Hybrid Rocket Design

MSU ROCKETRY

Hybrid Engine

Items:

- Brief Overview
- Hybrid Engine Physics
- Analysis and Modeling
- Final Design
- Testing
- Financial
- Future Improvements

Hybrid Engine

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- **Brief Overview**
- Hybrid Engine Physics
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Motivation

- New challenge
- More competition points
- Throttling capability
  - Only want on / off with this motor iteration
- Increased safety
  - Separated fuel / oxidizer storage
- More applicable to industry
- Put us on par with most other student rocket teams

Development Team

- Lead: Jordan Thayer
- Aerothermodynamics: Suhas Kodali
  - Member(s): Sarah Wegert, Douglas Heine
- Structures: Evan Patton
  - Member(s): Austin Smith, Tony Anason

Hybrid Engine

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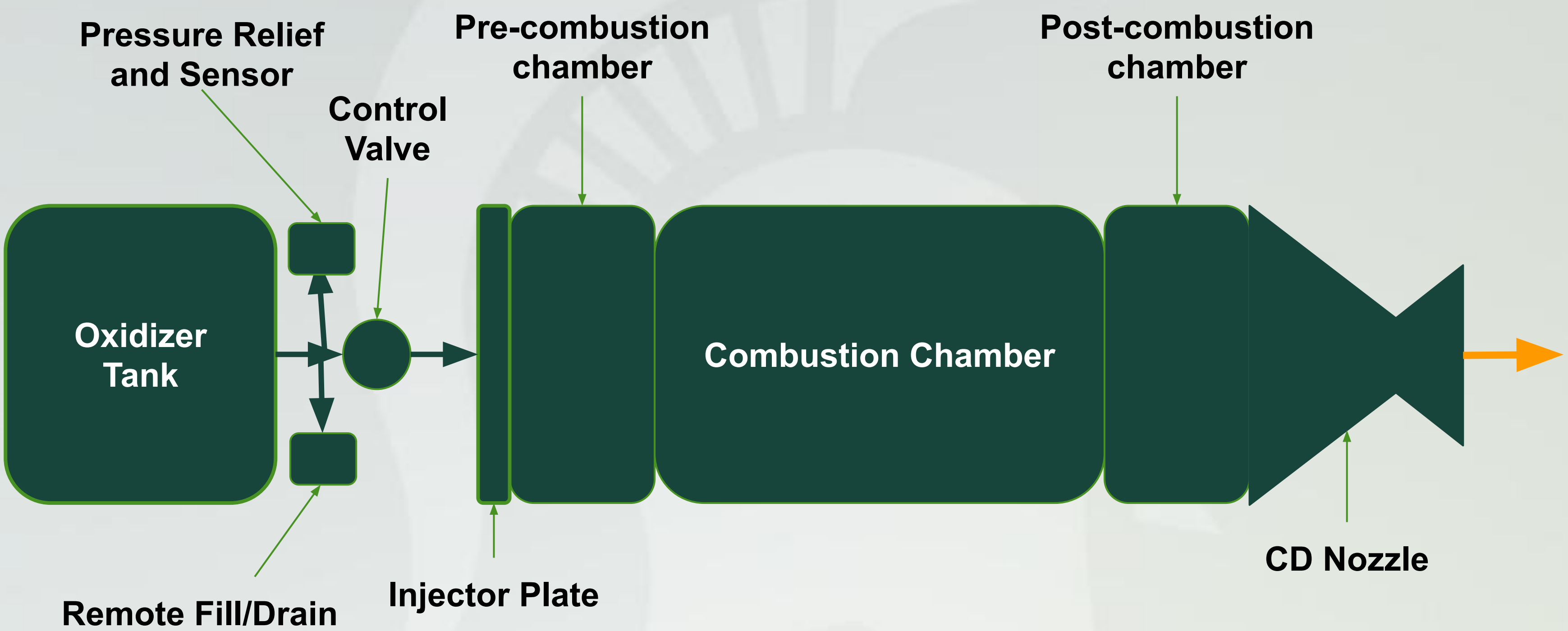
Hybrid Engine Schematic



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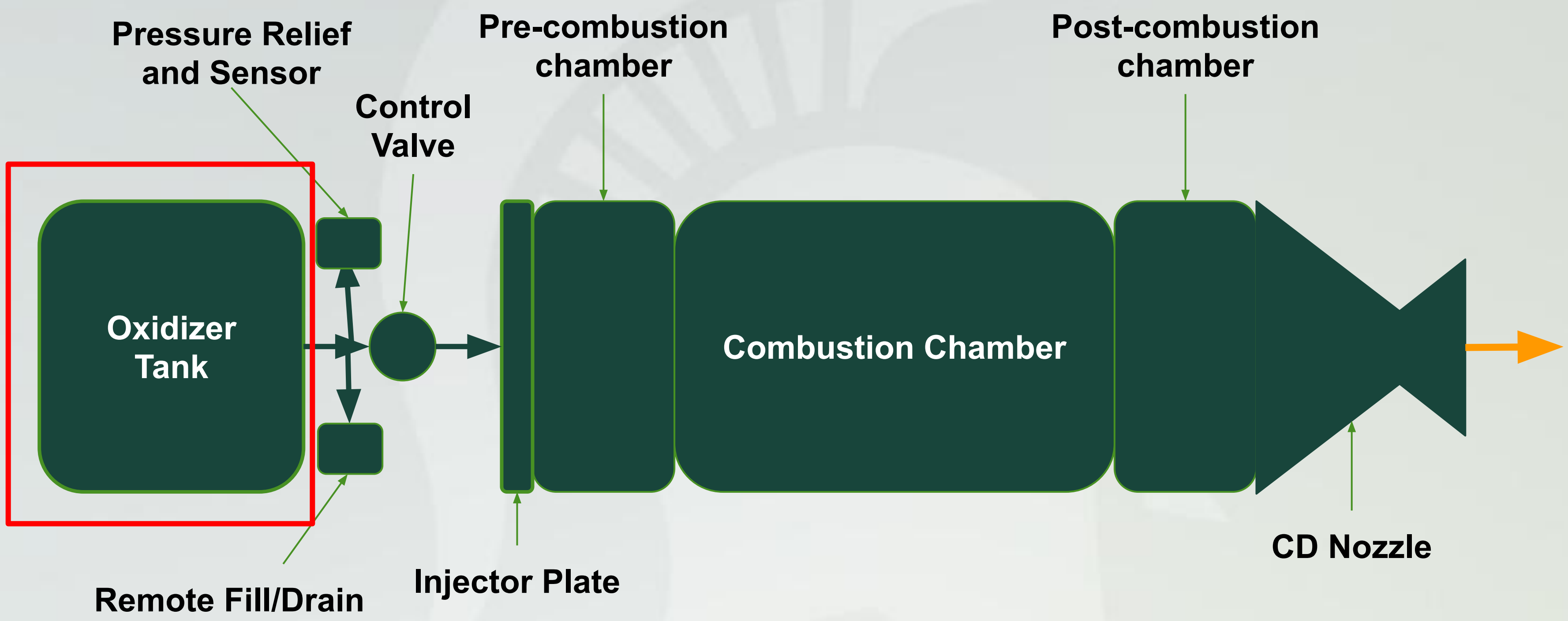
Hybrid Engine Schematic



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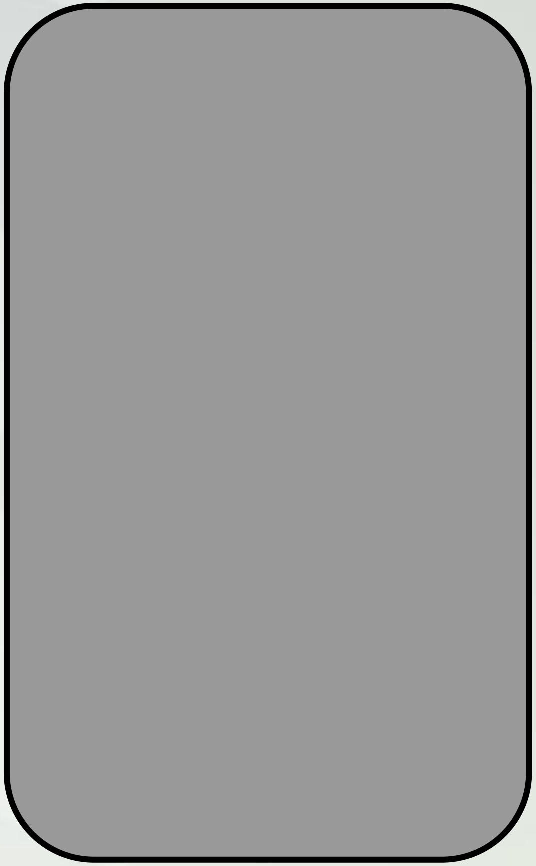
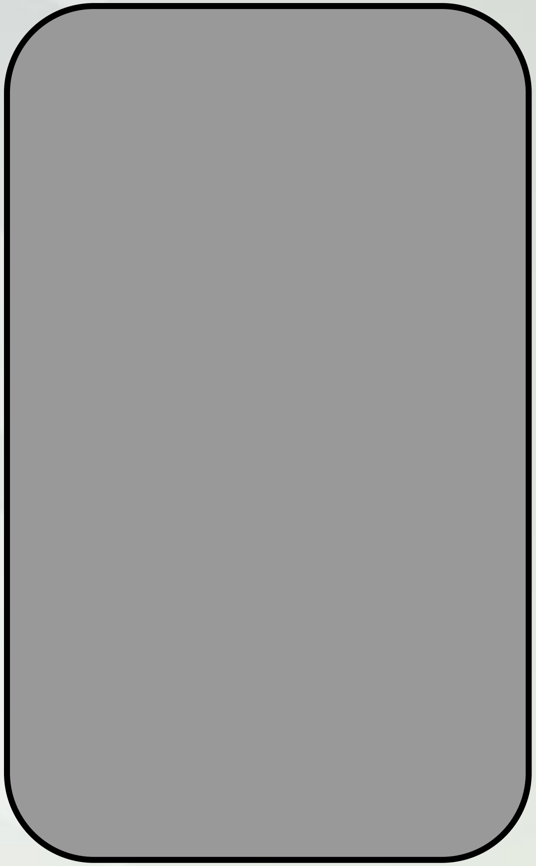
Tank - Physics

- The nitrous oxide tank is a closed-volume at a burn time of -0 seconds
- The walls of the tank are assumed to adiabatic
  - In reality, solar radiation and natural convection exchange heat with the rocket on the pad



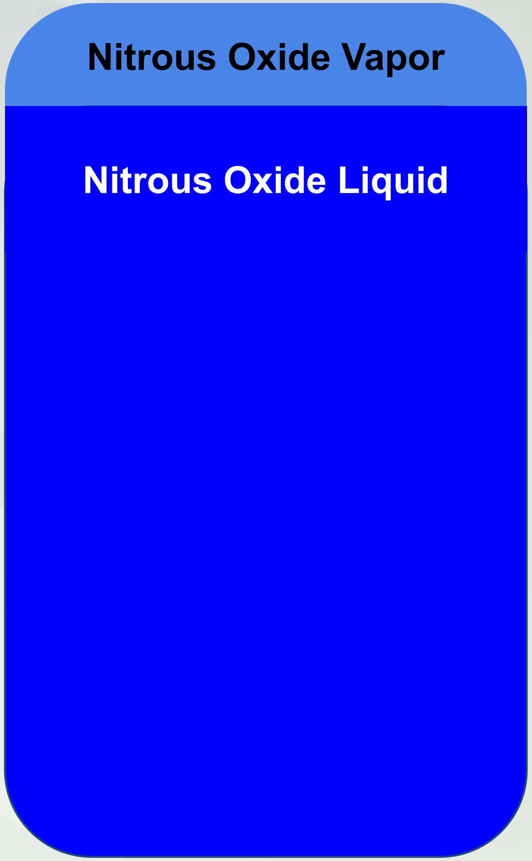
Tank - Physics

- Without heat addition, the initial state of the nitrous oxide can be determined and assumed constant until the run valve is opened
- The vapor pressure of nitrous oxide is higher than normal, ambient pressure at desert morning temperatures



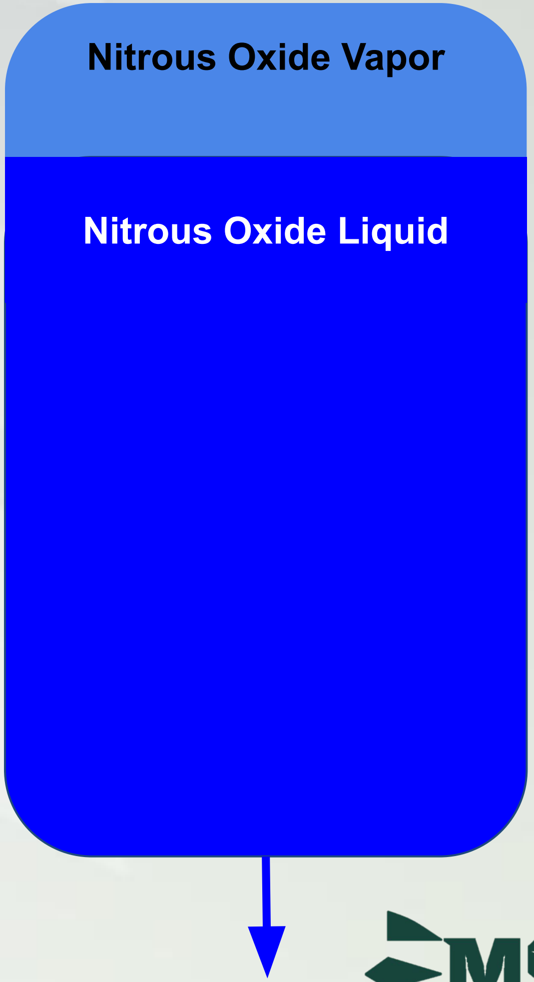
Tank - Physics

- Based on the residual tank volume not filled with liquid nitrous, the top layer of liquid nitrous will vaporize until the gaseous and liquidus nitrous states are at equilibrium at the vapor pressure
  - Renault's Law



