OAK RIDGE National Laboratory

# Preliminary MRA Structural Analysis

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U.S. DEPARTMENT OF ENERGY

# Structural analysis for MRA Reflector Vessels and Backbone

- Separate CFD thermal analysis* was done for the reflector vessels and Stainless Steel Backbone
- Three Abaqus Structural models were made for the upper reflector vessel, the lower reflector vessel and the backbone
- Temperature profiles from the CFD analysis were imported and mapped onto the Abaqus models

*Temperature Profiles from Min-Tsung Kao – Reflector Vessel Thermal hydraulic Analysis

# Reflector Vessel Analysis

- This structural analysis of the upper and lower reflector vessels included the temperature distributions from thermal hydraulic analysis
- The analysis was done for 5 different load cases which could occur during operation plus an evaluation of the thermal stress alone
- The analysis identified the minimum distance between the allowable membrane plus bending stress and the closest weld for both vessels
- Stresses were compared to the ASME BPVC code section 8 Division 2 allowable limits
- Peak deflections towards the target were found and compared to the limit of 1 mm

# Material Properties for Structural analysis

## Aluminum 6061T6 properties

| | |
|---|---|
| **Modulus of Elasticity (GPa)** | 68.9 |
| **Poisson's Ratio** | 0.33 |
| **Coefficient of Thermal Expansion (µ/°C)** | 23.6 |
| **(100° F) Sm (MPa)** | 84.8 ( 12.3 ksi) |
| **Sm Weld (MPa)** | 55 (8ksi) |

**ASME BPVC Section8 Division 2 Allowable equivalent stress values Code case 2478-1**

| | **Sm Membrane** | **Sm Membrane+ Bending (1.5x)** | **Sm Membrane+ Bending + Secondary (3x)** |
|---|---|---|---|
| **Non-Weld Regions (MPa)** | 84.8 MPa | 127 MPa | 254 MPa |
| **Weld regions** | 55 MPa | 83 MPa | 165 MPa |

***Temperature not exceeding 93° C***

## Beryllium Properties

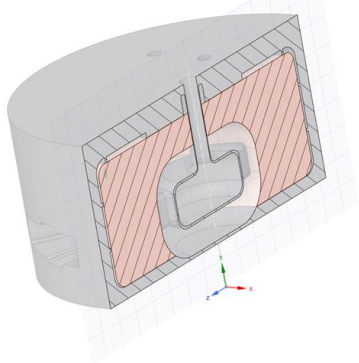
| | |
|---|---|
| **Modulus of Elasticity (GPa)** | 303 |
| **Poisson's Ratio** | 0.24 |
| **Coefficient of Thermal Expansion (µ/°C)** | 11.5 |
| **Tensile Yield Strength (MPa)** | **345 VHP-517 HIP** |

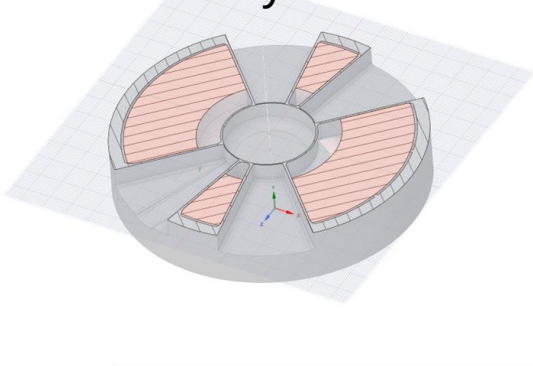
# Weld Heat Affected Zones

- ASME BPVC lists heat affected zone (HAZ) width of welds at 50 mm, 25 mm either side of the weld. The GTAW (arc) welds have a HAZ width up to 10 mm, correlating to 5 mm to either side of the centerline of welds. Stresses at or exceeding the allowable stress values for weld regions, detailed previously, were evaluated at half of these respective width values from the centerline of the weld.

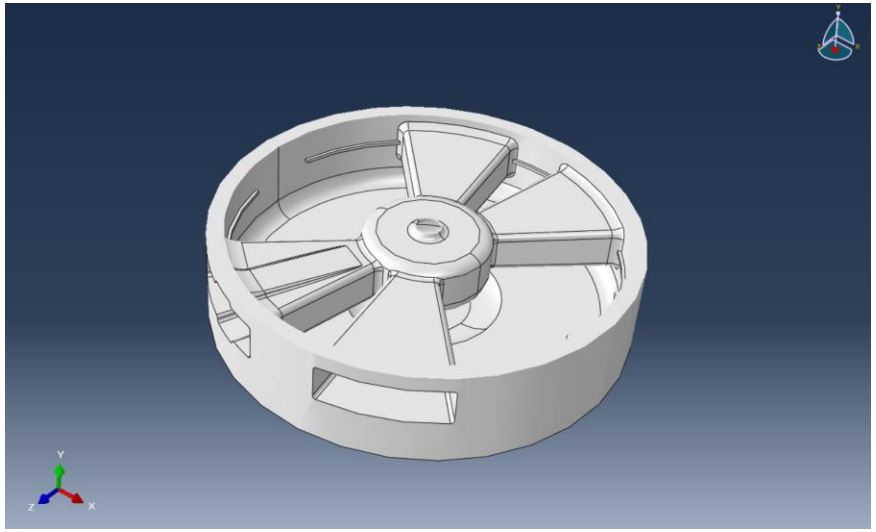
# MRA Upper Reflector Vessel

SpaceClaim model for Aluminum and Beryllium

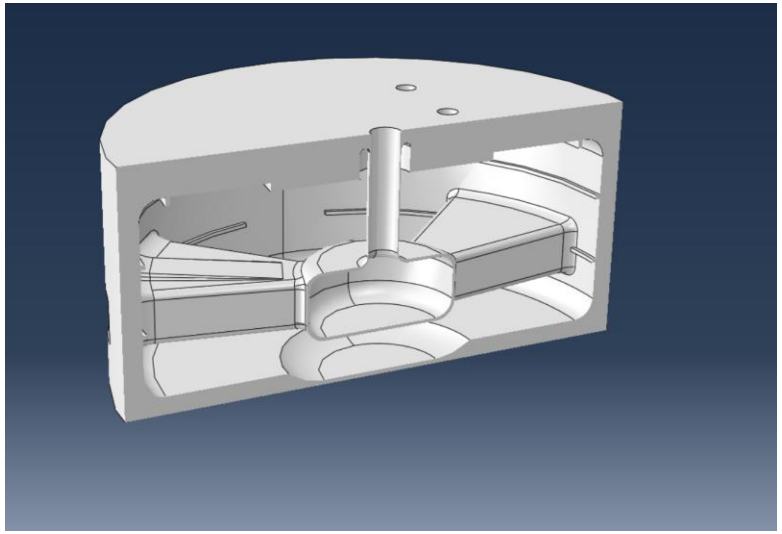




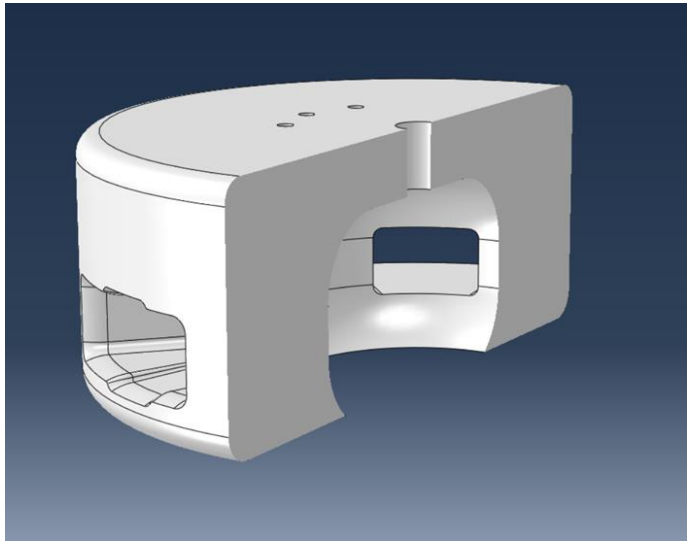
## View with a cut above moderator vessel



## Planar cut showing cylindrical moderator vacuum shell

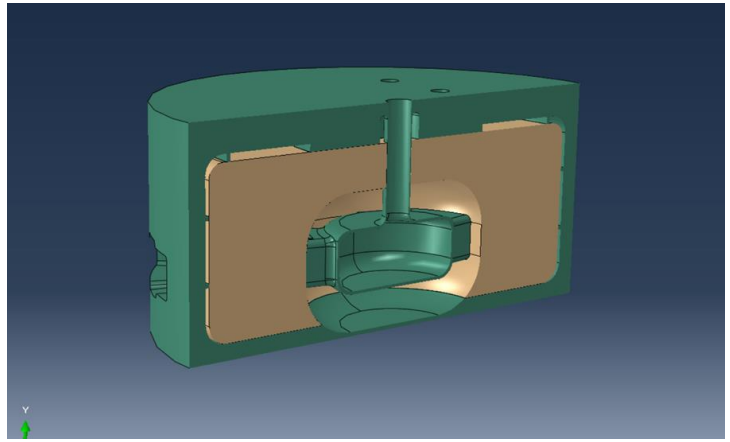


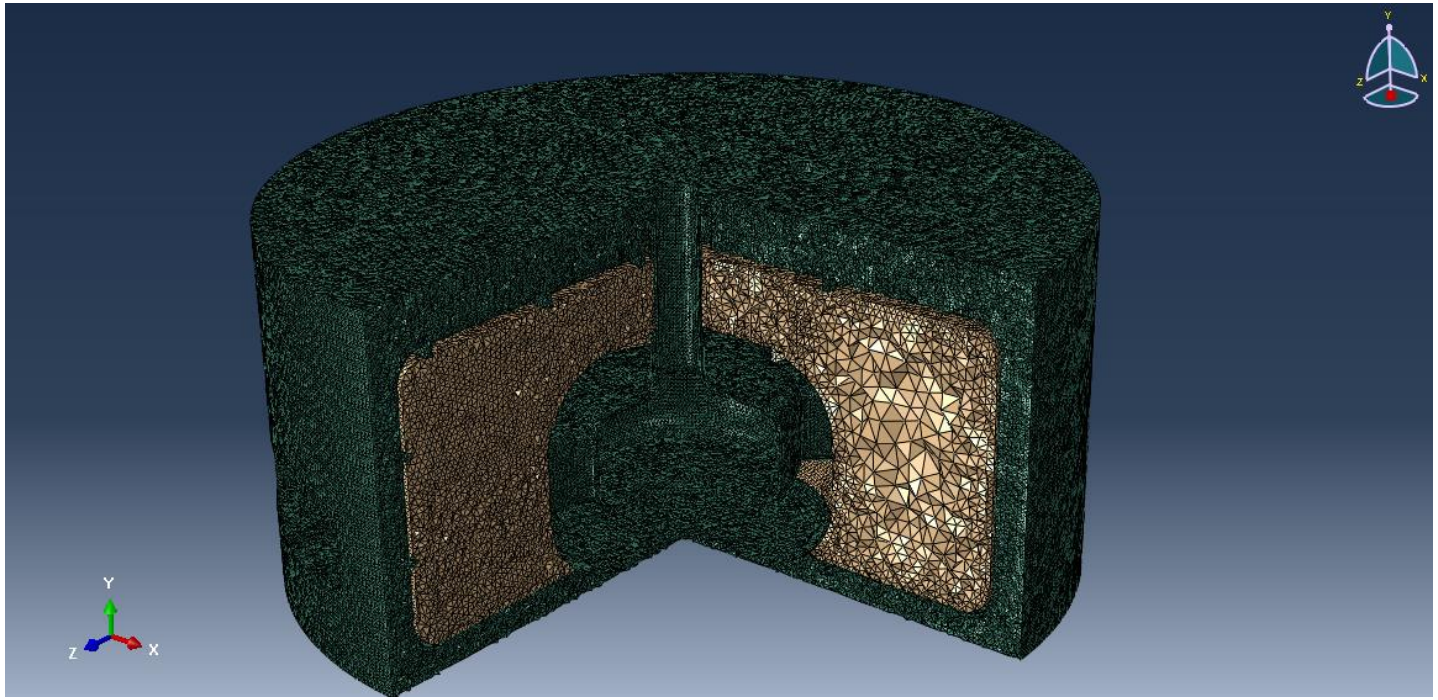
## Beryllium part with x plane cut



# Upper Vessel Model mesh

- **Aluminum**
  - C3D10 elements
  - 1.9 mm nominal edge
  - 2.5 mm on top and bottom outside edges
  - .05 Deviation
  - 1.05 Growth
  - 6,565,043 elements
- **Beryllium**
  - C3D10 elements
  - 3 mm nominal edge
  - .1 deviation
  - 1.1 Growth
  - 1,171,786 elements

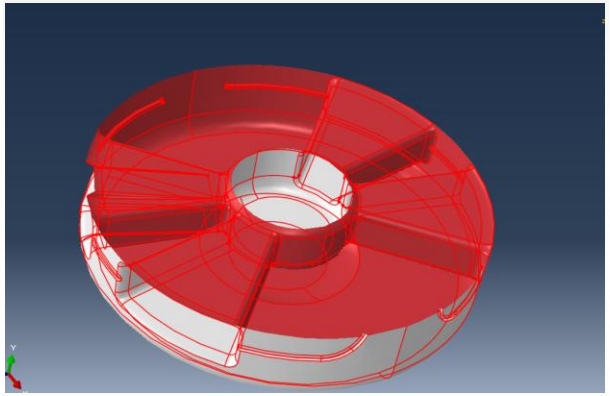




# Aluminum Reflector Vessel pressure loads

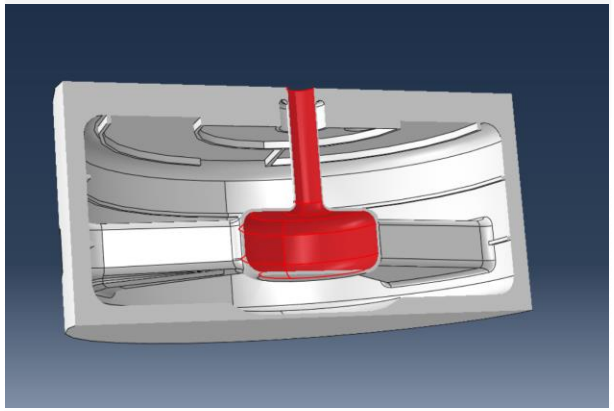
## Water pressure y-cut

(5 bar or 3 bar)



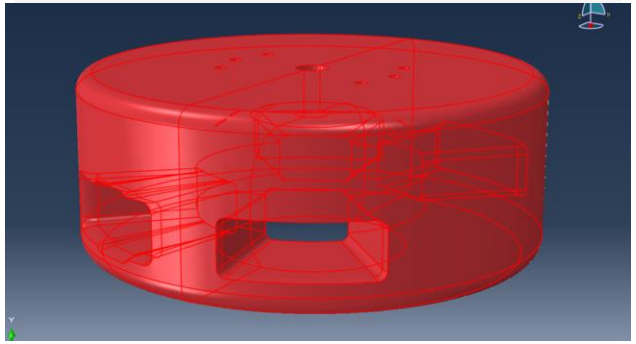
## Vacuum shell

(0 or 2 bar)



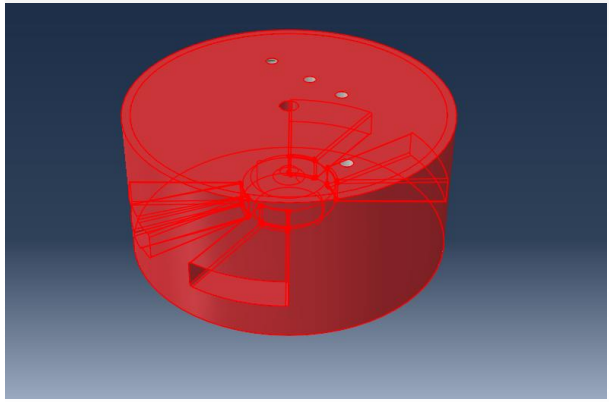
## Beryllium pressure

(5 bar or 3 bar)



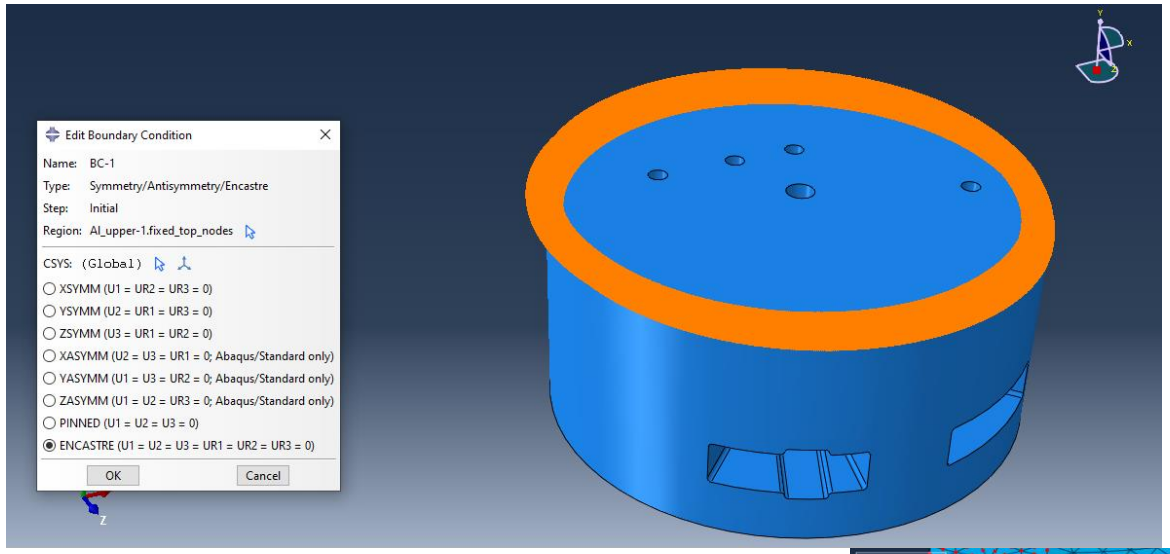
## Core Vessel Pressure

0 or 1.5 bar)

