Hybrid Rocket Engine
IDEAs Design Analysis Competition 2018

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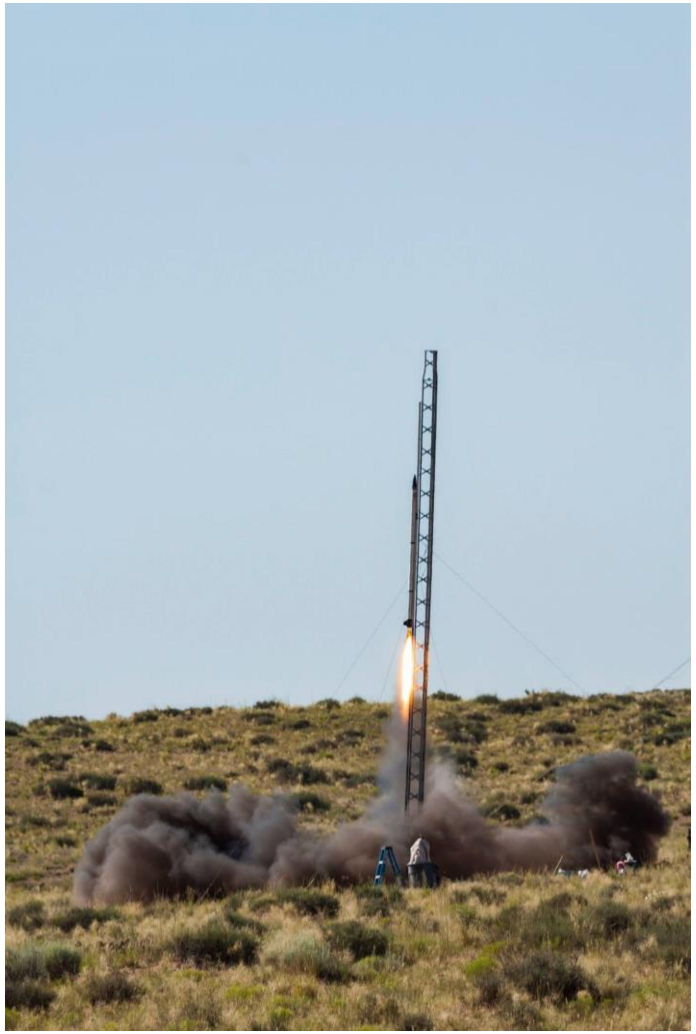
WATERLOO ROCKETRY

Introduction

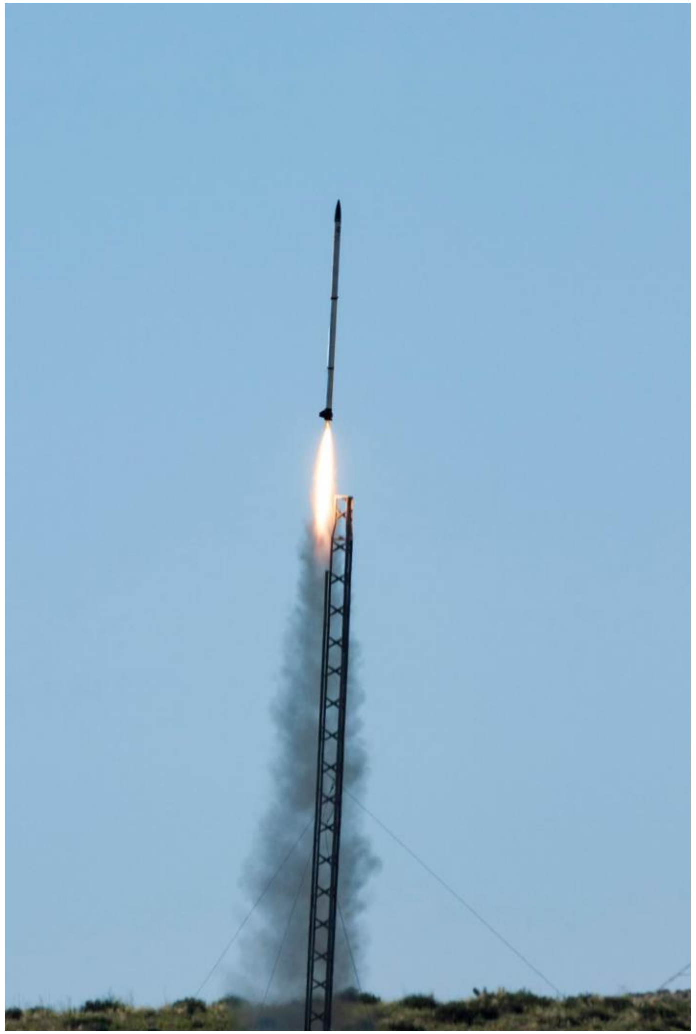


Background

- Waterloo Rocketry is competing in the 30,000 ft Student Researched and Designed (SRAD) Hybrid/Liquid category at the Spaceport America Cup.

Project Objective

- Design, build and test a hybrid rocket engine that will provide thrust for a rocket with a target apogee of 30,000 ft.



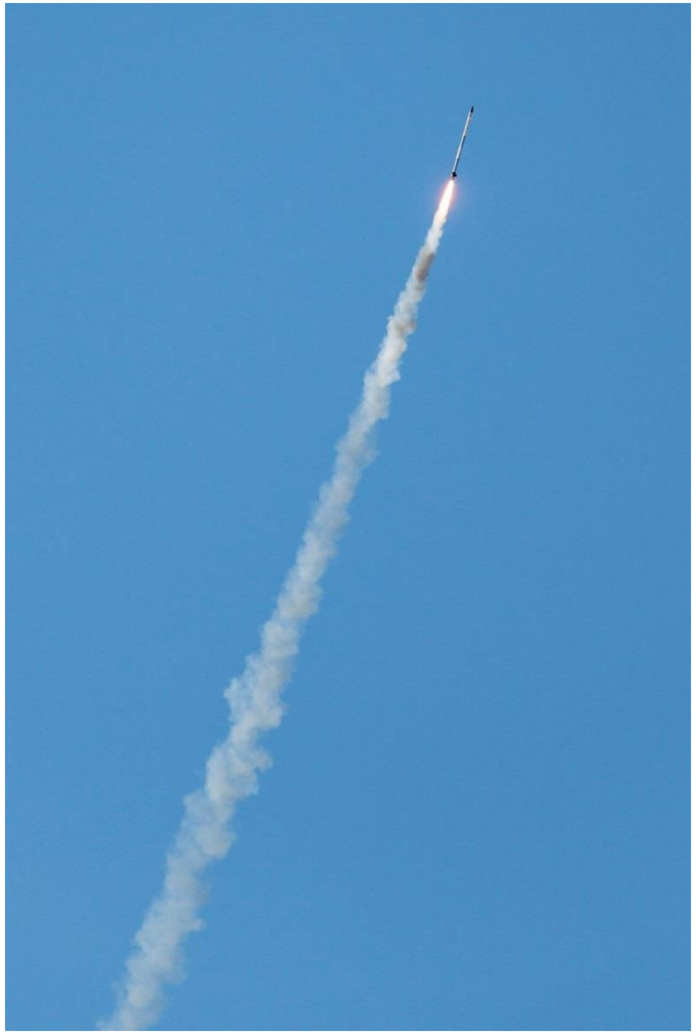
IDEAs Analysis Competition: Introduction | Project Requirements & Success Criteria

Project Requirements

- 6″ maximum diameter engine
- Provide thrust for a target apogee of 30,000 +/- 2,000 ft

Success Criteria

- ME 481/482: Perform a static hot fire engine test which predicts an apogee between 28,000 and 32,000 ft.
- Waterloo Rocketry: Strong performance in the Spaceport America Cup.



