Project Zephyrus: Solid Propulsion

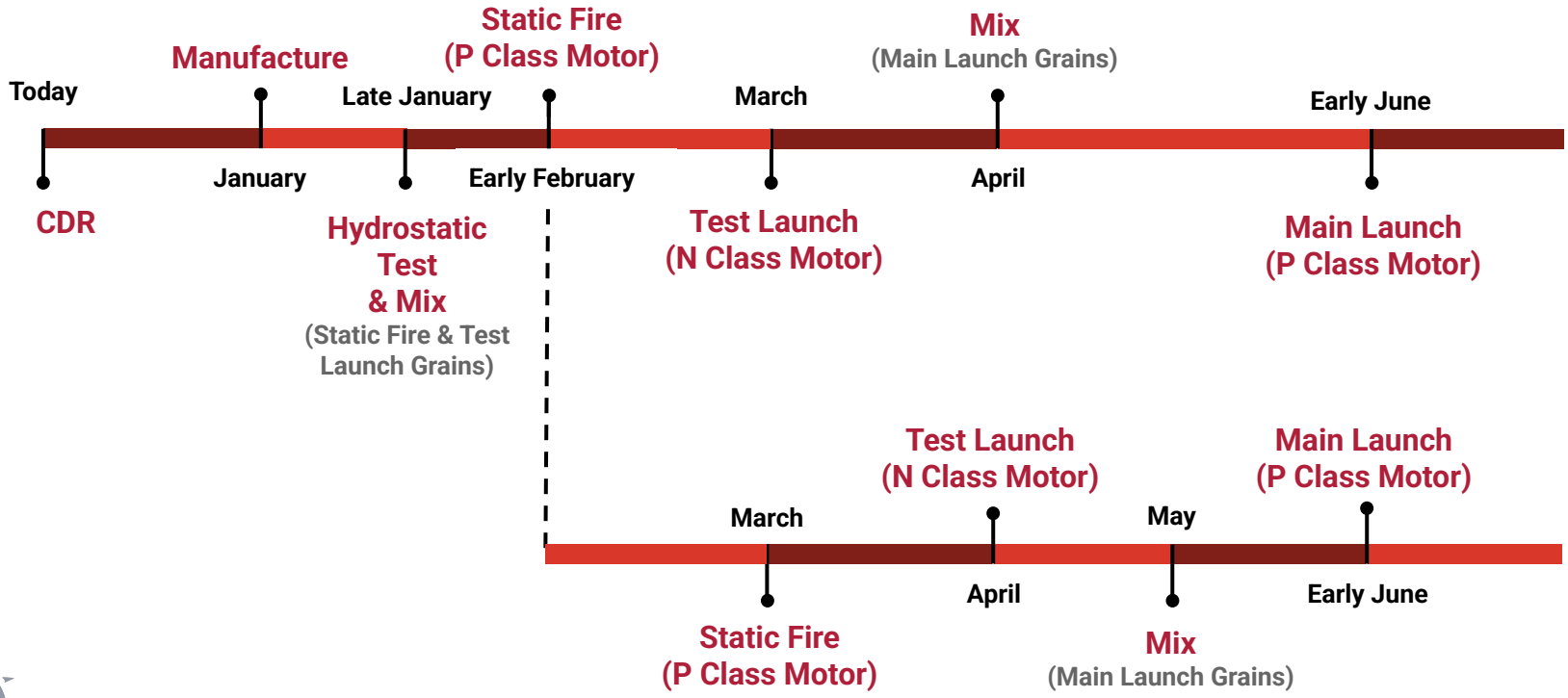
Critical Design Review

7 December 2025

Agenda

- Timeline
- Requirements
- Motor Sims + Grain Geometry
- Hardware

Timeline


Today
Manufacture
Late January
Static Fire
(P Class Motor)
March
Mix
(Main Launch Grains)
Early June
CDR
January
Hydrostatic
Test
& Mix
(Static Fire & Test
Launch Grains)
Early February
Test Launch
(N Class Motor)
April
Main Launch
(P Class Motor)
Test Launch
(N Class Motor)
Main Launch
(P Class Motor)
March
May
April
Early June
Static Fire
(P Class Motor)
Mix
(Main Launch Grains)

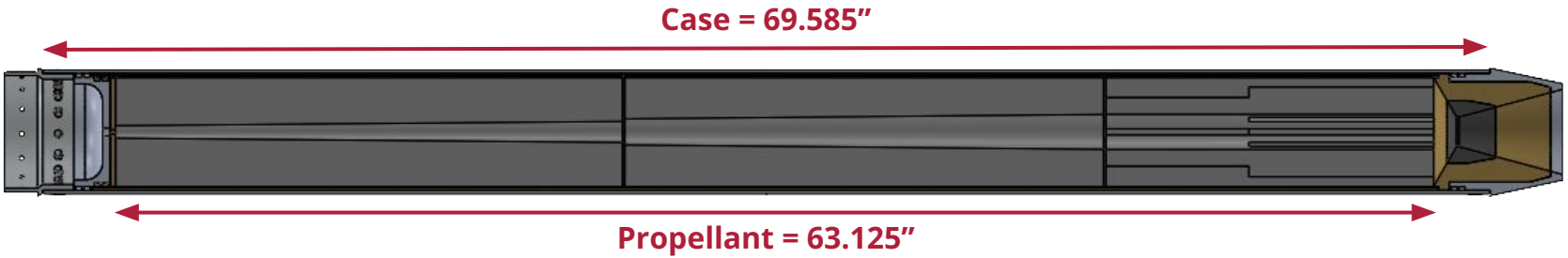
Requirements

- Case shall hold pressure without bursting or leaking:
  - Designed for **2x** FoS, tested to **1.5x** FoS
  - Bolts selected for **2x FoS**
  - Redundant O-rings (2 per seal)
- Motor Shall provide sufficient impulse to achieve 100,000 ft AGL
- Motor shall provide minimum Thrust:Weight Ratio of 10
- Peak Mass Flux < **1.50** lb/(in^2)*s
- Motor case shall not melt or degrade due to combustion heat