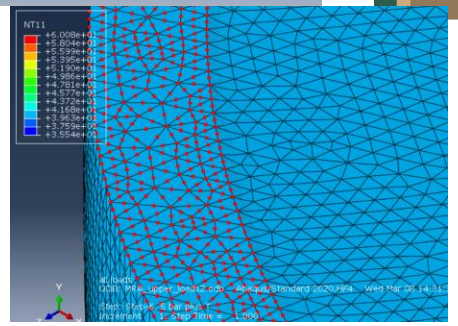


# Boundary condition and constraints

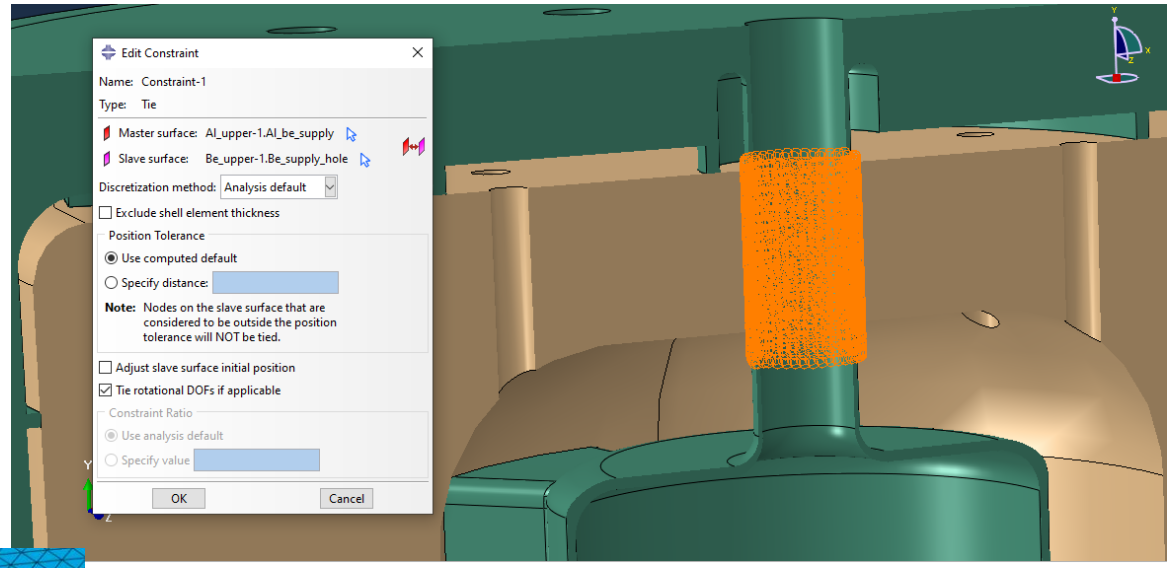
## Fixed boundary condition to mimic bolting to backbone




Top Surface nodes in ring from 180.5 mm radius to outside at 190.5 mm fixed



## Tie constraint




Artificial tie constraint used to keep beryllium centered within vessel

# Load Cases

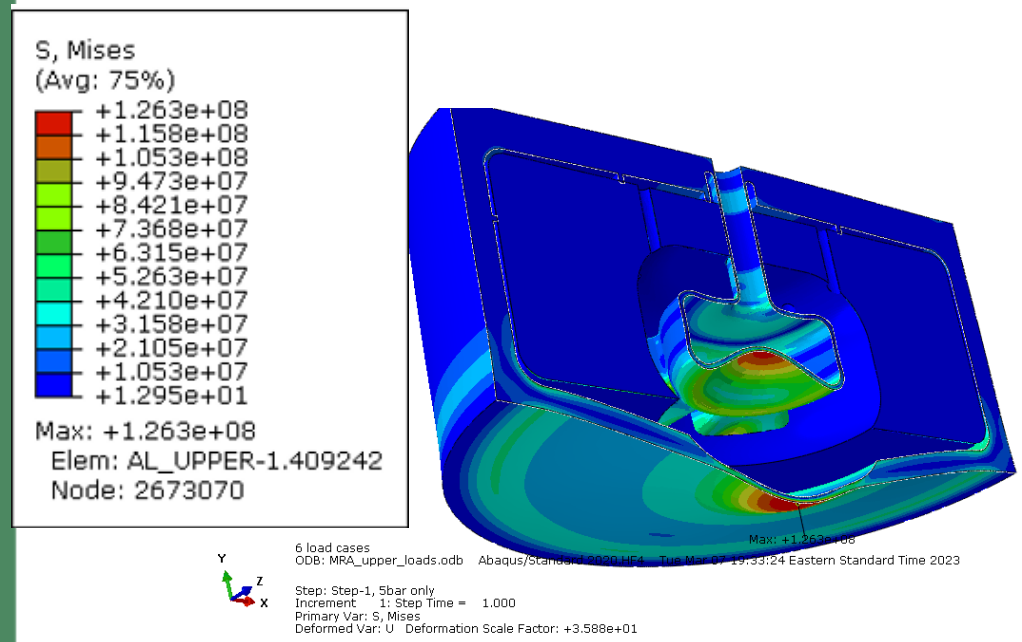
| Case # | Load Case | Reflector P (bar) | Vac Vessel P (bar) | Core Vessel P (bar) | Thermal |
|---|---|---|---|---|---|
| 1 | Reflector MAWP | 5 | 0 | 0 | off |
| 2 | Vac Vessel MAWP | 3 | 2 | 0 | off |
| 3 | Core Vessel MAWP | 3 | 0 | 1.5 | off |
| 4 | Thermal profile | 0 | 0 | 0 | on |
| 5 | normal ops | 3 | 0 | 0 | on |
| 6 | Reflector MAWP + thermal | 5 | 0 | 0 | on |

Results will be shown for Load Cases 1 and 6 which are limiting

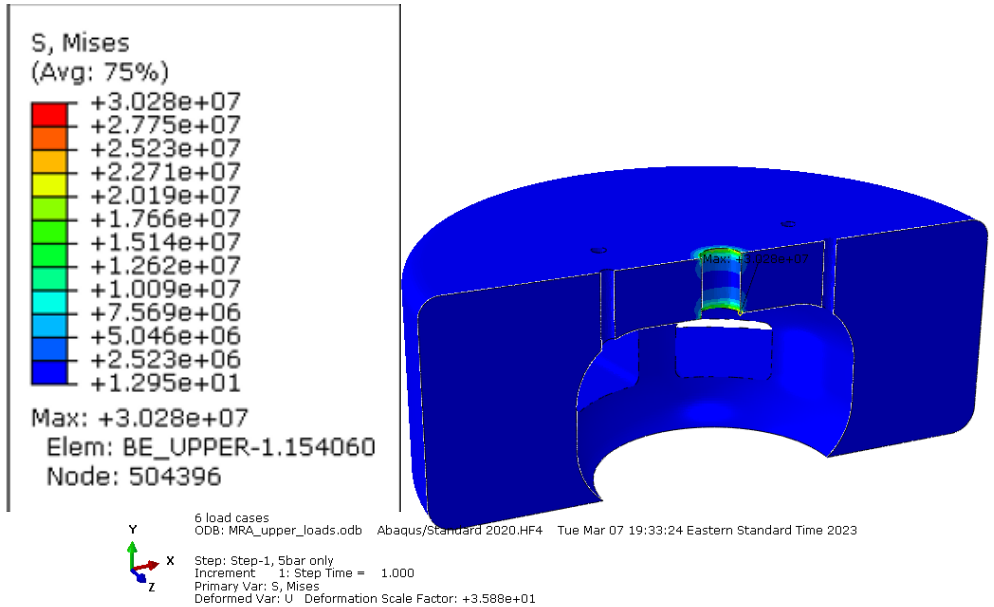
MAWP = Maximum Allowable Working Pressure

# Upper Case 1 – 5 bar only

S peak 126.3 MPa

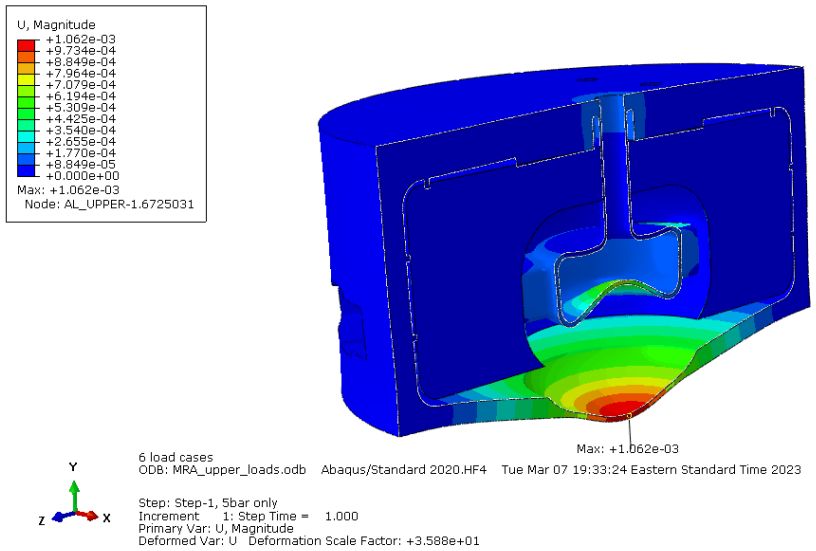



Beryllium S Mises peak 30.3 MPa by edge of tie to aluminum tube

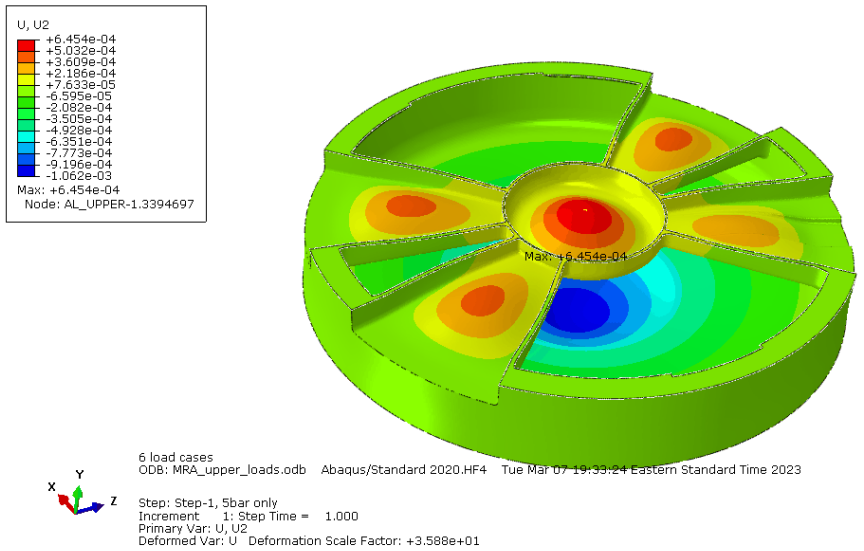


# Upper Case 1 – 5 bar only - Displacements

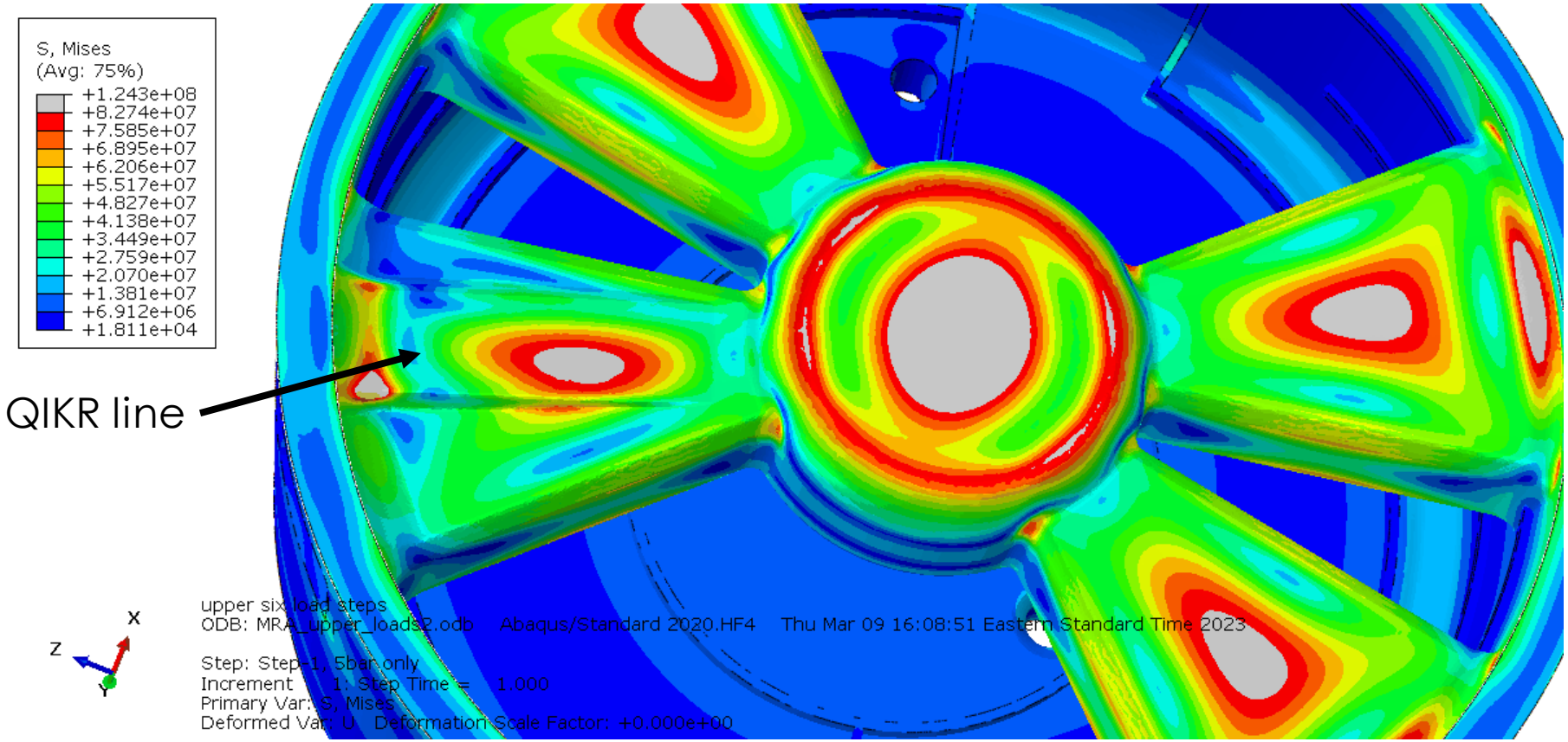
## Displacement peak 1mm




## Vertical Displacement with cut through beam line channels



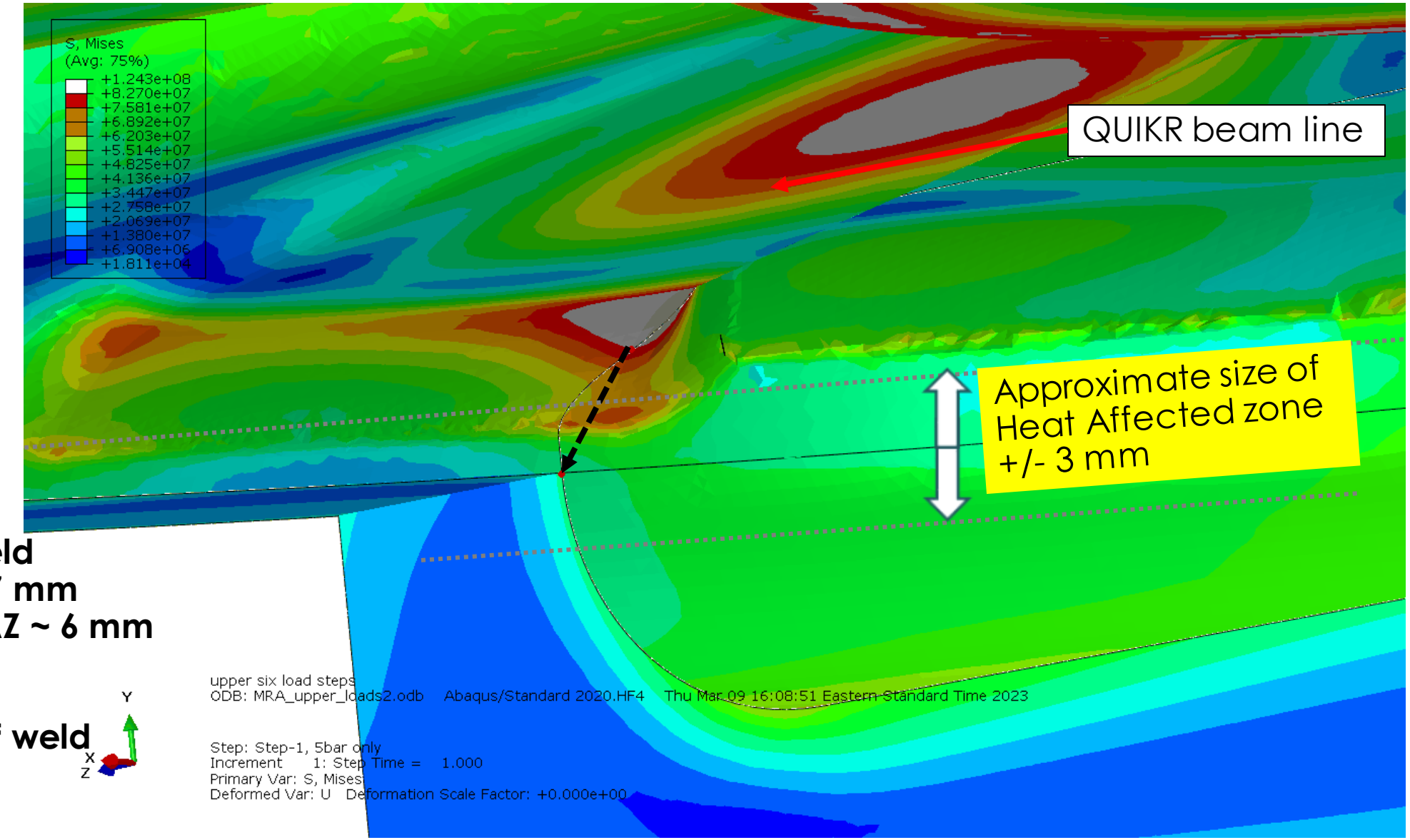
# Upper case 1  5 bar 82.74 MPa scale max