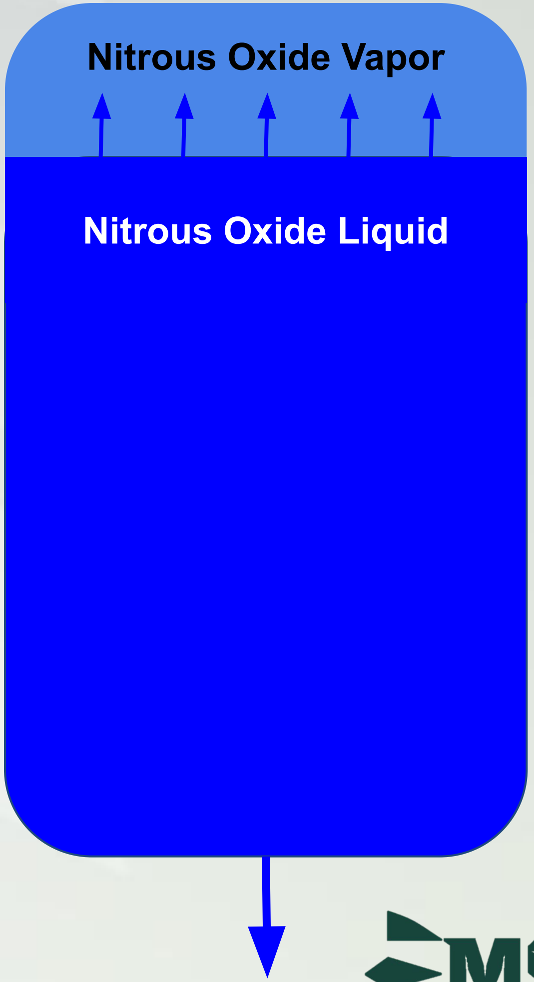
Tank - Physics

- At the burn time instant of +0 seconds, when the tank is drained, the removal liquid nitrous allows the vapor nitrous to expand
  - Dropping the static pressure below the vapor pressure



Tank - Physics

- Since the liquid nitrous oxide static pressure is now below the vapor pressure, the top layer continues to vaporize until the vapor is returned to the vapor pressure



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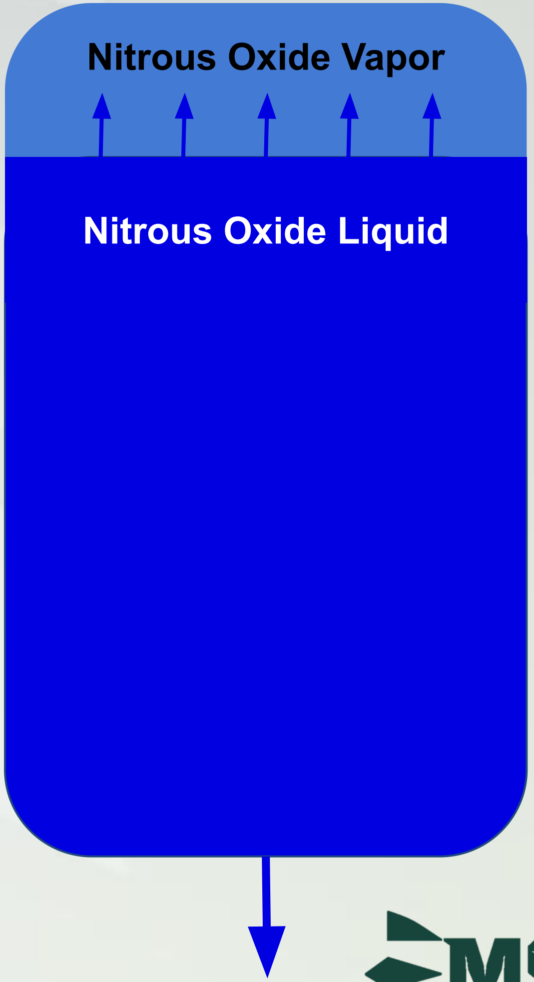
Tank - Physics

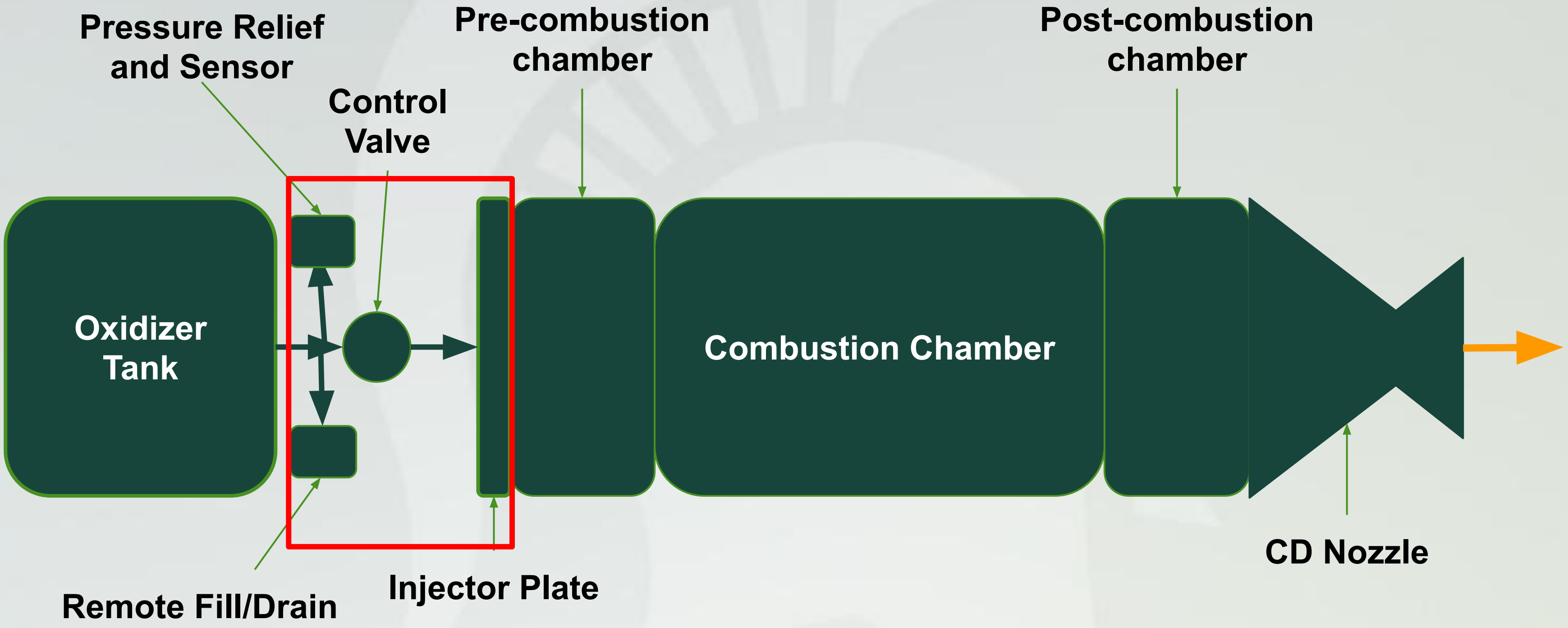
- However, the process to vaporize nitrous requires energy from the liquid nitrous
  - Adiabatic cooling
- Based on the new temperature and vapor volume, a lower equilibrium pressure is reached



Tank - Physics

- The temperature and pressure of the liquid nitrous drops with time until the tank is filled with only vapor at the end of the burn
  - Consequently, the oxidizer mass flow rate decreases with time
    - Reducing thrust

Hybrid Engine Schematic



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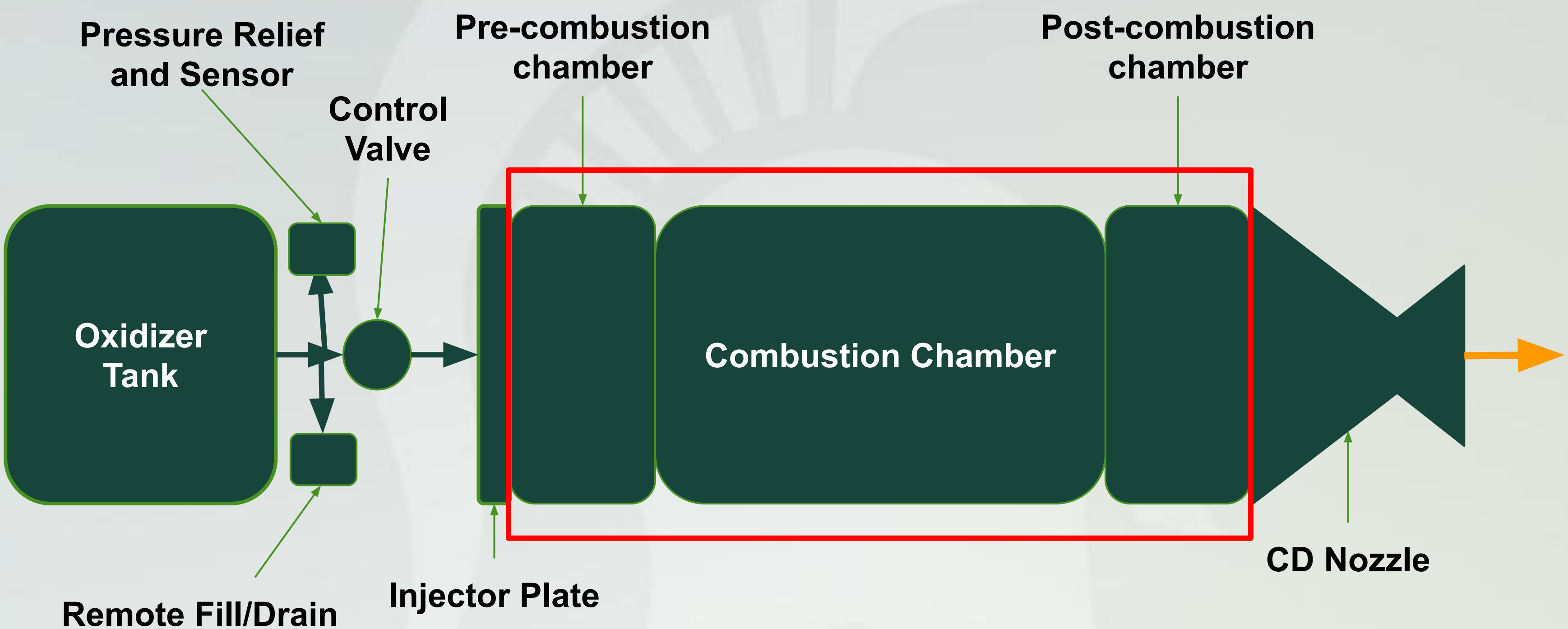
Hybrid Engine Schematic



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Chamber - Physics

- Atomized nitrous oxide enters pre-chamber
  - Atomizing increase heat transfer rate [1]
    - Higher surface area / volume ratio
  - Pre-combustion chamber size driven by vaporization residence time [3]
    - Swirl increases residence time

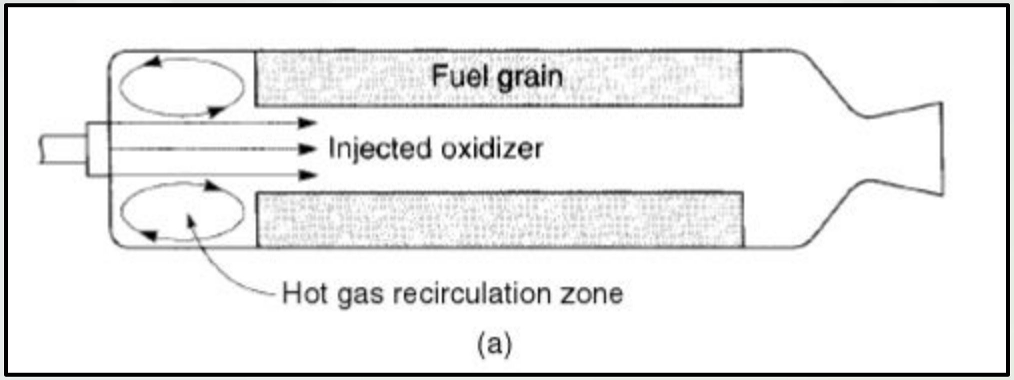


Figure 16.12 from Rocket Propulsion Elements

Chamber - Physics

- Vaporized (cold) nitrous flows over HTPB fuel surface
    - Convective heat transfer drives fuel surface regression at higher oxidizer mass flux levels
    - Radiation contribution dominates at lower mass flux levels [2]
        - Additives and other fuels contribute particulates into the free stream, increasing radiation contribution as well [2]

Chamber - Physics

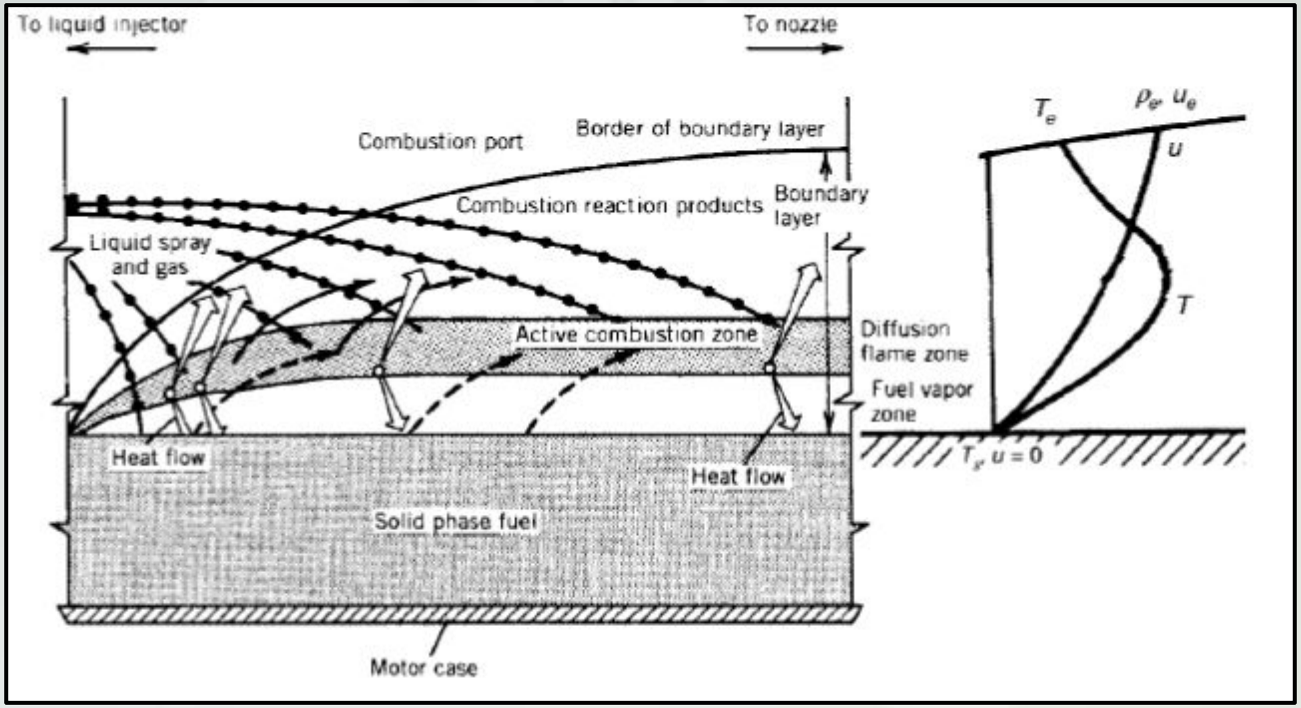


Figure 16.5 from Rocket Propulsion Elements

Chamber - Physics

- Fuel surface regresses with time
  - Decreasing oxidizer mass flux
  - Decreasing regression rate
  - Decreasing thrust