P Motor: Performance Overview

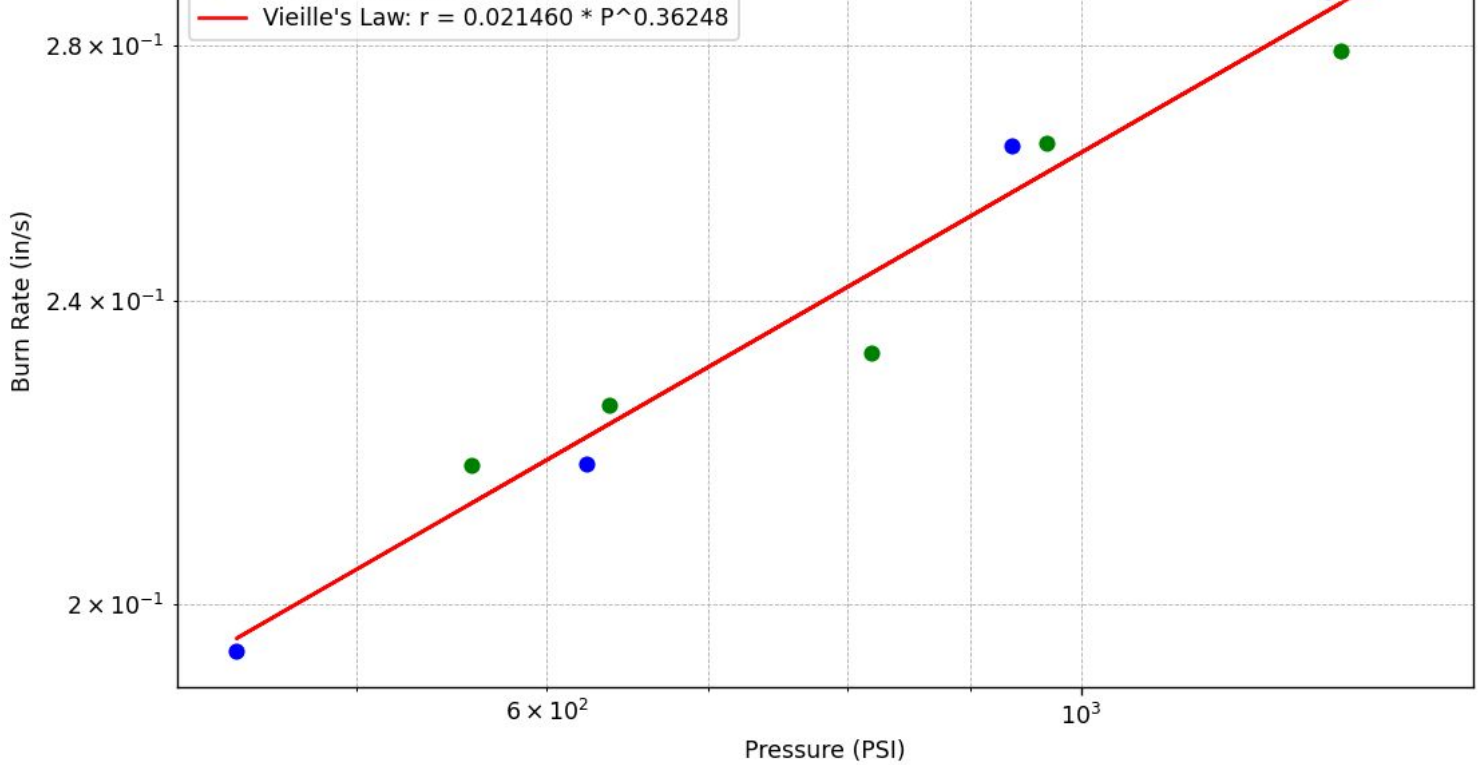
- Motor Class: P6911 (69% P)
- Propellant: Deimos
- Propellant Mass: 74.27 lb
- Dry Mass: 45.59 lb
- Thrust:Weight Ratio = 12.9
  - Total Wet Mass: 154.59 lb
  - Thrust off Rail (20ft): 1990 lbf
    * Initial Thrust = 1897 lbf

Motor Parameters	
Total Impulse	69.300 kNs
Specific Impulse	209.66 s
Peak Mass Flux	1.49 lb/in^{2}s
Average Pressure	681 psi
Peak Pressure	976 psi
Port/Throat Ratio	3.43
Burn Time	10.01 s



Propella

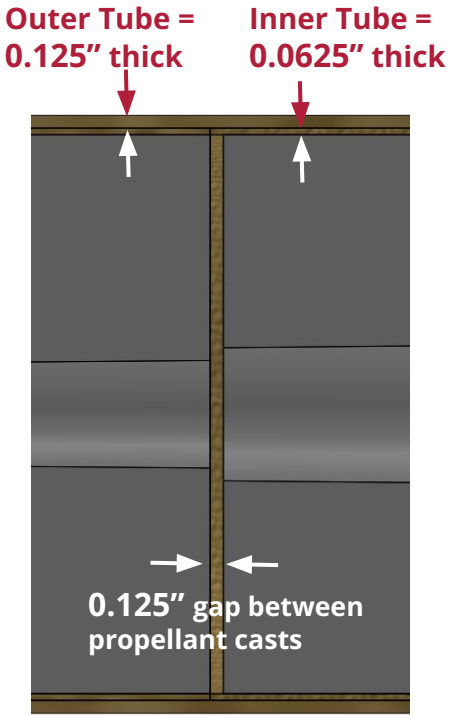
- Deimos:
  - Rea
    - ■
    - ■
    - ■
  - **0.2**
  - a =
  - n =



*percent of total propellant mass

Casting in Three Sections

- Why cast in three sections?
  - Can only produce ~30 lbs of propellant per mixed batch
- Manufacturing Procedure:
  - Cast into three short inner phenolic tubes
  - Coat outside of tubes with gorilla glue
  - Insert inner tubes into long outer phenolic tube

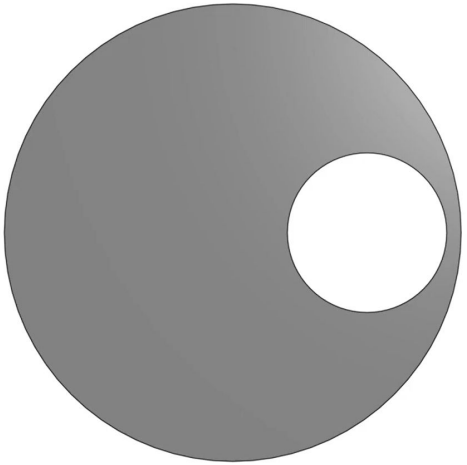


Forward Cast:
- Propellant Length = 24.375”
- Inner Tube Length = 25.25”

Middle Cast:
- Propellant Length = 23”
- Inner Tube Length = 23.25”

Aft Cast:
- Propellant Length = 15.5”
- Inner Tube Length = 15.75”

Phenolic Thickness Reference

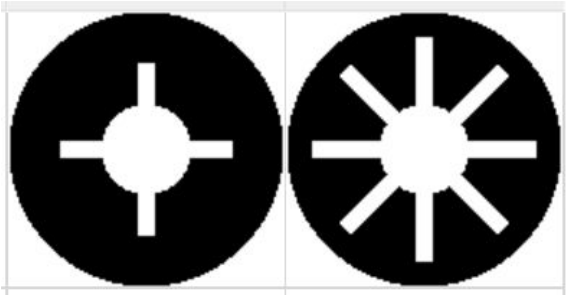


- Zephyrus Phenolic Thickness: 0.1875”
  - Space between grains exposed for 10.1 sec
  - Wall by finocyl exposed for 8.3 sec
- Example Phenolic thickness: 0.085”
  - Wall exposed for 8.5 sec
  - Phenolic almost burned through

