

Second Target Station Project: Structural Analysis of the Moderator Reflector Assembly



T. McManamy

July, 2026



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Second Target Station Project

MRA Analysis

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July 2026

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LIST OF ACRONYMS

ASME/BPVC	=	American Society of Mechanical Engineers Boiler & Pressure Vessel Code
DAC	=	Design Analysis Calculation
FEA	=	Finite Element Analysis
FOS	=	Factor of Safety
FTS	=	First Target Station
OS	=	Operating System
PLM	=	Product Lifecycle Management
QA	=	Quality Assurance
UTS	=	Ultimate Tensile Strength
bar / bara	=	Atmospheric Absolute pressure

ABSTRACT

This is a structural analysis for the STS Moderator Reflector Assembly components not including the cryogenic moderators and transfer line sections which are cooled to cryogenic temperatures and external piping. The analysis evaluates the stresses based on the applicable ASME Boiler and Pressure Vessel Code cases including preloads, gravity, pressures, temperatures and seismic loads. Screening for buckling and for fatigue from thermal stress due to beam trips is also included. Deflections critical for alignment are evaluated.

1. INTRODUCTION

The Second Target Station (STS) is optimized to produce high brightness cold neutron beams by closely coupling a rotating tungsten spallation target to 2 compact 20 K liquid hydrogen moderators. The liquid hydrogen moderators are located within the Moderator Reflector Assembly (MRA) and are composed of aluminum hydrogen vessels which are filled with liquid hydrogen and surrounded by vacuum vessels to provide vacuum insulation. The upper hydrogen vessel is cylindrical while the lower hydrogen vessel is an arrangement of three tubes in a triangle pattern. The vacuum pumping for the vacuum insulation is provided by the Cryogenic Moderator System, along with overpressure protection at 2 bara. The vacuum vessels are integral to and surrounded by the reflector vessels, which contain premoderator water zones and beryllium reflectors for improving neutron performance. The reflector vessels are supported by a water cooled stainless steel backbone which is designed to minimize thermal deflection associated with heating from proton beam operations. The water for cooling the reflector vessels and backbone is supplied by Target Process Systems at a normal operating pressure of 3 bara with overpressure protection at 5 bara.

The structural integrity of the MRA vacuum vessels, reflector vessels, and backbone is required for stable STS operations. The vacuum vessels must be able to hold insulating vacuum in order to maintain liquid hydrogen in the hydrogen vessels. Additionally, the vacuum vessels structural integrity at 2 bara relief pressure is required for venting of hydrogen in the unexpected case of hydrogen leaks into the vacuum space. The reflector vessels and backbone must maintain structural integrity to prevent leaks of water into the surrounding core vessel to prevent damage to surrounding equipment. Therefore, the MRA vacuum vessels, reflector vessels, and backbone will be designed to the intent of the ASME BPVC Section VIII, Division 2 in order to ensure their structural integrity. The vacuum and reflector vessel designs have been optimized to provide high brightness cold neutrons while still meeting the requirements of Section VIII, Division 2 and allowing robust fabrication. The elastic stress analysis methods of the design by analysis method were selected to demonstrate the compliance of the MRA vacuum vessels, reflector vessels, and backbone with the ASME BPVC and these analyses are documented herein.

In addition to the structural integrity requirements, the MRA operating deflections must be minimized to ensure optimal neutron performance and prevent interactions with surrounding structures. The compact STS moderators require precise alignment to the neutron instruments, which would be negatively impacted by excessive deflection. Therefore, the deflection of the hydrogen vessel mounting points is limited to 0.3 mm or less under normal operating conditions. In order to prevent interactions with surrounding core vessel and target assembly equipment, the deflections of the MRA are limited to +/- 1.5 mm under all expected loading conditions.

2. ASSUMPTIONS

The following conditions were assumed:

- Unirradiated material properties with a 20 °C reference temperature
- The core vessel environment could be vacuum or 1 bar helium
- Elastic material properties used for ASME BPVC code stress calculations
- Al6061T6 weld properties assumed within 5 mm of nominal joint
- Elastic-plastic aluminum properties used for Buckling stability analysis
- Nominal 700 kW beam operation
- No interaction with hydrogen vessels and transfer lines and surrounding structures
- 1e4 beam trips per year

3. PHYSICAL MODEL DEFINITION

3.1 GEOMETRY

The step file assembly mra_am_001struct2 was the basis for the analysis and the parts were imported into Abaqus. A revised middle backbone step file was imported in 2026 which included models of the welds to the upper and lower backbones. Most cover plates in the backbone parts which would be welded were merged. The moderator hydrogen system parts were not included in the Abaqus model. In 2026 minor modifications to the upper reflector vessel were also made and a new step file was imported for it. Where possible, parts were merged. One example was for the bimetal connections to the reflector vessels. These were merged with the aluminum reflector vessel shell, but the cell boundaries were retained so that the steel and aluminum materials could be applied to the separate cells. The upper reflector water jumper connection had bad step file geometry, and a separate step file was imported for it. Simplified models of the bolts and tie rods were made to avoid trying to model the threaded regions. Separate step files with these parts were also imported. Piping and tubing were not included except for the transfer line vacuum cover shell connected to the backbone and for the water jumper on the upper backbone. Thermal profiles from the CFD analysis were imported. Higher resolution CFD models for the backbone parts were used and a lower resolution model for the whole assembly applied to the remaining parts except for the seismic block on the top of the upper shielding. A uniform temperature to match the local shielding temperature was applied to that part which was not included in the CFD analysis. The analysis was done for the MRA assembly without the beryllium parts. These are not mechanically attached to vessels and were analyzed separately. Separate reflector vessel models were made for a buckling evaluation including elastic-plastic aluminum material properties,

The principal assembly step files are shown in Figure 1 and Table 1. These are included in the data files associated with this analysis

<https://ornl.sharepoint.com/sites/sts/targetsystems/Shared%20Documents/Forms/AllItems.aspx?id=%2Fsites%2Fsts%2Ftargetsystems%2FShared%20Documents%2FS%2E03%2E02%20Target%20Assembly%2F99%5FSANDBOX%2FMCMANAMY%2FMRA%5F2026%2Fmra%5F2026%5FDAC%5Fdata&viewid=9be9bc88%2D5a13%2D48c7%2D9fff%2Dd22f94ffdeb5&csf=1&cid=939335e4%2D4ccc%2D4c00%2Da2d2%2D814c53b7125a&FolderCTID=0x01200064187E8E25420543ACAD0BF1C3490EAC>

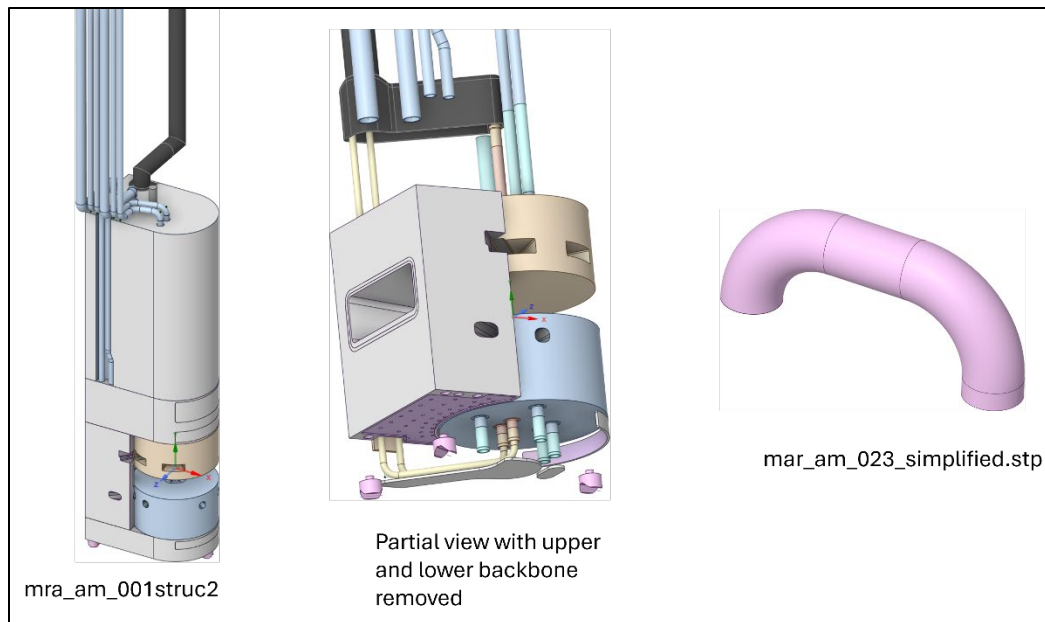


Figure 1 Assembly typical Step Files

The stainless-steel backbone assembly is to be made in three parts, upper, middle and lower with nominal 6 mm welds connecting them. Analysis showed that the joint could have a fatigue problem if there was a geometric discontinuity at the weld. A modified middle backbone step file was made which included the portion of a full penetration weld near the reflector vessels above the surface of the lower backbone which would be formed after welding and surface smoothing. The original step files for the three parts are shown in Figure 2.

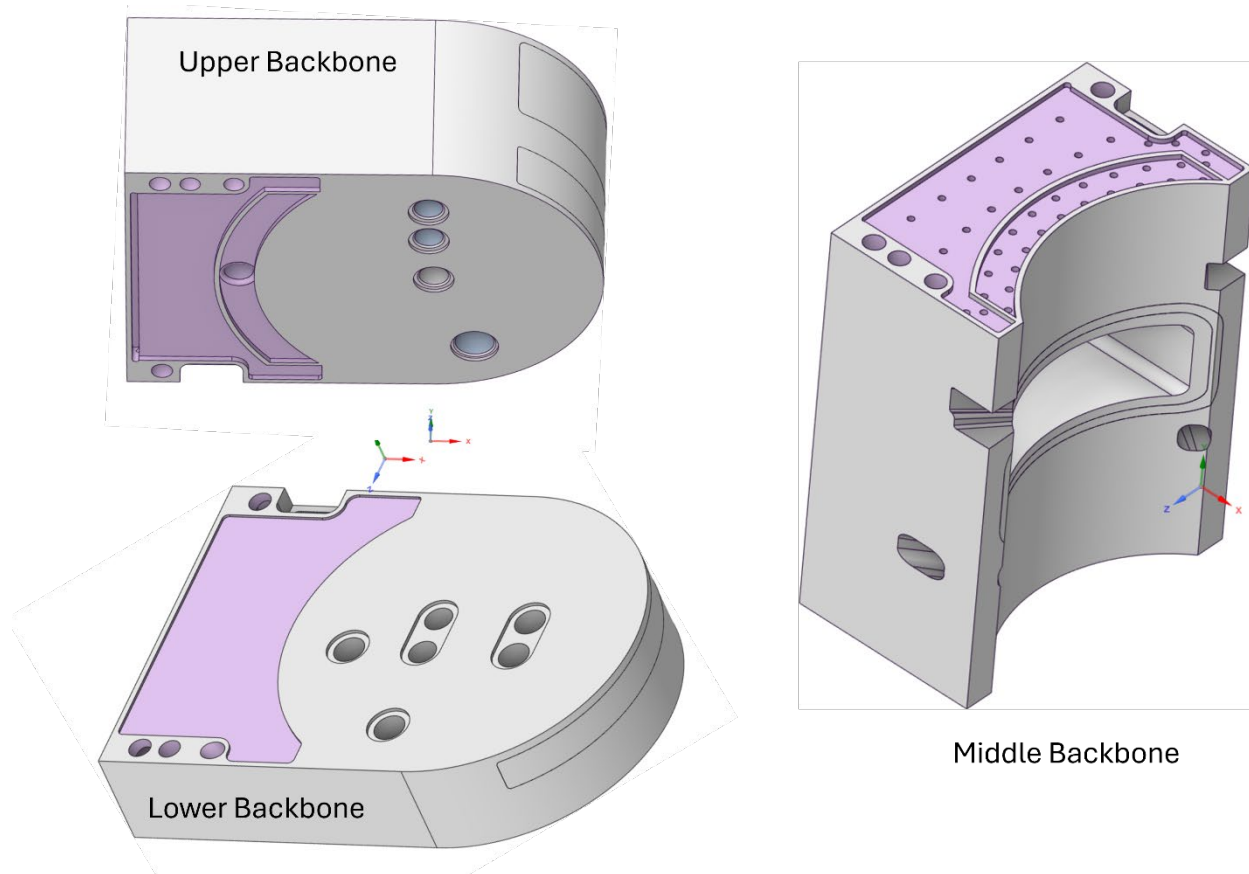


Figure 2 Backbone original step files

The modified Middle Backbone is shown in Figure 3 with the welds as they would be ground smooth after fabrication.

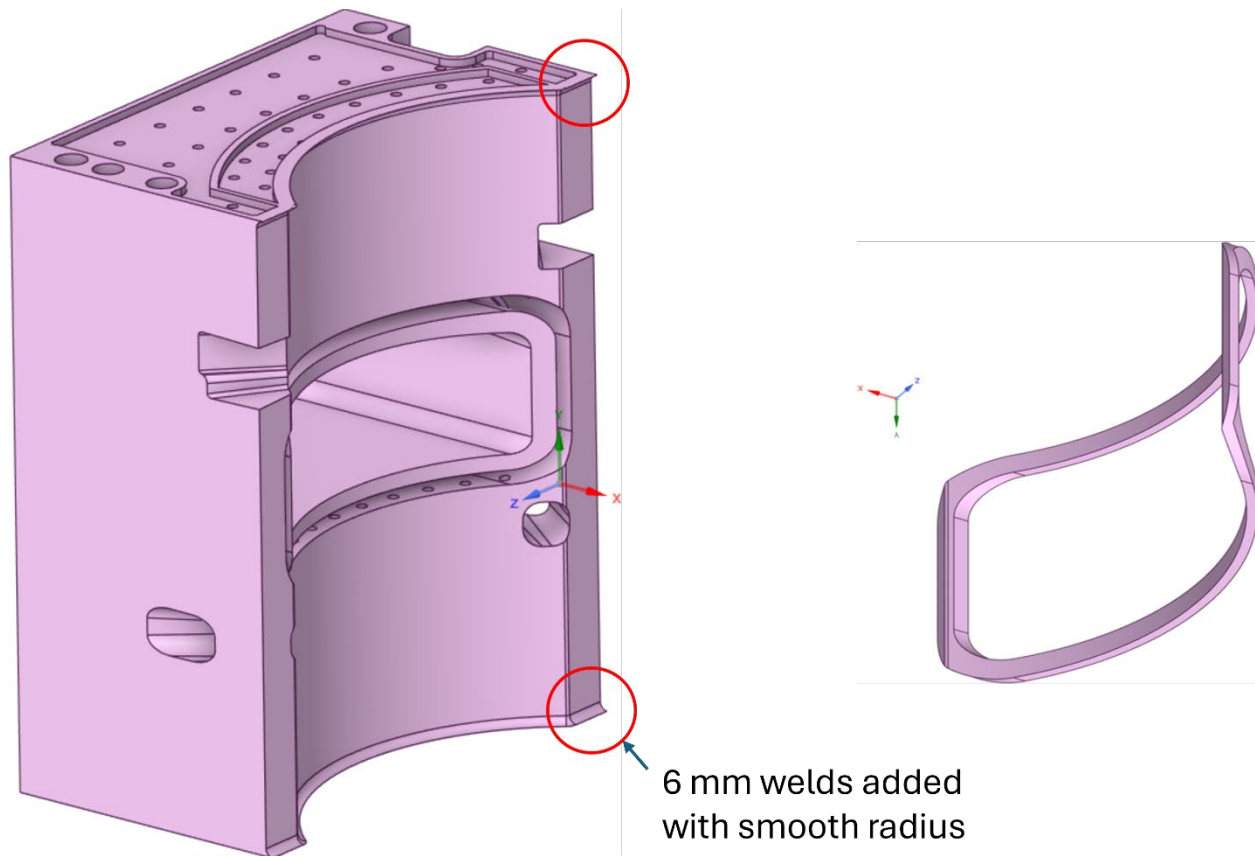


Figure 3 Modified Middle Backbone with welds

The PDR design had raised surfaces around the water channel joints between the middle backbone and the upper and lower backbones as shown in Figure 4. To allow full penetration welds between sections these raised sections were removed for final design with flow restrictions to be provided by sleeves inserted in the flow channels. These are not included in the Abaqus model. There are also flow baffles to separate flow in the region between the middle backbone and upper backbone as shown in Figure 5. The sections from the upper and middle backbone flow baffle are not welded together. The Abaqus model added a 1 mm gap in the baffle so the baffle sections would not merge and could not carry loads across a joint. This is also shown in Figure 5 along with a section through the merged regions which represent the full penetration weld which is 6 mm all around except where the welds near the reflector vessels extend to 12 mm with smoothing of the outer surface.

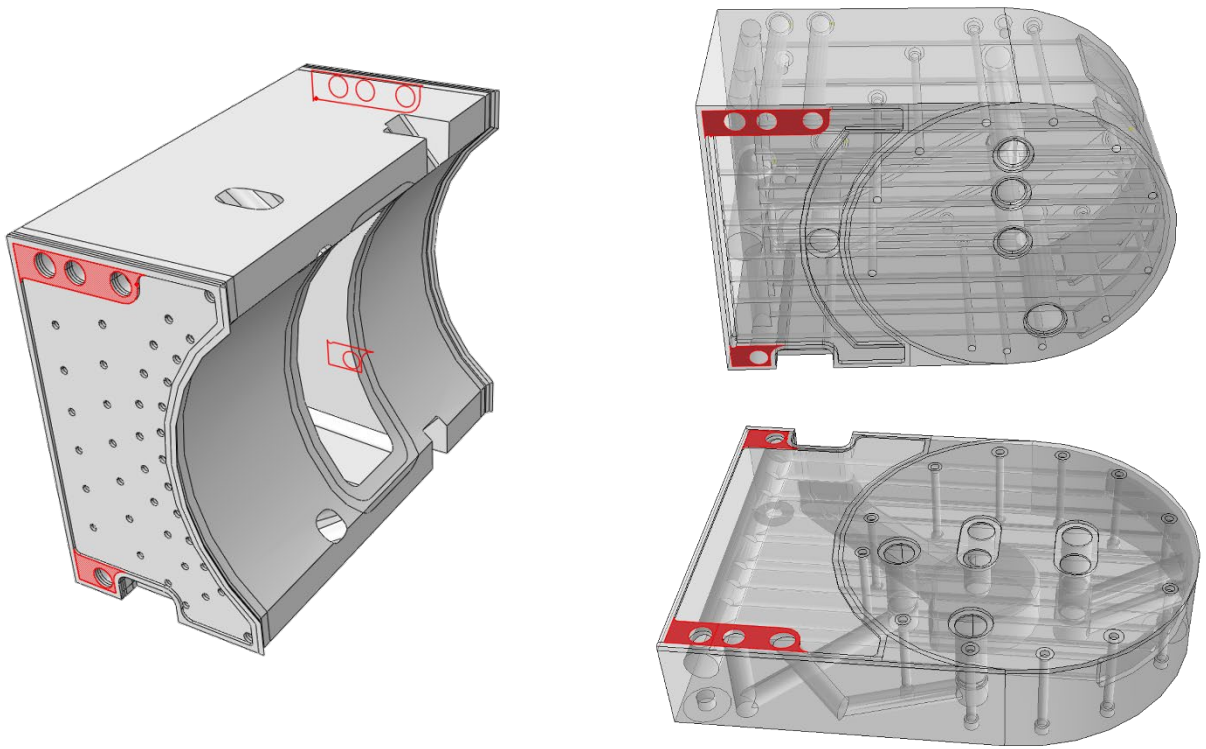


Figure 4 PDR backbone flow restriction raised surfaces by water channel joints

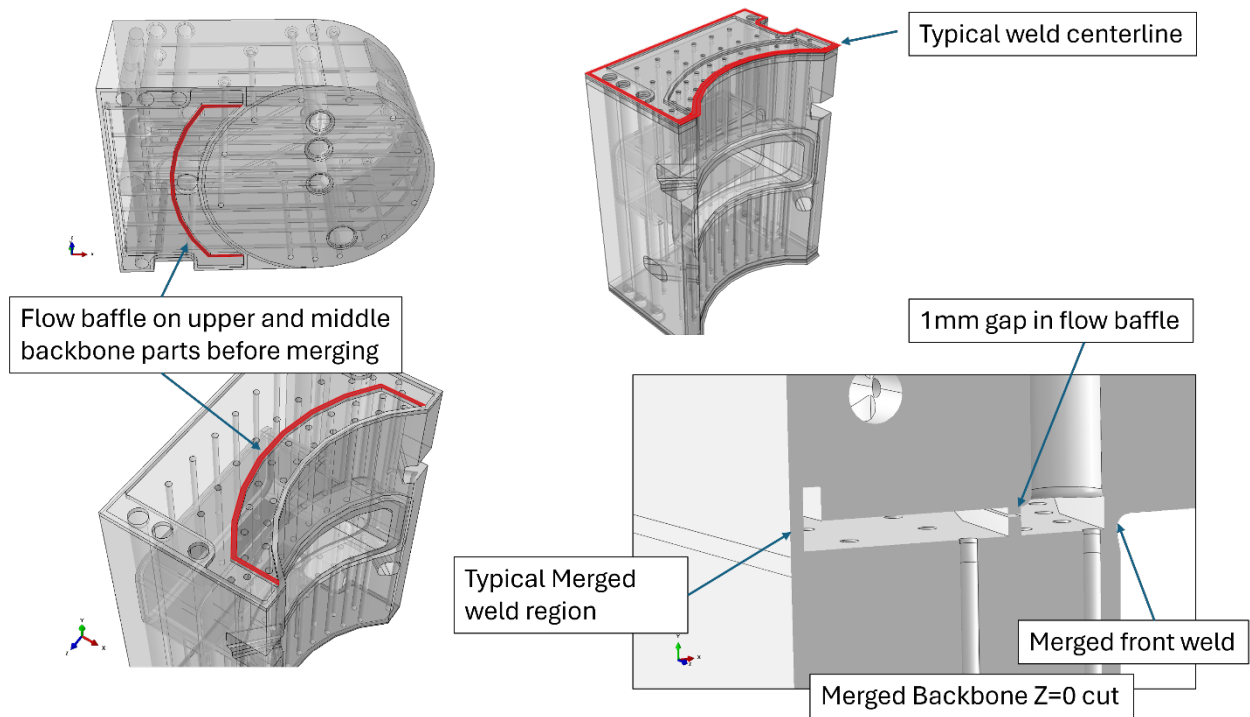


Figure 5 Flow baffles and merged backbone Z=0 cut

The merged part (backbone_all) is shown in Figure 6 with several view cuts to show welded regions.

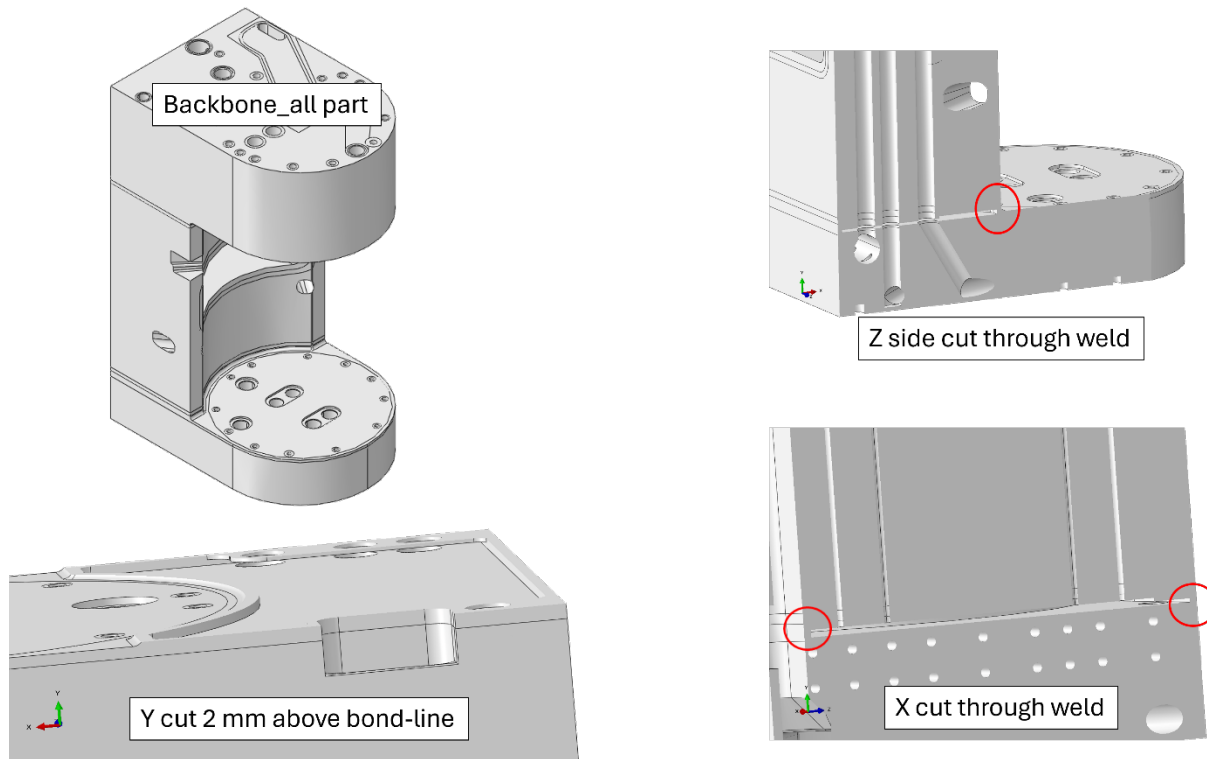


Figure 6 Merged Backbone part.

The merged assembly parts are shown in Figure 7. Figure 8 shows the upper and lower reflector vessels and the vacuum boundary within them. Also shown are the beryllium parts within the reflector vessels. These are not mechanically attached to the aluminum structure and are analyzed separately from the main assembly. The assembly parts included the upper shielding and cover plate, backbone and cover plates, the upper and lower aluminum reflector vessels without the hydrogen system components, the bolts and tie rods and the three lower mounts which would connect to the core vessel shielding. The vacuum transfer cover attached to the backbone is included but the vacuum tubing above will be analyzed in a separate analysis. The 24 bolts and 4 tie rod models are shown in Figure 9

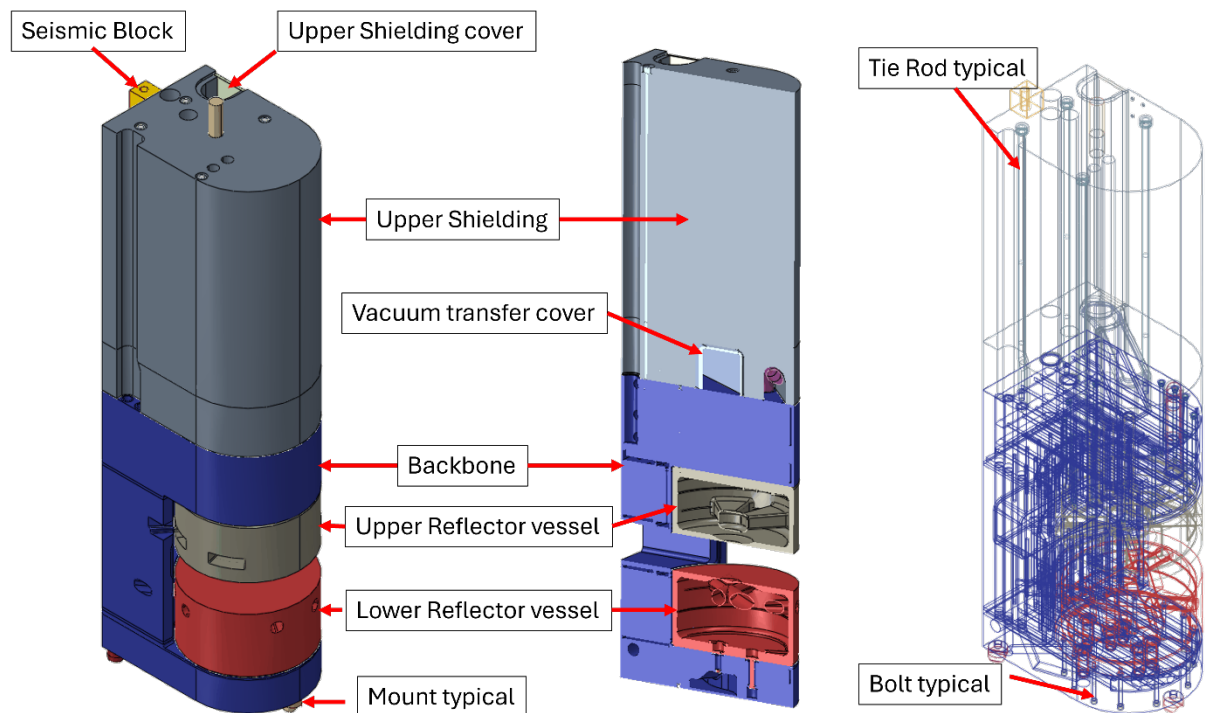


Figure 7 Assembly with merged parts – beryllium shown but analyzed separately

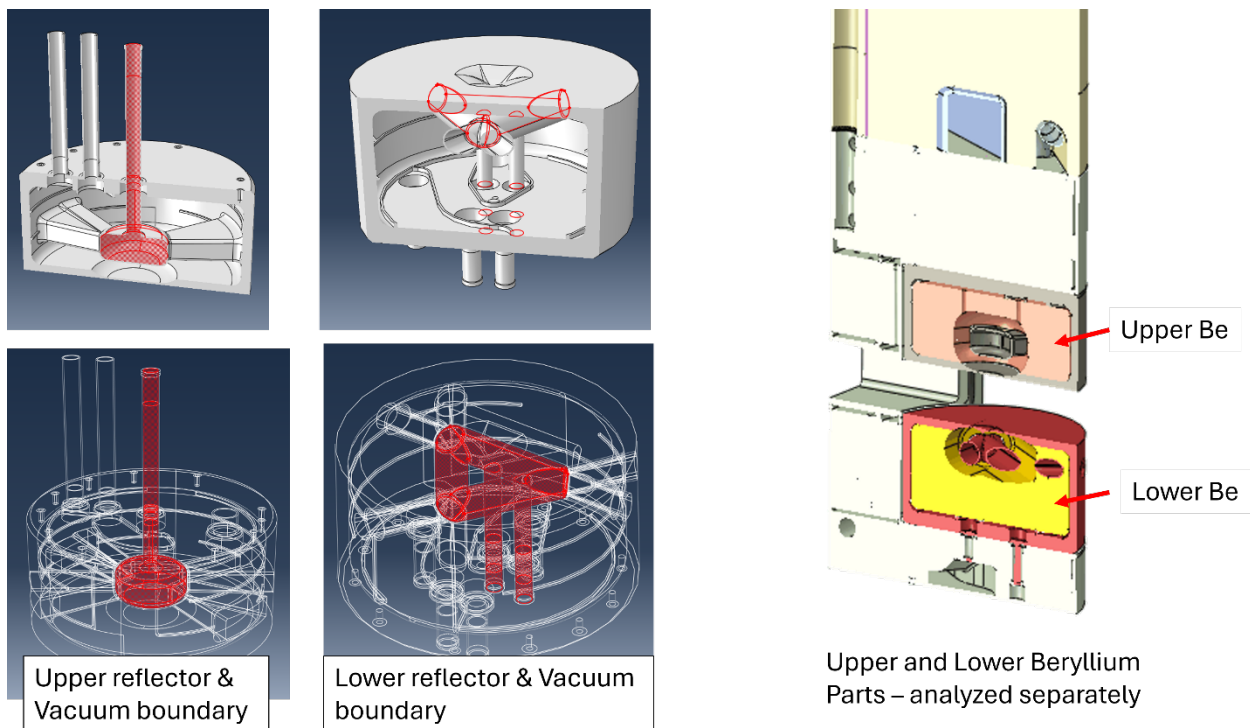


Figure 8 Reflector vessel vacuum boundaries and beryllium parts

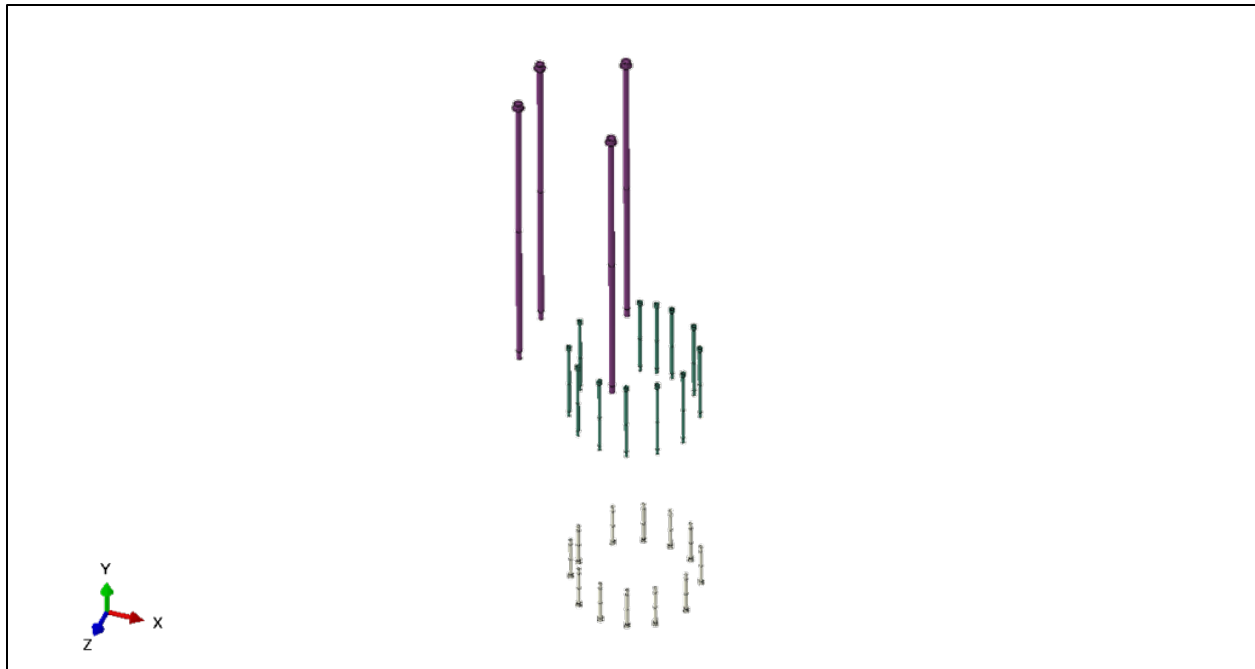


Figure 9 Four tie rods and 12 upper and 12 lower bolts

Table 1 MRA Step Files

Name	Description
mra am 001 TM.stp	Overall assembly
mra am upper reflector a.stp	Upper Reflector Vessel revised 2026
mra am 023 simplified.stp	Water Jumper with merged parts
mra am 021a rounds.stp	Middle backbone with welds
mra am 021c rounds.stp	Middle backbone welds around Proton beam port
mra am 121b.stp	Revised seismic block

3.2 MATERIAL PROPERTIES

3.2.1 Thermostructural Properties

The materials in the model included A36 steel for the upper shielding, aluminum 6061T6, stainless steel 316L and beryllium. The tie rods and 24 bolts were also 316L but used a material name “bolt steel” to help identifying them when post processing results. Elastic properties were used for the stress analysis evaluations. Elastic plastic properties were used for buckling analysis of the aluminum reflector vessels. The elastic properties are given in Table 2.

Table 2 Material Elastic Properties

Material	Density (kg/m ³)	Young's Modulus (GPa)	Poisson's ratio	Expansion Coefficient (m/K)	Reference Temperature °C
A36 Steel	7850	200	.26	11.7 x 10 ⁻⁶	20

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Aluminum 6061T6	2700	68.9	.33	23.6×10^{-6}	20
Beryllium	2160	303	.24	11.5×10^{-6}	20
316L	7969	195	.27	16.1×10^{-6}	20
Bolt Steel	7969	195	.27	16.1×10^{-6}	20

3.2.2 ASME BPVC Stress Intensity Limits

For ASME BPVC Section VIII Division 2 [1] (and Section III) designs, the 316L (SA-240 or SA-312) stainless steel Design Stress Intensity S_m is generally 16.7 ksi (approx. 115 MPa) at room temperature.

The A36 ASME BPVC Section VIII, Division 2 (Part 5) Design Stress Intensity S_m is 16.6 ksi (approx. 114 MPa) at up to 343 °C

Aluminum Al6061 ASME BPVC Allowable Stresses were established by code case 2478-2 as shown in Figure 10. [2]

CASE 2478-2

ASME BPVC.CC.BPV.S2-2025

Table 1
Allowable Stress Values, S

Specification No.	Temper	Size or Thickness, in.	Specified Min. Tensile Strength, ksi	Specified Min. Yield Strength, ksi	Notes	Allowable Stress Values, ksi for Metal Temperature not Exceeding, °F				
						100	150	200	250	300
Die and Hand Forgings										
SB-247	Die T6	Up to 4.000	38	35	(1),(2)	12.7	12.7	12.7	12.1	10.5
	Hand T6	Up to 4.000	37	33	(1),(2)	12.3	12.3	12.3	11.7	10.3
	Hand T6	4.000-8.000	35	32	(1),(2)	11.7	11.7	11.7	11.2	9.9
	T6 wld.	Up to 8.000	24	...	(1)	8.0	8.0	8.0	7.9	7.3

NOTES:

(1) Allowable stress values for 100°F may be used at temperatures down to -452°F without additional specification requirements.

(2) The stress values given for this material are not applicable when either welding or thermal cutting is employed.

Figure 10 Al6061 ASME BPVC Code Case Stress Values

The Stress values for Al6061 Hand T6 up 4 inches at up to 200 F of 12.3 ksi or 84.8 MPa were used for this analysis. T6 welded stress value of 8 ksi or 55 MPa was used in this analysis for welded material. Heat affected zones with weld material properties are assumed to extend to within 5 mm of a weld centerline based on STS upper moderator prototype testing. [3]

3.2.3 Aluminum properties for buckling analysis

The ASME BPVC method B buckling analysis requires the use of true stress strain material curves based on material yield and ultimate strength. The methodology of Section 3-D.3 was used to obtain stress strain curves for Al6061T6 and Al6061T6 as welded. ASME case 2478-1 defined yield and tensile strengths of 33 ksi (227.5MPa) and 37 ksi (255.1 MPa) respectively for the T6 condition with hand T6 up

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to 4 inch thickness. The welded condition had a tensile strength of 24 ksi (165.5 MPa) but no yield strength was defined. A conservative bounding case assumption of 8 ksi (55.2 MPa) was used for the welded yield strength. The resulting stress strain curves are shown in Figure 11. These were calculated in the Excel files **Al6061_T6_weld_8ksi** and **Al6061_T6_weld_plastic**.

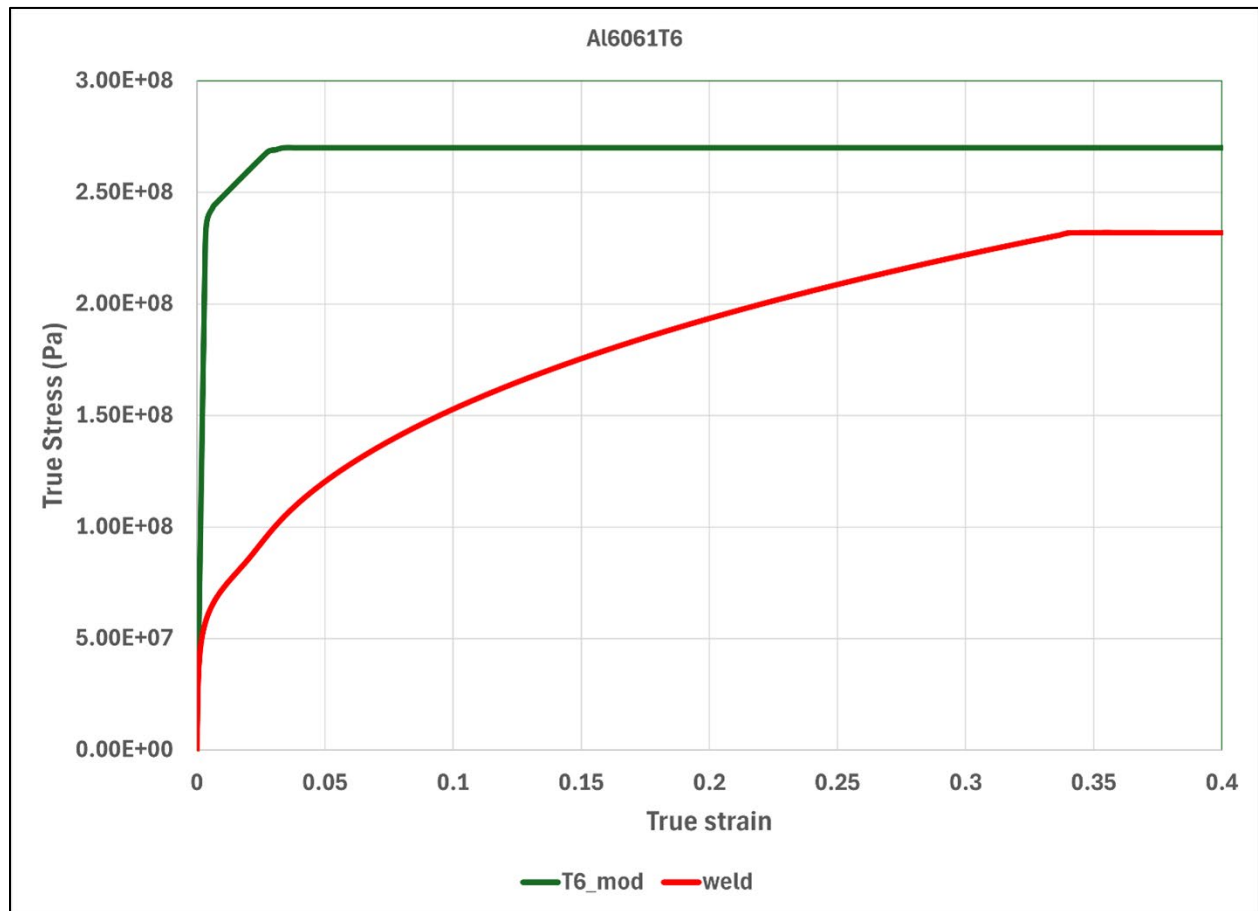


Figure 11 Al6061T6 True Stress – Strain

The ASME method for calculating the curve for the T6 condition gave some double value results between 244 MPa and 268 MPa and those points were not included.

3.2.4 Fatigue Properties

Fatigue properties for Al6061T6 are shown in Figure 12 from the ASME BPVC code case.

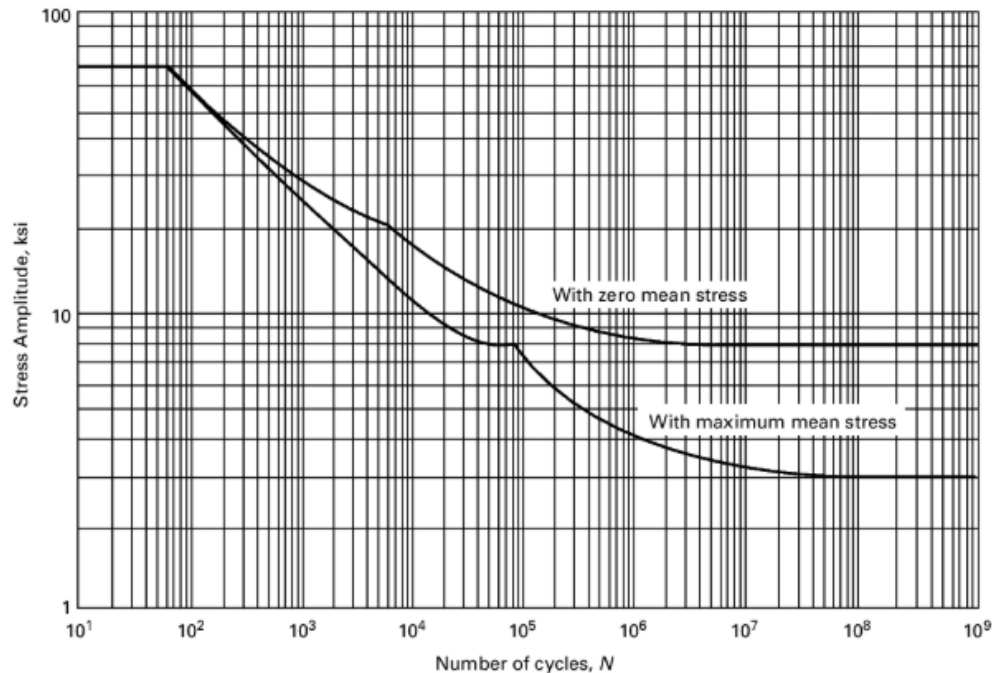
Table 1
Allowable Stress Values, S

Specification No.		Temper	Size or Thickness, in.	Specified Min. Tensile Strength, ksi	Specified Min. Yield Strength, ksi	Notes	Allowable Stress Values, ksi for Metal Temperature not Exceeding, °F				
							100	150	200	250	300
Die and Hand Forgings											
SB-247	Die T6	Up to 4.000	38	35	(1),(2)	12.7	12.7	12.7	12.1	10.5	
	Hand T6	Up to 4.000	37	33	(1),(2)	12.3	12.3	12.3	11.7	10.3	
	Hand T6	4.000-8.000	35	32	(1),(2)	11.7	11.7	11.7	11.2	9.9	
	T6 wld.	Up to 8.000	24	...	(1)	8.0	8.0	8.0	7.9	7.3	

NOTES:

- (1) Allowable stress values for 100°F may be used at temperatures down to -452°F without additional specification requirements.
 (2) The stress values given for this material are not applicable when either welding or thermal cutting is employed.

Figure 1
Design Fatigue Curve for 6061-T6 Aluminum for Temperatures Not Exceeding 300°F



GENERAL NOTE:

$$E = 10.0 \times 10^6 \text{ psi}$$

Figure 12 Al6061-T6 Allowable Stress and Fatigue Curve

Fatigue properties used for 316L are shown in Figure 13 from the ASME BPCV.

