BURPG

MAVERICKS
CIVILIAN SPACE FOUNDATION

ANSYS

Astos Solutions

Raytheon
GE Aviation

Parker

BU College of Engineering Allocations Board

C·S·P

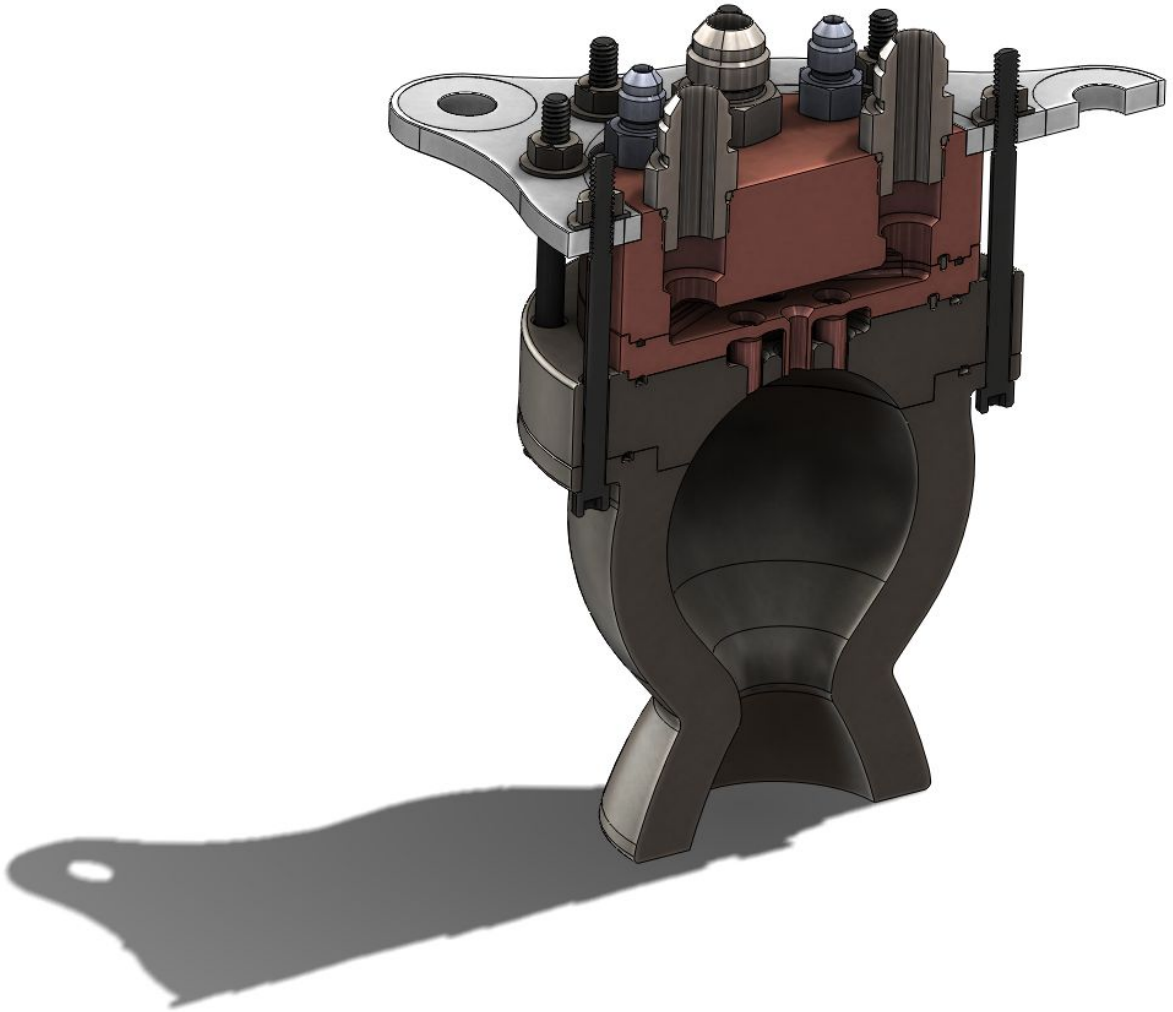
TRITON SPACE TECHNOLOGIES

DASSAULT SYSTEMES

# Mortise Delta CDR

Justin Fiaschetti
Adam Kotler
Carla Sheridan

# Mortise

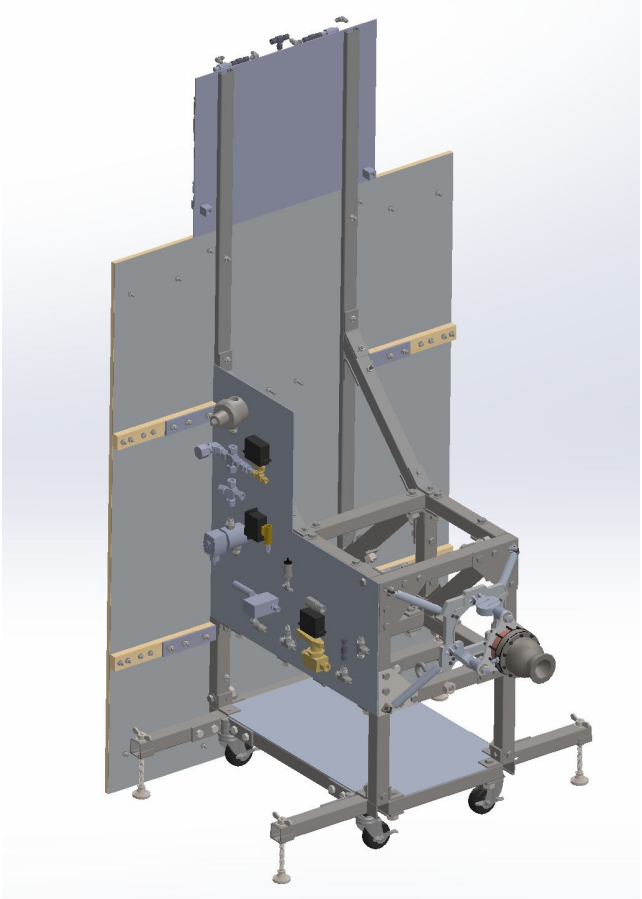


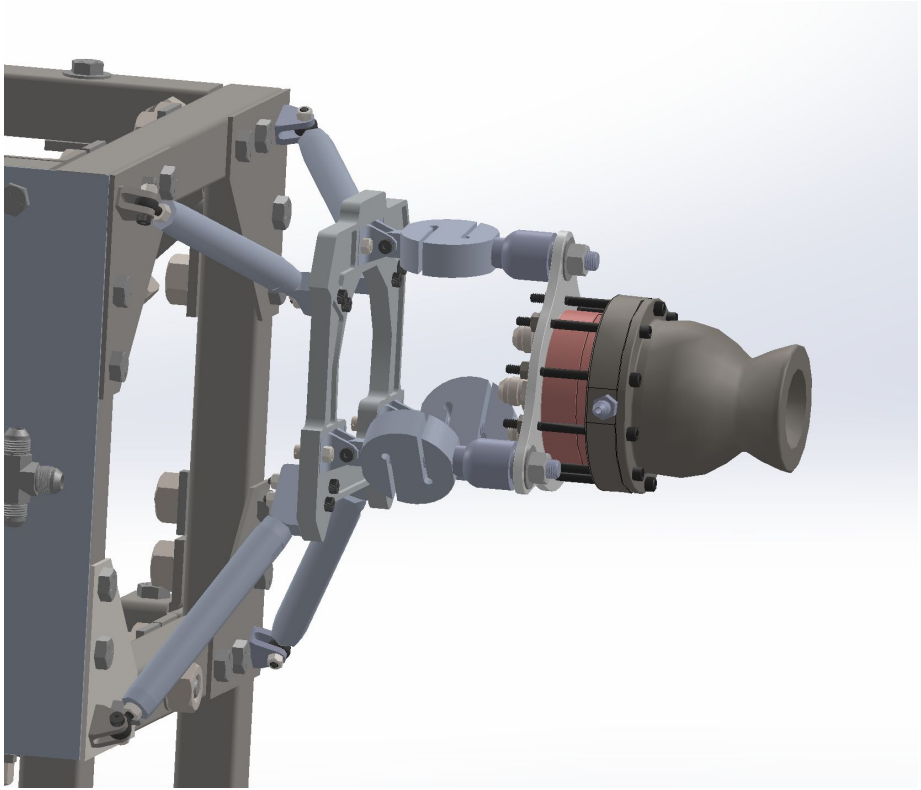
# Requirements

- Complies with safety design factors for **NASA-STD-5005D** -- NASA Standard for the Design and Fabrication of Ground Support Equipment
- Complies with safety design factors for **NASA-STD-5001** -- NASA Standard for the Design of Flight Hardware

| | | |
|---|---|---|
| **Chamber and Injector** | FSy | 1.5 |
| | FSu | 2.0 |

# Citadel





# Overview - Mortise

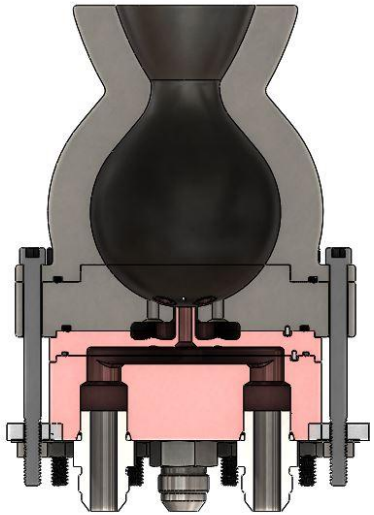
- Gaseous Oxygen-Gaseous Methane Heat-sink Engine
  - Implemented to verify injector and chamber design
  - Data collected will be used to refine dovetail injector and chamber
- DFM
  - All components are designed to be machined in house at the EPIC facility
- GOx Compatibility
  - Injector, chamber, and interface components designed and chosen to function successfully and safely with gaseous oxygen

# Design Brief

BURPG

## Performance

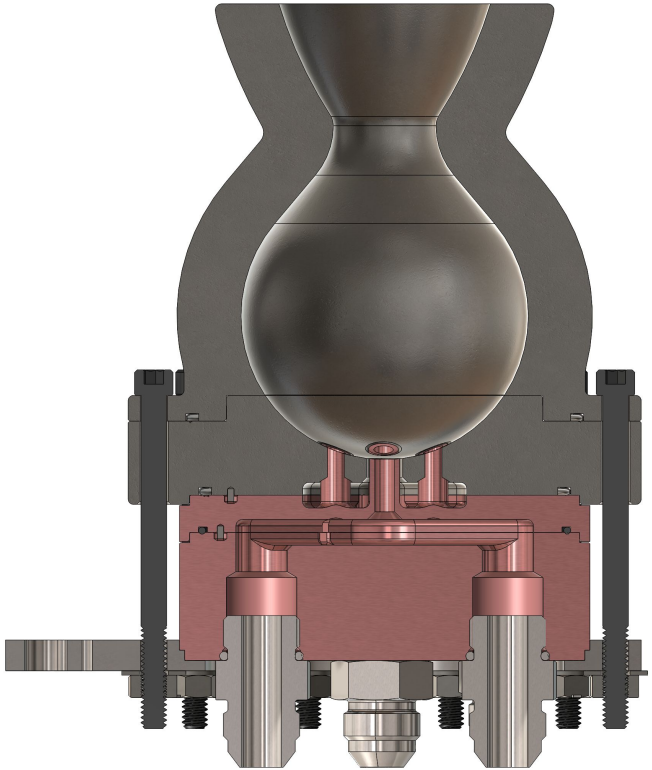
| | Value | Units |
|---|---|---|
| Thrust | 453 | lbf |
| ISP | 264 | s |
| Chamb. Press | 400 | psi |
| Mass Flow Rate | 1.72 | lbm/s |
| O:F | 2.00 | |
| Specific Heat Ratio | 1.24 | |
| C* | 1780 | m/s |



## Geometry

| | Value | Units |
|---|---|---|
| Area Ratio | 4.25 | |
| Throat Diameter | 1.00 | in |
| Exit Diameter | 2.06 | in |
| Cone Length | 1.98 | in |
| 60% Bell | 1.19 | in |
| Contraction Angle | 40 | deg |
| Chamber Volume | 20 | in^3 |
| L* | 20 | in |

# Mortise



Steel & Copper
Heat Sink
Ground Testing

# Dovetail

Inconel 718
Regen/Film Cooling
Gimbaled
Flight

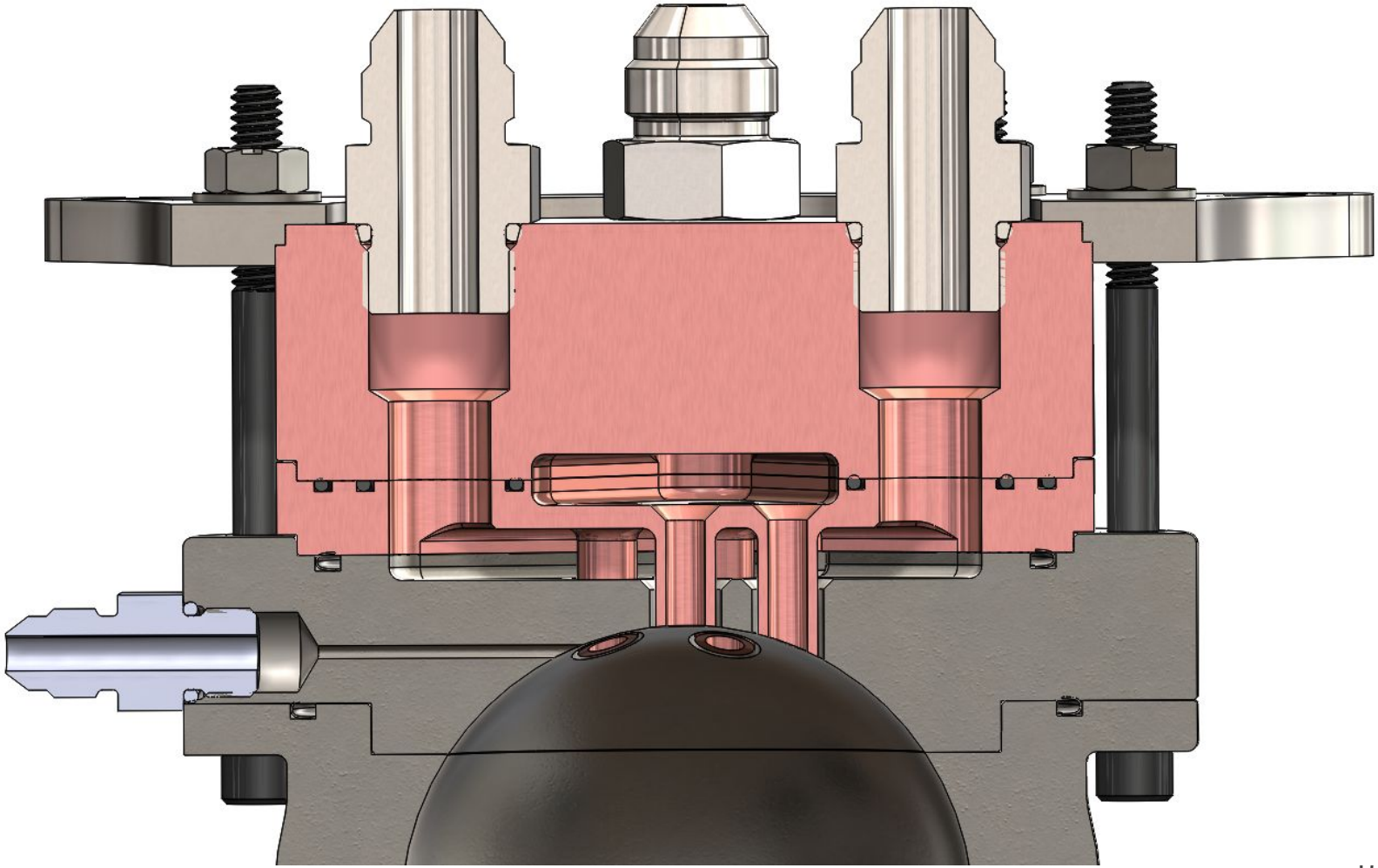
# Engine Design

- Spherical Chamber Geometry
  - 20% surface area savings compared to cylindrical equivalent
  - Implemented to optimize chamber cooling
- 4-Piece Engine Assembly
  - 3-Piece Injector
  - Single piece chamber

# Testing Goals

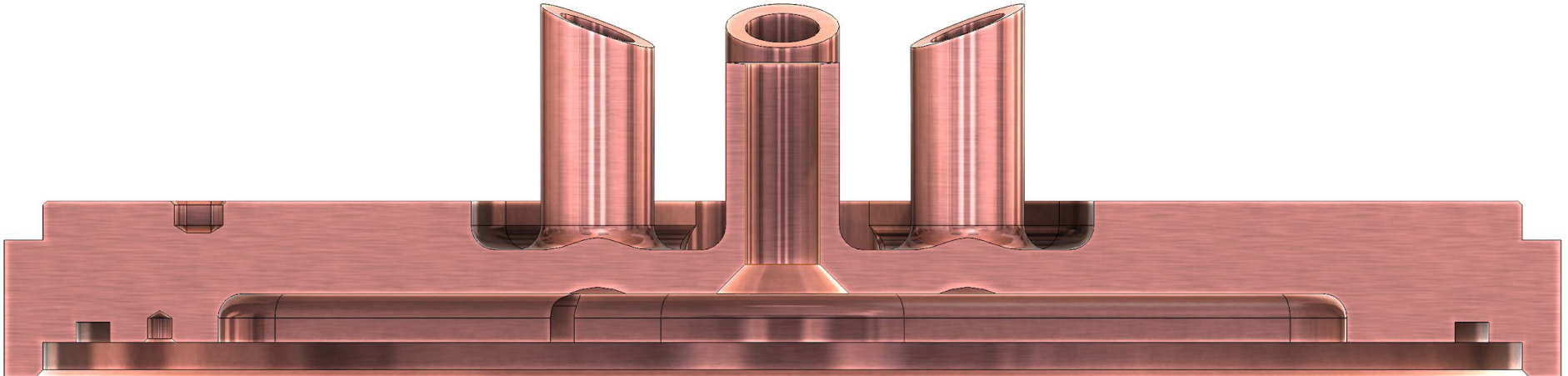
- Qualify thermal model (partially done with IL)
- Measure wall temperature to allow for design of Dovetail
- Measure efficiency of injector design
- Spherical Chamber testing
- Use Mortise data to refine Dovetail