P Motor: Grain Geometry

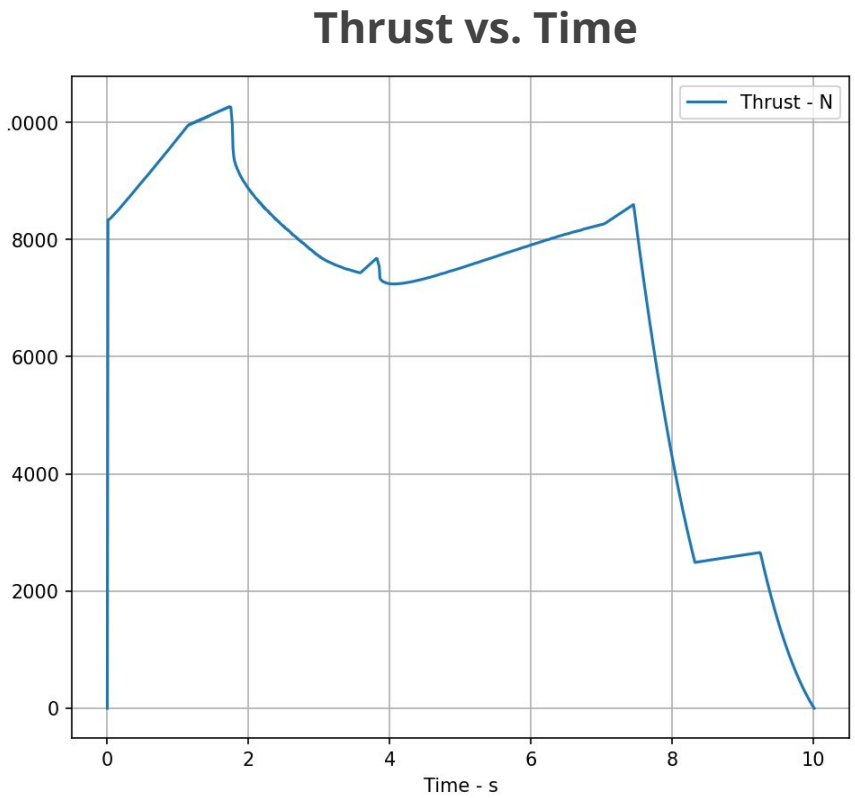
* Propellant OD: 5.25”

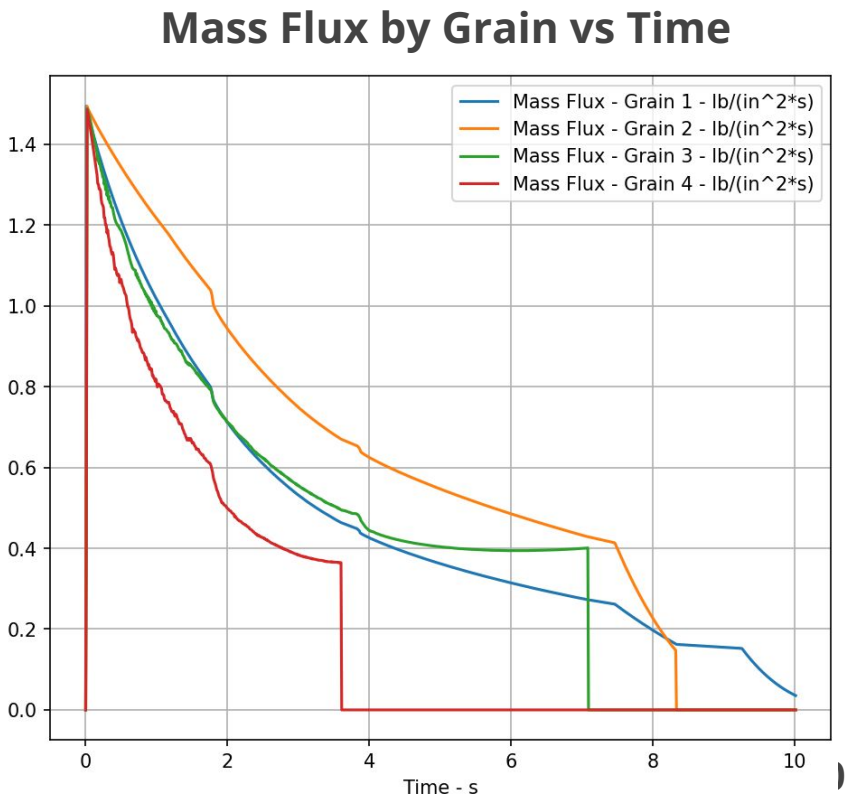
Cast Position	Forward	Middle	Aft	
Grain Shape	Conical	Conical	Finocyl (4 fins)	Finocyl (8 fins)
Mass [lb]	30.771	27.416	16.08	
Length [in]	24.375	23	6.875	8.875
Fwd Core Dia. [in]	0.6	1.25	1.72	
Aft Core Dia. [in]	1.01	1.68		
	Fin Width [in]		0.3	
	Fin Length [in]		0.8	1.3



* Wall is exposed for 8.28 s

P Motor: Thrust Curve and Mass Flux

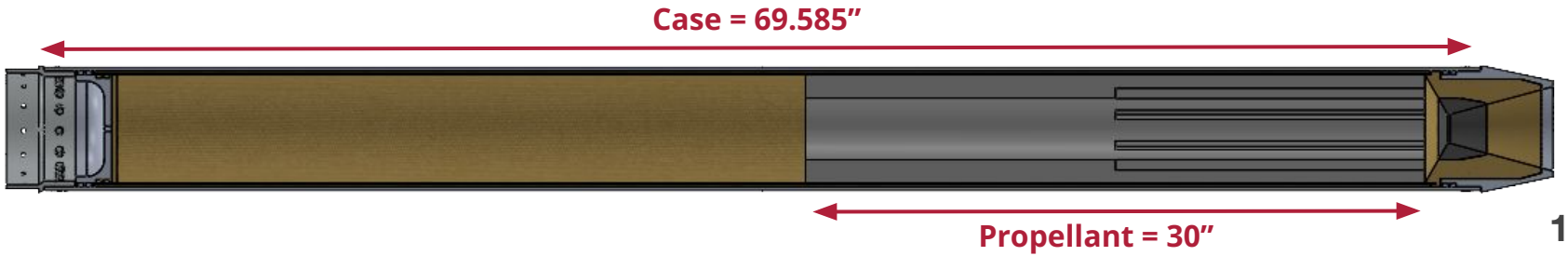




Test Launch: Performance Overview

- Motor Class: N2970 (84% N)
- Propellant: Deimos
- Propellant Mass: 24.76 lb
- Dry Mass: 45.59 lb

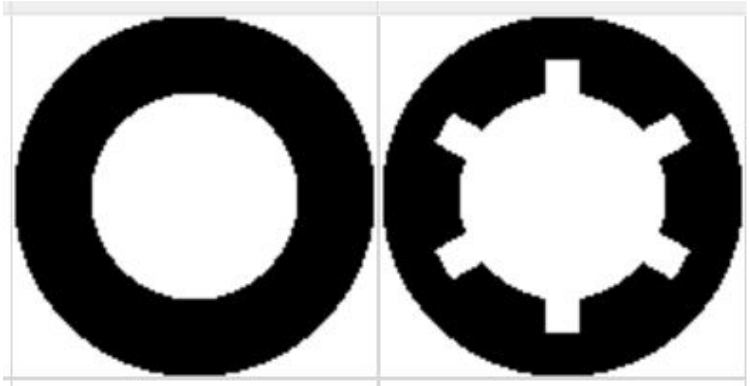
Motor Parameters	
Total Impulse	18.900 kNs
Specific Impulse	171.28 s
Peak Mass Flux	0.59 lb/in^{2}s
Average Pressure	357 psi
Peak Pressure	512 psi
Port/Throat Ratio	5.37
Burn Time	6.34 s