**Scale Maximum at 82.7 MPa =**
**1.5x $S_m$ limit for weld region**

# Upper Case1 Minimum distance from stress limit to weld

**Scale Maximum at 82.7 MPa = 1.5x $S_m$ limit**

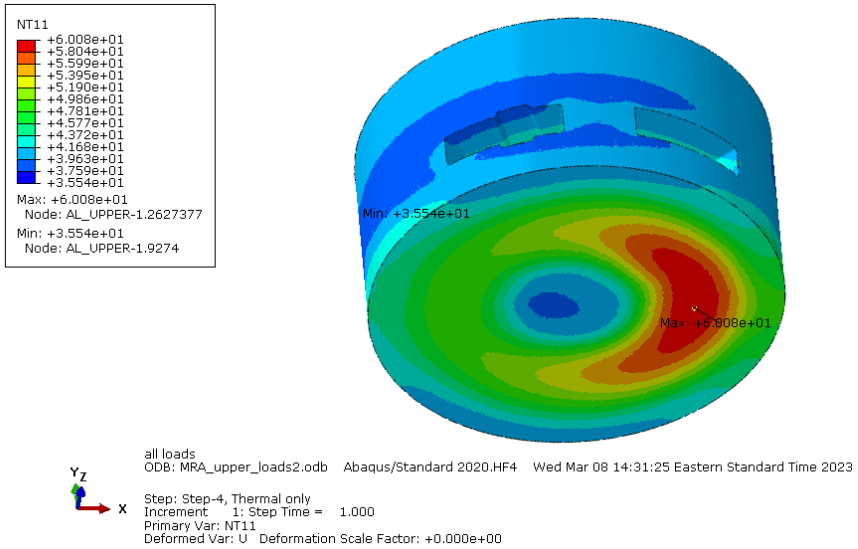



**Distance to weld centerline= 8.7 mm**
**Distance to HAZ ~ 6 mm**

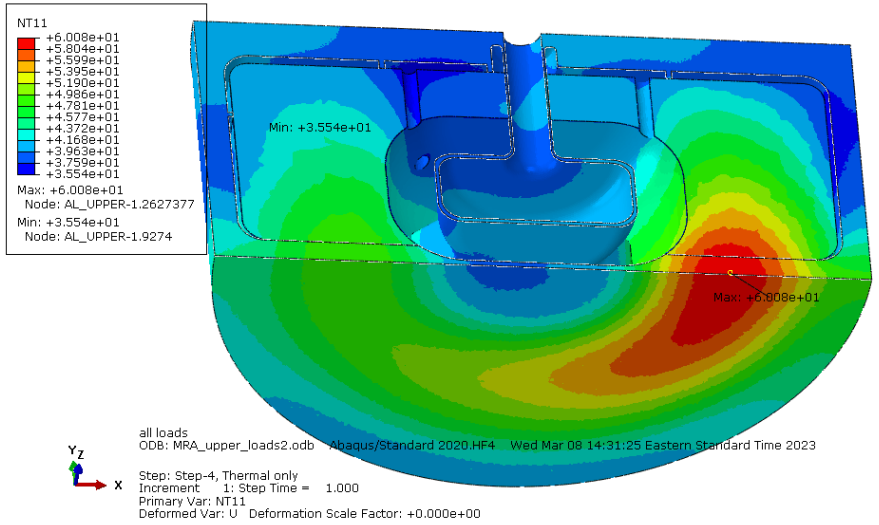
**Cut at Plane of weld centerline**

# Upper Imposed Temperature fields

## Outer surface peak 60 C




## Vertical cut z=0



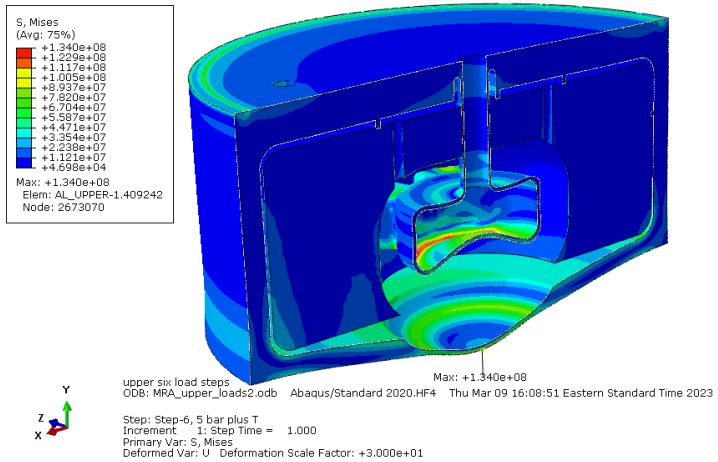

**Initial temperature 35 °C**

Temperature Profiles from Min-Tsung Kao – Reflector Vessel Thermal hydraulic Analysis

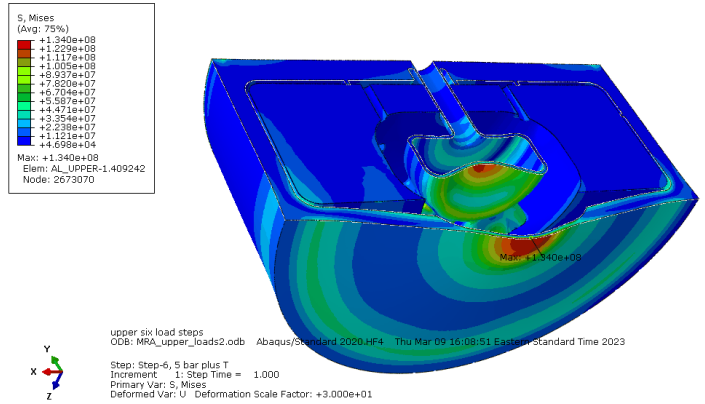
Min-Tsung Kao_STS_MRA_2023_01_18_Upper_MRA.

# Upper Case 6  5 bar plus thermal

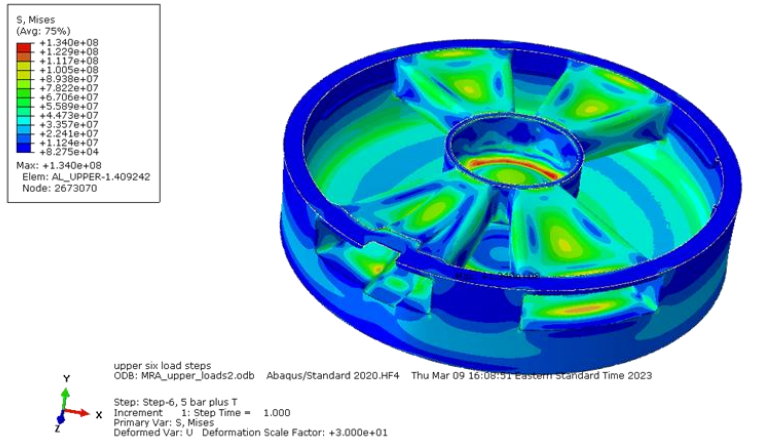
## S Mises peak 134 MPa




## Bottom view

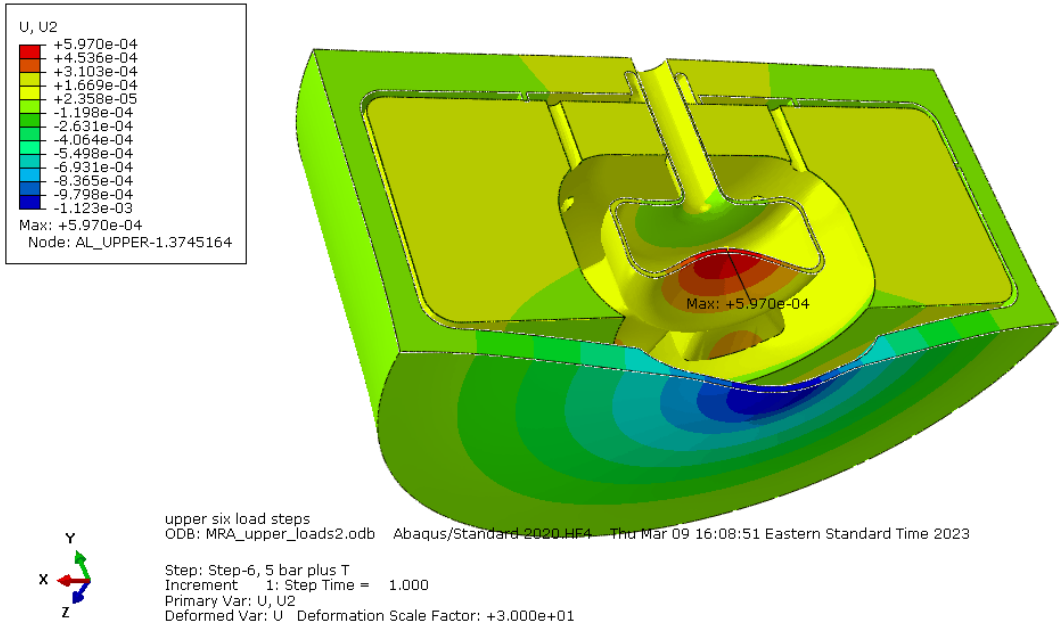



## Stress with view cut above neutron beam channels

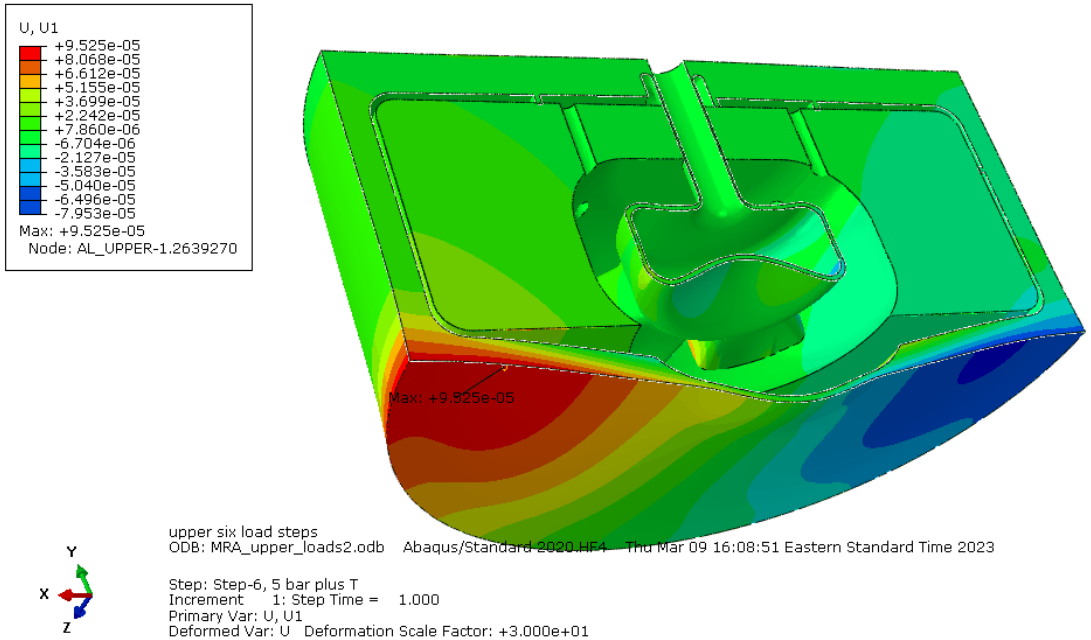


# Upper Case 6  5 bar plus thermal  Displacement

## Vertical displacement max -1.1 mm

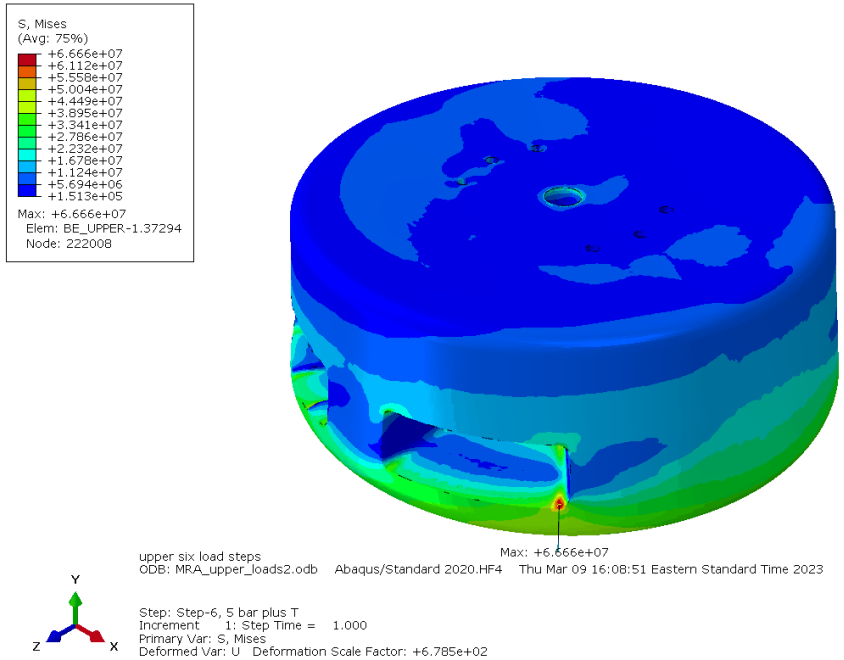



## Horizontal displacement U1 (x)

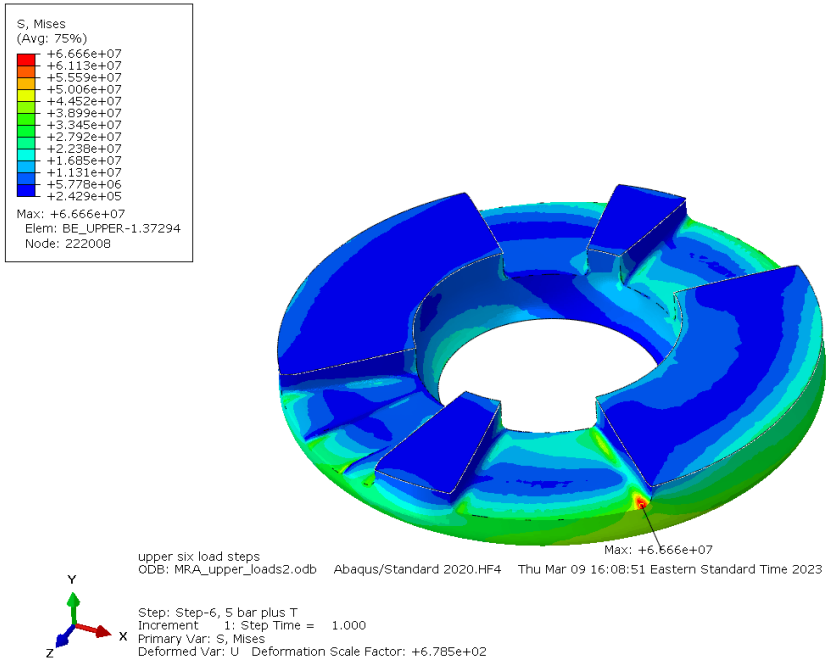


# Upper Case 6  5 bar plus thermal - Beryllium

## Beryllium Von Mises peak 66.7 MPa

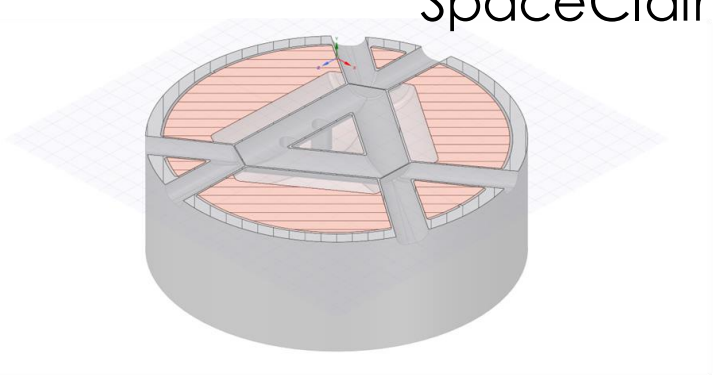


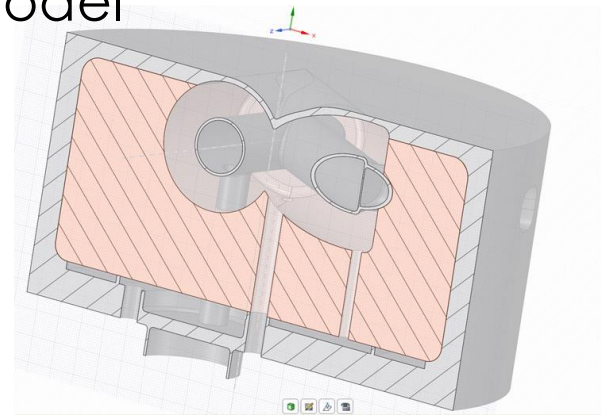

## Beryllium y cut to show beam lines



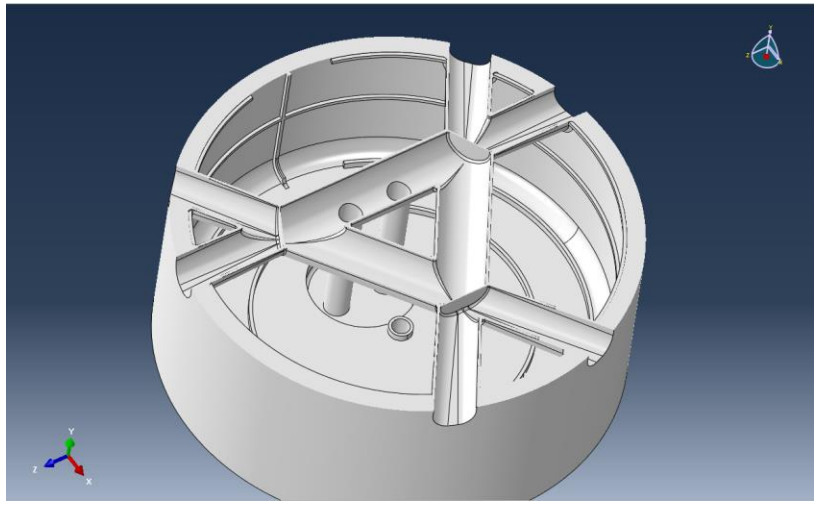
# Lower MRA Reflector

SpaceClaim model

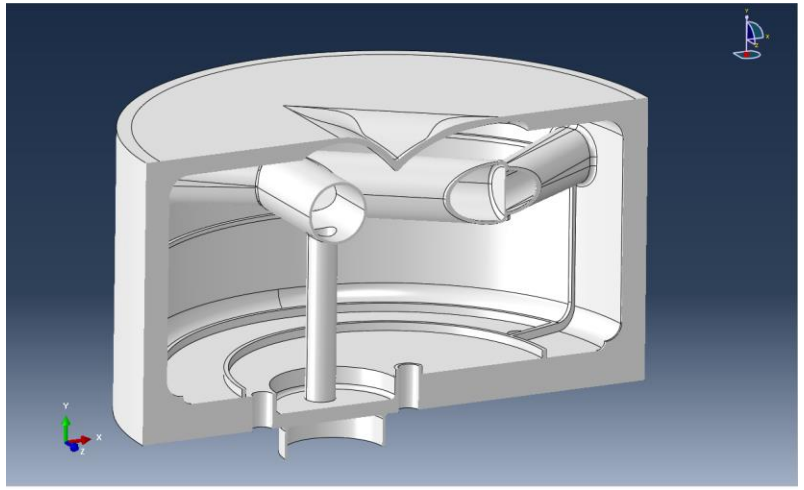




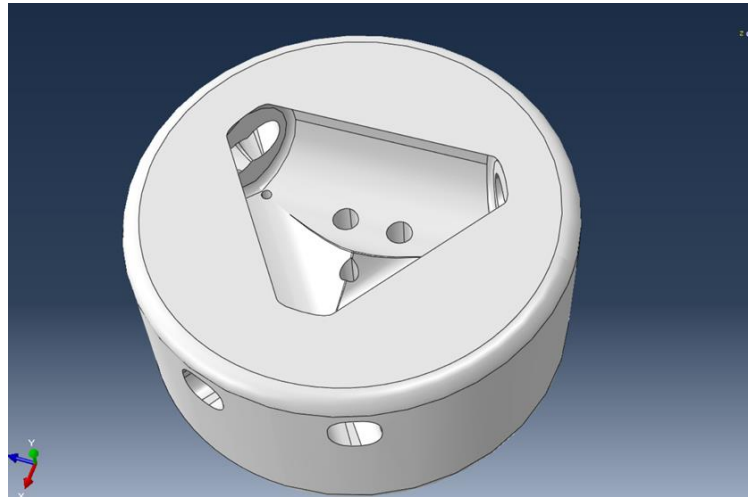
## Horizontal cut through hydrogen vacuum vessel tubes