Relevant Competition Rules:

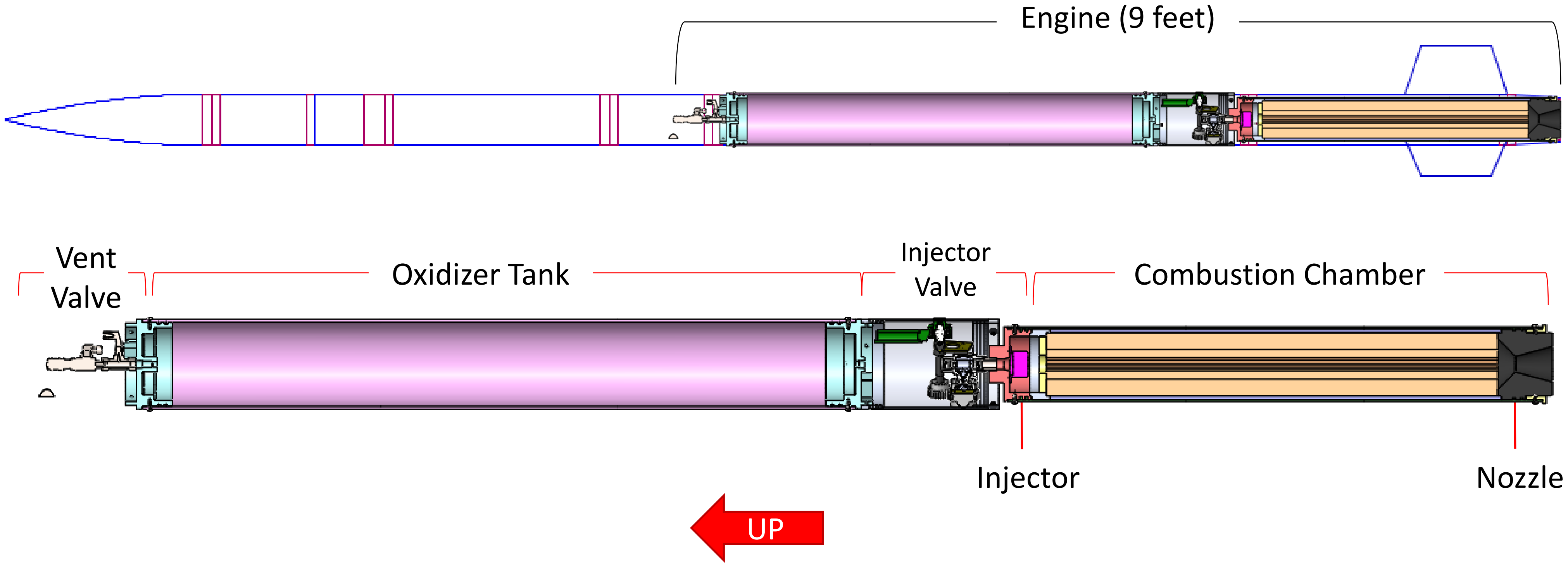
- SRAD Pressure Vessels
  - Burst FOS of 2.0
  - Hydrostatic testing to FOS of 1.5
  - Pressure relief valves

Design Basis: Waterloo Rocketry's 10,000 ft SRAD engine

- 4 years of iterative design and testing; many areas of the design do not need modification

IDEAs Analysis Competition: Introduction | Hybrid Rocket Overview

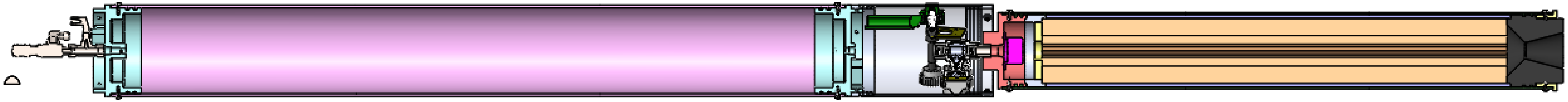
- Hybrid rocket combines solid and liquid propellants
- Oxidizer is saturated nitrous oxide (N_2O)
  - Vapor pressure of 750 psi at 25 C
- Fuel is 90% HTPB (rubber), 10% aluminum (by weight)



Analysis

Structural Analysis

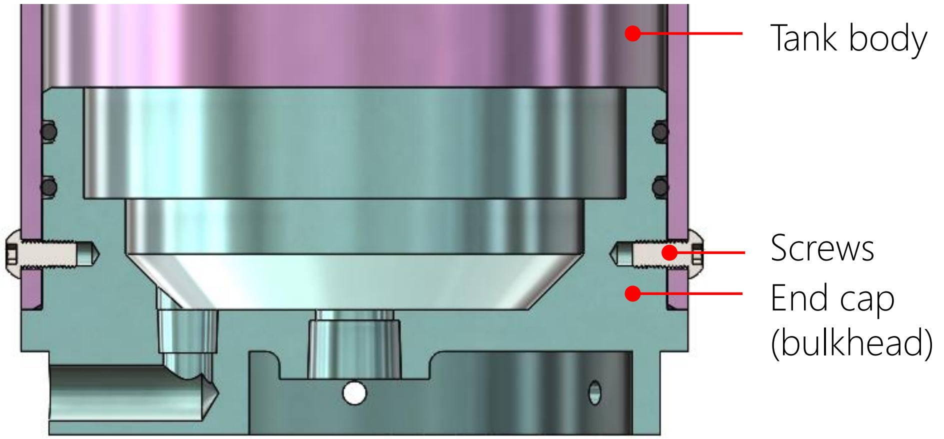
- End cap fastening
- Tube bulging
- End cap thickness



Background and Motivation

- End caps are fastened to pressure vessel body with screws around circumference
- Fastened connections can fail by
  - Bolt shear
  - Tensile failure
  - Bearing failure
  - Shear tear out
- **Goal: Ensure number and size of screws is sufficient to safely hold end caps on at all operating pressures**

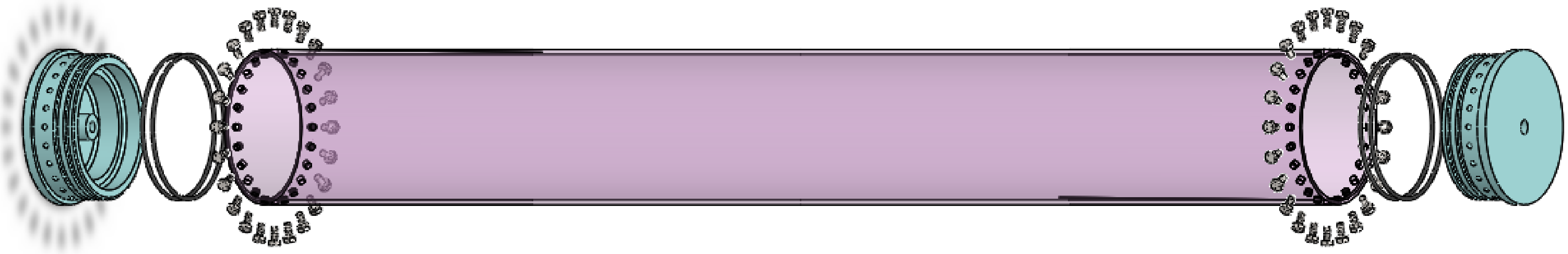
Internal Pressure: 1000 psi



Methodology

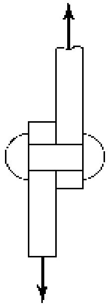
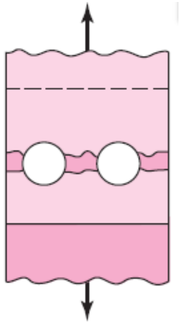
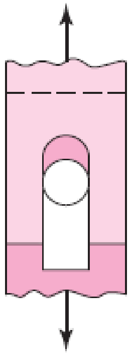
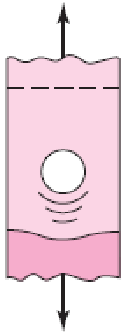
- Analytical closed form equations calculations used to determine stresses and factors of safety