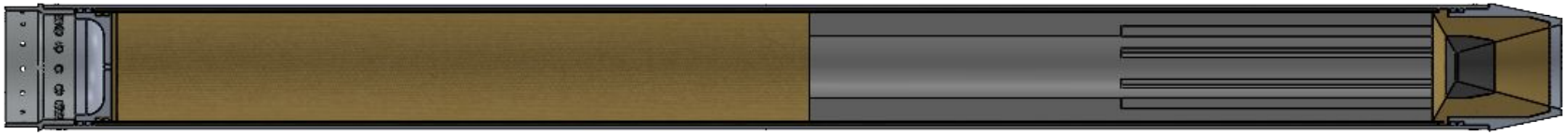


Test Launch: Grain Geometry

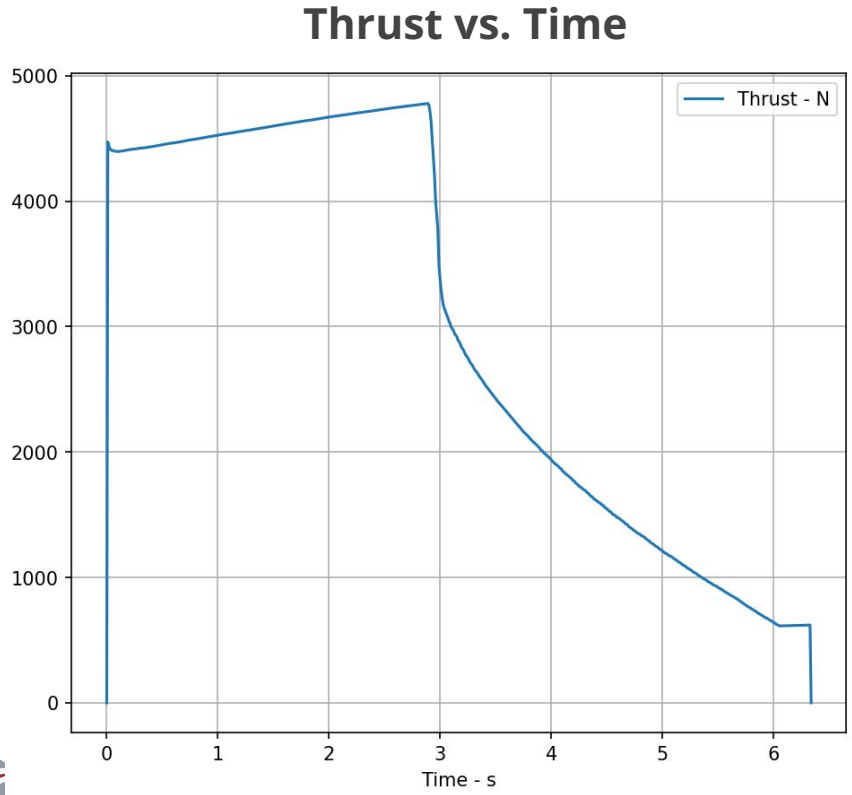
Grain Shape	Bates	Finocyl (6 fins)
Length [in]	15	15
Core Dia. [in]	3	3
	Fin Width [in]	0.5
	Fin Length [in]	0.5

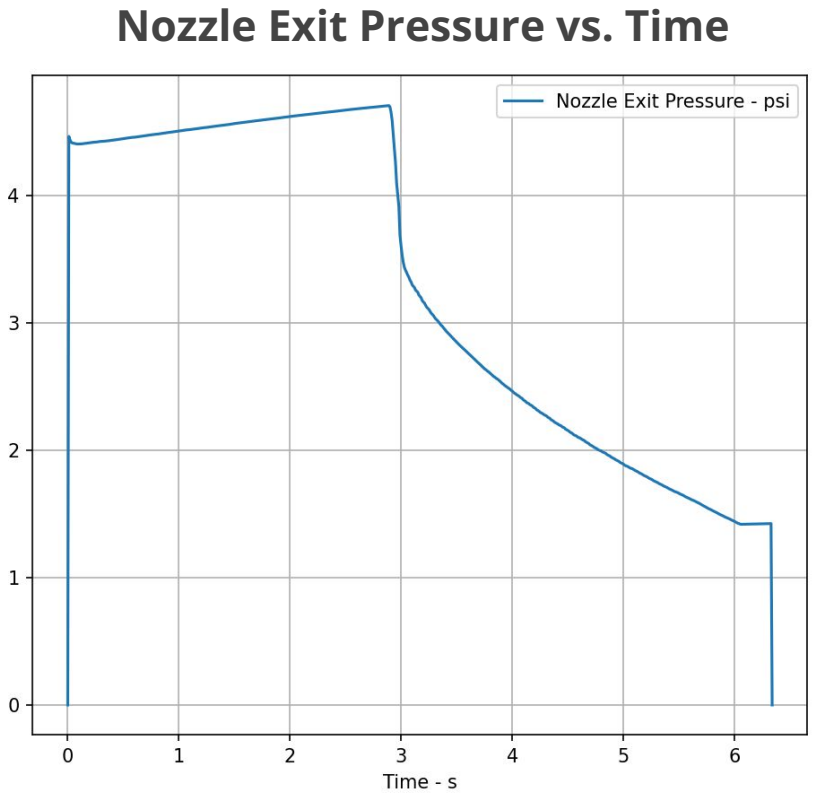
* Propellant OD: 5.25”