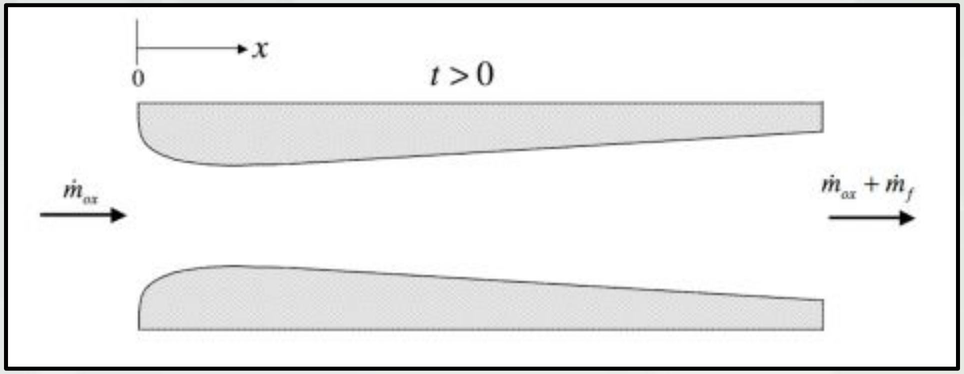
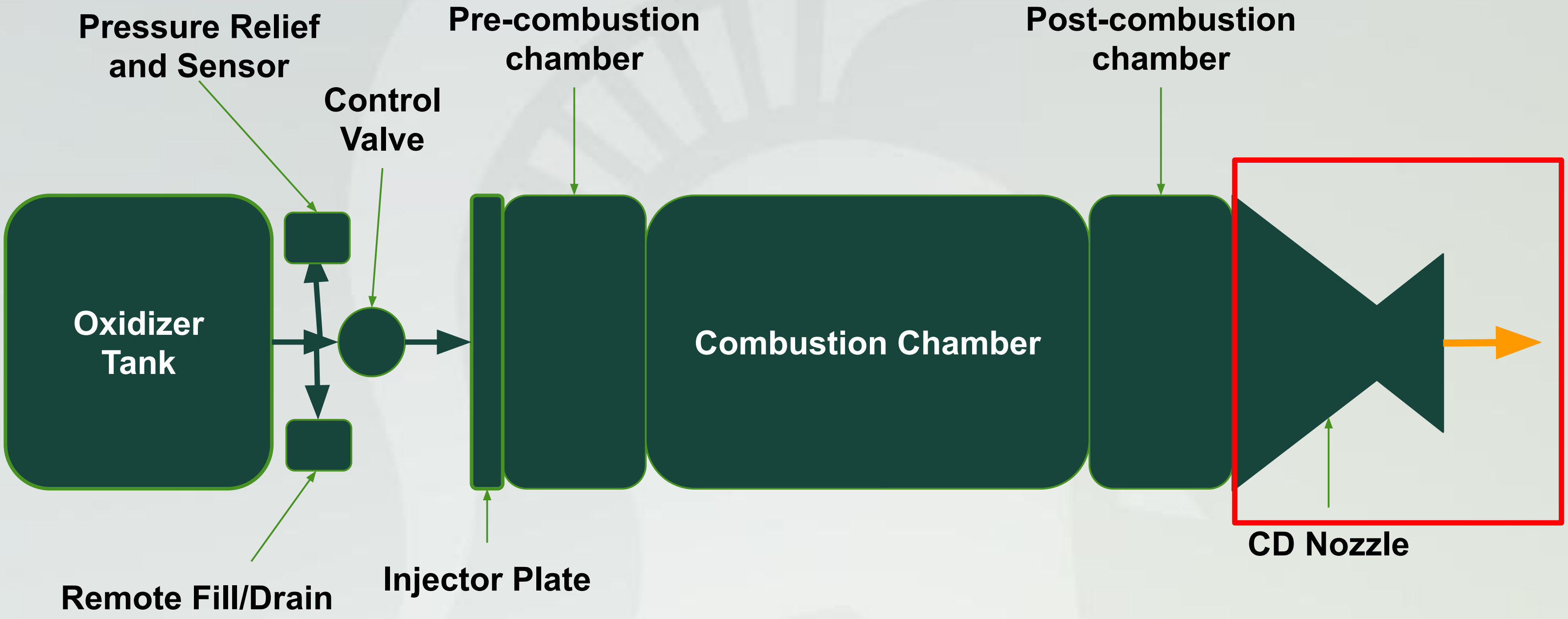


Figure 11.15 from Stanford University's AA283 Course Notes

Hybrid Engine Schematic



Nozzle Physics

- Converts thermal energy into kinetic energy
- High pressure / temperature flow at inlet
- Accelerates to throat, then expands to supersonic flow at outlet

Nozzle Physics

- All current analysis assumes the following:
  - Isentropic
  - Frozen Equilibrium (no more chemical changes)
  - Inviscid
  - No shocks

- Essentially, isentropic relations and supersonic flow tables were used

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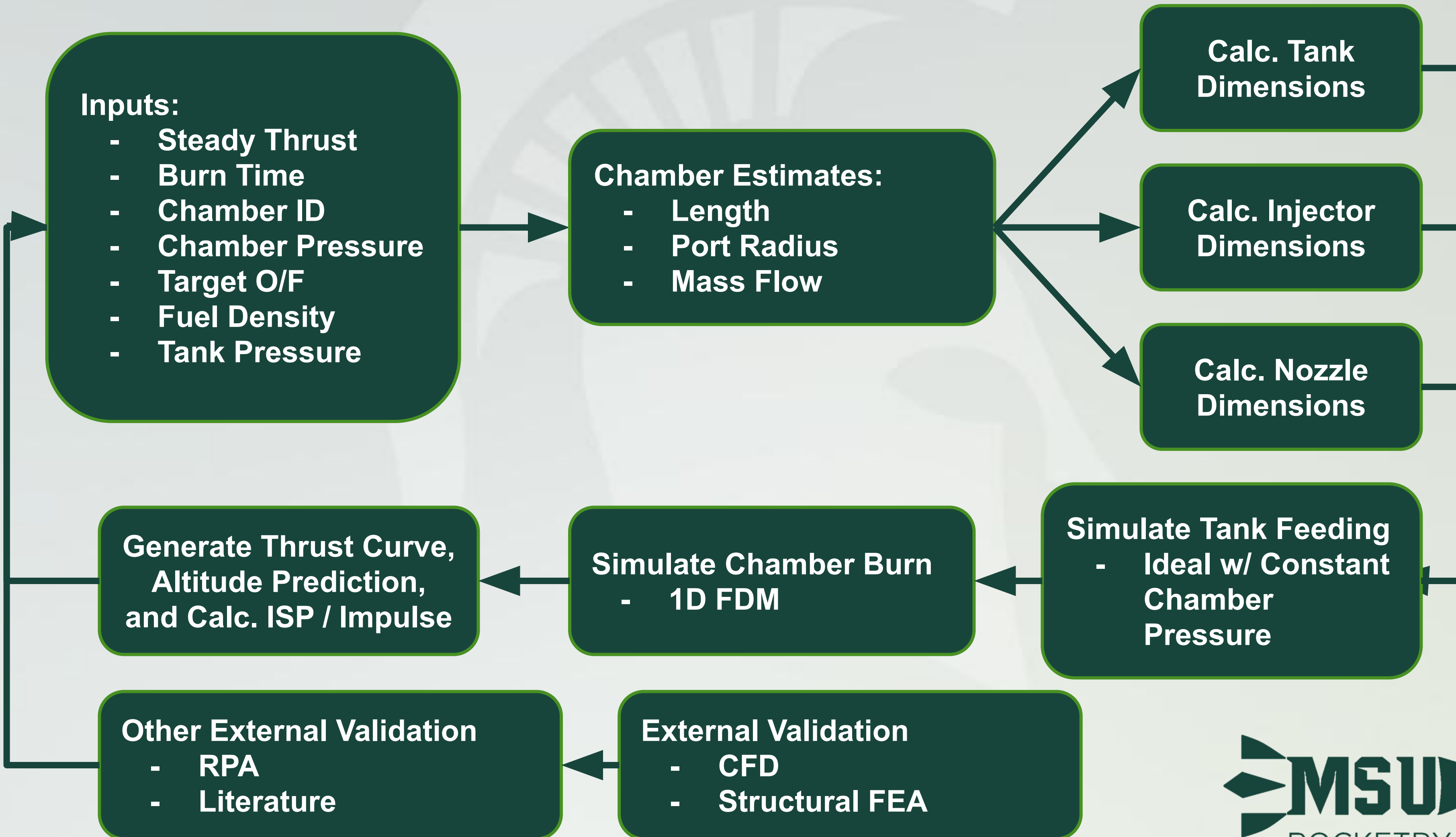
MATLAB Design Program



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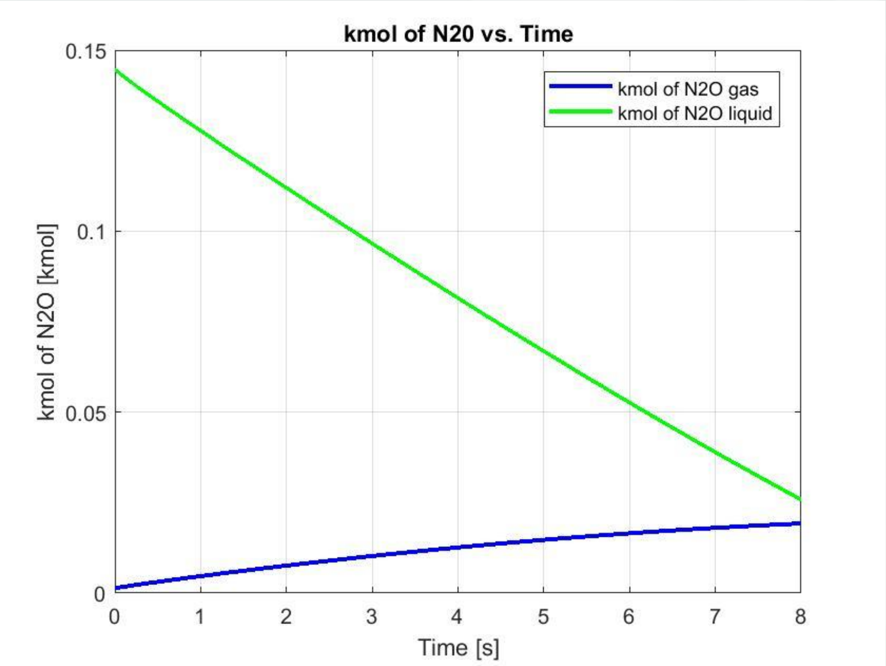
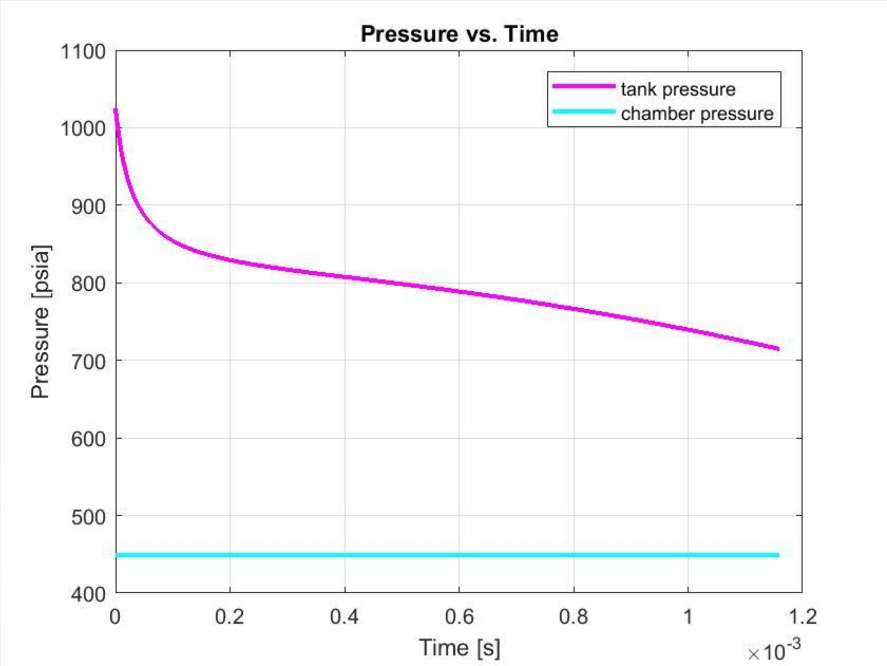
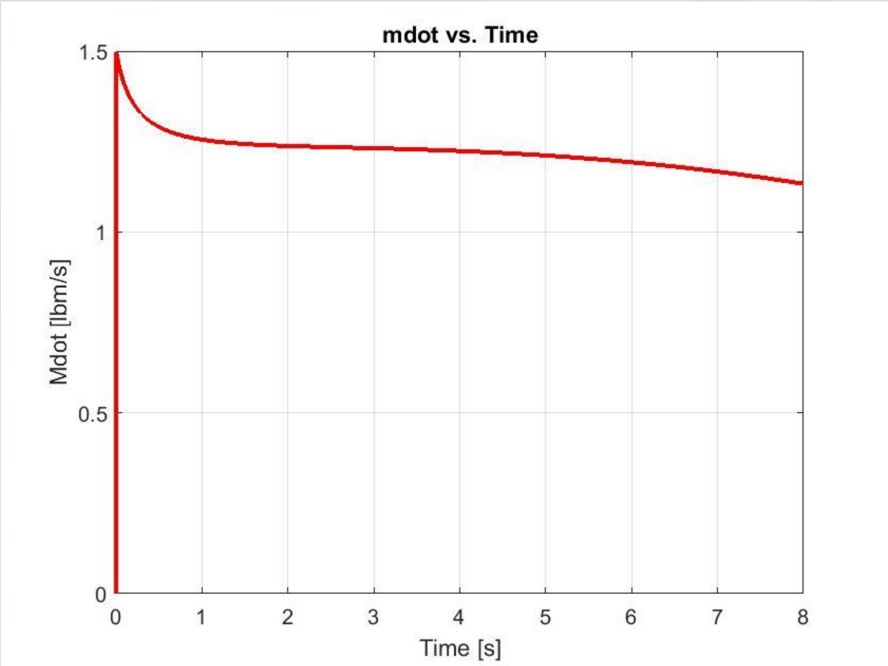
Injection System Modeling