# Injector



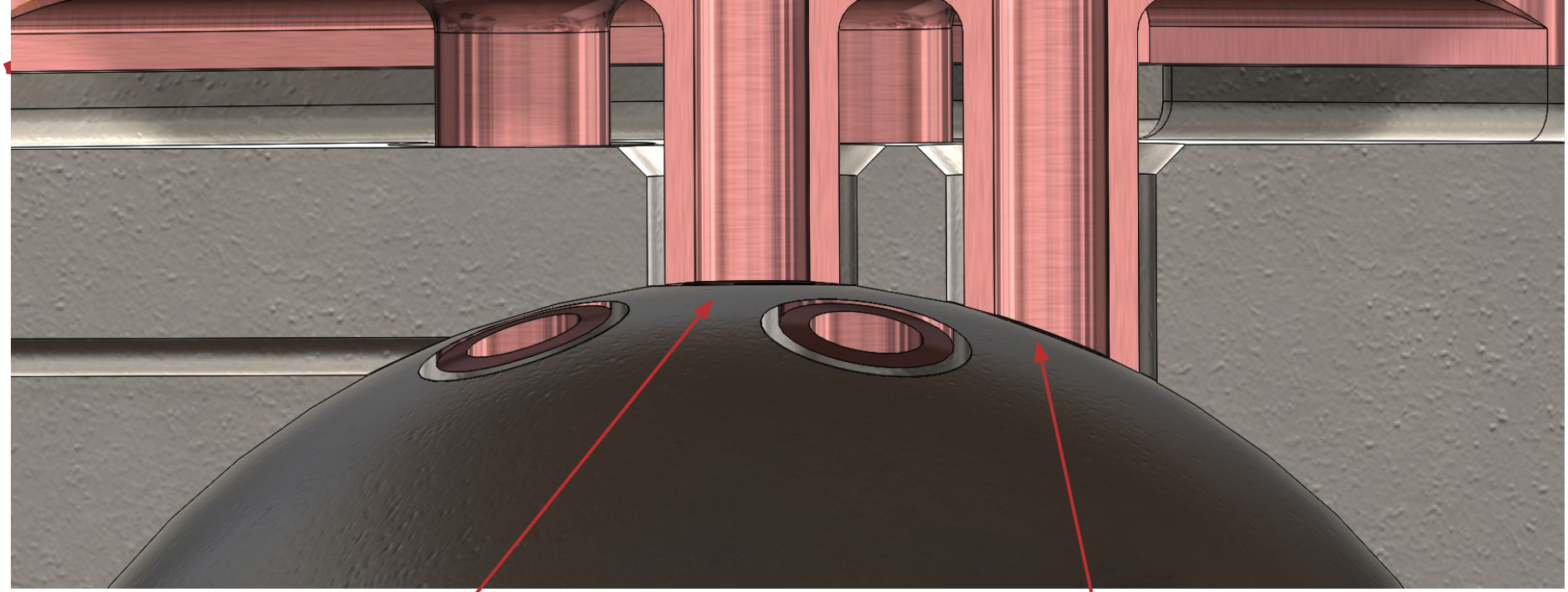
# Injector Overview

- Material: Copper C10100
  - GOx compatible
  - Stock in house → no new expense
- Stiffness: 20%
- OF: 2
- 1 central bowled Co-ax
- 5 radial scarfed, bowled Co-ax
- 2 times mixing area compared to single Co-ax element



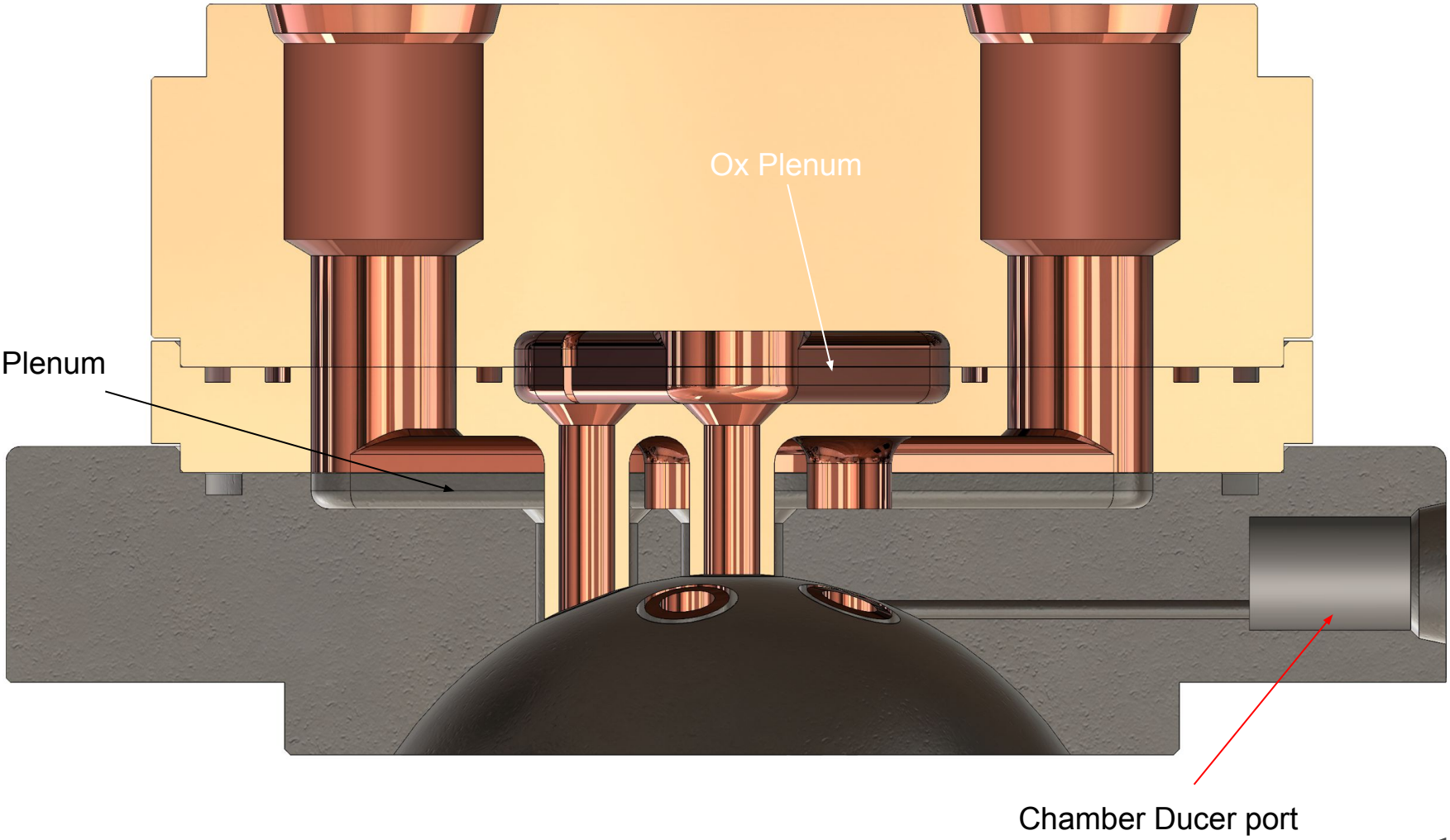
# 6 Coaxial Injector Elements

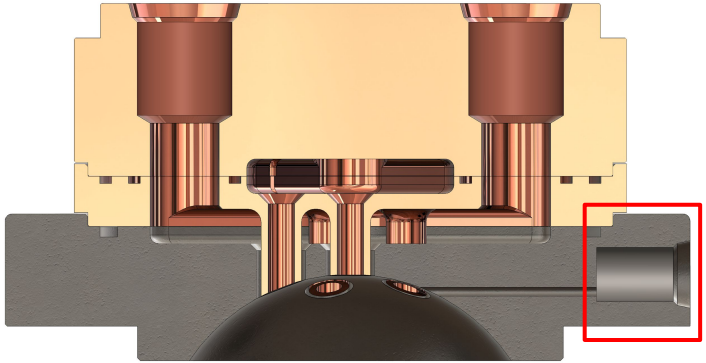
- 2x Combustion surface area compared to single element
- Lower wall temp than impining or recessed
- Even radial combustion

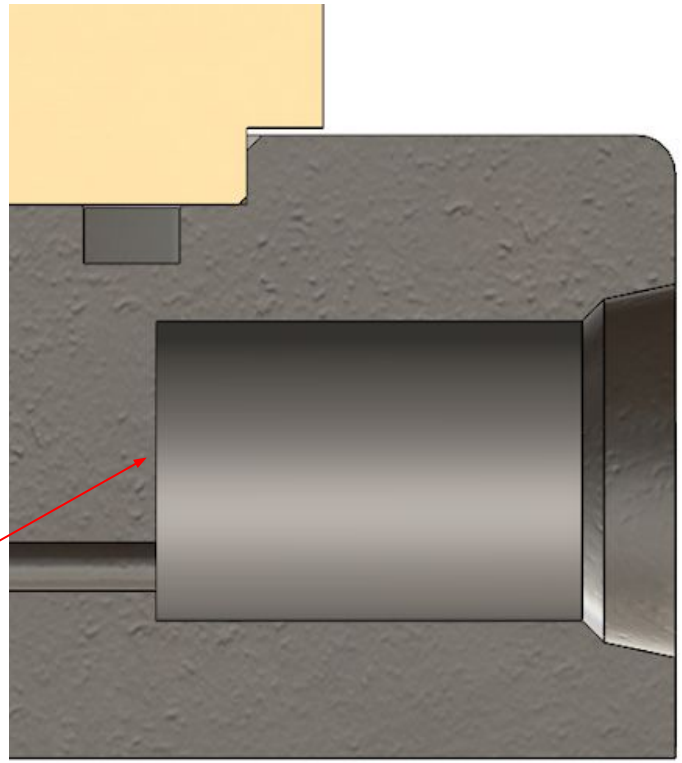


**Bowled**

**Scarfed and Bowled**


Ox Plenum
Fuel Plenum
Chamber Ducer port



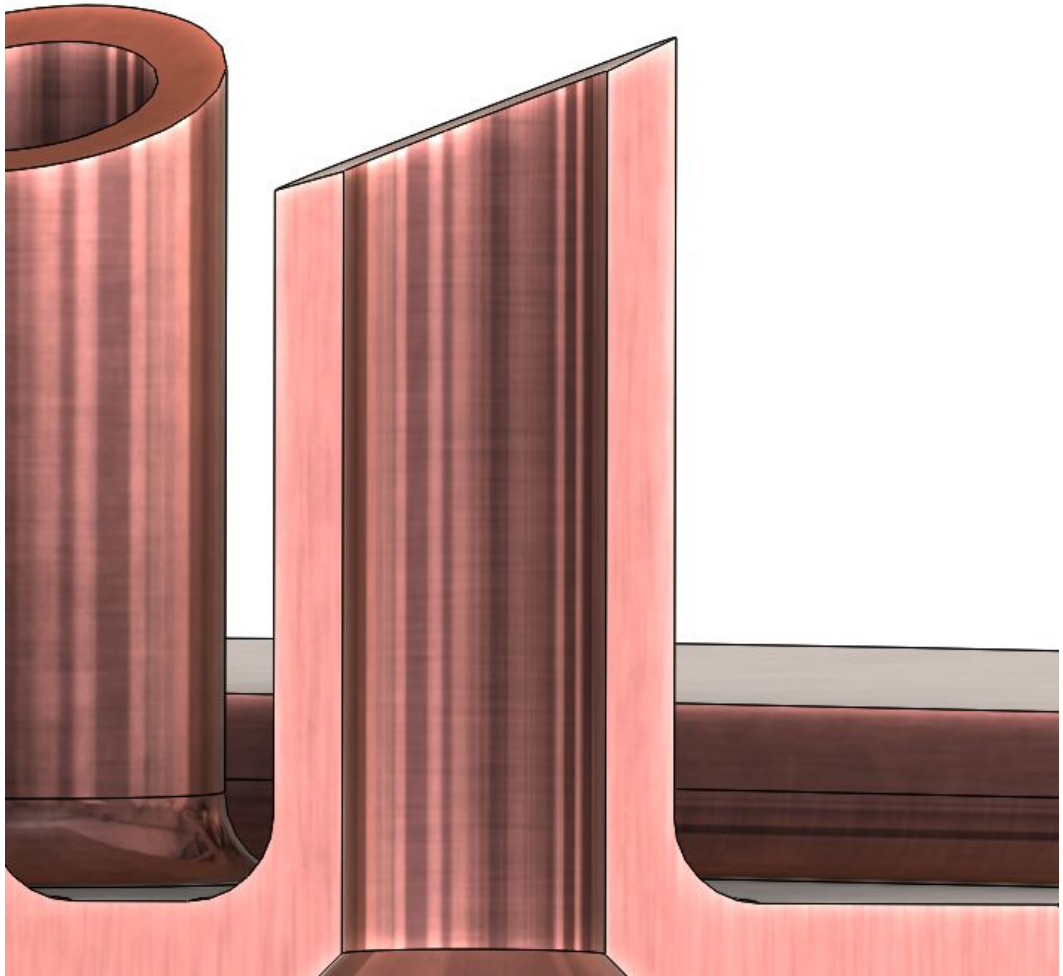


Flat to allow for drilling of hole

.125”

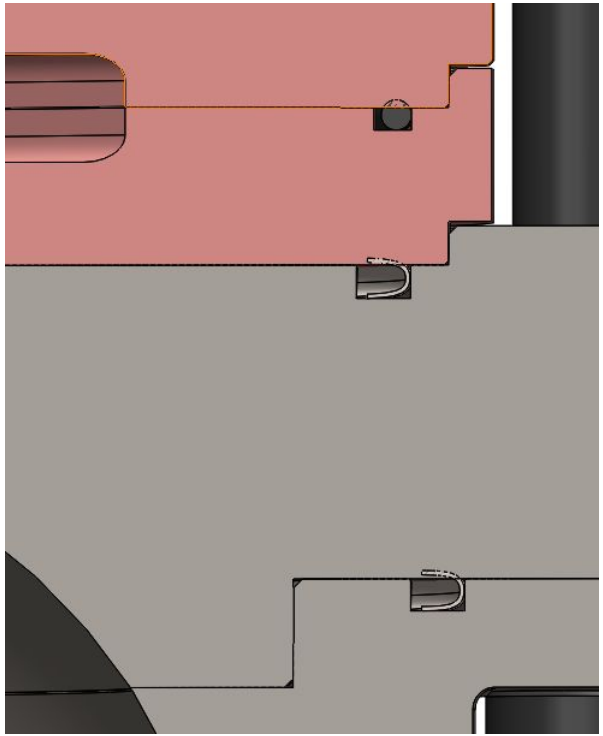
# Scarfed Injector

- Injection angle is in toward the chamber
  - Decreased wall temp
- Elements inping on each other
  - Increase mixing between elements
- Conforms to the contour of the chamber allowing for a spherical chamber
- 20.8° scarf off horizontal

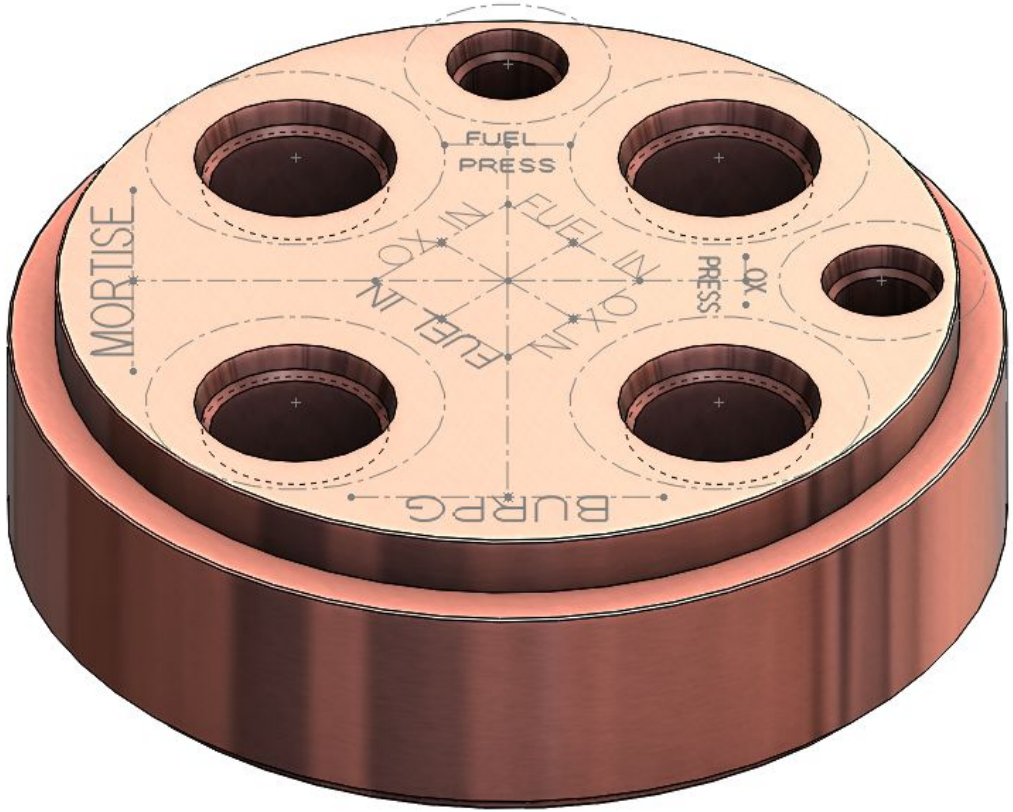


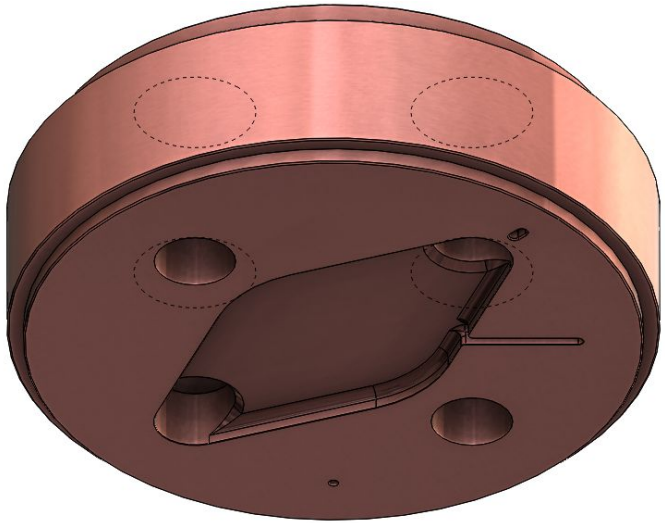
# Seals

- EUI Rings
  - High temp (1600f)
  - Allow for thermal expansion
  - Chamber and bottom injector
  - Bottom Injector to middle injector
- Fluorocarbon seals for injector
  - GOx Compatible
  - 60 DUROMETER
    - Better sealing in microstructure of metal
    - Better for gas