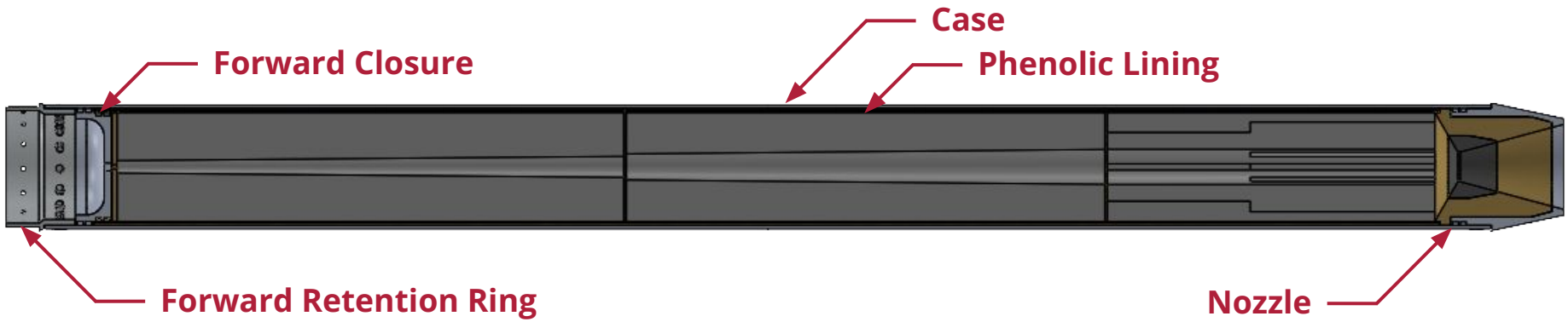


Test Launch: Thrust Curve and Nozzle Exit Pressure



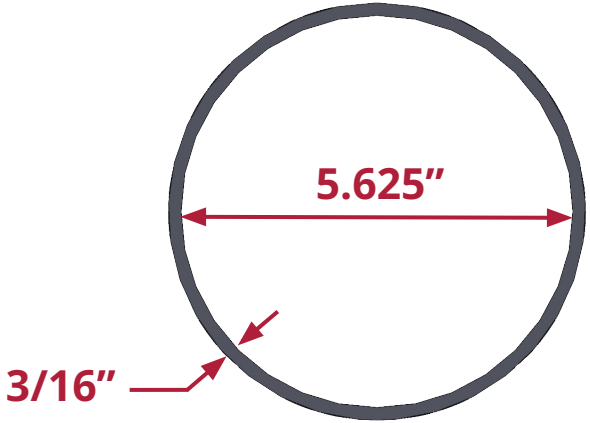


Motor Assembly

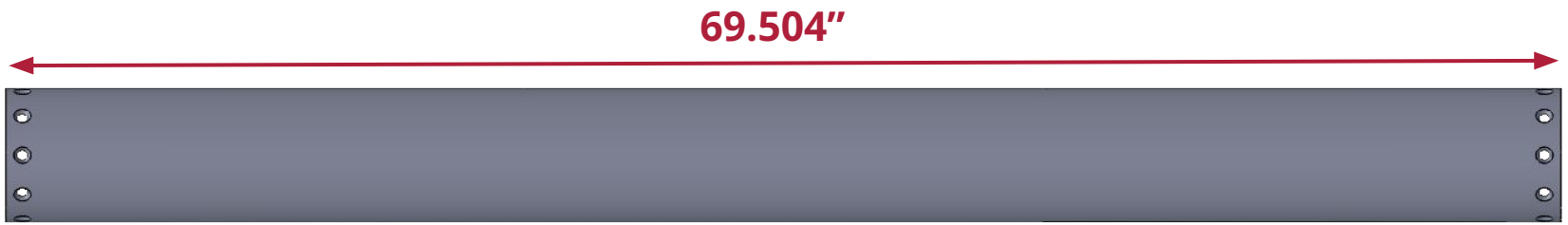


Aluminum Case

- Material: AL 6061-T6
- Case ID = 5.625” (size of phenolic in lab)
- Case Wall Thickness: 3/16”
- Hoop Stress (thin wall approx)
  - FoS = 2.001
  - Tensile Yield Strength = 40,000 psi * 0.775 = 31,000 psi
    - 0.775 strength knock down due to temperature
- **Max Allowable Pressure = 1033 psi**

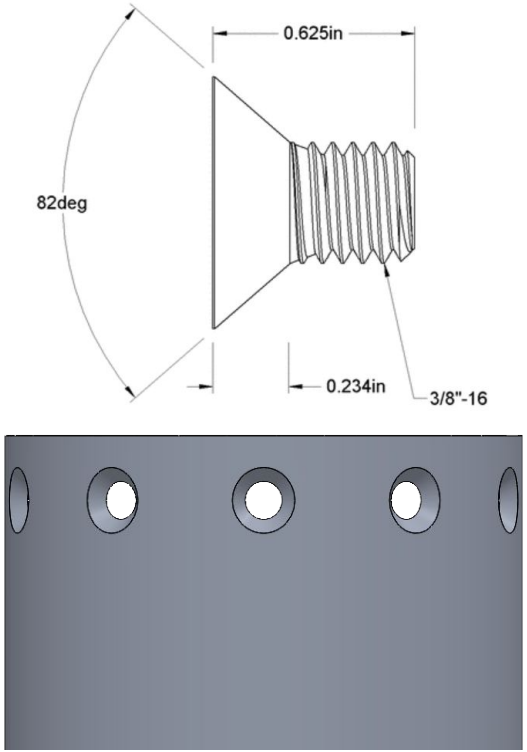


$$\sigma_h = \frac{p \cdot D}{2t}$$



Bolt Selection

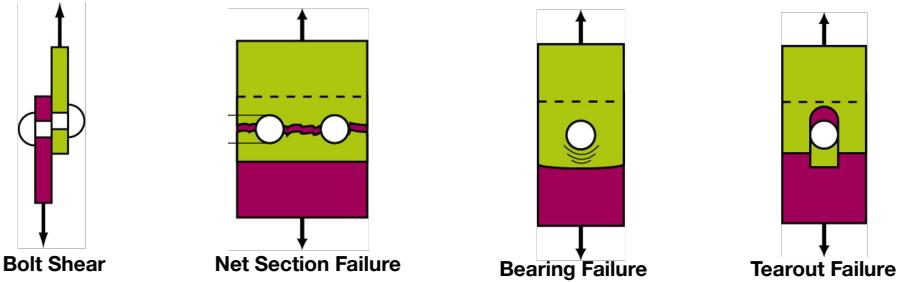
Bolt	
Threads	3/8”-16
Length	5/8”
Countersink Angle	82
Material	Black-Oxide Alloy Steel
Bolt Pattern	
Pattern	1 row of 14 bolts
Distance to Edge	2 * D_{Bolt} = 0.75 in



Bolt Calculations

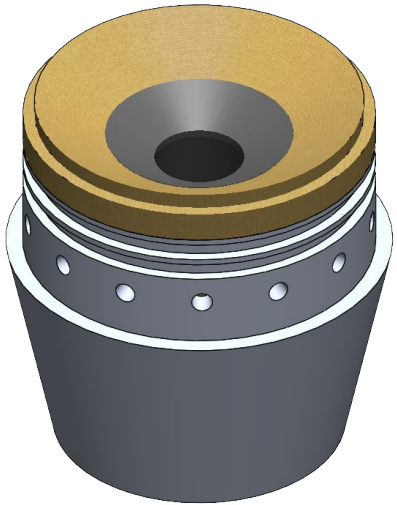
Length of Engagement (Nozzle/FRR): 0.281 in

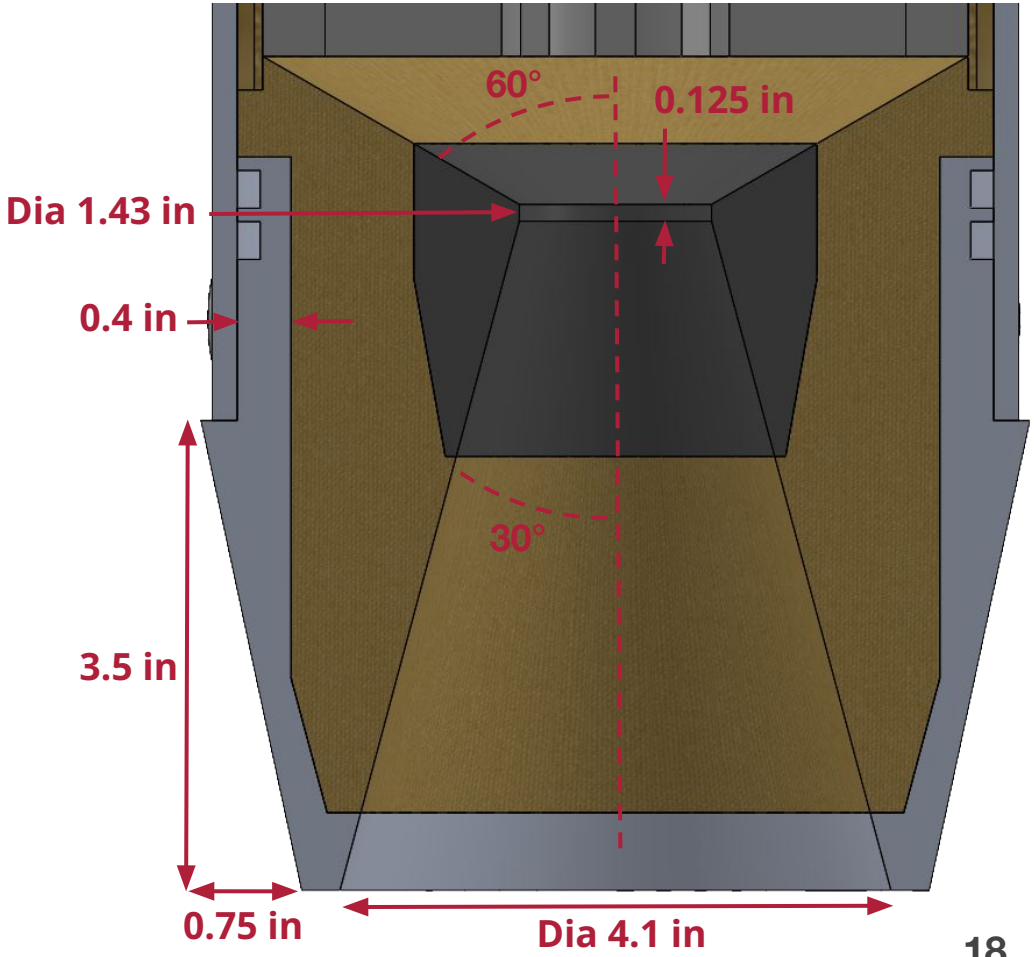
Bolt Failure Mode	FoS	Strength Type	Final Yield Strength	Raw Yield Strength	Strength Knockdown
Bolt Shear	**3.359**	Shear	80.78	140	$1/\sqrt{3}$
Net Section Failure	**2.394**	Tensile	31	40	0.775
Bearing Failure	**2.002**	Bearing	39.06	56	0.9*0.775
Tearout Failure	**3.566**	Shear	23.25	30	0.775
Int Thread Failure	**2.214**	Shear	23.25	30	0.775