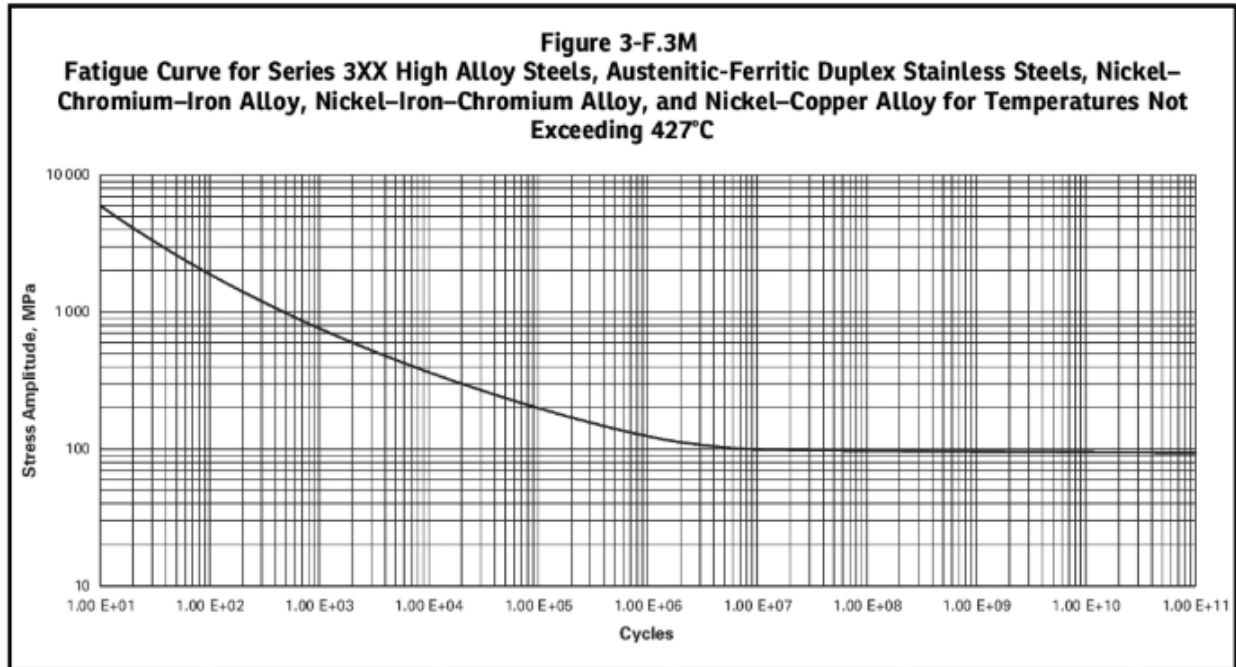


Figure 13 Fatigue curve for 3XX Stainless steel

3.3 EXTERNAL LOADS

Normal operating temperature data files from CFD analysis [4] were imported. Three separate files for the upper, middle and lower backbone were combined into one file (backbone_merged) which is included with the data files. The data sets also included one for the upper shielding and one for an overall model for all remaining parts with the exception of the seismic block. Node sets for each part or assembly were defined. The node sets are shown in Figure 14.

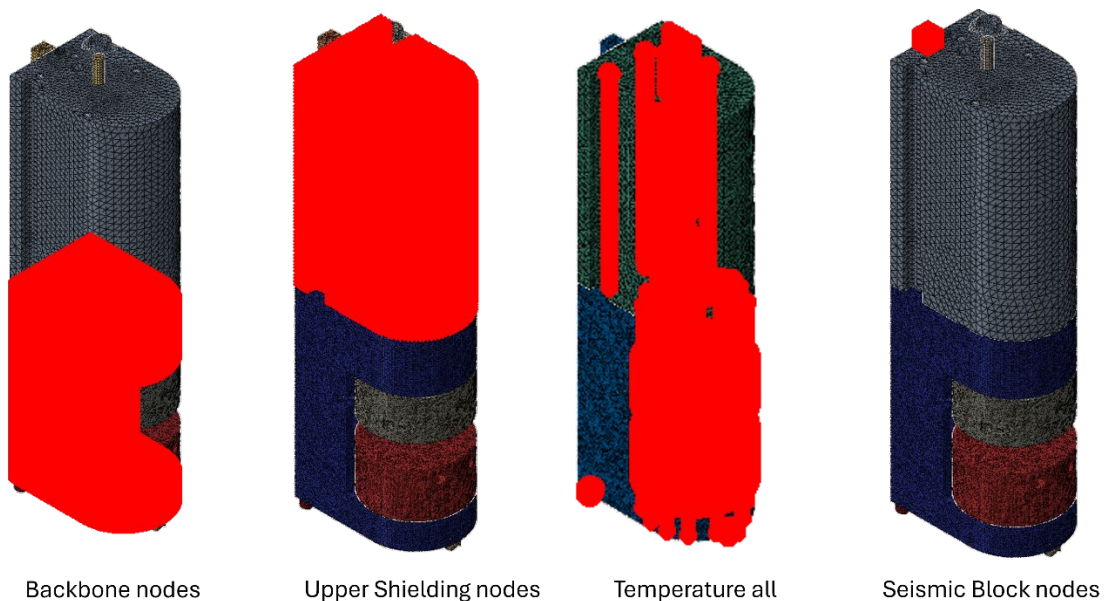


Figure 14 Node sets for temperature

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The CFD files used are shown in Table 3 CFD data for Normal Operating temperature.

Table 3 CFD data for Normal Operating temperature

Node Sets	Data .csv files
backbone_lower	Steady_State_Temperature_SS316_Lower_Block
backbone_middle	Steady_State_Temperature_SS316_Middle_Block
backbone_upper	Steady_State_Temperature_SS316_Upper_Block
backbone	backbone_merged
upper_shielding	Steady_State_Temperature_A36
temperature_all	Steady_State_Temperature_Whole_Model

The seismic block was not in the CFD model. A uniform temperature of 65.2 °C to match the contact surface of the upper shielding was applied to that node set. The overall temperatures mapped by Abaqus including a view cut on the z=0 plane, are shown in Figure 15 with a peak of 85 °C. A comparison with the CFD DAC assembly temperatures is shown in Figure 16 with a peak of 84.6 °C versus 84.9 °C as mapped with Abaqus.

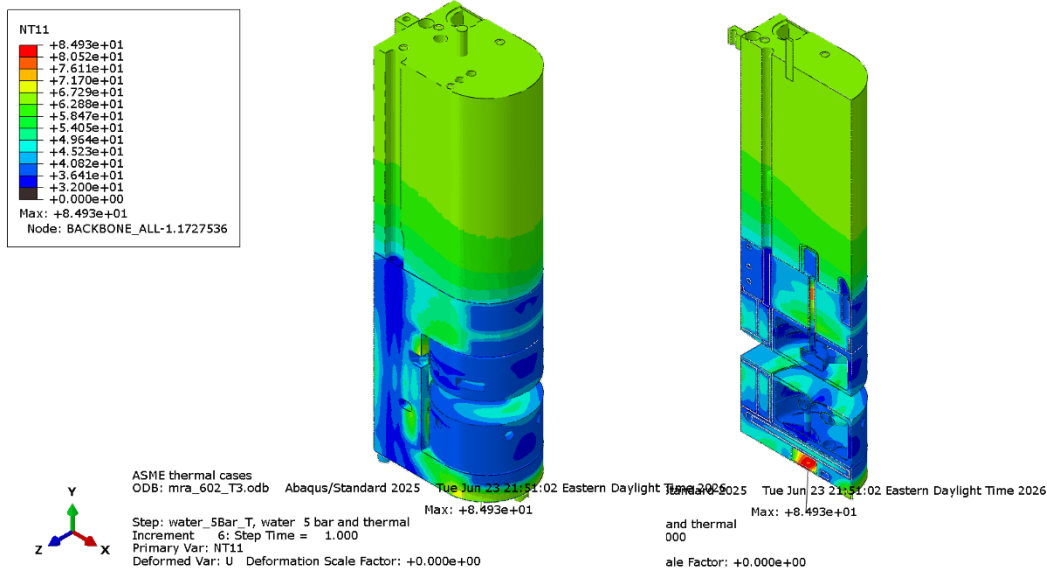


Figure 15 Assembly temperatures (°C) mapped by Abaqus with peak of 84.9 °C

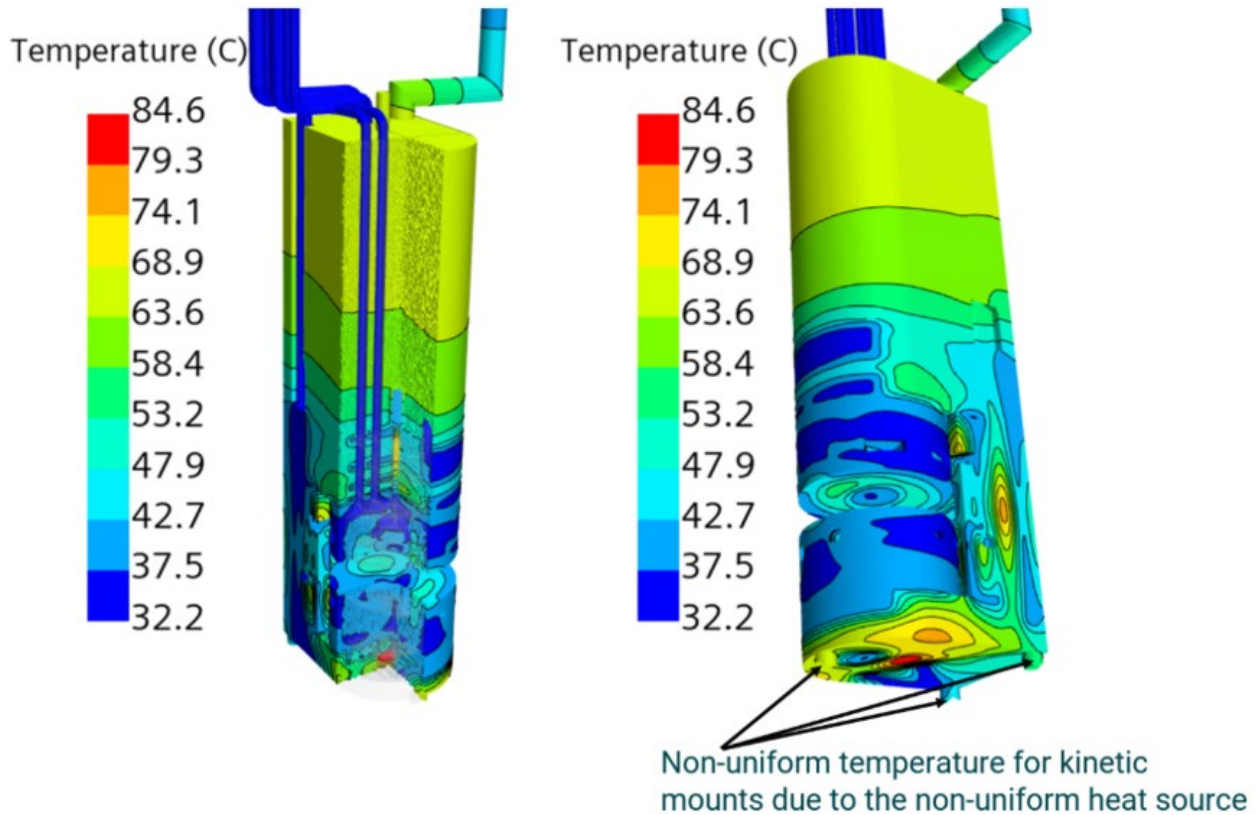


Figure 16 CFD analysis assembly temperature with peak of 84.6 °C [4]

3.4 DESIGN CRITERIA AND ACCEPTABLE VALUES

STS requirements for the Moderator Reflector Assembly are reported in controlled document S03040000-SR0001-R02. These include the following with Code Beamer reference Item ID:

Table 4 Moderator Reflector Assembly Requirements

Summary	Description	Item ID
MRA cyclic loading Requirement	The MRA shall be designed for a lifetime of 5 years (25000 hours of 700 kW beam power operation) or more with respect to cyclic loading. The hydrogen boundaries are expected to experience 50 full pressure cycles during commissioning and 10 full pressure cycles per year during operation. Hydrogen pressure is expected to fluctuate 2 bar or less during beam trips and ramps. The water boundaries are expected to experience 20 pump start cycles during commissioning and 4 pump start cycles per year during operation. A pump start cycle is expected to produce an MRA water pressure change of 1 bar or less. No full pressure cycles are expected for the water boundaries. 10000 beam trips are expected to occur each year.	2339
MRA Vacuum Vessel Requirement	The MRA vacuum vessels shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	2893

MRA Reflector Vessel Requirement	The MRA backbone shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	2355
MRA Backbone Requirement	The MRA reflector vessels shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	10921
MRA Vacuum Boundary Pressure Requirement	The MRA vacuum boundary MAWP shall be 2 bara.	2358
MRA Water Boundary Pressure Requirement	The MRA water boundaries shall have a MAWP of 5 bara	2361
MRA Deflection Requirement	The MRA outside surfaces shall not deflect more than +/- ~ 1.5 mm from their installed locations under any expected loading conditions.	2994
MRA Moderator Operational Displacement Requirement	The MRA moderators shall have a displacement of 0.3 mm or less relative to the MRA mounting points from installation to 700 kW operation.	2892

4. NUMERICAL MODEL OR SIMULATION

4.1 SOFTWARE

All analyses were performed on the BERNIE.sns.gov cluster with the Red Hat Enterprise Linux 8.10 (Ootpa) operating system. The cluster consists of 6 compute nodes. Each node has 64 processors (Intel Xeon CPU E5-2637 v2 @ 3.50GHz) and 768-GB memory.

The software packages used for analysis include:

- *Abaqus 2025* (BUILD ID: 2024_09_20-09.00.46 RELr427 198590) was used for steady state stress analysis and also for buckling analysis
- *Microsoft Excel* software was used to develop true stress strain curves for Al6061T6 and for welded Al6061T6 using ASME Method B section 5.4.3

4.2 UNIT SYSTEM

All work was done using SI units (m, kg, s, °C).

4.3 DISCRETIZATION

4.3.1 Upper Shielding

The A36 upper shielding part was meshed with 157244 C3D10 elements. The surface tied to the seismic block had 4 mm node separation on the edges and near the adjacent hole. Nominal mesh size was 25 mm. The model and views of the mesh are shown in Figure 17 along with mesh diagnostics. Poor elements are heightened in yellow on one figure.

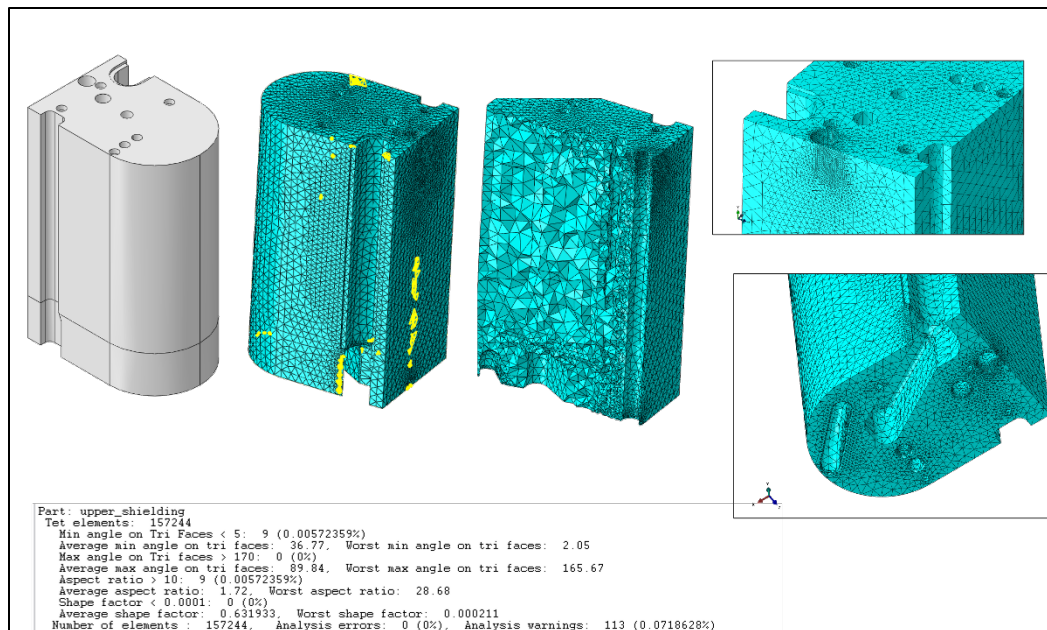


Figure 17 Upper Shielding model

The upper shielding channel for the vacuum tube has a cover plate of A36 material. This is shown in Figure 18. It was meshed with 1312 C3D8 elements as also shown.

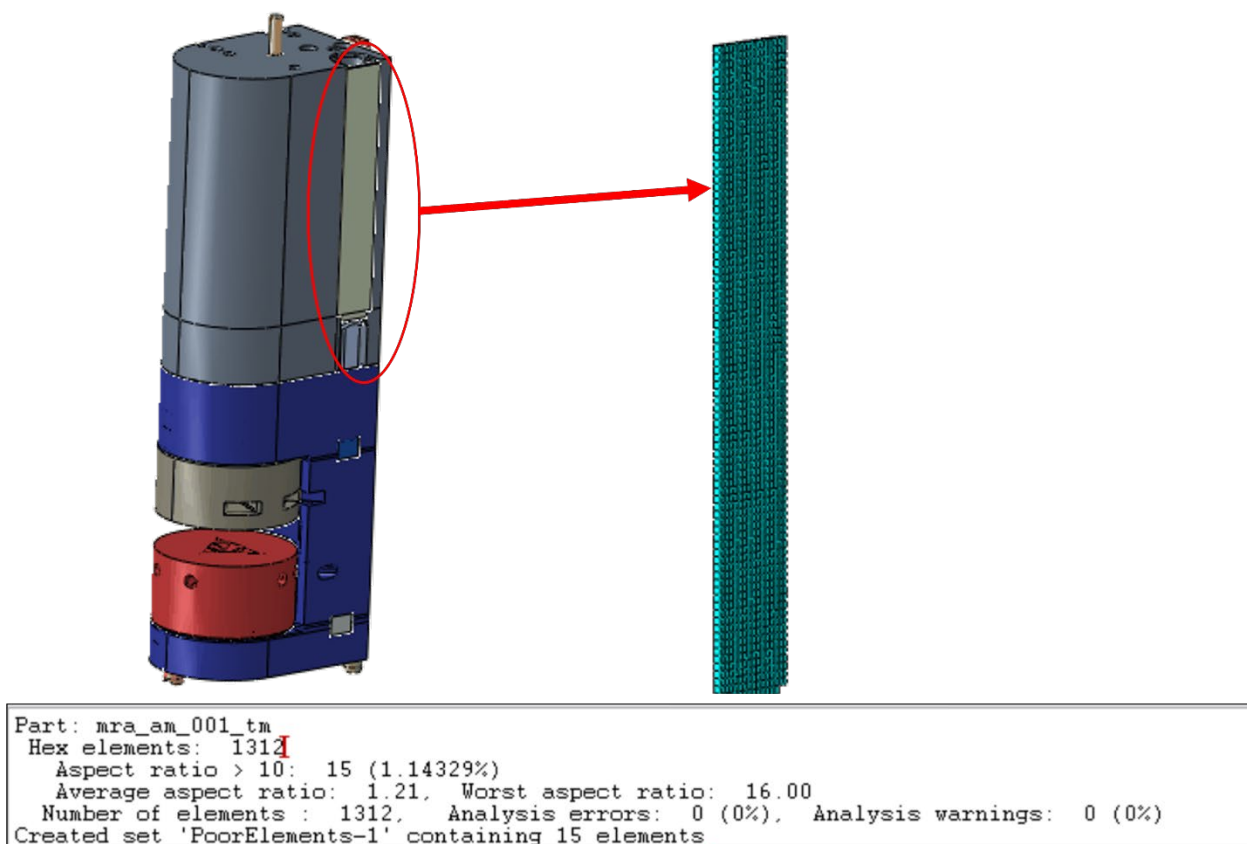


Figure 18 Upper Shielding cover plate

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4.3.2 Backbone

The 316L upper backbone model mesh had 4,505,980 C3D10 elements. Several mesh views are shown in Figure 19. The nominal mesh size was 8mm with 2 mm and 1 mm edge size by front weld, 3 mm edges by internal welds and 4 mm by vertical sharp curvature regions near reflector vessels. Internal step parts have been merged. Surface partitions were added to define contact regions. Figure 19 shows the locations of poor elements in yellow and the mesh diagnostics.

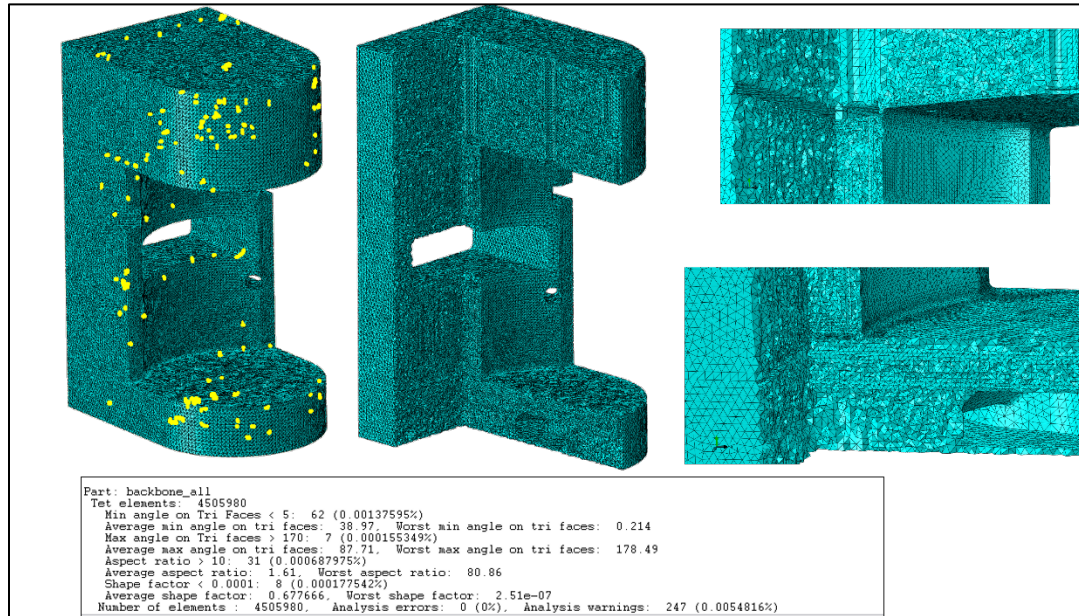


Figure 19 Backbone model

The backbone also has two 316L covers which seals the vacuum space and which are welded to the full backbone after the three sections are welded. These are shown in Figure 20 along with the C3D8 mesh used for both.

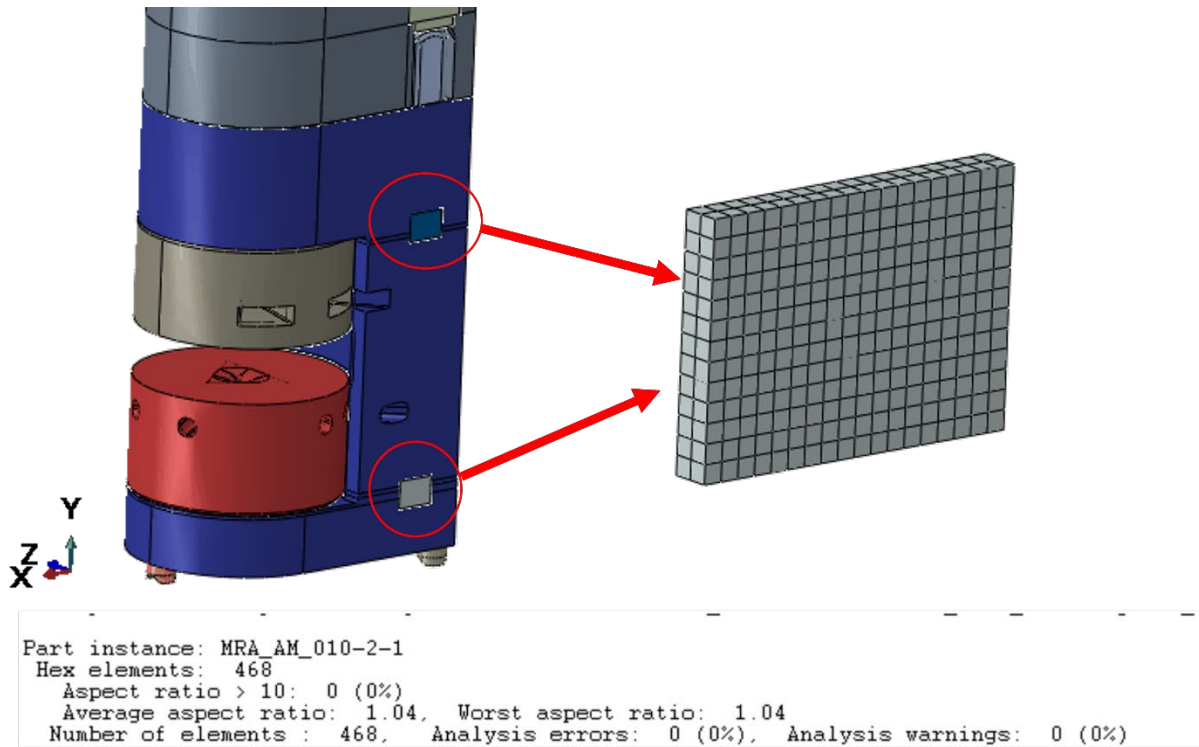


Figure 20 Backbone vacuum space covers

4.3.3 Upper Reflector Vessel

The upper reflector vessel was based on the mra_am_upper_reflector_a.stp Step file. The vacuum tube and bimetal tubes welded to the vessel were merged with the body. Section assignments for Al6061T6 and 316L material regions were applied. The part (UR_2026__merged) was meshed with 3.8e6 C3D10 tet elements with a nominal 2mm size. Several views of the part are shown in Figure 21 and the mesh with diagnostics is shown in Figure 22.

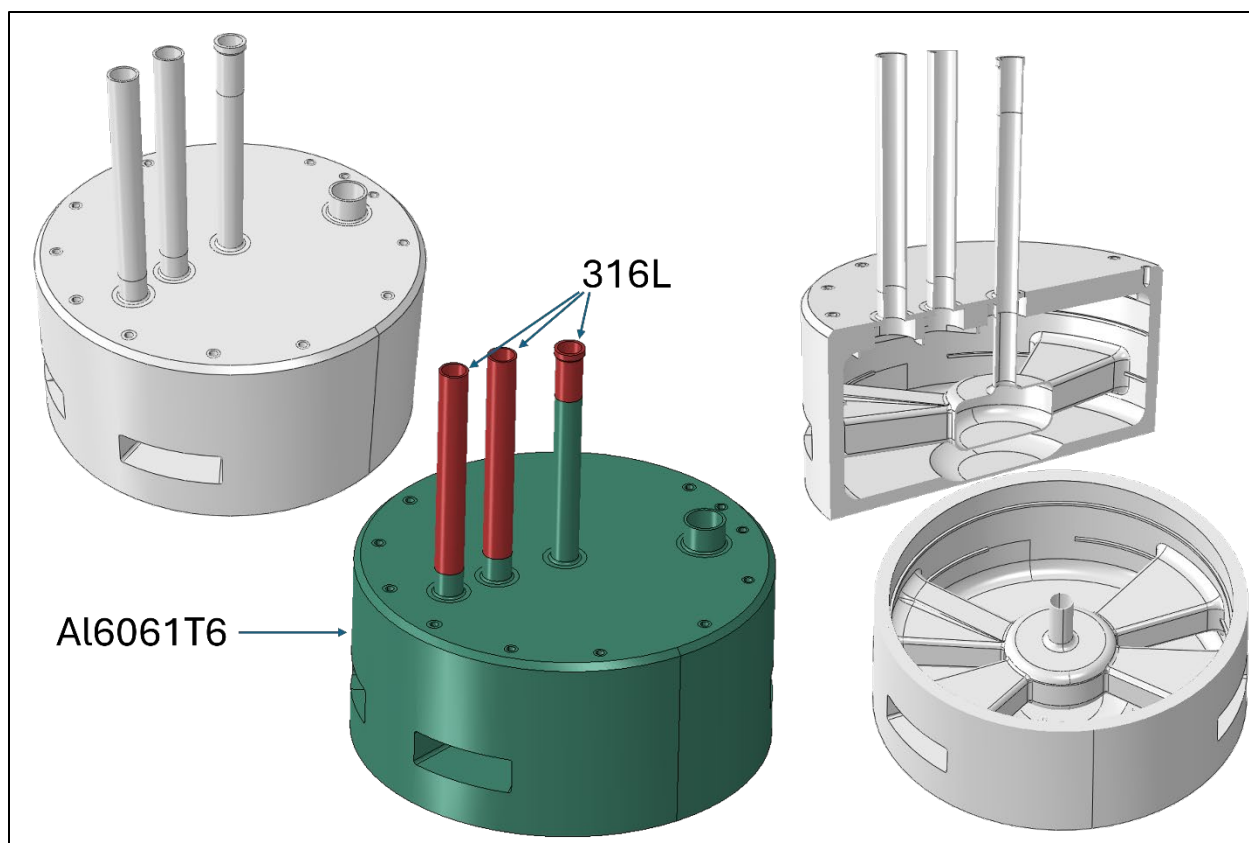


Figure 21 Upper Reflector with merged tubes

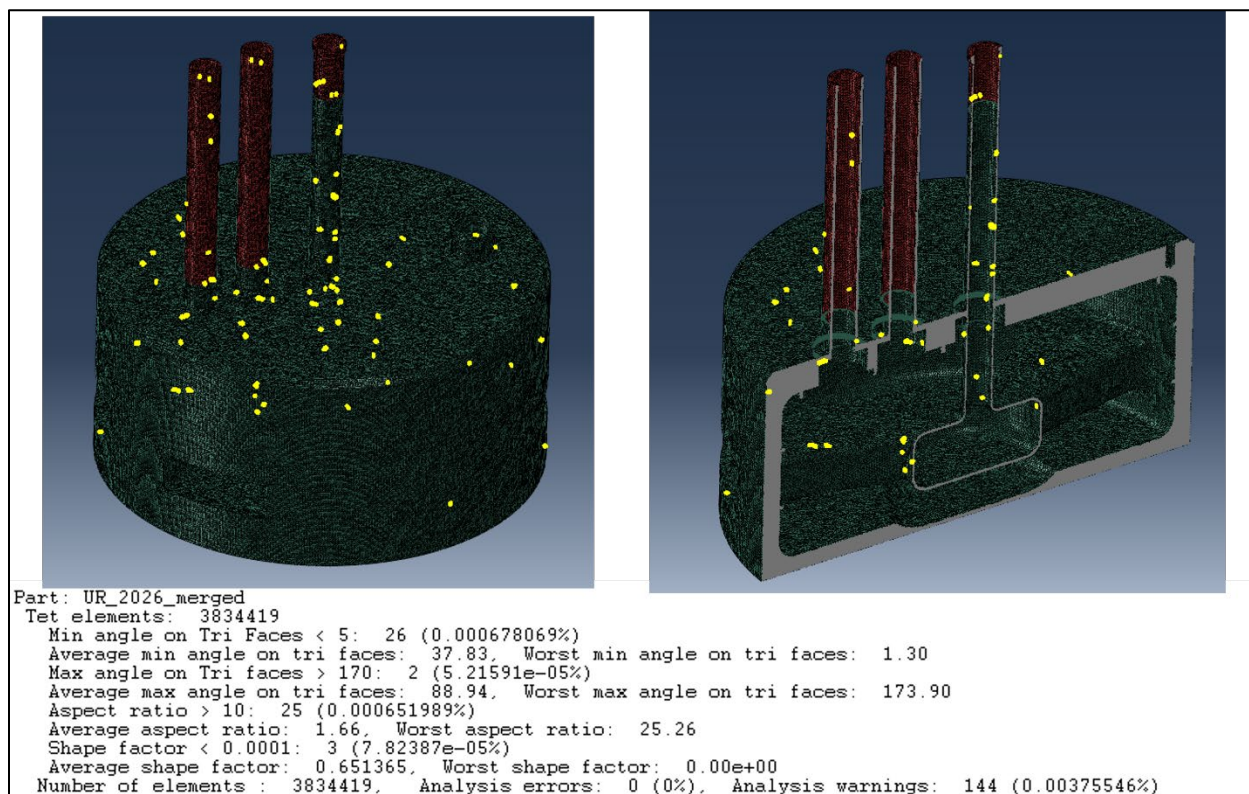


Figure 22 Upper Reflector model mesh and diagnostics

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4.3.4 Lower Reflector Vessel

The lower reflector part (LR_2026_merged) including merged bimetal tubes and vacuum tube is shown in Figure 23. The mesh used 1.6e6 C3D10 tet elements with a nominal size of 3mm. A cut view of the mesh and the diagnostics are shown in Figure 24 including material regions.

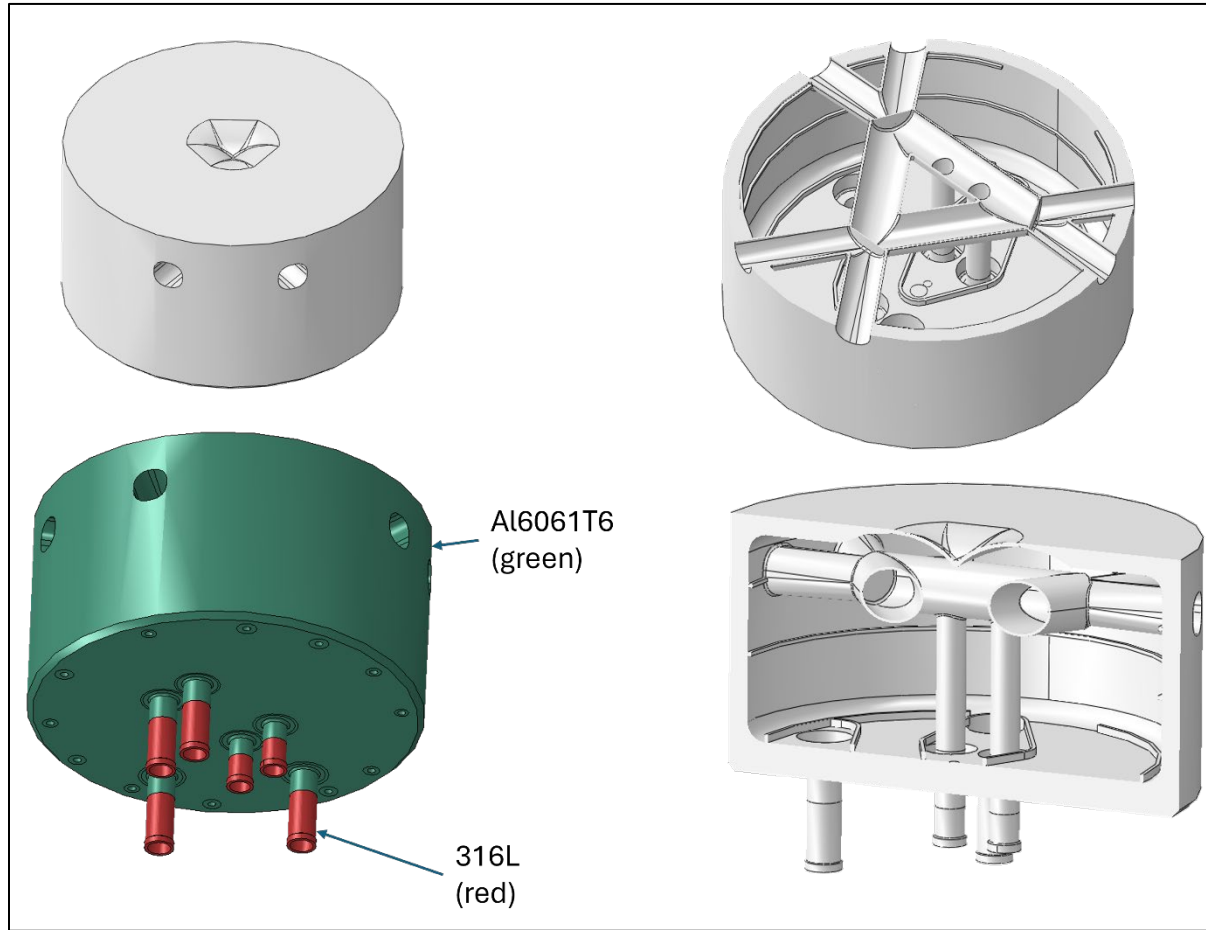


Figure 23 Lower Reflector model with merged tubes

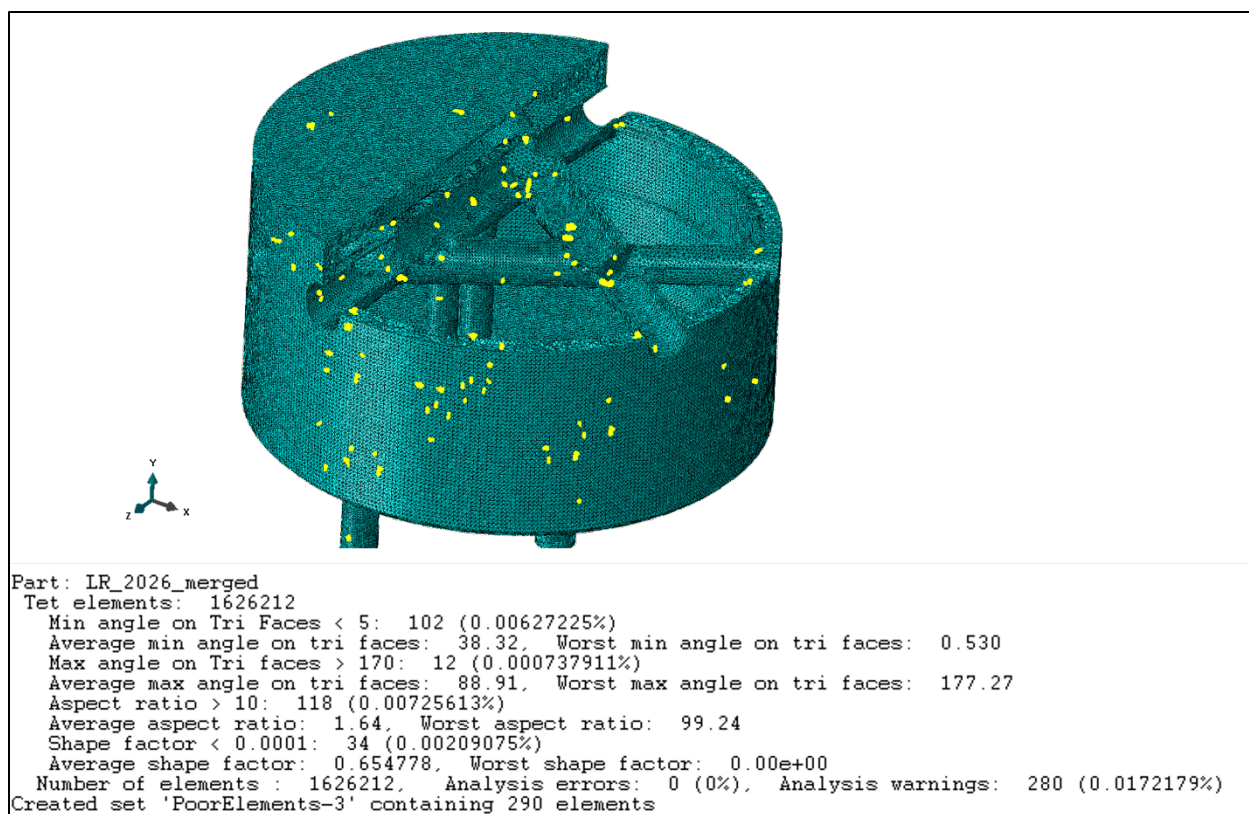


Figure 24 Lower Reflector mesh and diagnostics

4.3.5 Bolts and Tie rods

The Step file for the bolts and tie rods included threaded regions. The bolt models also had Belville washers and nuts at the top. These areas were simplified in Abaqus as shown in Figure 25 below. The intent was to be able to apply preloads on the bolts and tie rods to give the loading on the reflector vessels. Threaded connections were represented as cylindrical surface tie connections. Reflector vessel stresses several bolt diameters away from the connections should be accurate and the overall displacements should be realistic. High localized stresses around the connections are not realistic.

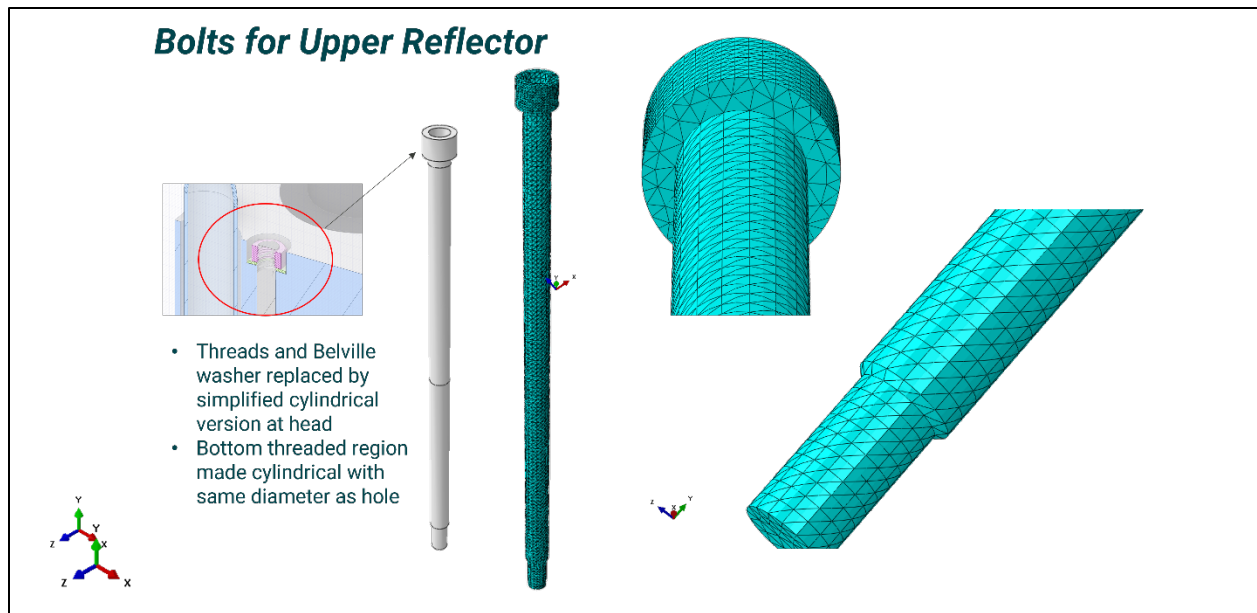


Figure 25 Typical bolt on the upper reflector showing simplified representation around head and threaded region

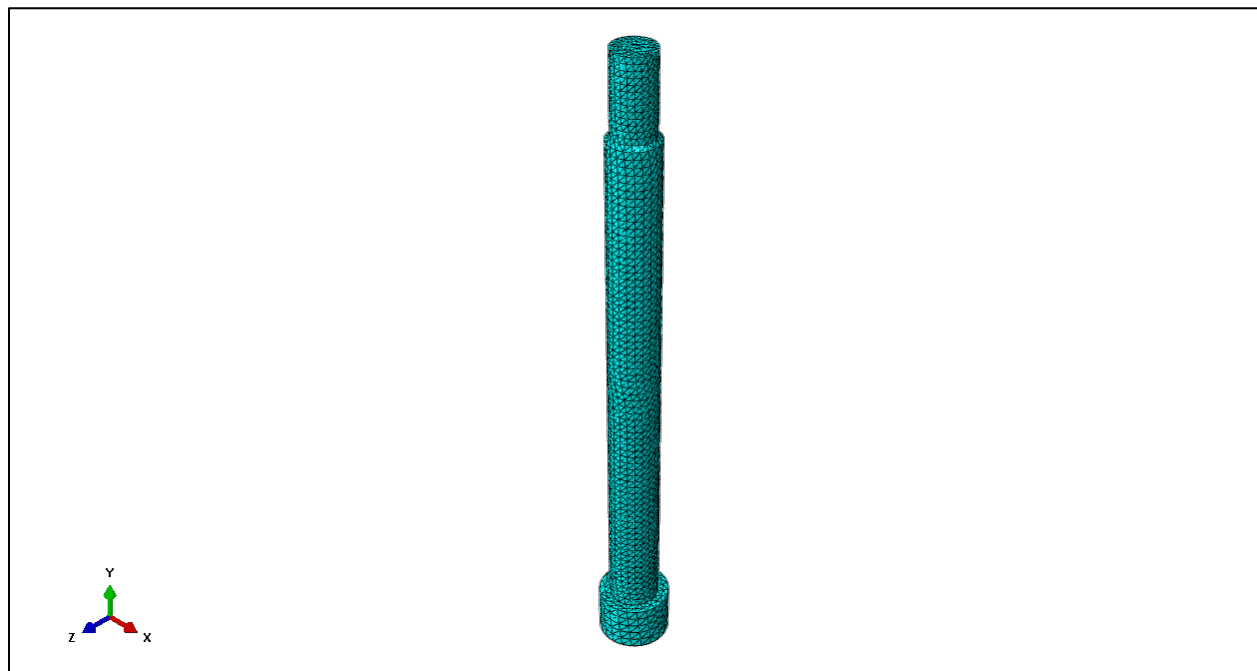


Figure 26 Typical lower bolt with simplified model and C3D10 mesh

The upper and lower bolt mesh models used 21,802 and 18,992 C3D10 tet elements respectively with few or no warnings. Figure 26 shows the mesh for a lower bolt. The tie rod model is shown in Figure 27 which uses 25,626 C3D10 tet elements with a nominal 4 mm size.