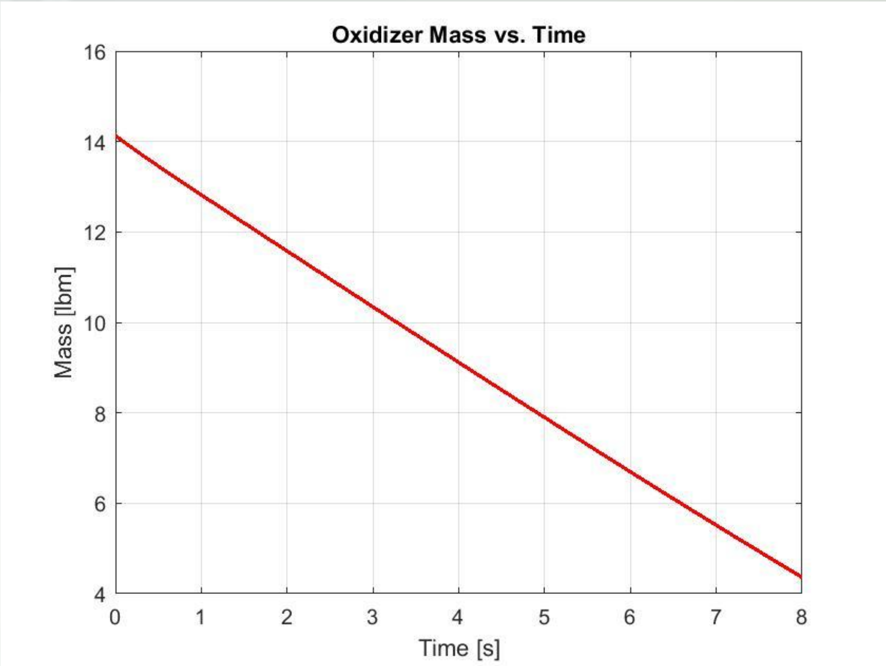




Modeling N2O Tank Bleed - Ideal Gas

Injection System Modeling





Modeling N2O Tank Bleed - Ideal Gas

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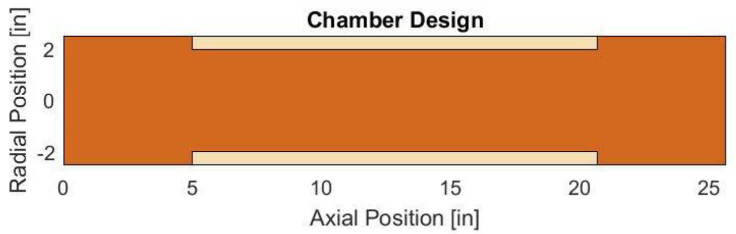
Fuel Grain Regression Modeling

- To initially size the fuel grain:
  - Target peak thrust
  - Burn time
  - Chamber ID
  - Peak chamber pressure
  - Peak oxidizer / fuel ratio
  - Final fuel grain radius

- Example 16.4 from RPE



	1	2	3
1	Chamber Length	in	25.6865
2	Port Radius	in	1.9694
3	Avg. Regression Rate	in/s	0.0368
4	Total Mass Flow	lbm/s	2.0091
5	Oxidizer Mass flow	lbm/s	1.7727
6	Fuel Mass flow	lbm/s	0.2364
7	Oxidizer Mass	lbm	14.1816

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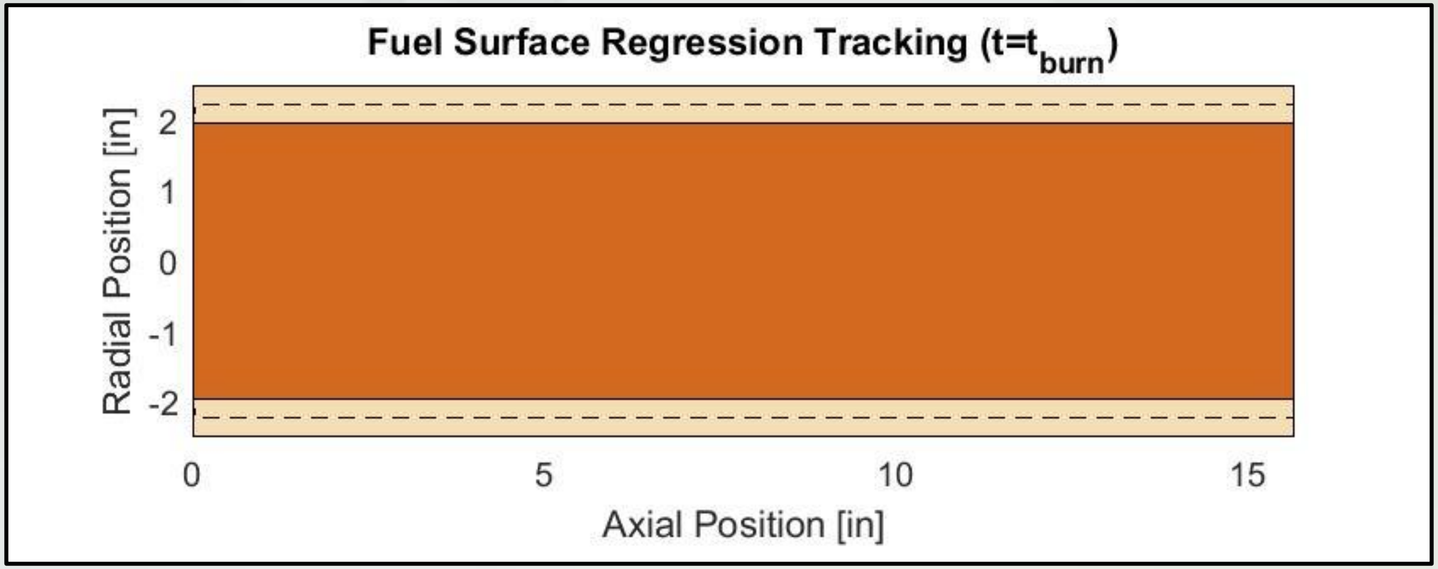
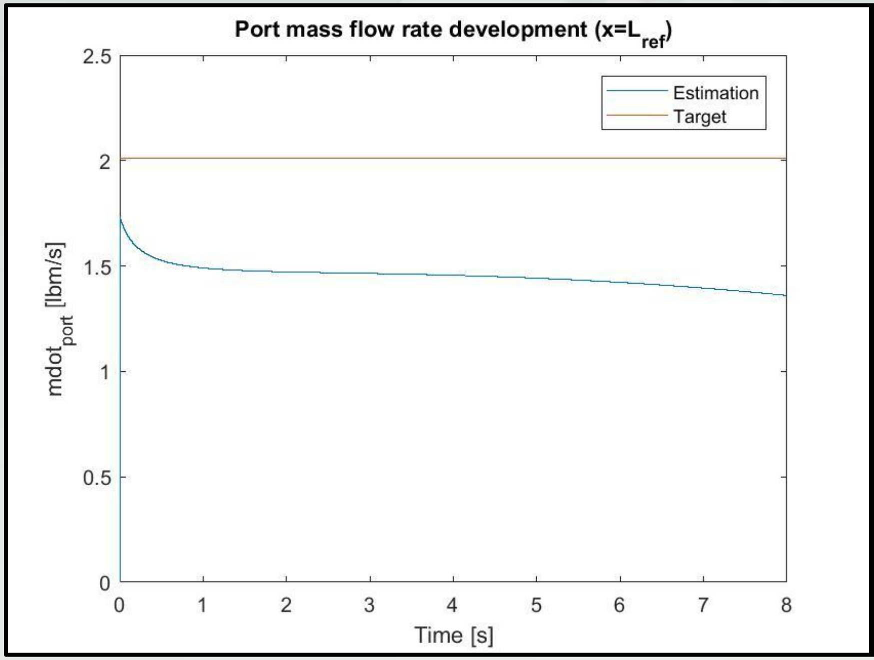
Fuel Grain Regression Modeling

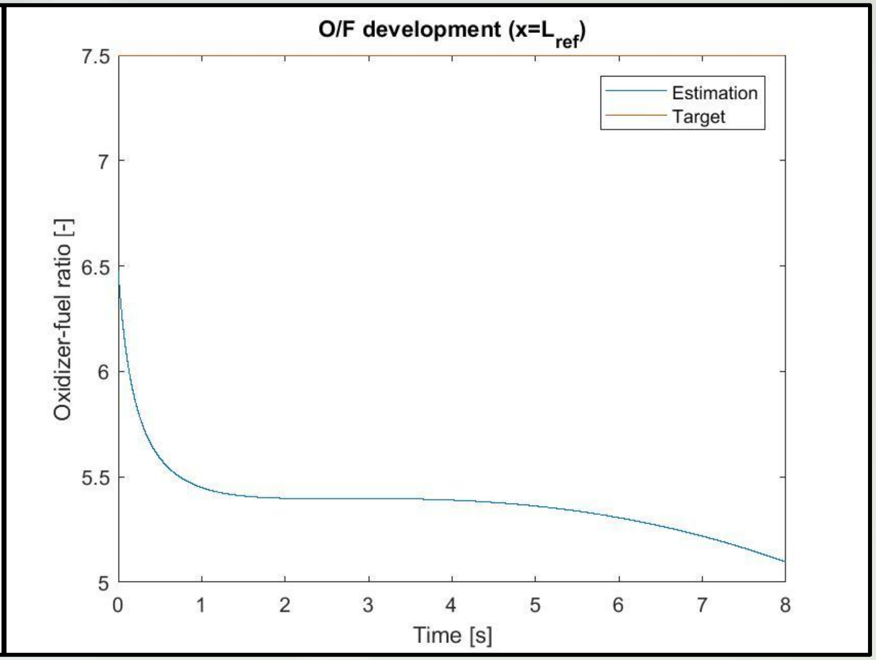
- Numerically solved fuel regression based on transient oxidizer mass flow model
  - Based on Stanford (Cantwell) course notes



Fuel Grain Regression Modeling

- Compute transient characteristic velocity





Ideal Nozzle Analysis

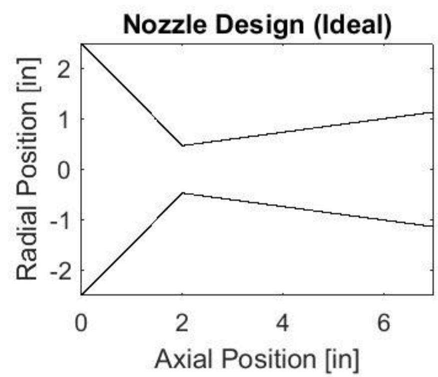
- Assumptions:
  - Compressible, adiabatic, steady, and inviscid
  - Need pressure, velocity, and temperature to characterize flow
    - Continuity, momentum, and energy
  - Flow in chamber is slow
    - Inlet stagnation pressure = inlet static pressure

- Isentropic flow relations allow the flow to be solved without having to solve momentum and energy

Ideal Nozzle Analysis

Recall: Total pressure = Static + Dynamic

Ideal Nozzle Modeling



	1	2	3
1	Total Length	in	6.9571
2	Inlet to Throat	in	2
3	Throat to Outlet	in	4.9571
4	Expansion Ratio	-	5.8191
5	Contraction Ratio	-	28.2629
6	Inlet Diameter	in	5
7	Throat Diameter	in	0.9405

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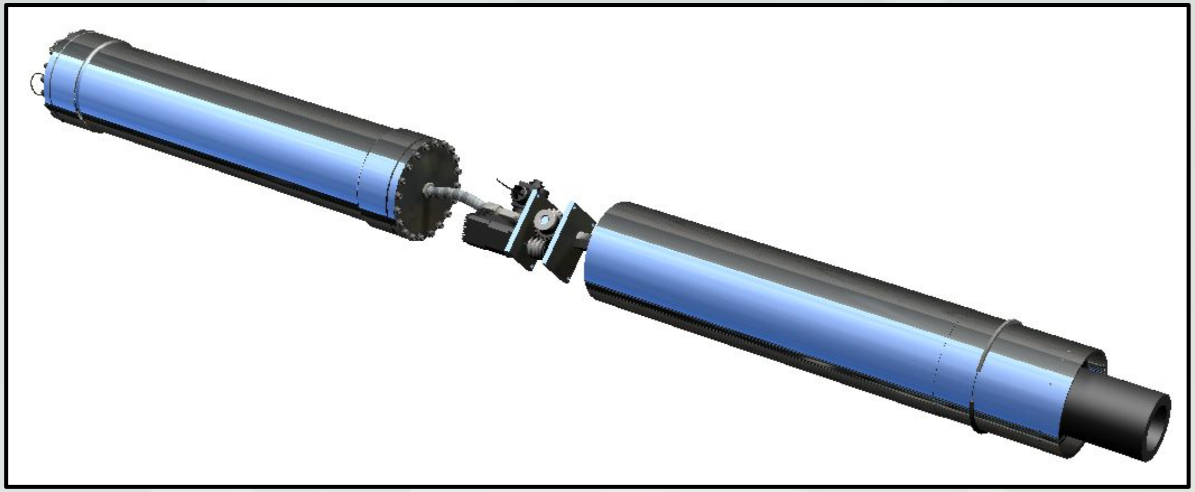
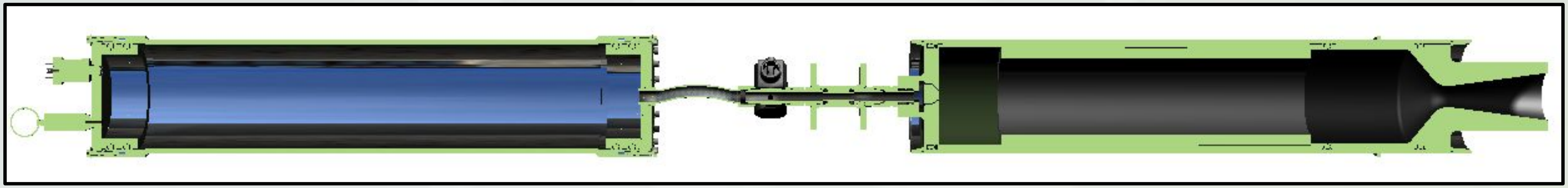
Final Design Overview