- 24 bolts equally spaced, 1/4-28 thread, strength 122 kpsi
- 6061-T6 aluminum components for high strength/weight ratio



IDEAs Analysis Competition: Structural Analysis | Fastened Connection

Results and Significance

	Bolt Shear	Tensile Failure of Tank	Shear Tear Out of Tank	Bearing Failure of Tank
				
Yield Strength (ksi)	70.4	40	23	56
Maximum Stress (ksi)	28.4	11.2	7.4	26.9
Factor of Safety	2.5	3.5	3.2	2.1

Fastened connection is designed to operate safely at all possible operating pressures
Verified through hydrostatic testing

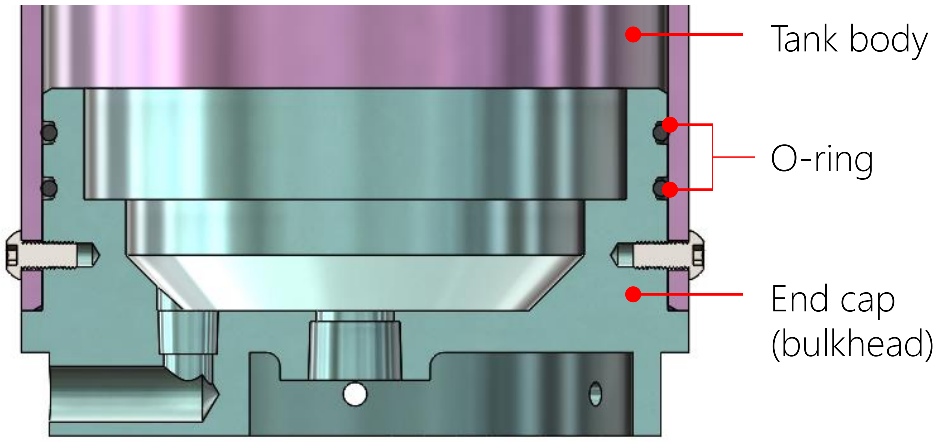
Background and Motivation

- Pressure vessel body is fastened to end caps at end so bulging will occur along length of tube
- O-rings have acceptable squeeze ranges – must stay within acceptable range with increased bore diameter

O-Ring 2-Size AS568B-	W Cross-Section Nominal	W Cross-Section Actual	L Gland Depth	Squeeze Actual	Squeeze %
201 through 284	1/8	.139 ±.004 (3.53 mm)	.111 to .113	.022 to .032	16 to 23

- **Goal: ensure sealing design is sufficient at all possible operating pressures**

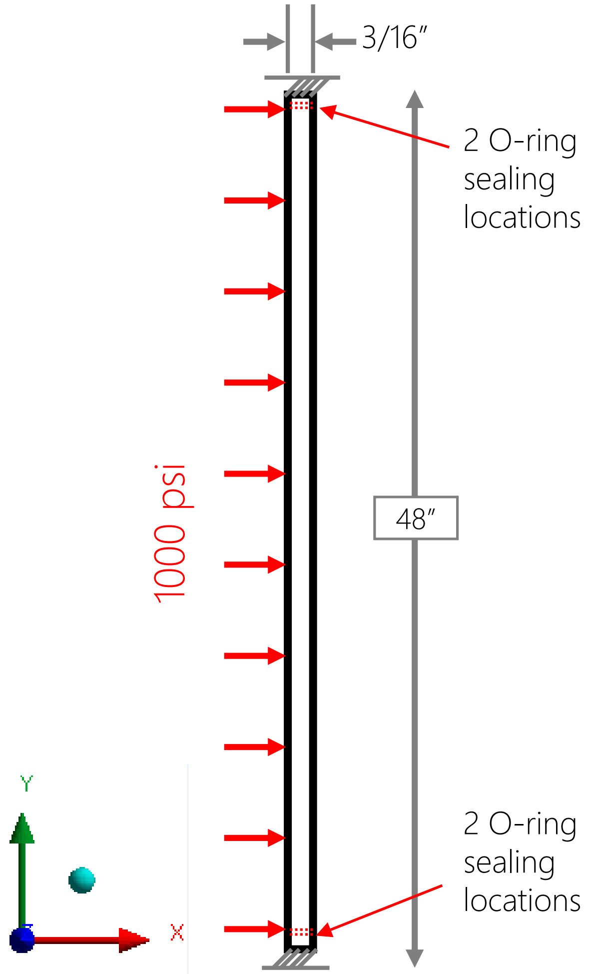
Internal Pressure: 1000 psi



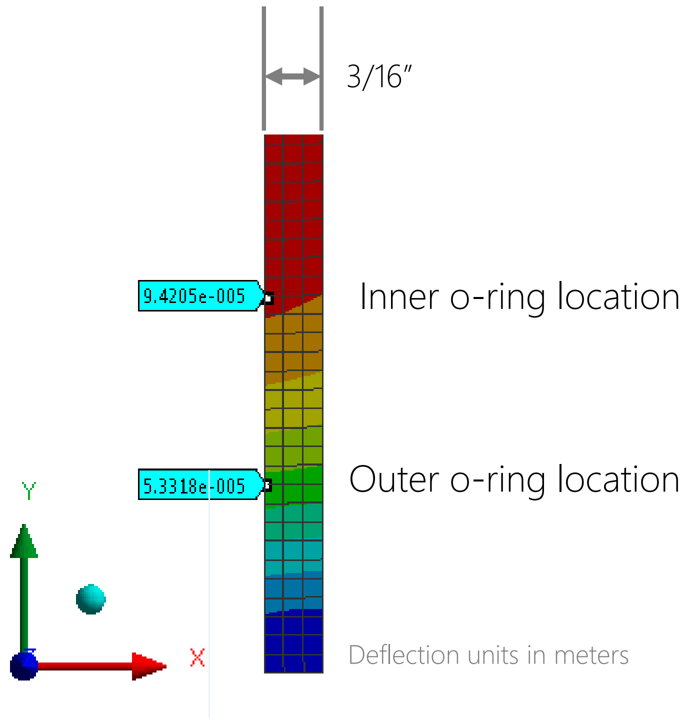
IDEAs Analysis Competition: Structural Analysis | Tube Deflection

Boundary Conditions

Axisymmetric model

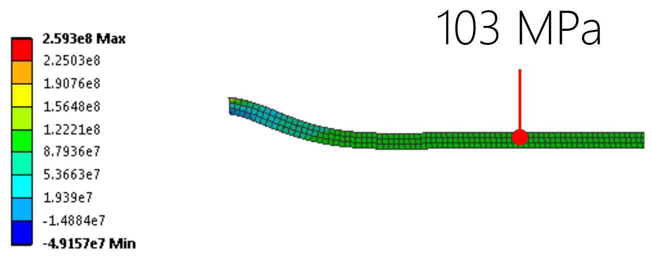


Deflection Results



~0.004" radial deflection at sealing surface

Stress Results



$$\sigma_{hoop} = \frac{P \times D_m}{2t} = 105\ MPa$$

Stress (simulation): 103 MPa
Stress (analytical): 105 MPa

Very small difference between simulation and analytical

→ Reliable simulation results

Waterloo Rocketry, 2018
N. Christopher, S. Dalgliesh, N. Wong

IDEAs Analysis Competition: Structural Analysis | Tube Deflection

Significance

O-Ring 2-Size AS568B-	W Cross-Section Nominal	W Cross-Section Actual	L Gland Depth	Squeeze Actual	Squeeze %
201 through 284	1/8	.139 ±.004 (3.53 mm)	.111 to .113	.022 to .032	16 to 23