Tie Rods

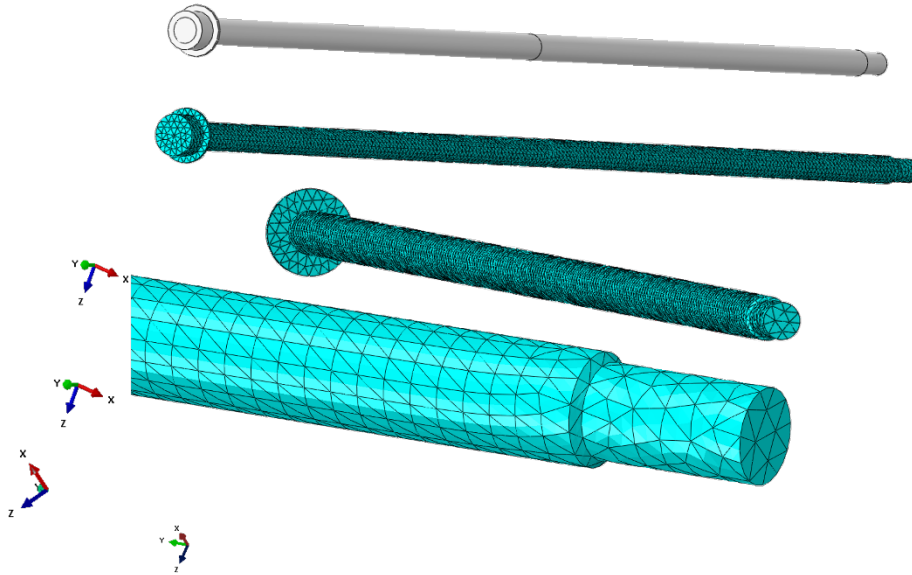


Figure 27 Typical tie rod model and mesh

4.3.6 Mounting Blocks, Seismic block and Vacuum Shell

The support for MRA is provided by 3 vee-block assemblies on the bottom. A simplified version was given in the step file, and the mesh with 6271 C3D10 with a nominal 4 mm size is shown in Figure 28. Support for seismic loads at the top rear of the upper shielding was provided by the seismic block shown in Figure 28. The mesh used 3465 C3D8R elements with a nominal 4 mm size. All parts are 316L material.

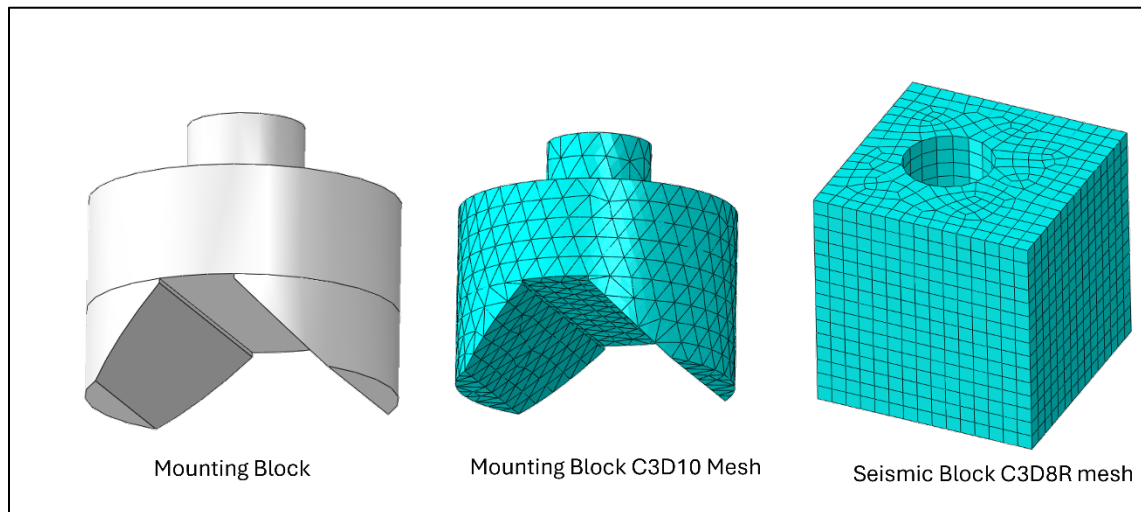


Figure 28 Typical mounting block and Seismic block showing mesh

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The Transfer Vacuum Cover is welded to the upper backbone block. Figure 29 shows the model and mesh with 29,101 C3D10 tet elements and the mesh diagnostics. The vacuum tube above the cover will be analyzed in a separate document for the piping and tubing.

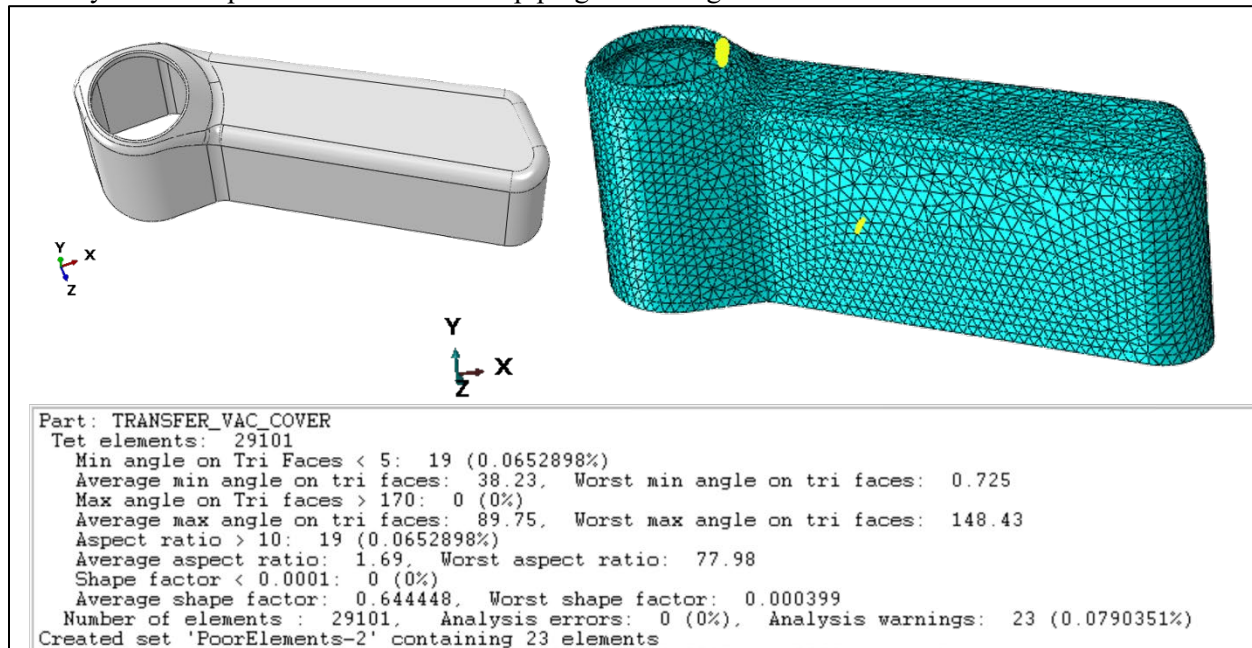


Figure 29 Transfer Vacuum Cover model with mesh diagnostics

4.4 BOUNDARY CONDITIONS

The three lower mounts are designed to constraint displacements towards the central axis. This is simulated in the Abaqus model by constraining the nodes on the angled faces against displacement normal to the surface. These surfaces point towards the central axis. The constraint was done on all 6 faces using local coordinate systems. This also does not allow displacement in the global vertical direction. Figure 30 shows the 6 local coordinate systems with the z direction normal to the angled surfaces on each mount. This figure also shows one of the boundary conditions constraining normal Z (U3) motion.

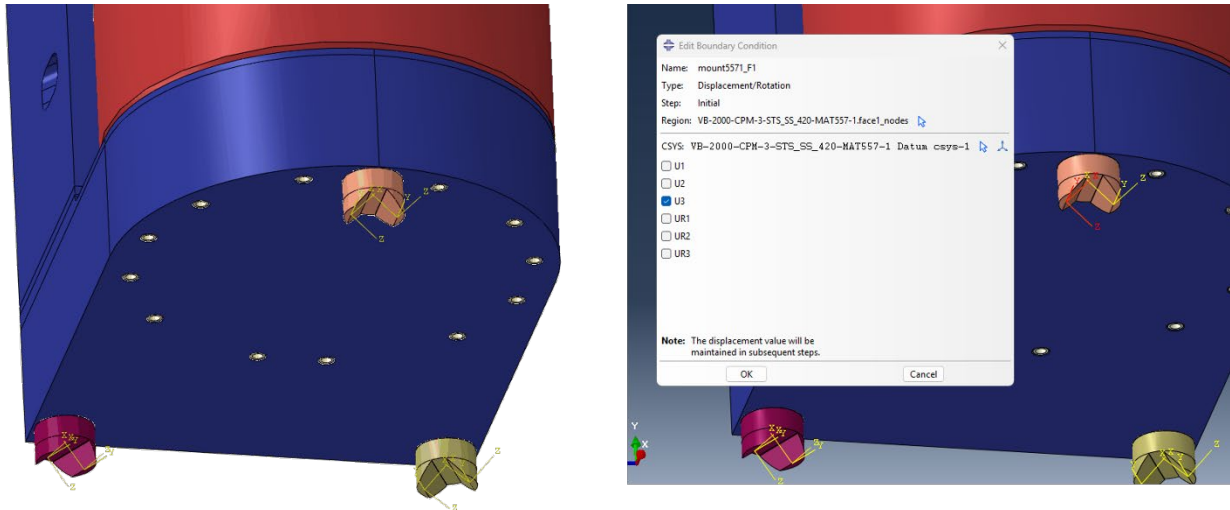


Figure 30 Lower Mounting block coordinate systems and typical boundary condition

The upper seismic block is intended to have a central pin which connects to the fixed core vessel shielding and would allow vertical displacements but not any in-plane displacements. This was simulated by constraining the central hole surface nodes against in plane displacements. This boundary condition was not applied for the non-seismic thermal load cases. This boundary condition is shown in Figure 31.

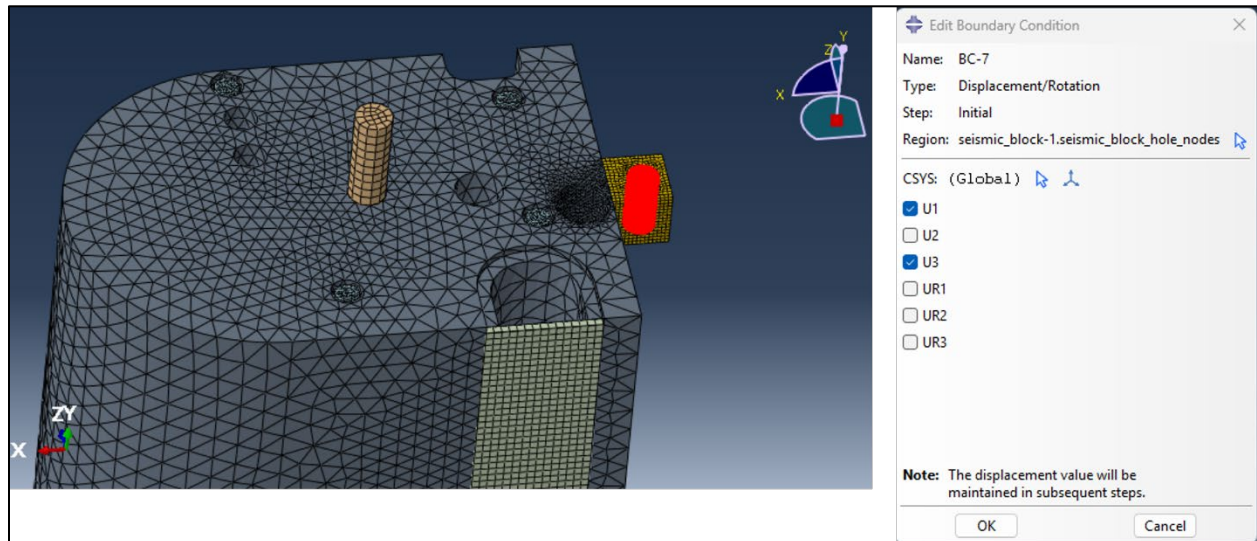


Figure 31 Seismic Block Boundary Condition BC-7

4.5 CONTACT CONDITIONS

4.5.1 Tie Constraints

All the bolts and tie rods had tie constraints on the heads and in the threaded connection regions. Typical bolt tie constraints are shown in Figure 32 and Figure 33 for the 24bolts. The tie rod typical constraint for the 4 rods is shown in Figure 34.

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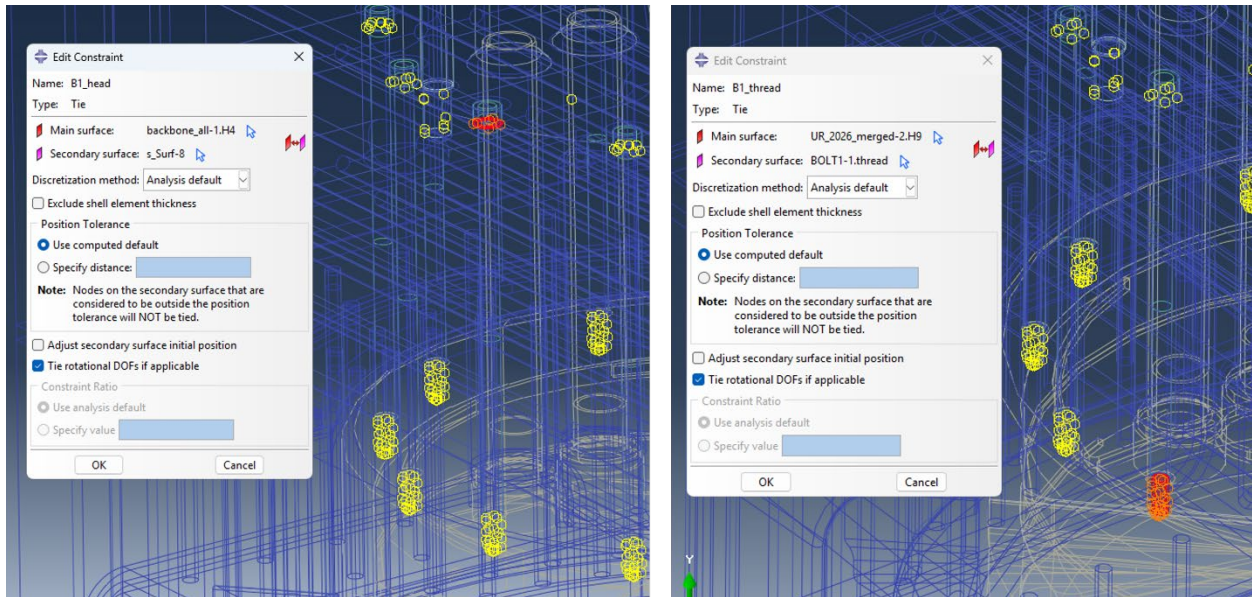


Figure 32 Typical upper bolt head and lower threaded region tie constraints

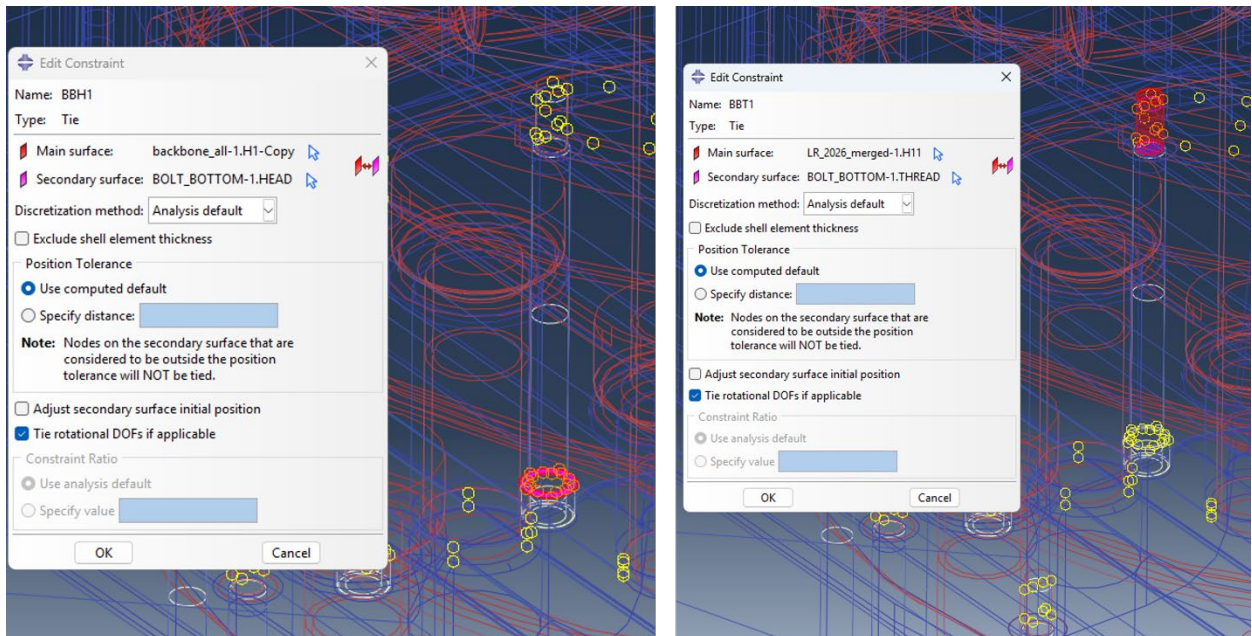


Figure 33 Typical lower bolt head and lower threaded region tie constraints

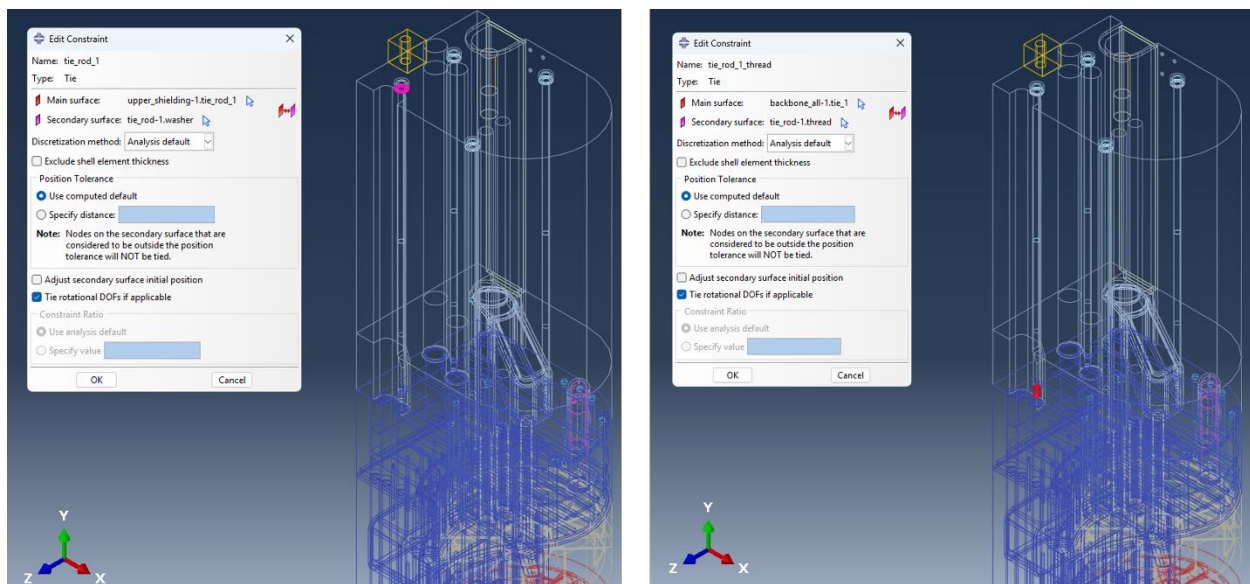


Figure 34 Typical tie rod head and threaded region tie constraints.

The assembly model includes a water jumper between the upper backbone and the upper reflector vessel. The weld connections on each end of the jumper are represented by the tie connections given in Figure 35.

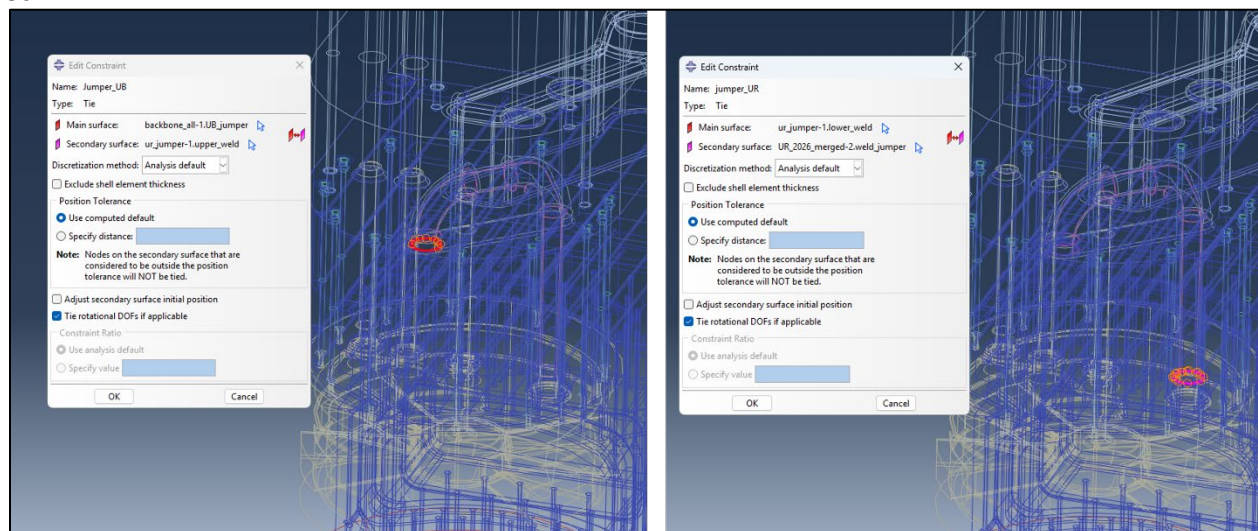


Figure 35 Water Jumper Tie Connections

The lower reflector vessel has 6 connections to the lower backbone. These are welds between the 316L regions of the bimetallic tubes and the lower backbone. Figure 36 shows the location on the lower reflector vessel and Figure 37 defines the tie connections in the model.

Lower Reflector showing locations of 6 fitting ties

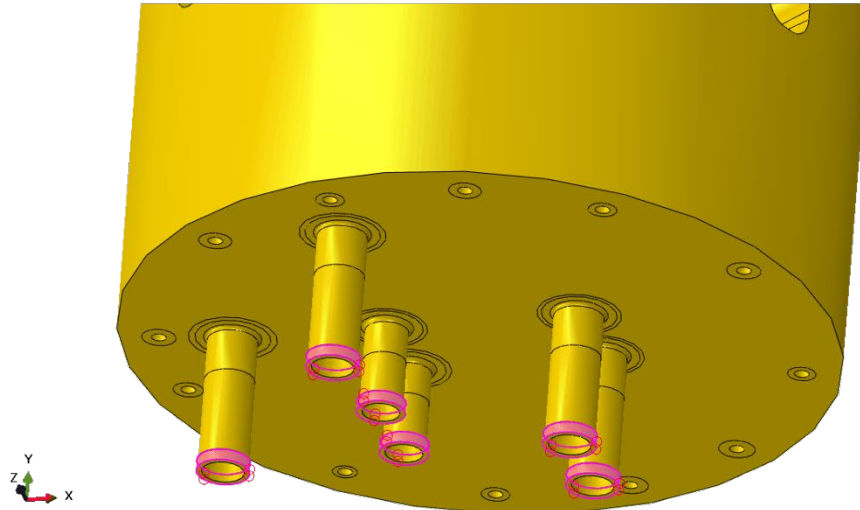


Figure 36 Lower Reflector Vessel locations of tie connection to backbone

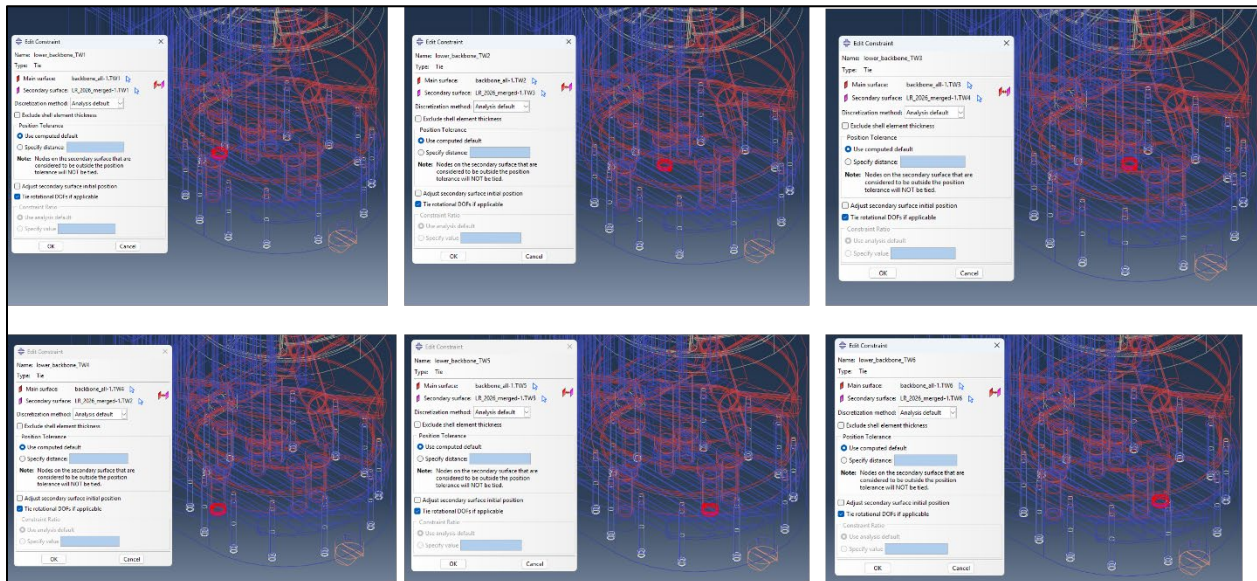
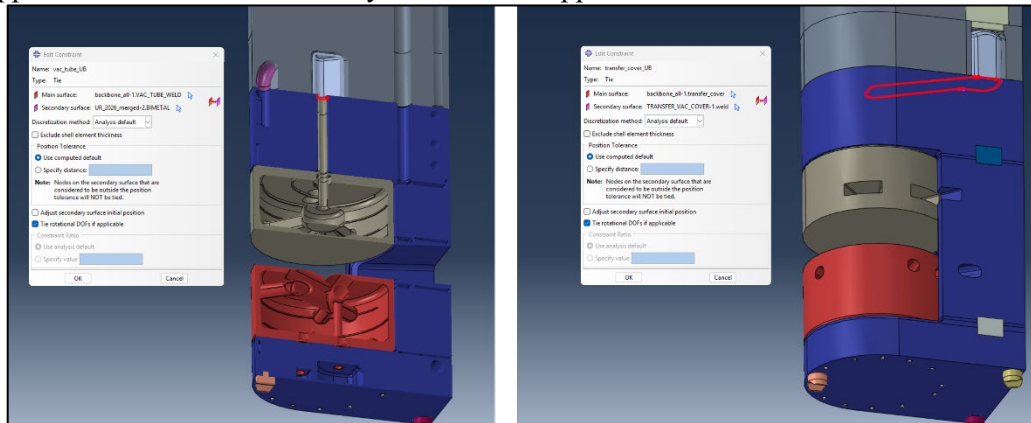


Figure 37 Lower reflector to backbone tie connections at 6 locations

The weld of the vacuum cover to the backbone tie connection is shown in Figure 38. The vacuum space for the upper reflector vessel is closed by a weld to the upper backbone which is also shown in Figure 38.



surface.

Figure 38 Vacuum cover tie to upper backbone and assumed tie between upper backbone and upper shielding

Figure 39 shows the tie assumed between the backbone upper surface and the upper shielding lower surface.

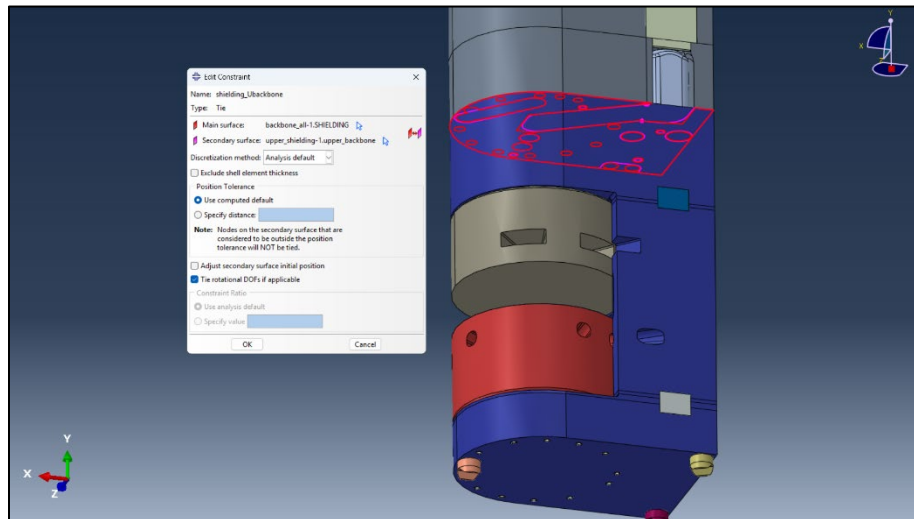


Figure 39 Upper Shielding to backbone tie constraint

The seismic block is bolted to the upper shielding on the beam centerline near the top of the shielding.. A simplified model without the bolts was made with a tie condition between the mating surfaces. Each of the three mounting blocks at the bottom were assumed to be tied to the backbone on the mating flat surfaces around the central pin. These constraints are shown in Figure 40.

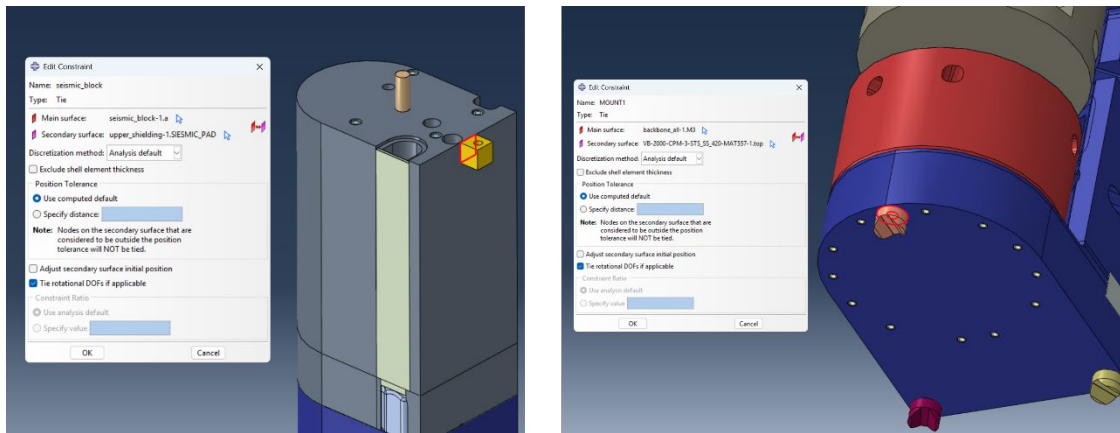


Figure 40 Seismic block tie to upper shielding and mounting block typical tie to backbone

In addition to the main backbone welds described previously, there were two side cover welds which helped to complete the vacuum boundary as shown in Figure 41. The upper shielding side cover ties are also shown in Figure 41.

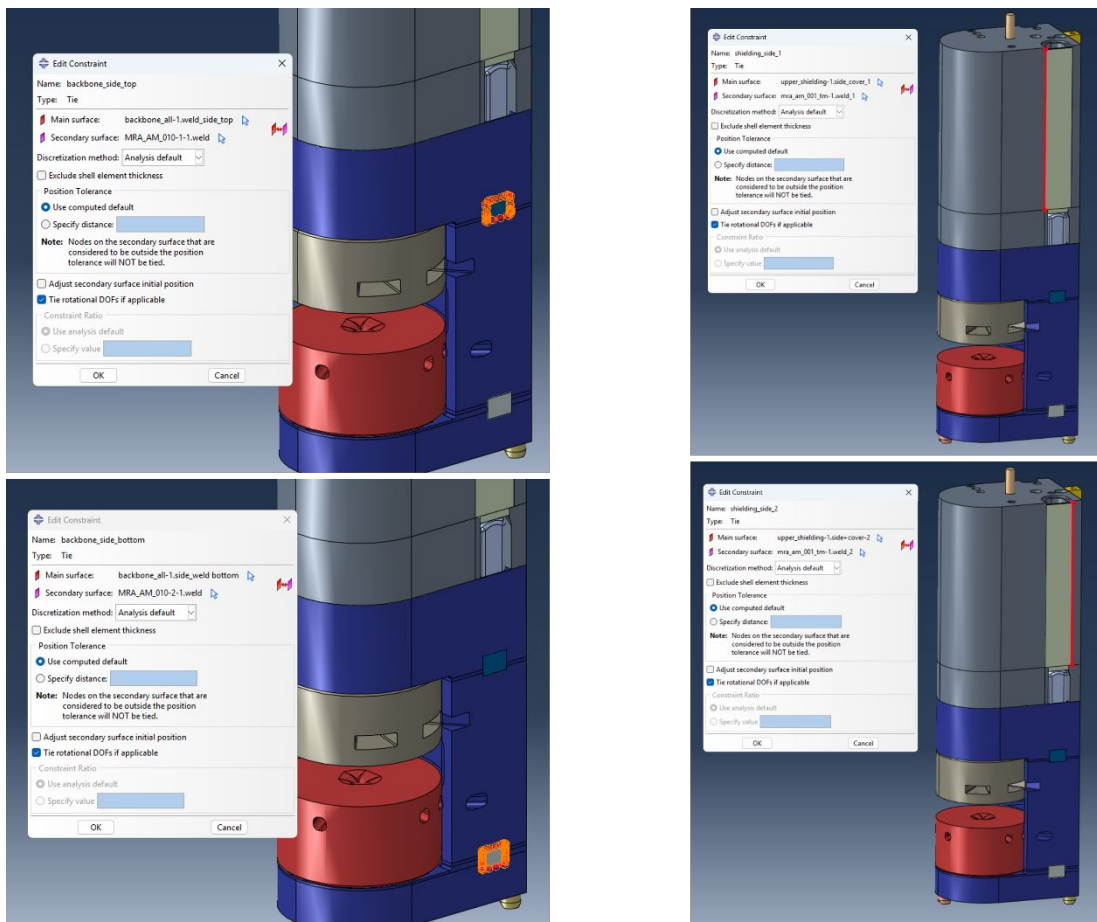


Figure 41 Backbone and Upper Shielding Side cover plate weld tie constraints

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4.5.2 Surface to Surface Interactions

The contact surface between the backbone and the upper reflector vessel was defined as a surface-to-surface hard contact allowing separation with no friction. The same interaction definition was used for the contact between the lower reflector vessel and the backbone. These are shown in Figure 42.

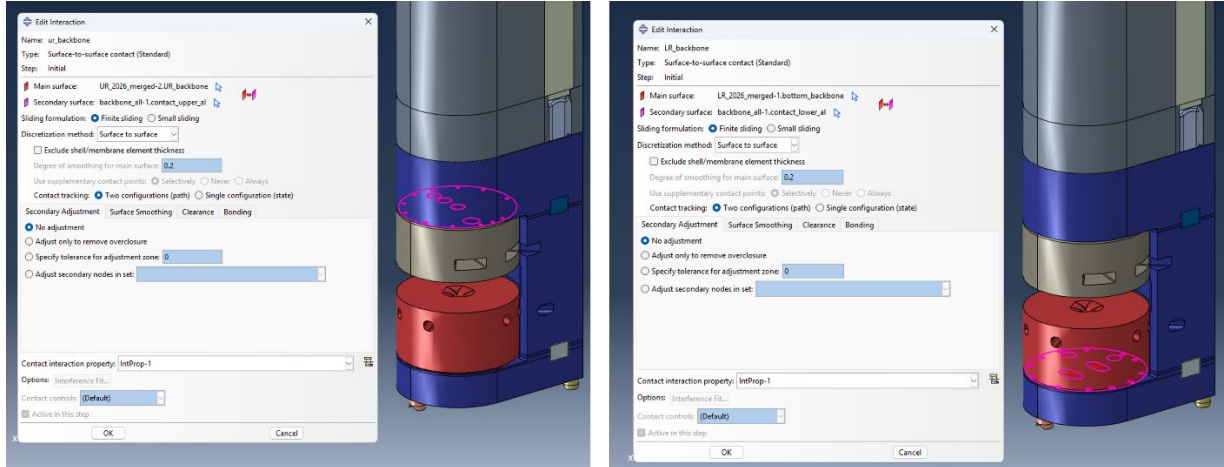


Figure 42 Surface to Surface interactions between reflector vessels and backbone parts

4.6 LOADS

4.6.1 Preloads

Each bolt and tie rod had a cross-section surface defined near the axial middle. Each of the 24 bolts had a 5 kN preload applied and each of the 4 tie rods had a 10 kN preload applied as shown in Figure 43.

Preloads

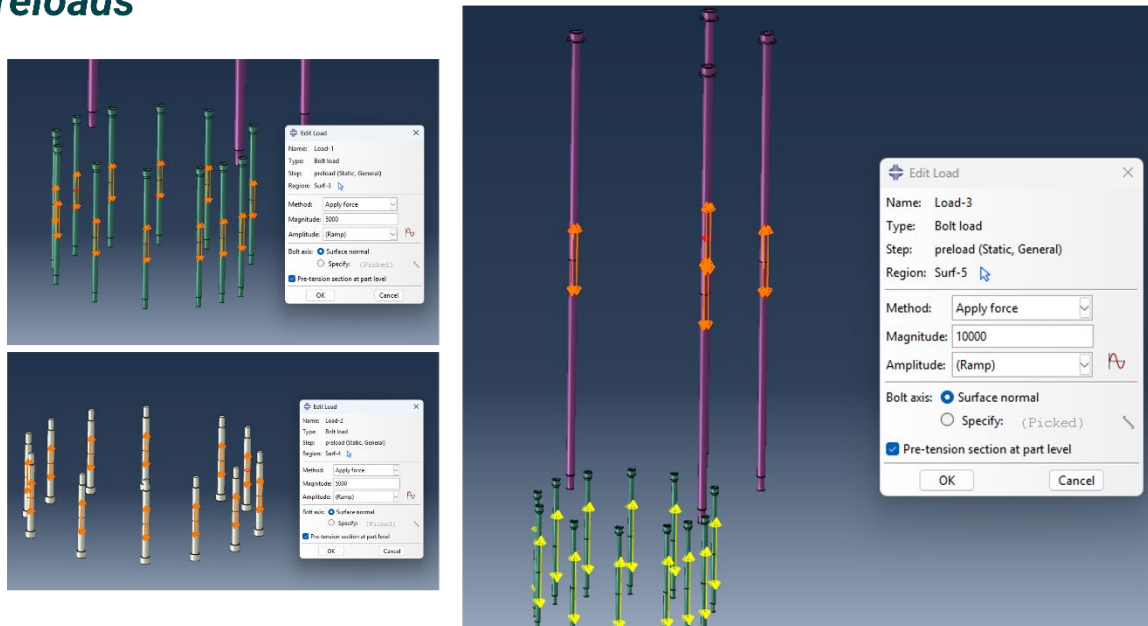


Figure 43 Upper and lower Bolt 5 kN preload and tie rod 10 kN preloads

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4.6.2 Pressure loads

4.6.2.1 Water Pressure

Figure 44 shows all the surfaces which see water pressure in the model. Water tube extensions are not included in the model except for the jumper between the upper reflector vessel and the upper backbone. Depending on the load case the pressure could be 3, 5 or 5.75 bar. Pressure on water tube surfaces external to the model were not included, so the open tubes at the top do impose a net body force on the assembly.

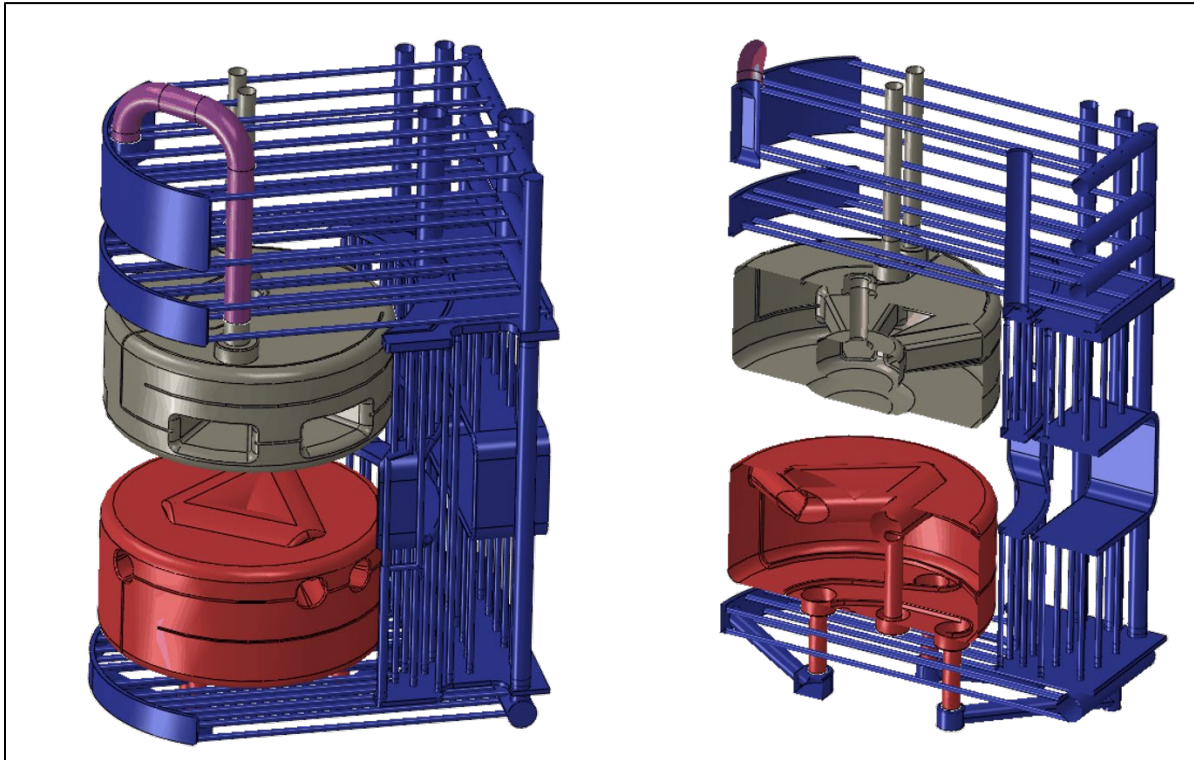


Figure 44 Water Pressure Surfaces

4.6.2.2 Vacuum Boundary loads

The surfaces which see the transfer line vacuum space are shown in Figure 45. These surfaces would normally see vacuum, but under accident conditions could see up to 2 bar pressure. This does not include the hydrogen boundary.



Figure 45 Vacuum Boundary Surface

4.6.2.3 Core Vessel Atmosphere

Figure 46 shows surfaces which would see core vessel atmosphere (vacuum or 1 bar) with a $z=0$ cut view. Solid upper shielding sections were not included.

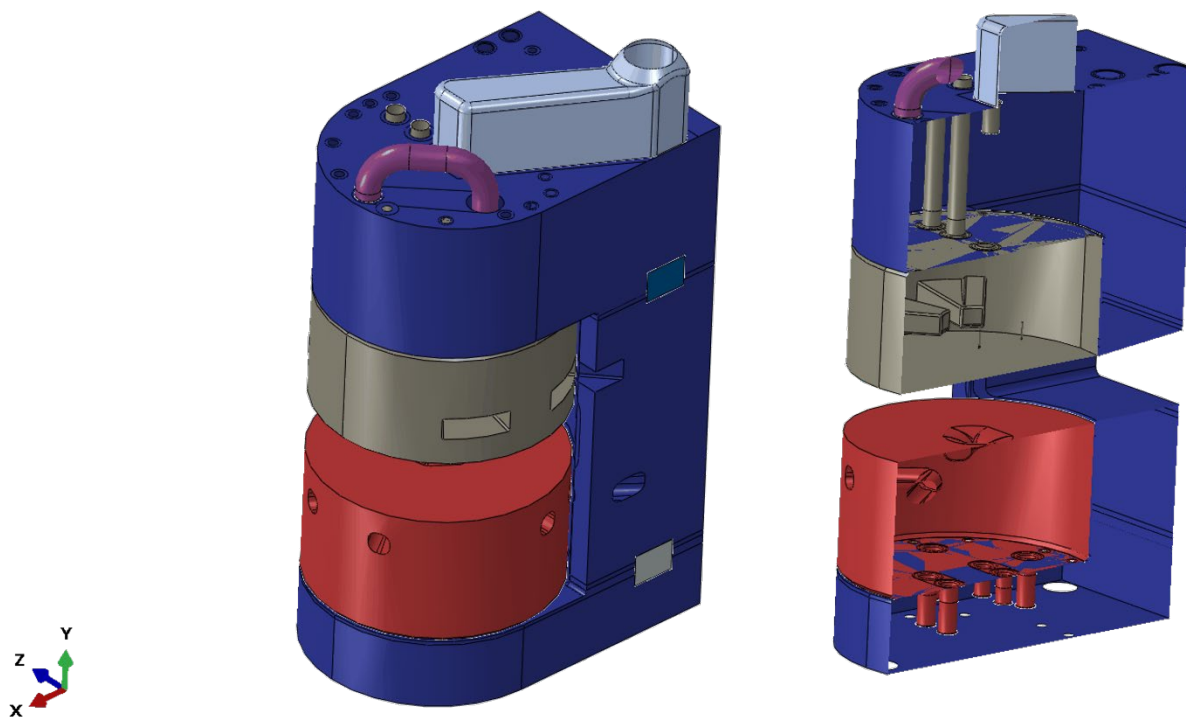


Figure 46 Surfaces which see core vessel atmosphere including a z cut view

4.6.3 Thermal Loads

The CFD analysis determined the operating temperatures. Several different reduced data sets were made for the structural analysis which did not need the fine detail in the full CFD results. Separate data sets were used for the upper shielding and the backbone sections. A lower resolution set for the whole model was applied to the rest of the parts. This was summarized in section 3.3 and Table 3. Three analytic data fields for x,y,z and temperature data points were imported into Abaqus. These were for the upper shielding (A36-2), backbone_merged, and a lower resolution model for the whole assembly. The Abaqus function “plot source data” was run for each to show that the data aligns with the assembly model. Figure 47 shows these temperature fields with an arbitrary color scale as imported into Abaqus before mapping onto the structural mesh. The parts which were mapped using the whole assembly temperature file were shown separately. A default value of 35 °C was applied during mapping for nodes which did not receive a mapped value. Result files will show the temperatures as mapped onto the mesh.

