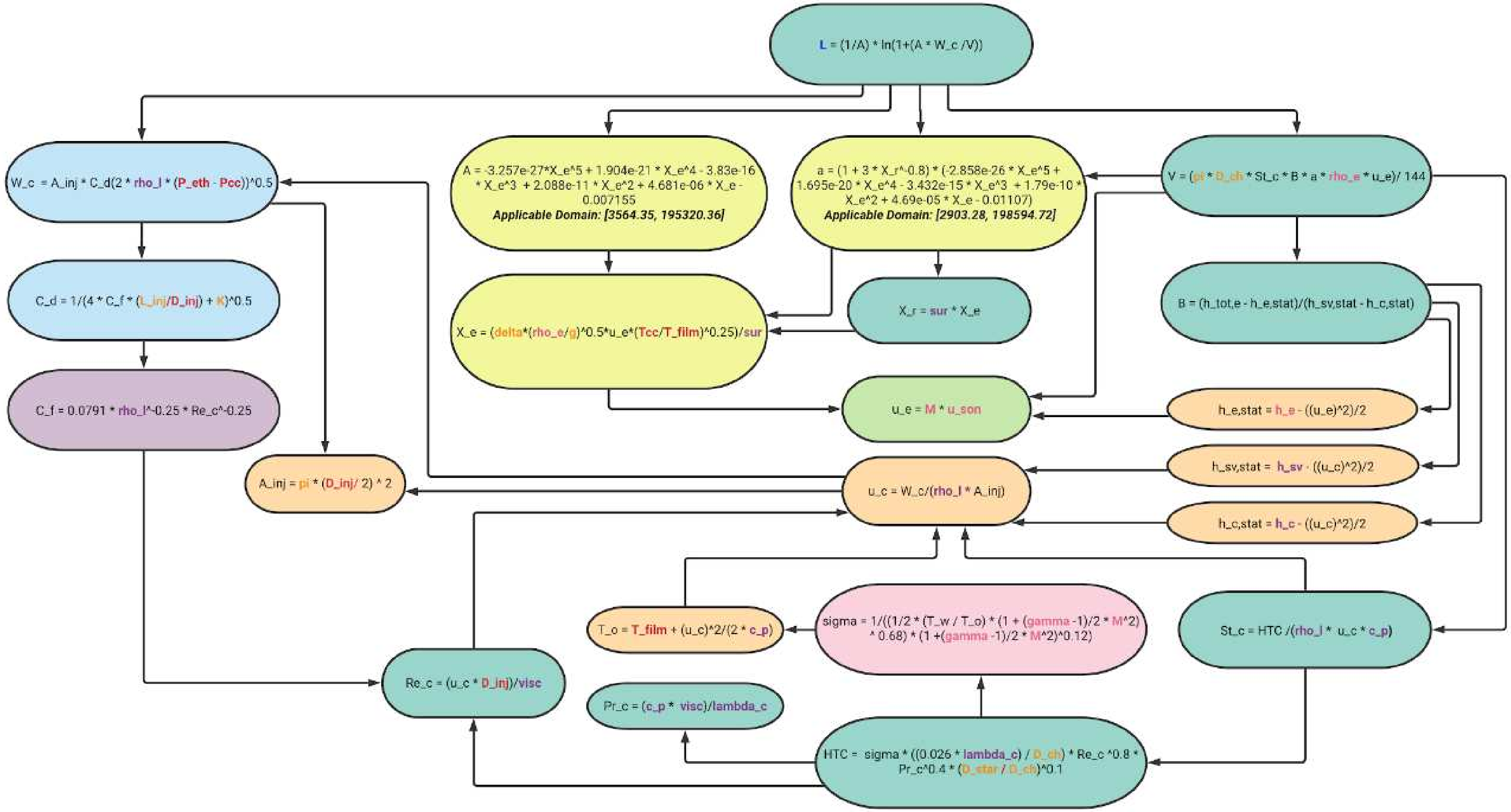


Figure 2.1: Model of film cooling process

Source: Trotti, M. (2012)

Film Cooling Algorithm



L = (1/A) * ln(1+(A * W_c /V))

W_c = A_inj * C_d(2 * rho_l * (P_eth - Pcc))^0.5

A = -3.257e-27*X_e^5 + 1.904e-21 * X_e^4 - 3.83e-16 * X_e^3 + 2.088e-11 * X_e^2 + 4.681e-06 * X_e - 0.007155
Applicable Domain: [3564.35, 195320.36]

a = (1 + 3 * X_r^-0.8) * (-2.858e-26 * X_e^5 + 1.695e-20 * X_e^4 - 3.432e-15 * X_e^3 + 1.79e-10 * X_e^2 + 4.69e-05 * X_e - 0.01107)
Applicable Domain: [2903.28, 198594.72]

V = (pi * D_ch * St_c * B * a * rho_e * u_e)/ 144

C_d = 1/(4 * C_f * (L_inj/D_inj) + K)^0.5

X_e = (delta*(rho_e/g)^0.5*u_e*(Tcc/T_film)^0.25)/sur

X_r = sur * X_e

B = (h_tot,e - h_e,stat)/(h_sv,stat - h_c,stat)

C_f = 0.0791 * rho_l^-0.25 * Re_c^-0.25

u_e = M * u_son

h_e,stat = h_e - ((u_e)^2)/2

A_inj = pi * (D_inj/ 2) ^ 2

u_c = W_c/(rho_l * A_inj)

h_sv,stat = h_sv - ((u_c)^2)/2

h_c,stat = h_c - ((u_c)^2)/2

T_o = T_film + (u_c)^2/(2 * c_p)

sigma = 1/((1/2 * (T_w / T_o) * (1 + (gamma -1)/2 * M^2) ^ 0.68) * (1 +(gamma -1)/2 * M^2)^0.12)

St_c = HTC /(rho_l * u_c * c_p)

Re_c = (u_c * D_inj)/visc

Pr_c = (c_p * visc)/lambda_c

HTC = sigma * ((0.026 * lambda_c) / D_ch) * Re_c ^0.8 * Pr_c^0.4 * (D_star / D_ch)^0.1

REFERENCES

- Karnal, M [3]
- Niño & Razavi [4]
- NASA-SP-8124 Paper [5]
- CEA Analysis [7]
- Trotti Master's Thesis [9]
- Waxman Dissertation [10]
- General Knowledge

LEGEND

Blue: output
Red: proposed input
Orange: constant
Pink: from RocketCEA
Purple: from CoolProp

Arrow Convention: tip points in direction of variables to be calculated

Next Steps

- Finalize BOM for ablative material test stand, purchase, assemble
- Test ablative material coupons
- Finish implementing film cooling model
- Implement model in python simulation

FUTURE PLANS

Next Steps

- System simulation
  - Finish python simulation
  - Use the simulator to drive preliminary rocket design
- Routing & Plumbing
  - Confirm sizing of valves, fittings, and tubing
  - Redesign Oxidizer and Fuel tank Caps
- Pressurization Control System
  - Implementation of needle valve for ethanol tank
  - Validate results against the complete python simulation
- Injector
  - Modify pintle dimensions according to design code
  - Determine dimensions for O-rings and bolts
- Engine
  - FEA analysis of Nozzle to verify structural integrity
  - Choose and develop ignition system
- Engine cooling
  - Test ablative material coupons
  - Finish implementing film cooling model

Questions?