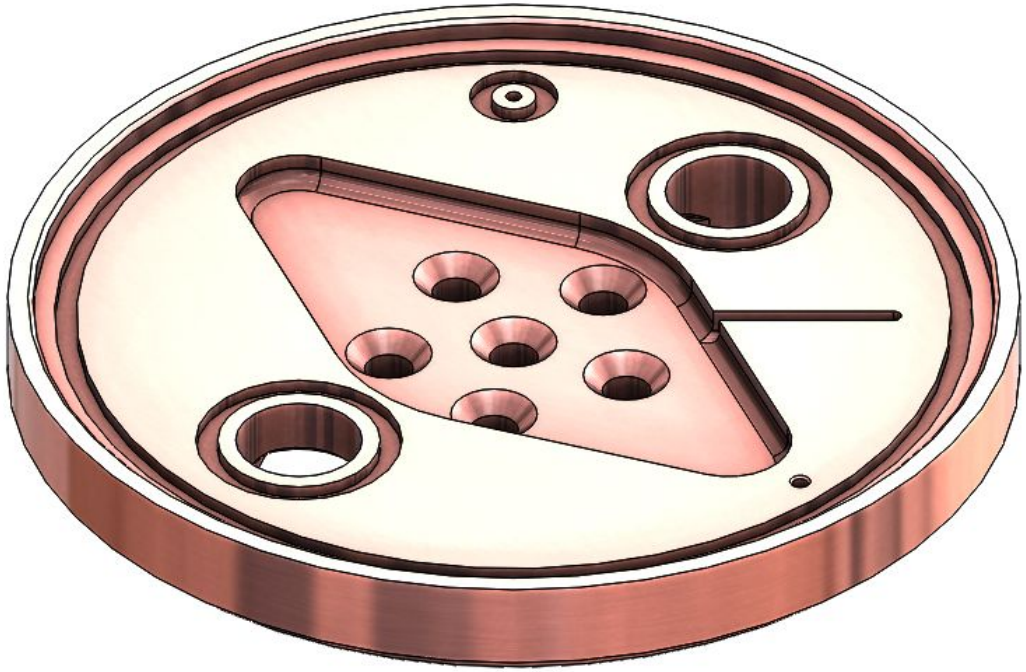
# INJ-0001

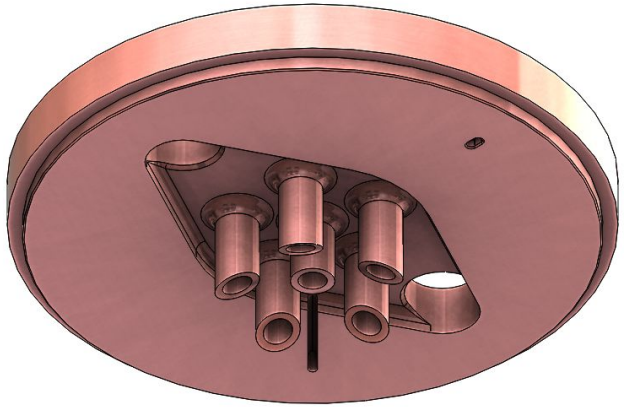


Material: C10100
Diameter: 4”
Thickness: 1.25”

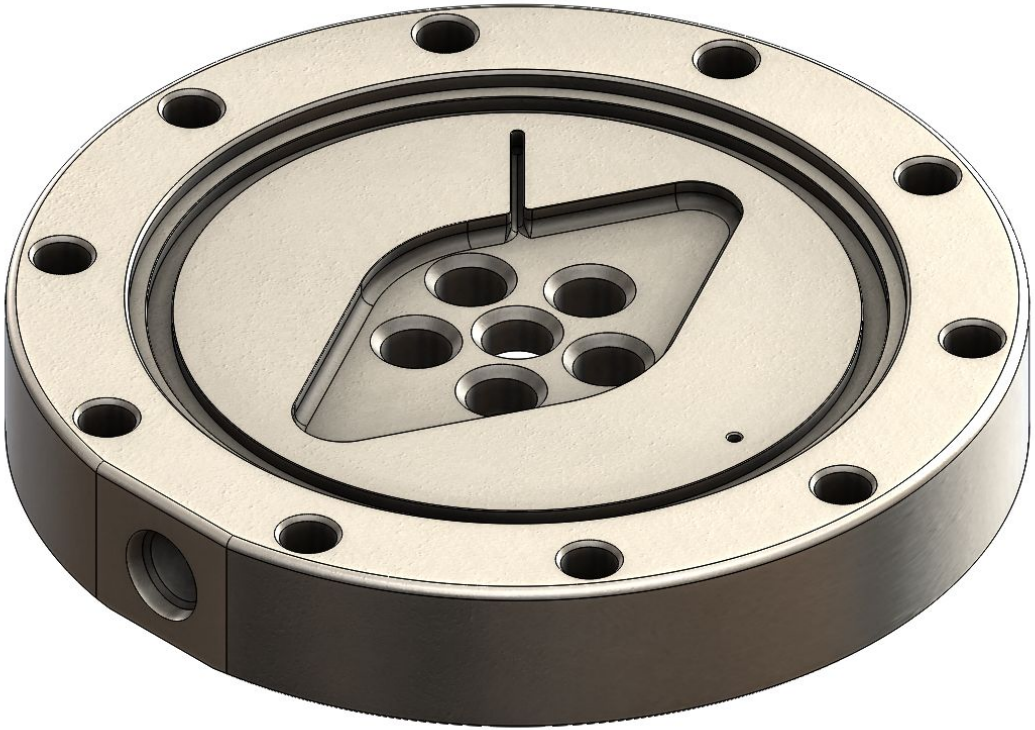
# INJ-0002



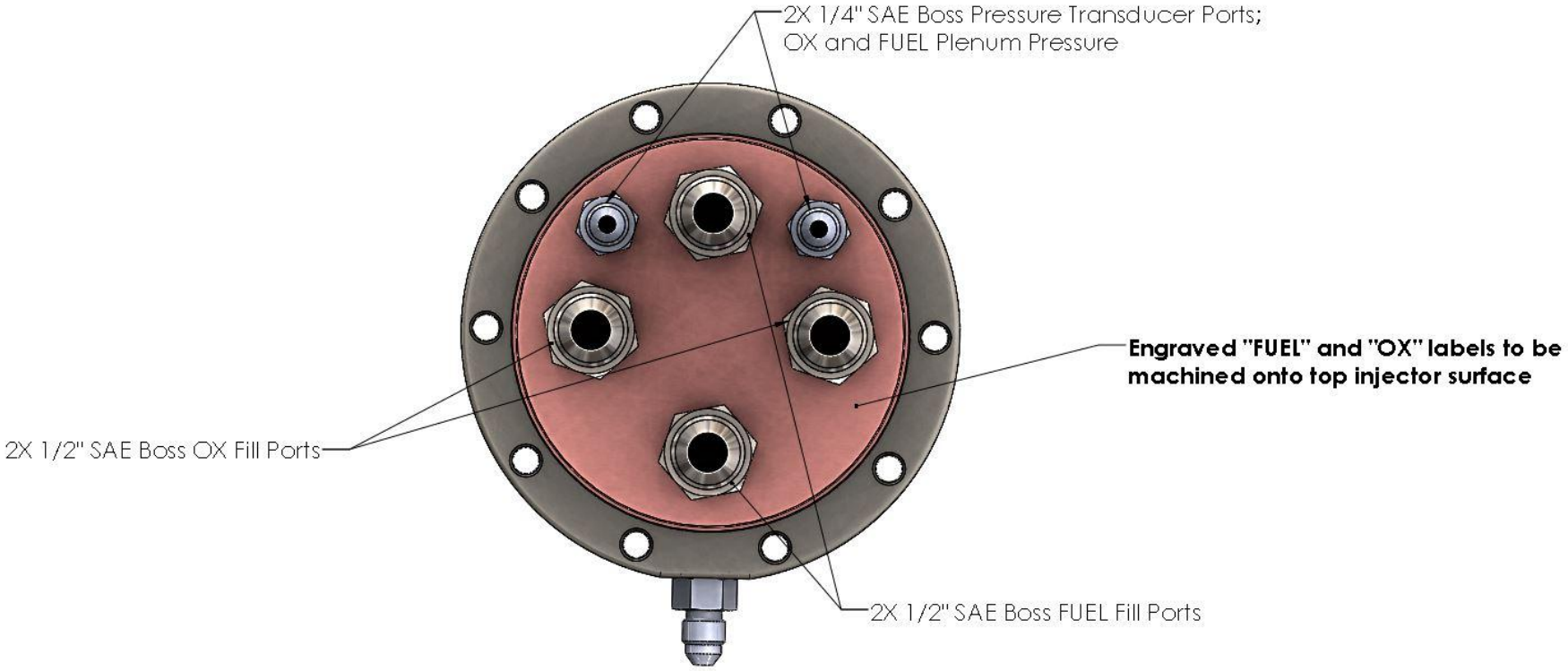


Material: C10100
Diameter: 4”
Thickness: 1”

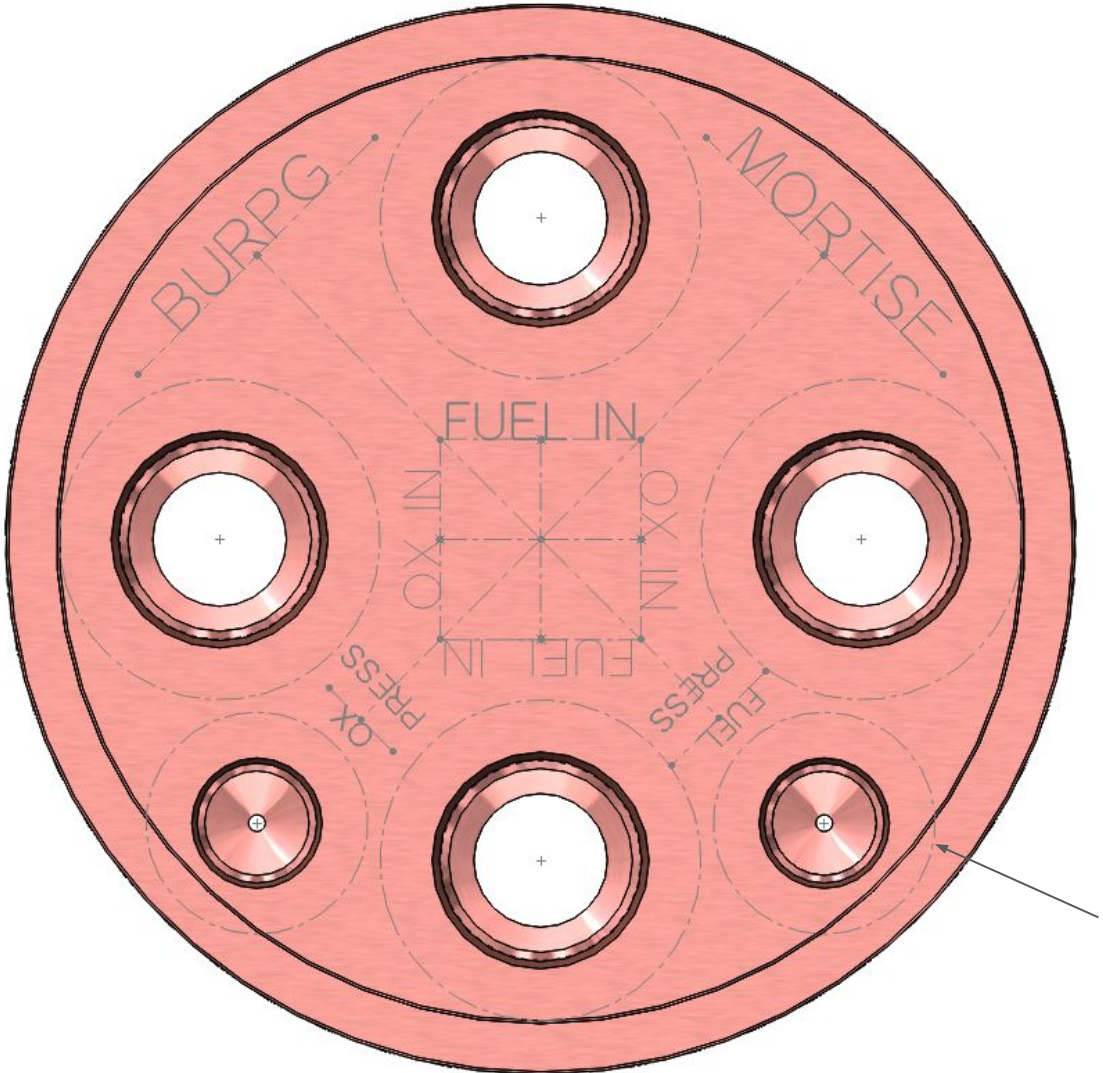
# INJ-0003



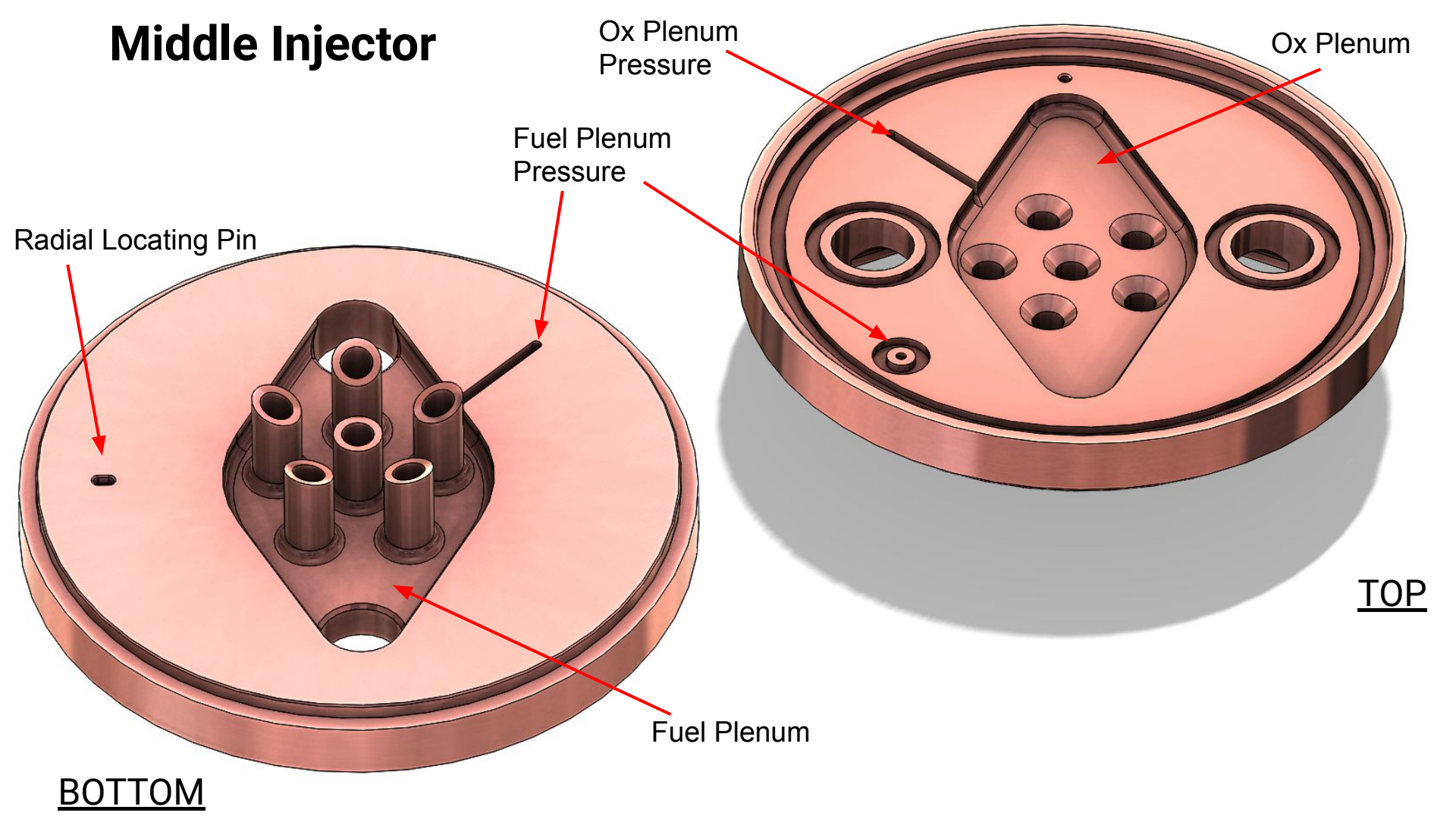
Material: AISI 1045
Diameter: 5”
Thickness: 1.0625”


2X 1/4" SAE Boss Pressure Transducer Ports;
OX and FUEL Plenum Pressure
Engraved "FUEL" and "OX" labels to be machined onto top injector surface
2X 1/2" SAE Boss OX Fill Ports
2X 1/2" SAE Boss FUEL Fill Ports