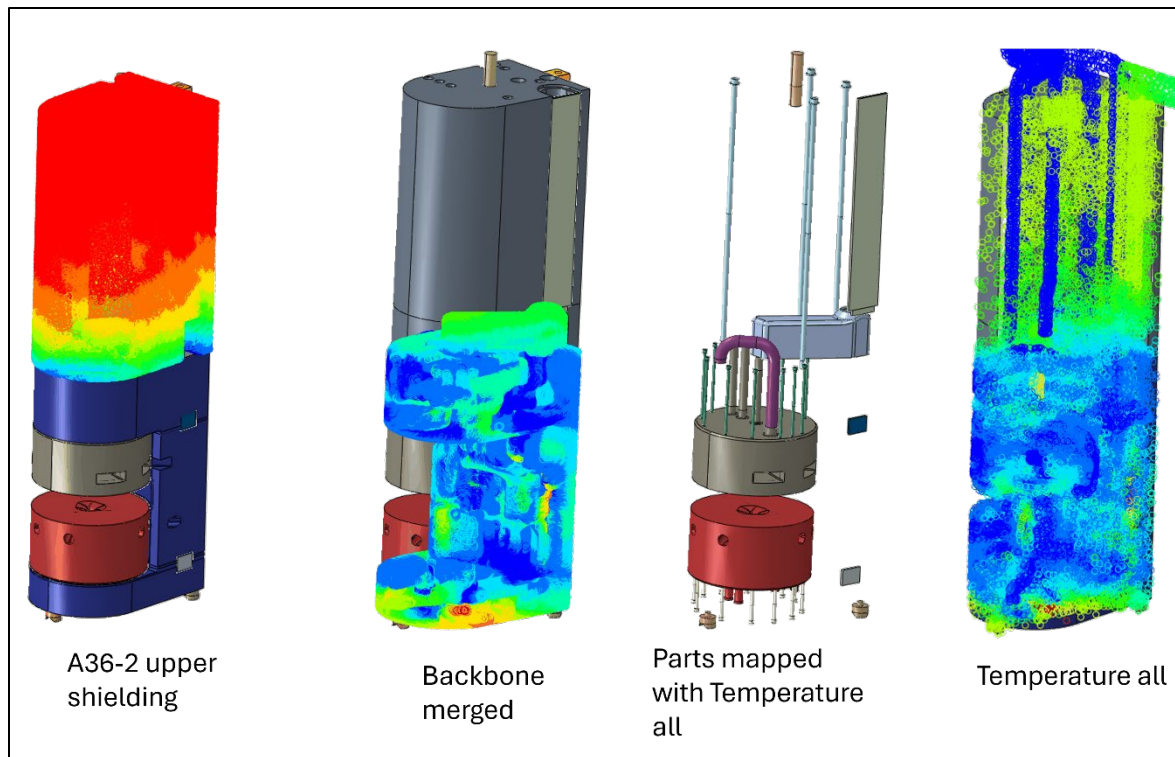


Figure 47 CFD temperature fields

4.6.4 Seismic loads

As shown in Appendix A Seismic Loads at the conservative attachment location near the top the horizontal force $F_p = .308 W_p$ and the vertical $E_v = 0.1 W_p$. The accelerations to be applied for Abaqus cases in the horizontal plane (X,Z) are $0.7F_p$ or 2.11 N/m^2 . In the vertical plane it would be $.69 \text{ N/m}^2$. The overturning load case would apply the horizontal load in the direction most likely to cause overturning. The worst-case direction is normal to a line connecting the downstream mount center to a side mount center. As shown in Figure 48 this angle is 71.3 degrees. The x component will be proportional to the cosine of this angle and the z component to the sine. The acceleration components were then 2.0 m/s^2 in the z direction and $.68 \text{ m/s}^2$ in the x direction. Loads in the negative directions or alternative overturning direction were assumed to give similar results and were not applied.

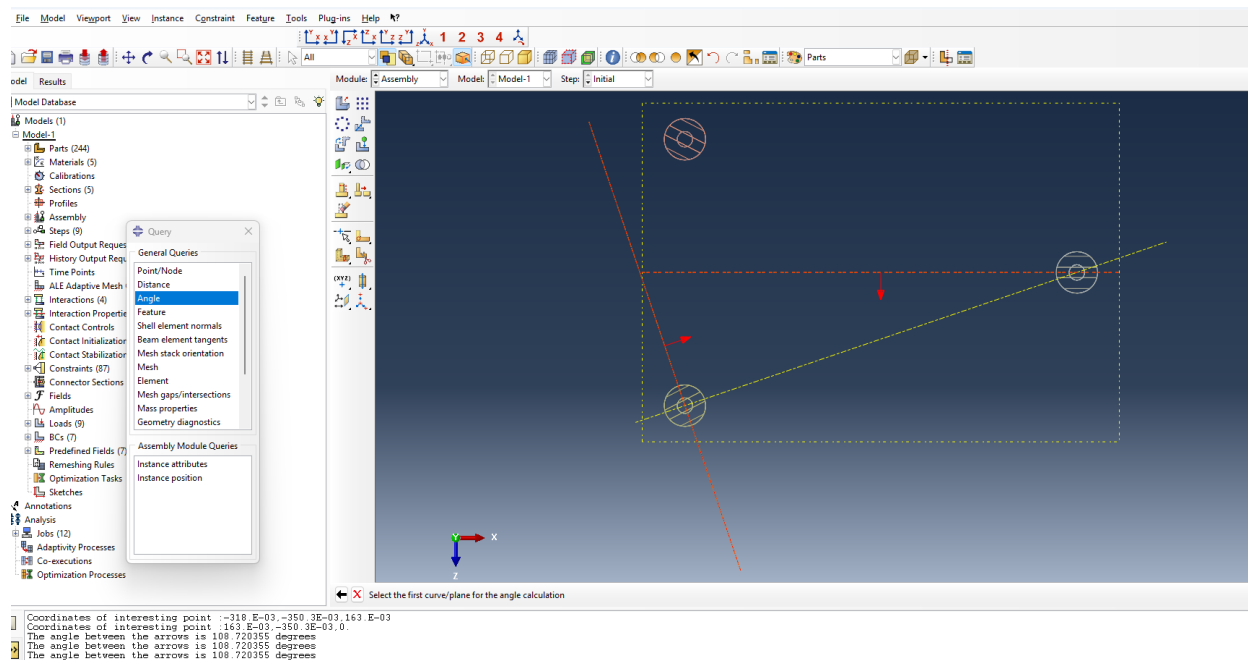


Figure 48 Seismic Overturning load direction

4.7 ASME BPVC ANALYSIS

The MRA assembly without beryllium was evaluated against the applicable ASME BPVC cases including seismic loads and thermal loads. The MRA will have negligible Live and Snow Loads. The Maximum Allowable working pressure with water will be 5 bar and the normal operating pressure 3 bar. The operating environment in the core vessel will be either vacuum or approximately 1 bar with helium. The earthquake (E) load will be evaluated for positive x and z in the lateral directions and negative y in the vertical direction. Negative directions were not analyzed because the results were expected to be similar. The overturning earthquake load will be applied in the most conservative direction. An accident case will be considered with normal 3 bar water pressure and 2 bar in the vacuum space. Thermal loads will be applied with 5 bar water pressure and 3 bar water pressure. A case with 3 bar water pressure and 1 bar core vessel pressure and a case for 3 bar water pressure with 2 bar in the vacuum space will also be included. ASME Case 18 is for a pressure test at 1.15×5 bar or 5.75 bar. The analysis was done with two Abaqus models. The first was to include all cases without thermal and the second job to include the thermal cases with same mesh model. The preload (P) for all bolts and tie rods was included for all cases.

Table 5 shows the ASME Code cases and loads with the corresponding Abaqus cases number, in the sequence to be used for the two jobs. Thermal Fatigue evaluations were done for beam trips from normal operation with 3 bar water pressure and vacuum in the core vessel. Piping stress analysis will be done separately and are not included in this analysis. Bolt and tie rod pull out stress evaluations will be done separately and are not included in this analysis.

Table 5 ASME MRA Cases and loads

ASME Case	Abaqus case	Water Pressure (P bar)	Core Vessel pressure (bar)	Weight (D)	Vacuum Space Pressure (bar)	Seismic load (E)	Thermal T
1	1	5	0	D			
1	3	3	0	D	2	0	
3	10	3	1	D	0	0	T
3	8	5	0	D	0	0	T
5	7	3	0	.6D	0	.7E overturn	
6	4	3	0	D	0	.7 Ex	
6	5	3	0	D	0	.7 Ez	
6	6	3	0	D	0	.7 Ey	
9	9	3	0	D	0	0	T
18	2	5.75	0	D	0	0	
	11	3	0	D	2	0	T

The Abaqus case numbers show the sequence for calculations. The first 9 Abaqus cases without thermal loads were developed with the cae file mra_602_S.cae with one input file (mra_602_S5.inp). An initial predetermined field of 20 °C was applied to all nodes. Bolt and tie rod prestress was applied as the first step in all analysis and propagated for remaining steps. In these following steps the preloads were modified to be constant length rather than constant stress. Figure 49 shows the load manager for the steps. Loads 1,2 and 3 are the preloads previously described. Load 6 is gravity (-9.8 m/s²). Steps 3 through 9 correspond to Abaqus cases 1 through 7 from

Table 5 ASME MRA Cases and loads.

Load Manager

	Name	preload	gravity	Step-3	Step-4	Step-5	Step-6	Step-7	Step-8	Step-9
✓	EX						Created	Deactivated		
✓	EY								Created	Deactivated
✓	EZ							Created	Deactivated	
✓	Eoverturning									Created
✓	Load-1	Created	Modified	Propagated	Propagated	Propagated	Propagated	Propagated	Propagated	Propagated
✓	Load-2	Created	Modified	Propagated	Propagated	Propagated	Propagated	Propagated	Propagated	Propagated
✓	Load-3	Created	Modified	Propagated	Propagated	Propagated	Propagated	Propagated	Propagated	Propagated
✓	Load-6		Created	Propagated	Propagated	Propagated	Propagated	Propagated	Propagated	Deactivated
✓	vac 2bar					Created	Deactivated			
✓	water_3bar					Created	Propagated	Propagated	Propagated	Propagated
✓	water_5_75_ba				Created	Deactivated				
✓	water_5_bar			Created	Deactivated					

Edit...

Move Left

Move Right

Activate

Deactivate

Step procedure: Static, General

Load type: Gravity

Load status:

Create...

Copy...

Rename...

Delete...

Dismiss

Figure 49 mra_602_S load manager for non-thermal cases

The applied loads for the seismic overturning case are shown in Figure 50.

Edit Load

Name: Eoverturning

Type: Gravity

Step: Step-9 (Static, General)

Region: (Whole Model)

Distribution: Uniform $f(x)$

Component 1: 0.6775

Component 2: -5.88

Component 3: 2

Amplitude: (Ramp) $f(t)$

OK

Cancel

Figure 50 Overturning loads

The four thermal cases were developed from the mra_602_T cae file with one input file (mra_602_T3.inp). The load manager for these cases is shown in Figure 51. Initial conditions and preloads were the same as for the non-thermal cases. A step was added for all nodes at 32 °C and with 3 bar water pressure. This was used for thermal fatigue evaluation as the conditions after a beam trip from normal operation. The 5 bar, 3 bar and 3 bar with 1 bar Core Vessel pressure with normal operating temperatures correspond to the Abaqus cases 8,9 and 10. The case with 2bar in the vacuum space and 3 bar water pressure is Abaqus case 11.

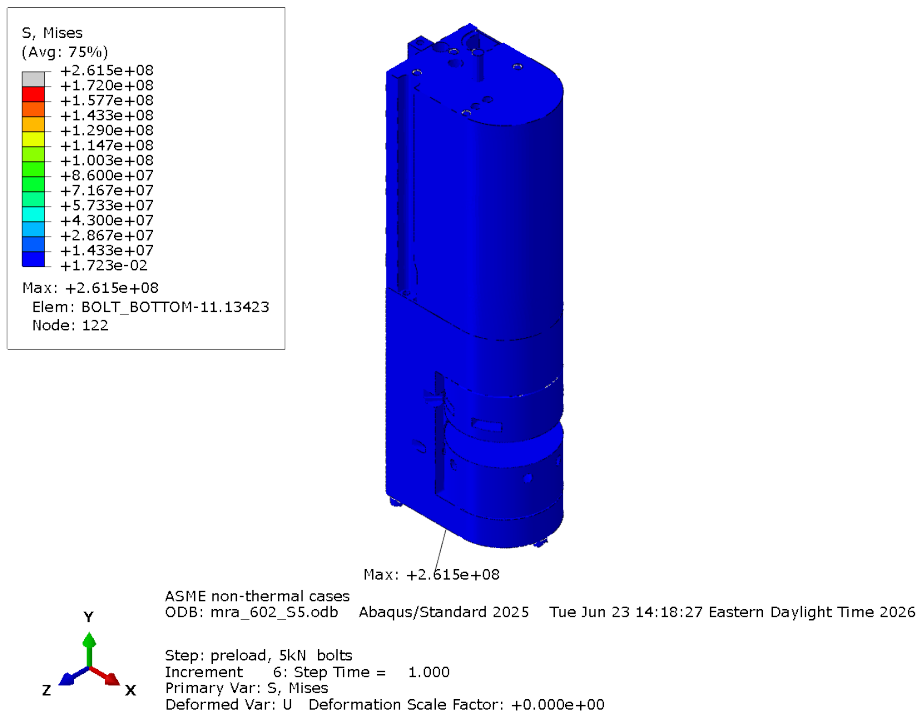


Figure 52 Preload overall assembly stress (Pa) peak stress was 262 MPa at a bottom bolt connection

Tie rod stresses are shown in Figure 53. The midplane axial stress is 49.7 MPa as expected for a 16 mm diameter rod with 10 kN preload. The peak of 170 MPa is at a node singularity just above the tie connection at the bottom where a taper starts.

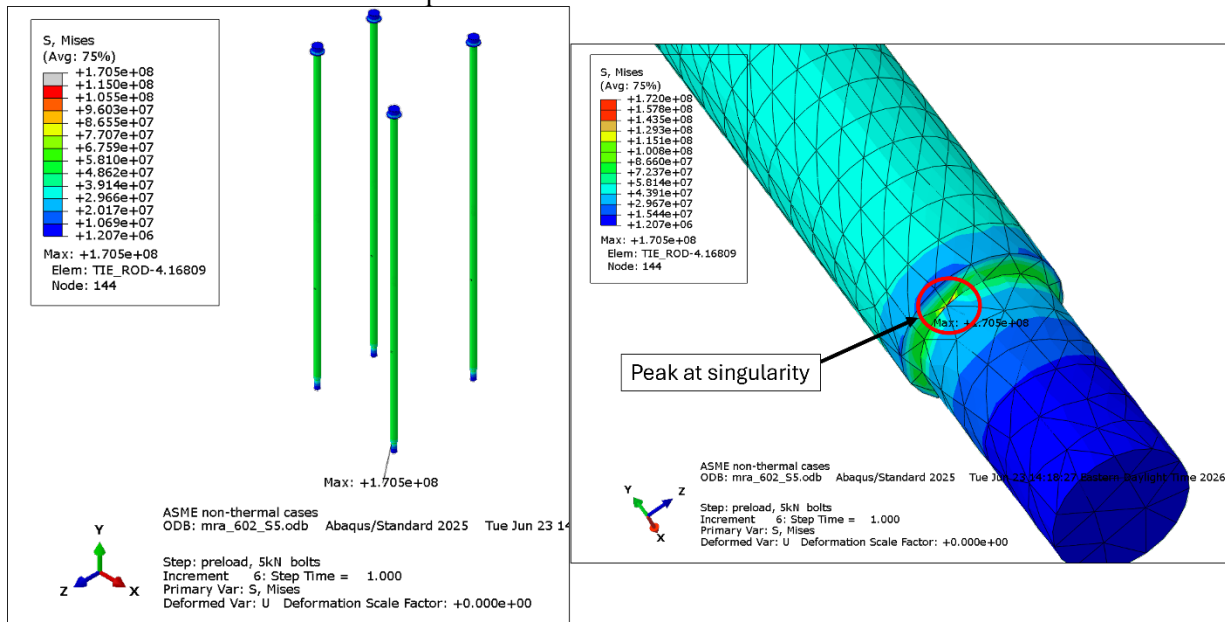


Figure 53 Tie rod stress (Pa) peak stress 170 MPa at bottom tie with 49.7 MPa axial midplane stress

The bolt stresses are shown in Figure 54 with an axial midplane stress of 70.12 MPa as expected for the 9.525 mm diameter bolt with a 5 kN load. Figure 55 shows the total load for 12 bolts as 60 kN as

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expected. Figure 56 shows that the high peak stress of 261 MPa is at a singularity where the bolt head connects with the shaft near the tie to the backbone.

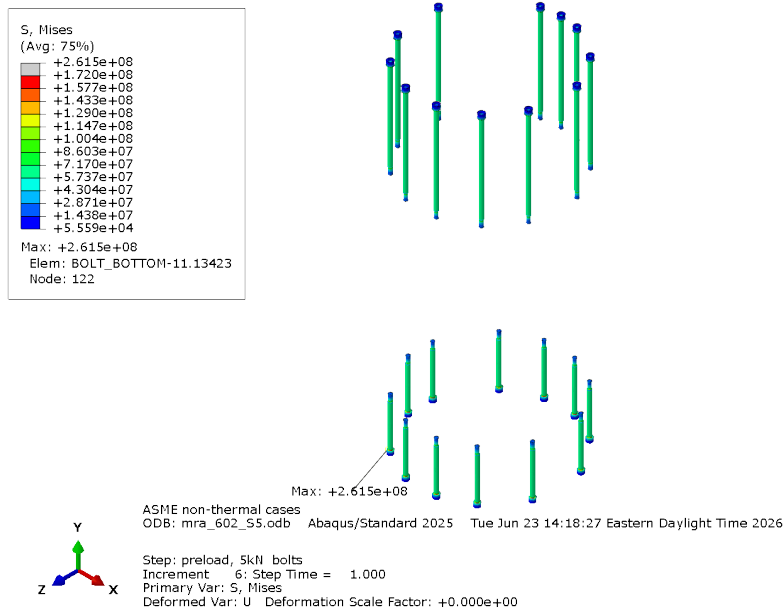


Figure 54 Bolt stress (Pa) peak stress 262 MPa at connection and 70.2 MPa axial midplane stress

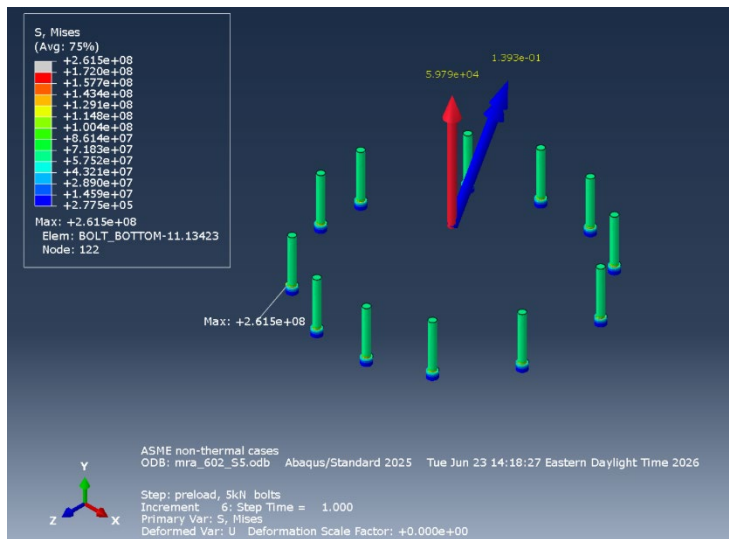


Figure 55 Lower 12 bolts stress (Pa) and load (N) with y cut showing total preload of 60 kN

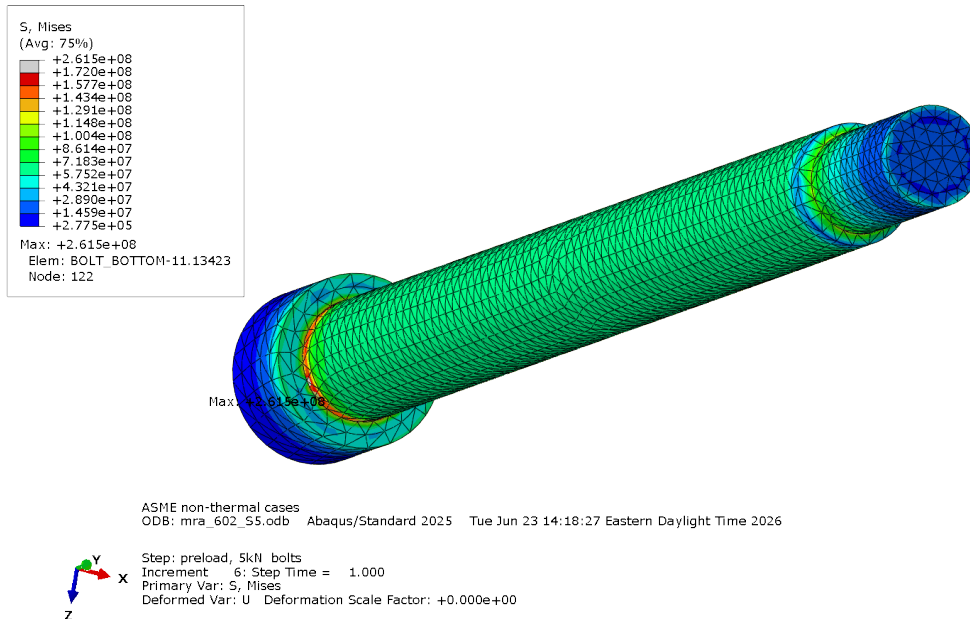


Figure 56 Lower bolt stress (Pa) singularity at joint with head with 172 MPa scale maximum

Figure 57 shows the backbone with a peak stress of 125 MPa in the contact tie area edge for a lower bolt. This is below the 1.5 Sm limit of 172 MPa for 316L.

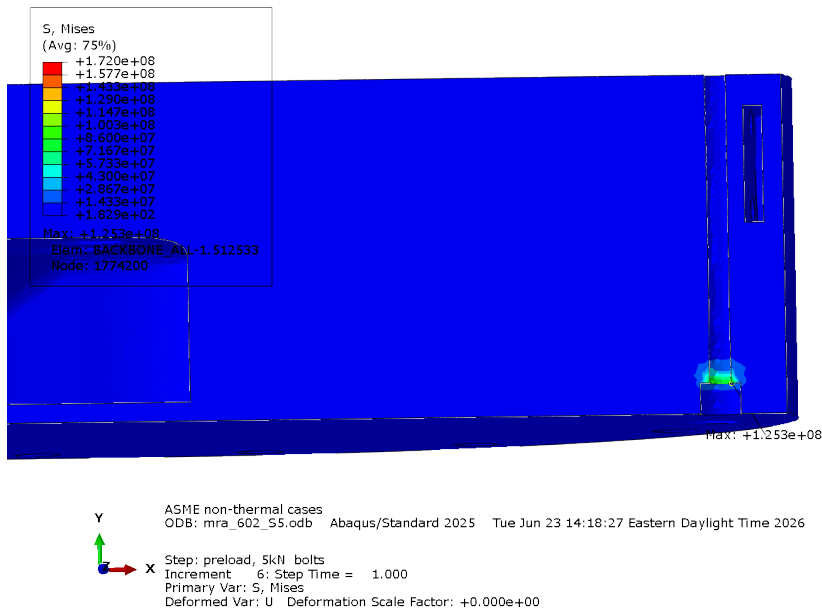


Figure 57 Backbone stress (Pa) peak stress 125MPa at bolt head tie

The Contact Pressure on the surfaces of the backbone with the upper and lower reflector vessels is shown in Figure 58 with a peak of 38 MPa adjacent to bolt connections.

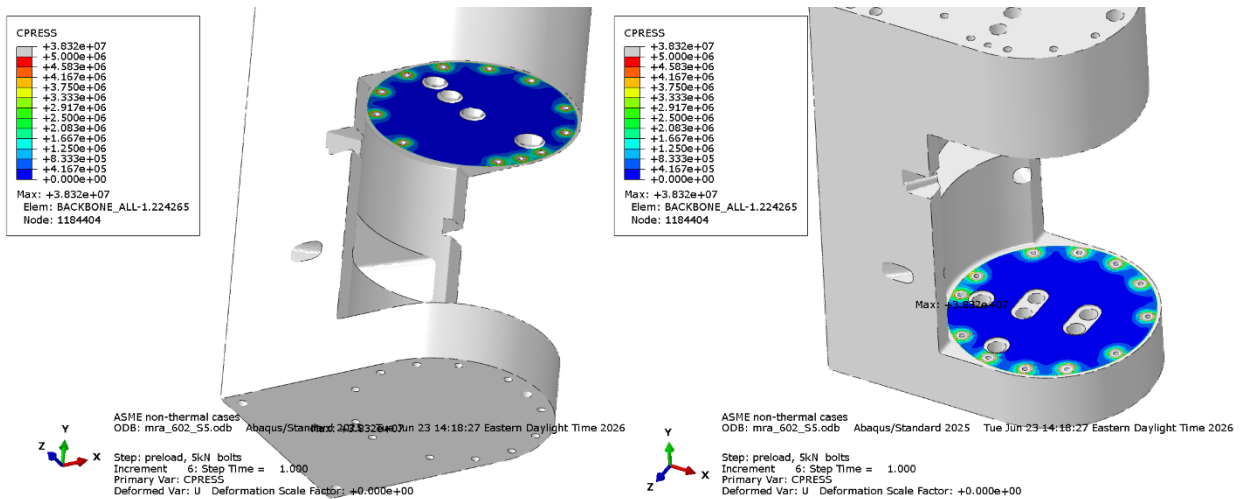


Figure 58 Backbone to reflector vessel contact pressures (Pa) with preload – peak 38 MPa

The upper shielding peak stress shown in Figure 59 is 82.9 MPa in the contact area with the head of a tie rod.

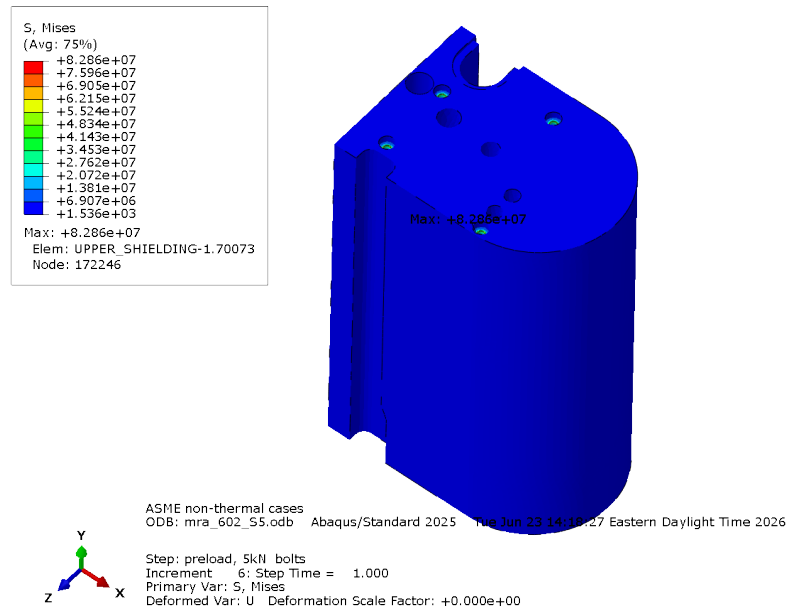


Figure 59 Upper shielding stress (Pa) prestress peak stress 82.9 MPa at tie rod head tie

The upper reflector vessel peak stress was an artificial value of 121 MPa around the tie connection to bolts. The actual threaded connection is expected to spread the load and reduce the peak stress. No other high stress areas are seen in the vessel. Figure 60 shows the vessel stress with a cut view through a mounting hole shows the peak stress localized on the edge where the tie connection ends.

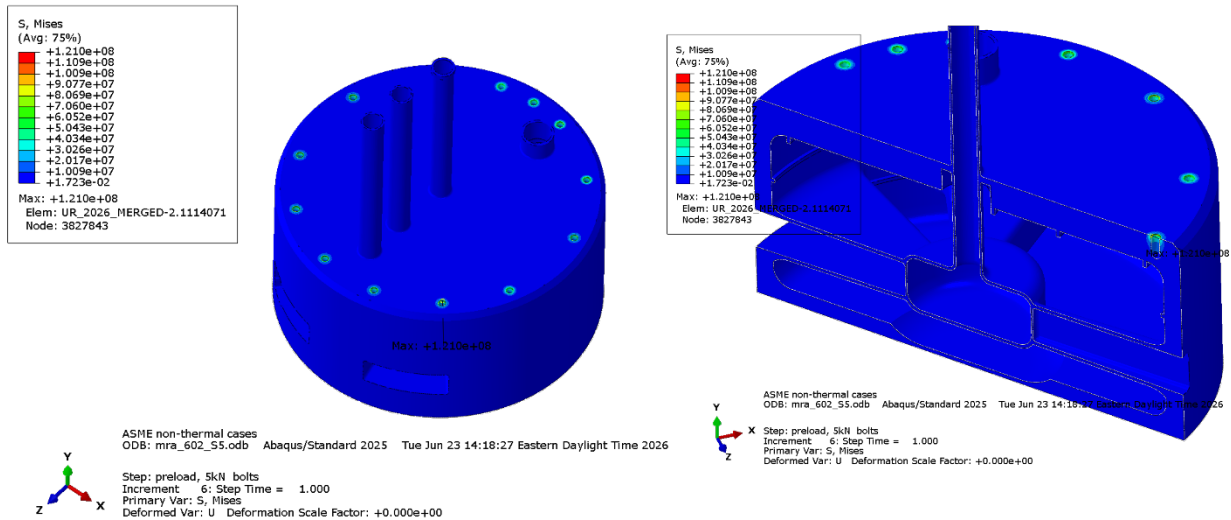


Figure 60 Upper reflector vessel stress (Pa) artificial peak stress 121 MPa at bolt tie

The lower reflector vessel stresses also have a peak near the bolts with a maximum of 89 MPa as shown in Figure 61. A contact status Figure 62 shows that contact is only around the outer radius and not in the central zone.

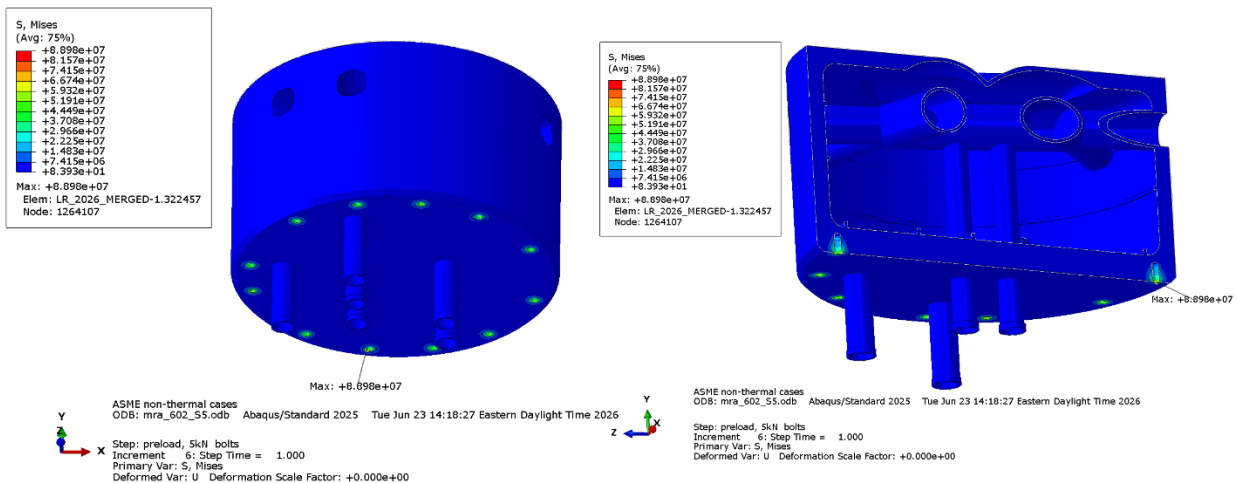


Figure 61 Prestress Bottom reflector vessel stress (Pa) peak stress 89 MPa by bolt tie edges

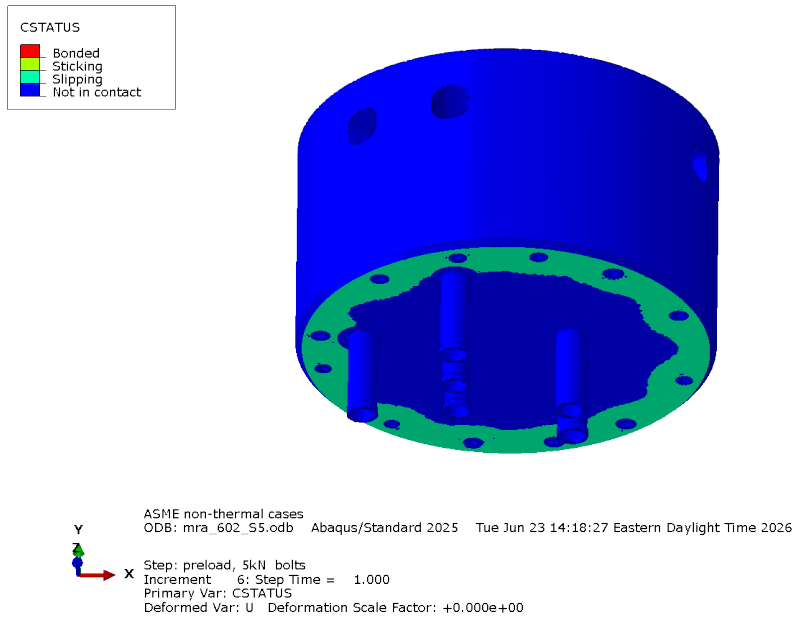


Figure 62 Prestress bottom reflector vessel contact status

5.2 PRELOAD AND GRAVITY

Gravity loads were small compared to the preload. The assembly peak stress was similar to preload case. The lower mounts showed peak stresses of approximately 100 MPa around the edges of the central channel between the angled faces as shown in Figure 63. A view cut through the three mounts show a total vertical load of 17.6 kN, consistent with the total model mass of 1,794 kg.

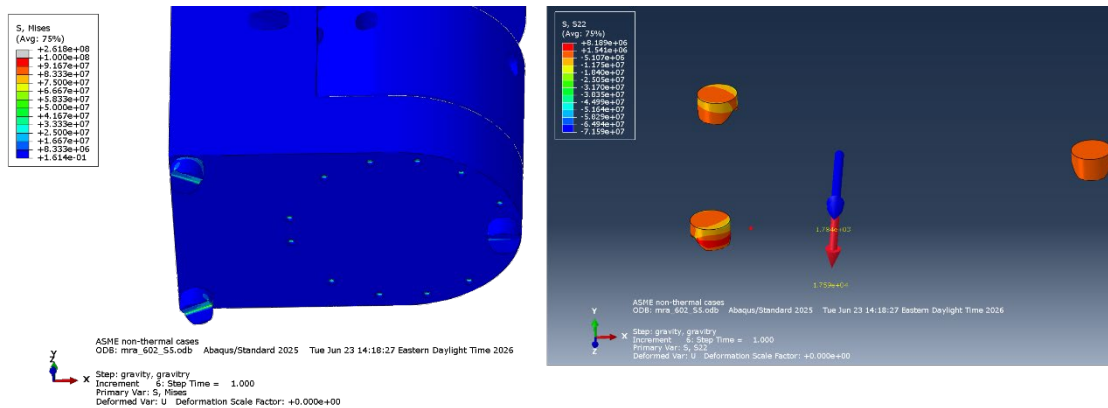


Figure 63 Preload and gravity stress (Pa) on lower mounts with 100 MPa scale maximum and mount with S22 and 17.6 kN load

5.3 PRELOAD GRAVITY WATER 5 BAR – (ASME CASE 1 ABAQUS CASE 1)

The following results are for 5 bar water pressure with gravity and preload. The preload was modified to give constant length rather than constant stress on the bolts and tie rods. The core vessel was assumed to be in vacuum.

The overall assembly peak stress was 262 MPa in a lower bolt connection as shown in Figure 64 with a scale maximum of 100 MPa. The bolt connection peak by the head was similar to the preload case.

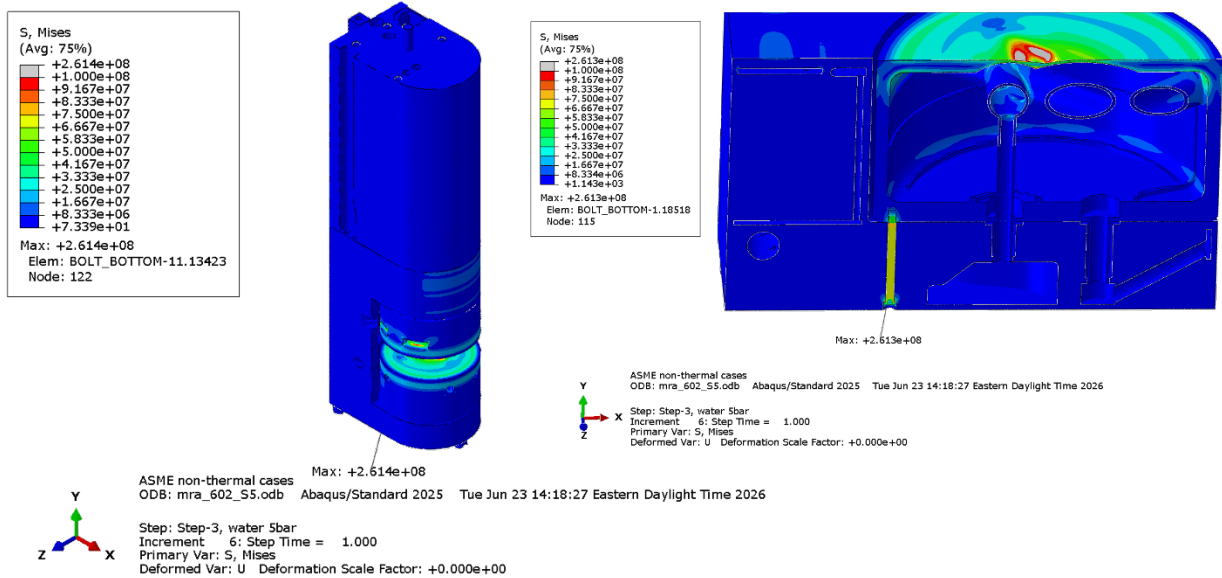


Figure 64 Overall assembly stress (Pa) Stress Peak 262 MPa at a bottom bolt with 100 MPa scale maximum

The peak stress in the backbone was 127 MPa by the connection to a lower bolt as shown in Figure 65. This also shows that the stresses in the thinner water channel covers were below 50 MPa.

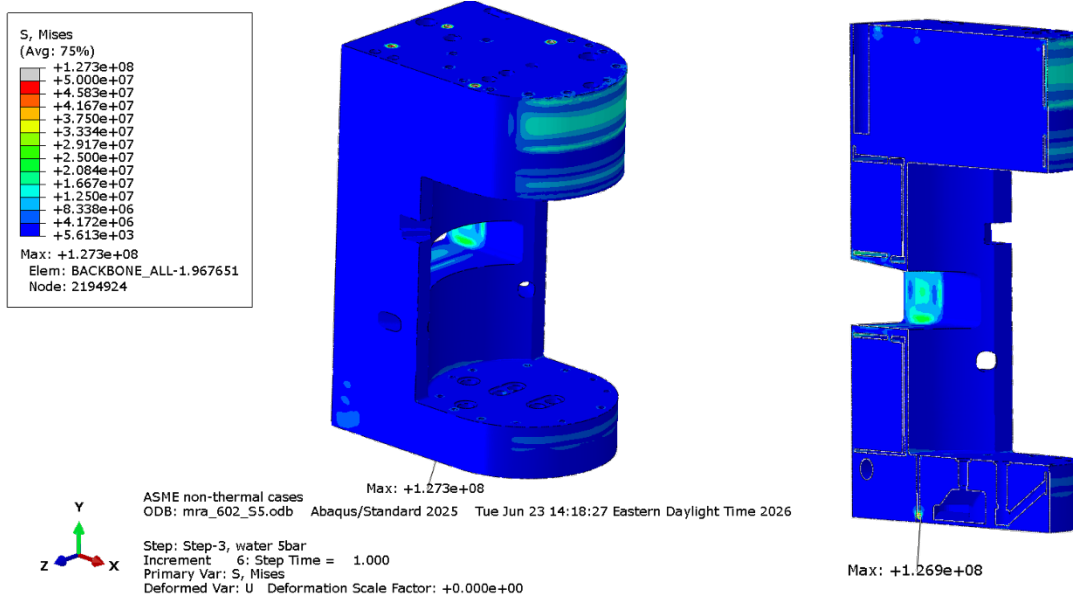


Figure 65 Backbone stress (Pa) with gravity, preload and 5 bar (5e5 Pa) water pressure

The 5 bar water pressure in the upper and lower reflector vessels increased the contact areas with the backbone as shown in Figure 66 as compared to preload only in Figure 62.

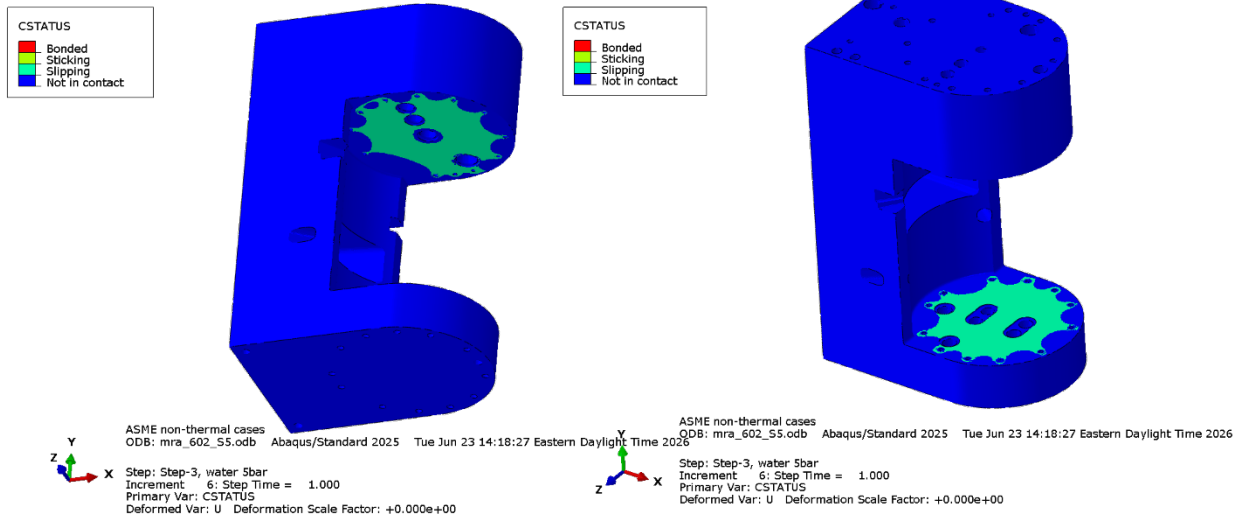


Figure 66 Backbone contact status with 5 bar (5e5 Pa) water pressure in reflector vessels

The stresses on the welds connecting the backbone sections were all below 20 MPa for this case. Figure 67 shows views at the elevation of the contact surfaces of the upper and lower reflector vessel looking vertically up and down at the areas which have been bonded to simulate the welds with a 20 MPa scale maximum.

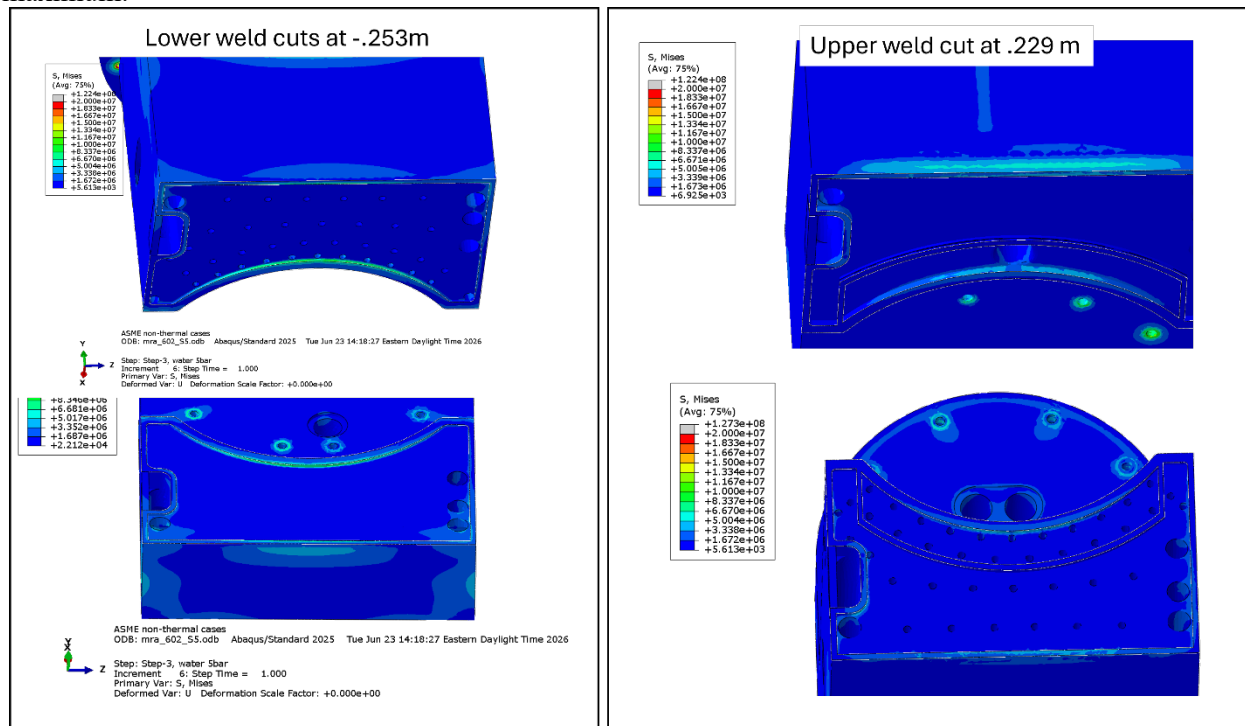


Figure 67 backbone upper and lower weld stresses Pa for 5 bar water pressure case with a 20 MPa scale maximum

Views of the backbone cut at $z=0$ with a 30 MPa scale maximum and 400X displacements are shown in Figure 68.