## Vertical cut z=0 showing one 1mm vacuum window

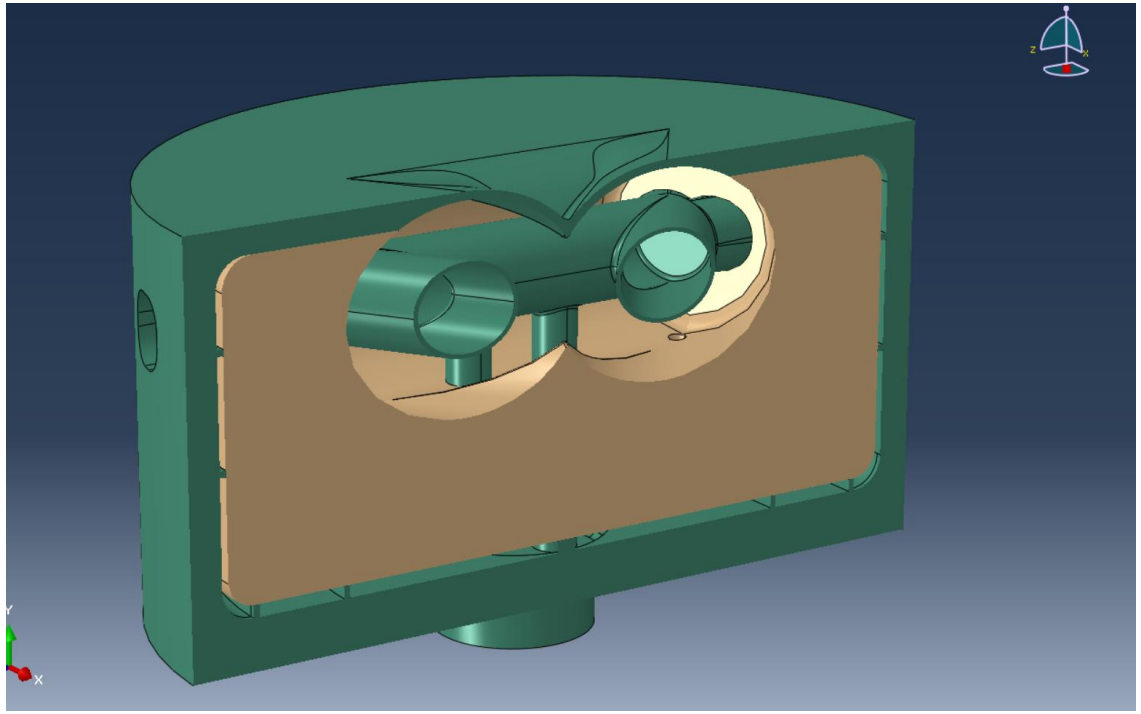


## Beryllium Part

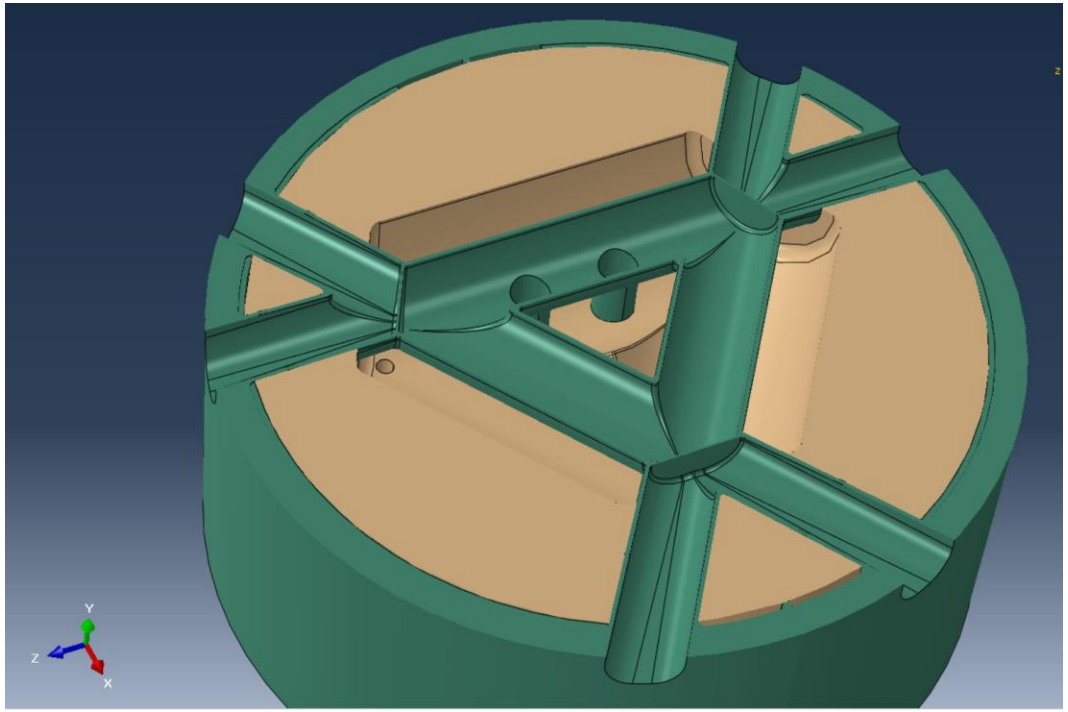


# Assembly Views

Vertical cut x=0

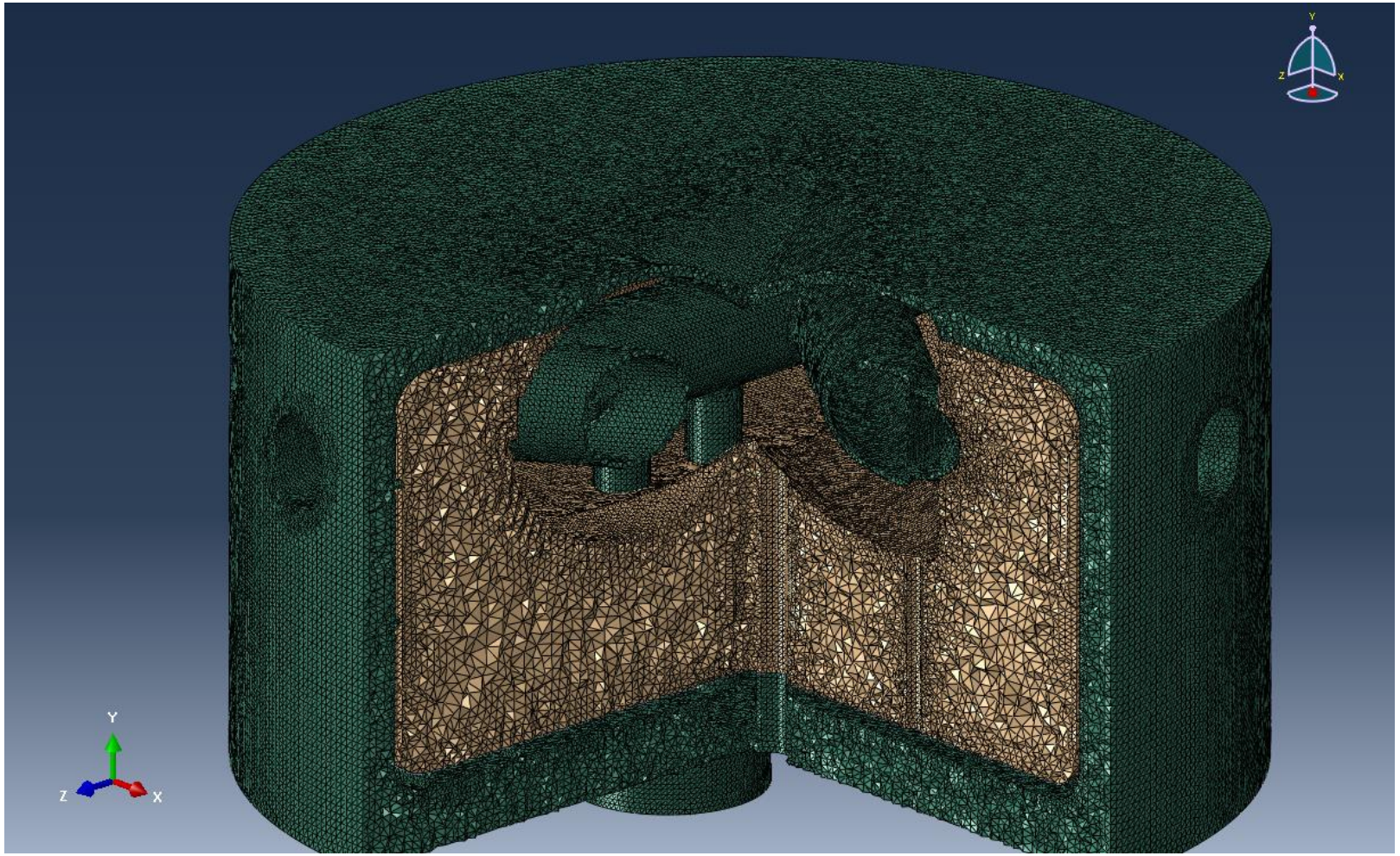


Horizontal cut y=-.0992m



# Lower MRA Mesh

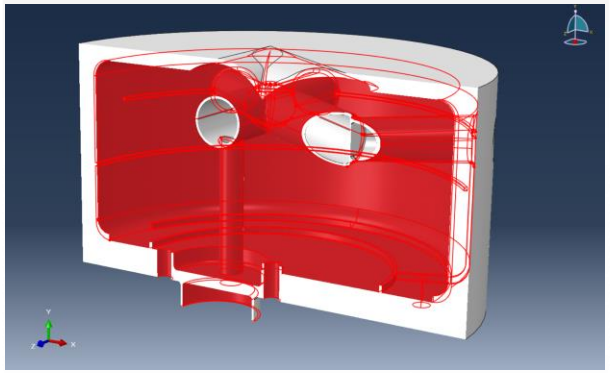
- **Aluminum**
  - C3D10 elements
  - 2.0 mm nominal edge
  - 3.5 mm on top and bottom outside edges
  - .1 Deviation
  - 1.05 Growth
  - 3,312,375 elements
- **Beryllium**
  - C3D10 elements
  - 2 mm nominal edge
  - 3 mm on top and bottom outside edges
  - .1 deviation
  - 1.05 Growth
  - 2,364,100 elements



# Pressure loads for Lower MRA

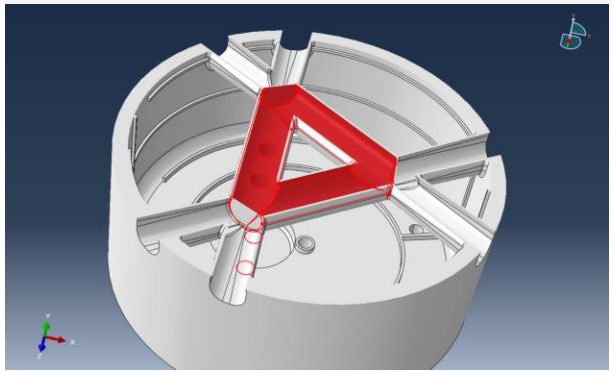
## Water Pressure surface

5 bar and 3 bar cases



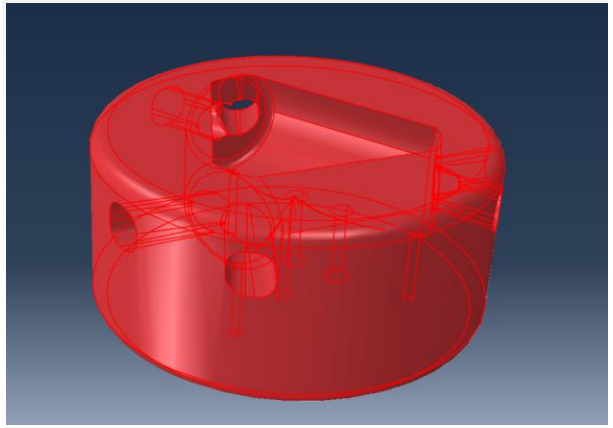
## Vacuum vessel surface

0 or 2 bar cases



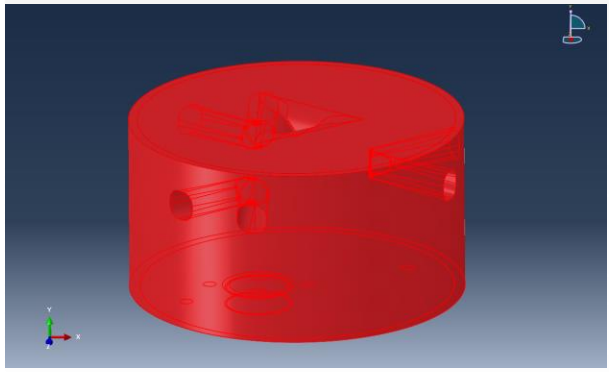
## Beryllium pressure surface

5 bar and 3 bar cases



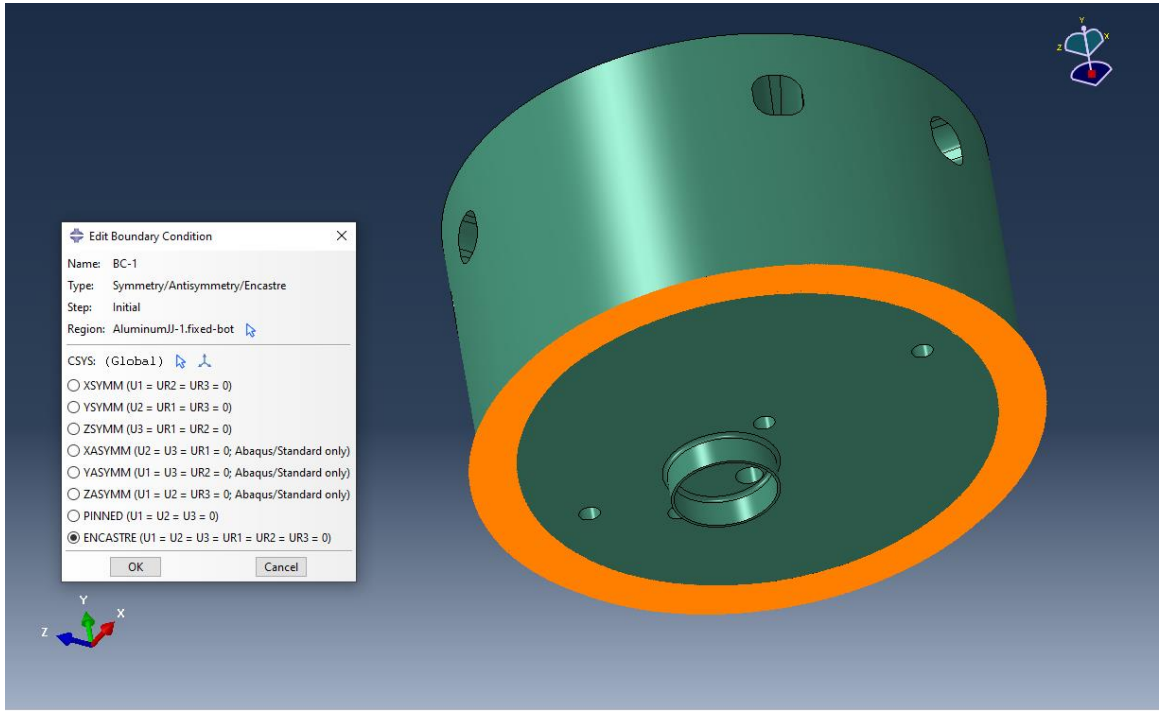
## Aluminum outer surface

0 or 1.5 bar

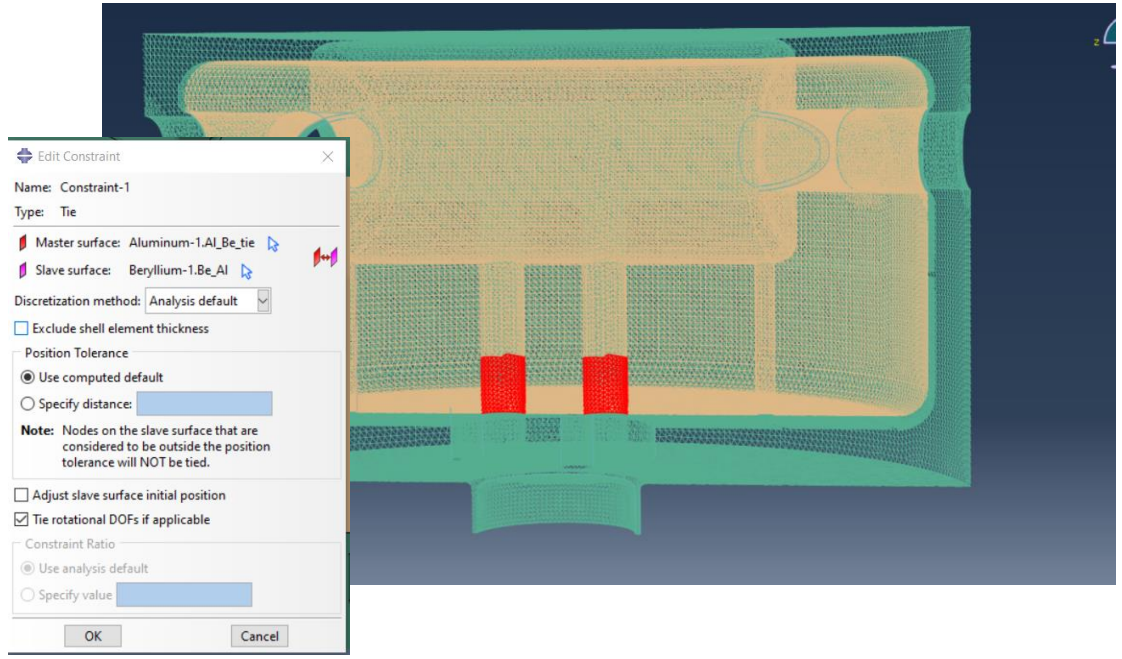


# Boundary Condition and Constraints

## Fixed Boundary condition on bottom surface nodes




## Tie constraint between Be and Al on tubes




Artificial tie constraint used to keep beryllium centered within vessel

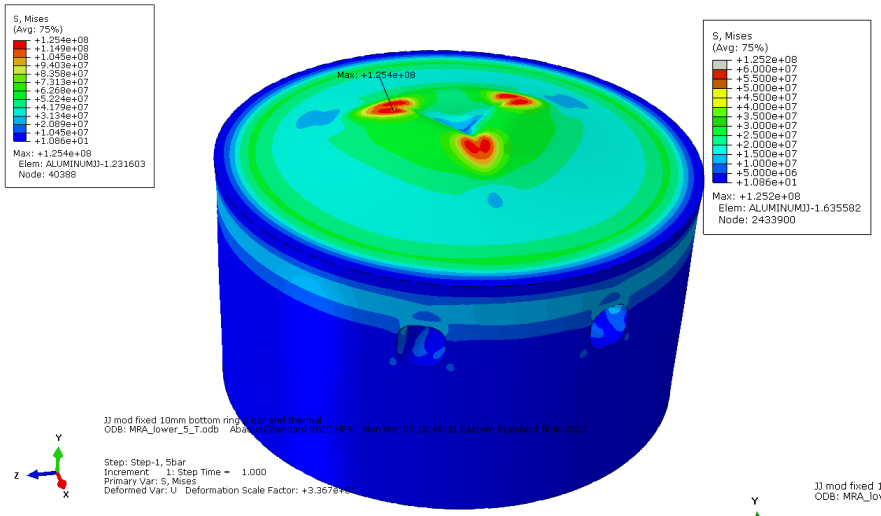
# Lower MRA Load Cases

| Case # | Load Case | Reflector P (bar) | Vac Vessel P (bar) | Core Vessel P (bar) | Thermal |
|---|---|---|---|---|---|
| 1 | Reflector MAWP | 5 | 0 | 0 | off |
| 2 | Vac MAWP | 3 | 2 | 0 | off |
| 3 | CV MAWP | 3 | 0 | 1.5 | off |
| 4 | Thermal | 0 | 0 | 0 | on |
| 5 | normal ops | 3 | 0 | 0 | on |
| 6 | Reflector +thermal | 5 | 0 | 0 | on |