Engravings for assembly ease

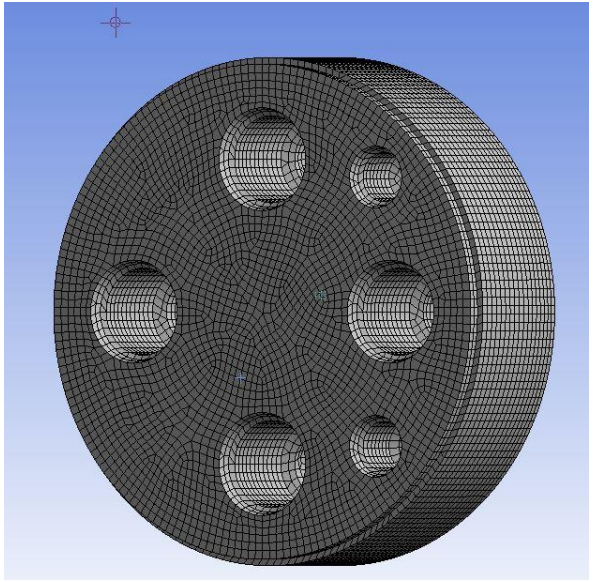


# Middle Injector



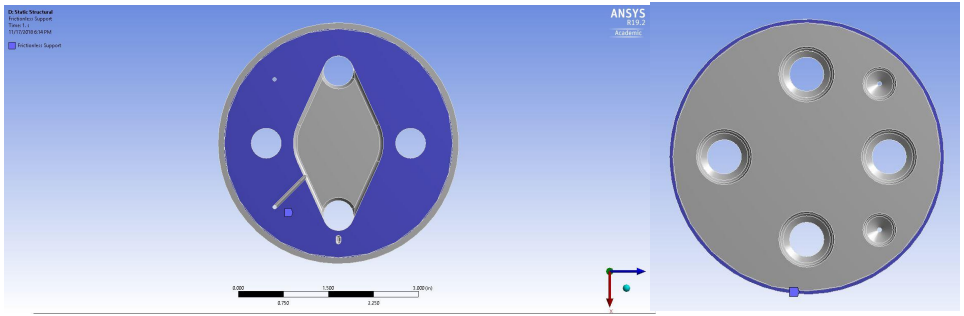
# MTS-INJ-0001: ANSYS Structural

| MTS-INJ-0001: FEA | | | |
|---|---|---|---|
| Applied load | 600 psi | 500 psi | 300 psi |
| Max Actual | 4467 psi | 3724 psi | 2234 psi |
| Margin Yield | 0.08 | 0.29 | 1.16 |
| Margin Ultimate | 2.50 | 3.10 | 5.82 |

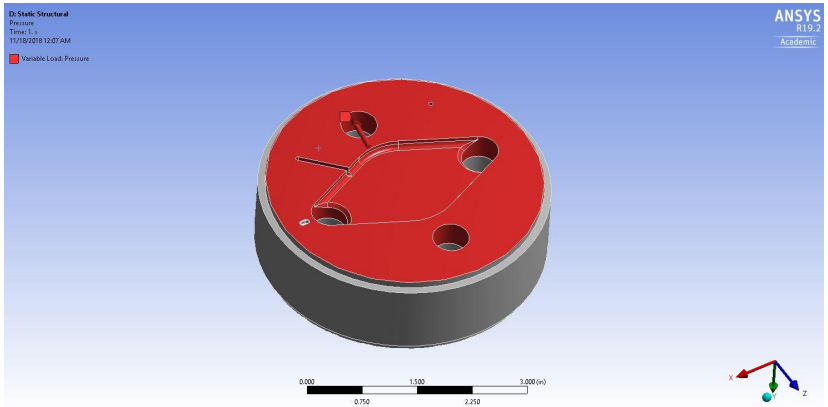


## Cylindrical Supports

## Frictionless Supports




## Applied Pressure Load

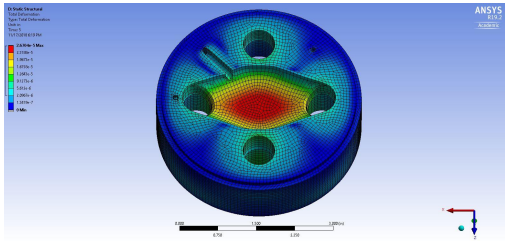


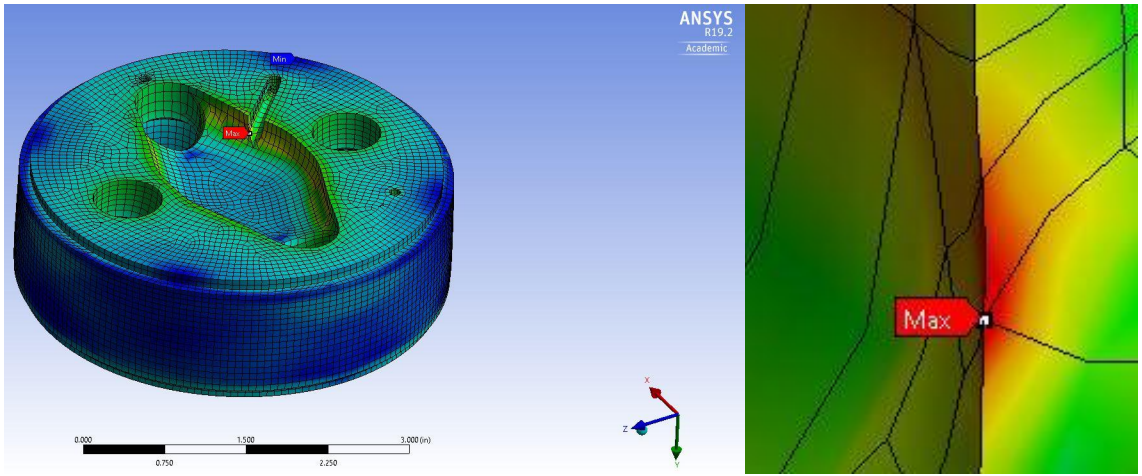
# MTS-INJ-0001: ANSYS Structural

Nominal 500psi applied load

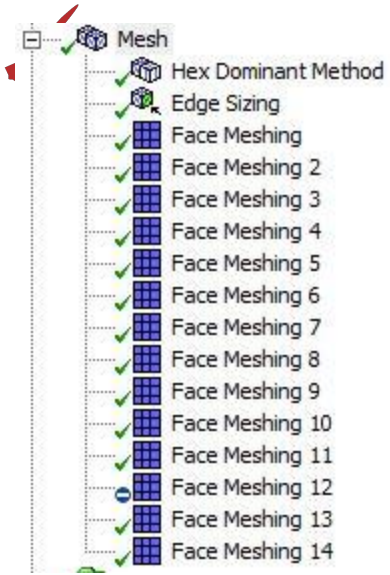
Max Stress: 3758 psi
Max Deformation:  2.98 E-5 in

*Deformation*




*Stress*



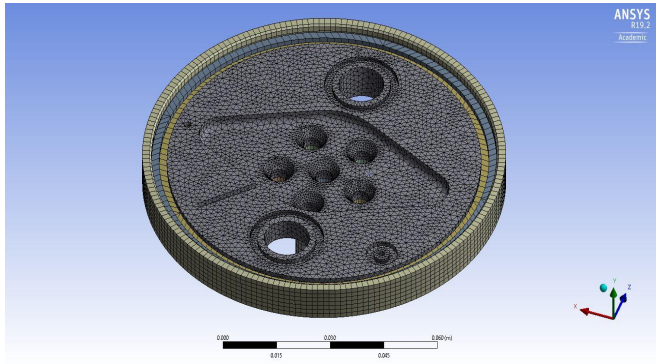

| Display | |
|---|---|
| Display Style | Use Geometry Setting |
| **Defaults** | |
| Physics Preference | Mechanical |
| Element Order | Program Controlled |
| Element Size | 2.e-003 m |
| **Sizing** | |
| Use Adaptive Sizing | Yes |
| Resolution | Default (2) |
| Mesh Defeaturing | Yes |
| Defeature Size | 2.54e-005 m |
| Transition | Fast |
| Span Angle Center | Medium |
| Initial Size Seed | Assembly |
| Bounding Box Diagonal | 0.14715 m |
| Average Surface Area | 4.3807e-004 m² |
| Minimum Edge Length | 3.5921e-004 m |

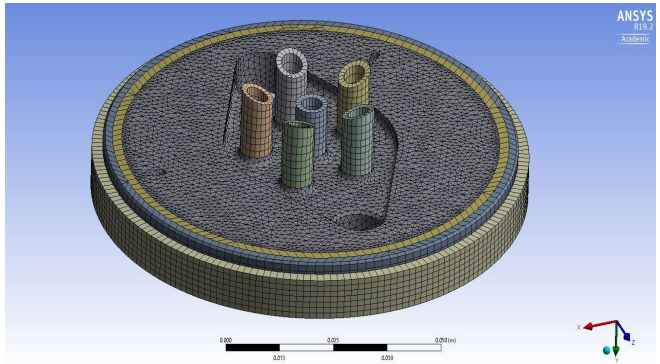
| Quality | |
|---|---|
| Check Mesh Quality | Yes, Errors |
| Error Limits | Standard Mechanical |
| Target Quality | Default (0.050000) |
| Smoothing | Medium |
| Mesh Metric | Skewness |
| Min | 8.4383e-003 |
| Max | 0.99999 |
| Average | 0.40696 |

| Quality | |
|---|---|
| Check Mesh Quality | Yes, Errors |
| Error Limits | Standard Mechanical |
| Target Quality | Default (0.050000) |
| Smoothing | Medium |
| Mesh Metric | Orthogonal Quality |
| Min | 1.3103e-005 |
| Max | 0.99996 |
| Average | 0.70369 |

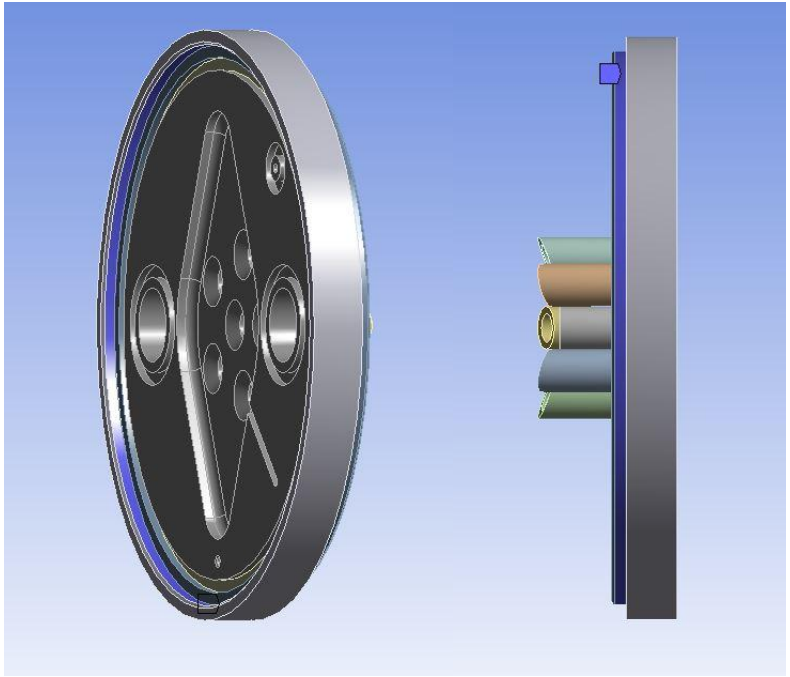
# MTS-INJ-0002: ANSYS Structural

| MTS-INJ-0002: FEA | | | |
|---|---|---|---|
| Applied load | 600 psi | 500 psi | 300 psi |
| Max Actual | 4508 psi | 3758 psi | 2254 psi |
| Margin Yield | 0.07 | 0.28 | 1.14 |
| Margin Ultimate | 2.38 | 3.05 | 5.76 |

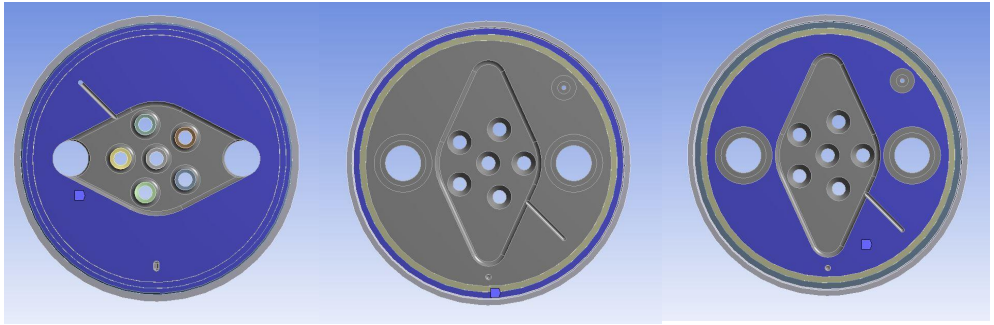


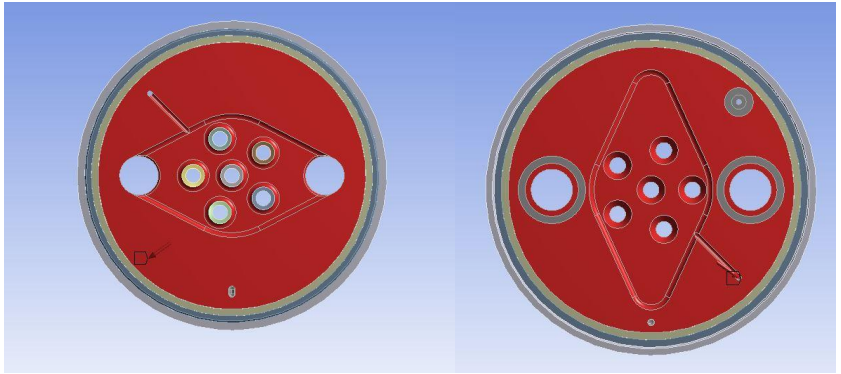
## Cylindrical Supports



## Frictionless Supports



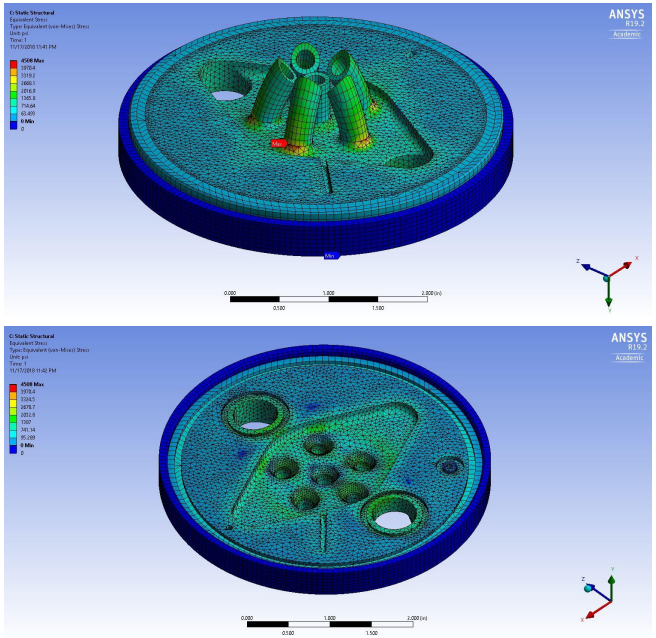
## Applied Pressure Load



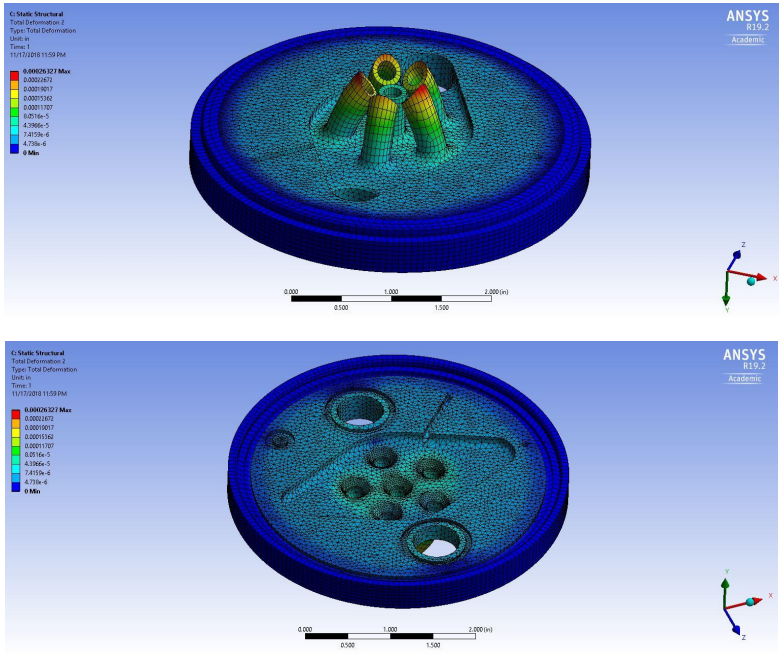
# MTS-INJ-0002: ANSYS Structural

Nominal 500psi applied load

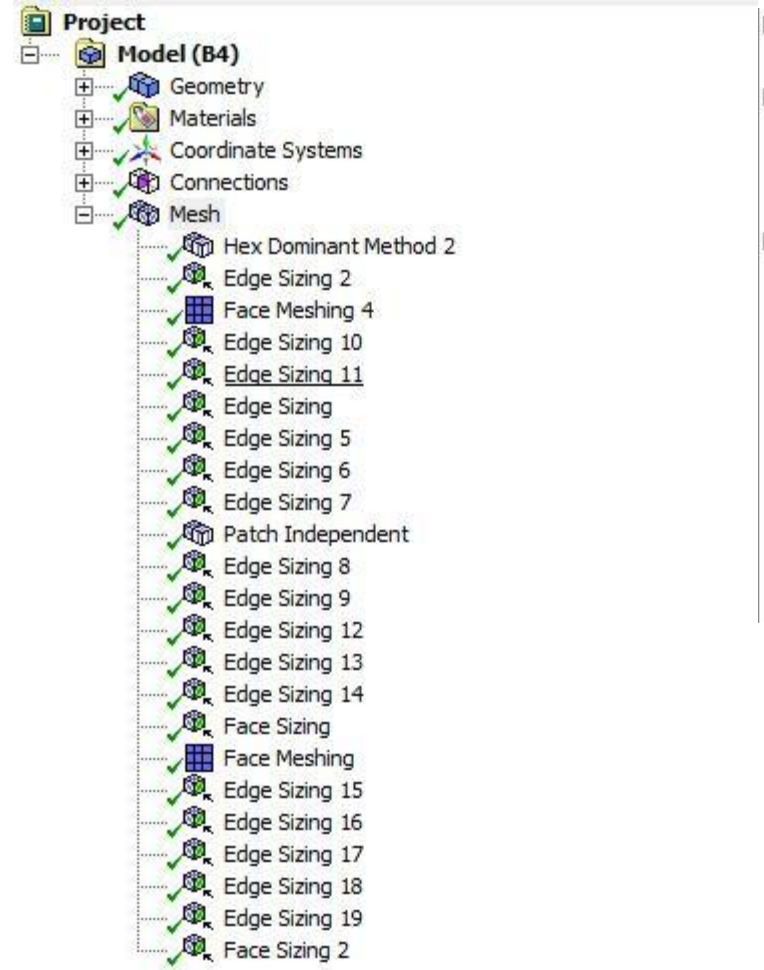
Max Stress: 3758 psi
Max Deformation:  3.05 E-5 in.