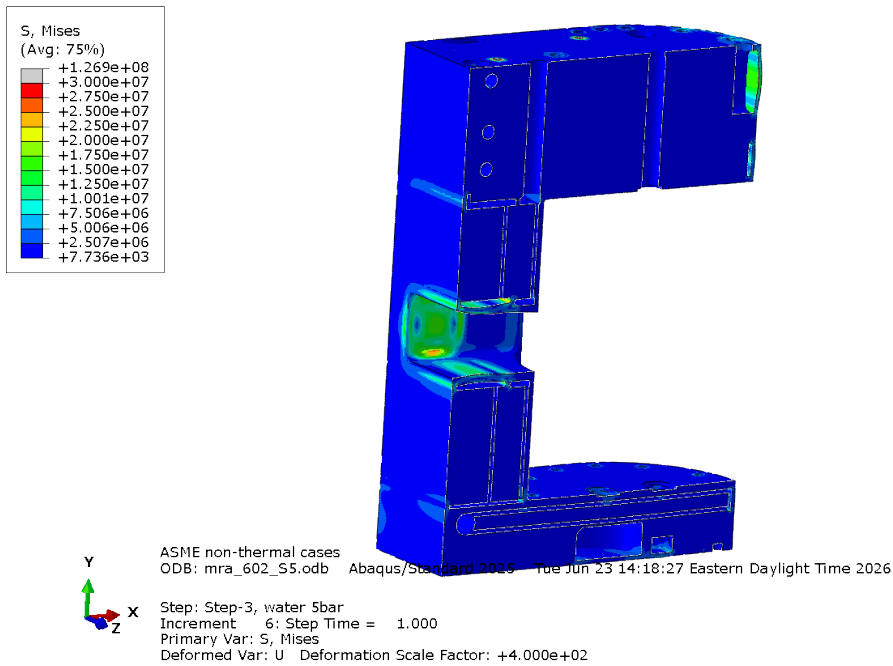


Figure 68 backbone stress (Pa) with 30 MPa scale cut at z=0 and 400x displacements

The bolt and tie rod stresses did not change significantly from the preload values as shown below with a 115 MPa scale maximum.

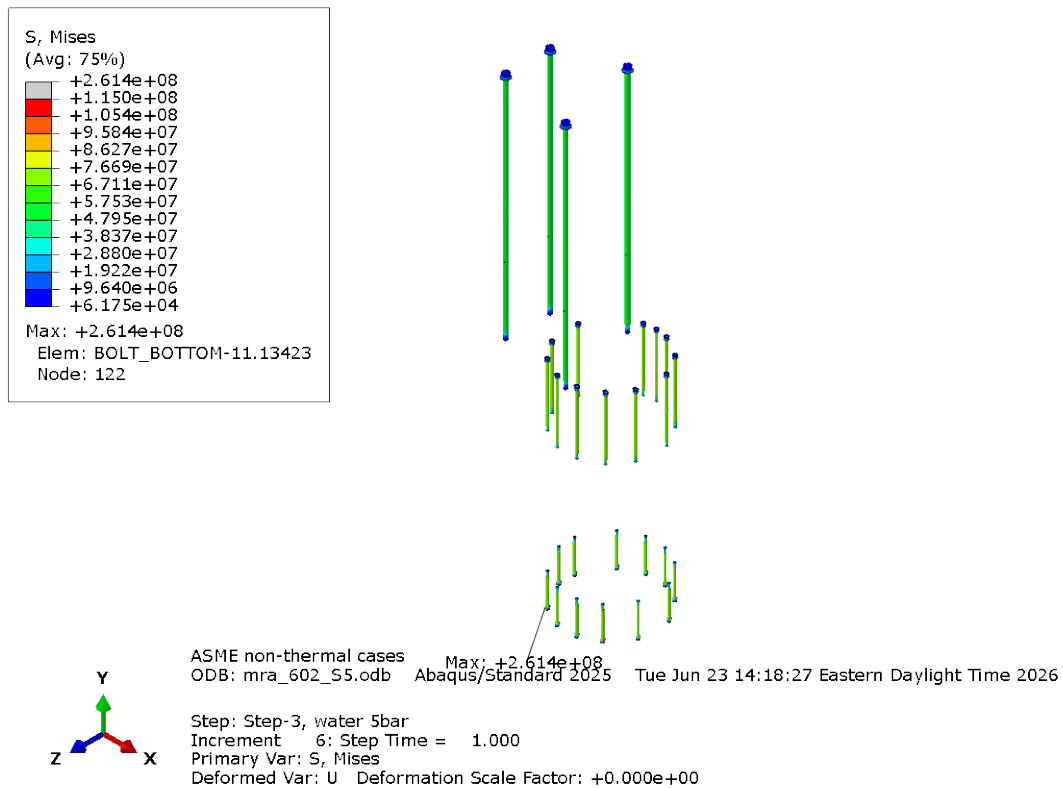


Figure 69 Bolt and tie rod stresses(Pa) for 5 bar (5e5 Pa)water pressure case

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The peak stress in the upper shielding was 83 MPa by a tie rod connection as shown in Figure 70.

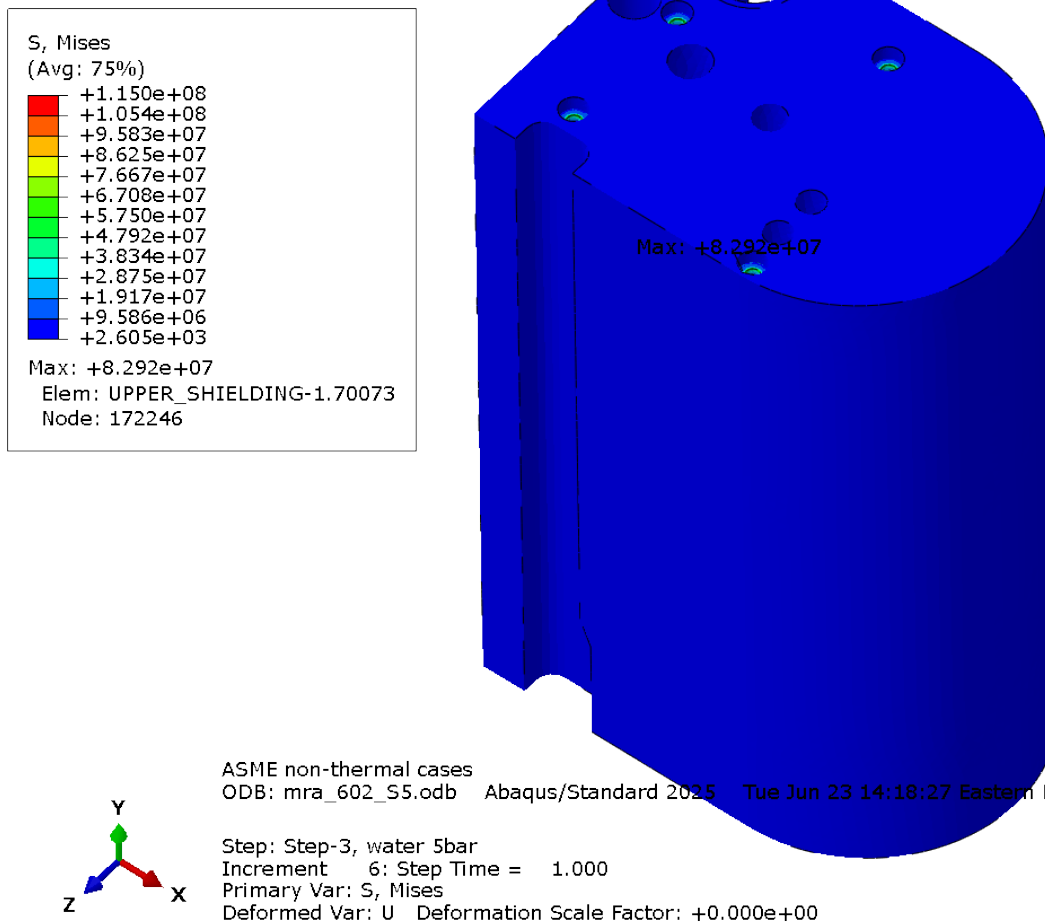


Figure 70 Upper shielding Stress (Pa) with 5 bar (5e5 Pa) water pressure gravity and preload

The upper reflector vessel stress is shown in Figure 71 with a peak value of 126.3 MPa on the inner shell corner around the moderator. This meets the 127 MPa 1.5 Sm limit for Al6061 T6. Figure 72 also shows the beam tubes with stresses below 127 MPa.

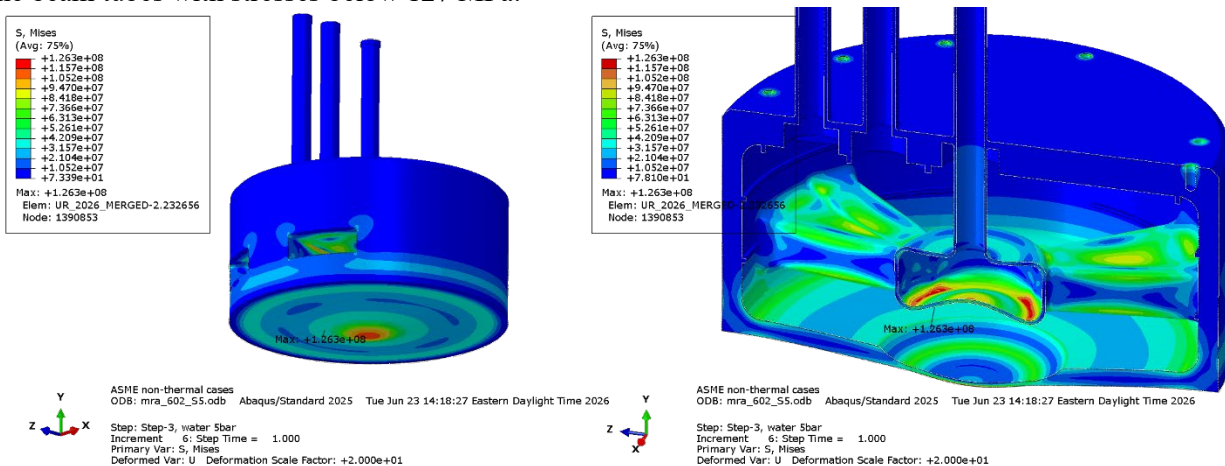


Figure 71 Upper Reflector Vessel stress (Pa) peak stress 126 MPa for 5 bar (5e5 Pa) case

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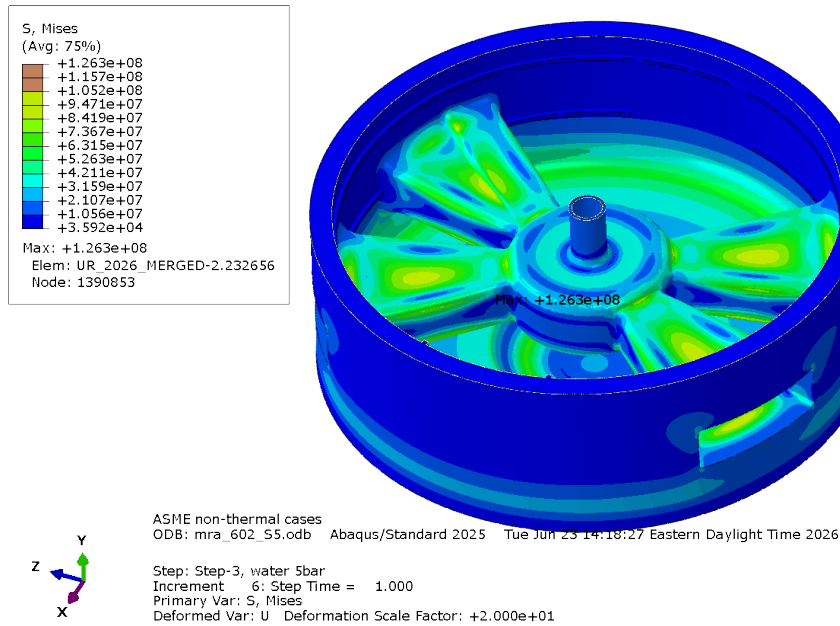


Figure 72 Upper Reflector vessel cut to show beam tubes Stress (Pa)

The allowable stress intensity limit for welded and heat affected T6 material is 83 MPa. A plot with an 83 MPa scale maximum is given in Figure 73.

Figure 73 shows several views of the upper reflector vessel with a scale maximum of 82.7 MPa which is the limit for welded material. Welds of the top and bottom plate have heat affected zones of approximately 5mm from the weld centerline. The closest location of a stress area above 82.7 MPa to a weld centerline is approximately 10 mm by the bottom of a beamline as shown in Figure 74.

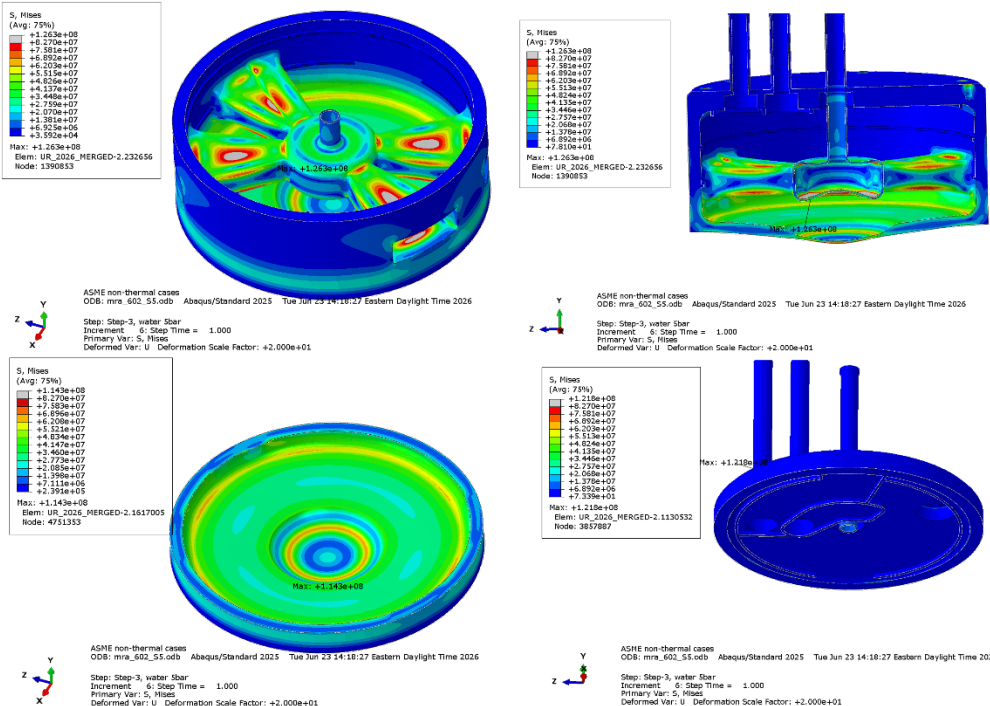


Figure 73 Upper reflector vessel stress (Pa) showing regions above the 82.7 MPa limit for welded 6061T6

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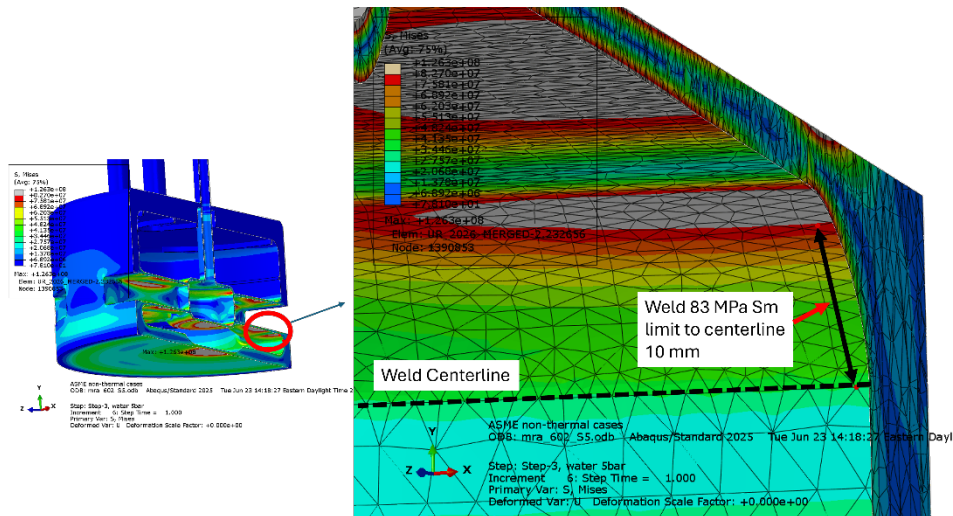


Figure 74 Upper Reflector 5bar (5e5 Pa) water case closest surface stress (Pa) above 82.7 MPa to weld centerline

The vertical displacements for the upper vessel are shown in Figure 75 with a peak of 0.7 mm up in the vacuum vessel shell and 0.99 mm down on the bottom surface. The lower vessel peak displacement up was 0.93 mm as shown in Figure 76.

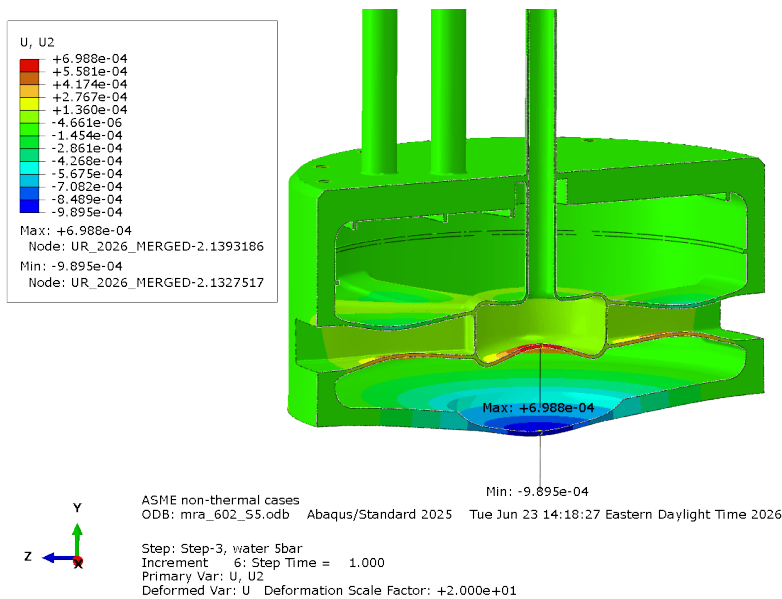


Figure 75 Upper Reflector vessel vertical displacement (m) peak 0.7 mm up in vacuum shell and 0.99 mm down on outer vessel wall.

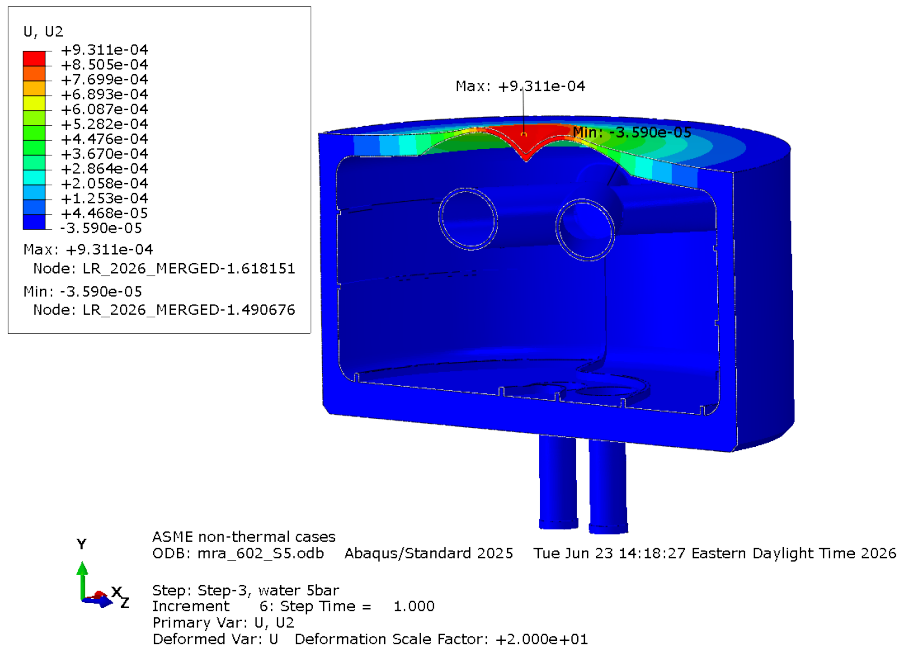


Figure 76 Lower reflector vertical displacement (m) with 5 bar (5e5 Pa) pressure

The lower reflector vessel peak stress was 124 MPa on the inner surface of the upper shell as shown in Figure 77.

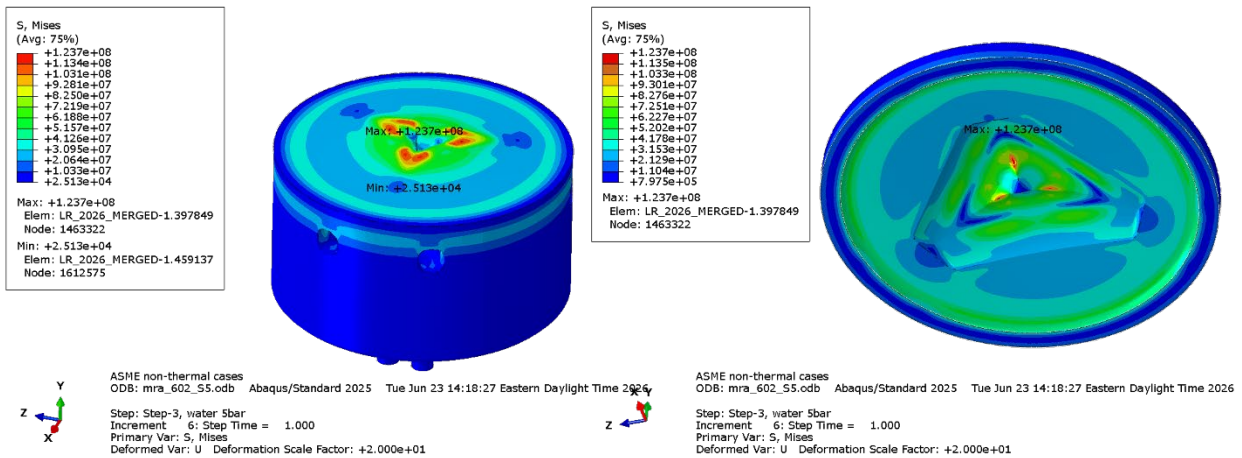


Figure 77 Bottom Reflector Vessel Stress (Pa) with 5 bar (5e5 Pa) water, preload and gravity – peak 124 MPa

A cut view just below the upper plate shows that all material near welds is below the 83 MPa limit for welded material (Figure 78).

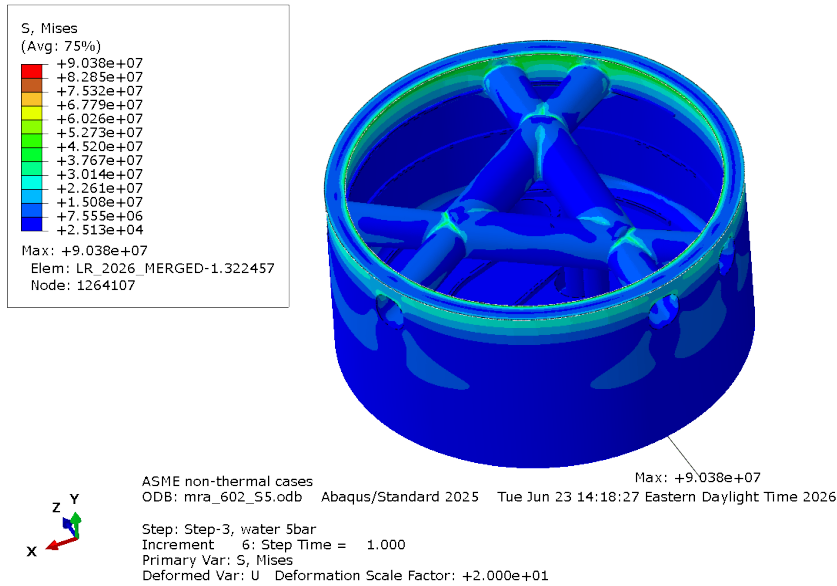


Figure 78 Bottom reflector vessel stress (Pa) showing all regions near welds below the 83 MPa limit for welded 6061 T6

The peak of 90 MPa is again at the edge of a tie to a bolt head and not realistic.

The backbone and reflector vessel water passages are all connected. The water wetted surfaces and the stress on those surfaces are shown in Figure 79. The peak was 125 MPa in the upper reflector vessel with most surfaces well below that.

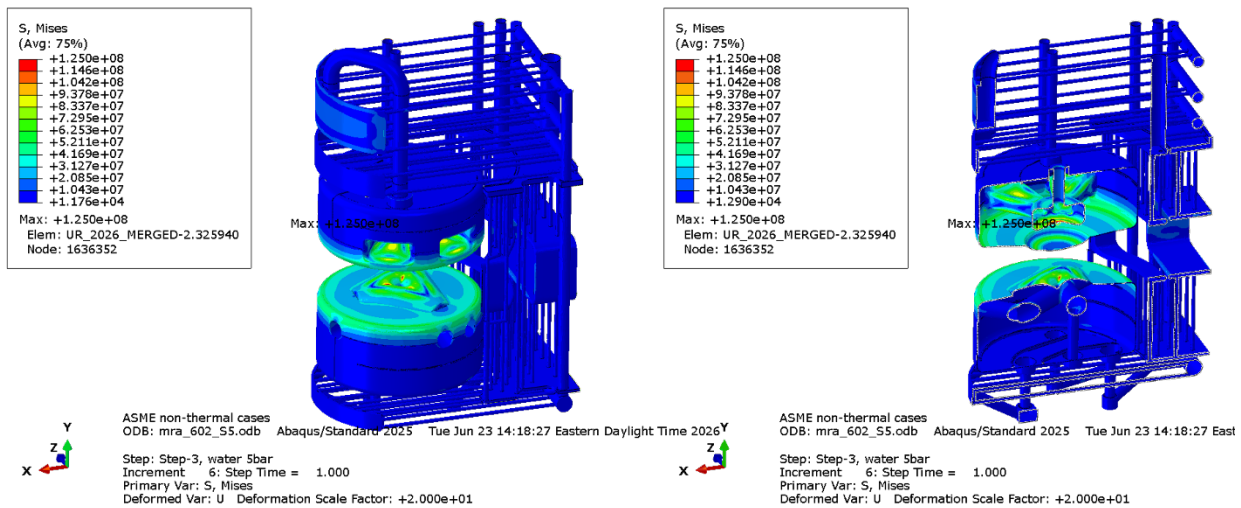
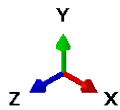
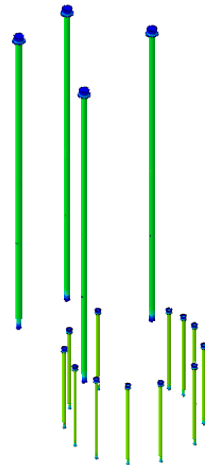
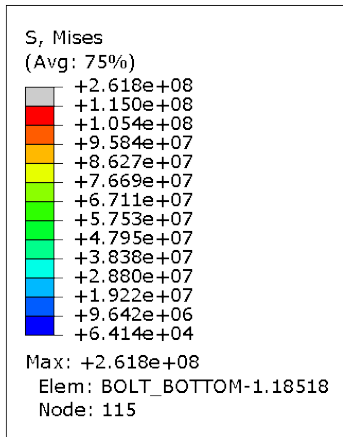


Figure 79 All water wetted surface stresses (Pa) with 5 bar (5e5 Pa) water pressure showing a 125 MPa maximum

5.4 PRELOAD GRAVITY WATER PRESSURE TEST (ASME CASE 18, ABAQUS CASE 2)

The results in this section are for the AMSE test pressure case with 1.15 x 5 bar pressure including preload and gravity. The tie rod and bolt stress is shown in Figure 80 with a peak of 261 MPa on a lower bolt adjacent to the tie connection at the bottom at a singularity.

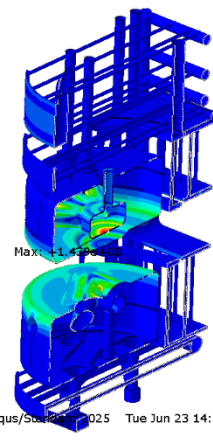
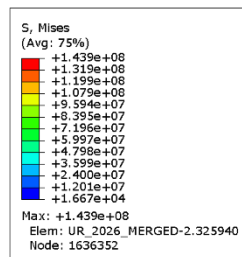
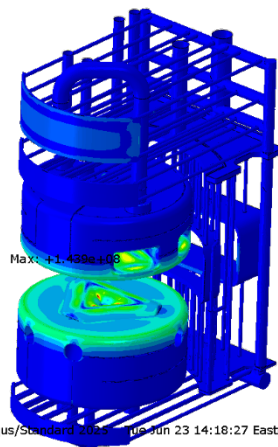
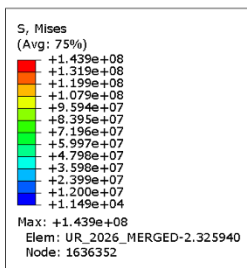


ASME non-thermal cases
ODB: mra_602_S5.odb Abaqus/Standard 2025 Tue Jun 23 14:18:27 Eastern Daylight Time 2026

Step: Step-4, water 5.75 bar
Increment: 6; Step Time = 1.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +0.000e+00

Figure 80 Bolt and tie rod stress (Pa) with 0 deformation scale factor. Bolt peak stress 261 MPa at singularity

Figure 81 shows the stress on the water wetted surfaces with a peak of 144 MPa on the upper reflector vessel inner shell.



ASME non-thermal cases
ODB: mra_602_S5.odb Abaqus/Standard 2025 Tue Jun 23 14:18:27 Eastern Daylight Time 2026

Step: Step-4, water 5.75 bar
Increment: 6; Step Time = 1.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +0.000e+00



ASME non-thermal cases
ODB: mra_602_S5.odb Abaqus/Standard 2025 Tue Jun 23 14:18:27 Eastern Daylight Time 2026

Step: Step-4, water 5.75 bar
Increment: 6; Step Time = 1.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +0.000e+00

Figure 81 Water surfaces stress (Pa) with 5.75 bar(5.75e5 Pa) water pressure

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The upper reflector vessel peak stress was 145.5 MPa in the corner of the shell around the moderator. A stress linearization path and evaluation was done starting at the peak stress location as shown in Figure 82.

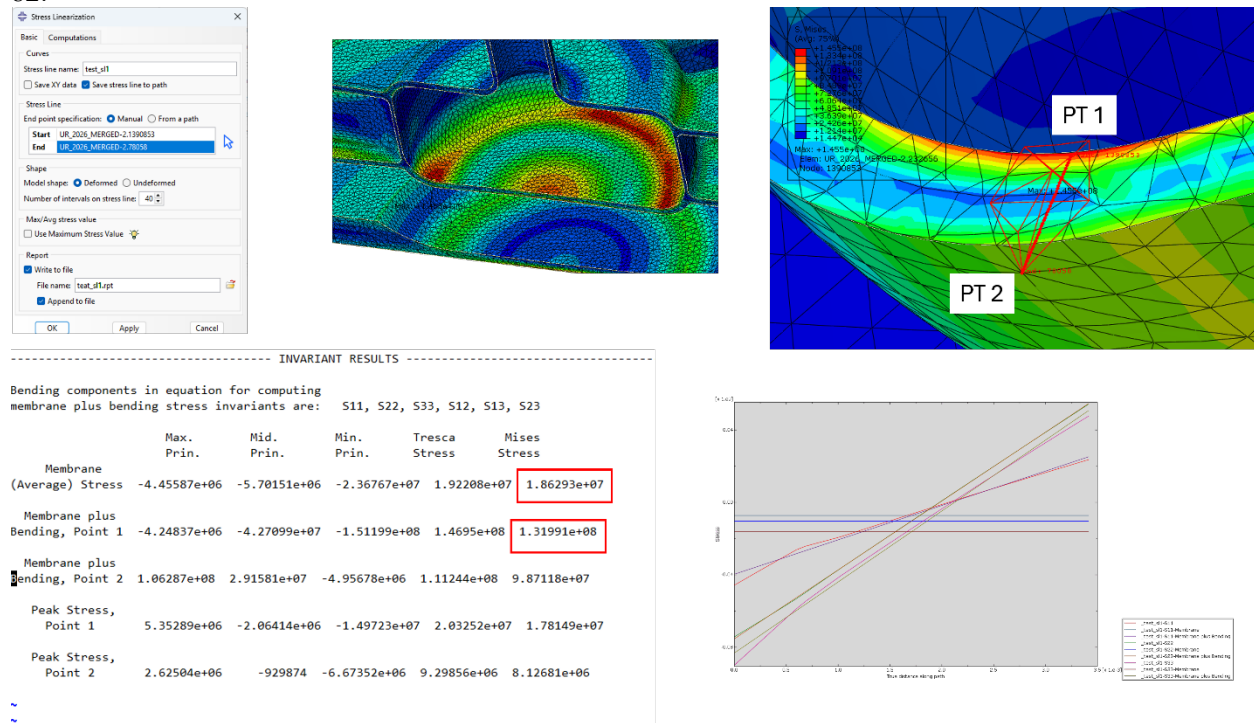


Figure 82 Upper Reflector vessel test pressure stress linearization (Pa,m)

The elastic stresses in the upper reflector vessel for the test pressure case were evaluated against the criteria in ASME case 4.1.6.2 Test Conditions. The shell with the peak stress is Al6061T6 with a yield stress (S_y) of 227.5 MPa (33 ksi). The membrane stress as shown in Figure 82 is 18.6 MPa which is less than $S_y/1.5$ so the acceptance criteria is

$$P_m + P_b < \gamma_{\min} S_y$$

Where

$$\gamma_{\min} = 1.5 \beta_\gamma \text{ and } \beta_\gamma = .8 \text{ for pneumatic testing and } \gamma_{\min} S_y = 273 \text{ MPa}$$

For this case $P_m + P_b = 131 \text{ MPa}$ at point 1 which is less than $\gamma_{\min} S_y$

A similar analysis for the lower vessel with the results shown in Figure 83. Stress linearization point 1 was the high stress node at 142 MPa. The membrane stress was 52 MPa and membrane plus bending was 141 MPa would show the elastic test condition criteria of 273 MPa is met.

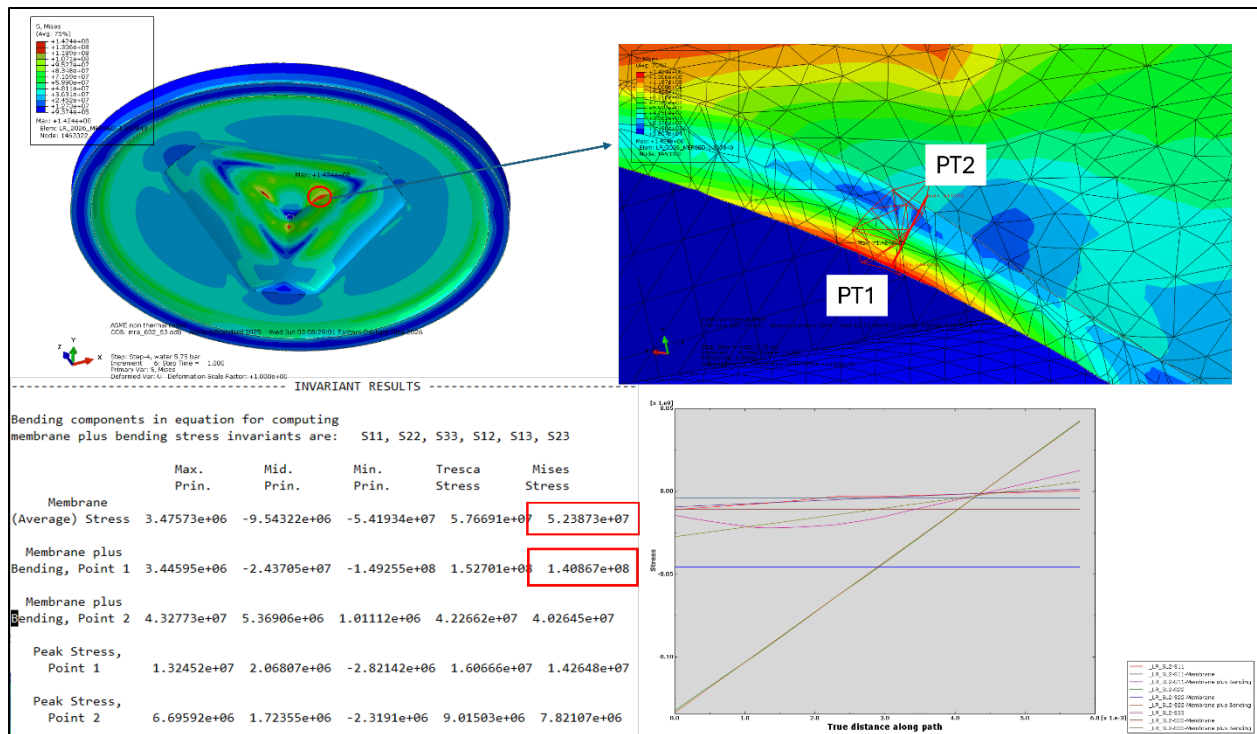
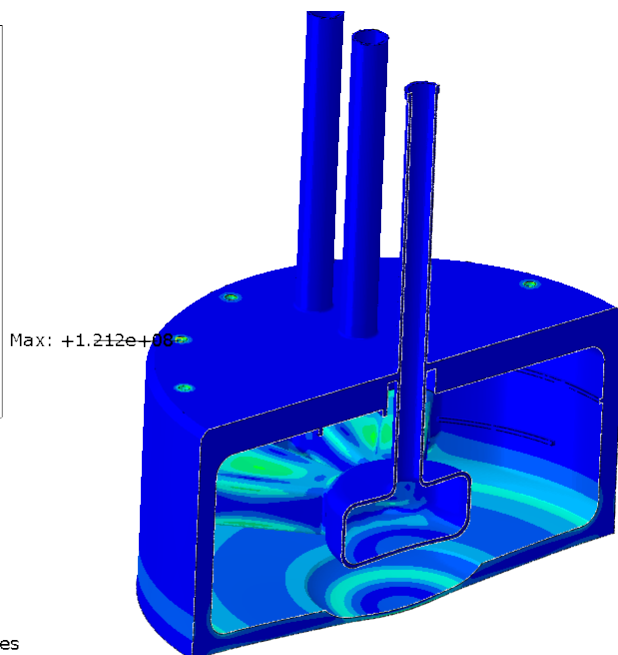
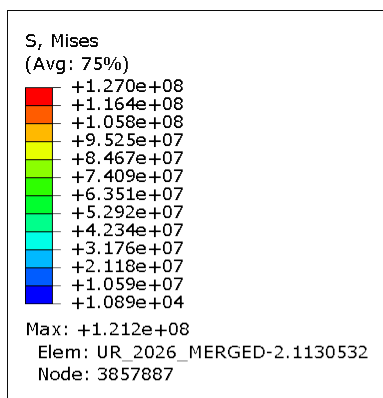


Figure 83 Lower Reflector Vessel test pressure stress linearization (Pa,m)

5.5 PRELOAD GRAVITY WATER 3 BAR, VACUUM 2 BAR, (ASME CASE 1 ABAQUS CASE 3)

Results in this section are for the ASME case with normal operating water pressure of 3 bar (3e5 Pa) and off-normal pressure of 2 bar in vacuum space. Preload and gravity also included with vacuum in core vessel.

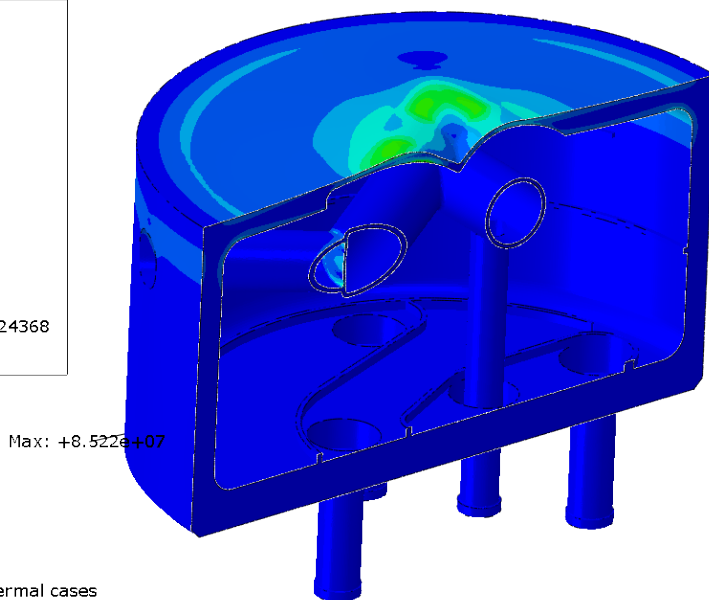
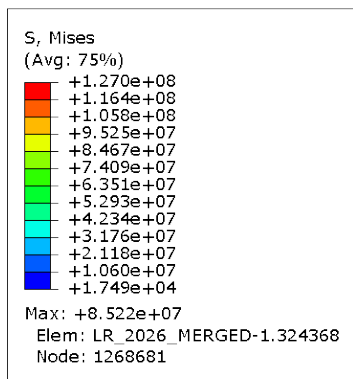
The upper and lower reflector vessel stresses are shown in Figure 84 and Figure 85 with a scale maximum of 127 MPa. The stress distributions are similar but reduced from the case with 5 bar water pressure. The peak stress at the bottom center outer surface of the upper reflector vessel for example reduced from 126 MPa to 71 MPa.



ASME non-thermal cases
ODB: mra_602_S5.odb Abaqus/Standard 2025 Tue Jun 23 14:18:27 Eastern Daylight Time 2026

Step: Step-5, water 3bar vacuum 2bar
Increment 6: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +2.000e+01

Figure 84 Upper Reflector vessel stress (Pa) with 127 MPa scale maximum. All stresses reduced from 5 bar case



ASME non-thermal cases
ODB: mra_602_S5.odb Abaqus/Standard 2025 Tue Jun 23 14:18:27 Eastern Daylight Time 2026

Step: Step-5, water 3bar vacuum 2bar
Increment 6: Step Time = 1.000
Primary Var: S, Mises
Deformed Var: U Deformation Scale Factor: +2.000e+01

Figure 85 Lower Reflector vessel stress (Pa) with 127 MPa scale maximum. All stresses reduced from 5 bar case

The surfaces which see 2 bar in an off-normal event are shown in Figure 86 with a peak stress of 44 MPa. This peak is in the lower reflector vessel aluminum with a 20X scale factor on displacements.

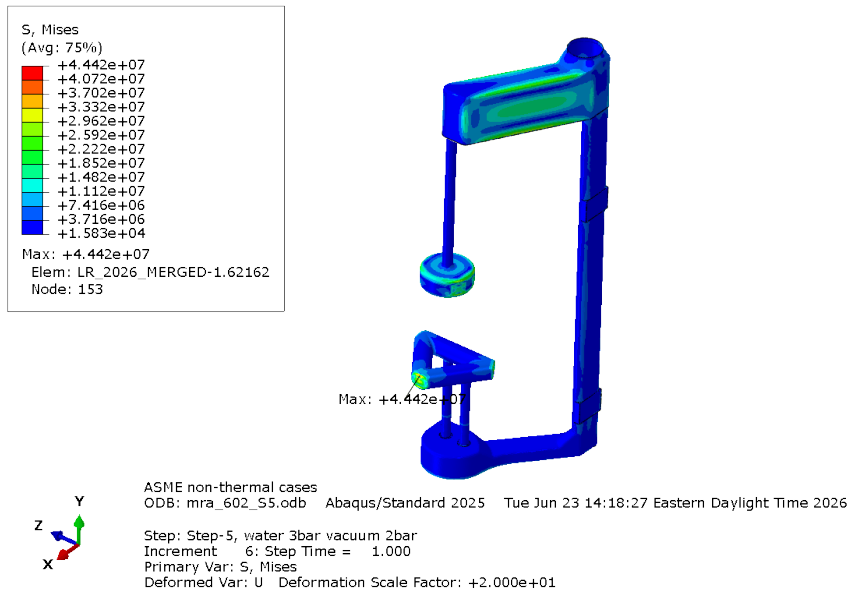


Figure 86 Vacuum surfaces stress (Pa) with 2 bar internal pressure – peak stress 44 MPa

A view showing the bottom of the assembly with a stress scale maximum of 20 MPa is shown in Figure 87 with a peak of approximately 18 MPa in the 316L vacuum cover plate at the bottom of the backbone.