Acceptable squeeze: 16% to 23%

Condition	Squeeze	Acceptable?
Without Deflection	20%	Yes
With 0.004" Deflection	17%	Yes

O-ring selected is still within acceptable operating window with the deflection from internal pressure

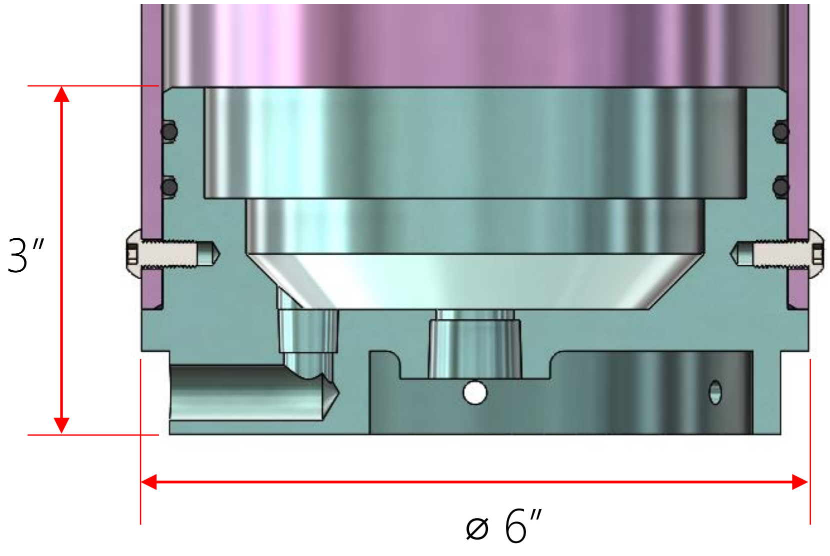
Verification of Results

Hydrostatic testing

- Pump water into sealed pressure vessel to 1.5x operating pressure
- O-ring seals were able to hold pressure within the tank

Background and Motivation

- End caps contribute significant mass to system
  - Analytical solution gave 0.5″ minimum thickness (3.58 lbs each)
- Desire good geometry for manufacturing
  - Flat ends are not optimal for pressure vessels
- **Goal: Minimize mass of end caps through geometry optimization while ensuring safe operation**

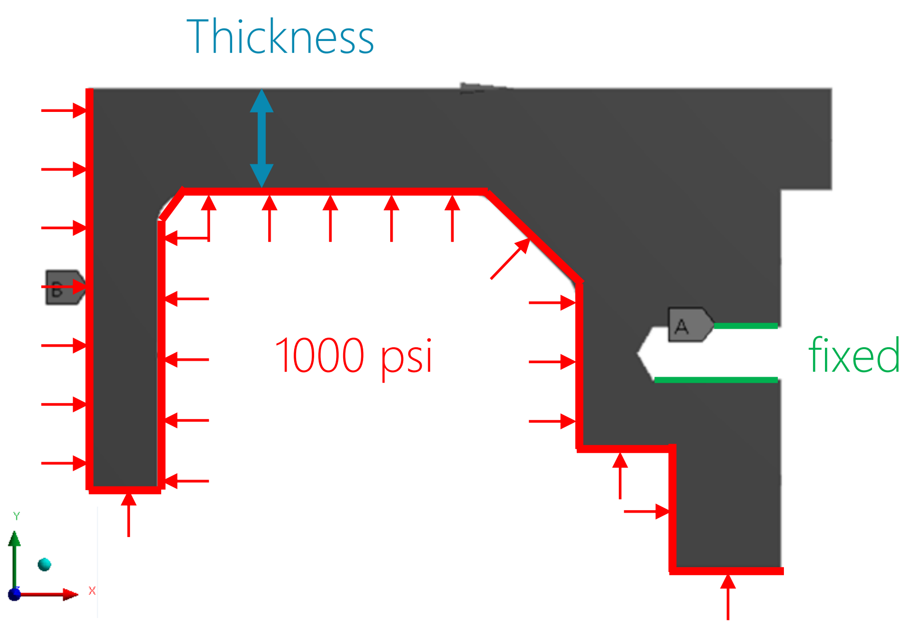


Boundary Conditions

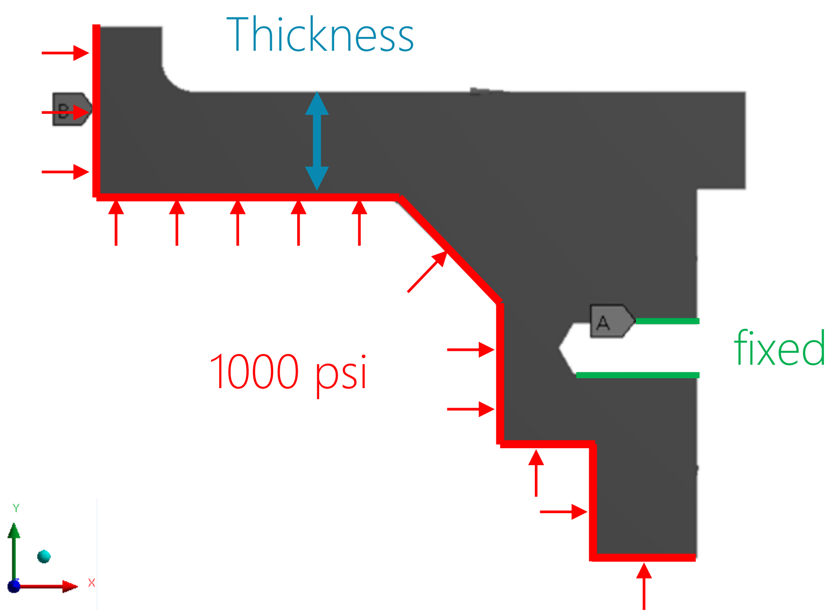
Axisymmetric models for two end cap geometries
Simulated different thicknesses to find minimum allowable thickness

Aluminum 6061-T6 (tensile yield strength 270 MPa)