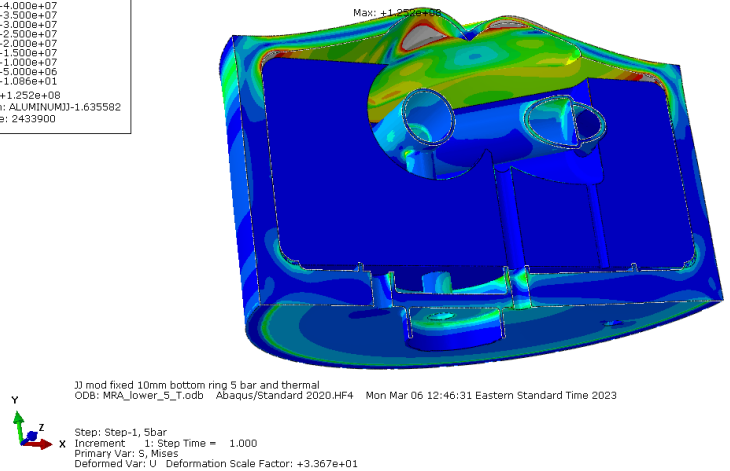
Only Cases 1 and 6 which are limiting to be presented

# Lower Case 1 - 5 bar

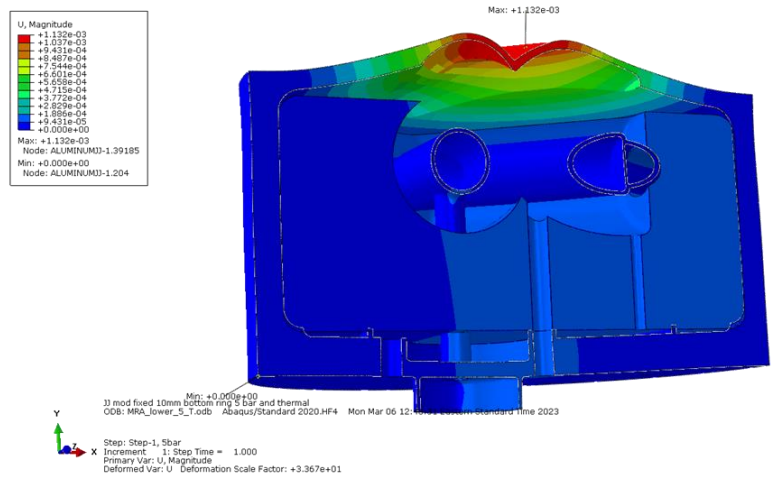
S Mises peak 125.4 MPa



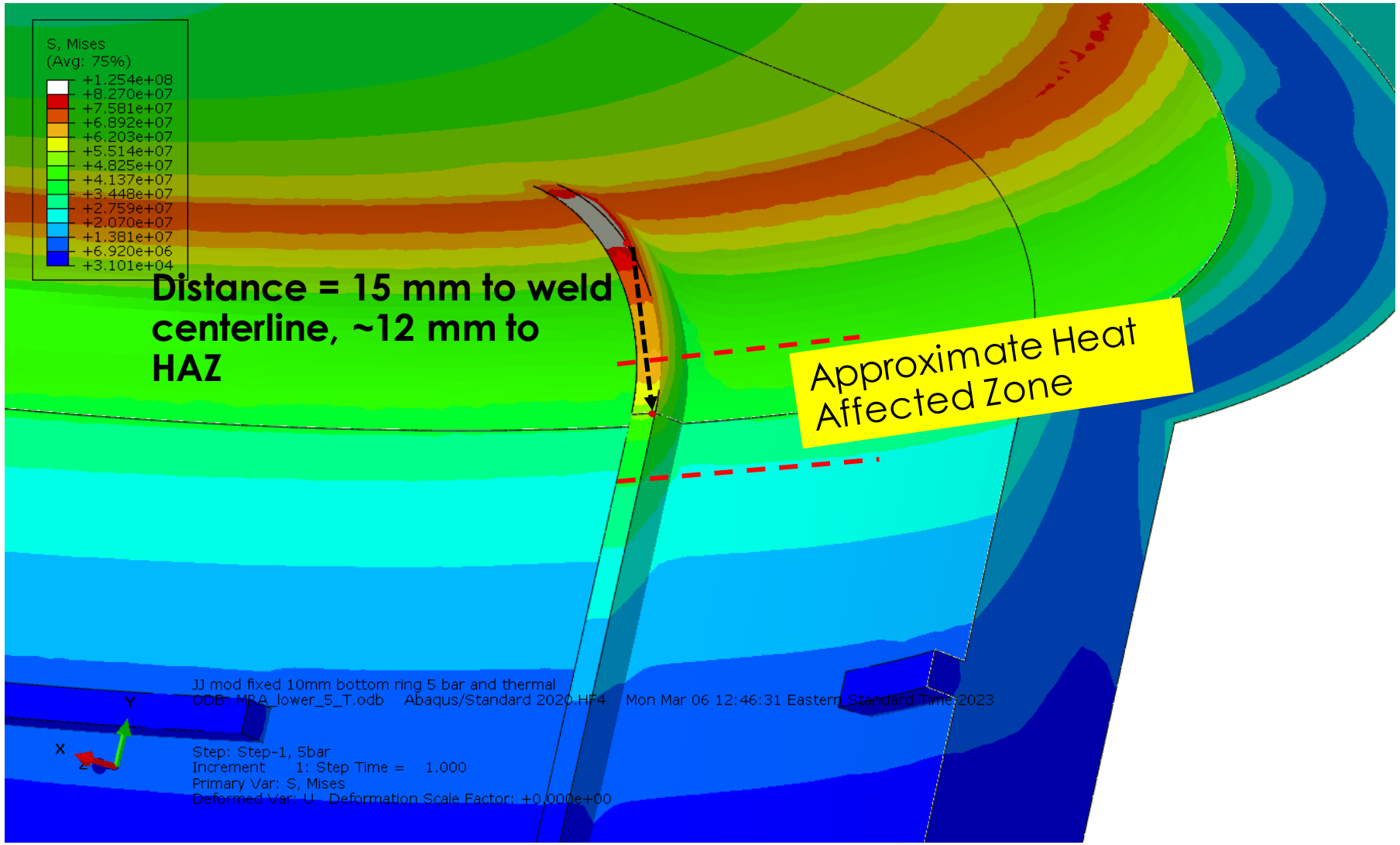

Z=0 cut with 60 MPa scale maximum




Displacement peak 1.1 mm

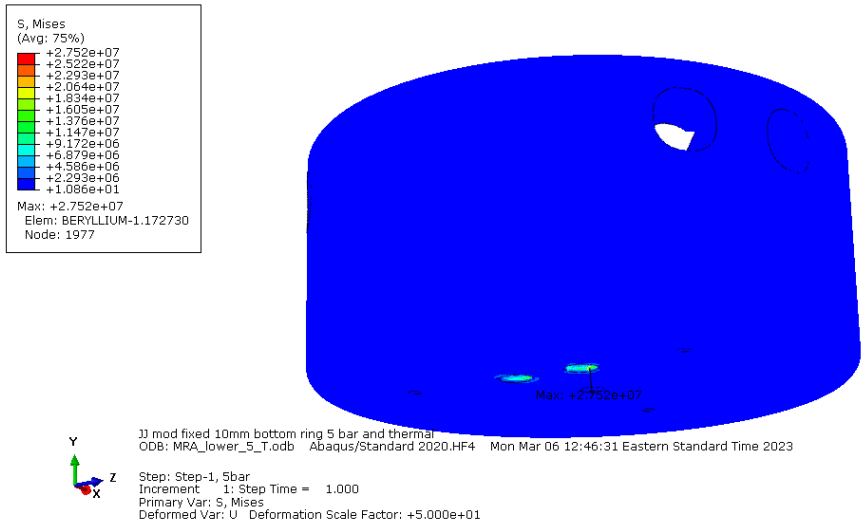


# Lower Case 1 Minimum distance from weld to stress limit

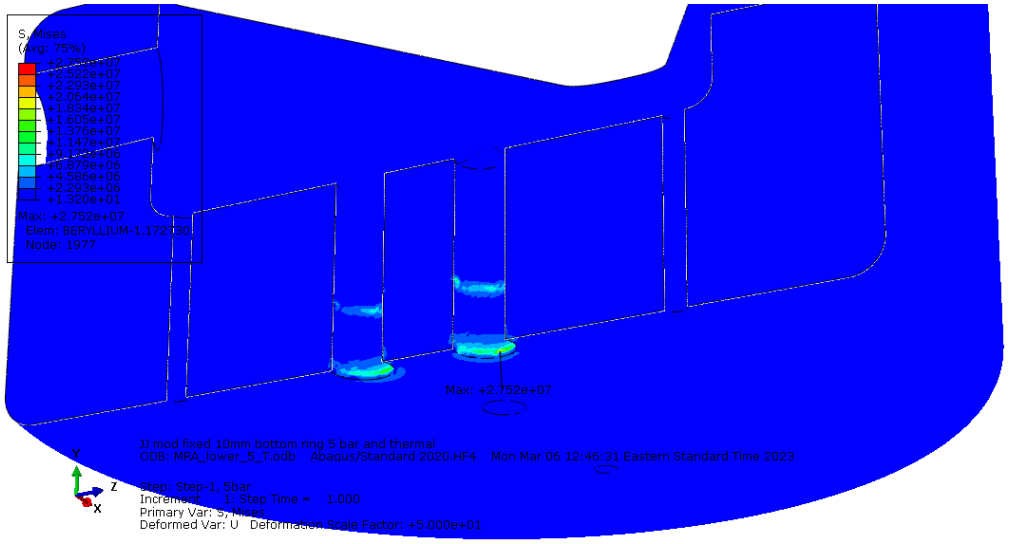


# Lower Case 1 - 5 bar Beryllium

## Beryllium S Mises peak 27.5 MPa

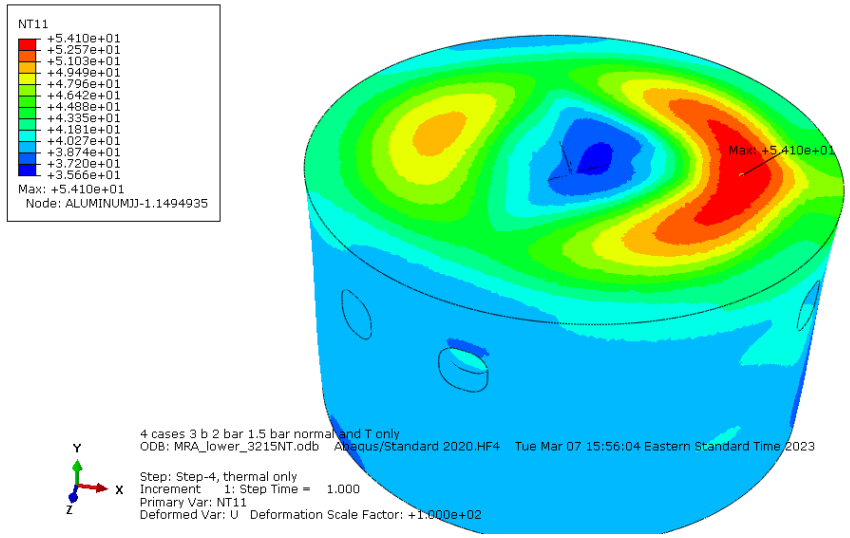



## Cut showing peak around tie area

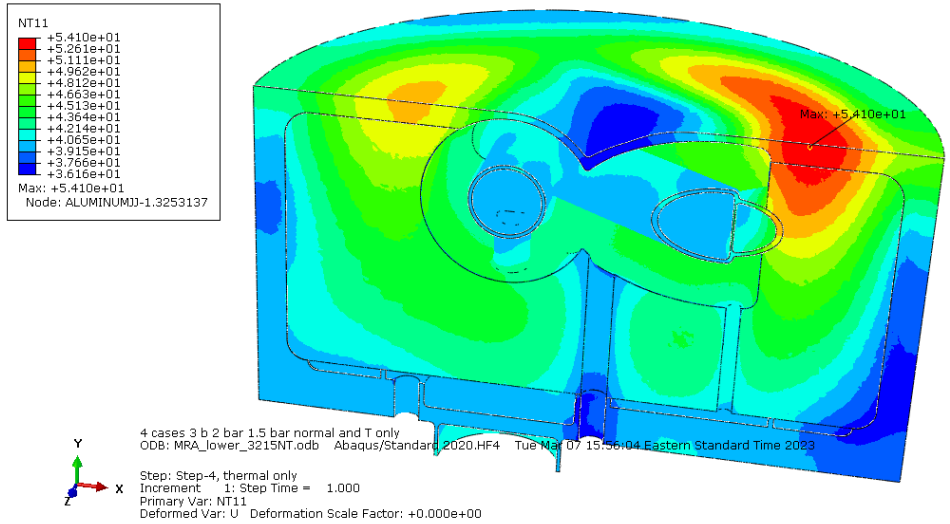


# Lower Temperature Profile

## Outer Al surface peak 54.1C




## Z=0 cut through Be and Al

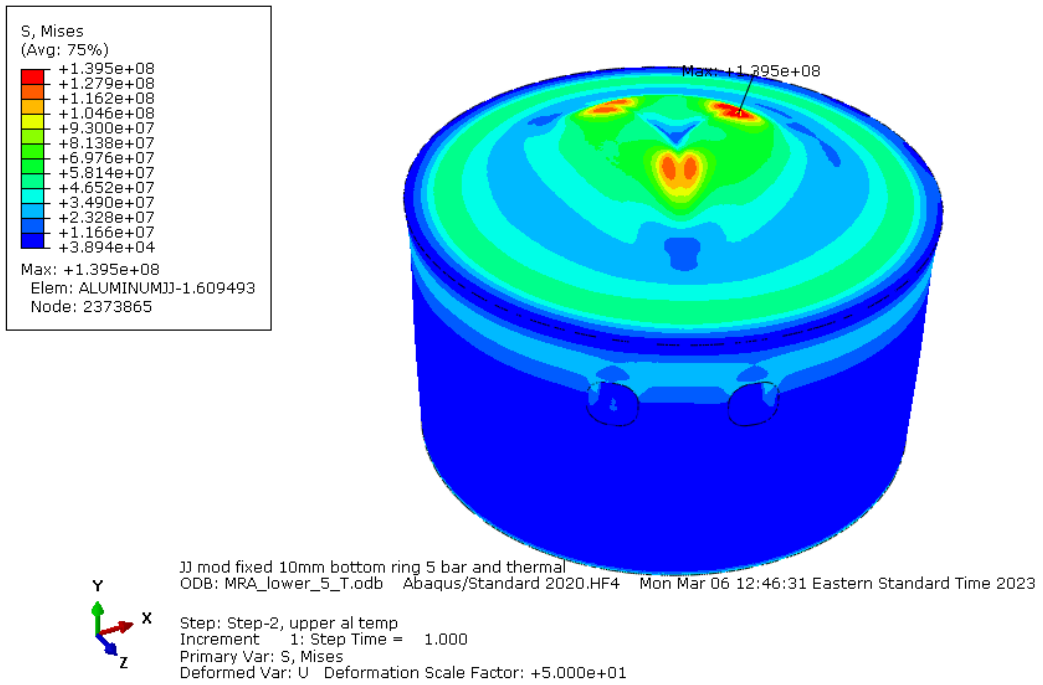



Temperature Profiles from Min-Tsung Kao – Reflector Vessel Thermal hydraulic Analysis

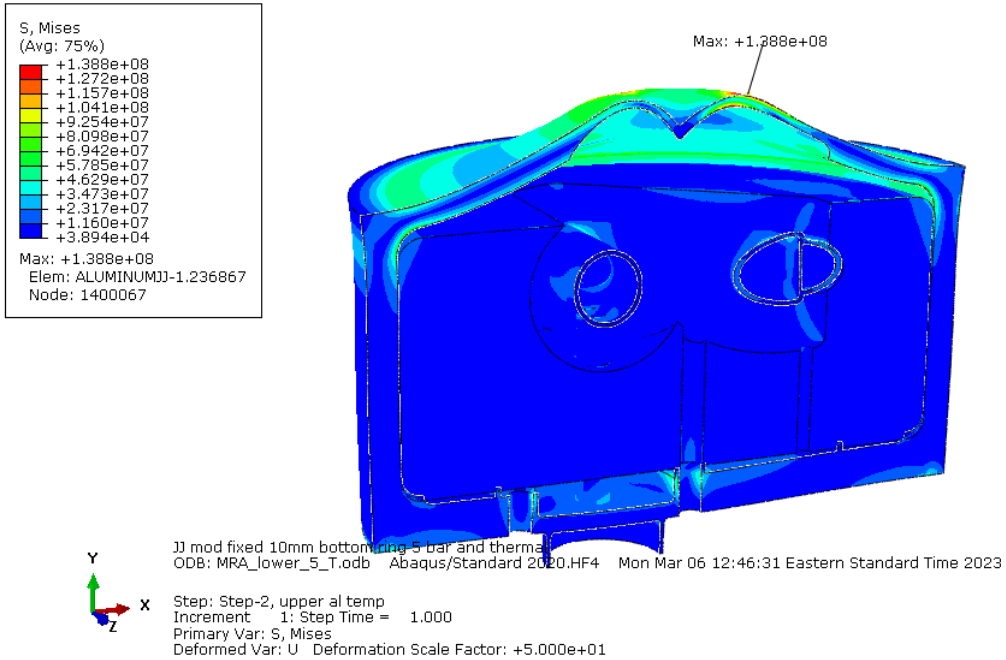
Min-Tsung Kao_STS_MRA_2022_12_07_Lower_MRA_Update_2.