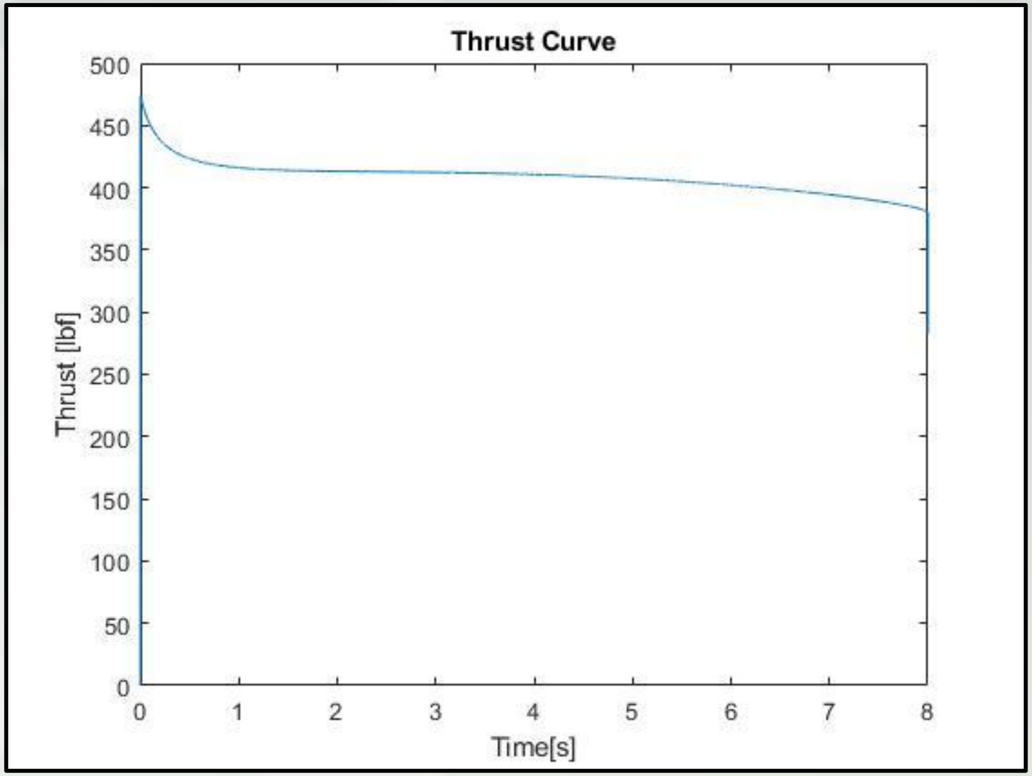




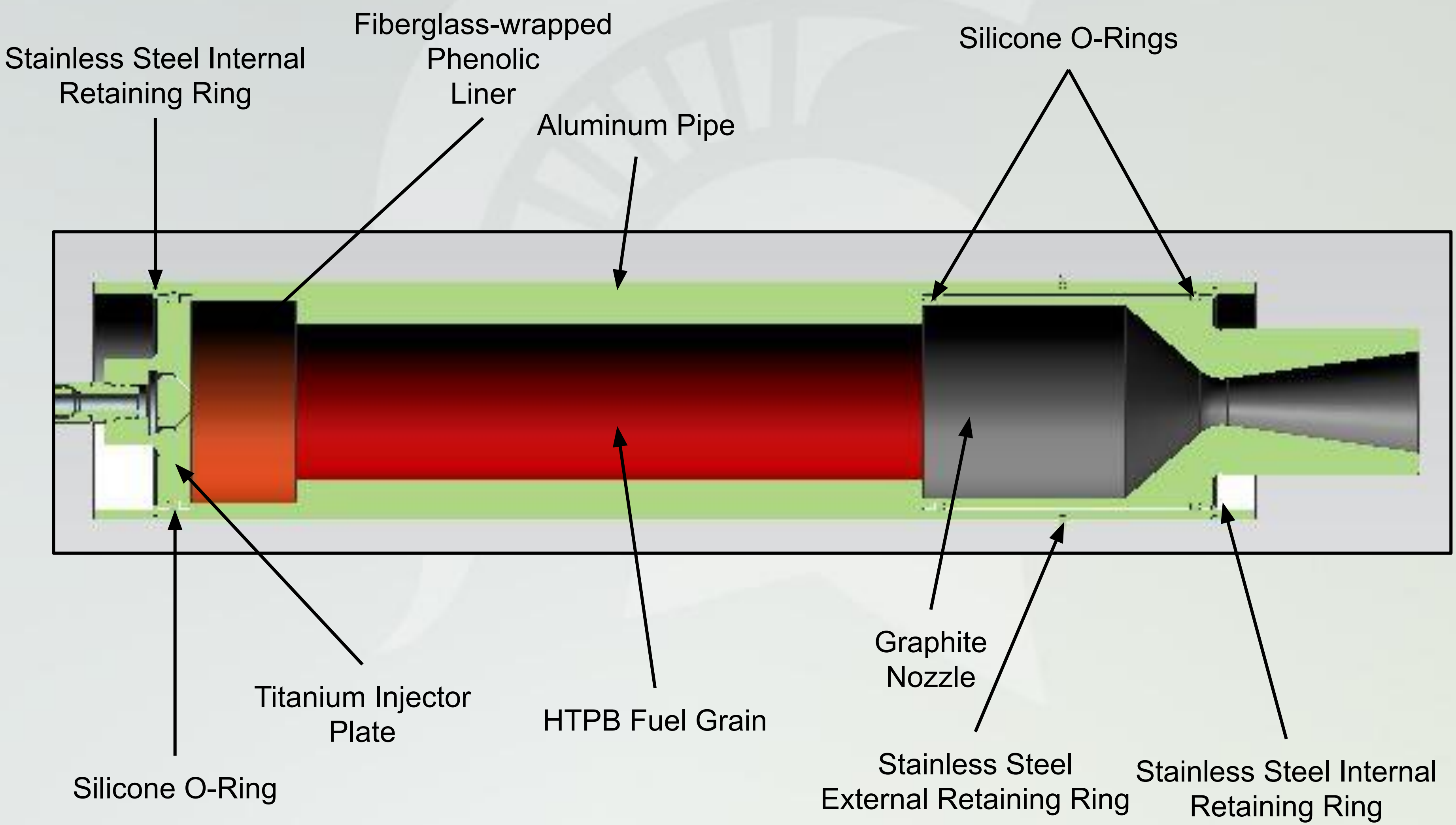
Fuel: HTPB
Oxidizer: Nitrous Oxide

Predicted Performance

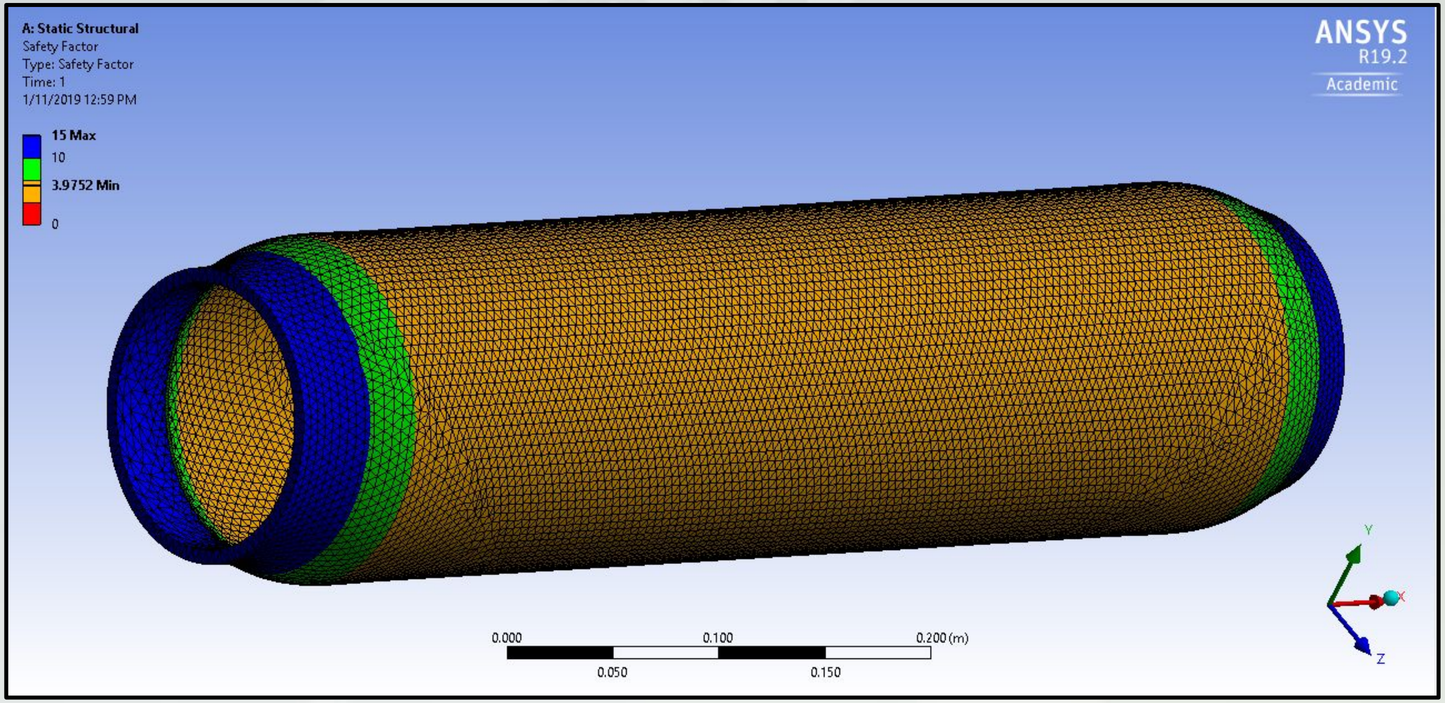
Peak Thrust	475 lb
Total Impulse	3800 lb-s
Burn time	8 s
Propellant Mass	18.5 lb
ISP	211 s
Total Length	83 in
Outer Diameter	5.5 in
Total Weight	65 lb
Peak Thrust to Weight	6.7
Design Altitude	14,000 ft



Chamber Design Overview



Chamber Structural Modeling



Fuel / Oxidizer Selection

- We needed a combination that fulfilled the following needs:
  - Reliable data and case studies in literature
  - Could not be hazardous to store or transport
  - Oxidizer with less required mechanical parts
    - Cooling system
    - Pumps
  - Fuel could not melt on the pad
    - Although wax-based offers higher regression, wax-based fuels melted in hot desert

Fuel / Oxidizer Selection

- Fuel: HTPB
- Oxidizer: Nitrous

- HTPB is safe to store and transport and will not melt on the pad
- Nitrous is self-pressurizing at room temperatures
  - High vapor pressure drives liquid flow in tank
  - Critical temperature is near noontime temperature in Las Cruces
    - Early morning flight

Chamber - Design

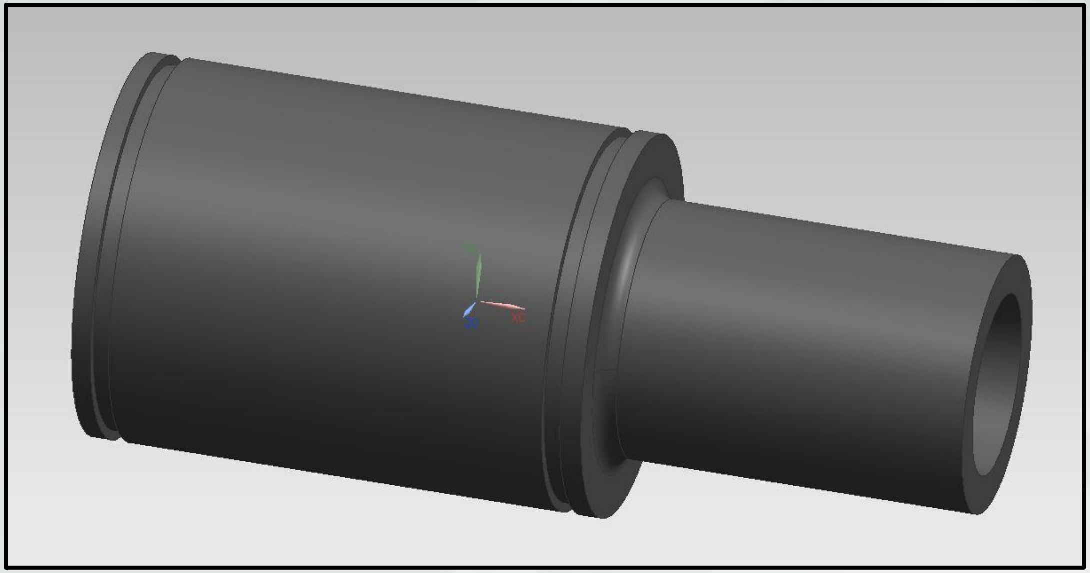
- Need pre-chamber
  - Oxidizer ignition and mixing
- Post-chamber also highly recommended
  - Letting reaction become more complete before entering nozzle
  - Mass addition may offset thrust benefit

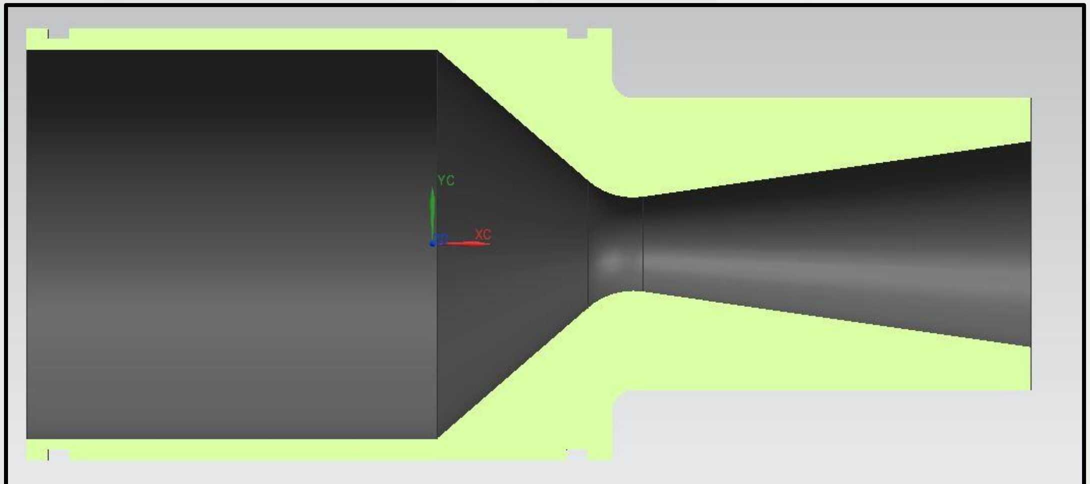
- Recommended pre-chamber ratio: .5 - 1 ID
- Recommended post-chamber ratio: .5 - 1 ID