Top End Cap



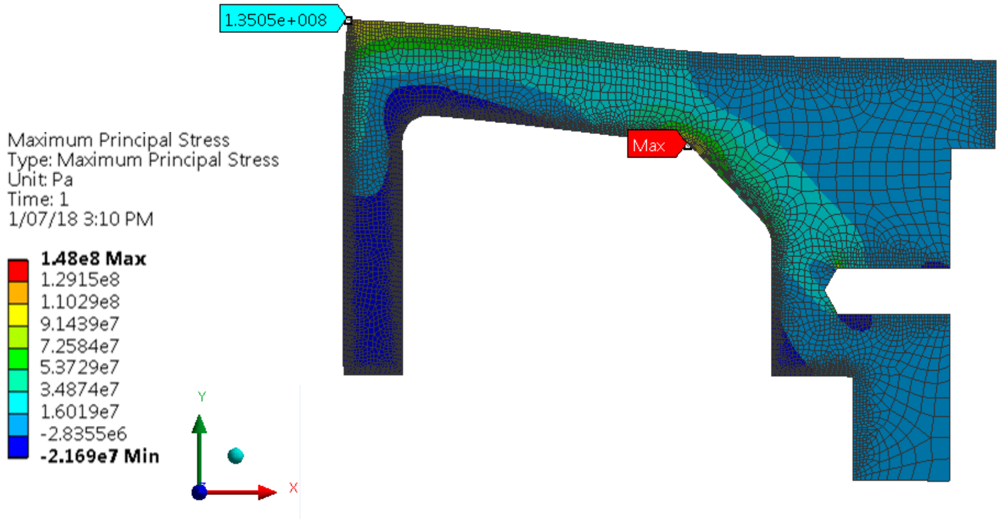
Bottom End Cap



IDEAs Analysis Competition: Structural Analysis | End Cap Thickness

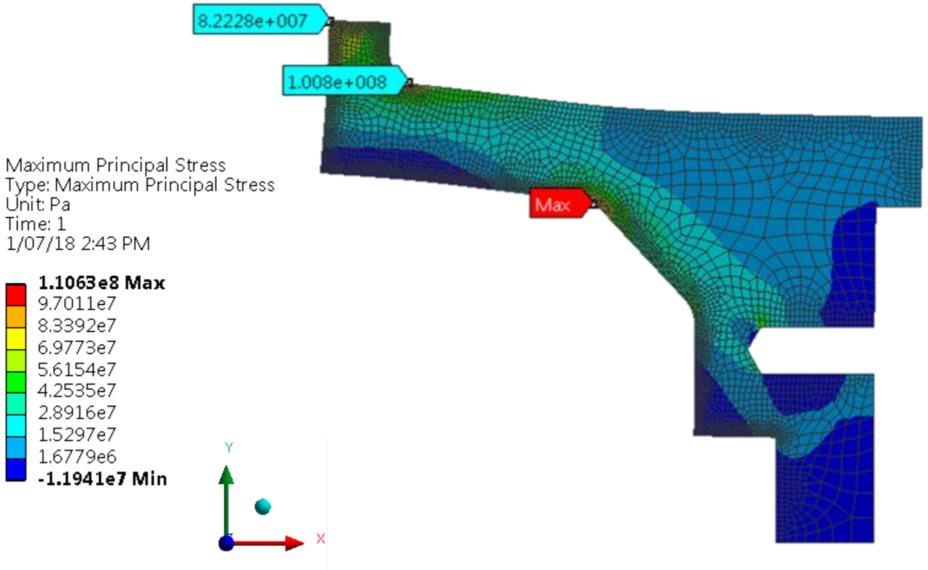
Stress Results

Top End Cap



Maximum stress = 135 MPa
Factor of Safety = 2.0

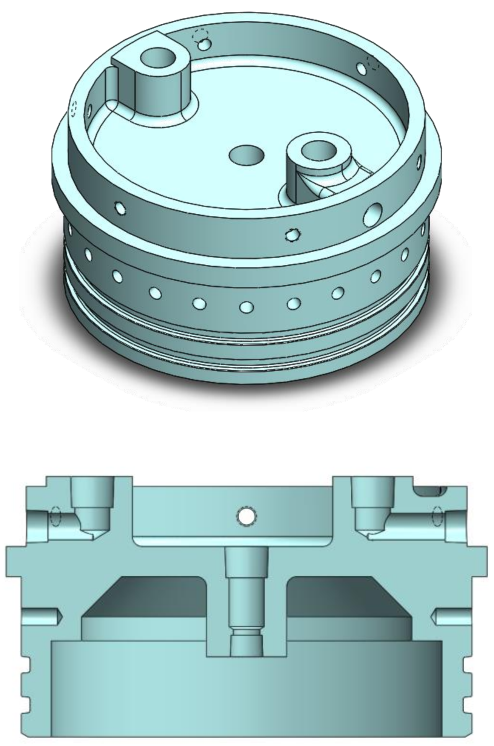
Bottom End Cap



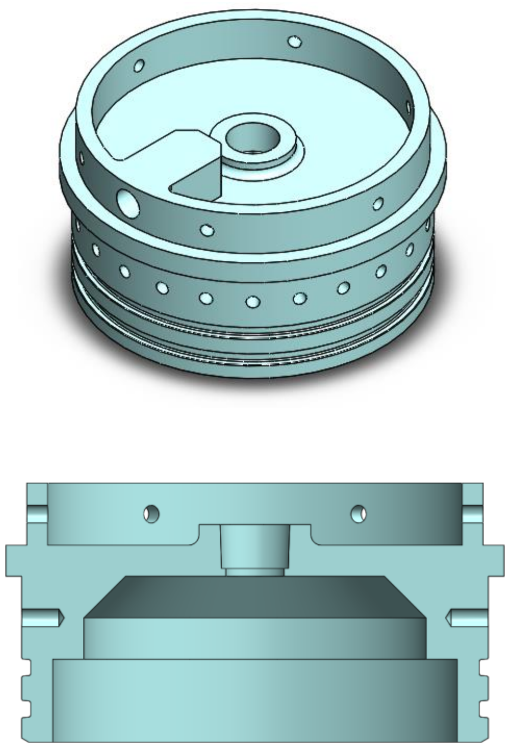
Maximum stress = 100 MPa
Factor of Safety = 2.7

Minimum allowable thickness: 3/8"

IDEAs Analysis Competition: Structural Analysis | End Cap Thickness



Top End Cap



Bottom End Cap

Significance

	Top	Bottom	Sum
Original (0.5” thick)	3.6 lb	3.6 lb	7.2 lb
Final (0.375” thick)	3.2 lb	3.2 lb	6.4 lb

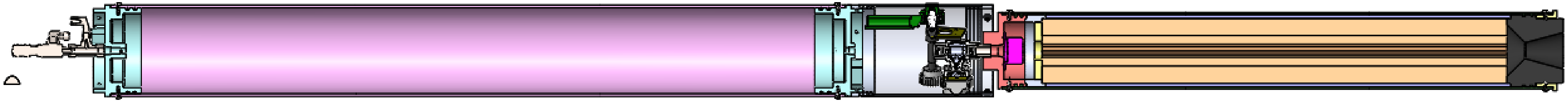
Weight reduction of assembly by 0.8 lb (10%)