# Lower Case 6 – 5 bar and thermal stress

## S Mises peak 139.5 MPa

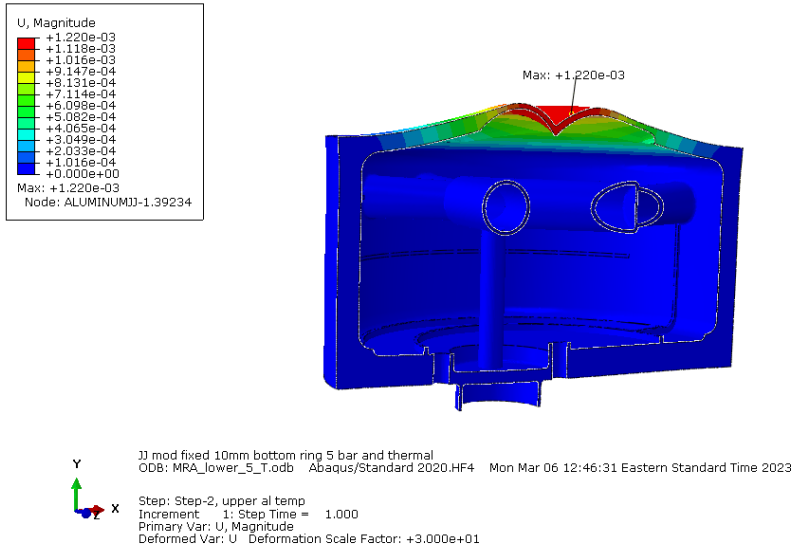



## S Mises Z=0 cut

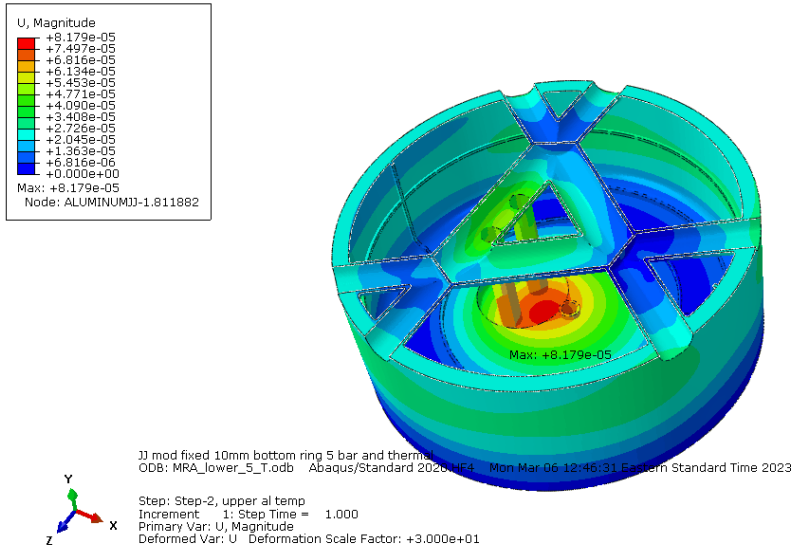


# Lower Case 6 – 5 bar and thermal stress

## Displacement peak 1.2 mm

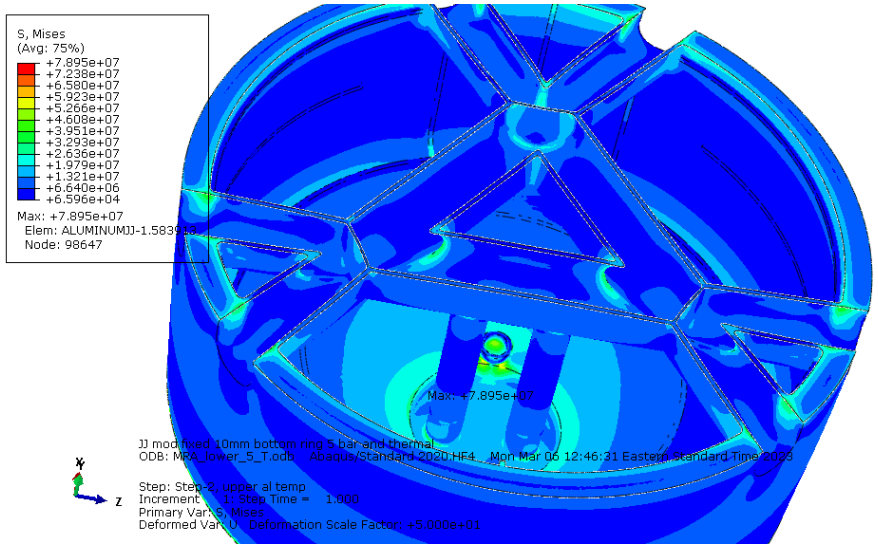



## Displacement cut through neutron beam channels

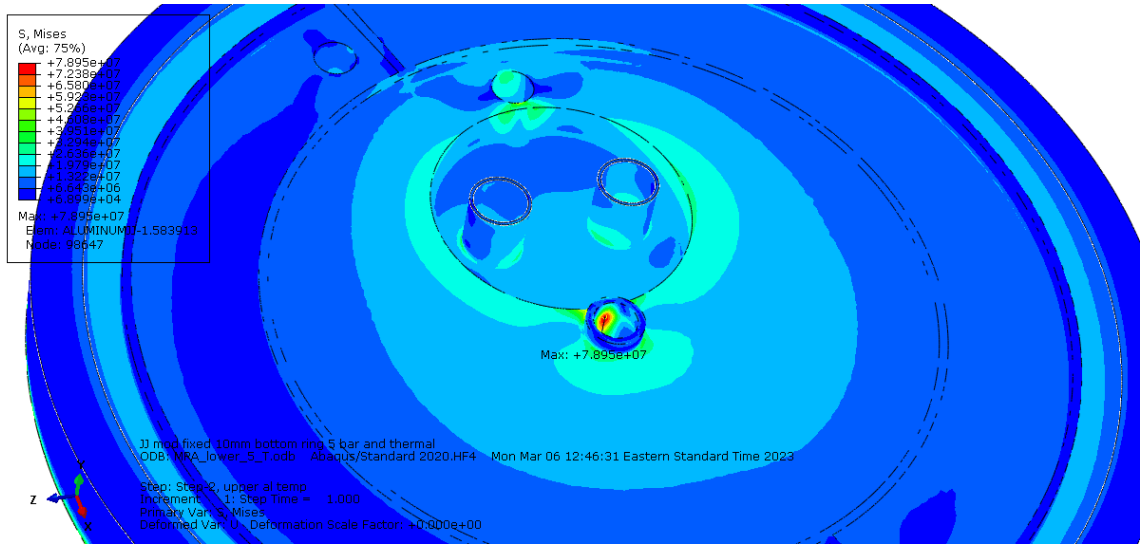


# Lower Case 6- 5 bar and thermal Aluminum

## Y cut – S max 79 MPa near base




## Peak stress near base



# Summary Aluminum Peak stresses for Upper and Lower assemblies

| Case # | Load Case | Reflector P (bar) | Vac Vessel P (bar) | Core Vessel P (bar) | Thermal | Allowable Aluminum Von Mises stress (MPa) | Upper Vessel Peak Von Mises stress (MPa) | Lower Vessel Peak Von Mises stress (MPa) | Allowable displacement toward target (mm) | Upper vessel Displacement (mm) | Lower vessel displacement (mm) | Upper vessel minimum dist. Limit to weld (mm) | Lower vessel minimum dist. Limit to weld (mm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Reflector MAWP | 5 | 0 | 0 | off | 127/82.7 | 126.3 | 125.4 | 1 | 1.06 | 1.13 | 8.7 | 15 |
| 2 | Vac MAWP | 3 | 2 | 0 | off | 127/82.7 | 75.8 | 75.2 | 1 | .24 | 0.68 | N/A | N/A |
| 3 | CV MAWP | 3 | 0 | 1.5 | off | 127/82.7 | 73.5 | 37.6 | 1 | .38 | 0.34 | N/A | N/A |
| 4 | Thermal | 0 | 0 | 0 | on | 254/165* | 89 | 68.7 | 1 | .09 | .09 | N/A | N/A |
| 5 | normal ops | 3 | 0 | 0 | on | 254/165* | 92.6 | 91.4 | 1 | .70 | 0.77 | N/A | N/A |
| 6 | Reflector +thermal | 5 | 0 | 0 | on | 254/165* | 134 | 139.5 | 1 | -1.12 | 1.22 | N/A | N/A |

* 93° C Primary+Bending+Secondary (3Sm) : non-weld/weld

# Beryllium Peak Von Mises Stress Summary

| Case # | Load Case | Upper Vessel Be peak stress (MPa) | Lower Vessel Be peak stress (MPa) |
|---|---|---|---|
| 1 | Reflector MAWP | 30.3 | 27.5 |
| 2 | Vac MAWP | 8 | 15.5 |
| 3 | CV MAWP | 16.9 | 9.4 |
| 4 | Thermal | 66.7 | 50.2 |
| 5 | normal ops | 66.7 | 50.2 |
| 6 | Reflector +thermal | 66.7 | 50.2 |

In all cases the peak stress was well below the tensile yield strength of 345 to 517 MPa

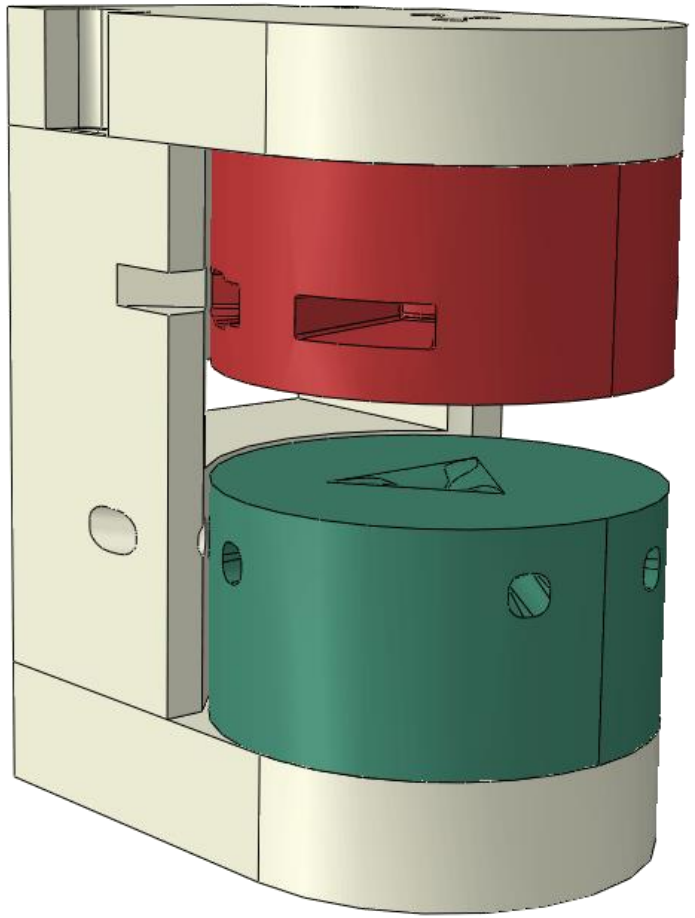
# Reflector Vessel Summary

- The design meets nearly all structural requirements with a minor exception for the 1 mm deflection limit towards the target
  - The deflections are over the limit by only ~0.2 mm or less and can be compensated by slightly dishing the heads
- The addition of thermal stresses added little to the aluminum peak stresses which are dominated by the pressure loads
- The highest beryllium stresses were due to thermal effects, but were localized and only 20% or less of the tensile limit
- No stresses in Heat Affected Zones were over the ASME limits with the closest distance of the limit to a weld HAZ was approximately 6 mm
- More realistic boundary conditions will be used in final design as the surrounding design matures

# MRA Backbone Structural Analysis

- A preliminary stress analysis was done for the three lower stainless steel backbone sections without Moderator Vessels
- The principal result of concern was displacements which could affect moderator location and a limit of 0.5 mm at the center of the mounting surfaces for the reflector vessels was desired
- A full CFD analysis by Min-Tsung Kao had been done and a data file for the temperatures in the region of interest was provided
- Analysis was done for 5 bar MWAP for the water and vacuum in the core vessel. A load case was also done for a failed moderator boundary with 2 bar pressure on the internal vacuum boundary

# Lower Backbone Shown with Moderator Reflector Vessels



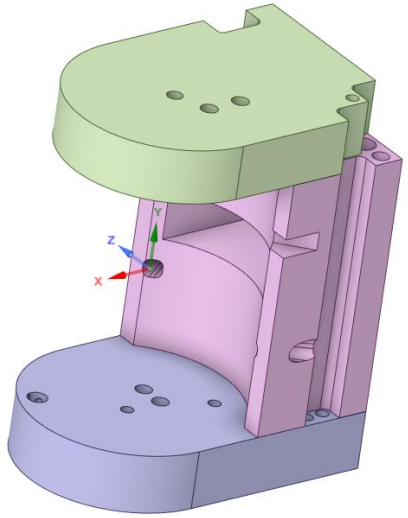
Backbone Abaqus material input data – bi-linear elastic-plastic model*

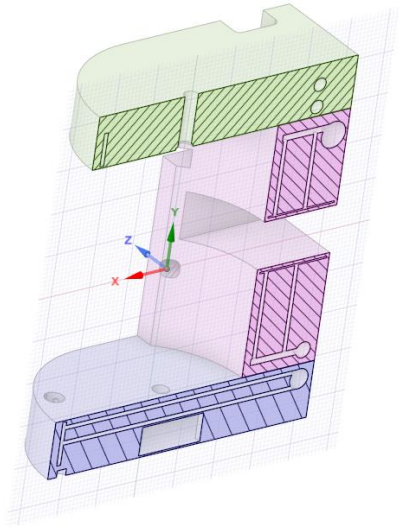
```
** MATERIALS
**
*Material, name=SS3161
*Density
7969.,
*Elastic
 1.95e+11, 0.27
*Expansion, zero=20.
 1.61e-05,
*Plastic
  2.5e+08,     0.
 2.55e+08, 0.005
**
```

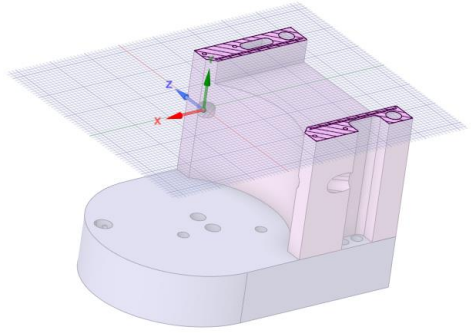
Assembly showing moderator reflector vessels alignment and material assumptions