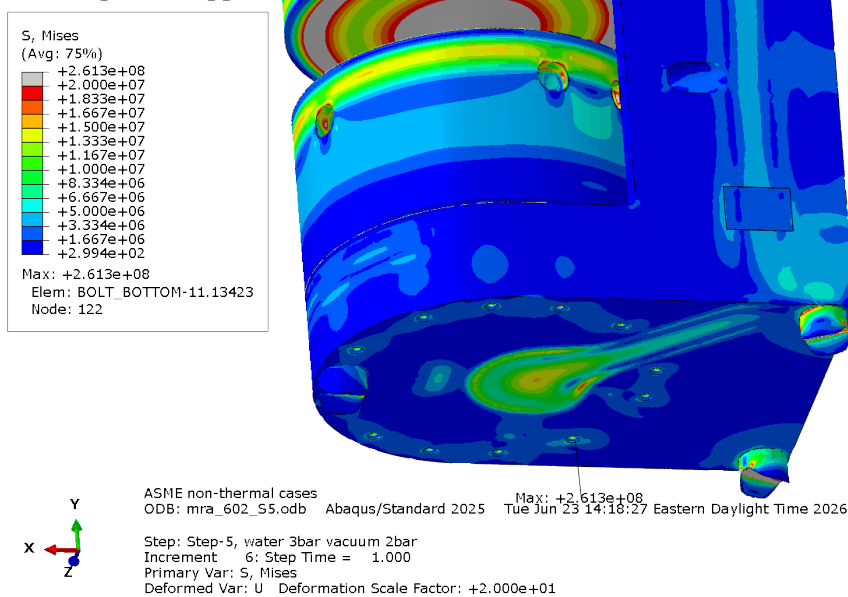
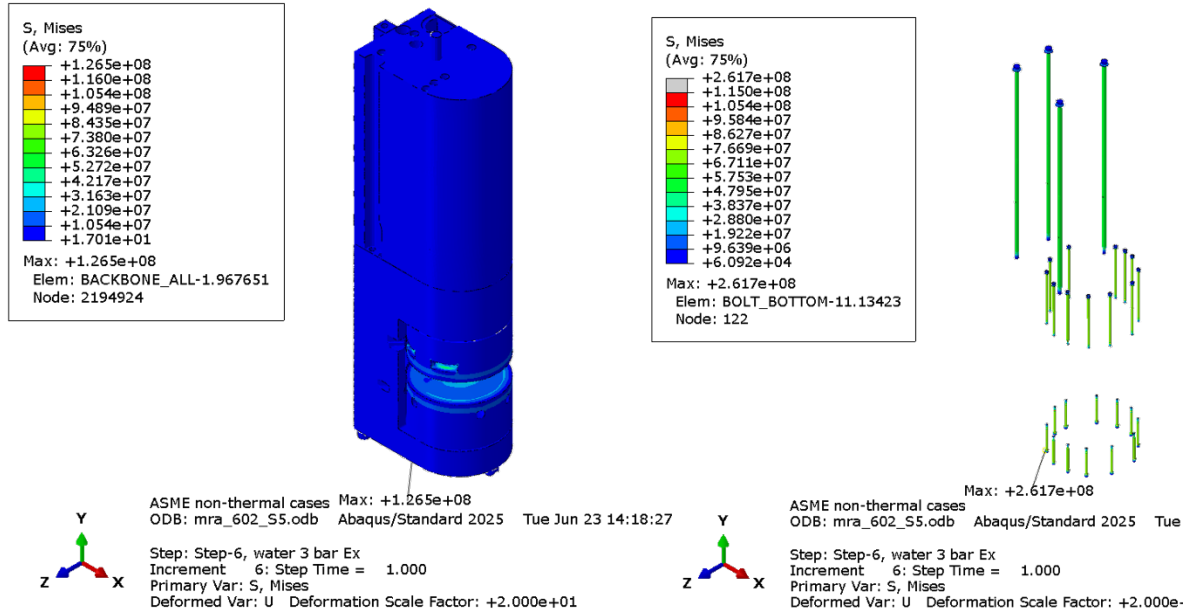


Figure 87 Bottom view of assembly showing peak stress (Pa) of approximately 18 MPa in vacuum cover for lower backbone

5.6 PRELOAD GAVITY WATER 3 BAR SEISMIC X (ASME CASE 6, ABAQUS CASE 4)

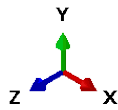
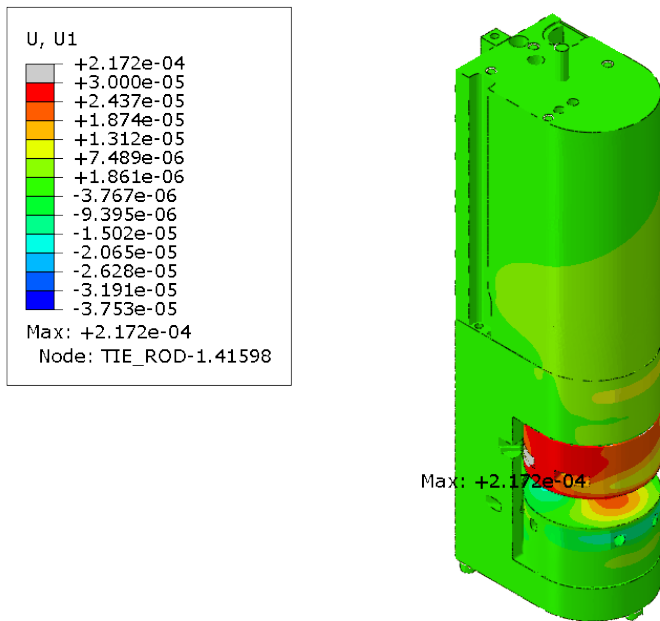
The following section results are for ASME case with seismic load in the +x direction of 0.2156 G or 2.113 m/s². The load development is given in Appendix A. The boundary condition only allowing vertical displacements on the seismic block hole surface nodes was applied for all seismic cases. Figure 88 shows the assembly stress without the bolts and tie rods which are shown separately. The overall peak assembly stress was 126 MPa, again by a lower bolt tie connection. The bolt and tie rod stresses were similar to previous cases with a peak at a singularity of 261 MPa. A view cut near the tie between the seismic block and upper shielding shows a load of approximately 4kN in the +x direction in the seismic block (Figure 90).



+

Figure 88 Seismic x Assembly stresses (Pa) not including bolts and tie rods with bolt and tie rod stresses shown separately

The seismic load in the positive x direction (U1) towards the target causes very little displacement in that direction. Figure 90 for U1 displacements shows peak displacement towards the target of 0.22 mm. Figure 90 shows a top view with a factor of 2000 on displacement. Displacement of reflector vessels towards the target can be seen. A cut was also taken through the seismic block close to the connection to the upper shielding which shows the load in the target (+X) direction was 3.8 kN.



ASME non-thermal cases
ODB: mra_602_S5.odb Abaqus/Standard 2025 Tue Jun 23 14:18:27 Eastern Daylight Time 2026

Step: Step-6, water 3 bar Ex
Increment 6: Step Time = 1.000
Primary Var: U, U1
Deformed Var: U Deformation Scale Factor: +2.000e+01

Figure 89 X direction (U1) displacement (m) with Ex seismic load

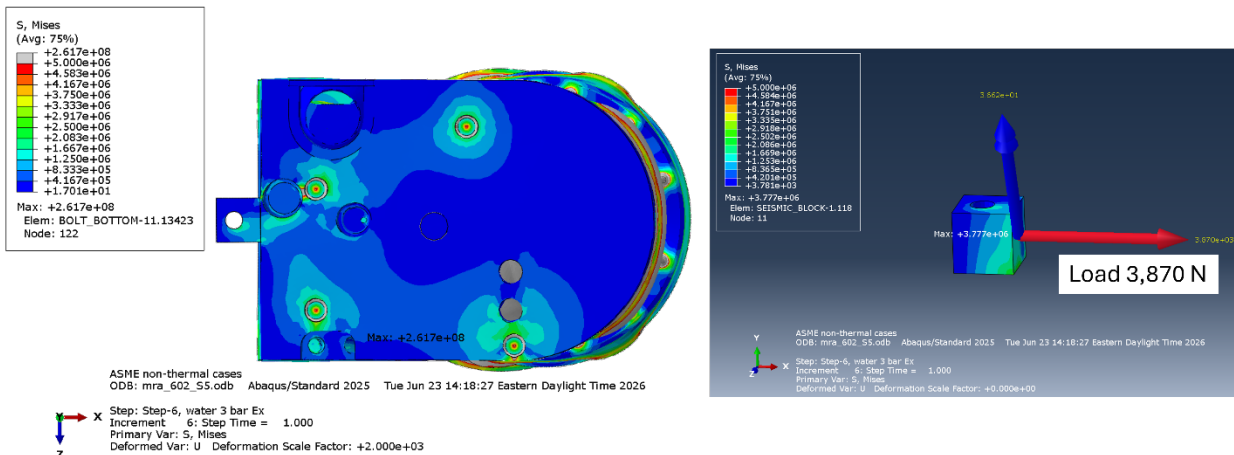


Figure 90 Assembly stress (Pa) with +X seismic load with factors of 2000 on displacement (m) showing 3.9 kN load on seismic block

The stress distribution in the upper shielding is shown in Figure 91 with a peak of 83 MPa near a tie rod head connection. The stresses around the tie to the seismic block are also shown with a scale maximum of 10 MPa.

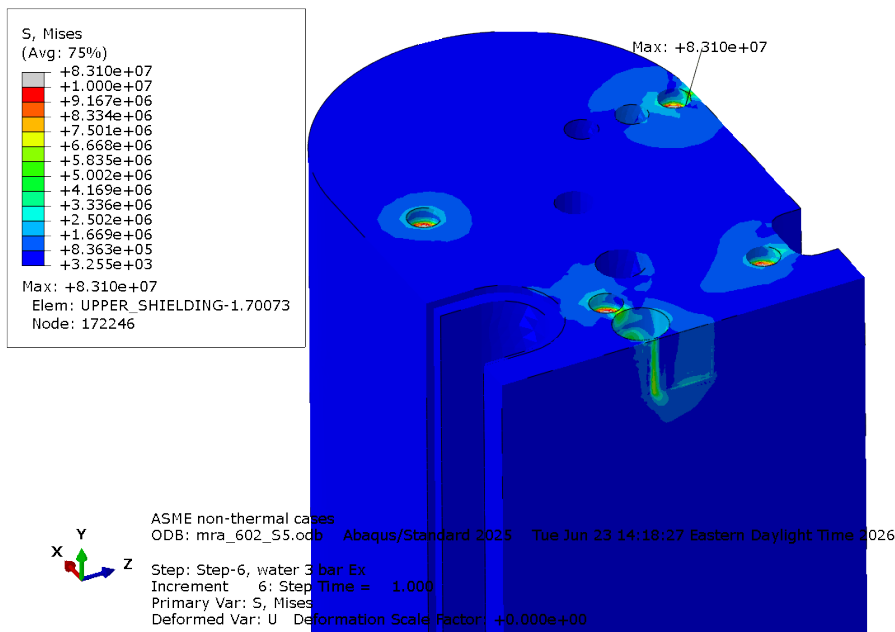


Figure 91 Seismic x case upper shielding stress (Pa) peak 83 MPa near tie rod connection

The stress in the backbone sections are shown in Figure 92 with a scale maximum of 15 MPa. The peak was 126 MPa, again at a bolt head connection on the lower backbone. The stresses are well below the 172 MPa limit for membrane plus bending.

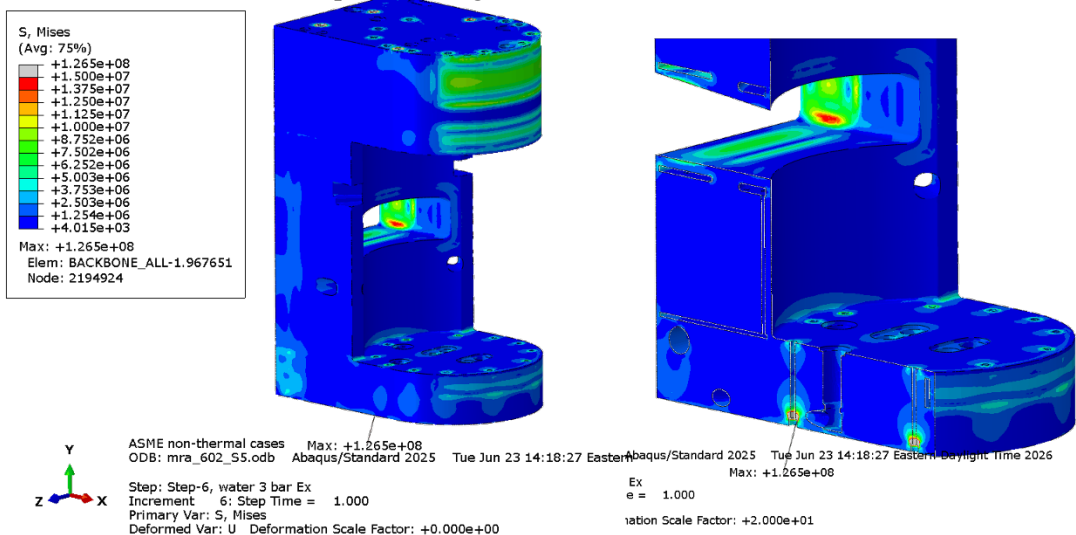


Figure 92 Backbone stress (Pa) with 15 MPa scale maximum

The upper and lower reflector vessel stresses with a $z=0$ cut are shown in Figure 93 with a peak of 124 MPa by an upper bolt tie connection. The internal stresses are very similar to the previous case with 3 bar water pressure and below allowable limits.

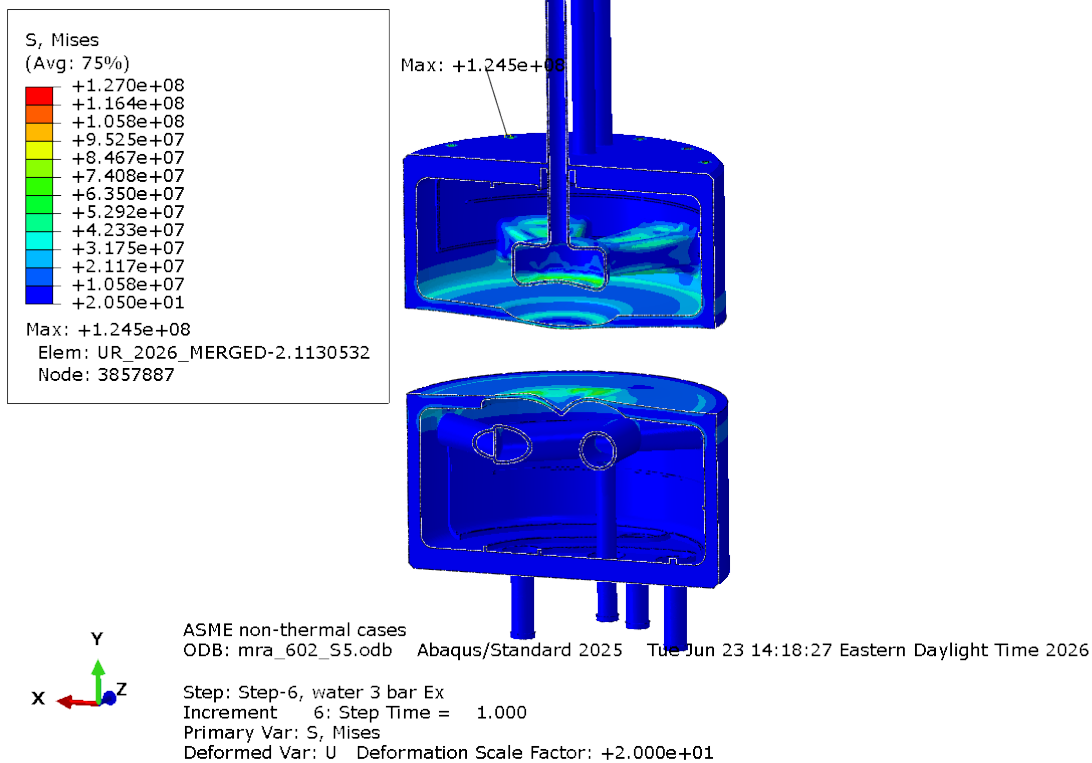


Figure 93 Seismic x upper and lower reflector vessels stress (Pa) -peak 124 MPa by bolt connection

The lower mount stresses are shown in Figure 94 with a localized peak of 100 MPa in the small groove face next to an angled face and corner.

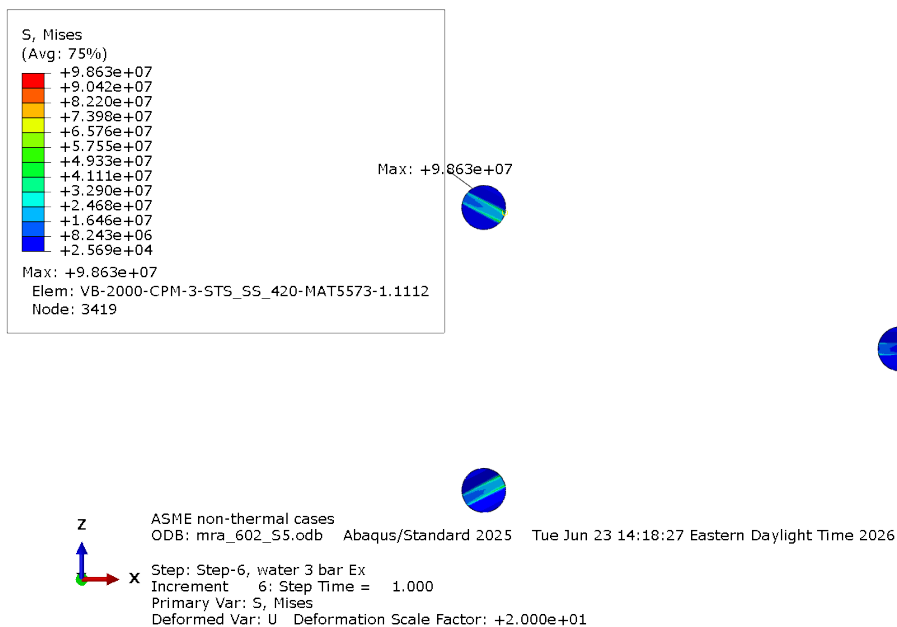


Figure 94 Seismic x load case – mounts stress (Pa) peak 99MPa

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Figure 95 shows the vertical stress on a y cut through the 3 lower mounts. The total vertical load on this plane is 1.894×10^4 N.

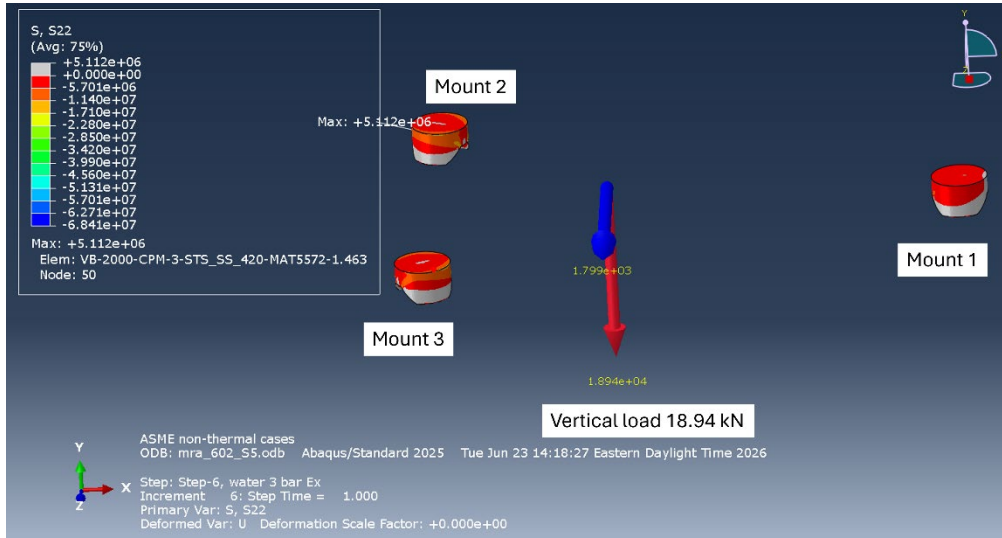


Figure 95 Seismic x load case – mounts – total vertical load $1.894e4$ N

5.7 PRELOAD GRAVITY WATER 3 BAR SEISMIC Z (ASME CASE 7, ABAQUS CASE 5)

The +z direction seismic load results for the backbone and reflector vessel stresses was similar to the previous case with no significant increases in stresses. Figure 96 shows the assembly peak stress of 126 MPa not including the bolts and tie rods. The bolting and tie rod stresses are also similar to previous cases as shown.

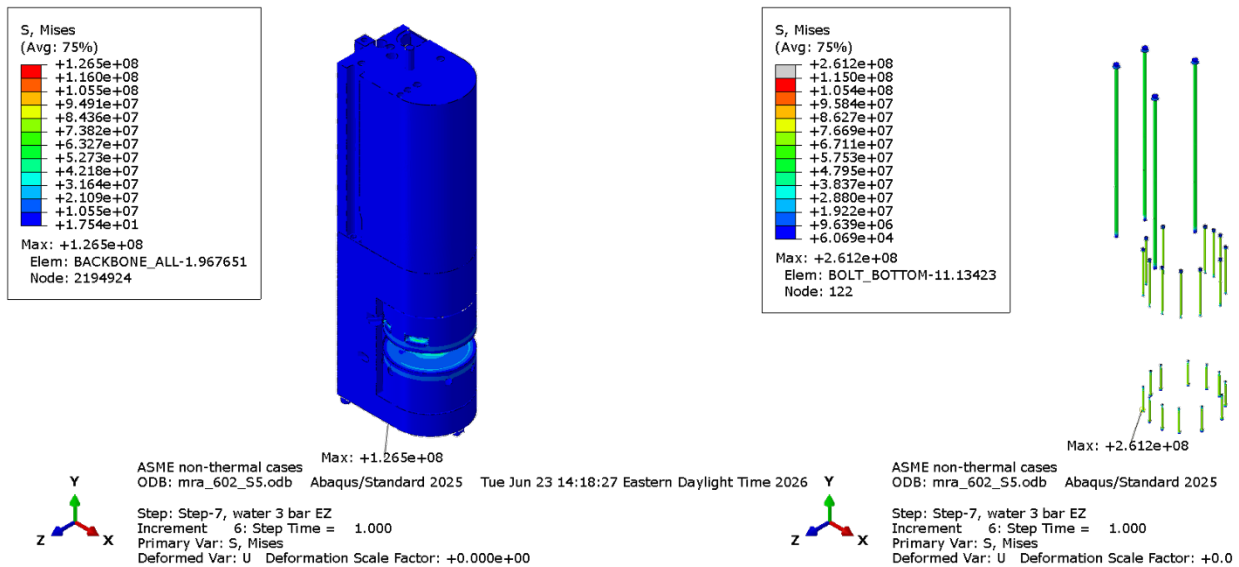


Figure 96 Seismic z load case-Assembly stress, bolt, and tie rod stress (Pa)

The z direction load changed the small out of plane displacements for the reflector vessels with a peak z direction displacement (U3) of .06 mm or less as shown in Figure 97 and a peak U1 displacement of .22 mm.

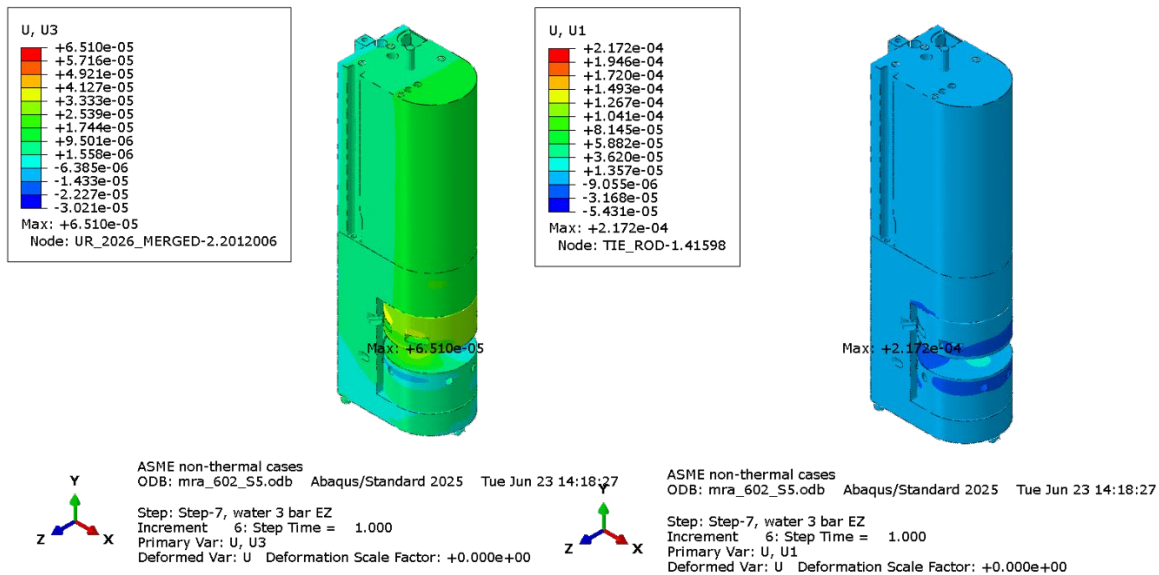


Figure 97 Seismic case with z load showing x (U1) and z (U3) displacements (m)

Figure 98 shows a top view for this case with a factor of 2000 on displacements, stress with a 5 MPa scale maximum and the load on the seismic block close to the connection to the upper shielding.

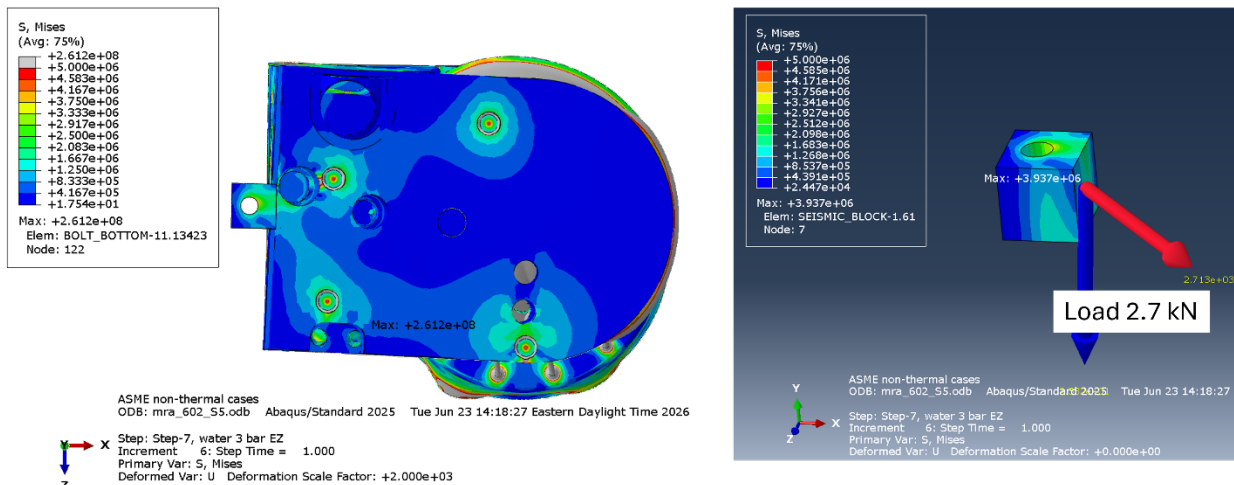


Figure 98 Z (U3) seismic load Stress (Pa), displacement (m) x 2000 and seismic block load (N)

The peak compressive stress on mount 3 increased from 63MPa for the x load case to 88 MPa as shown in Figure 99. Figure 100 shows that the load on mount 2 on the -Z side is approximately 7.3e3 N down, showing that it would remain in contact.

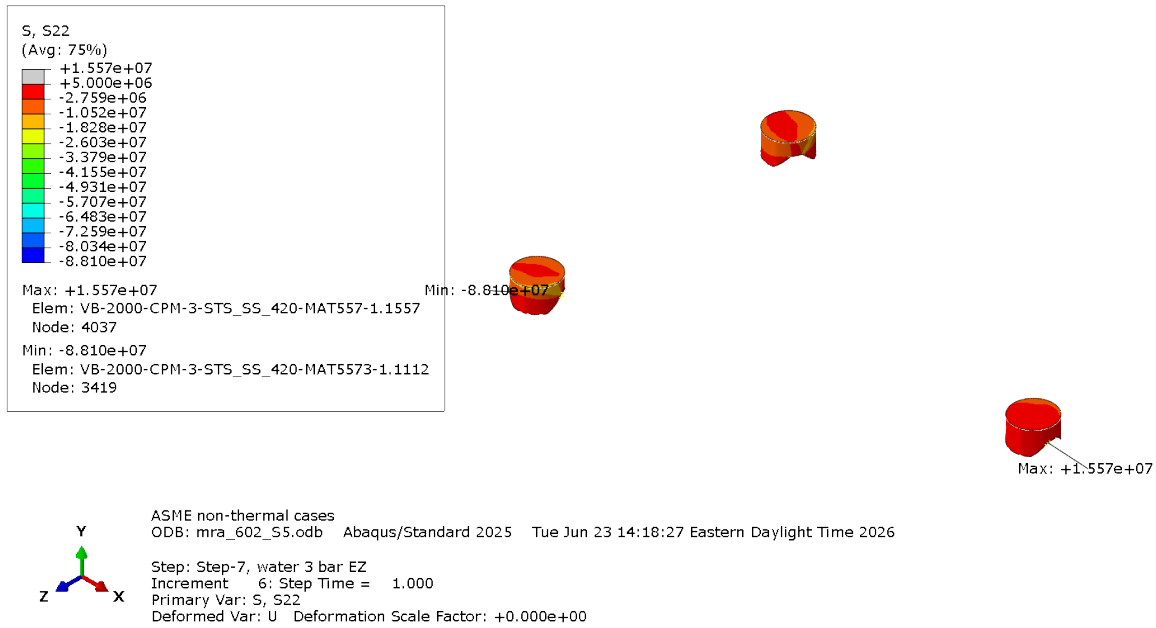


Figure 99 Seismic z load case mount vertical (S22) stress (Pa)

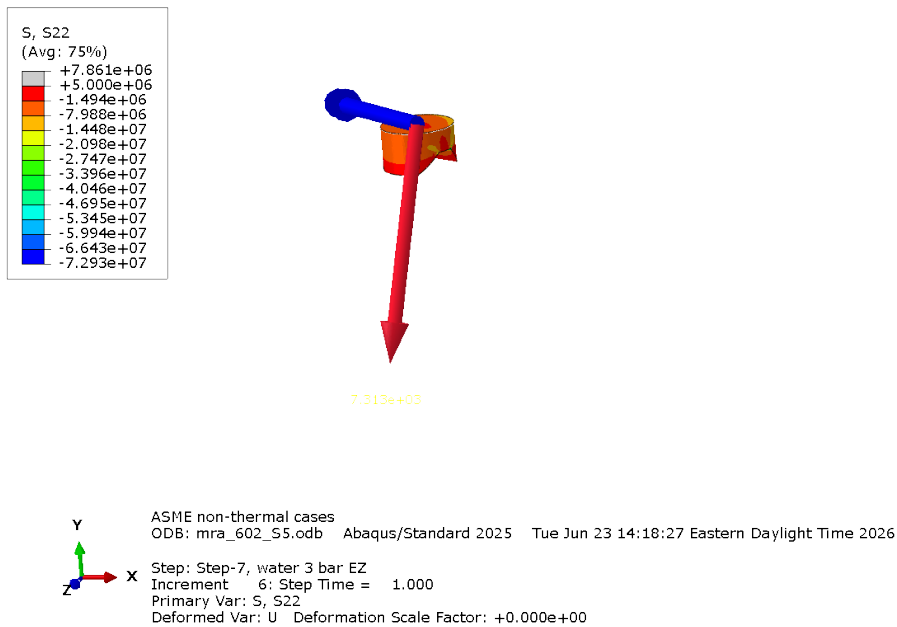


Figure 100 Z load case mount 2 load 7.3e3 N down

The upper shielding stress peak is approximately 83 MPa as shown in Figure 101 with a scale maximum of 8 MPa.

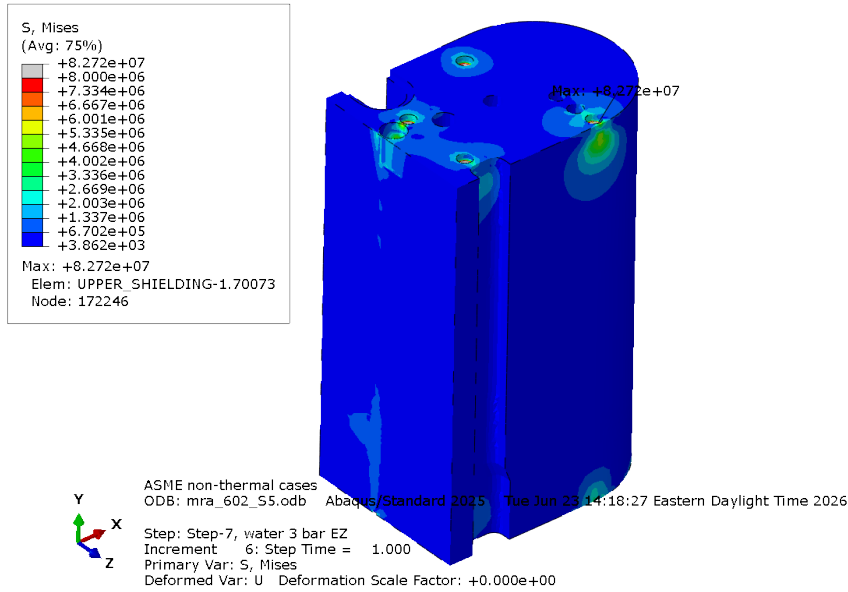


Figure 101 Seismic z upper shielding stress (Pa) – peak 83 MPa by tie rod connection 8 MPa scale maximum

A tie condition was assumed on the surface between the upper shielding and upper backbone under the assumption that the tie rod prestress would keep the parts in contact.

Figure 102 shows the vertical stress S22 on the bottom of the upper shielding with any tensile stress greater than 0 MPa in gray. Nearly all of the surface is in compression indicating that the tie condition assumption is realistic, and no significant separation should be expected.

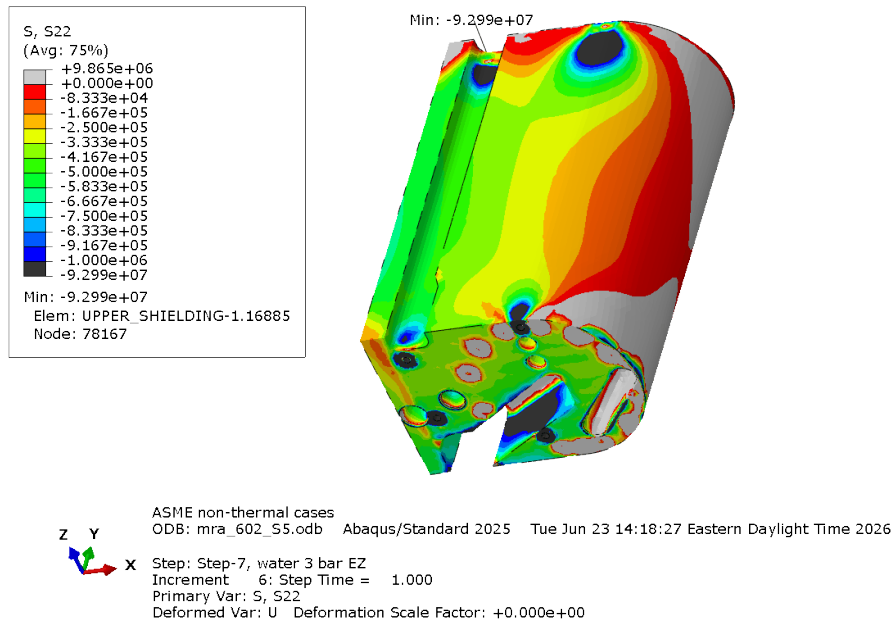


Figure 102 Vertical stress (Pa) on the tie surface between the upper shielding and upper backbone showing nearly all compression

The moderator reflector vessel displacements in the z direction (U3) are shown in Figure 103.

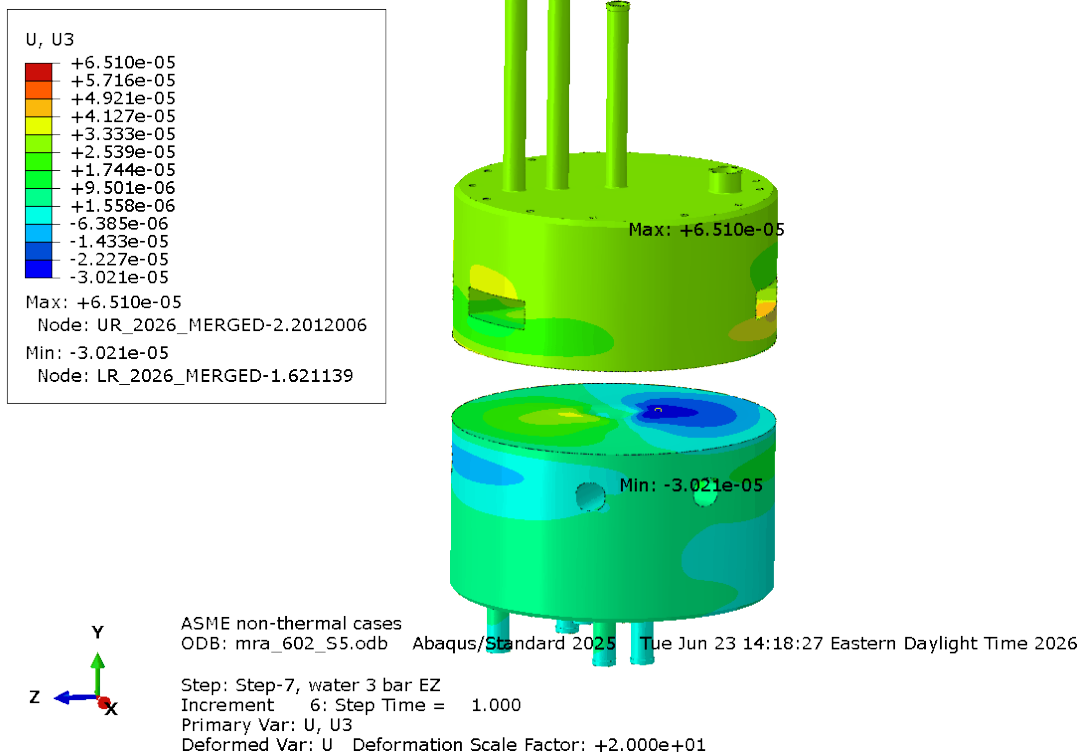


Figure 103 Seismic z reflector vessels Z displacement (m) – maximum .065 mm

5.8 PRELOAD GRAVITY WATER 3 BAR, SEISMIC Y (ASME CASE 6, ABAQUS CASE 6)

The following results are for ASME case with vertical seismic load of .07 G or $.69 \text{ m/s}^2$ and also include preload, normal gravity vertical load and 3 bar water pressure with vacuum in the core vessel. The increased vertical load had little effect on the reflector vessels. The vertical displacements of the vessels and attached bolts are shown in [Figure 104](#) and the stresses in [Figure 105](#). The largest displacement down was .61 mm on the bottom surface of the upper reflector vessel. The nominal axial stress on the bolts did not change significantly from the preload values. The peak stress of 261 MPa was again artificial near a tie connection on a lower bolt. All aluminum stresses were below 127 MPa.

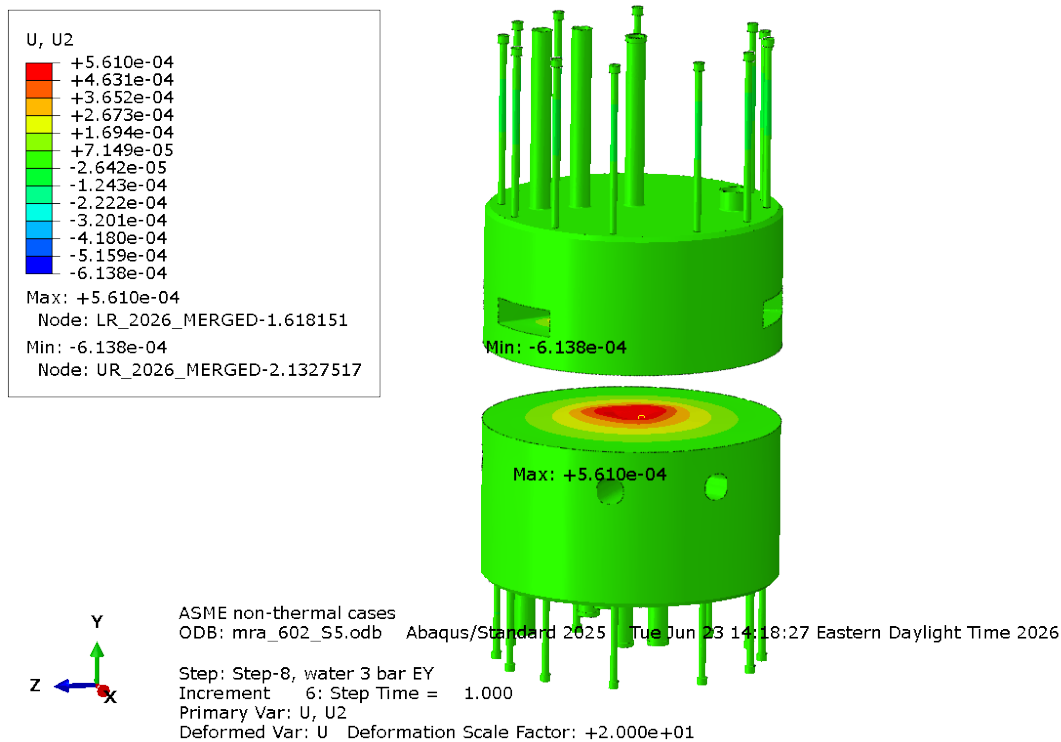


Figure 104 Seismic y, reflector vessels and bolts, vertical displacement (m) – minimum .61 mm down

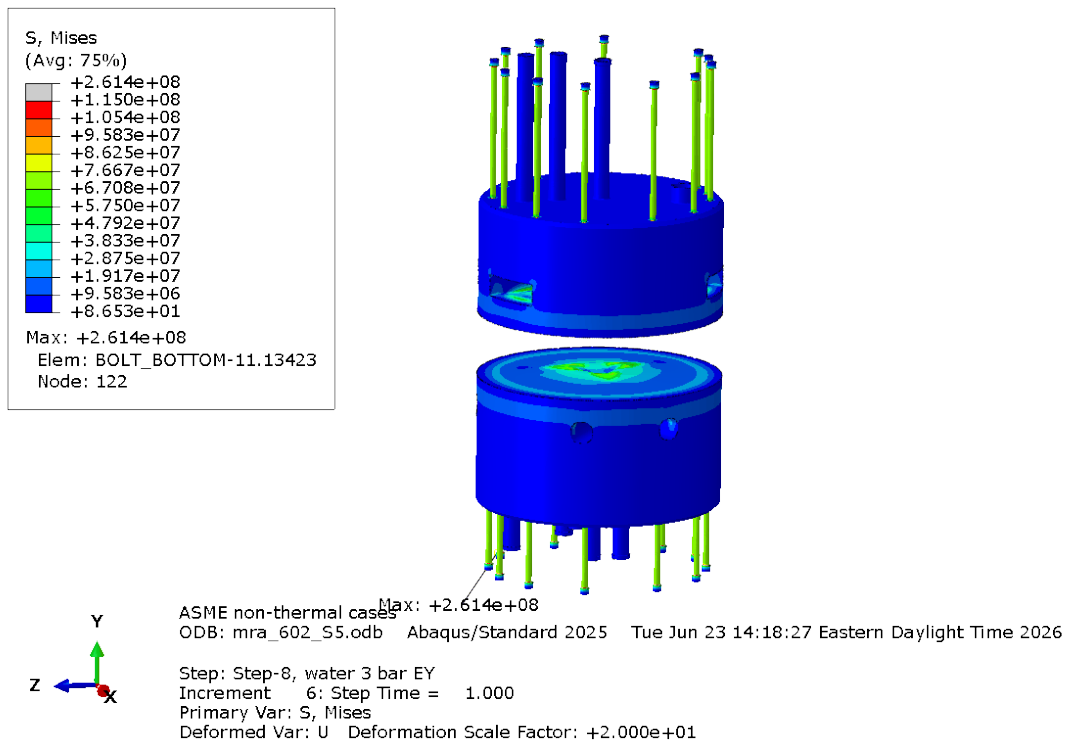


Figure 105 Seismic Y load case reflector vessels and bolts stress (Pa)

The stresses in the backbone parts is shown in Figure 106 with a 15 MPa scale maximum and a peak stress of 126 MPa by a bolt connection edge singularity as in previous cases.