Verification of Results

Hydrostatic testing

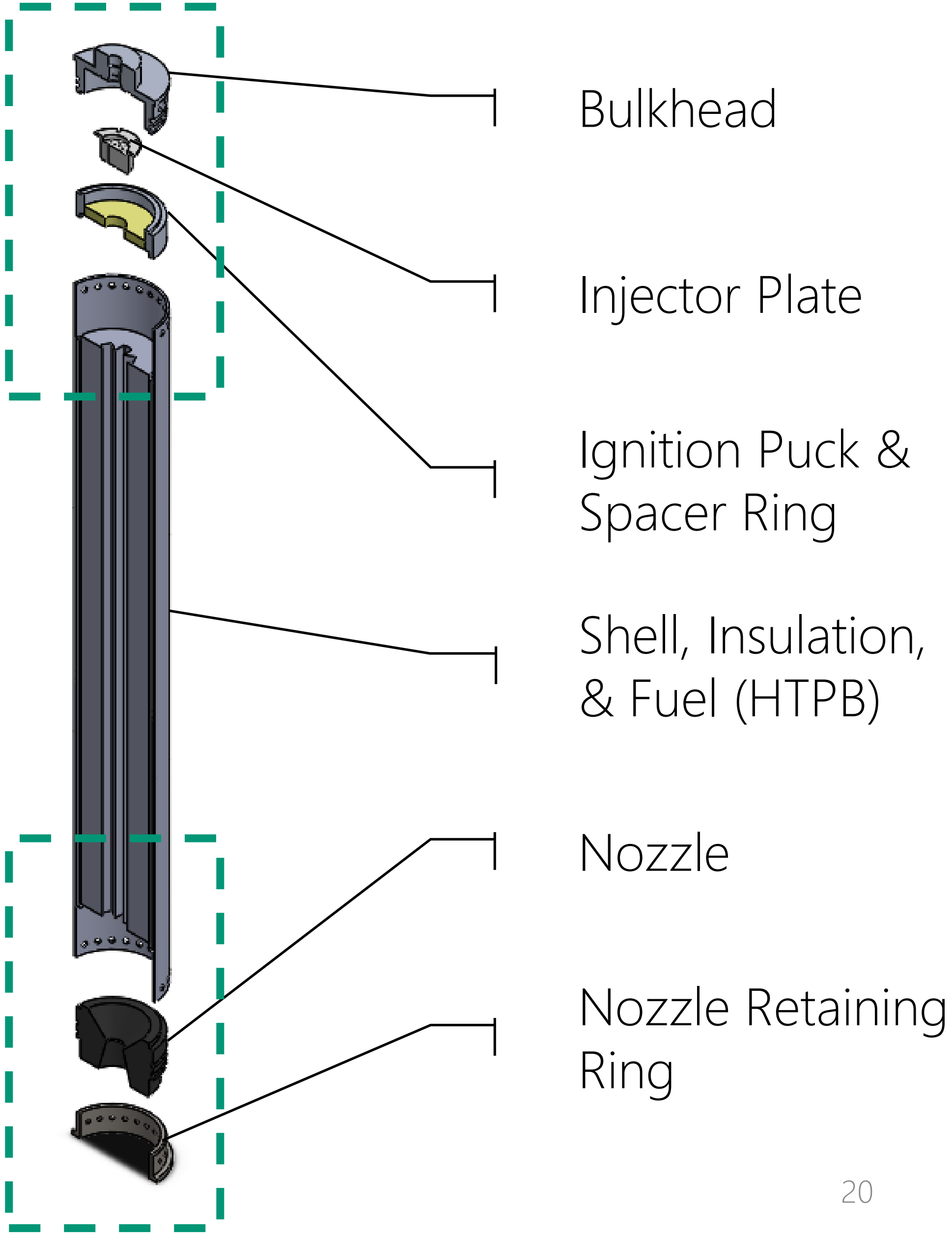
- Pump water into sealed pressure vessel to 1.5x operating pressure
- Tank was able to hold pressure
- No measurable plastic deformation of end caps

Thermal Analysis



Motivation

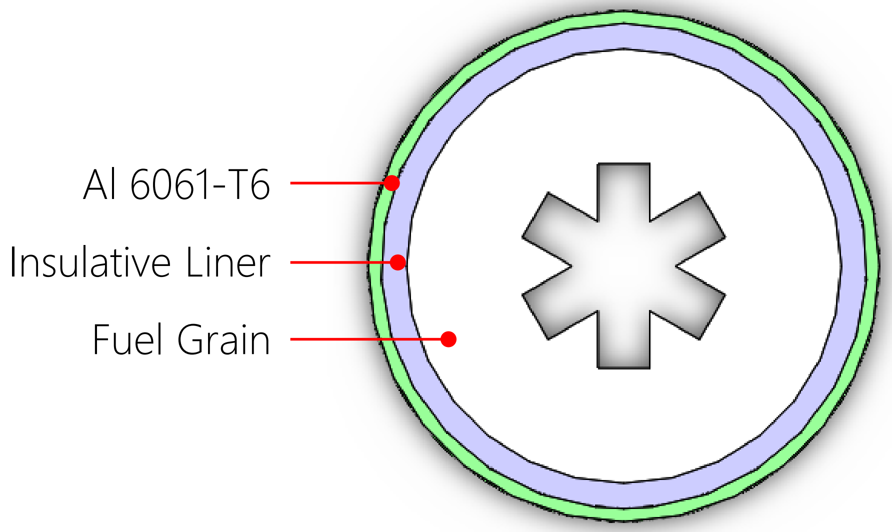
- High temperature lowers the strength of components
  - Will components fail at launch?
  - Will components suffer later thermal effects (annealing)?
- Understand thermal conditions in the key areas (injector and nozzle)



Methodology

Combustion Chamber Heat Transfer

- Heat transfer mechanisms very complicated:
  - Generation, convection, radiation, conduction, ablative cooling, varying mass flow rate, regressing fuel wall



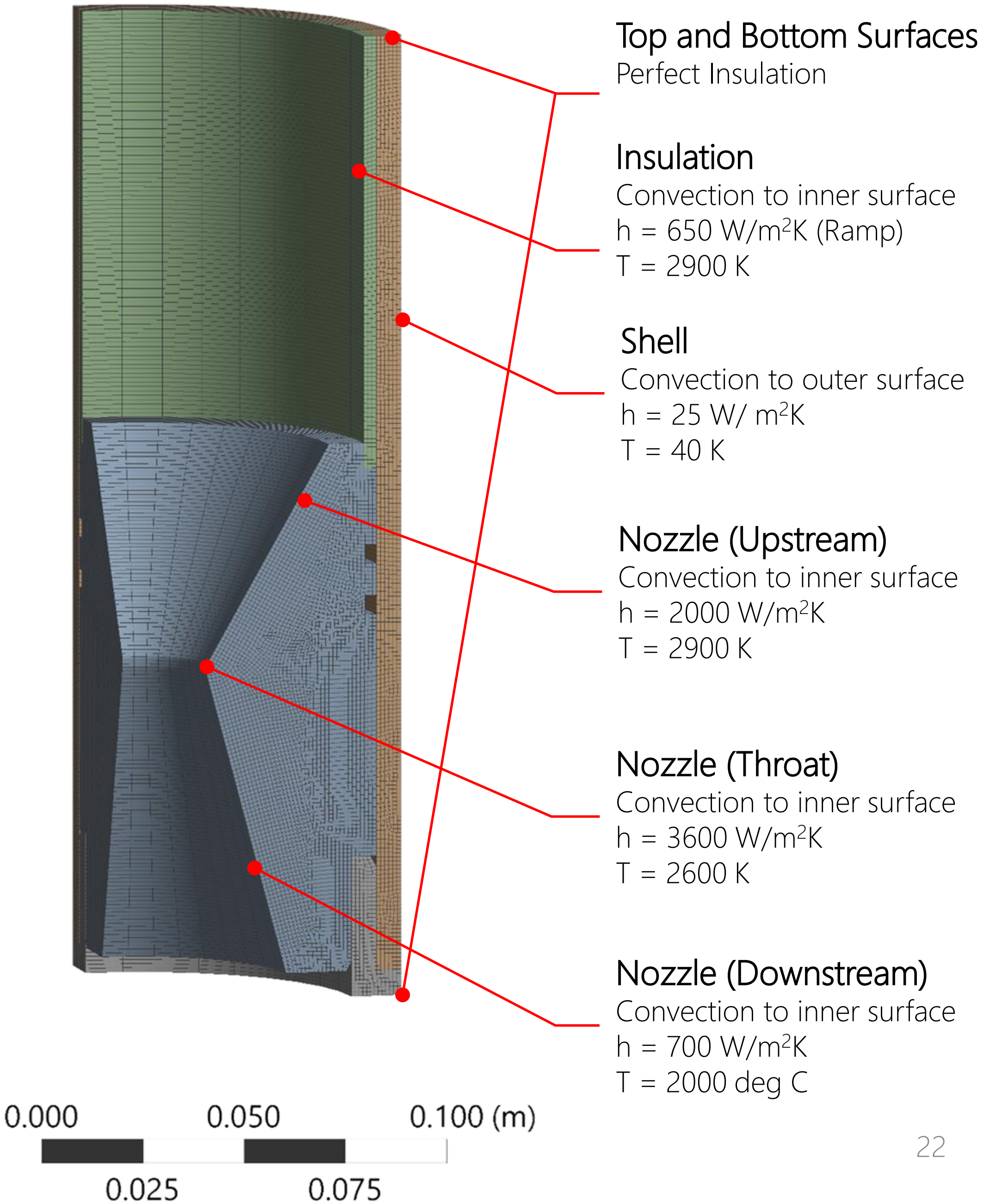
Heat Transfer Model

- Modelling the full complexity is non-feasible
- A conservative, simplified model employed