*Stress*




*Deformation*




| Display | |
|---|---|
| Display Style | Use Geometry Setting |

| Defaults | |
|---|---|
| Physics Preference | Mechanical |
| Element Order | Program Controlled |
| Element Size | 2.e-003 m |

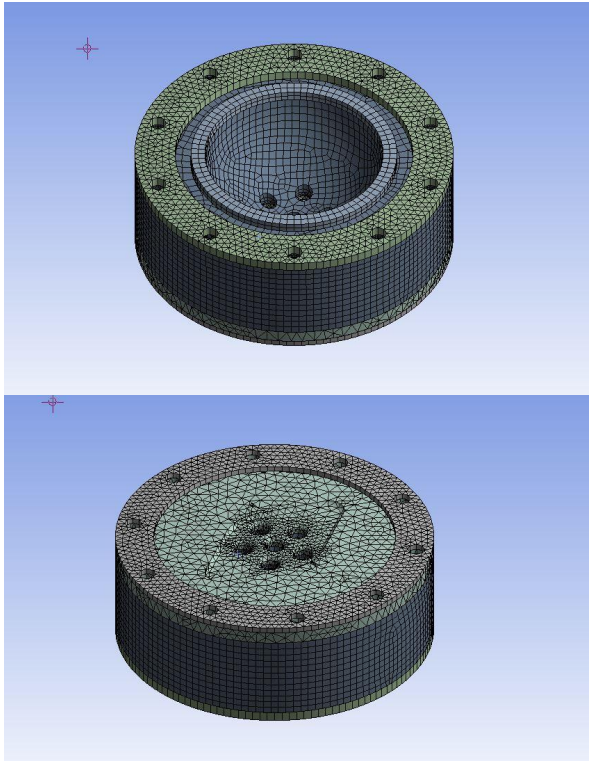
| Sizing | |
|---|---|
| Use Adaptive Sizi... | Yes |
| Resolution | Default (2) |
| Mesh Defeaturing | Yes |
| Defeature Size | 2.e-003 m |
| Transition | Fast |
| Span Angle Center | Fine |
| Initial Size Seed | Assembly |
| Bounding Box Di... | 0.14573 m |
| Average Surface ... | 2.7021e-004 m² |
| Minimum Edge L... | 3.5921e-004 m |

| Quality | |
|---|---|
| Check Mesh Quality | Yes, Errors |
| Error Limits | Standard Mechanical |
| Target Quality | Default (0.050000) |
| Smoothing | Medium |
| Mesh Metric | Skewness |
| Min | 1.0696e-003 |
| Max | 1. |
| Average | 0.37402 |

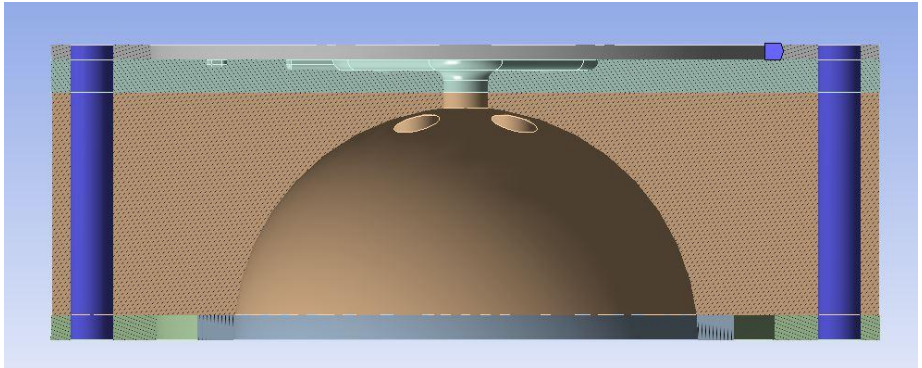
| Quality | |
|---|---|
| Check Mesh Quality | Yes, Errors |
| Error Limits | Standard Mechanical |
| Target Quality | Default (0.050000) |
| Smoothing | Medium |
| Mesh Metric | Orthogonal Quality |
| Min | 2.5105e-007 |
| Max | 0.99927 |
| Average | 0.63383 |

# MTS-INJ-0003: ANSYS Structural

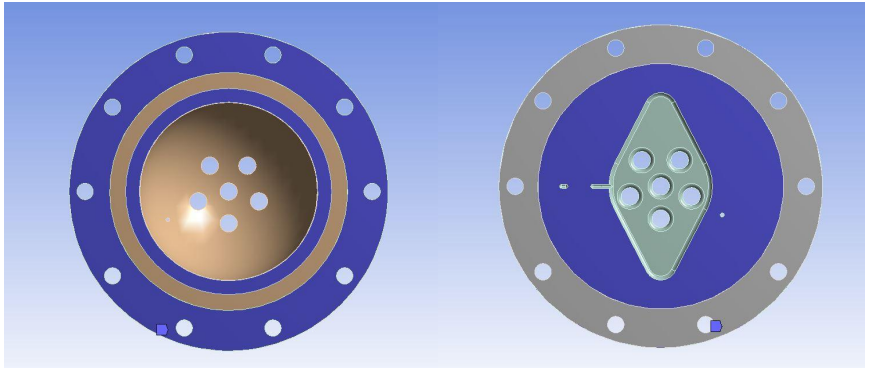
| MTS-INJ-0003: FEA | | | |
|---|---|---|---|
| Applied load | 600 psi | 500 psi | 300 psi |
| Max Actual | 3085 psi | 2570 psi | 1542 psi |
| Margin Yield | 13.1 | 15.9 | 27.2 |
| Margin Ultimate | 12.7 | 15.5 | 26.5 |



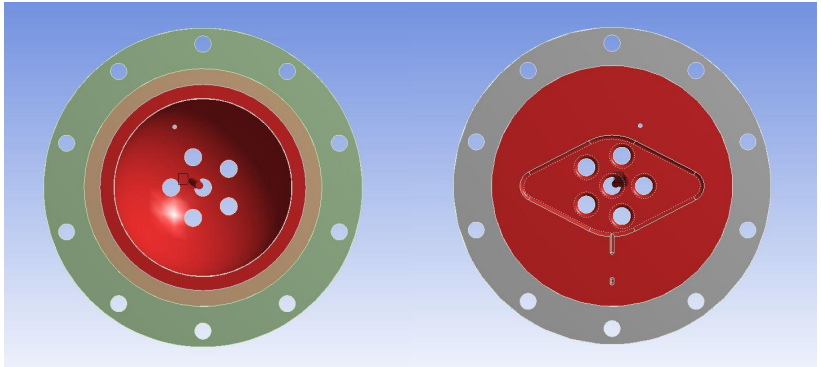
Cylindrical Support



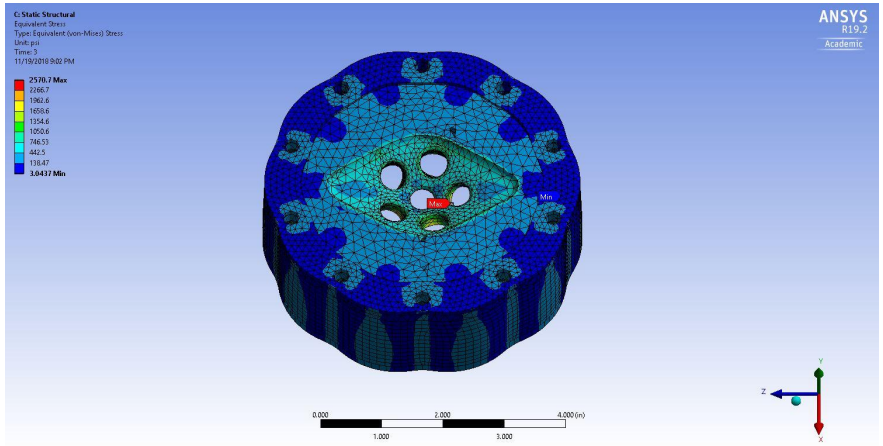
Frictionless Supports



Applied Pressure Loads

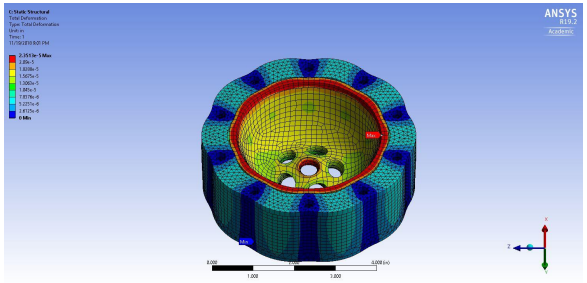


# MTS-INJ-0003: ANSYS Structural

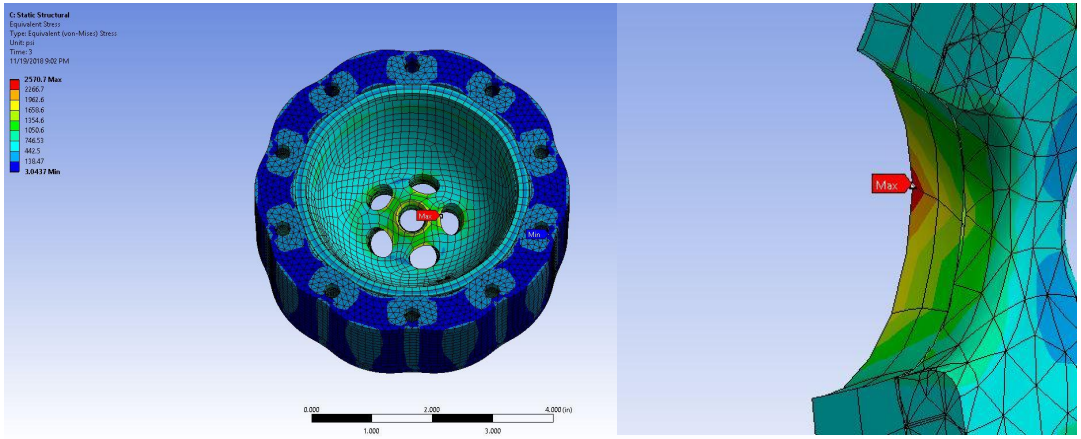



Nominal 500psi applied load

Max Stress: 2570psi
Max Deformation: 2.86E-05in




***Deformation***

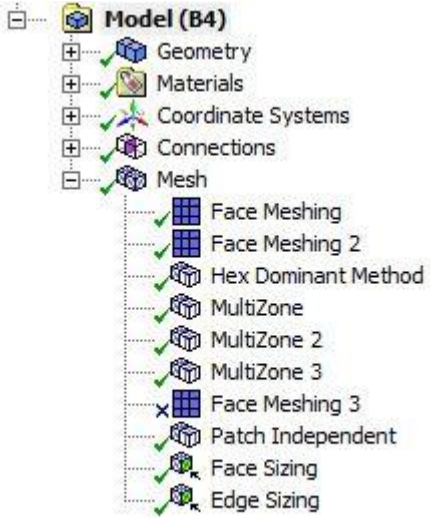



***Stress***

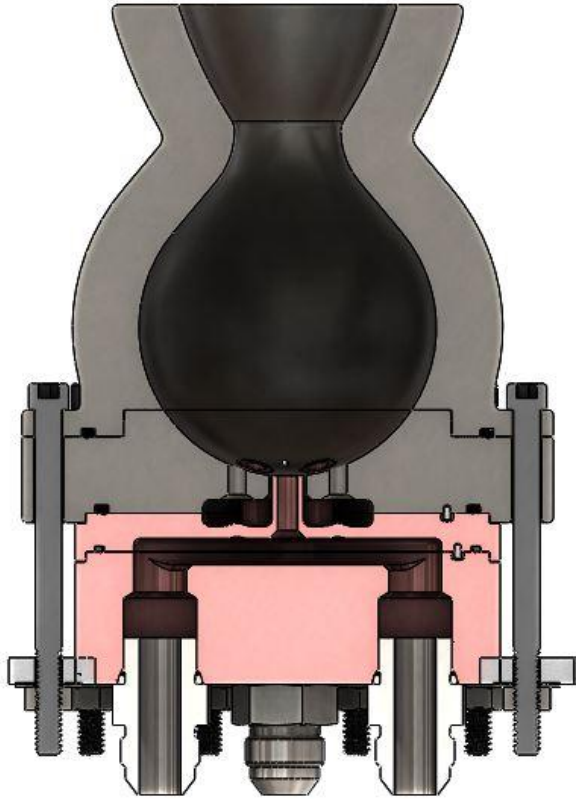
| Display | |
|---|---|
| Display Style | Use Geometry Setting |
| **Defaults** | |
| Physics Preference | Mechanical |
| Element Order | Program Controlled |
| Element Size | 3.e-003 m |
| **Sizing** | |
| Use Adaptive Sizing | Yes |
| Resolution | Default (2) |
| Mesh Defeaturing | Yes |
| Defeature Size | Default |
| Transition | Fast |
| Span Angle Center | Fine |
| Initial Size Seed | Assembly |
| Bounding Box Diagonal | 0.18518 m |
| Average Surface Area | 1.0355e-003 m² |
| Minimum Edge Length | 7.62e-004 m |

| Quality | |
|---|---|
| Check Mesh Quality | Yes, Errors |
| Error Limits | Standard Mechanical |
| Target Quality | Default (0.050000) |
| Smoothing | Medium |
| Mesh Metric | Orthogonal Quality |
| Min | 2.9085e-009 |
| Max | 0.99991 |
| Average | 0.58959 |
| Standard Deviation | 0.29871 |

| Quality | |
|---|---|
| Check Mesh Quality | Yes, Errors |
| Error Limits | Standard Mechanical |
| Target Quality | Default (0.050000) |
| Smoothing | Medium |
| Mesh Metric | Skewness |
| Min | 2.2158e-003 |
| Max | 1. |
| Average | 0.47972 |
| Standard Deviation | 0.25185 |

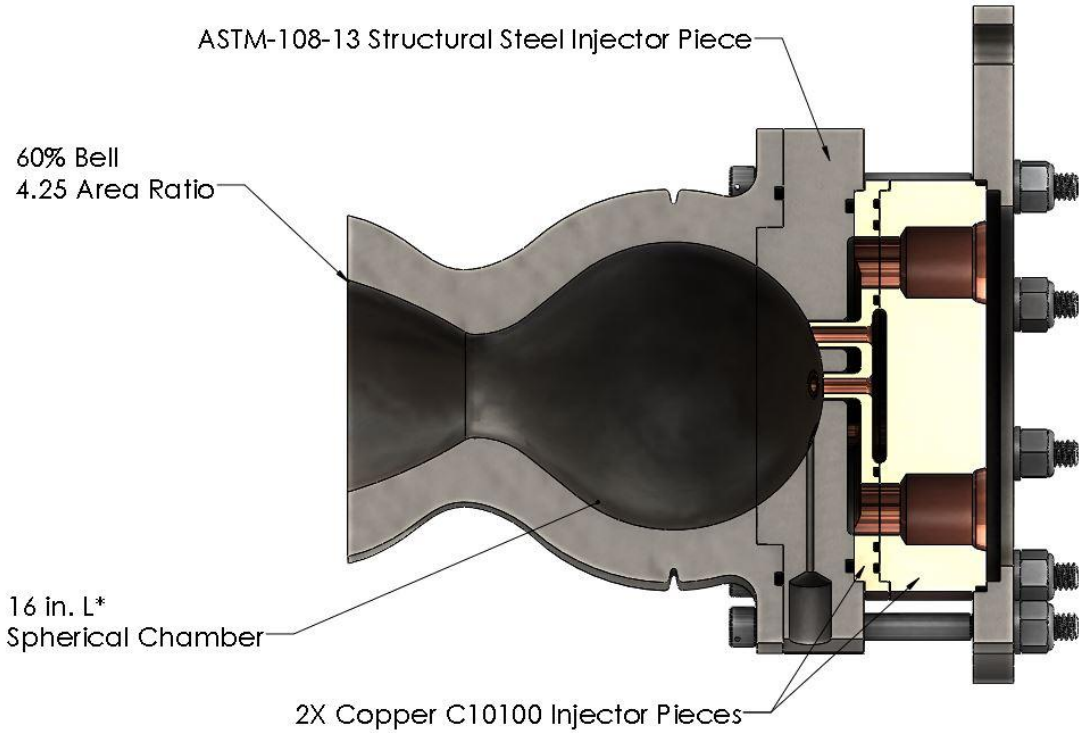


# Chamber



## Performance

| | Value | Units |
|---|---|---|
| Thrust | 453 | lbf |
| ISP | 264 | s |
| Max. Chamb. Press | 400 | psi |
| Mass Flow Rate | 1.72 | lbm/s |
| O:F | 2.00 | |
| Specific Heat Ratio | 1.24 | |
| C* | 1780 | m/s |