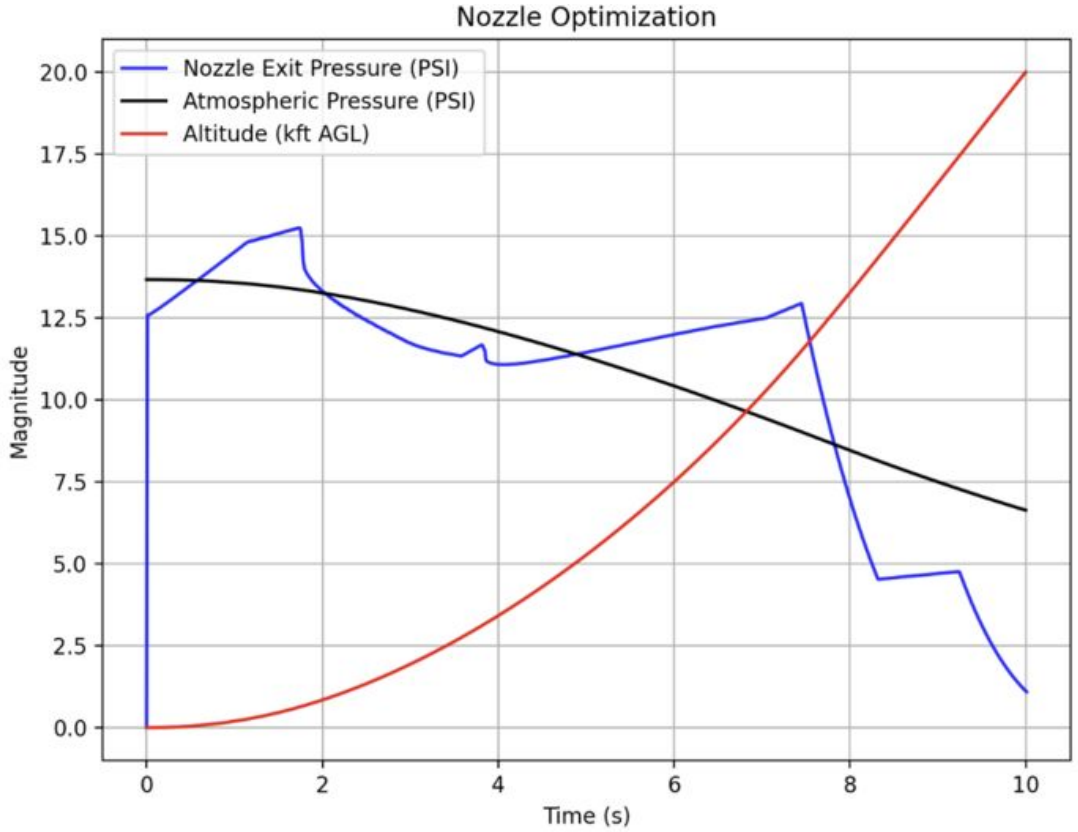
Nozzle Overview

Material	AL 6061-T6 Canvas Phenolic Isomolded Graphite
Throat to Expansion Area Ratio	0.114





Nozzle Optimization



Verifications/Derivations

- Barometric Formula for Pressure

$$p_a = \frac{p_r}{6895} e^{\left(\frac{-\frac{gMh}{3.281}}{RT}\right)}$$

- Isentropic Gas Flow Equations for Mach Number and Expansion Ratio

$$M_e = \sqrt{\frac{2}{\gamma - 1}\left(\left(\frac{p_c}{p_a}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right)}$$

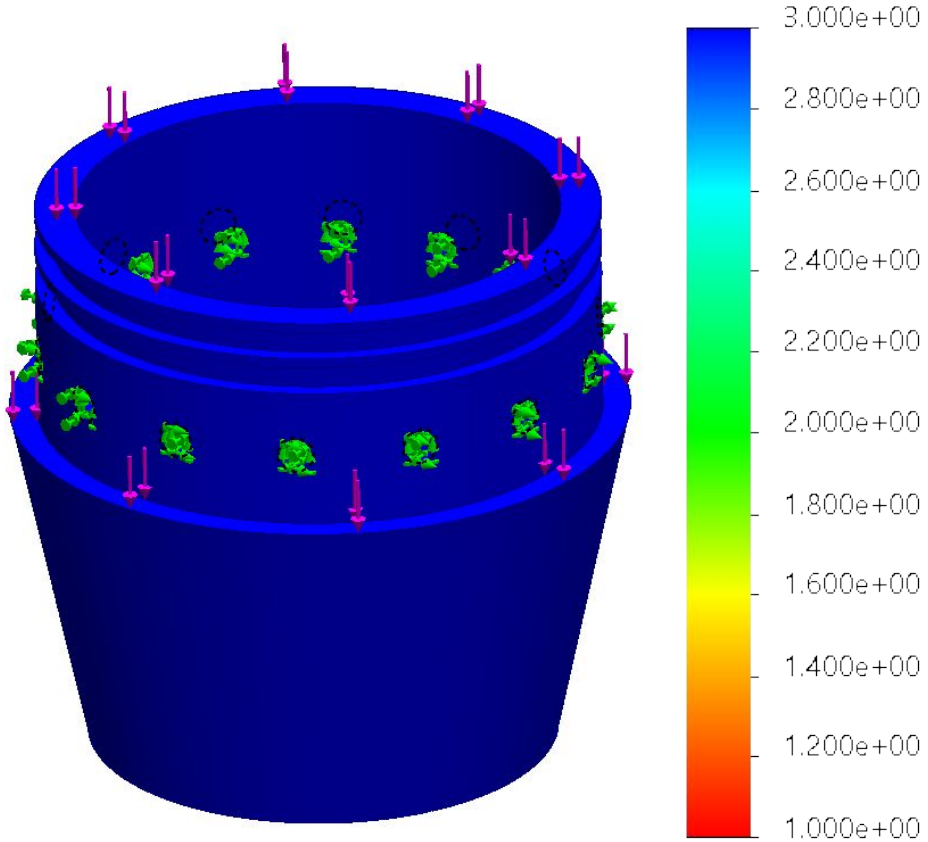
$$\frac{A_e}{A_t} = \frac{1}{M_e}\left(\frac{1+\frac{\gamma-1}{2}M_e^{\,2}}{\frac{\gamma+1}{2}}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

P_r: 101325 Pa; T: 288.16 K; g: 9.81 m/s^2; M: 0.0289 kg/mol; R: 8.3145 J/(Mol*K);
h: height above sea level;
M_e: exit mach number; γ: specific heat of propellant; p_c: chamber pressure; p_a: ambient pressure