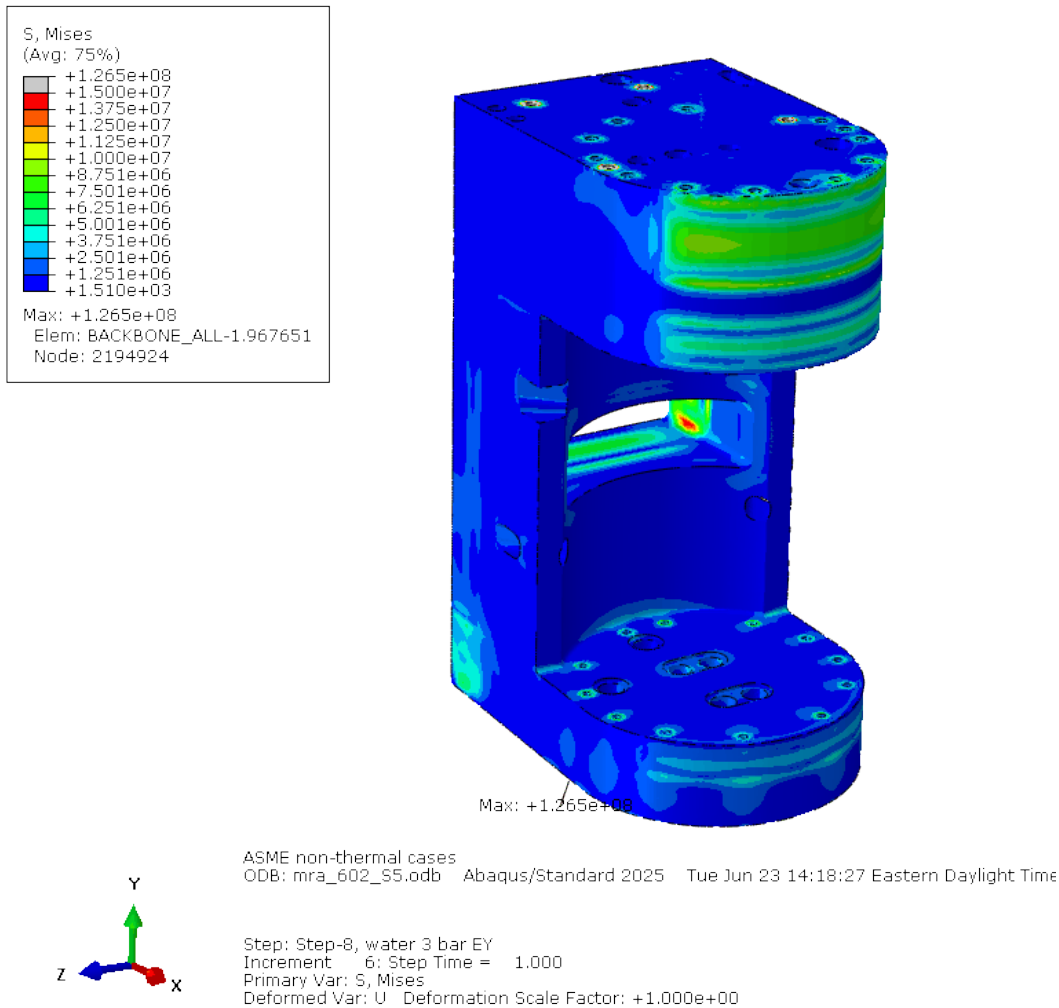


Figure 106 Seismic Y load case backbone stress (Pa)

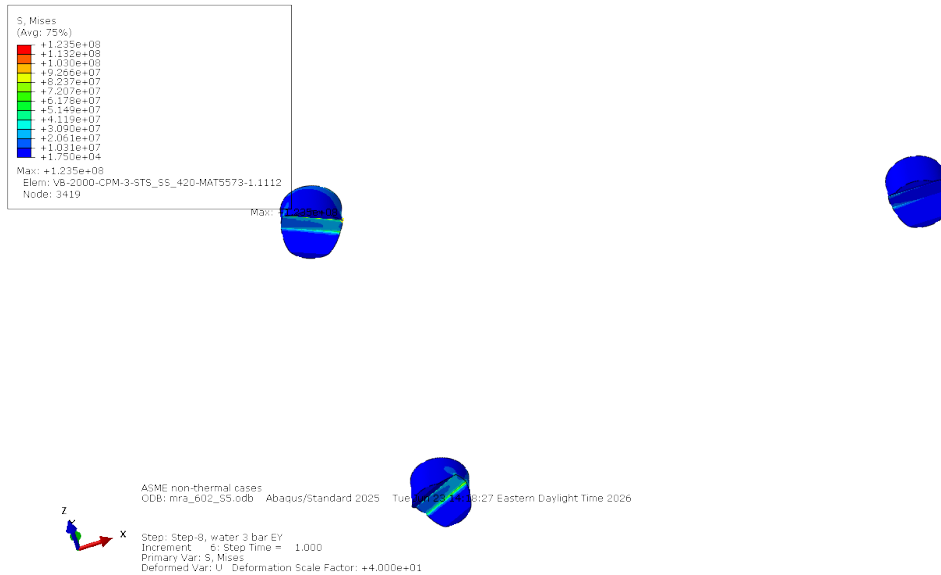


Figure 107 Seismic y, mount stress (Pa)- peak stress 123.5 MPa by groove edge with sharp corner

The total vertical load on the mounts increased to 2.04e4 N.

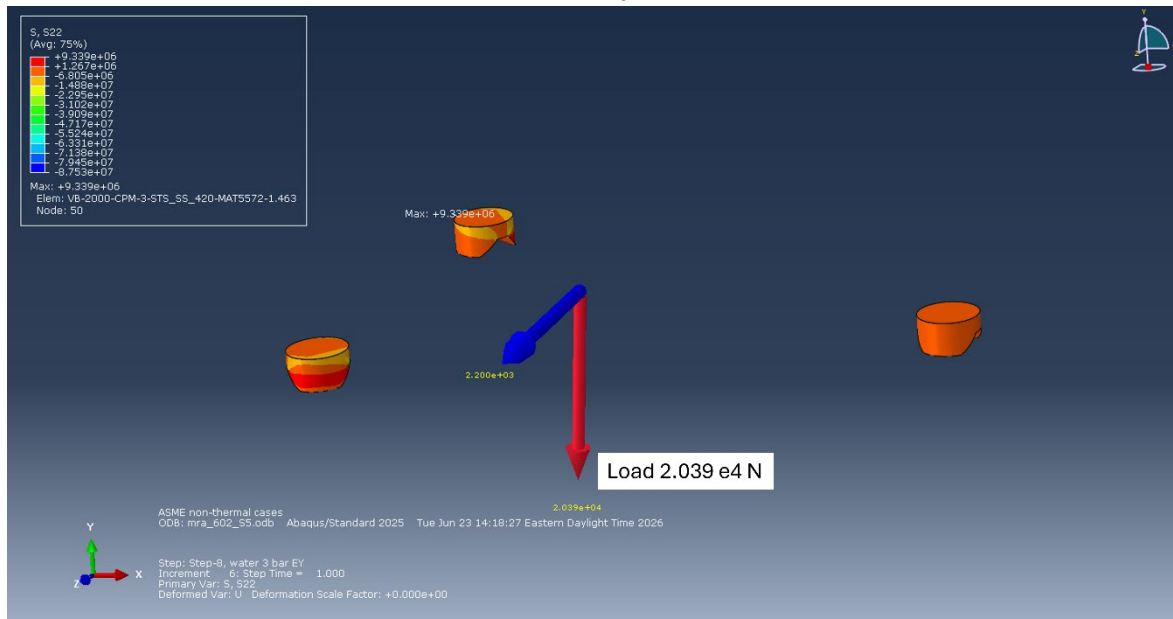


Figure 108 Seismic y, S mounts peak vertical load 2.04 e4 N

5.9 PRELOAD 0.6 X GRAVITY WATER 3 BAR SEISMIC OVERTURNING (ASME CASE 5, ABAQUS CASE 7)

This ASME case is with 70% of the horizontal earthquake load in the worst case overturning direction and includes preload, 60% of the gravity load and with vacuum core vessel operation. The worst case direction is normal to a line connecting the downstream mount center to a side mount center. As shown below this angle is 71.3 degrees. The x component will be proportional to the cosine of this angle and the

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z component to the sine. The acceleration components were then 2.0 m/s^2 in the z direction and $.68 \text{ m/s}^2$ in the x direction.

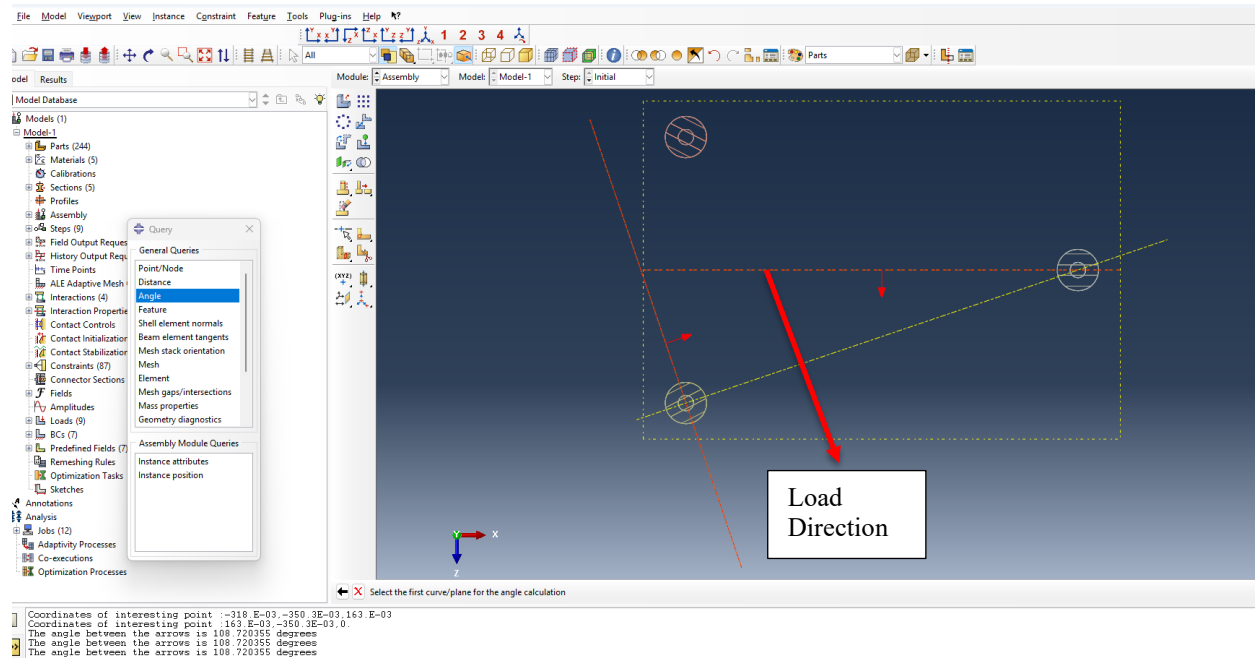


Figure 109 Development of overturning angle of 71.3 degrees between load direction and x axis

Assembly displacements in the x,y and z directions are small with a maximum of .6 mm as shown in Figure 110.

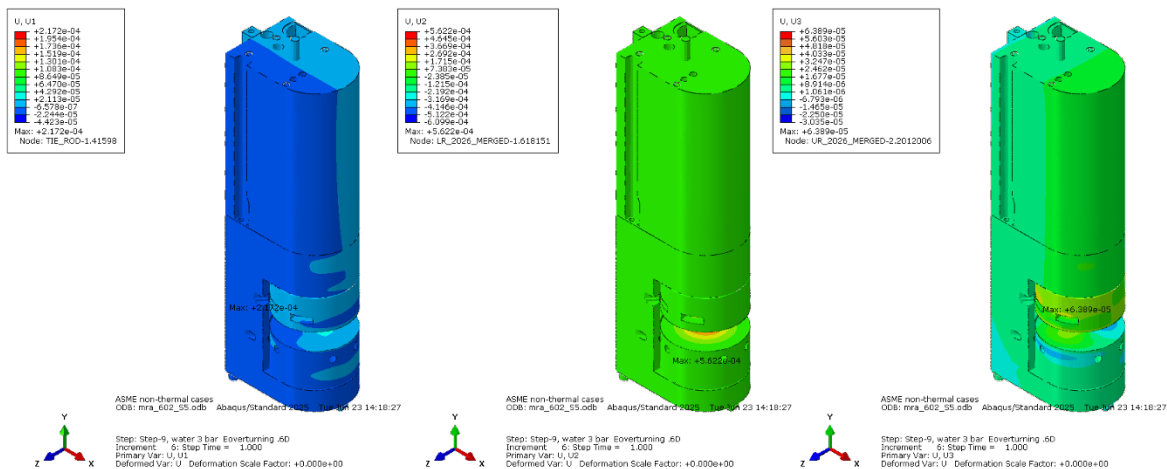


Figure 110 Seismic overturning case displacement (m) - maximum 0.6 mm vertical

Stresses in the upper shielding are similar to the z seismic case and Figure 111 shows the results with a 10 MPa scale maximum.

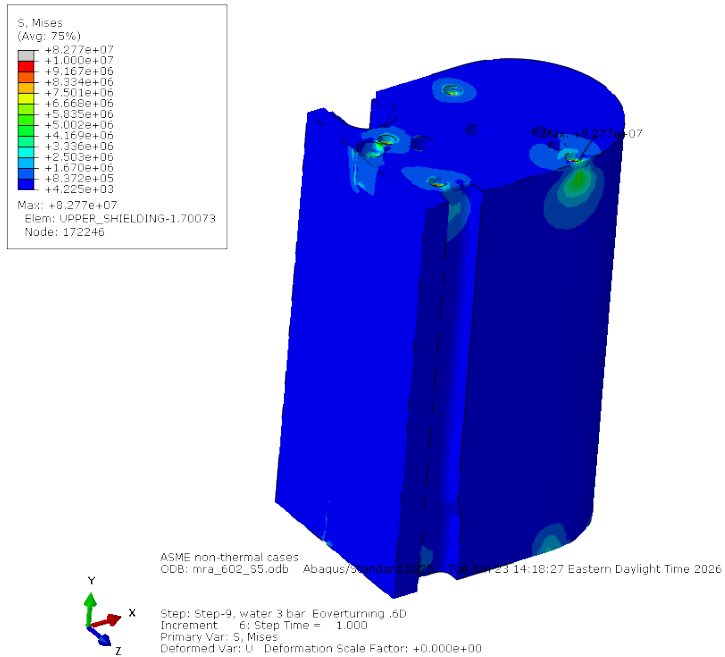


Figure 111 Seismic overturning case upper shielding showing stress (Pa) with 83 MPa peak with 10 MPa scale maximum

Stresses and load in the seismic block on a cut are shown in Figure 112 with a load of approximately 2.6e3 N in the overturning direction.

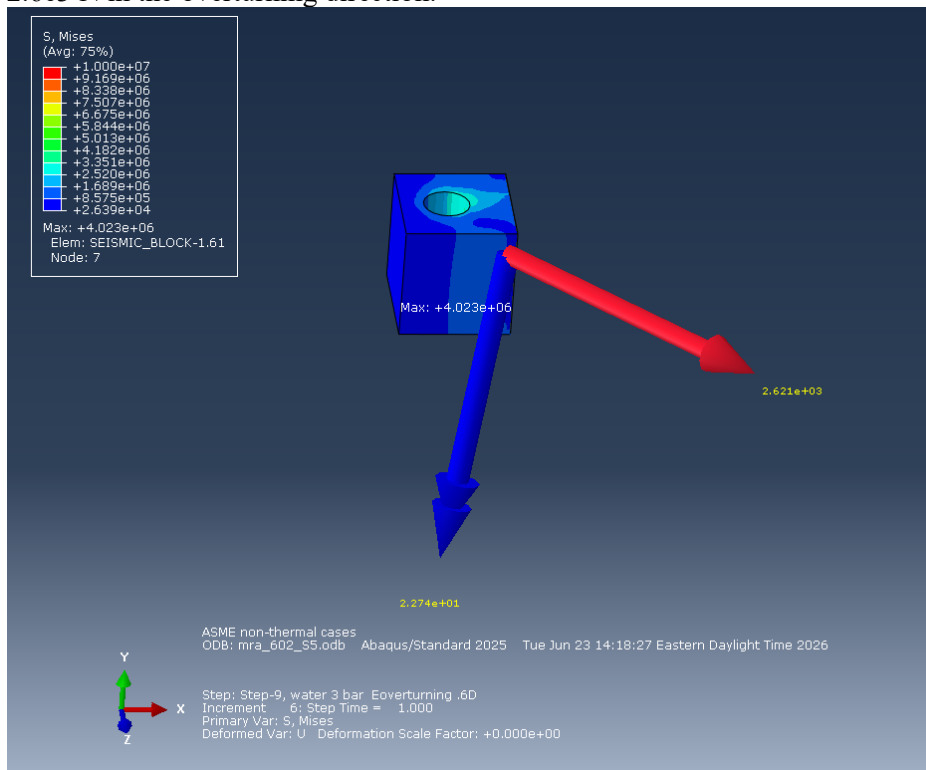


Figure 112 Seismic overturning case seismic block z cut horizontal load 2.6e3 N

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The stresses in the three mounts are shown in [Figure 113](#) with a peak of 78.1 MPa.

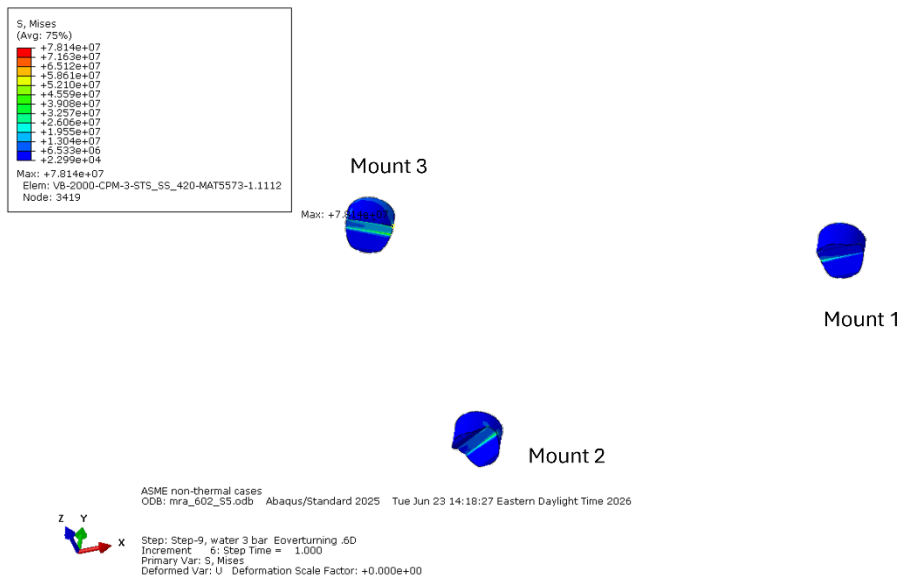


Figure 113 Seismic overturning case mounts stress (Pa) peak 78 MPa

The mount vertical load for all three mounts was $1.22e4$ N as shown in [Figure 114](#). This is consistent with the load case using .6D and .7E with a mass of 1791 kg. The horizontal load is also carried in part by the seismic block as shown in [Figure 112](#).

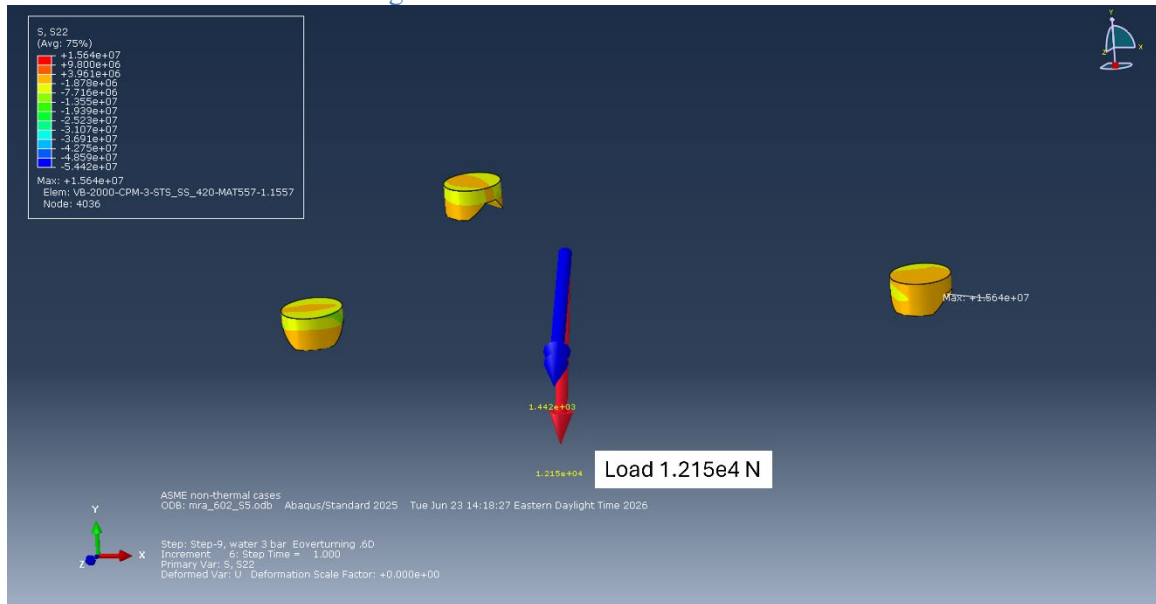


Figure 114 Seismic overturning case Vertical load 1.04e4 N

The individual mount 2 load is shown in [Figure 115](#). The overturning load is in the direction which would try to make mount 2 lift. Since the mount 2 load for this case is downward and the vertical stress S22 is compressive, the mount would remain in contact even if the angle face constraints were removed. A case was run without the seismic block constraint which did show overturning with tensile stresses in the mount and an upward directed vertical load.

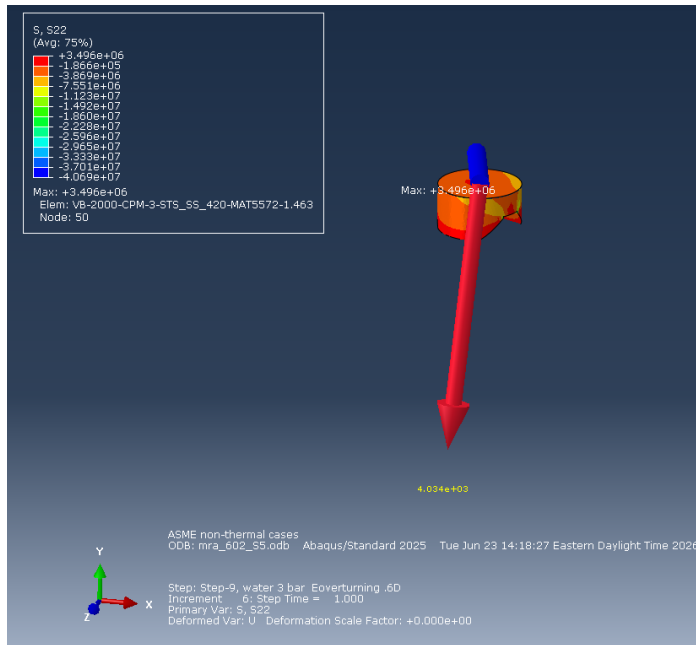


Figure 115 Seismic overturning case M2 vertical load 4.0 e3 N

The results show that the overturning load will not cause the assembly to tip.

5.10 THERMAL ANALYSIS RESULTS – INITIAL CONDITIONS AND TEMPERATURES

The Abaqus analysis for the thermal cases started with an imposed 20 °C temperature on all elements followed by prestress loads and gravity loads, the same as was done for the non-thermal analysis. As shown in Figure 51 the next step applied 3-bar water pressure and a 32 C temperature on all nodes. This represents the conditions prior to beam heating or after steady state following a beam trip. Figure 116 shows the applied temperature, assembly stress and the stresses in bolts and tie rods with a 115 MPa scale maximum.

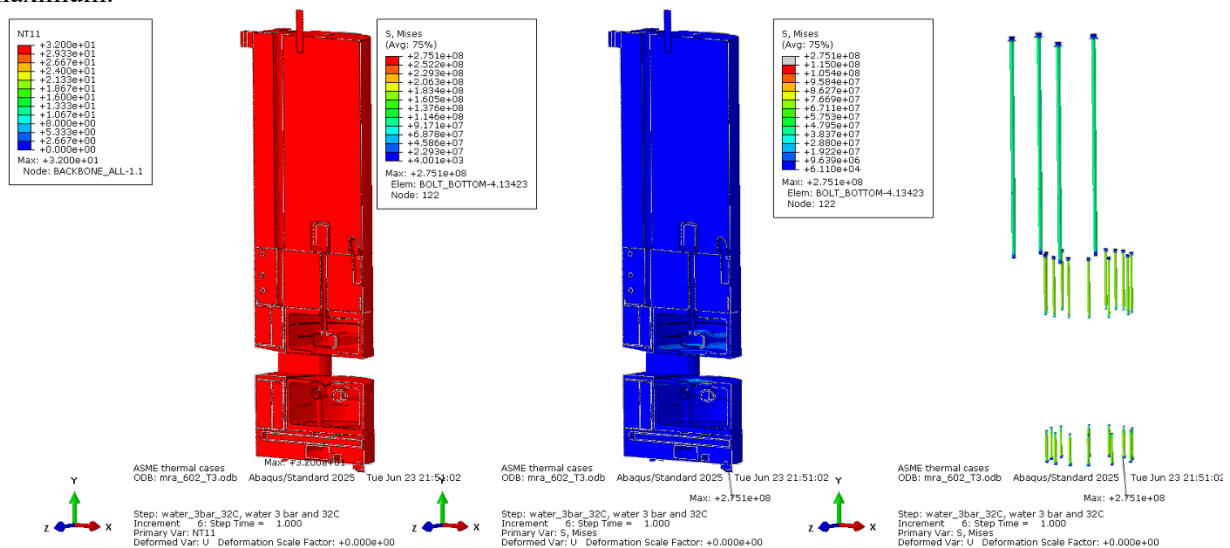


Figure 116 Initial conditions for thermal analysis – stress (Pa) temperature (°C)

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The assembly stresses were basically the same as for the non-seismic case with 3 bar water pressure. The bolt and tie rods stress were also similar but with a very slight increase for the peak at a lower bolt singularity from 262 MPa to 275 MPa. This case will be used as the low stress condition for thermal fatigue analysis .

The CFD temperature data as shown in Figure 47 was imported and mapped by Abaqus onto the mesh. Figure 117 through Figure 123 show the mapped temperatures with a peak of 84.9 C.

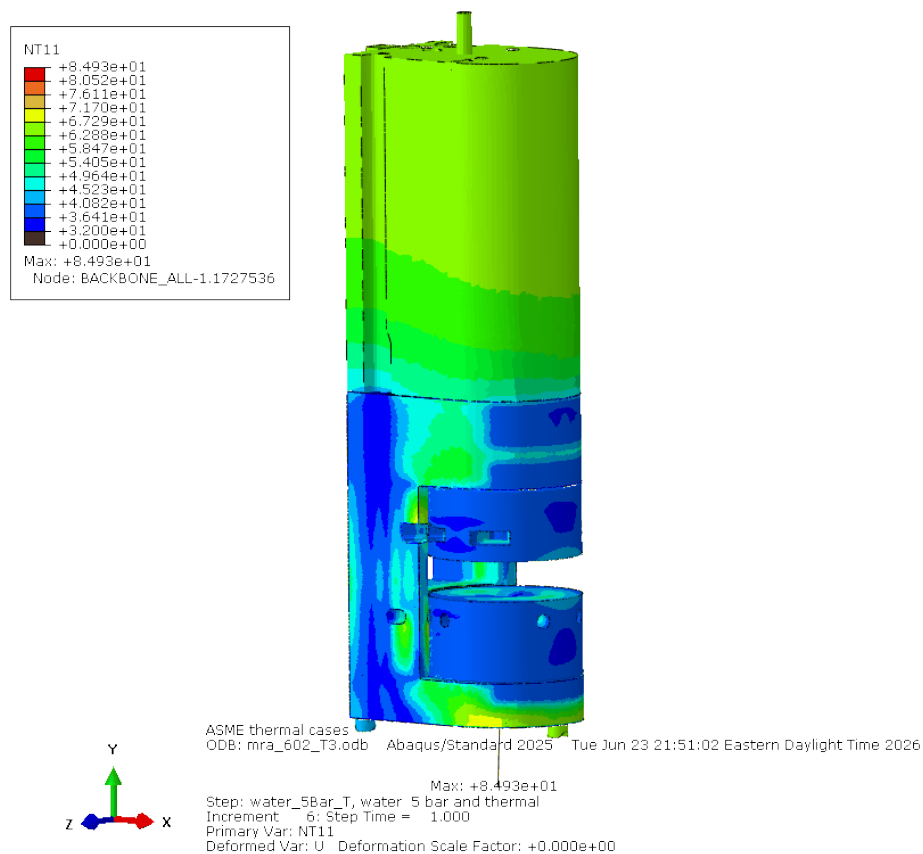


Figure 117 Assembly temperature (°C) with 85 °C maximum

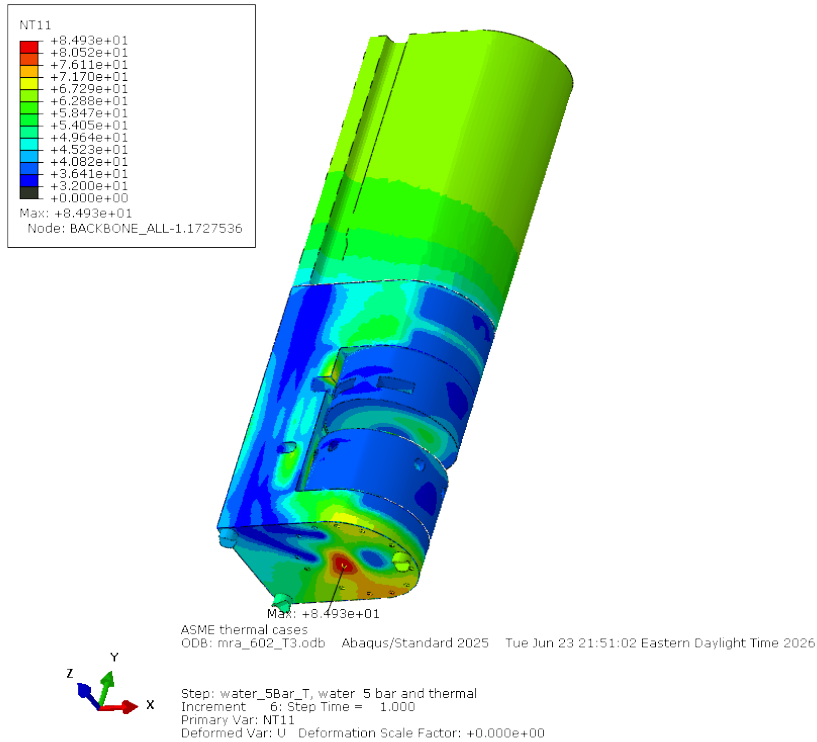


Figure 118 Assembly bottom view (°C) showing peak of 84.9 °C

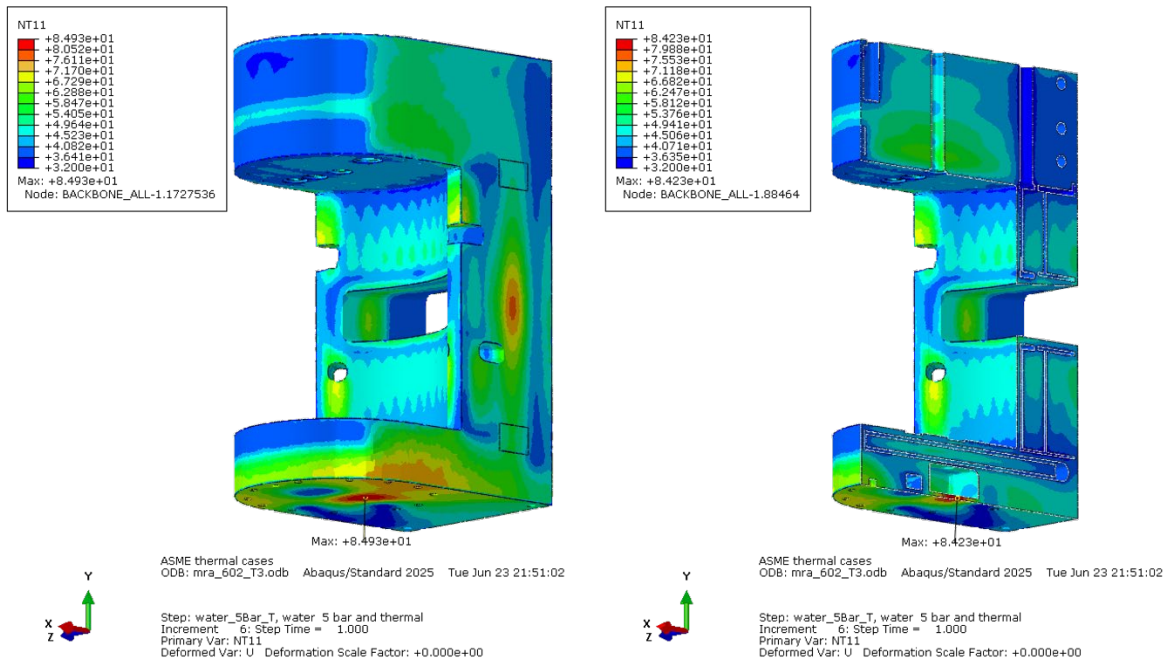


Figure 119 Backbone temperatures (°C)

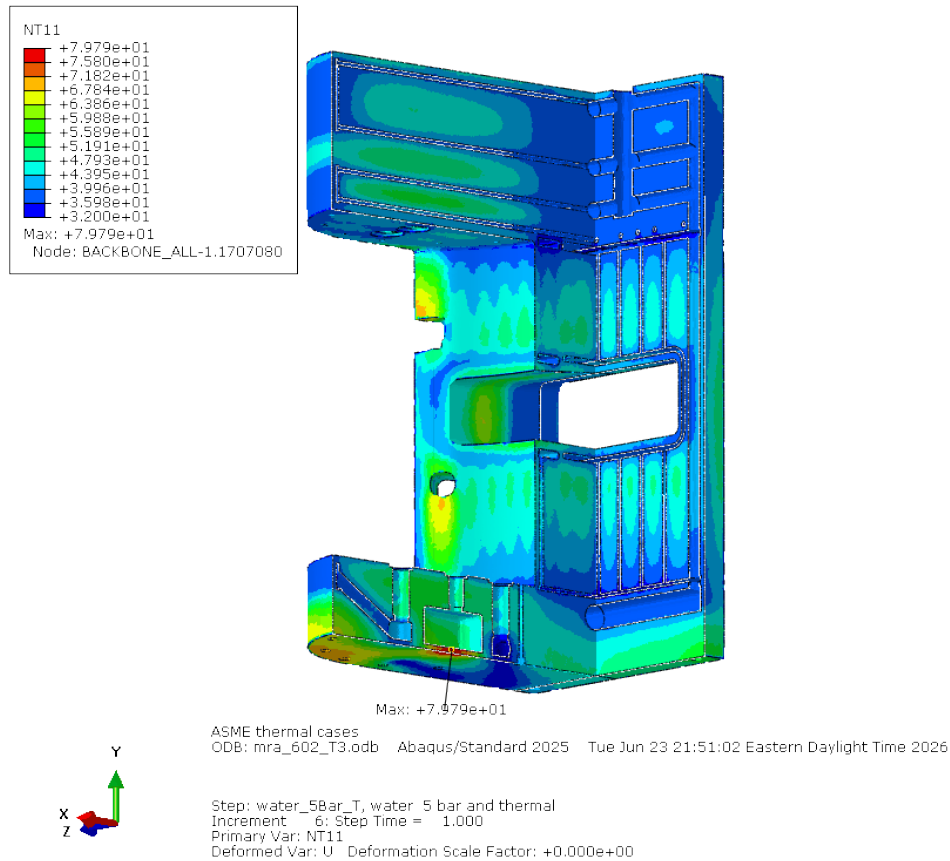
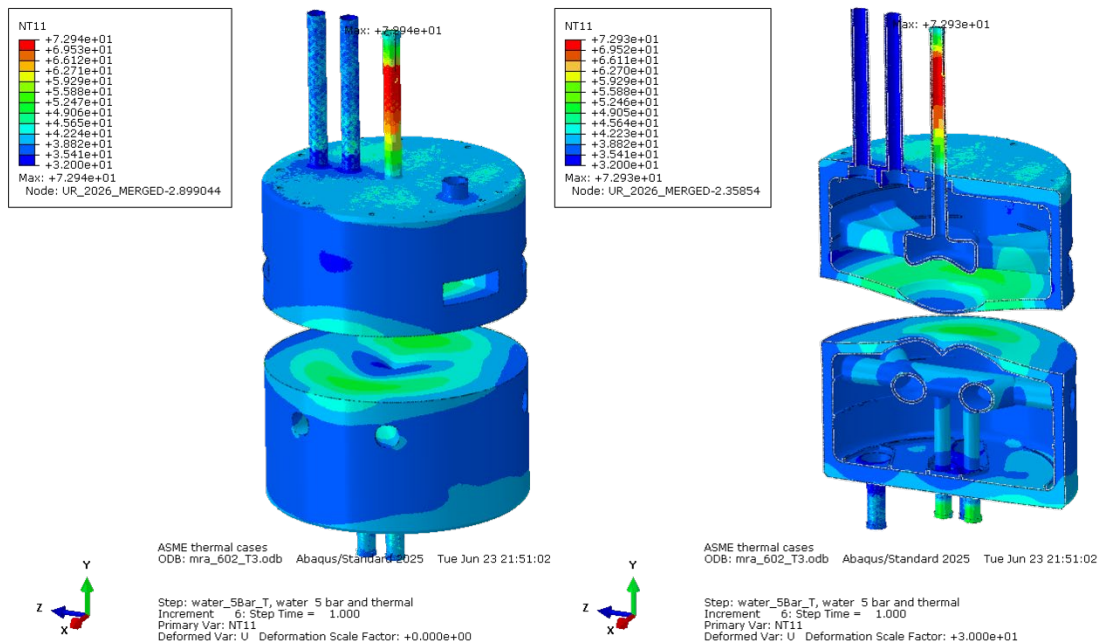


Figure 120 Backbone temperatures(°C) with X and Z cuts



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Figure 121 Upper and Lower Reflector Vessel temperature (°C) with 72.9 C peak on vacuum tube

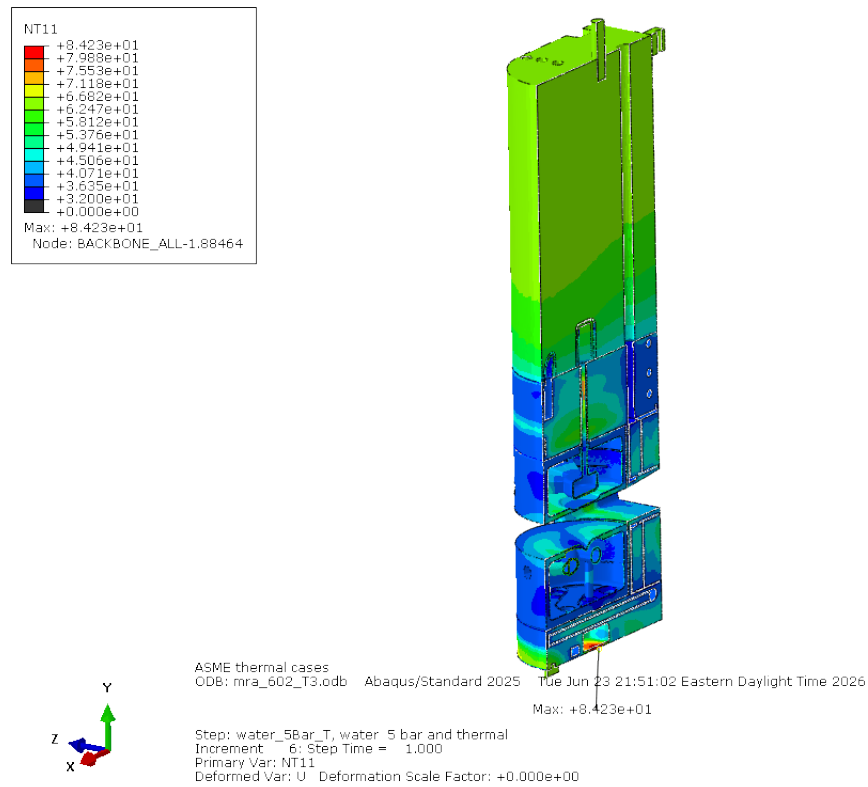


Figure 122 Assembly temperatures (°C) with z=0 cut

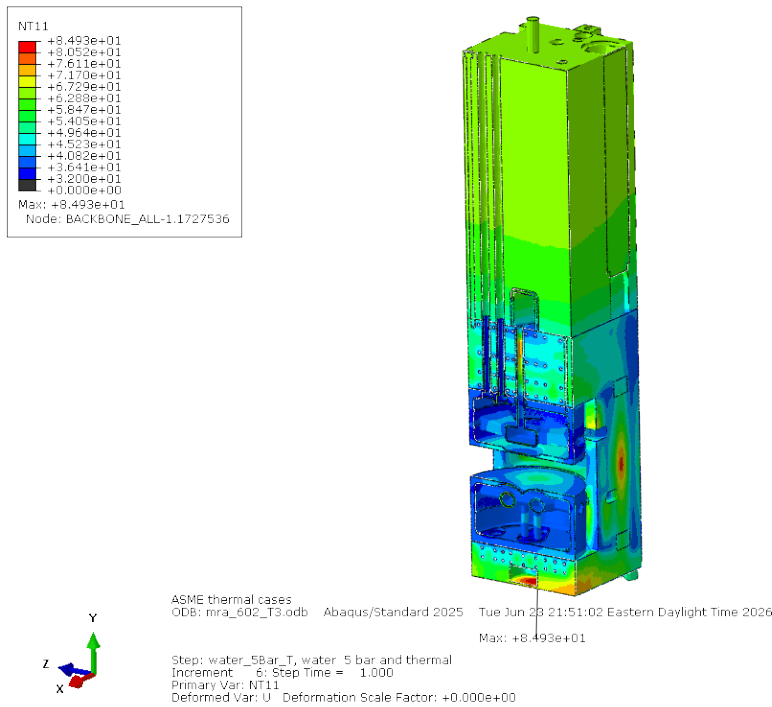


Figure 123 Assembly temperatures (°C) with $x=0$ cut

5.11 PRELOAD GRAVITY WATER 5 BAR THERMAL (ASME CASE 3 ABAQUS CASE 8)

The overall assembly stress is shown in Figure 124 with a scale maximum of 127 MPa. The peak of 656 MPa is at a singularity by a groove on a lower mount caused by the boundary conditions of no displacements normal to the angle surfaces with temperature of up to 66 °C.

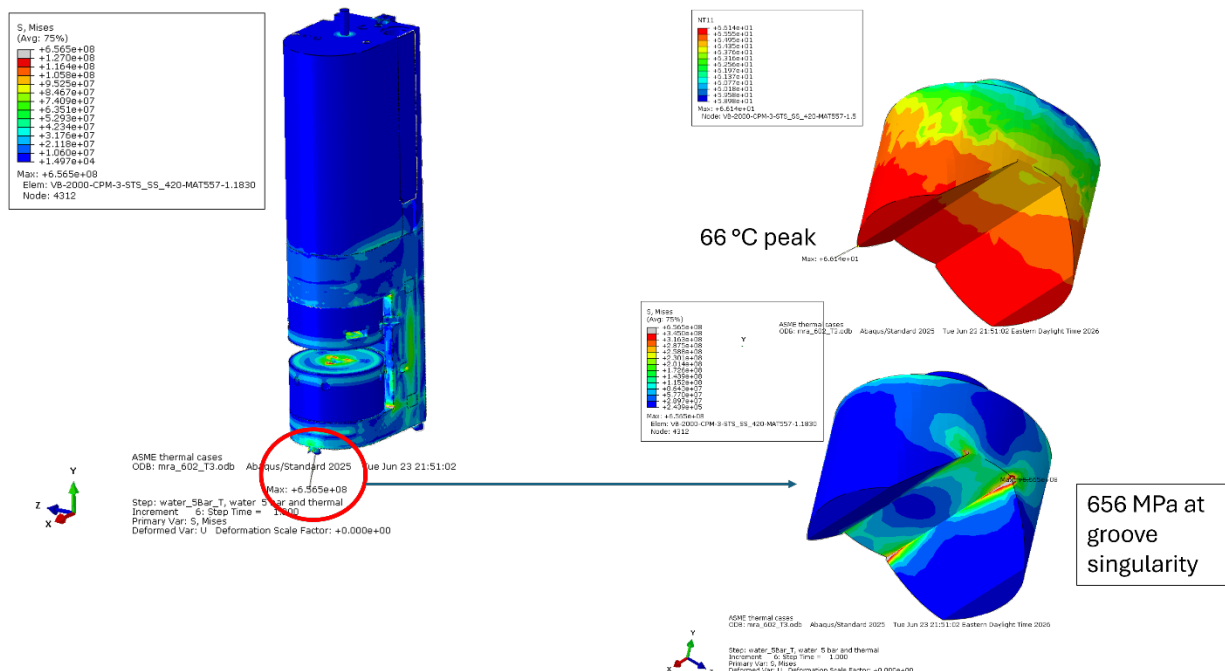


Figure 124 ASME case 3 assembly stress (Pa) with 127 MPa scale maximum showing peak on a lower mount with 345 MPa scale

The assembly displacements in the x, y and z directions are shown in Figure 125. The boundary condition on the seismic block was not included. The U1 displacement of 0.52 mm towards the target is an upper limit. Figure 126 shows the peak displacement of a reflector vessel towards the target is .28 mm. Peak vertical displacements are in reflector vessel surfaces facing the target segments of approximately 1 mm.