Ignition System Design Plans

- **Manufacturing and operating procedure needs discussion and advisement for safety**
- Current plan:
  - Buy a ring of solid rocket fuel (likely ammonium perchlorate) and lay in pre-chamber
  - Install ematch when rocket is on pad and remotely send current through ematch
  - After lighting solid fuel, slowly bleed nitrous oxide into the combustion chamber until pre-chamber is sufficiently heated and ignition is achieved

Nozzle Design Overview





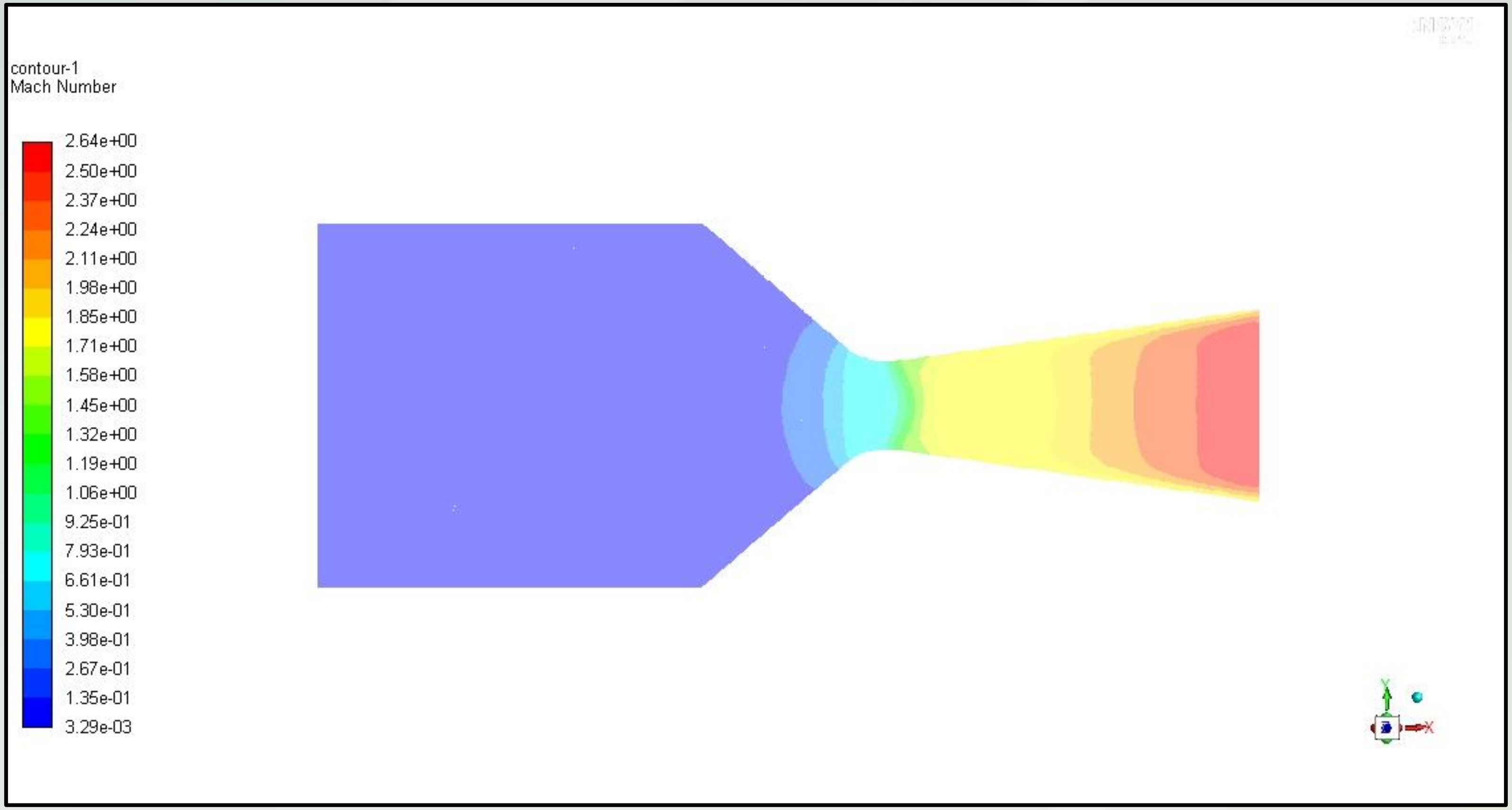
Total Length	11.63 in
Design Elevation	3000 ft
Expansion Ratio	4.84
Contraction Ratio	17.32
Exhaust Mach	2.168

Melting point is far above exhaust gas temperature

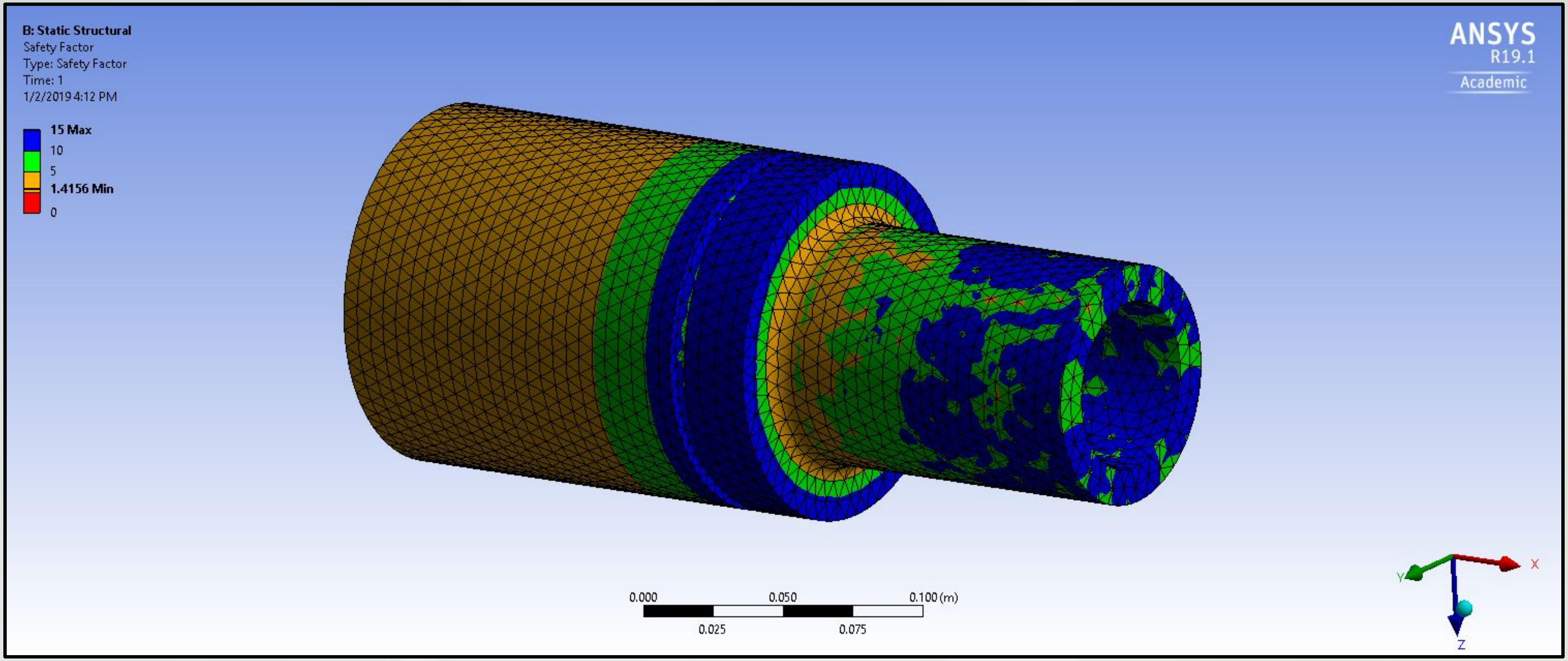
Nozzle Fluid-Structure Modeling

- Simulate steady-state nozzle flow at maximum OF in ANSYS Fluent
  - Highest chamber pressure / exhaust temperature
- Import steady-state nozzle flow as a BC in ANSYS Mech
  - Static structural
    - Strain induced by pressure / temperature
  - Transient thermal
    - Nozzle heating
    - Chamber wall heat flux estimate

Nozzle Fluid-Structure Modeling



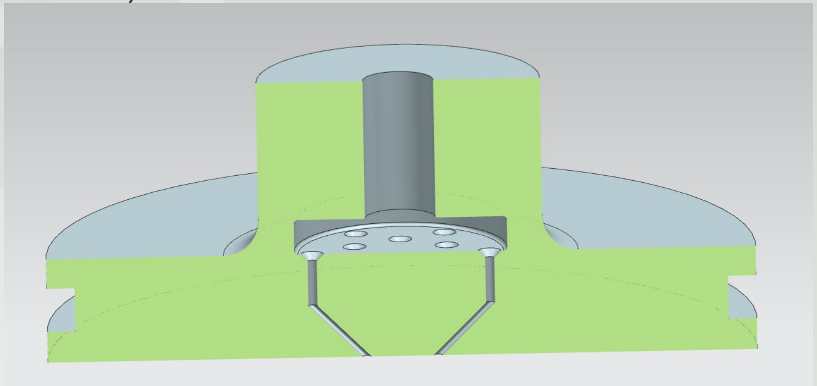
Nozzle Fluid-Structure Modeling



Injector Design Overview

- Total injector hole area based off of calculated mass flow (0.3834 in^2)

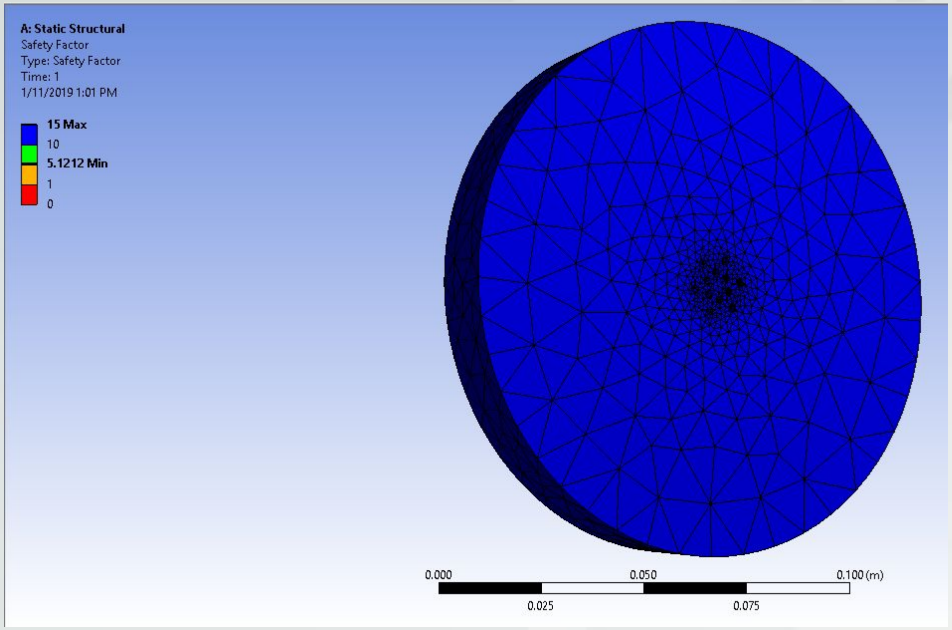
Number of injection holes	12
Injection hole diameter	0.06378 in (about 1/16th inch)
Impingement angle	~60° - 90°

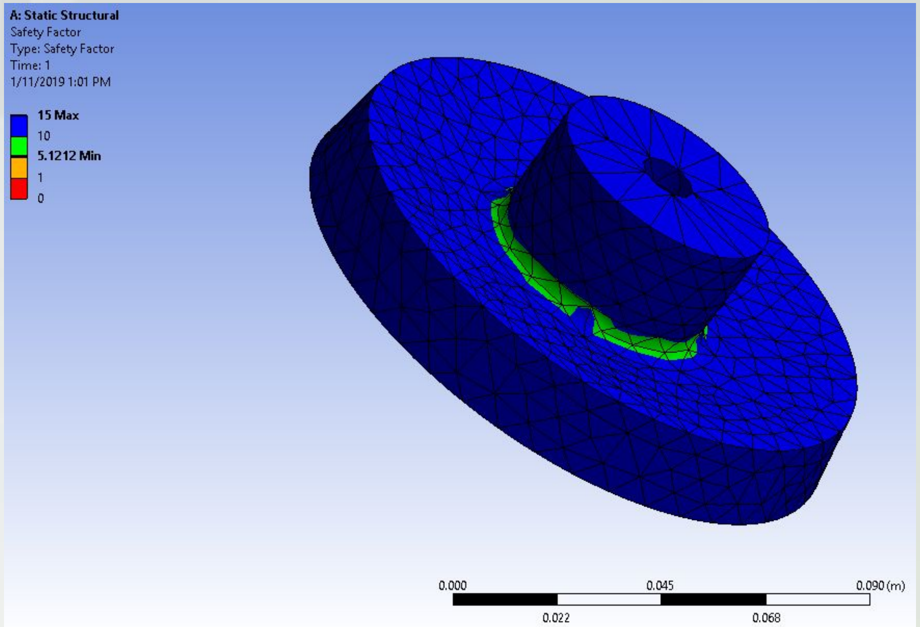


- Material: LaserForm **Ti Gr23 (A)**

Property and Condition	**U.S.**	**Metric**
Thermal Conductivity @ 50°C	3.87 Btu in/(h*ft²°F)	6.7 W/(m*k)
Coeff. Of Thermal Expansion (20-600°C)	4.8 μ inch/(inch . °F)	8.6 m/(m*°C)
Melting Point	3046 °F	1692 °C
Surface Roughness (Vertical)	200-400 μin	5-10 μm