Nozzle Carrier FEA

Factor of Safety: 4.2
Fixture: bolts to motor case
External Loads:

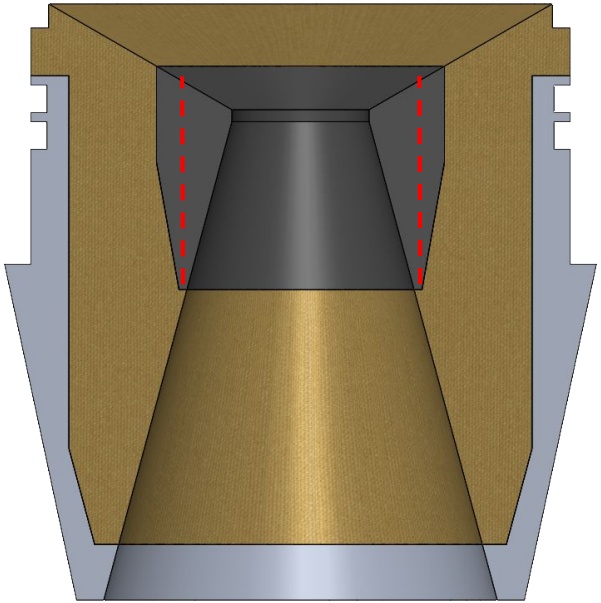
- Force: weight from rocket
  (155.09 lbf * 18 = 2,792 lbf)
- Force: combustion pressure on nozzle surfaces
  (1,033 psi * 23.3 in^2 = 24,069 lbf)

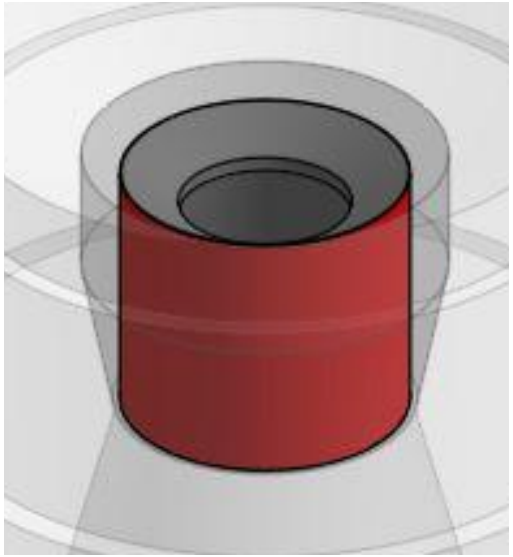


Nozzle Graphite Throat

Shear Stress on Graphite	
Combustion Pressure	1033 psi
Force on unsupported area (red area)	3305.6 lbf
Shear strength*	3625.5 psi
FoS	17.4

* Flexural Strength = 7251 psi
Assume Tensile Strength = Flexural Strength
Shear Strength = 0.5 * Tensile Strength

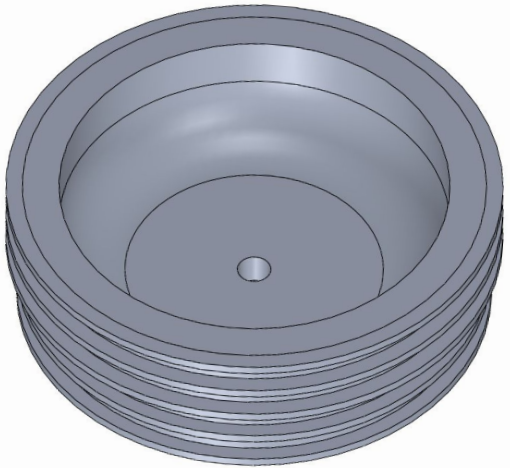


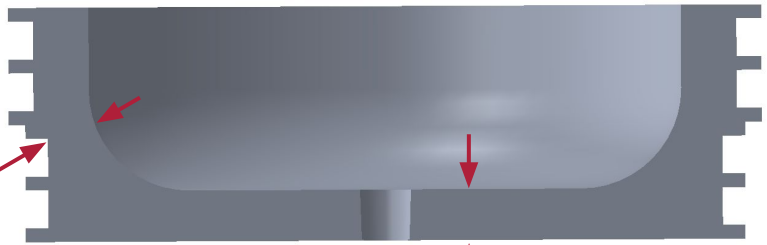


Forward Closure Overview

- Material: AL 6061-T6
- Prevent gas escape from combustion chamber
- Hold pressure tap for static fire data collection
- O-ring redundancy
- 0.25” phenolic disk on bottom of Forward Closure