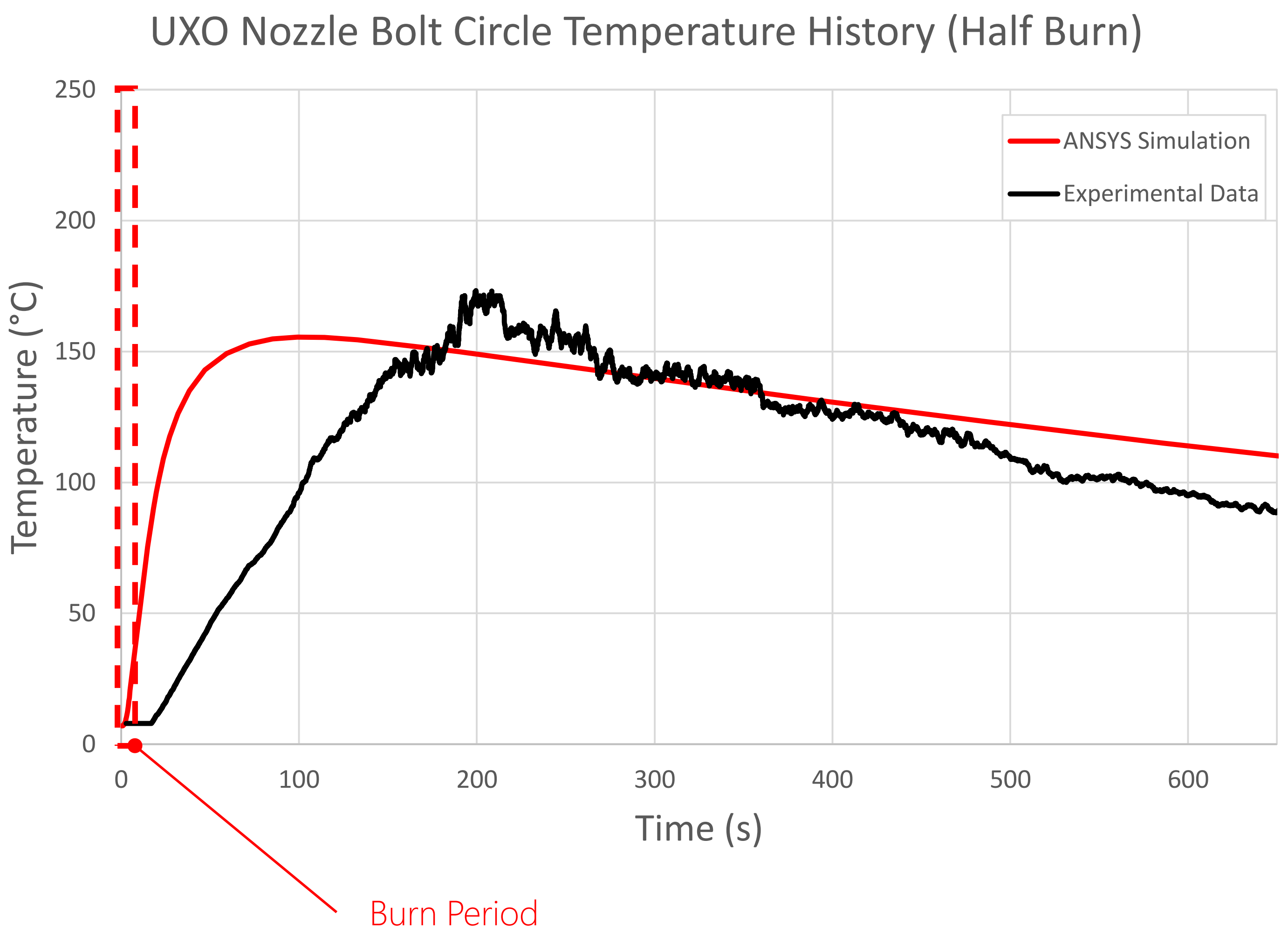
IDEAs Analysis Competition: Combustion Chamber | Nozzle Thermal Analysis

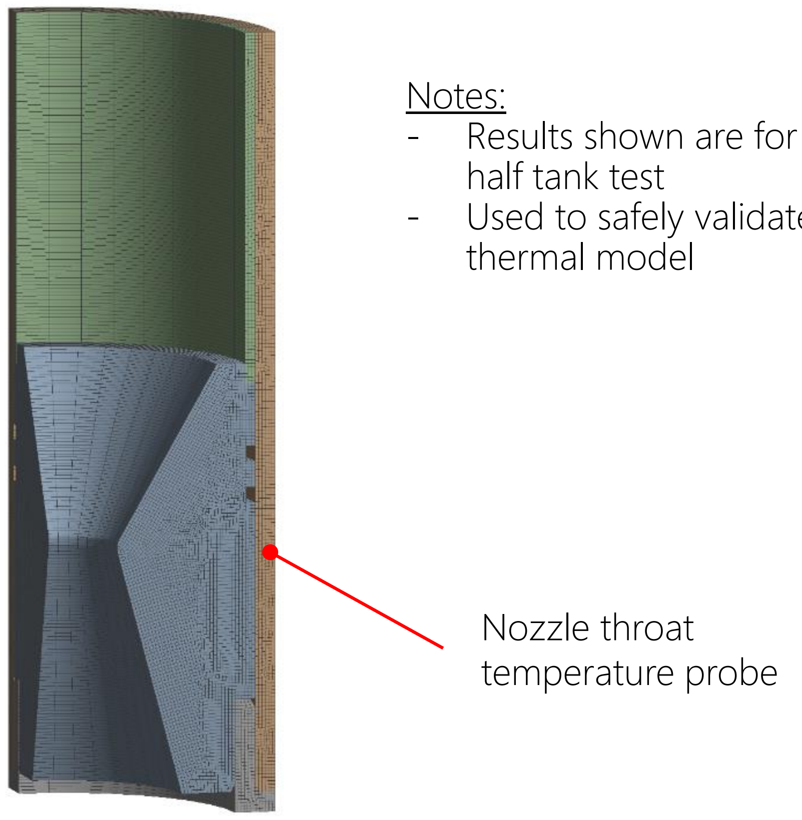
Model

- Axisymmetric (quarter shown for clarity)
- Shell, Insulator, Nozzle, Retaining Ring
- Heat transfer coefficients and temperatures from Rocket Propulsion Analysis (RPA) software