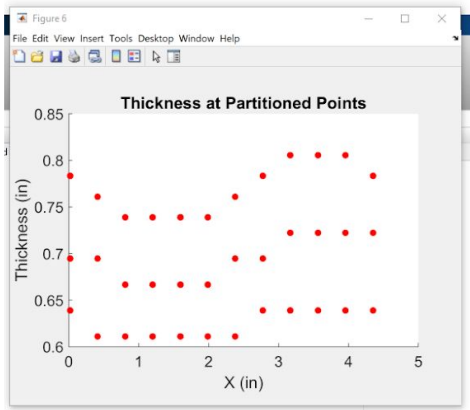


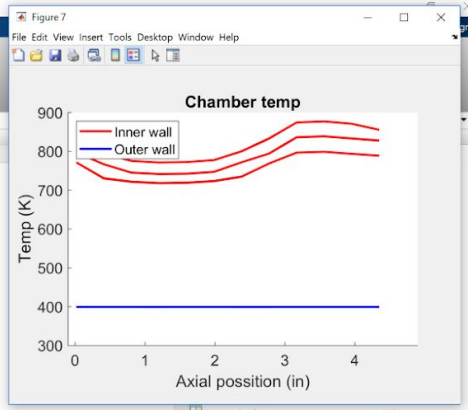
# Thermal Analysis - Code

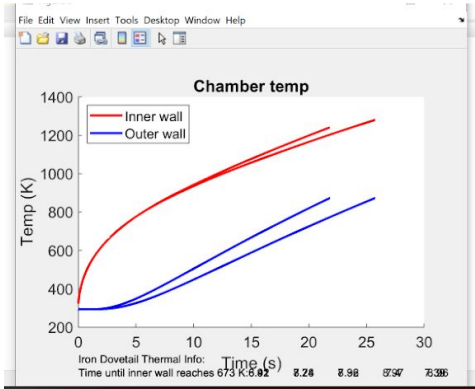
- Using legacy Iron Lotus Code
- Uses slab series solution to do 1 dimensional analysis
- Updated to optimize outerwall geometry to give run time needed
  - Can easily adjust chamber pressure, OF, Geometry, and run time
- Allows for rapid reconfiguration of test parameters

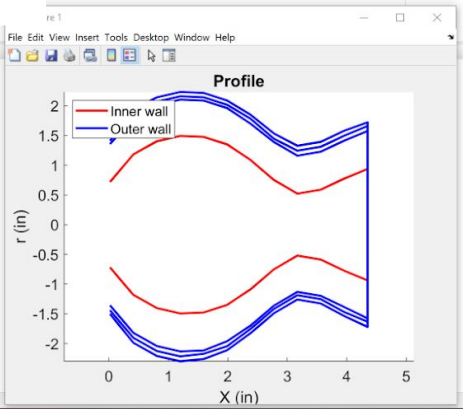
# Wall Thickness Optimizations

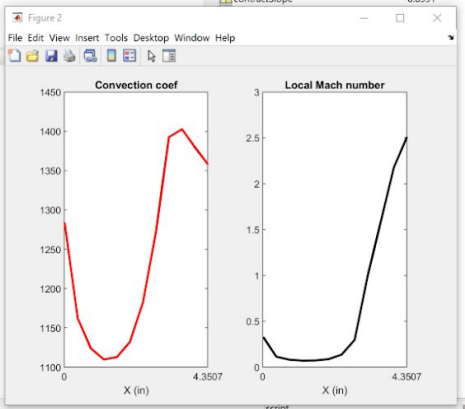
- Constants
  - OF: 2
  - Pc: 400 psi
  - Run time: 5s
  - Min allowable inner wall strength: 50%
    - Confirmed with ansys sims
- Final wall thickness: 0.625”



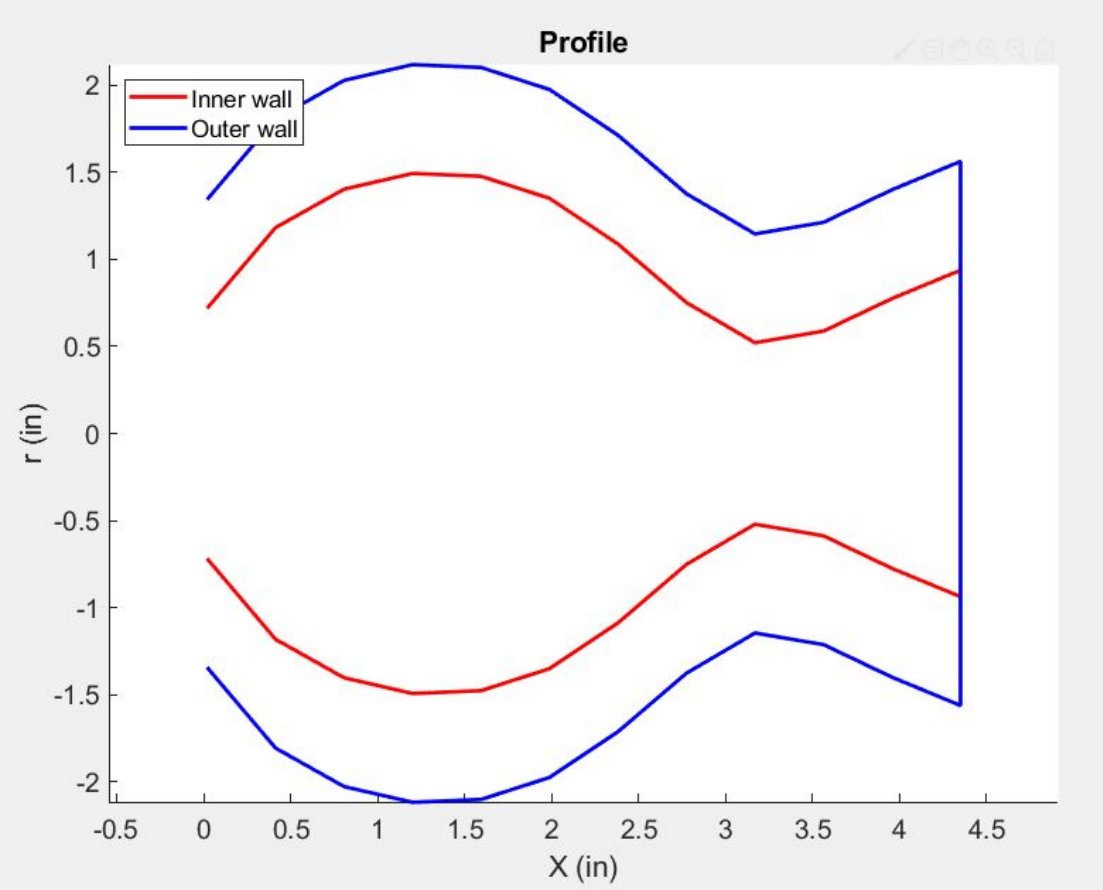



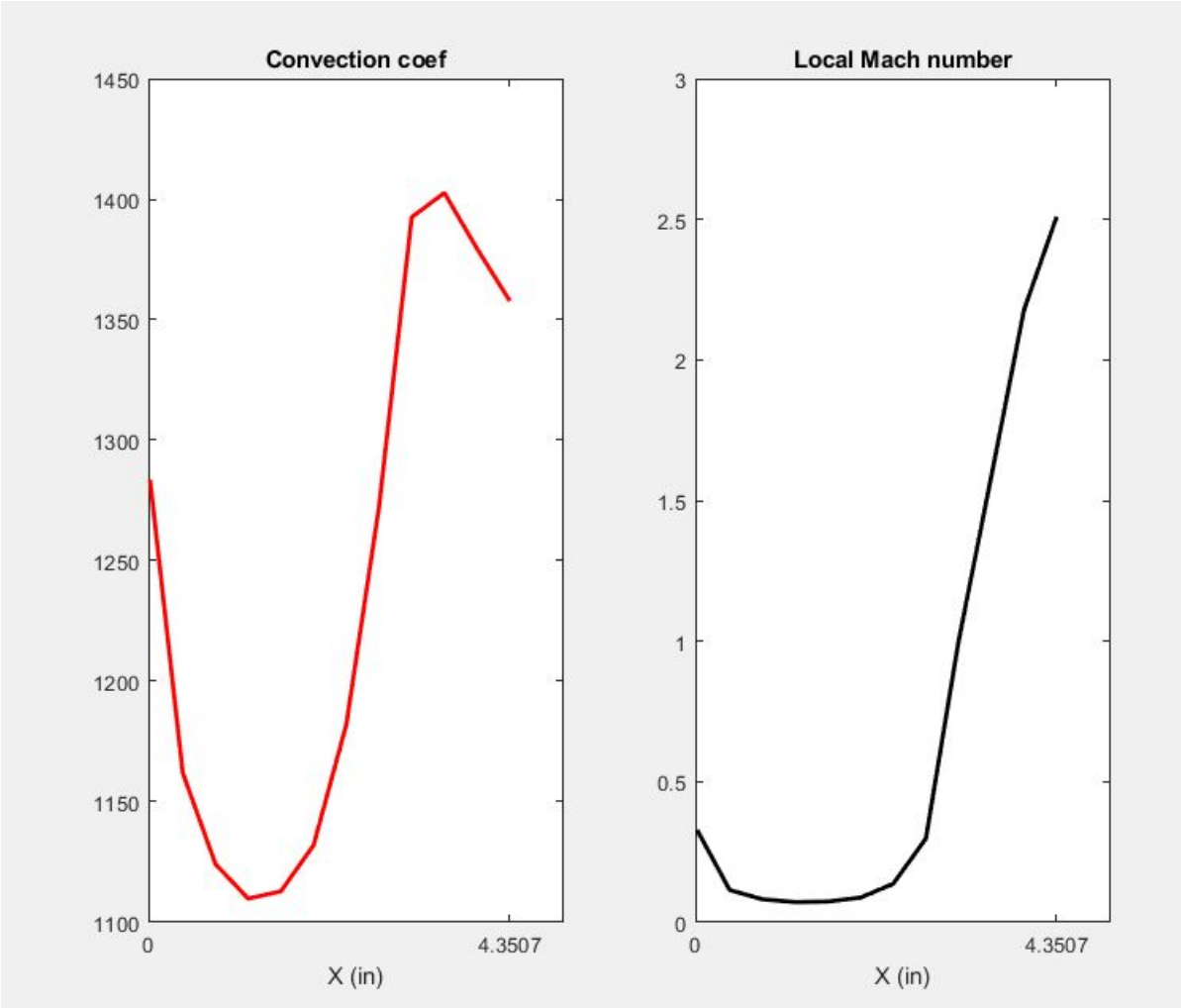



# Profile


Profile
Inner wall
Outer wall
r (in)
X (in)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5


Convection coef
1450
1400
1350
1300
1250
1200
1150
1100
0
4.3507
X (in)
Local Mach number
3
2.5
2
1.5
1
0.5
0
0
4.3507
X (in)

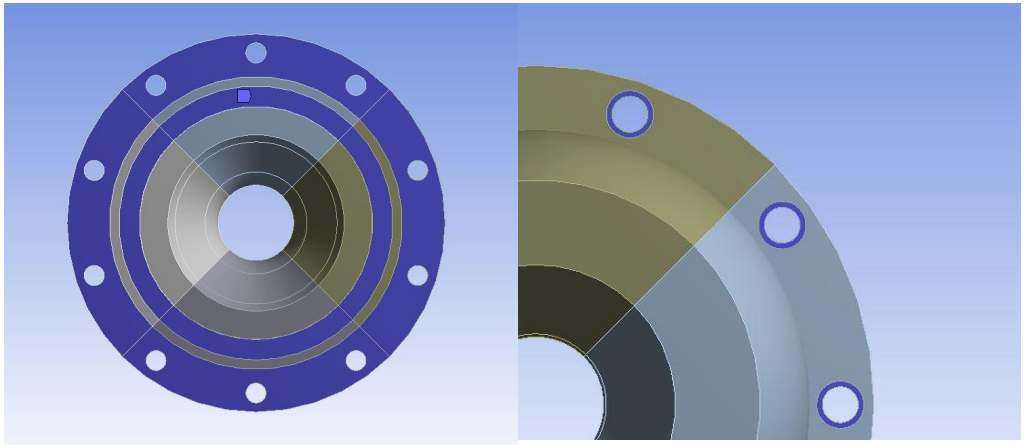
# MTS-INJ-0003: ANSYS Structural, Margins for Yield

| | MTS-INJ-0003: Margins for Yield | | | |
|---|---|---|---|---|
| | | 600 psi | 400 psi | 240 psi |
| | | 3767 psi | 2511 psi | 1093 psi |
| 25°C (Room temp) | 100% YS | 10.5 | 16.3 | 38.8 |
| 400°C | 80% YS | 8.24 | 14.6 | 34.8 |
| 500°C | 50% YS | 4.78 | 7.67 | 18.9 |

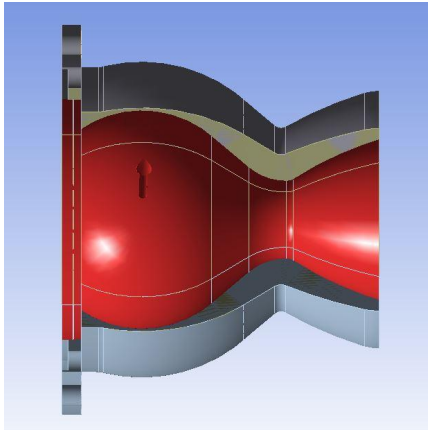
# MTS-INJ-0003: ANSYS Structural, Margins for UTS

| | MTS-INJ-0003: Margin to UTS | | | |
|---|---|---|---|---|
| | | 600 psi | 400 psi | 240 psi |
| | | 3767 psi | 2511 psi | 1093 psi |
| 25°C (Room temp) | 100% UTS | 10.3 | 16.1 | 38.3 |
| 400°C | 80% UTS | 8.11 | 12.7 | 30.9 |
| 500°C | 50% UTS | 4.10 | 7.5 | 18.6 |

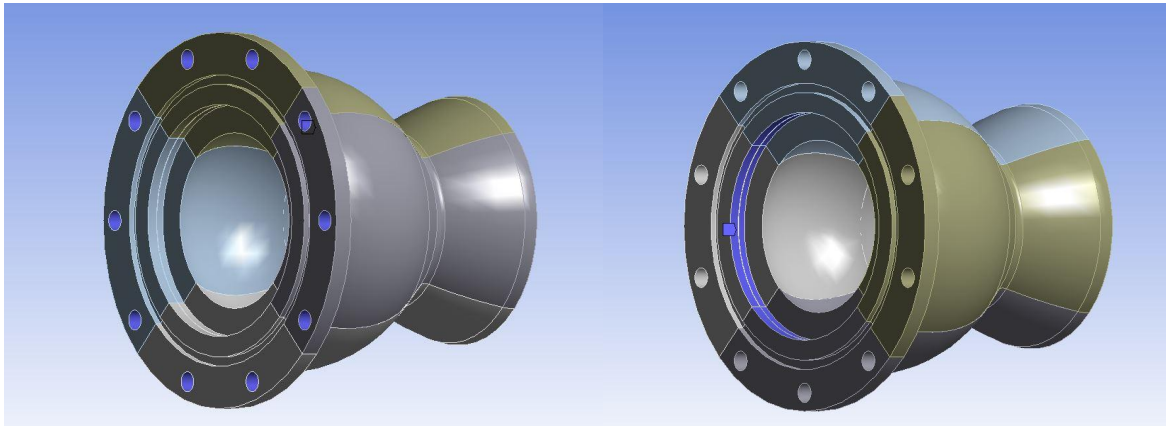
## Frictionless Supports



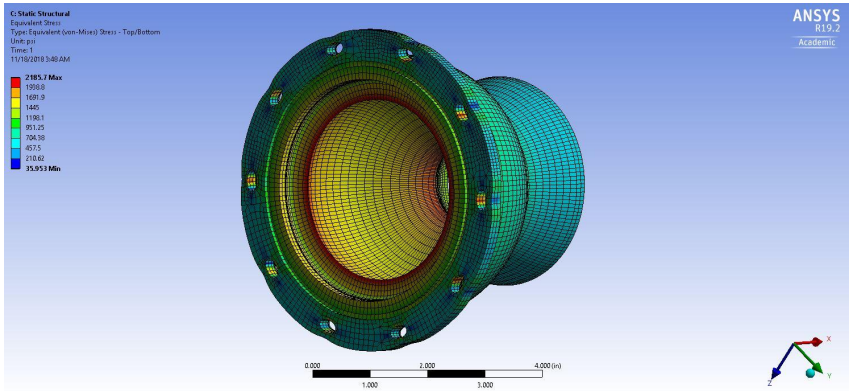
## Applied Pressure Loads

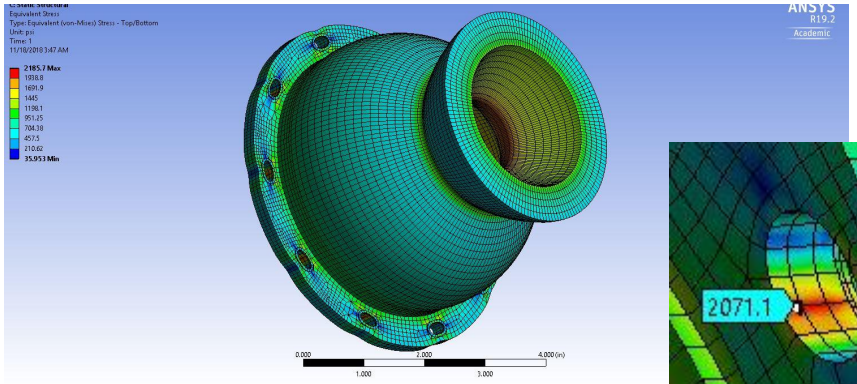


## Cylindrical Supports



# MTS-INJ-0003: ANSYS Structural



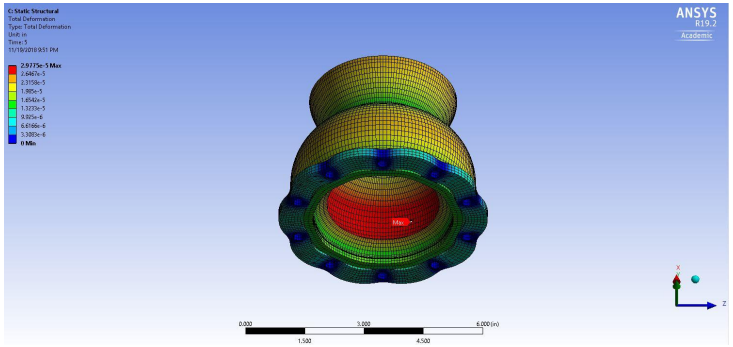




***Stress***

<u>Nominal 400psi applied load</u>

Max Stress: 2570 psi
Max Deformation:  2.98 E-5in




***Deformation***

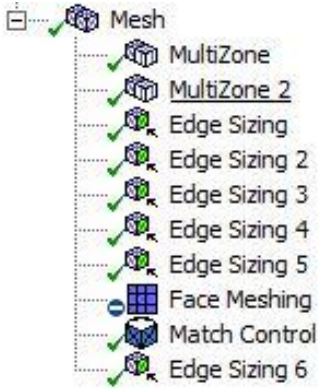
| Display | |
|---|---|
| Display Style | Use Geometry Setting |

| Defaults | |
|---|---|
| Physics Preference | Mechanical |
| Element Order | Program Controlled |
| Element Size | 2.e-003 m |

| Sizing | |
|---|---|
| Use Adaptive Sizing | Yes |
| Resolution | Default (2) |
| Mesh Defeaturing | Yes |
| Defeature Size | 1.e-003 m |
| Transition | Fast |
| Span Angle Center | Medium |
| Initial Size Seed | Assembly |
| Bounding Box Diagonal | 0.20722 m |
| Average Surface Area | 6.7534e-004 m² |
| Minimum Edge Length | 1.1777e-004 m |

| Quality | |
|---|---|
| Check Mesh Quality | Yes, Errors |
| Error Limits | Standard Mechanical |
| Target Quality | Default (0.050000) |
| Smoothing | High |
| Mesh Metric | Skewness |
| Min | 2.3054e-003 |
| Max | 0.96692 |
| Average | 0.13999 |

| Quality | |
|---|---|
| Check Mesh Quality | Yes, Errors |
| Error Limits | Standard Mechanical |
| Target Quality | Default (0.050000) |
| Smoothing | High |
| Mesh Metric | Orthogonal Quality |
| Min | 0.29584 |
| Max | 0.99999 |
| Average | 0.96509 |