# Backbone SpaceClaim Model  Section views

| Assembly | Z=0 section | Y=0 section |
| --- | --- | --- |

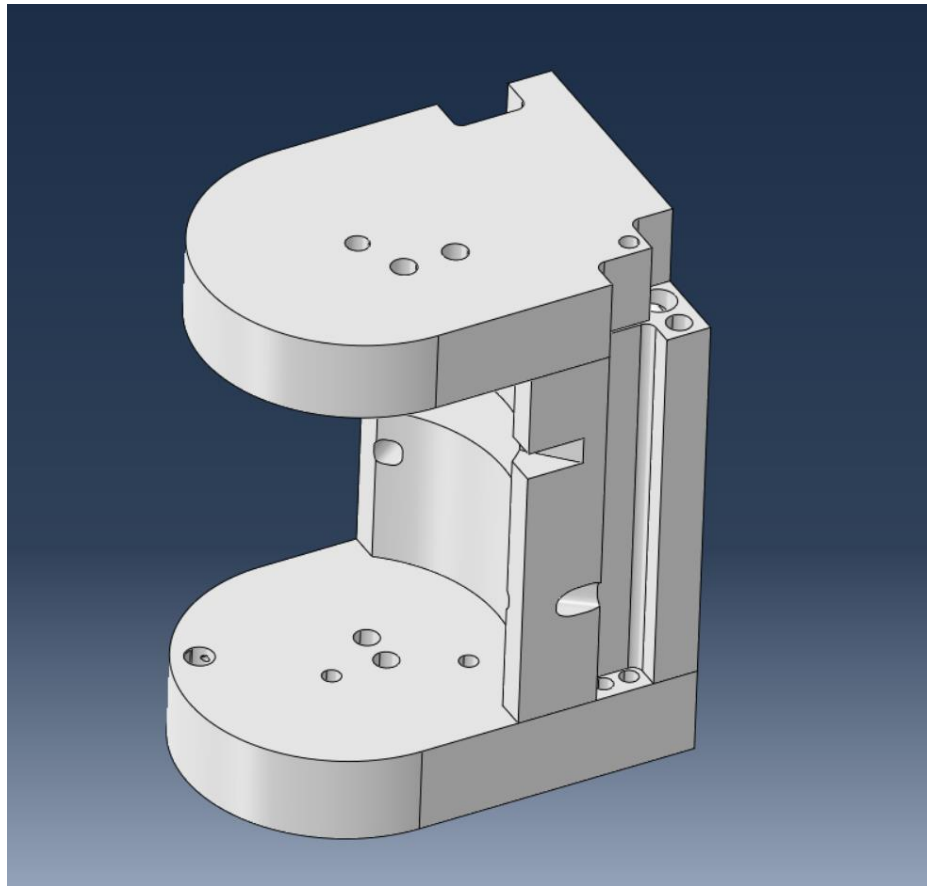




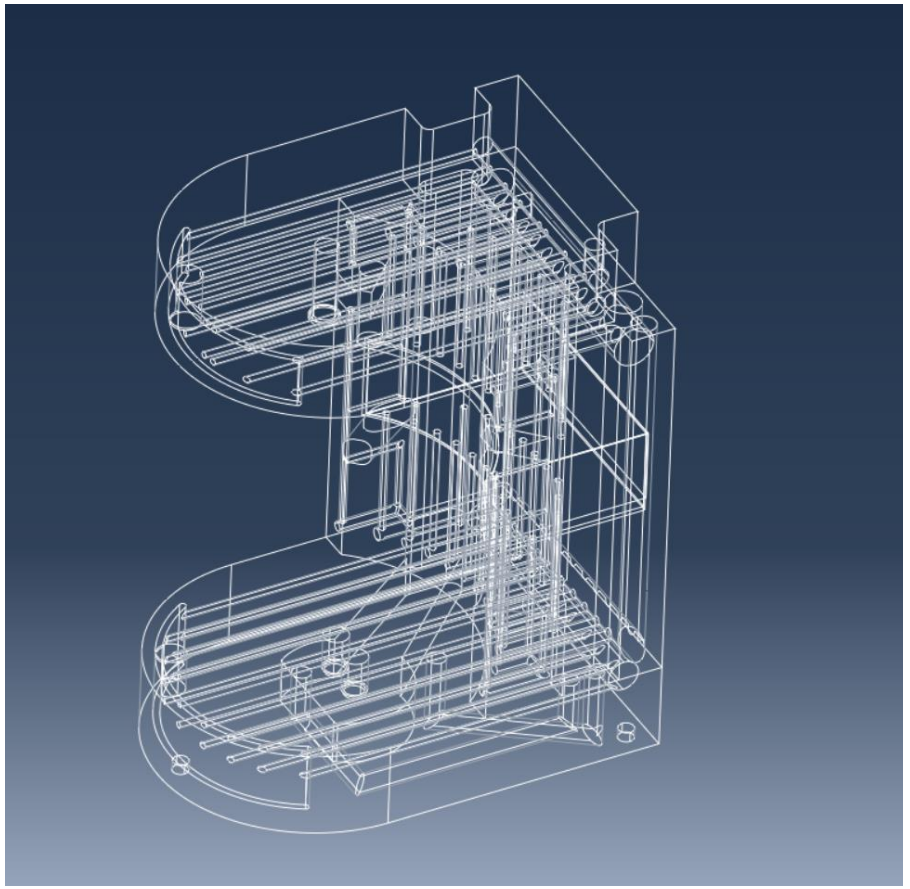


# Abaqus Model with all 3 parts merged

Full model

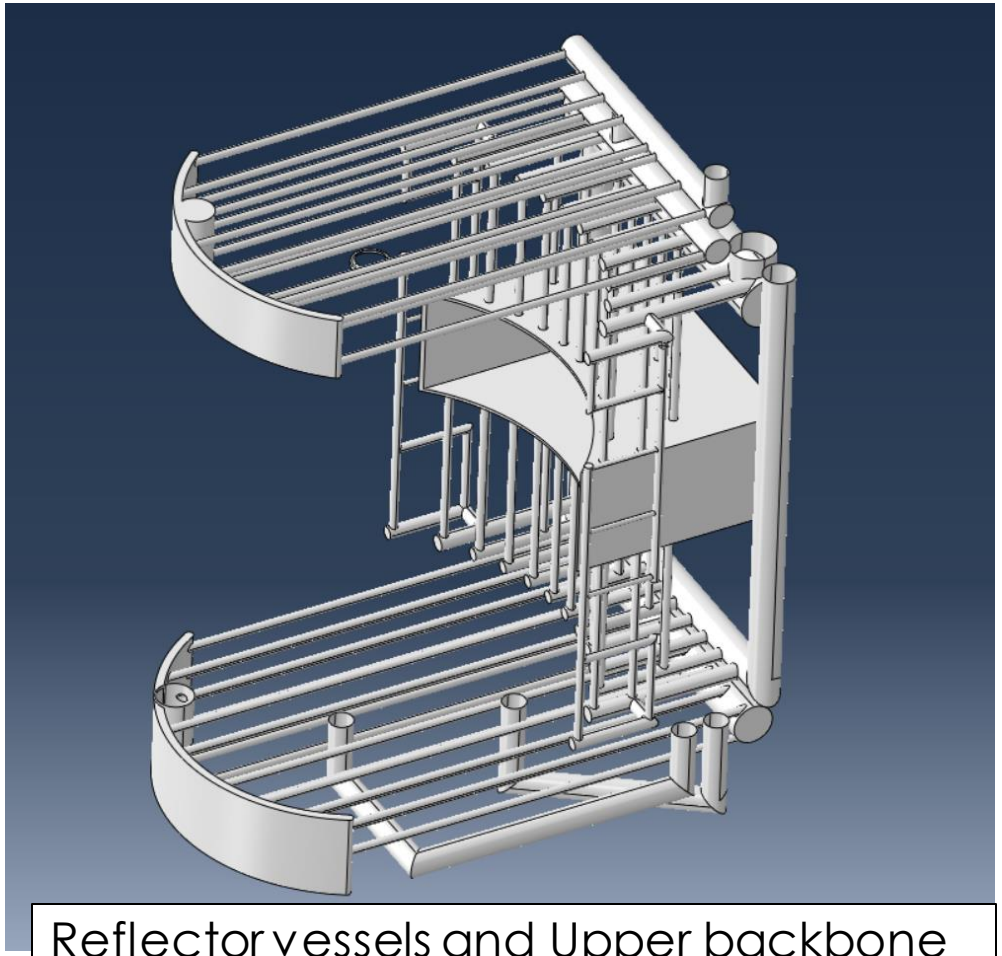


Wire Frame view showing internal passages



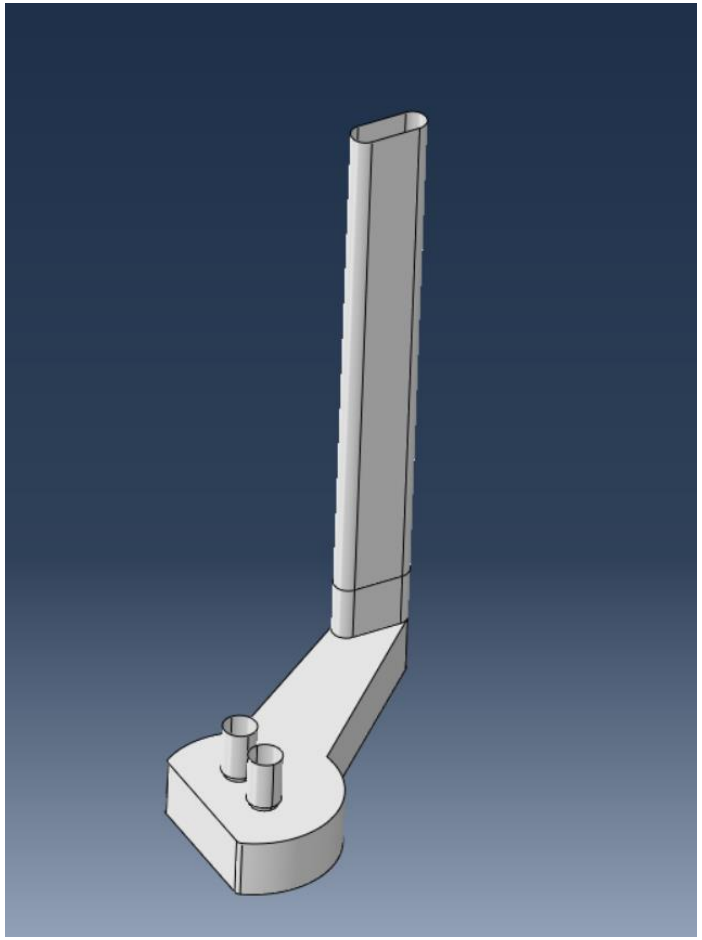
# Pressure boundary surfaces

5 Bar water surfaces



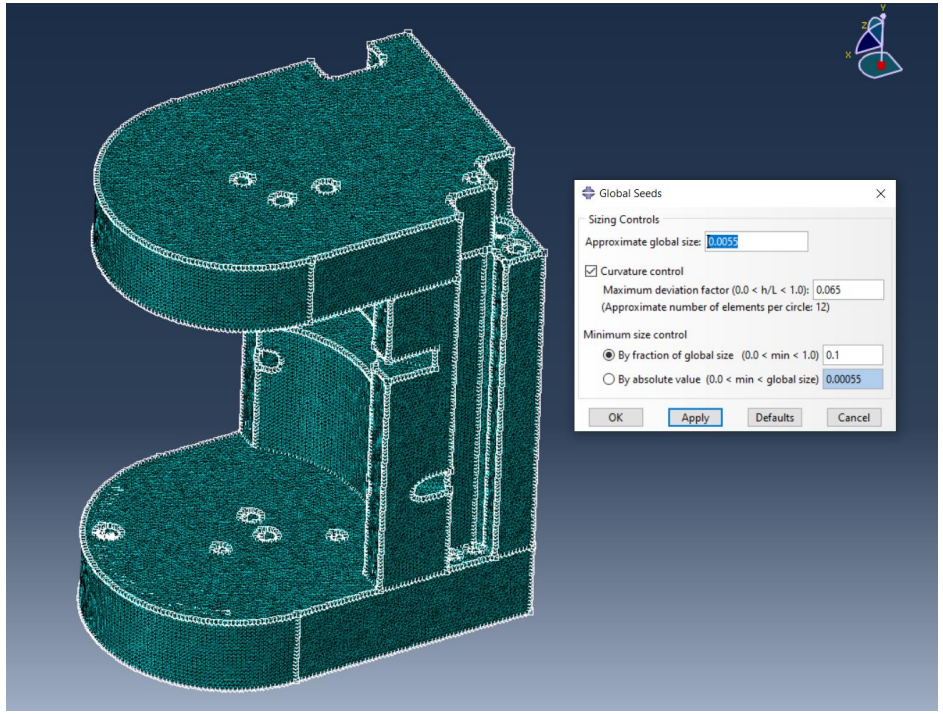
Reflector vessels and Upper backbone not included in the model so some pressure boundaries are not closed

Vacuum or 2 Bar Surface



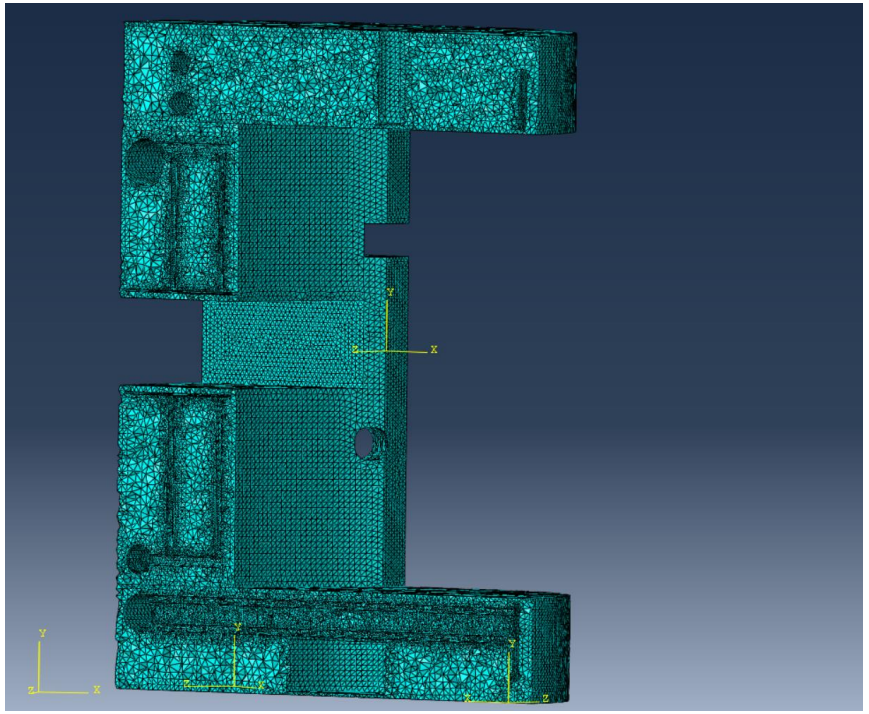
# Model Mesh with C3D10 Tet elements

Nominal 5.5 mm size with 12 elements around circles



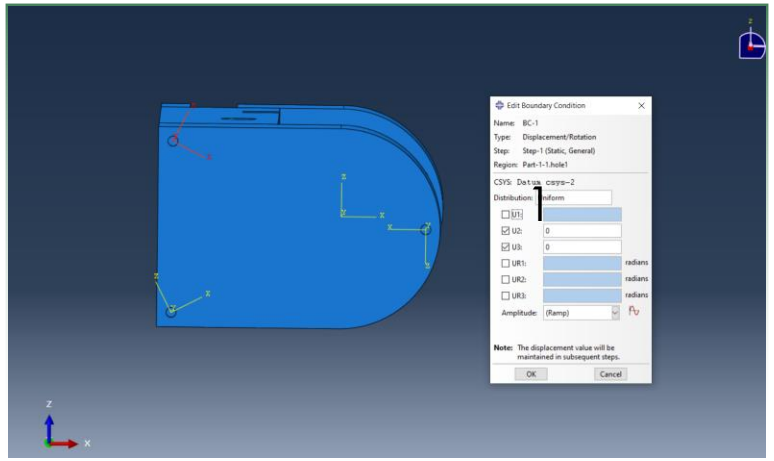

Total 3,731,555 elements

Cut near Z=0 plane

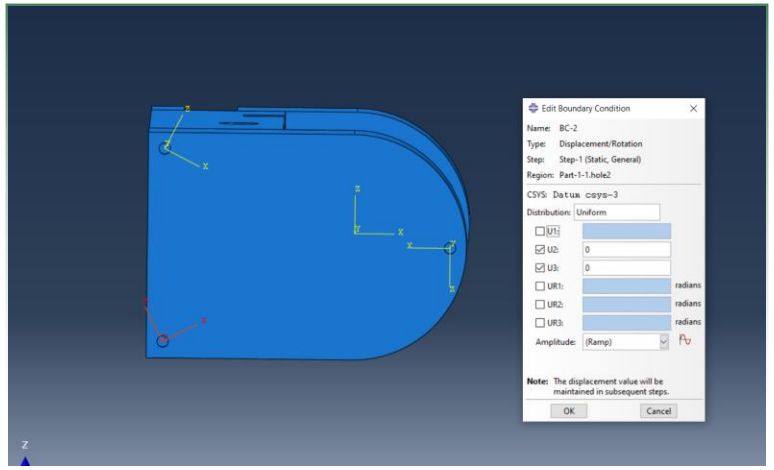


# Boundary Conditions

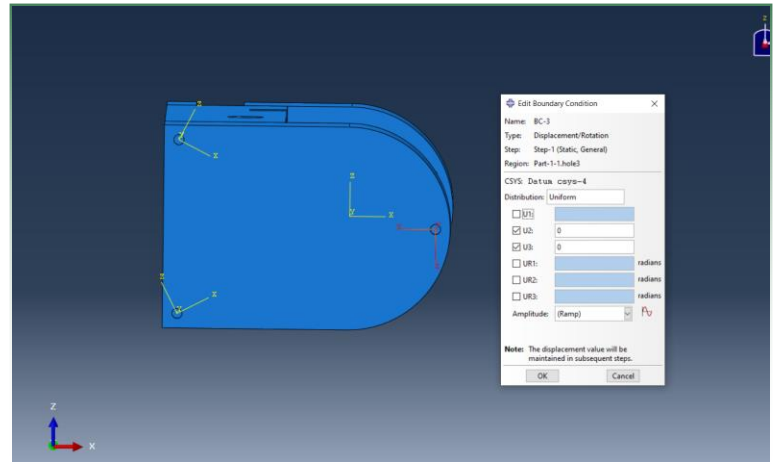
Hole 1 node constraint



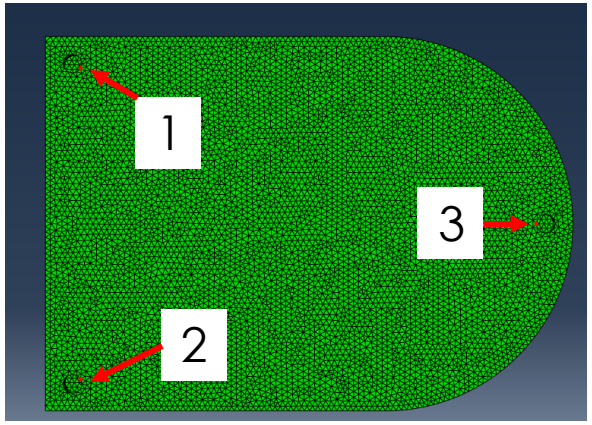

Hole 2 node constraint




Hole 3 node constraint

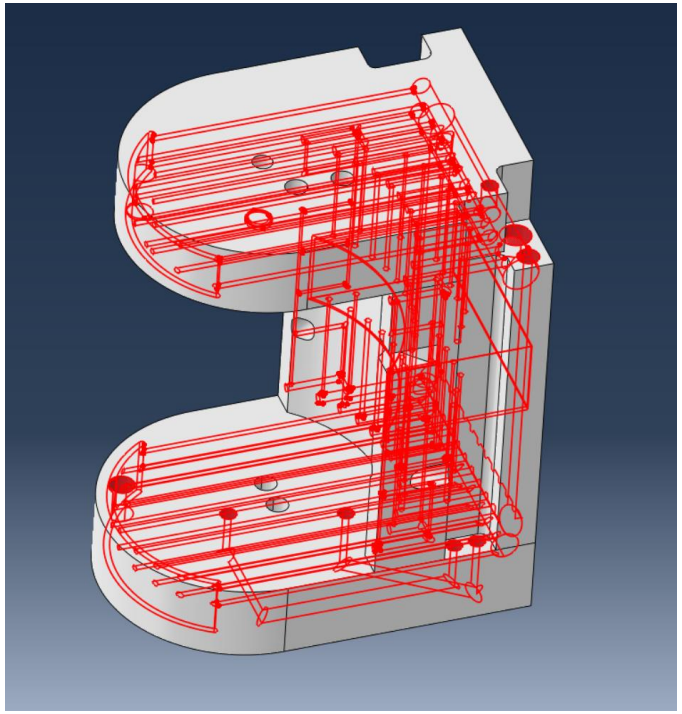



- Boundary condition to simulate "V" groove restraint on pins in holes to force displacement in direction of central axis
- Fixed vertically at the 3 nodes
- Applied to one node on bottom surface of each hole