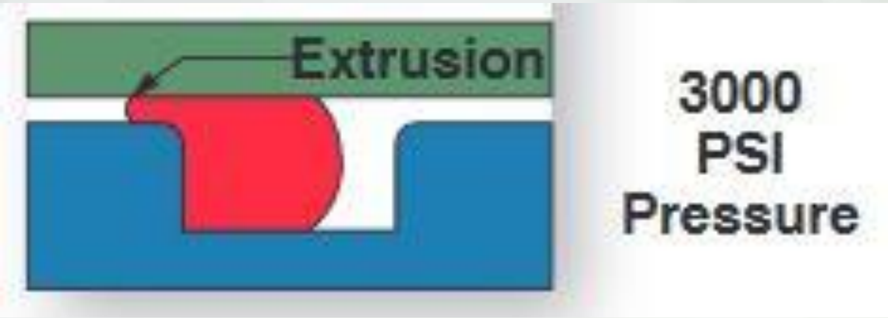
Injector Structural Modeling





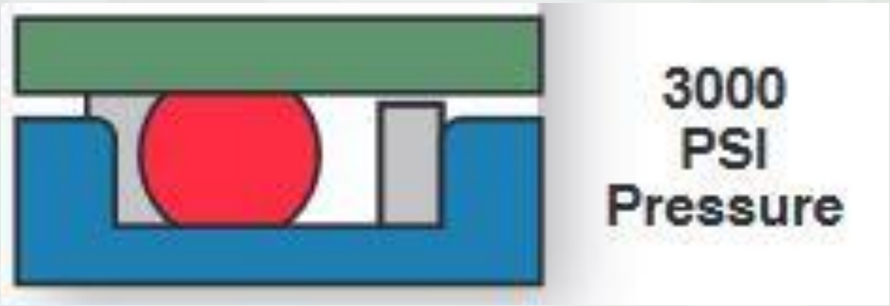
Tank Seal Design

- Nearly 3000 psi pressure differential across the seal during hydro testing
  - Could force the seal into the diameter gap, causing leaks and failure

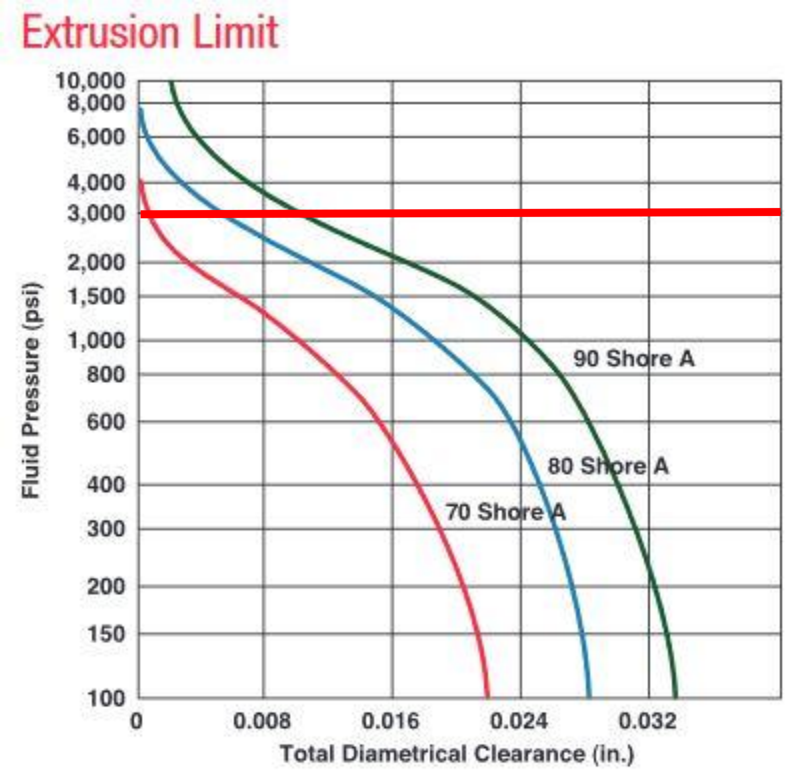


Tank Seal Design

- To combat potential seal failure:
  - Increase o-ring hardness (durometer)
  - Use back-up rings
  - Reduce diameter clearance gap
  - Add redundant seals



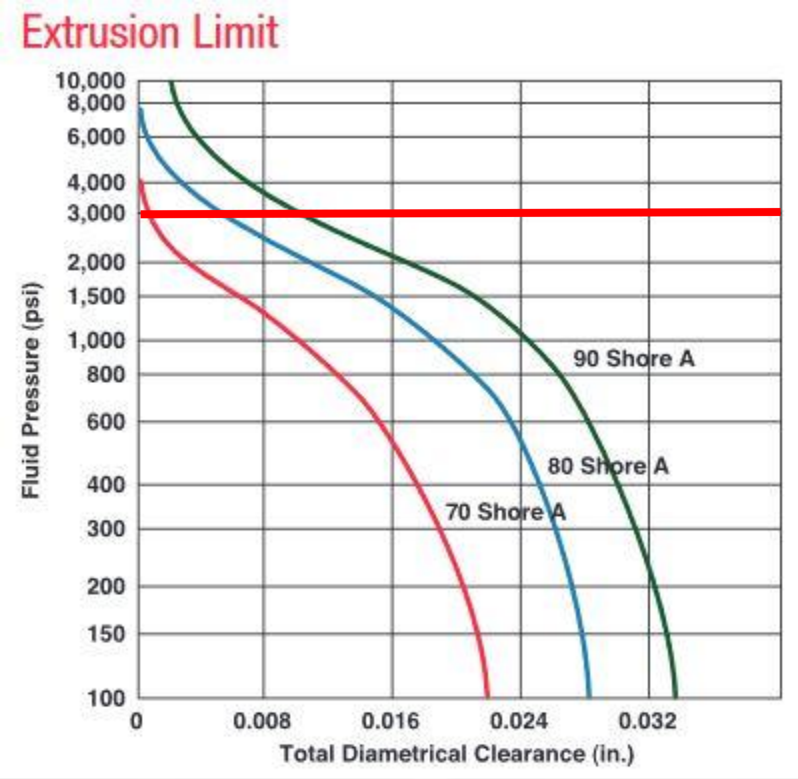
Tank Seal Design



Current Total OD Clearance: .047”
Current Seal Hardness: 70A

Required OD Clearance: .01”
Required Seal Hardness: 90A

Tank Seal Design



<u>Tolerance Stack-up</u>

Plate Max OD: 5.001”

Plate Min OD: 4.999”

Tube Max ID: 5.009”

Tube Min ID: 5.002”

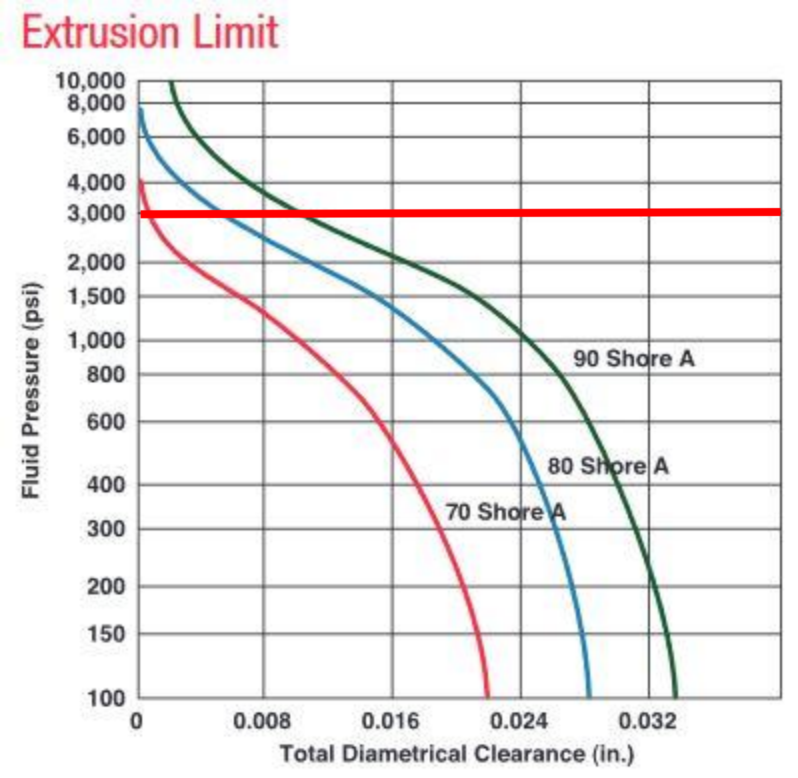
Max OD Clearance: .01”

Min OD Clearance: .001”

Pipe Max ID: 5.097”

Pipe Min ID: 4.997”

Tank Seal Design



<u>Tolerance Stack-up</u>

Tube Max ID: 5.009”

Tube Min ID: 5.002”

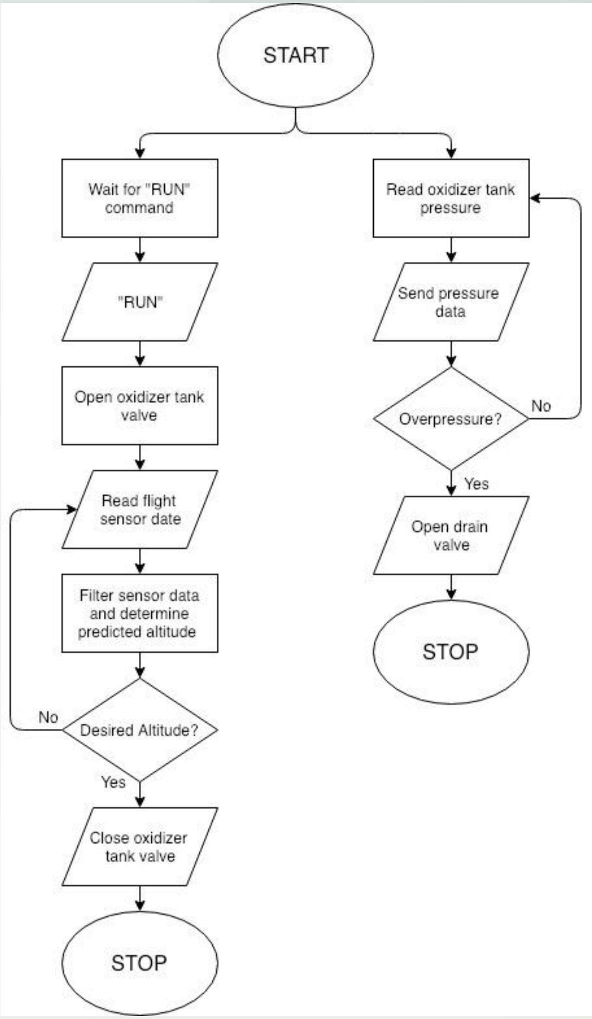
O-ring Max OD: 5.162”

O-ring Min OD: 5.105”

Max compression: .16”

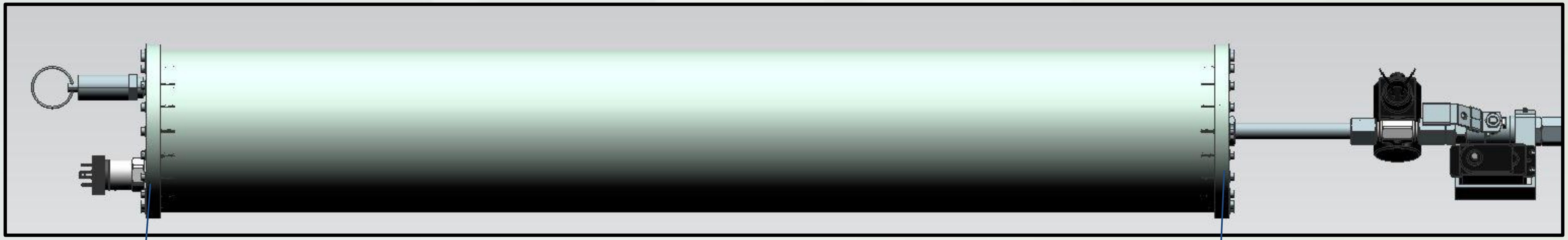
Min compression: .096

Motor Control Overview



Motor Integration

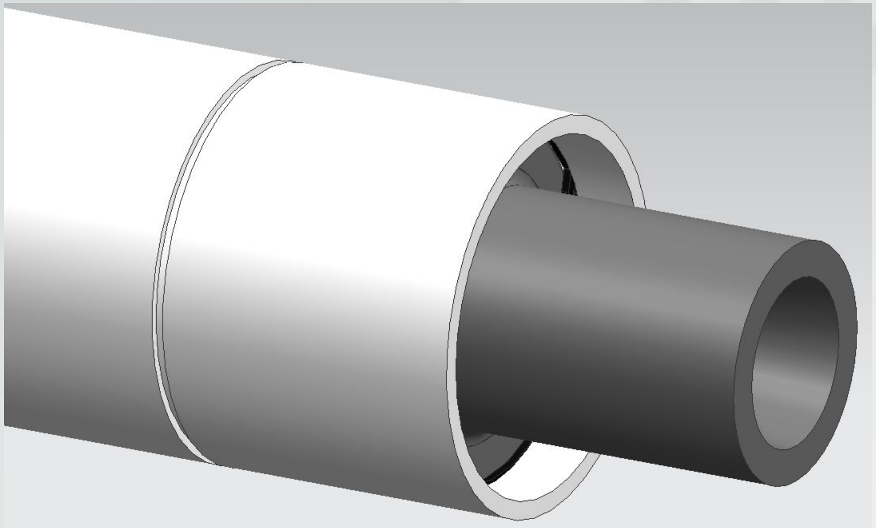
- The motor will be slid in from the rear, as one system
  - The boat tail and thrust retaining plate will be removed before integration
  - Lower closure of oxidizer tank will match the ID of the airframe, functioning as a centering ring
  - The upper closure is a smaller diameter, to allow the motor to slide past the bracing between the middle and lower airframe tubes