# MTS-NZL-0003: Modal Analysis

| Natural Modes | | |
|---|---|---|
| First Frequency | 4319 | Hz |
| Second Frequency | 8120 | Hz |
| Third Frequency | 10166 | Hz |

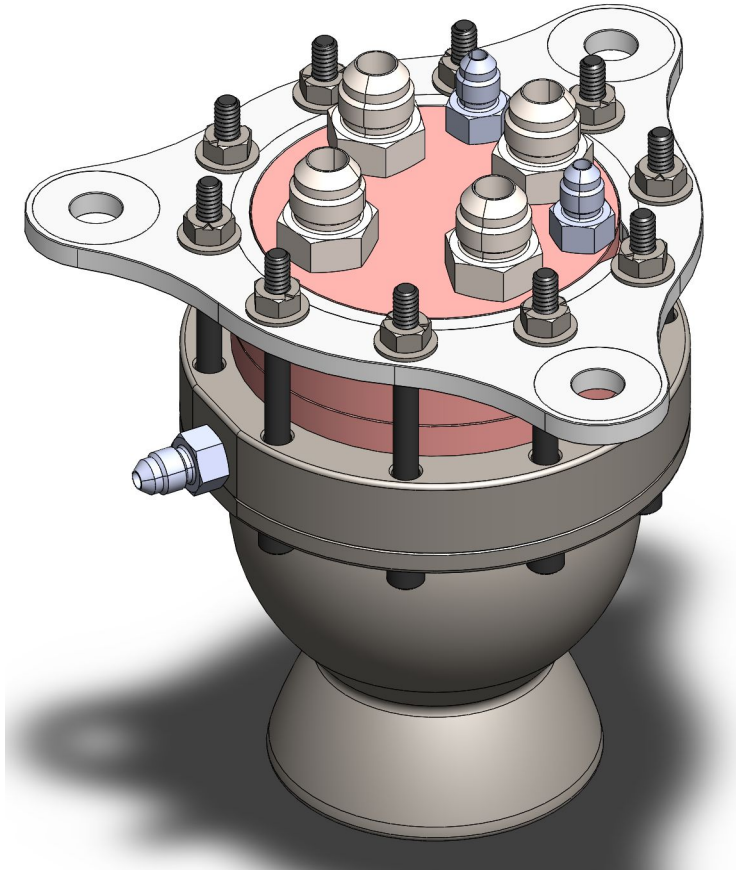
| Instability Modes | | |
|---|---|---|
| First Radial | 7549 | Hz |
| First Longitudinal | 2657 | Hz |
| First Tangential | 3651 | Hz |

**Acoustic Analysis:**

- 1st radial, tangential, and longitudinal modes calculated using analytical solutions provided in SP-125, ch. 4
  - ***Assumes*** *cylindrical chamber*
  - Could not find analytical solutions for spherical chambers
- Natural modes determined using Ansys Modal
- Acoustic coupling prevention out-of-scope
  - Can capture pressure fluctuations with chamber ducer

# Mounting Plate

# General Design



# Constraints

- Three load cells measuring thrust
- Ten shoulder bolts to attach to Mortise
- Need cutouts to fit valves and allow fluid lines to attach
- Try to maximize area where the plate and injector overlap

# Interface with Mortise

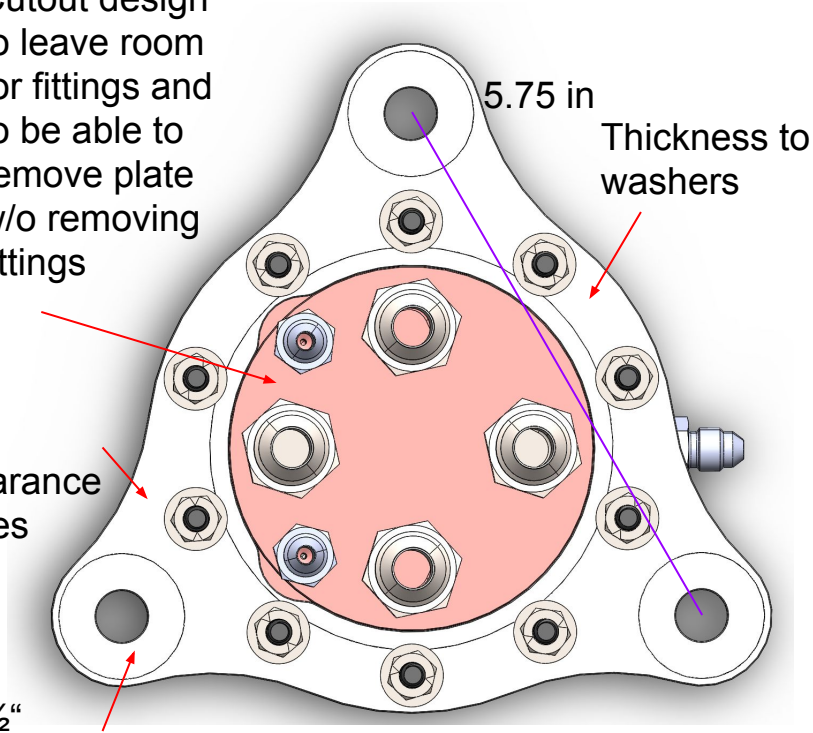
Cutout design to leave room for fittings and to be able to remove plate w/o removing fittings

5.75 in

Thickness to fit washers

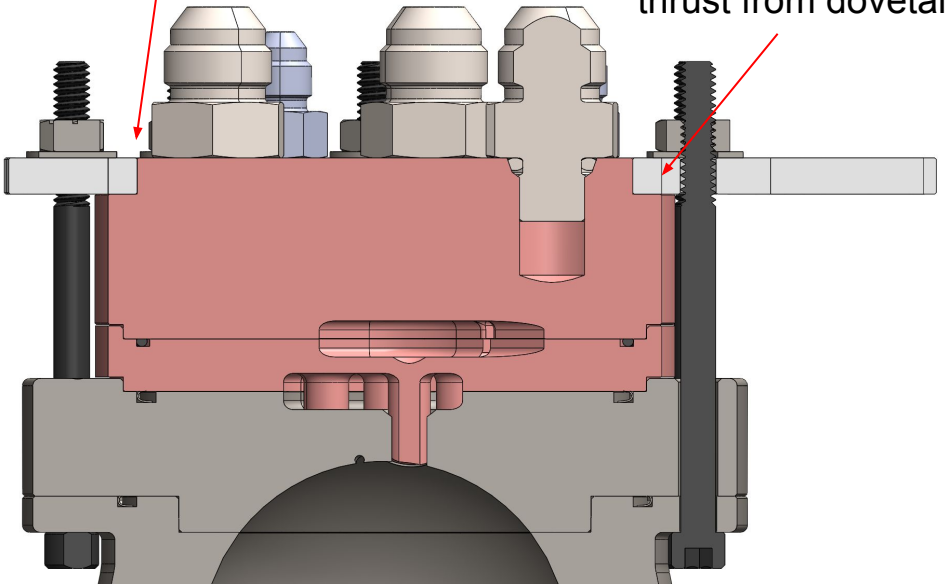
¼“ clearance holes

½“ clearance holes

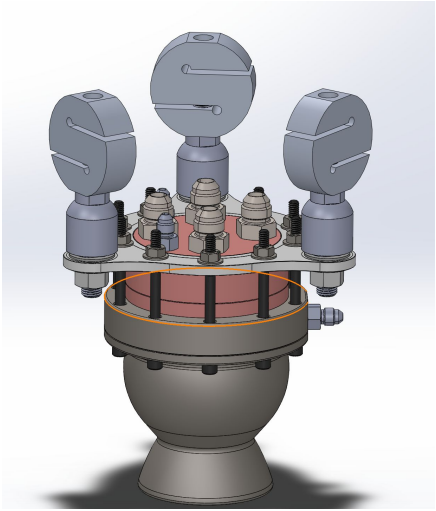


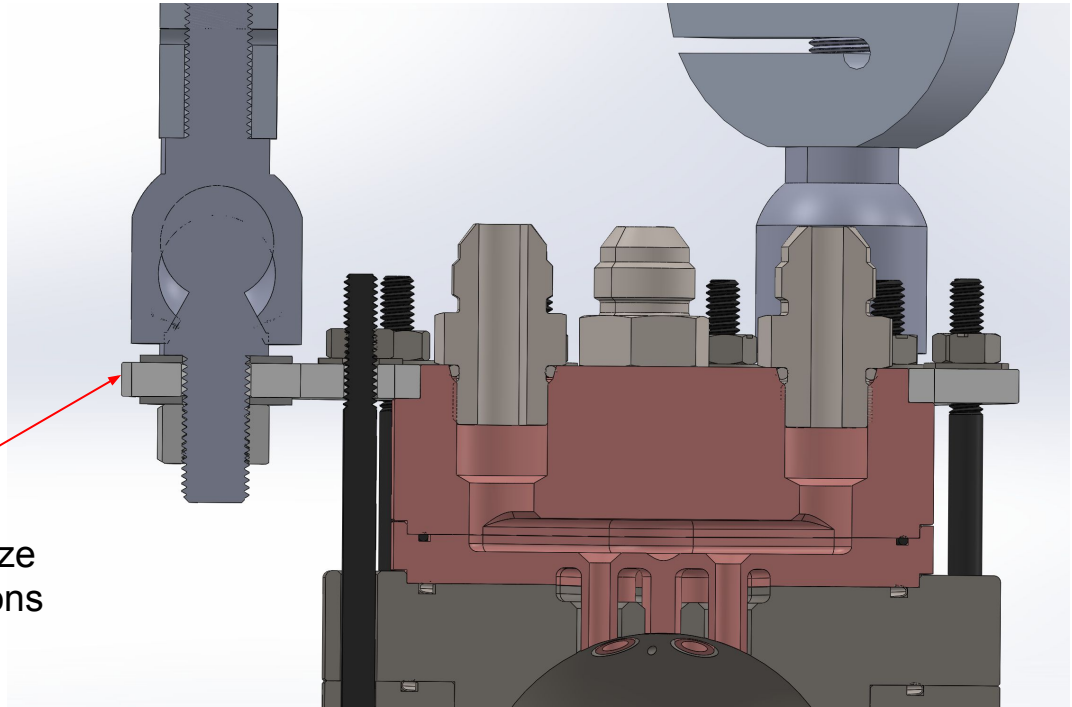
Top faces flush to not interfere with fittings

Face of plate taking thrust from dovetail

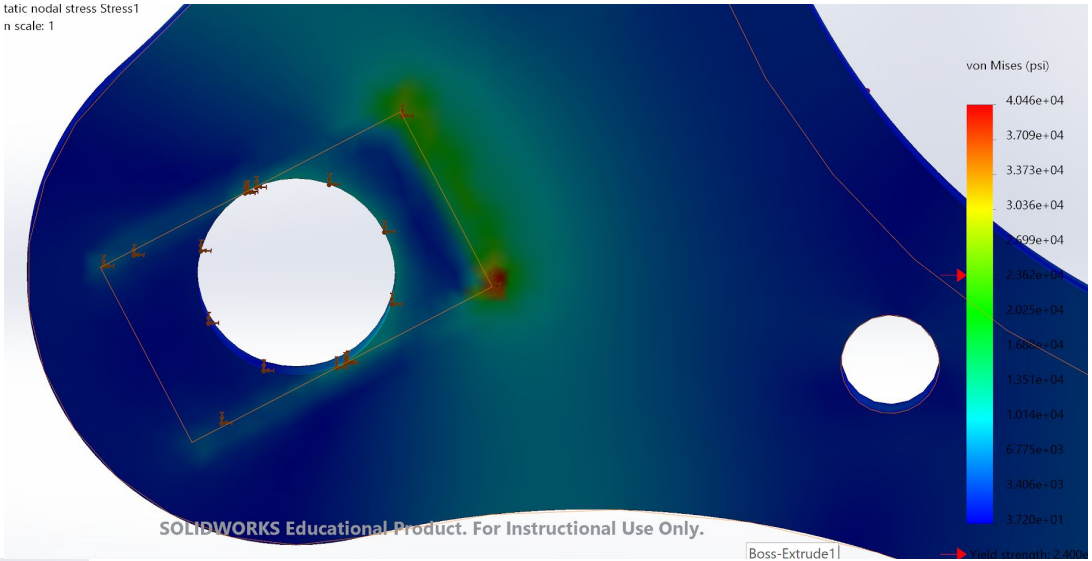


# Interface with load cells





Washers to minimize stress concentrations


tatic nodal stress Stress1
n scale: 1
von Mises (psi)
4.046e+04
3.709e+04
3.373e+04
3.036e+04
2.699e+04
2.362e+04
2.025e+04
1.688e+04
1.351e+04
1.014e+04
6.775e+03
3.406e+03
3.720e+01
Yield strength: 2.400e+04
SOLIDWORKS Educational Product. For Instructional Use Only.
Boss-Extrude1


1
von Mises (psi)
4.046e+04
3.709e+04
3.373e+04
3.036e+04
2.699e+04
2.362e+04
2.025e+04
1.688e+04
1.351e+04
1.014e+04
6.775e+03
3.406e+03
3.720e+01
Yield strength: 2.400e+04
SOLIDWORKS Educational Product. For Instructional Use Only.

# Calculations

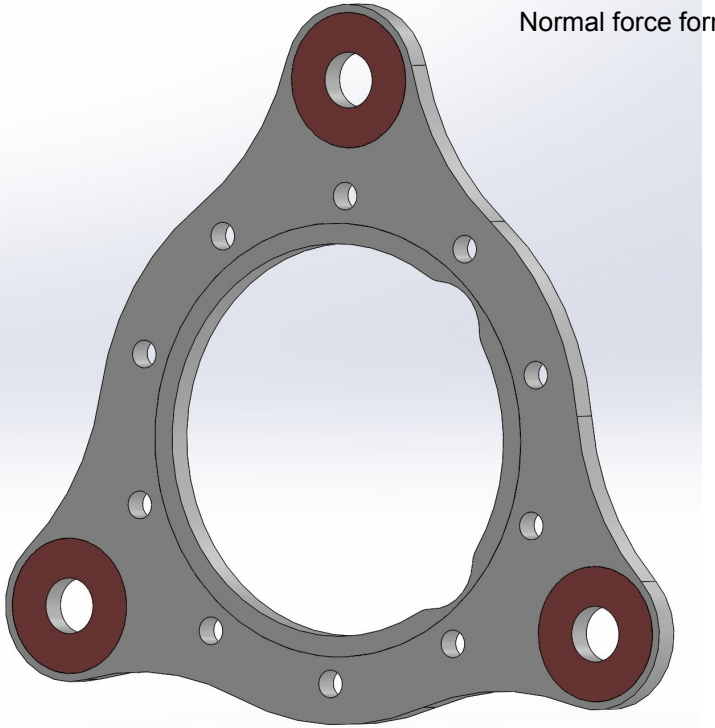
| | |
|---|---|
| Mass of Mortise | 18 lbs |
| Bolt thread size | ½-20 |
| Bolt diameter (D) | 0.5 in |
| Static friction coefficient (c) | 0.61 |
| Required compression force | 29.5 lbs |
| Required compression force for each bolt (F) | 9.83 lbs |
| Torque spec (T) | 3 in-lbs |