Case O-ring : 355
Liner O-ring: 353



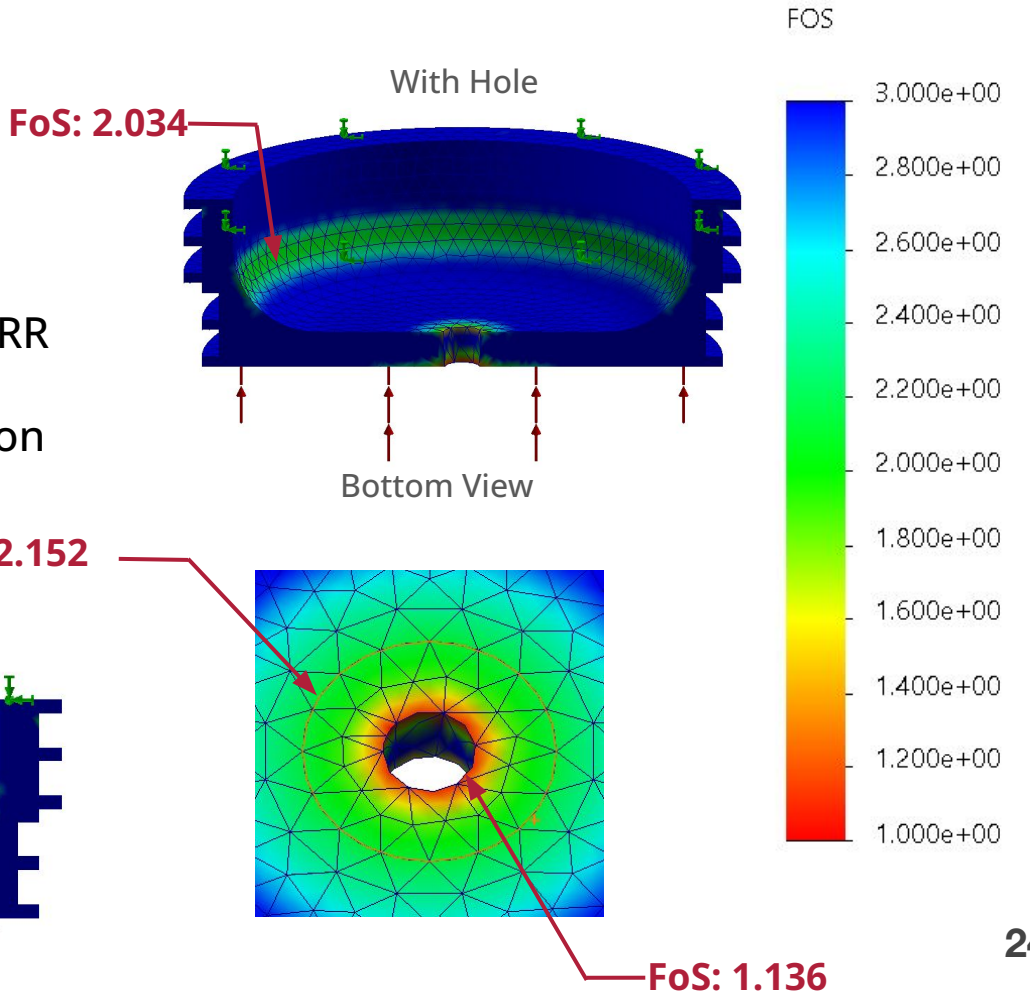


Forward Closure FEA

Factor of Safety:
- **With Hole: 2.152**
- **Hole Suppressed: 2**

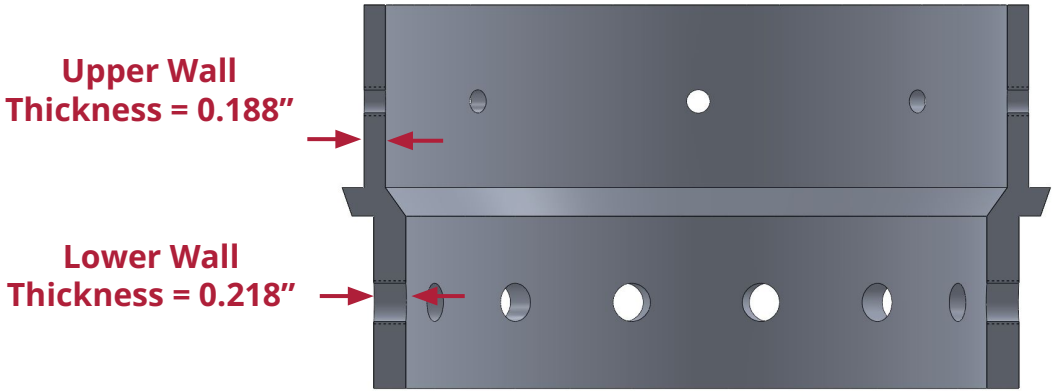
Fixture: top face of closure against FRR

External Loads:
- Pressure: combustion pressure on bottom face (1,033 psi)



Forward Retention Ring (FRR) Overview

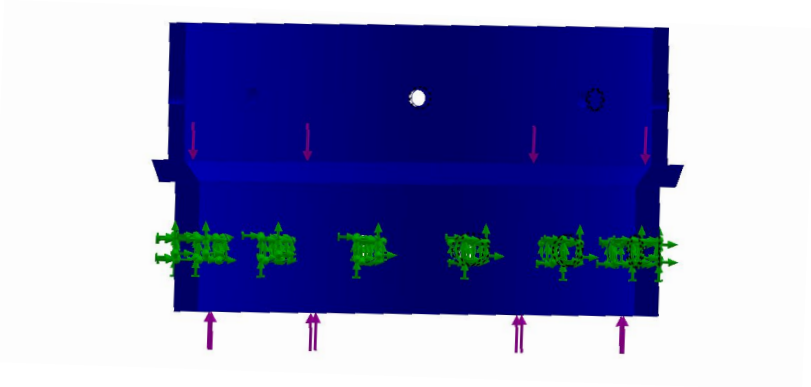
- Material: AL 6061-T6
- Holds the Forward Closure in place
- Attaches motor to rest of rocket (air brakes)

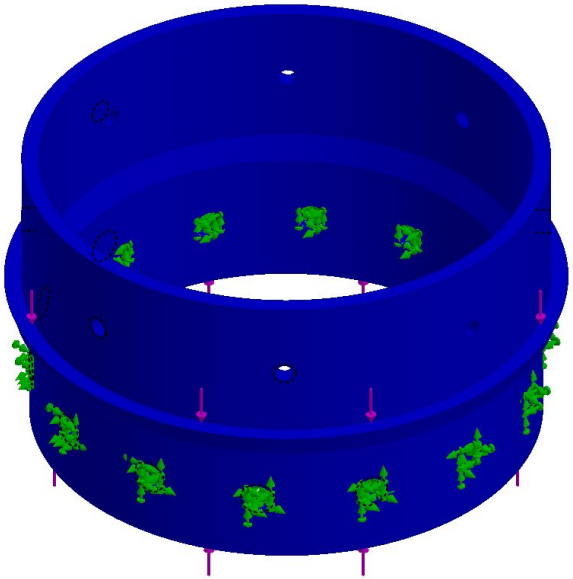


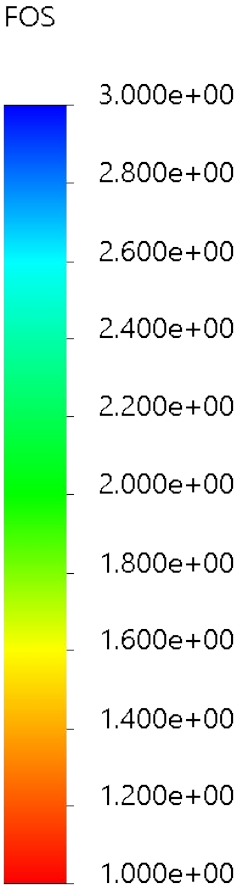
Forward Retention Ring (FRR) FEA

Factor of Safety: 2.9
Fixture: bolt holes to motor case
External Loads:

- Force: weight of rocket down on lip (23.5 lbf * 18 = 423 lbf)
- Force: combustion pressure on Forward Closure translated to FRR: (1,033 psi * 24.85 in^2 = 25,670 lbf)







Safety Margins

Part	Factor of Safety
Case	2.001
Forward Retention Ring	2.9
Forward Closure	2.152
Nozzle Assembly	4.2
Bolts (Bearing Failure)	2.002

Risk Assessment and Navigation - 1 of 3

Failure Mode	Probability	Severity	Mitigation
Case Bursts	Low	High	2.0 Safety Factor; Conduct epoxy curing procedures at high temperatures; use strict manufacturing processes
O-ring seals leak	Low	High	Redundant O-rings; look for defects; choose materials and dimensions to withstand sufficient bending stress; ensure lubrication
Propellant delaminating from liner	Low	High	Fully constrain motion of flammables cabinet and motor inside cabinet during transportation; sand outside phenolic liner before casting propellant; surface prep phenolic liner for casting

Risk Assessment and Navigation - 2 of 3

Failure Mode	Probability	Severity	Mitigation
Propellant mixed incorrectly	Low	High	Adhere to the mixing procedure; have an experienced person lead mix
Ablative liner fails	Low	High	Sufficient thickness; inspect for cracks
Bolts torqued incorrectly	Medium	Low	Use a torque wrench and a FoS of 1.25 in torque calculations; use grease
Bolts Fail	Low	High	Perform conservative bolt calculations

Risk Assessment and Navigation - 3 of 3

Failure Mode	Probability	Severity	Mitigation
Slag builds up in throat	High	Low	Choose a wide throat
RTV between graphite, phenolic, and carrier fails	Medium	Medium	Surface prep (sand) RTV to seal
Structural failure of graphite throat	Low	Medium	Choose sufficient thickness of graphite and utilize a FoS of 2

Component Mass Breakdown

Part	Mass (lb)	Percent Mass (%)
Propellant Grains	74.27	**62.8**
Liner & Casting Tubes	9.64	8.3
Case	23.07	19.8
Forward Retention Ring	1.35	1.2
Forward Closure	1.58	1.4
Nozzle Assembly	6.782	5.8
Bolts (Excluding Airframe Bolts)	0.03 x (28 bolts) = .84	0.7
O-rings	0.026 x (4 o-rings) = 0.104	0.08
Total	**116.806**	100

Questions?