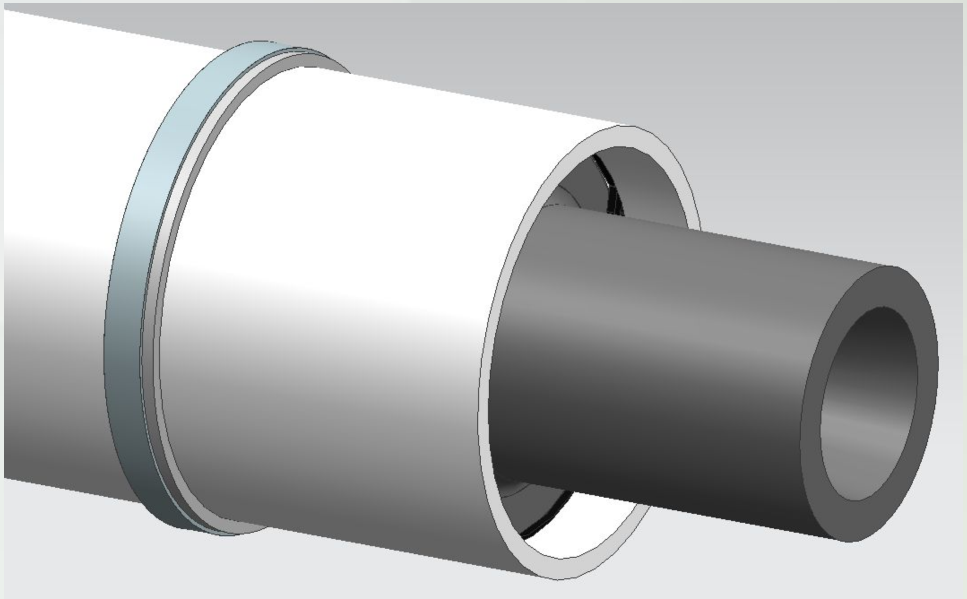


Motor Integration

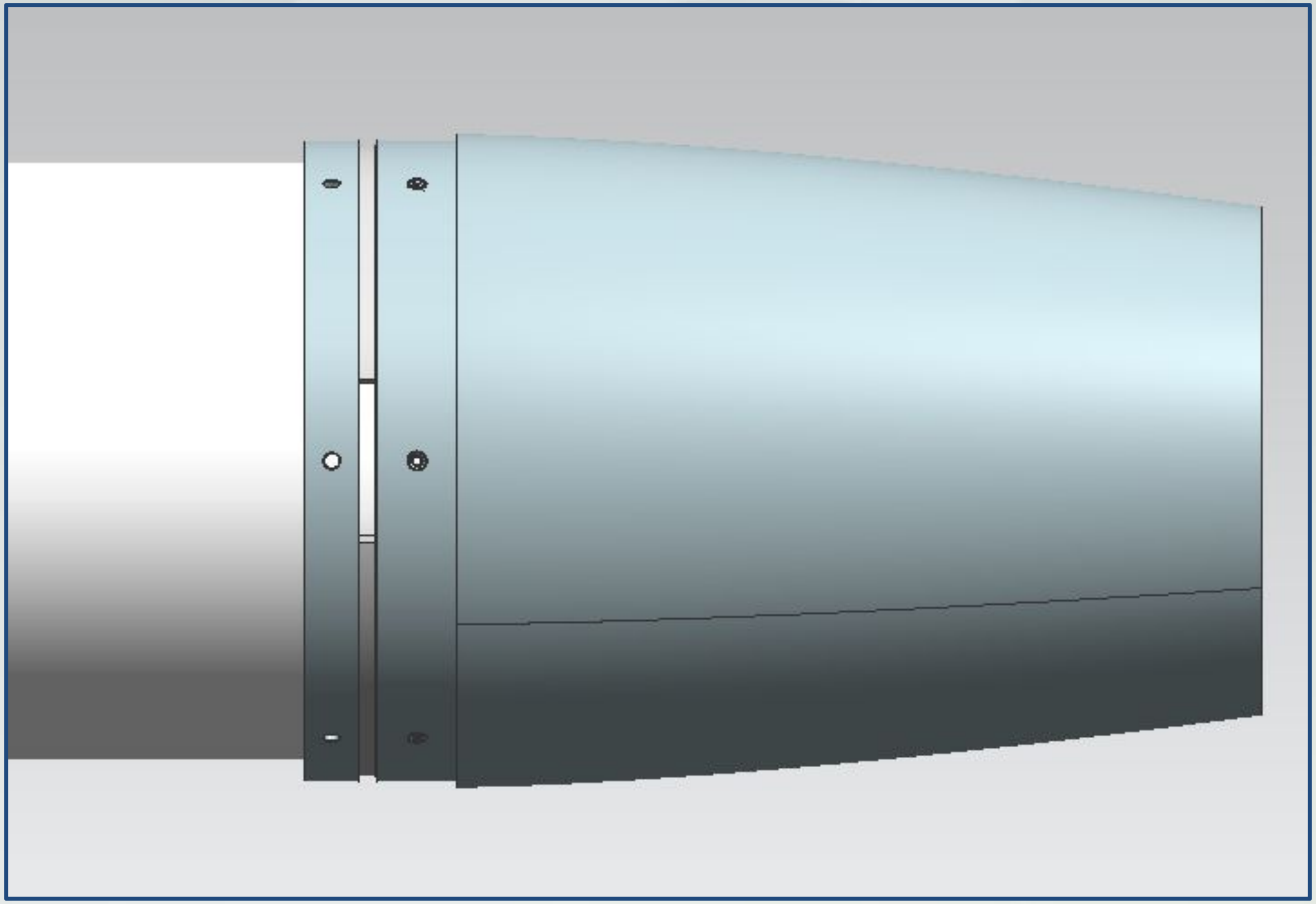
- Thrust retention plate will be slid over the motor from the rear, and bolted to the airframe
- An external snap ring will be installed on the combustion chamber, preventing movement of the motor past the thrust retention plate
- The boat tail will then be slid over the rear of the motor, and bolted to the airframe, and prevent rearward movement of the motor

Motor Integration





Motor Integration



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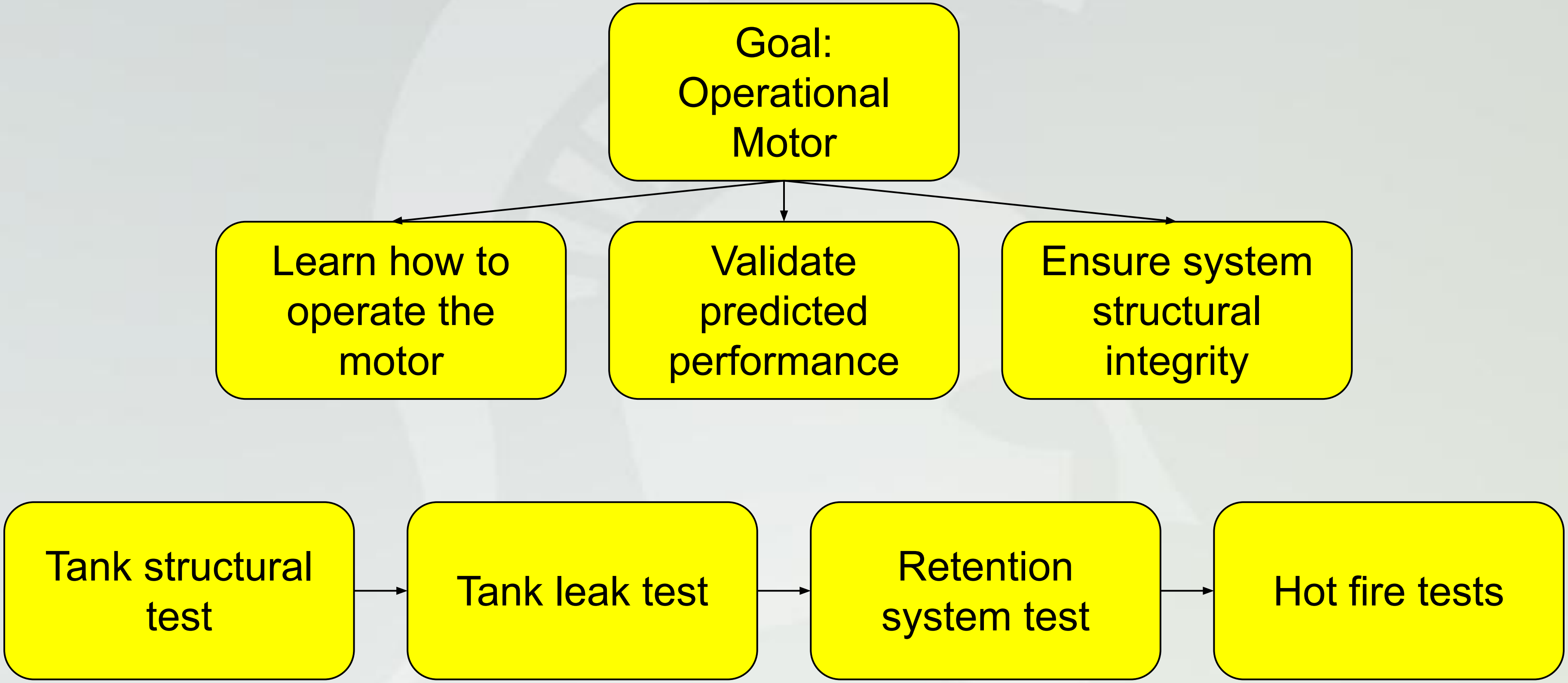
Testing - Overview



Tank Hydro Test Plan

- Goals:
  - (1) Practice remote fill/drain
  - (2) Test structural integrity of tank
  - (3) Test pressure transducer

- If failure, liquid water expands less rapidly than a gas
  - Less destructive

Retention System Test Plan

- Goals:

  (1) Ensure retention system can survive higher loads than predicted

Retention System Test Plan

- Assemble retention system around tank, internal system for nozzle, internal system for oxidizer plate, and external system for chamber
- Statically load the systems with weight beyond the expected load

Hot Fire Test Plan

- Goals:
  - (1) Satisfy competition requirement
  - (2) Practice operating the motor
  - (3) Practice remote fill/drain
  - (4) Check measured performance compared to predicted

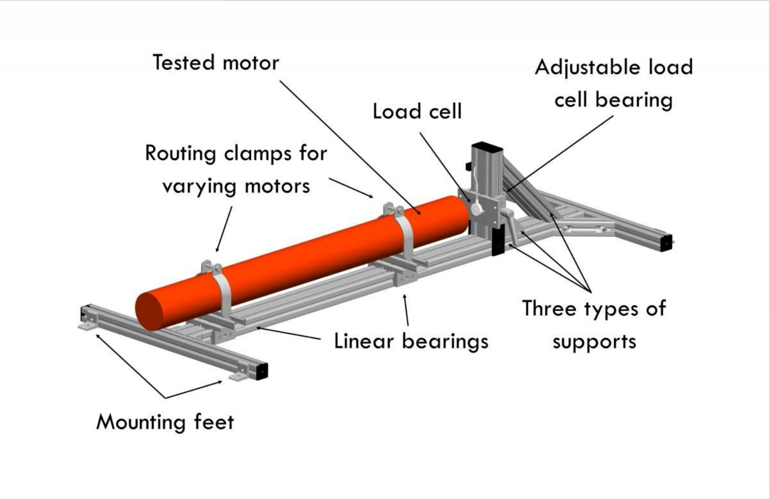
Hot Fire Test Plan

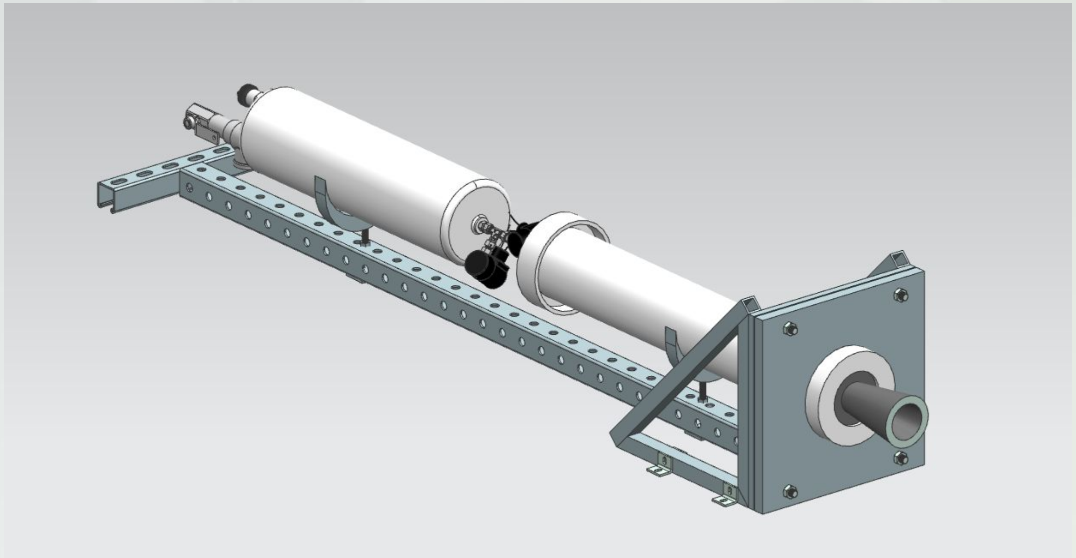
- Clean and degrease tank and feed system prior to assembling the motor
- Assemble motor and load onto test stand
- Hook up the remote fill/drain system to the tank
- Install ignitor up the combustion chamber
- Remotely fill the tank with nitrous
  - Monitor tank pressure

Hot Fire Test Plan

- Once the tank is filled and at pressure, commence into the ignition sequence
  - Fire ignitor
  - Open nitrous valve to reduced setting until ignition
  - Once ignited, completely open nitrous valve
- Record thrust and tank pressure throughout the test

Test Stand Design





Hybrid Engine

Items:

- Brief Overview
- Hybrid Engine Physics
- Analysis and Modeling
- Final Design
- Testing
- Financial
- **Future Improvements**

Future Improvements

- Higher fidelity chamber model
  - Estimation of temperature and pressure field developments
  - Ignition, boundary layer thermal lag, fuel surface thermal lag, and thrust shutdown lag estimations
- Swirl flow oxidizer injection
  - Pre-combustion chamber mass budget savings due to residence time
- Aluminum additives into HTPB fuel
  - Higher ISP due to higher fuel surface regression rates

Future Improvements

- Throttling oxidizer flow
  - More precise apogee control
- Building 6-DOF flight solver into MATLAB model
  - Reducing use of OpenRocket during engine development
- More advanced hot fire testing
  - Refining fuel surface regression coefficient / multiplier
  - Determining axial dependence of fuel surface regression
  - Characterizing vibrational and thermal loading
  - Characterizing transients

Future Improvements

- MATLAB GUI
  - User-friendly experience
- Building minimization of Gibbs free energy code directly into chamber solver
  - NASA CEA library greatly lengthens solving time
- Wax-based fuels
  - Higher regression
- Advanced nozzle shapes
  - Mass budget savings and performance gain

Future Improvements

- 1D / 2D Nozzle CFD solver built into MATLAB
  - Transient thrust coefficient estimation
- Shifting equilibrium nozzle calculations
  - Account for reacting flow and changing flow properties in nozzle

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