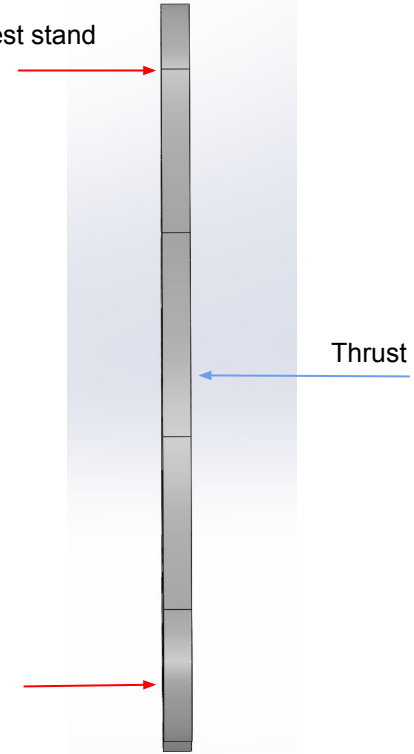
# Assembly Bolt Torque Specs

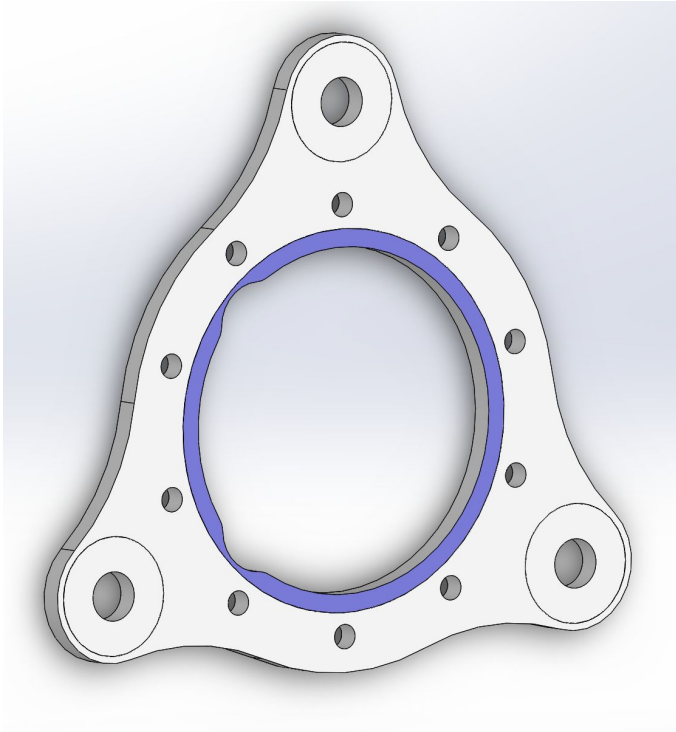
| | | |
|---|---|---|
| Preload per bolt | 1032.60 | lbf |
| Total Preload | 10325.95 | lbf |
| Margin | 1.73 | |
| Torque Spec | 51.63 | in*lbf |

Preload = Force needed to compress seals + Force from chamber pressure + Force of Belleville washers

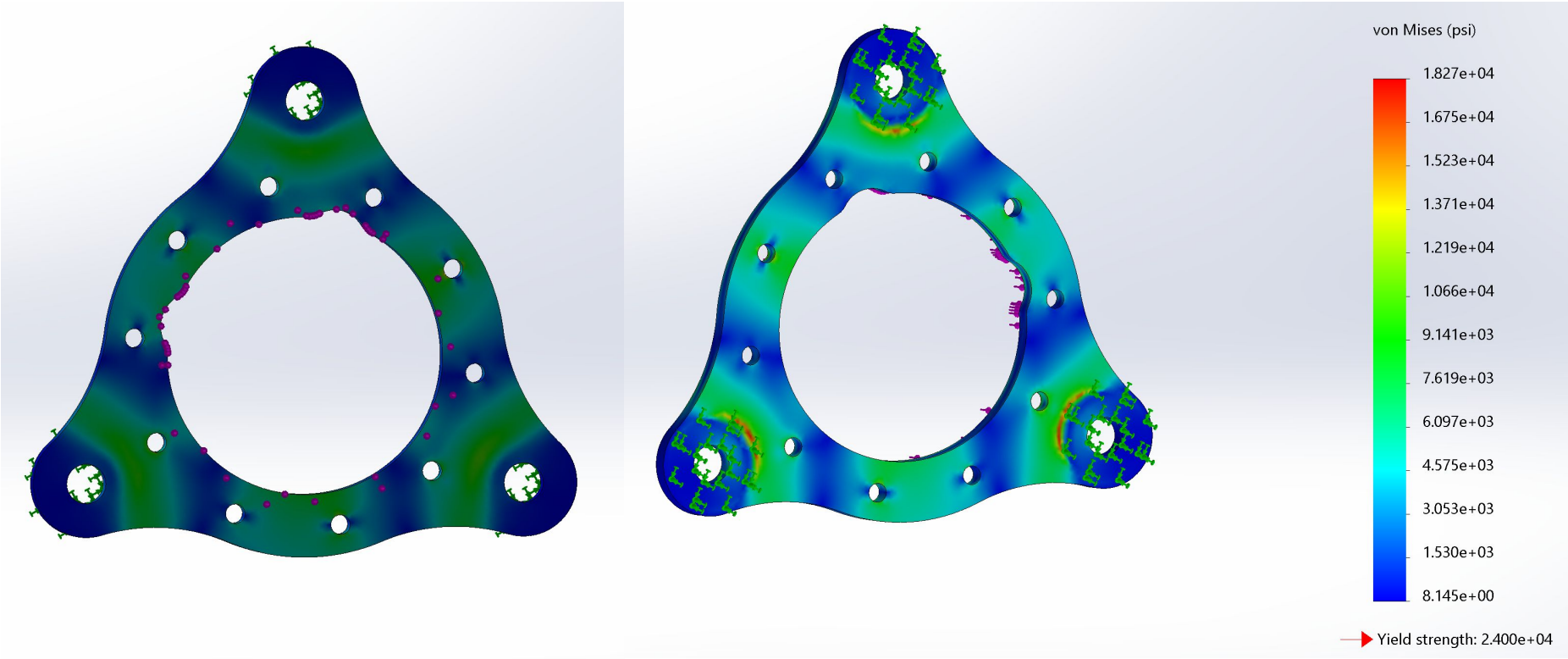
# FBD





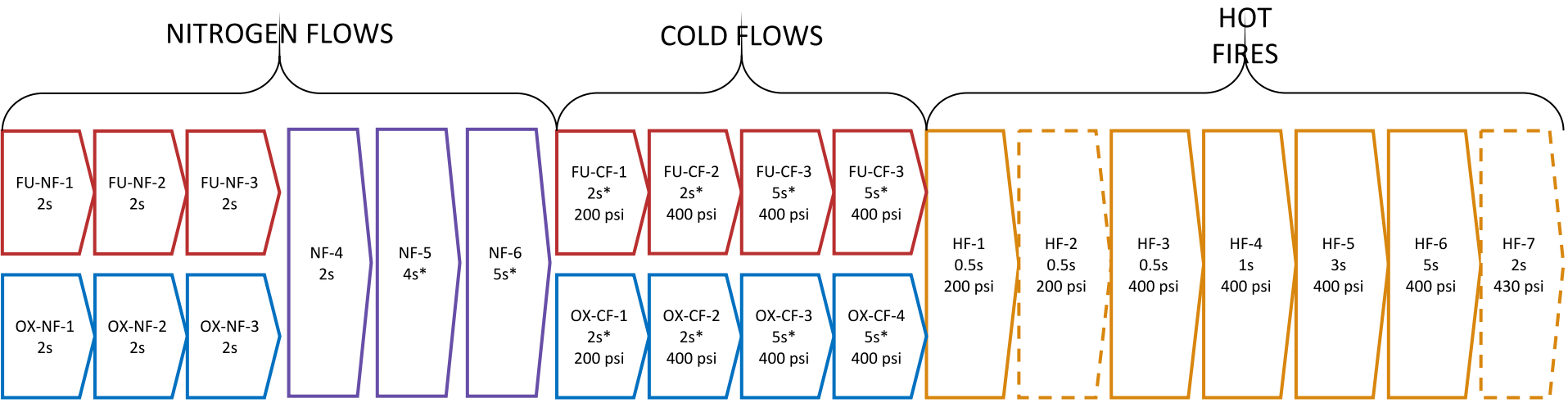
# Simulations




Load applied: 750 lbf (max. Thrust * FOS of 1.5)
Simulations were run at 80% strength which is the percentage strength of 304 stainless steel at 400 K

# Mortise Test Campaign

OPTIONAL, SLIP OR DEPENDANT




## STATISTICS

| ITEM | EXPECTED (MAX) |
|---|---|
| Burn time | 12.5s |
| Ignitions | 7 |
| Partial thermal cycles | 7 |
| Full structural cycles | 4 |
| Partial structural cycles | 7 |

*Steady state flow, timing subject to influence from proceeding test data

# Additional Tests

| TEST | FUNCTION |
| --- | --- |
| HF-8 \| 3s \| 100 psi \| 2 OF | COMBUSTION STABILITY AT LOW PRESSURE<br>*LOWER PRESSURE POSSIBLE* |
| HF-9 \| 30s \| 300 psi \| .5 OF | VALIDATES TANK PRESSURE DECAY MODEL<br>TESTS SYSTEM DURABILITY<br>DOVETAIL MAX OP TIME |
| HF-11 \| 5s \| 400-40 psi \| 2 OF | THROTTLING CONTROLS<br>THROTTLING CAPABILITY |
| HF-10 \| 7s \| 400 psi \| 2 OF | VALIDATES TANK PRESSURE DECAY MODEL<br>TESTS SYSTEM DURABILITY<br>DOVETAIL MAX OP TIME |

# HF-1

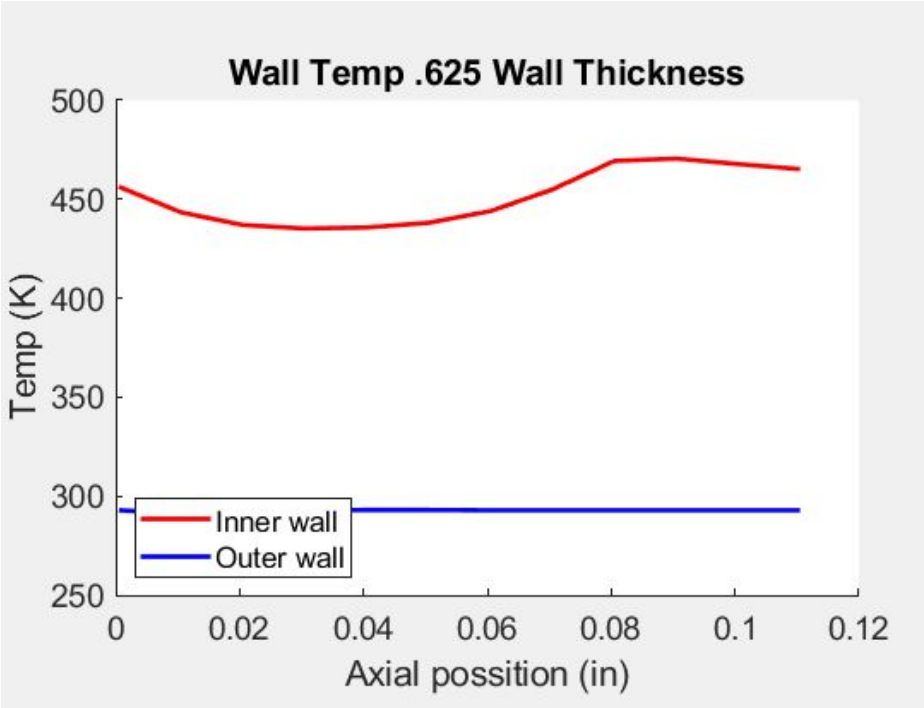
| Time | Chamber Pressure | OF | Testing |
|---|---|---|---|
| .5 | 200 | 2 | Ignition |

TS-LCI100 will be held upstream of throat by a 3d printed holder that will expand into the throat. Pieces will be blown out on ignition.

*Must not get blown out during Pre-Fire Purge

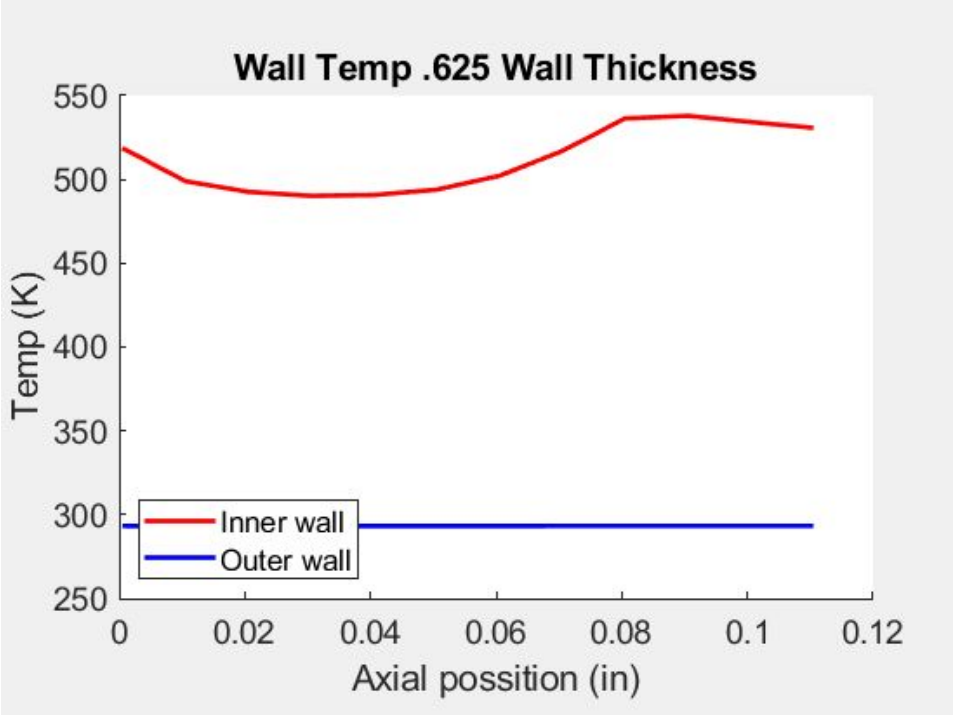
# HF-3

| Time | Chamber Pressure | OF | Testing |
|---|---|---|---|
| .5 | 400 | 2 | Ignition at Full Chamber Pressure |



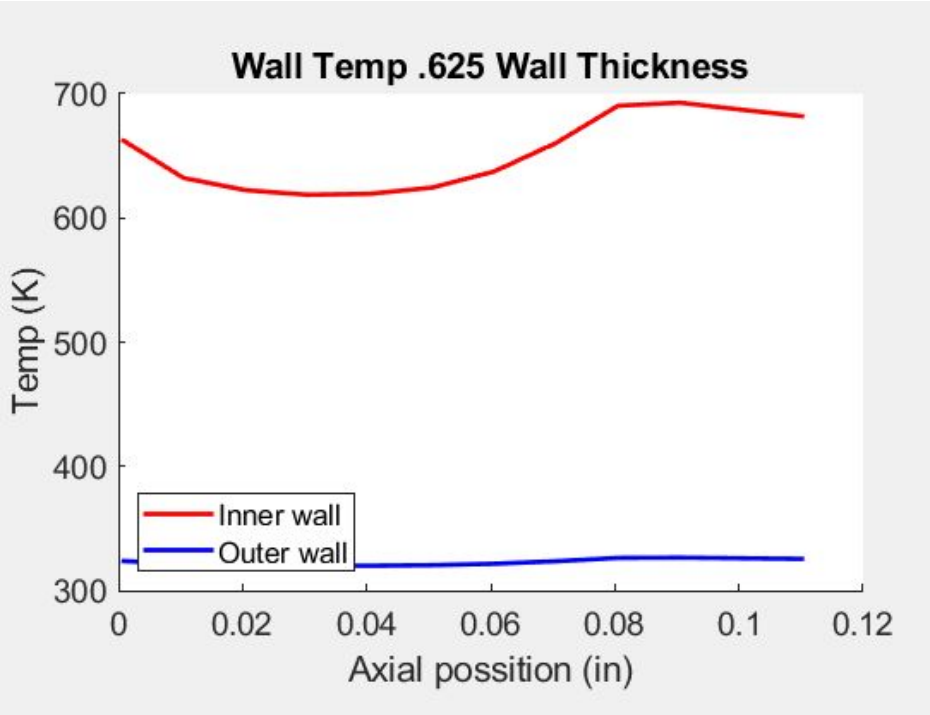
# HF-4

| Time | Chamber Pressure | OF | Testing |
|---|---|---|---|
| 1 | 400 | 2 | Structural |



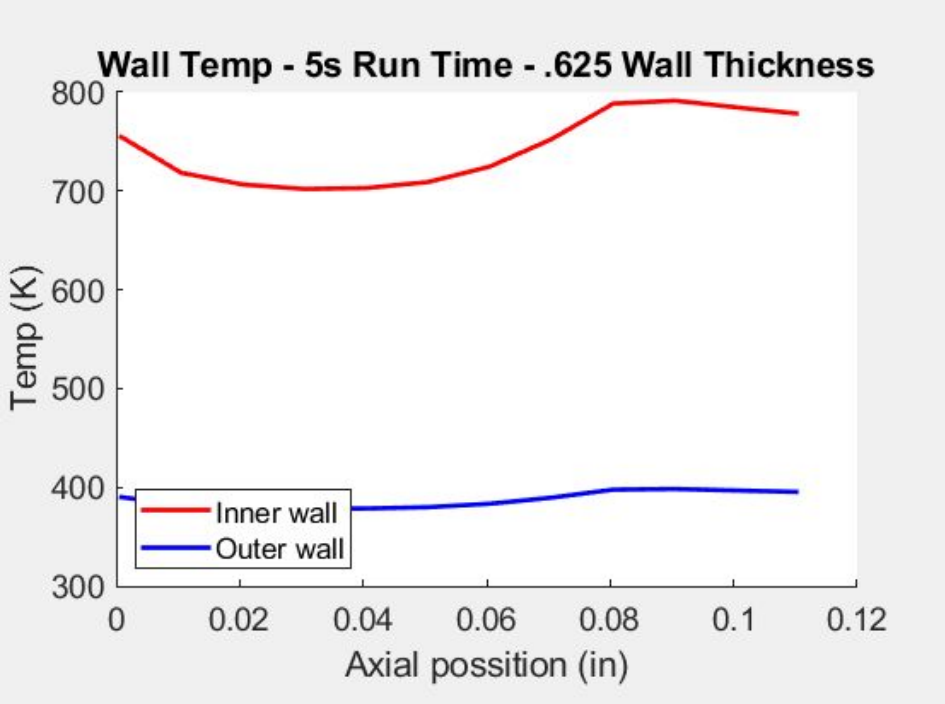
# HF-5

| Time | Chamber Pressure | OF | Testing |
|---|---|---|---|
| 3 | 400 | 2 | Thermal, Structural |



# HF-6

| Time | Chamber Pressure | OF | Testing |
|---|---|---|---|
| 5 | 400 | 2 | Thermal, Structural |



# Oring Compression