Verification of Results

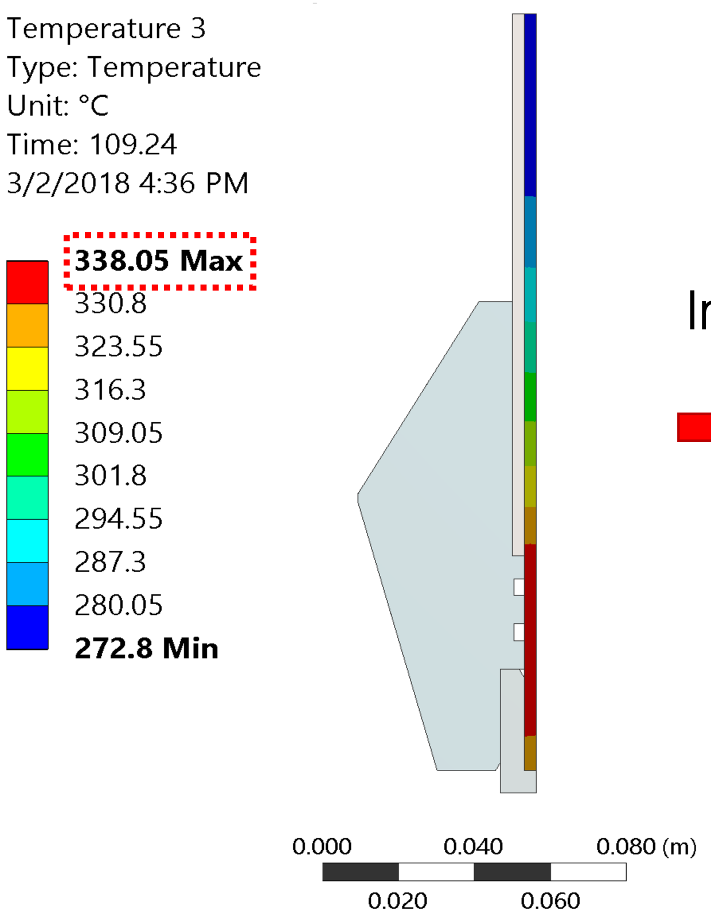




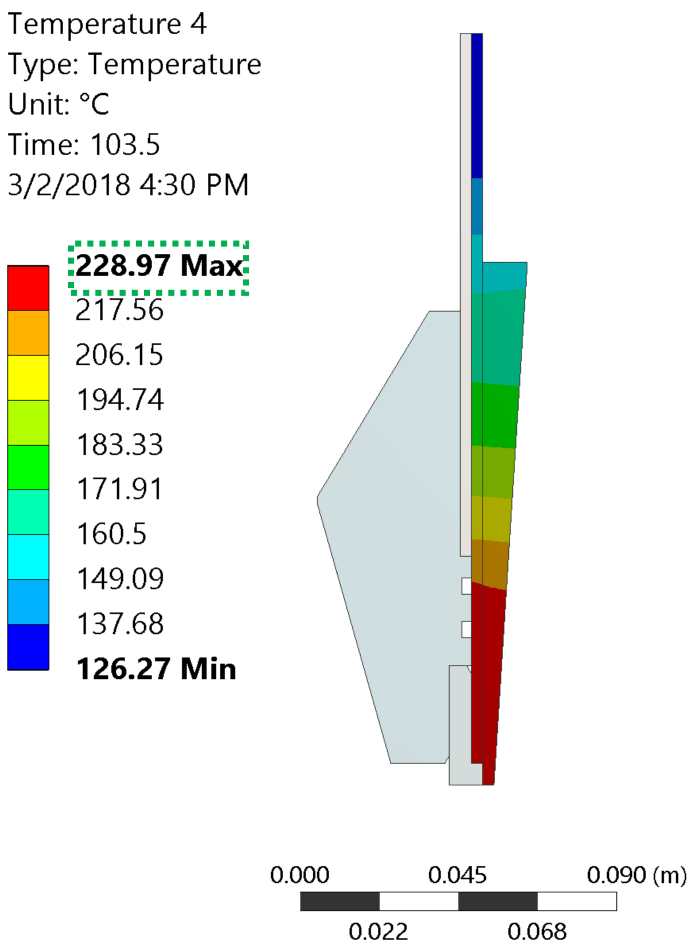
Notes:

- Results shown are for half tank test
- Used to safely validate thermal model

IDEAs Analysis Competition: Combustion Chamber | Nozzle Thermal Analysis



Implementation of Heat Sink



At 340 °C, aluminum is annealed (softer, lower strength)

At 230 °C, the aluminum strength is sufficient

Flight Analysis

IDEAs Analysis Competition: OpenRocket Flight Simulation

Motivation

- Want to predict rocket apogee to ensure flight of 30,000 ft

Approach

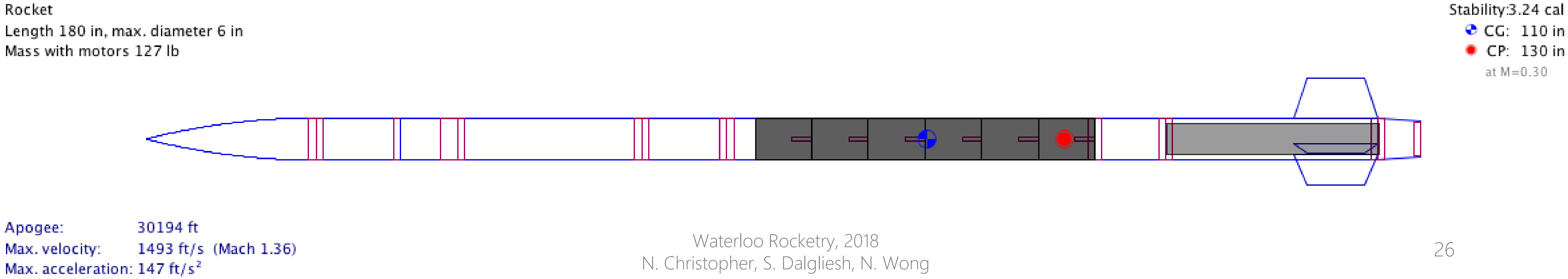
- Create a model of the rocket and engine thrust curve in OpenRocket

Results

- Current apogee prediction: 30,194 ft

Conclusions

- Based on current knowledge of rocket geometry and thrust, the design is acceptable
- Will continue to update this simulation as components are finalized



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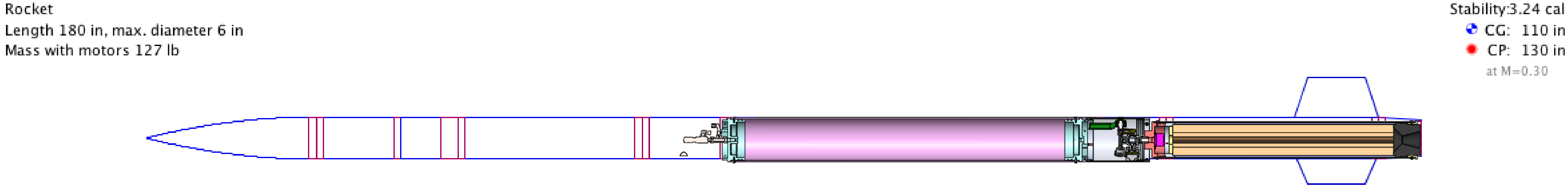
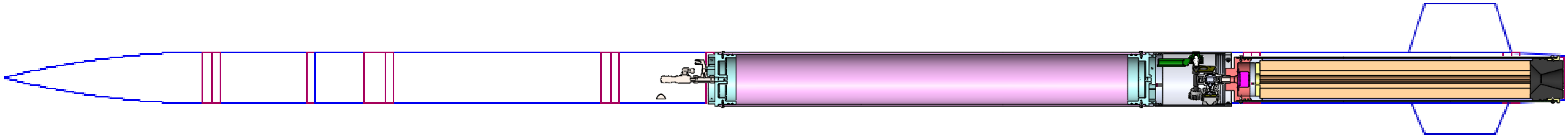


Apogee: 30194 ft
Max. velocity: 1493 ft/s (Mach 1.36)
Max. acceleration: 147 ft/s²

Conclusions

- Through analytical and computer aided design analysis, able to design rocket to operate safety and achieve performance goals
- Results verified through both component level and system level testing



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