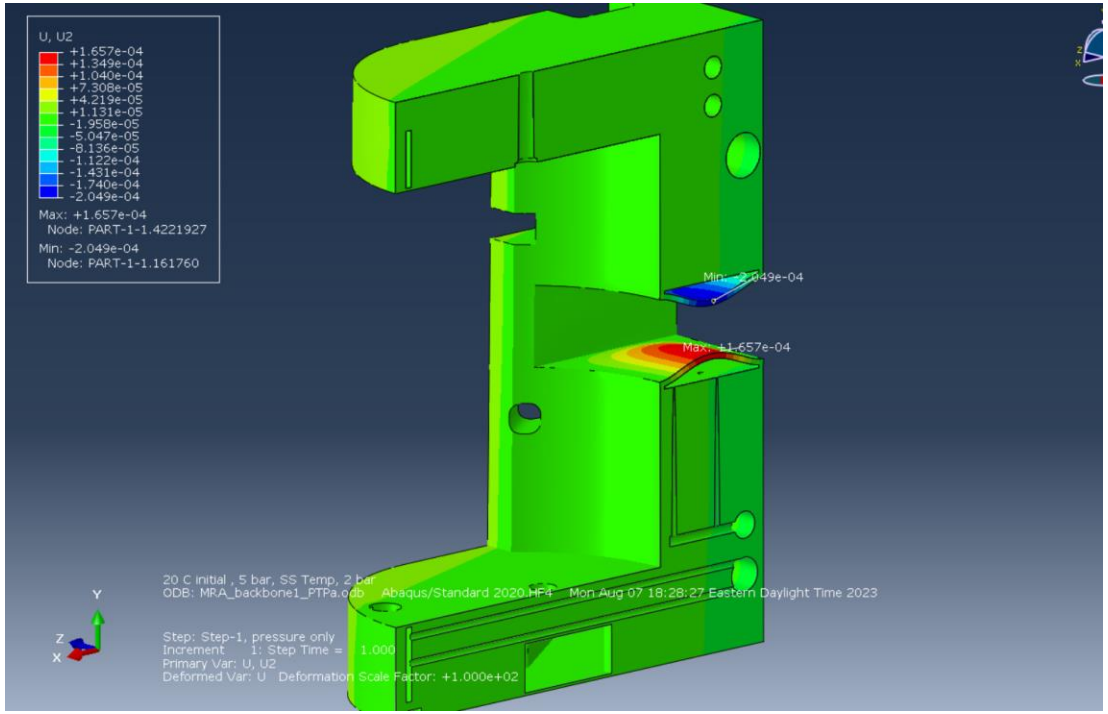


# Results with 5 bar pressure and all nodes at reference temperature of 20 C

Assembly with 5 bar load applied

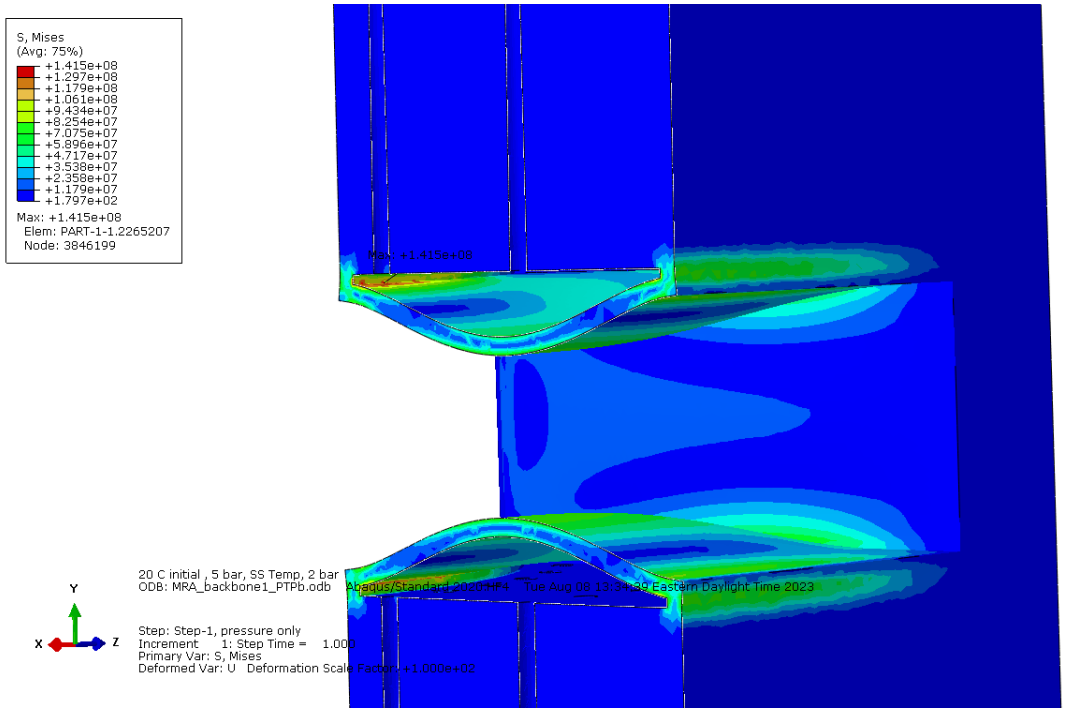


Vertical displacement - peak ~ 0.2 mm on thin walls by Proton Beam channels

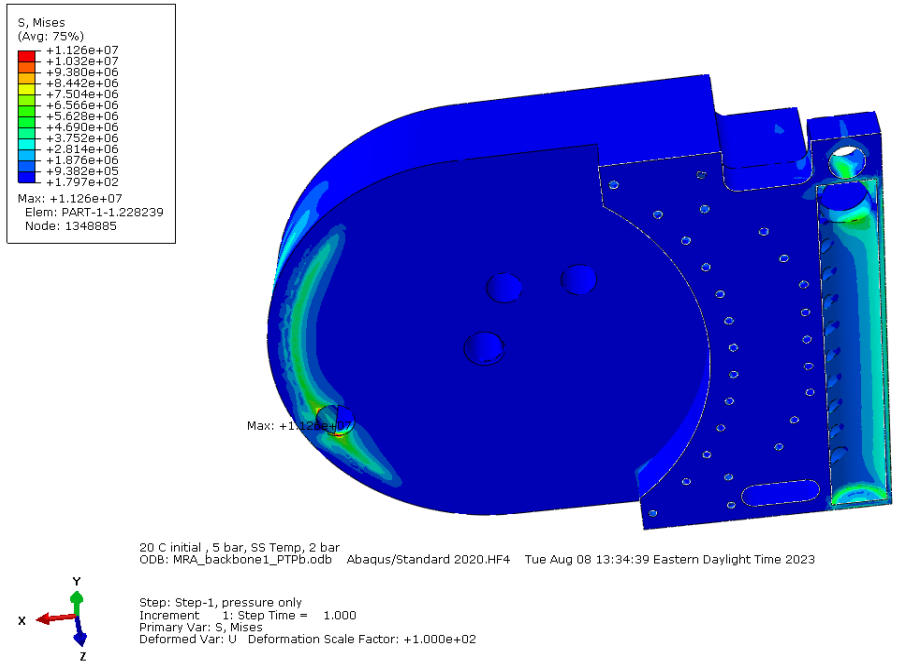


# 5 bar Pressure only results

S Mises 141 MPa peak by thin wall edge

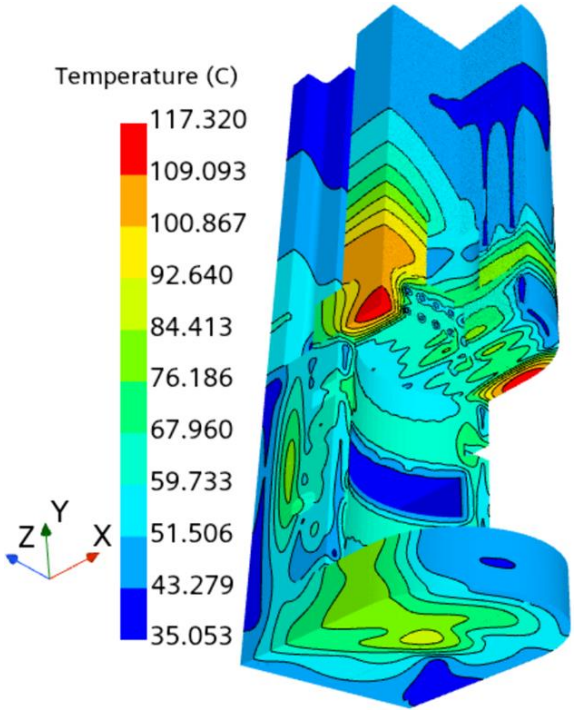



Stresses in Top zone low ~ 11 MPa

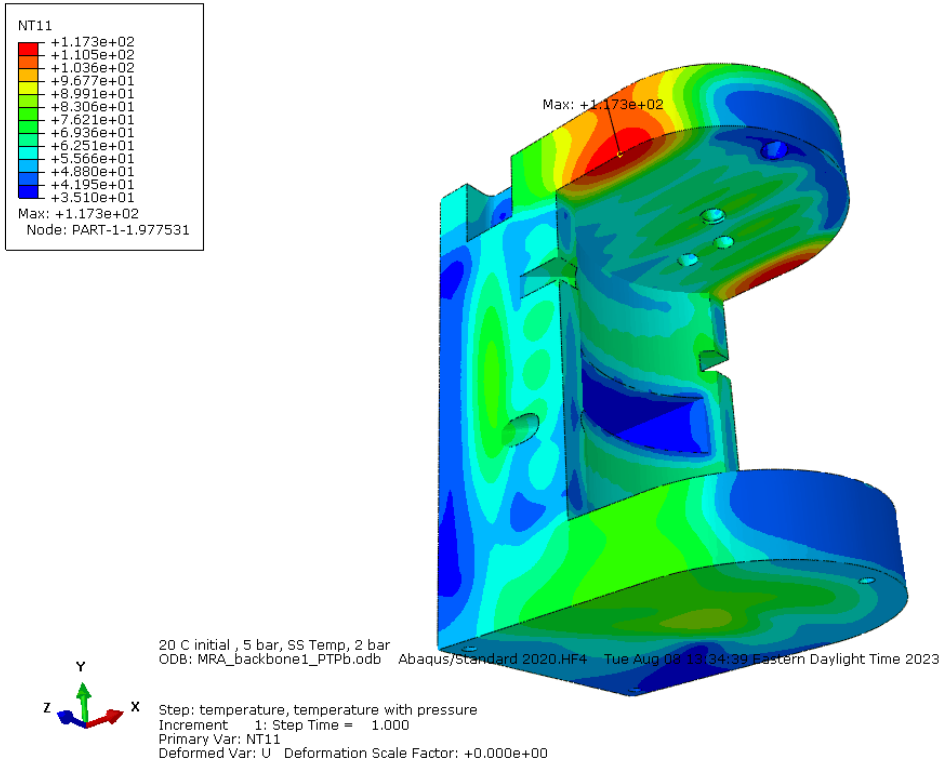


# Temperature Profiles

Full Backbone Temperature profile with 0.1mm helium gap



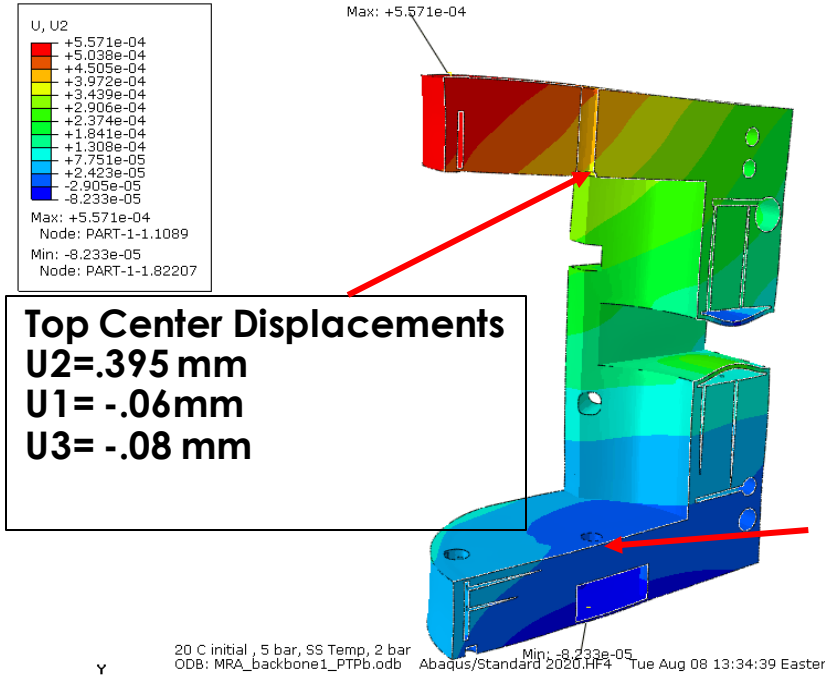

Abaqus Mapped Temperatures – 117 C peak




M.Kao, 7/25/23 CFD Model update

# Temperature and 5 bar Pressure

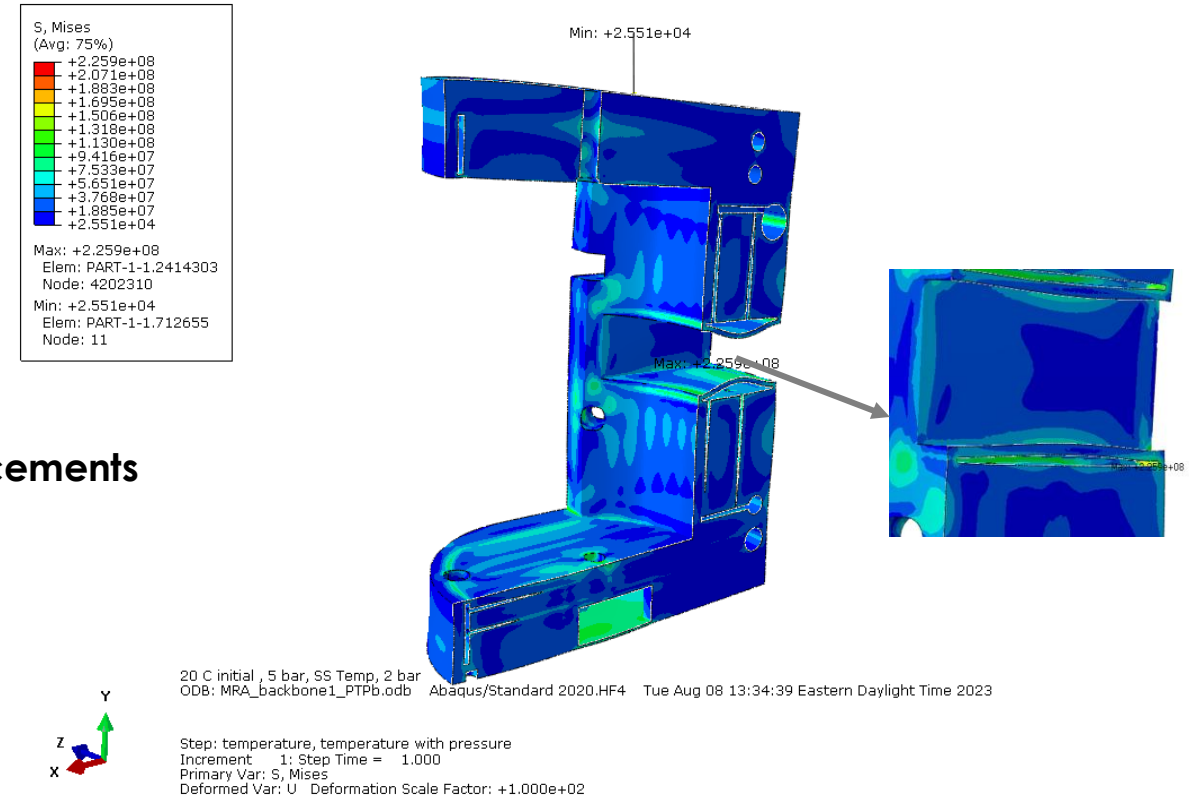
Vertical Displacement < 0.5 mm on axis on upper zone




**Top Center Displacements**
**U2=.395 mm**
**U1= -.06mm**
**U3= -.08 mm**

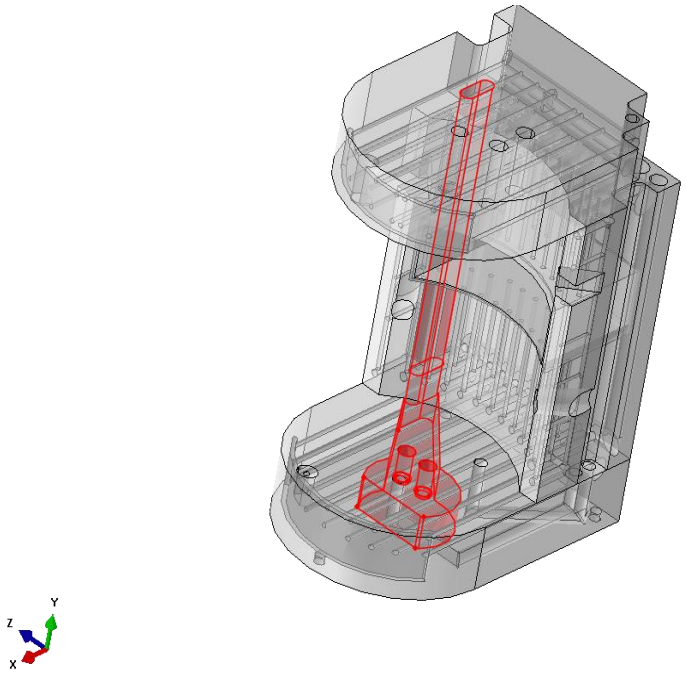
**Bottom Center Displacements**
**U2=.009 mm**
**U1= .02mm**
**U3= .001 mm**

Peak Von Mises peak stress 226 MPa in sharp corner by proton beam opening

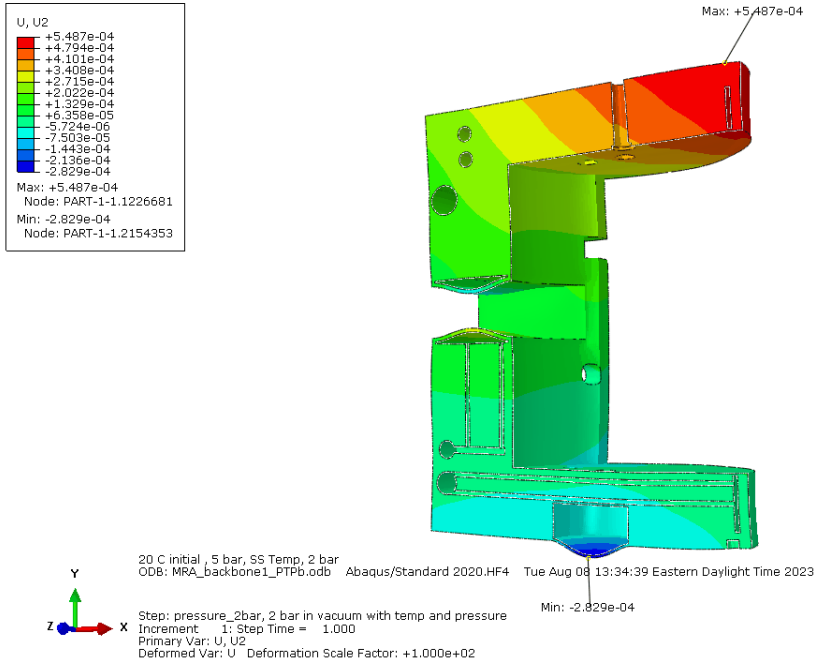


# 5 bar , Temperature Distribution and 2 bar pressure

Model with additional 2 bar pressure




Vertical Displacement – additional 0.28 mm on lower surface moderator zone not changed



# Backbone Results

- Top center reflector vessel mounting surface peak deflection was 0.4 mm on axis with temperature profile and 5 bar internal cooling pressure compared to a limit of 0.5 mm
- Bottom center reflector vessel mounting surface peak deflection was approximately 0.02 mm
- Peak Von Mises stress in thin wall section by beam opening was 141 MPa with 5 bar internal stress
- Peak stress of 226 MPa at localized corner near beam opening
- 2 bar pressure in vacuum region from hydrogen release did not change mounting surface deflection

# Backbone Summary

- Center mounting surface deflections for normal operation due to water pressure and the temperature profile are below the 0.5 mm limit
- Final design will adjust cooling pattern to reduce rotation of top reflector
- Peak stresses for normal operation are around the thin proton beam channel wall at a sharp corner. Peak model value was 226 MPa but this was at a singularity location and no mesh refinement was attempted.
- Final design is expected to improve proton beam tube region by adding corner radii and increasing wall thickness to reduce high stresses
- Final design is also expected to include kinematic mounts and improve other regions to reduce high stresses
- The 2 bar pressure excursion stress on the lower surface was approximately 200 MPa and the mounting location deflections were not affected by this pressure release