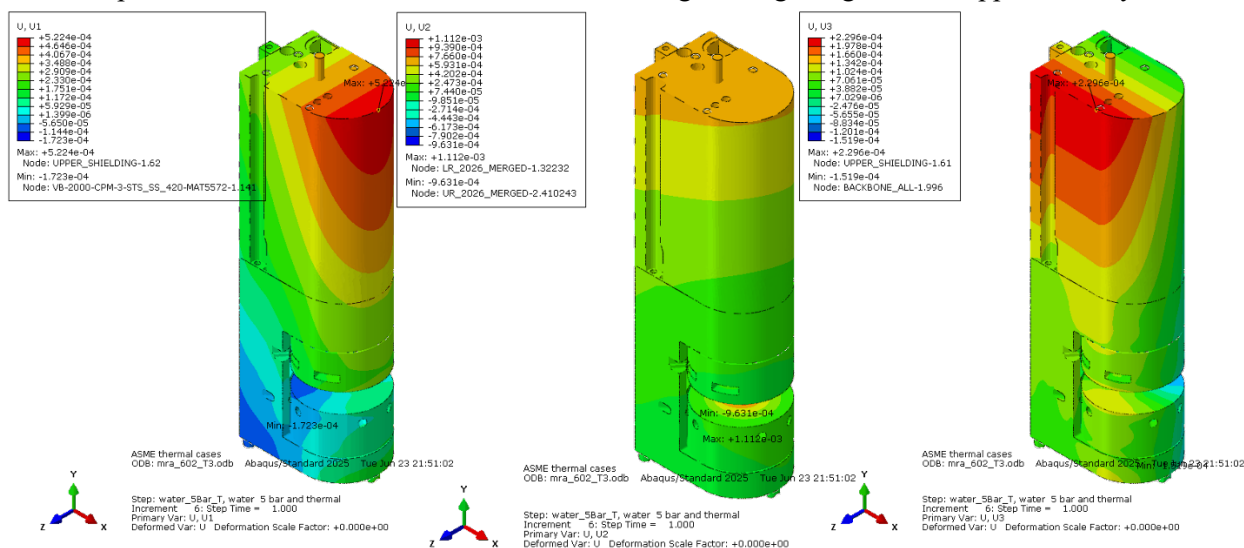


Figure 125 ASME case 3 Assembly X,Y and Z displacements (m)

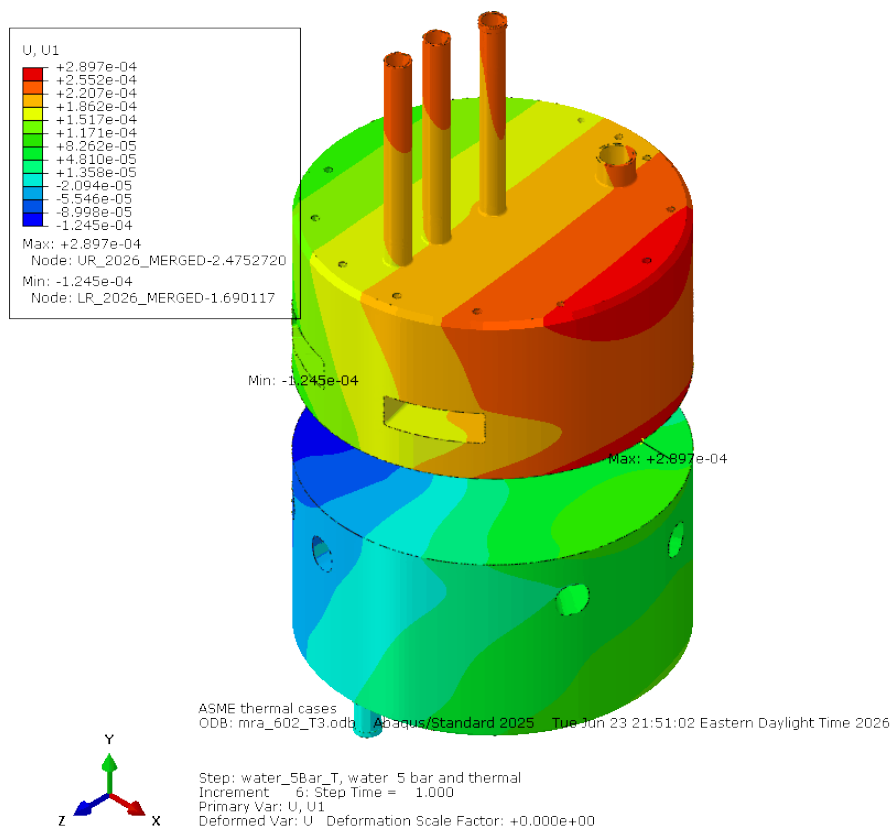


Figure 126 Reflector vessel x displacements (m) toward the target with a 0.3 mm maximum

Upper Shielding stress for this case is shown in Figure 127. The peak with 75% averaging is 108 MPa near the tie connection to the head of a tie rod.

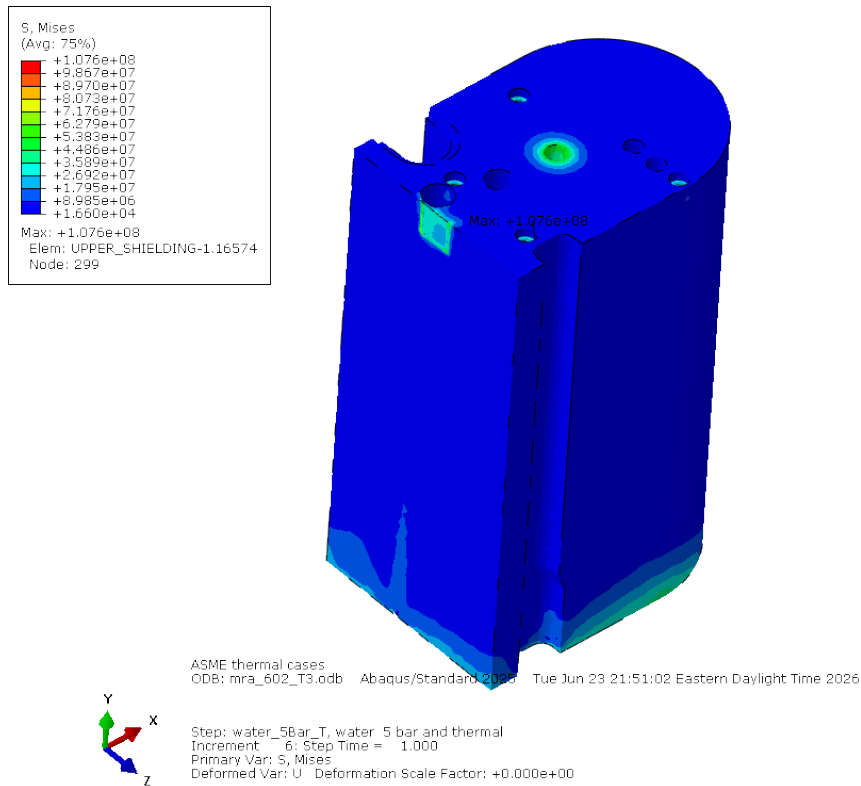


Figure 127 ASME Case 3 Upper Shielding Stress (Pa) - peak 108 MPa

The backbone stress for ASME Case 3 is shown in Figure 128 with a peak of 261 MPa on the surface of the smoothed weld between the middle and lower backbone regions.

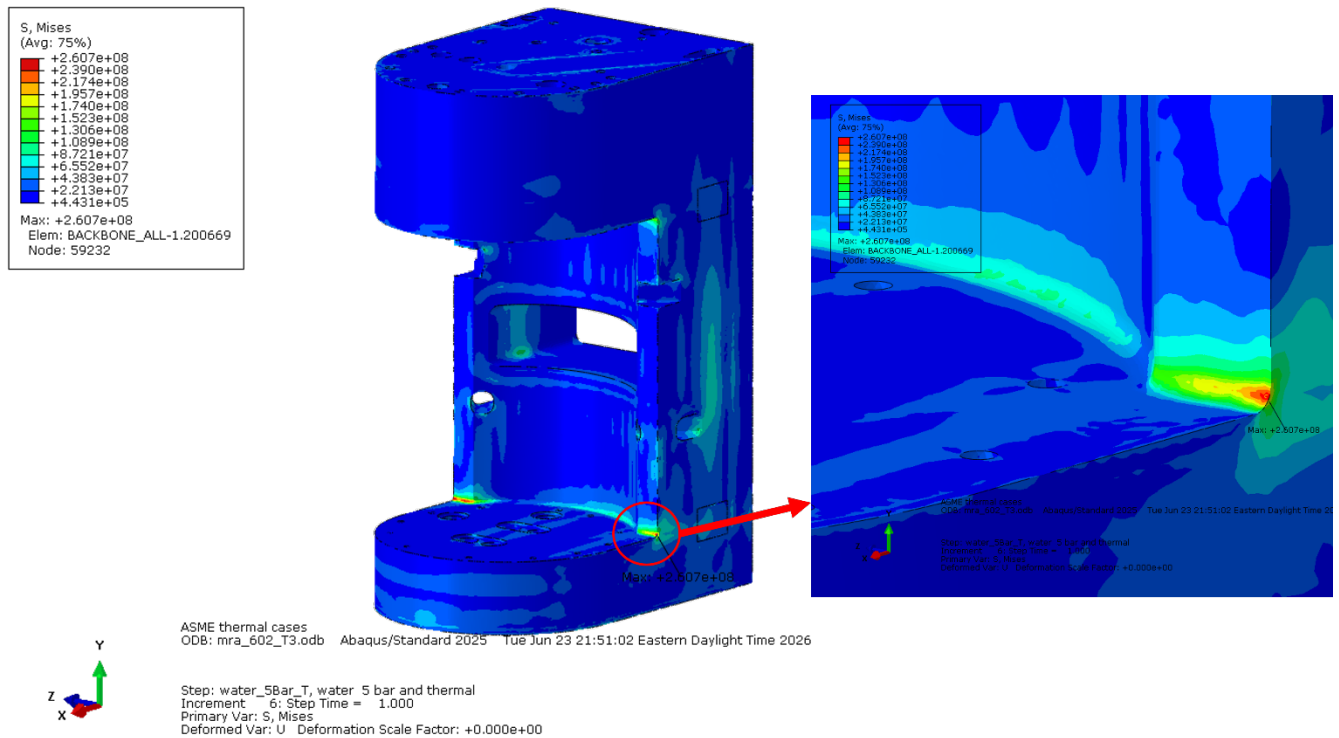


Figure 128 ASME Case 3 Backbone Stress (Pa) with 261 MPa peak

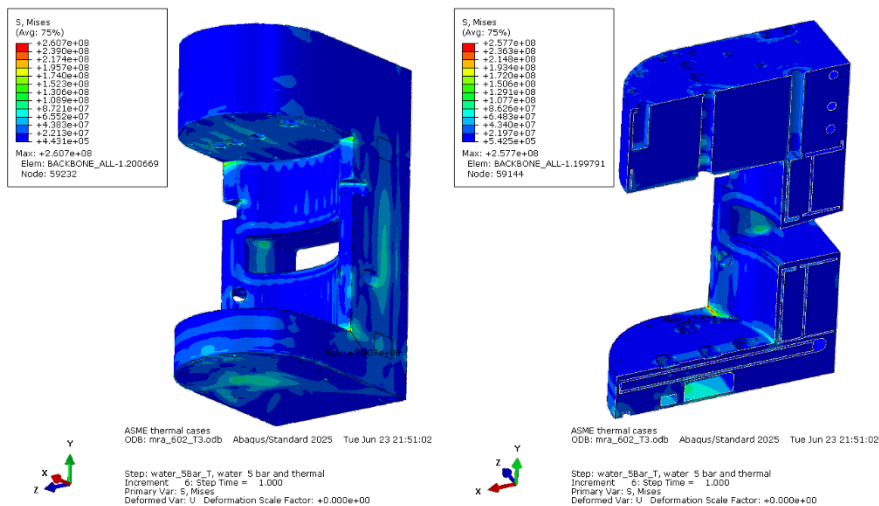


Figure 129 Case 3 Backbone stress (Pa) views

Figure 130 shows the vertical stress S22 for this case with the outer high stress weld regions in compression at about 219 MPa and the inner region in tension.

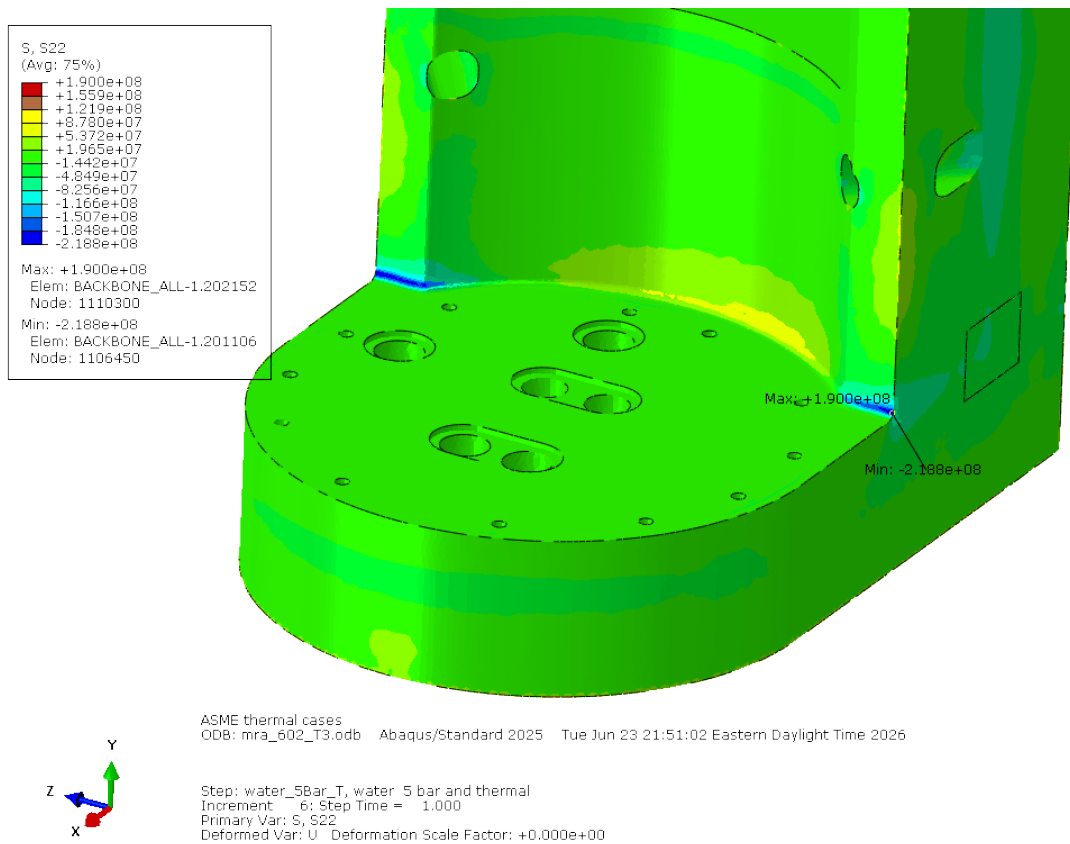


Figure 130 ASME Case 3 Backbone Vertical Stress S22 (Pa) showing compression in weld in high stress region

A view around the weld near the 261 MPa peak stress region showing the mesh is shown below .

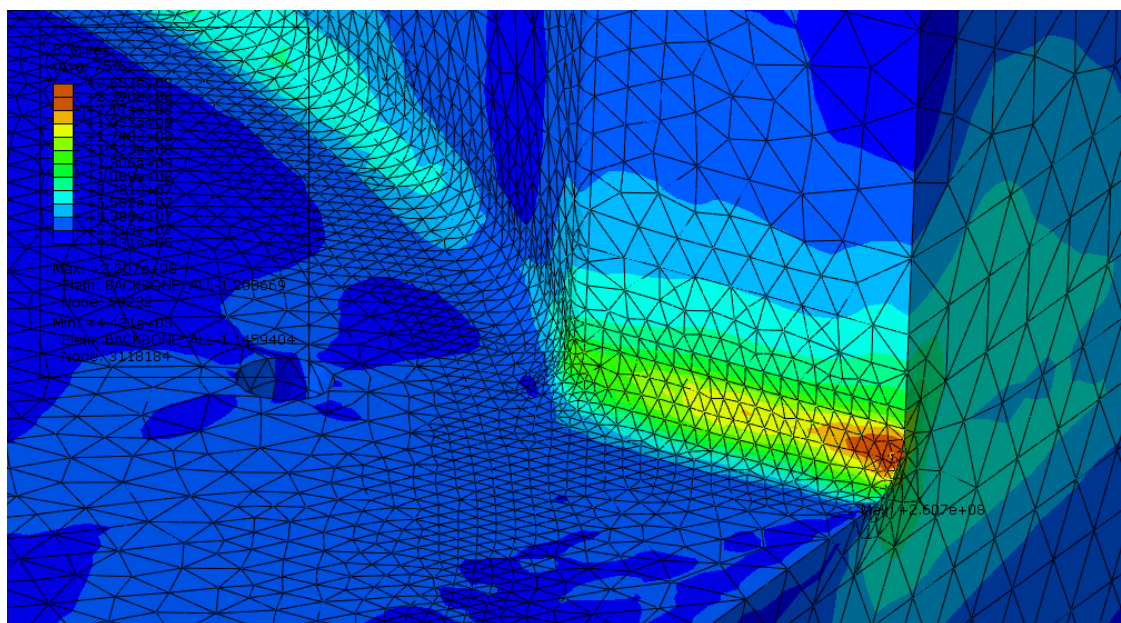


Figure 131 ASME Case 3 Mises Stress (Pa) view by weld with mesh shown

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Figure 132 shows a view cut through the lower weld at -0.252 m which is 1 mm above the weld vertical centerline. The weld stresses are generally below 100 MPa except the peaks in the front corners of about 250 MPa.

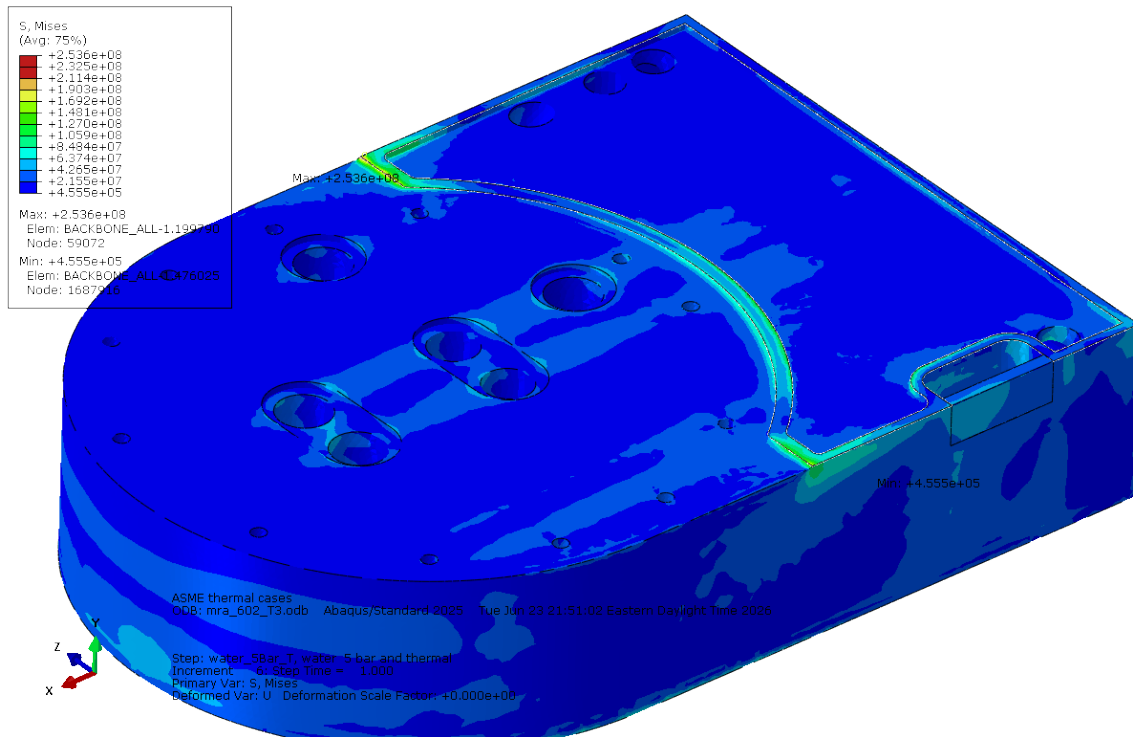


Figure 132 5bar thermal case backbone and side cover cut at $y = -0.252$ m showing Mises Stress (Pa)

Figure 133 shows views cut near the top of the upper weld. The peak in the upper welds is 208 MPa with most of the weld regions below 115 MPa. Thermal stress is the primary driver and the full penetration weld stresses are all below the 345 MPa Sm limit with thermal stress.

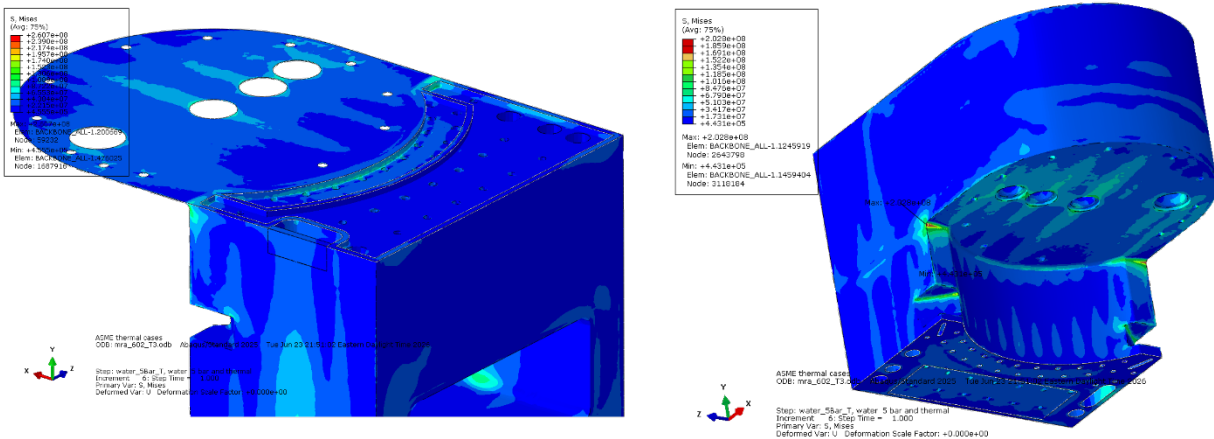


Figure 133 5bar thermal case backbone stress (Pa) near upper weld

The contact status and contact pressure on the backbone surfaces in contact with the moderator reflector vessels are shown in Figure 134 with a 5 MPa scale maximum for pressure. The stripping is likely because of thermal expansion differences between the backbone water channels.

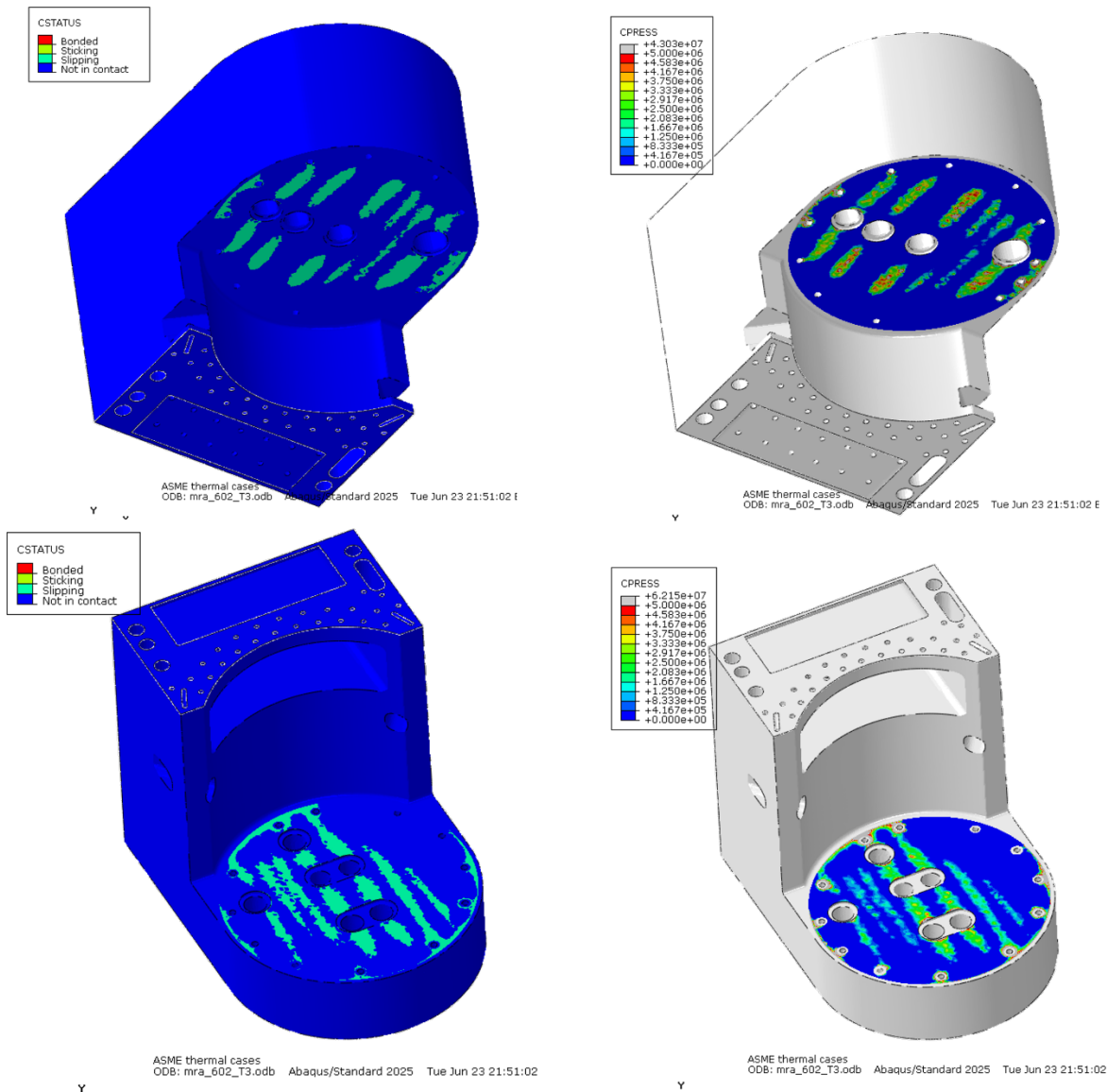


Figure 134 5 bar thermal backbone contact status and contact pressure (Pa) with a 5 MPa scale maximum

The upper reflector vessel stress is shown in Figure 135 with a peak of 131 MPa. This is only slightly higher than the 5 bar case without thermal stresses peak of 126 MPa as shown in Figure 71. All material is below the 3 Sm limit of 165 MPa for welded Al6061T6.

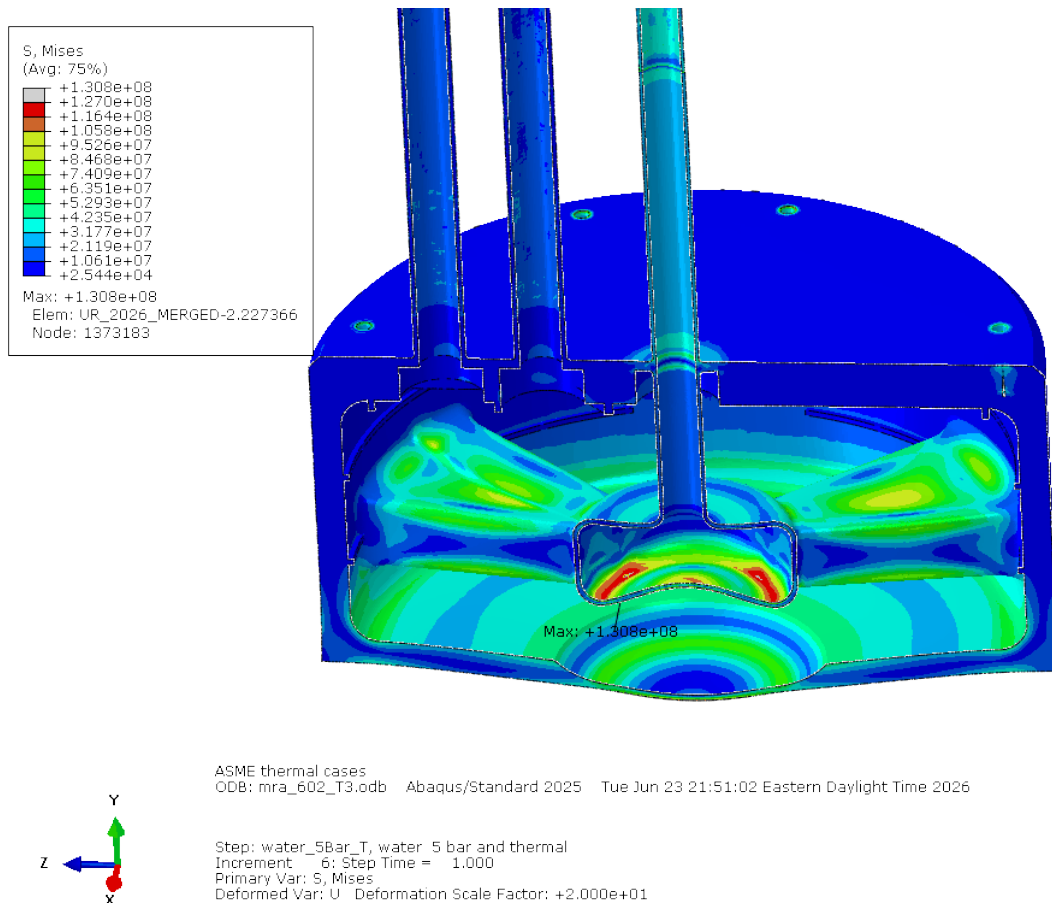


Figure 135 5 bar with thermal upper reflector vessel stress (Pa) with 131 MPa peak with displacements 20X

Vertical displacements for the reflector vessels for this case are shown in Figure 136 with peaks of 1.1 mm up on the lower vessel top surface and 0.97 mm down on the bottom surface of the upper vessel. The actual closest approach to the target surface from the lower reflector surface is closer to 1.0 mm since the peak vertical displacement is within a depression on the top surface.

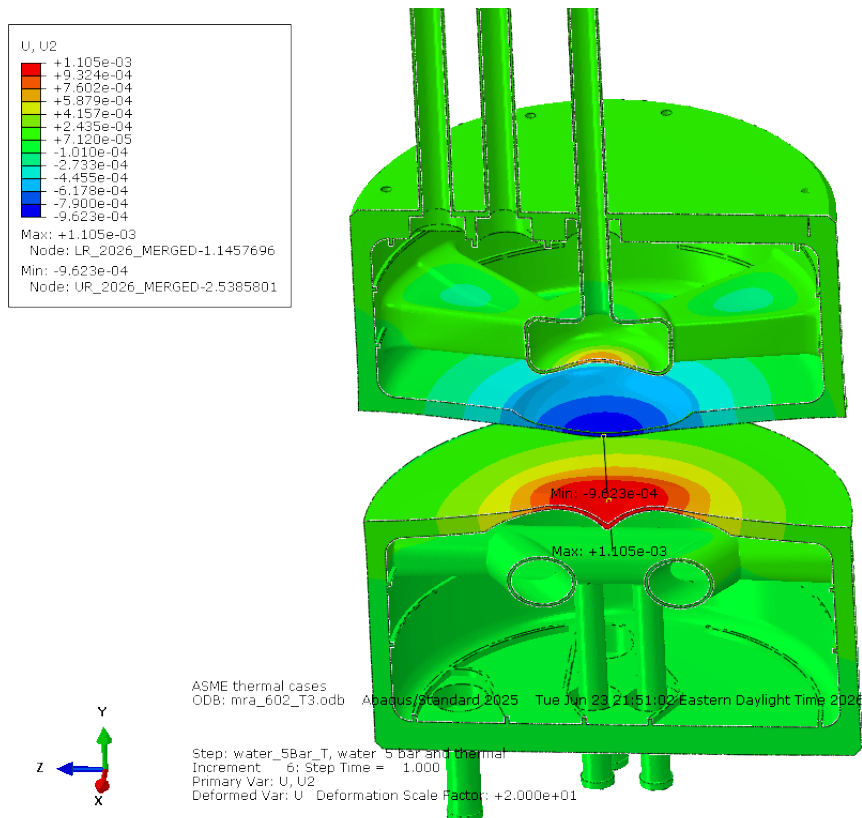


Figure 136 5bar thermal reflector vessel vertical displacements (m) with peak 1.1 mm up

The lower reflector vessel stress for this case is shown in Figure 137 with a peak of 139 MPa. This is below the 3 Sm limit of 254 MPa for Al6061T6 material or 165 MPa for welded Al6061T6.

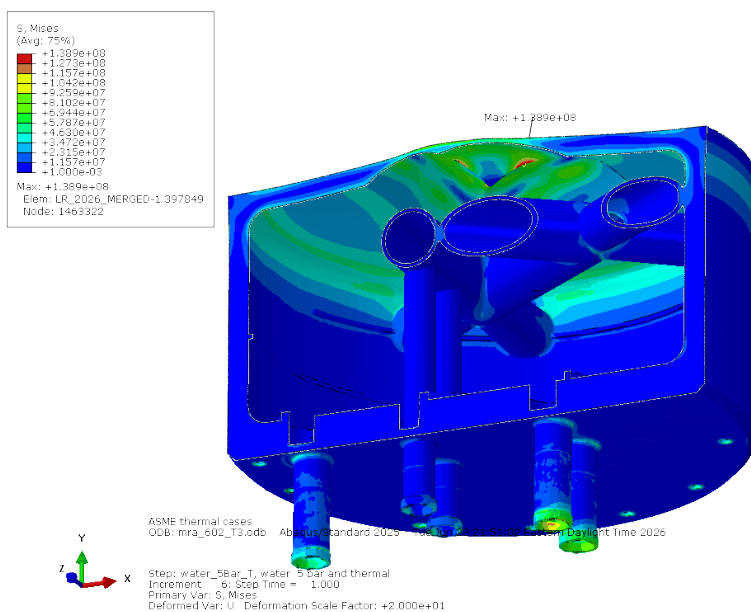


Figure 137 5bar thermal Lower Reflector Vessel Stress (Pa)

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5.12 PRELOAD GRAVITY WATER 3 BAR THERMAL (ASME CASE 9 ABAQUS CASE 9) NORMAL OPERATION

Stresses for this case are all bounded by the previous 5 bar water pressure Abaqus Case 8. Displacements for operation are given below. The lower vessel top surface peak displacement is .74 mm up and the upper vessel peak displacement down is 0.6 mm.

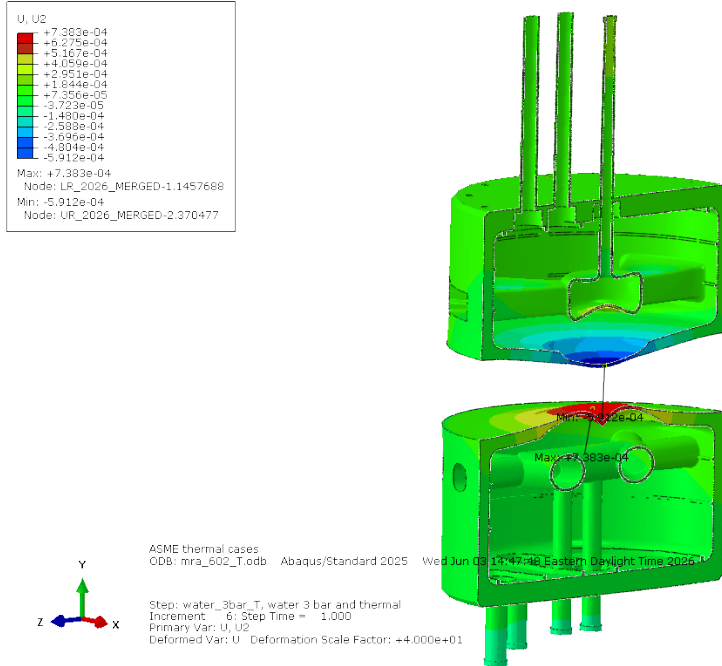


Figure 138 3bar thermal Upper and Lower Reflector Vessels Vertical displacements (m)

The peak overall assembly displacement towards the target is 0.51mm at the top of the upper shielding as shown in Figure 139. Vertical (U2) and lateral (U3) displacements are also shown. This is conservative and does not include the boundary condition on the seismic block which could reduce U1 and U3 displacements. Figure 140 shows the displacements around the seismic block hole without constraints of approximately 0.22 mm in the X direction and 0.14 mm in the Z direction.

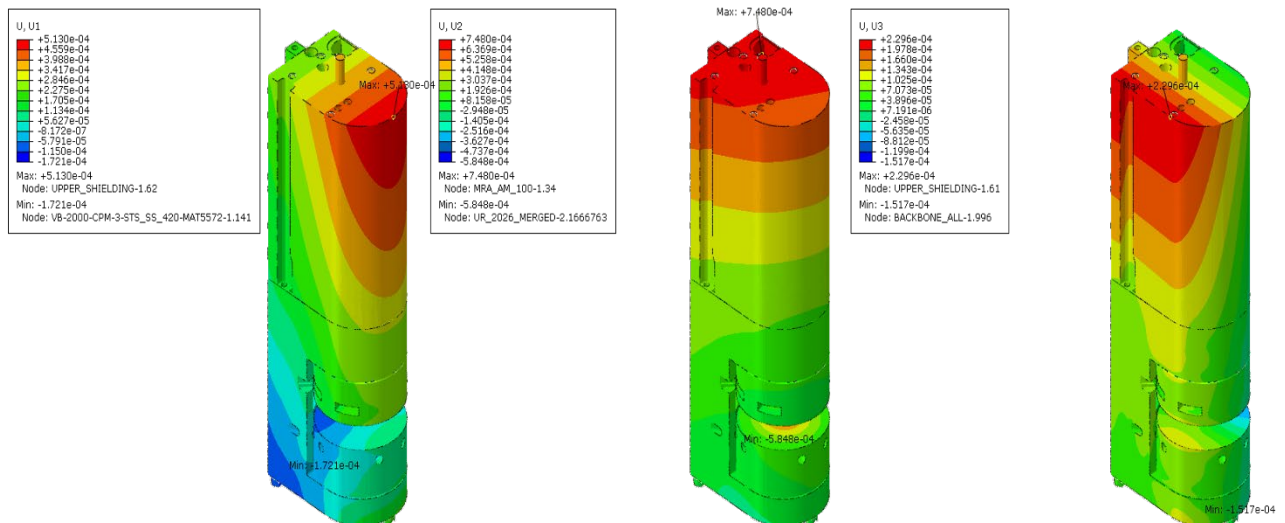


Figure 139 3bar thermal Assembly Displacements (m) X (U1) Y(U2) and Z (U3)

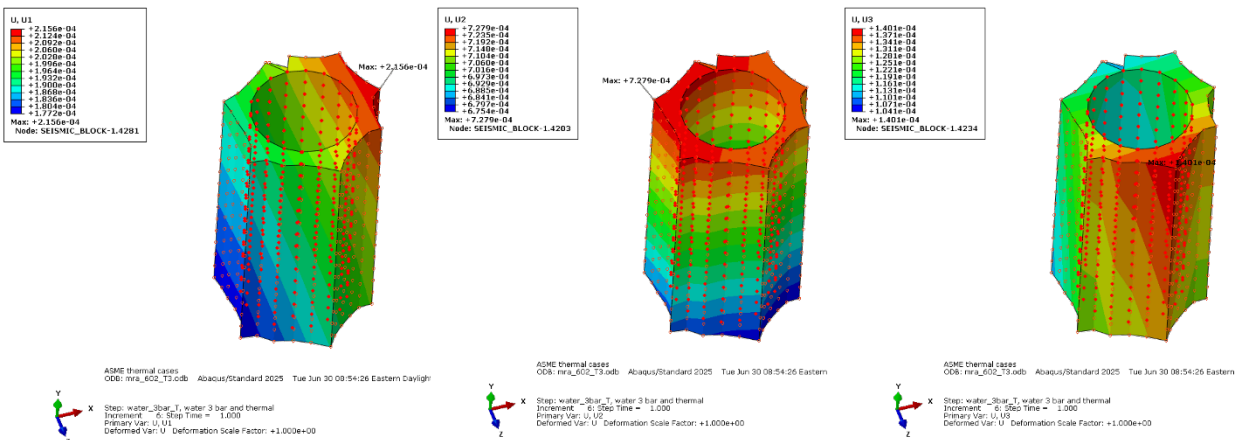


Figure 140 3 bar thermal displacement (m) around seismic block hole

Displacements at six moderator attachment locations for the upper and lower reflector vessels were evaluated for this case. The closest mesh nodes to these locations were identified and the displacements found. Figure 141 shows the upper and lower reflector vessel total displacement with the attachment nodes highlighted. The node numbers, locations and displacements are given in Table 6. The largest magnitude displacement was 0.25 mm in the upper reflector. The largest displacement towards the target in the +X direction was 0.19 mm.

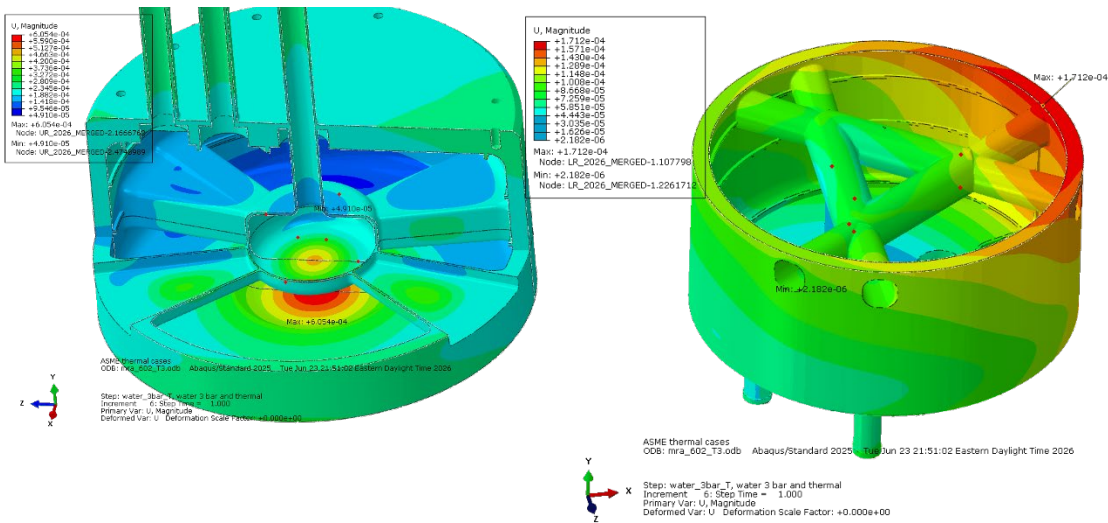


Figure 141 Upper and lower reflector vessel displacement (m) and attachment nodes

Table 6 Upper and Lower Reflector Vessel moderator attachment locations and displacements

		Node base location (mm)			Node displacements (mm)			
	NODE #	X	Y	Z	magnitude	ux	uy	uz
Upper								
U1	1387493	-0.497	85.700	-38.733	0.230	0.161	0.165	-0.008
U2	60962	-33.081	85.700	19.796	0.234	0.136	0.189	0.018
U3	1368983	33.787	85.700	19.796	0.246	0.178	0.168	0.023
U4	1158278	-0.290	132.280	38.964	0.192	0.166	0.091	0.033
U5	1604049	-34.048	132.280	-19.700	0.187	0.155	0.105	0.004
U6	1493301	34.048	132.280	-19.654	0.206	0.186	0.090	0.009
Lower								
L1	2010272	72.728	-81.651	0.039	0.111	0.011	0.110	0.015
L2	151810	-43.697	-81.508	54.408	0.078	-0.029	0.066	0.028
L3	151761	-43.697	-81.508	-54.408	0.078	-0.022	0.074	-0.015
L4	2157730	72.727	-121.349	-0.039	0.091	0.026	0.086	0.012
L5	153775	-43.697	-121.492	54.408	0.054	-0.021	0.041	0.028
L6	152931	-43.697	-121.492	-54.408	0.055	-0.014	0.048	-0.022

5.12.1 Normal Operation Thermal Fatigue Evaluation

Fatigue screening was done following the intent of ASME BPVC 5.5.2.3 Fatigue Analysis Screening, Method A. Expected pressure cycles are expected to be less than 20% of the MAWP and can be excluded. Thermal fatigue cycles are generated by beam trips from normal operations with 3 bar water pressure. It is conservatively modeled as all components going from normal operating temperatures to the inlet temperature of 32 °C. An alternating stress field was created in Abaqus by subtracting the 3bar 32 °C step stress results from the 3bar with thermal case. The result file was modified to include a fatigue step with the new field results for thermal fatigue stress on all components. An alternating temperature field

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was also created in Abaqus by subtracting the 3bar 32 °C step NT11 results from the 3bar with thermal case. The result file was modified to include a fatigue NT11 step with the new field results for thermal fatigue temperature change on all components. The operation to create these fields is shown in Figure 142.

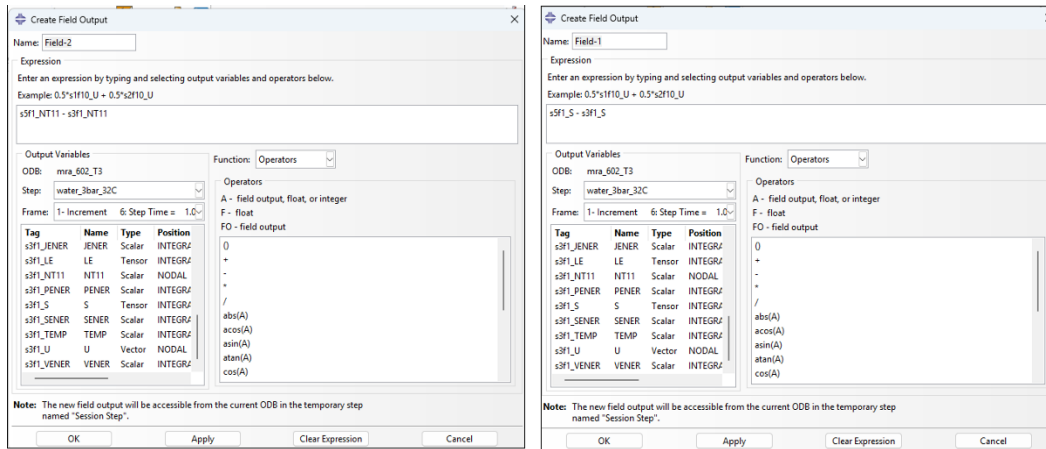


Figure 142 Fatigue temperature and stress field creation

The fatigue temperature change field (°C) is shown in Figure 143 with a maximum of 53 °C.

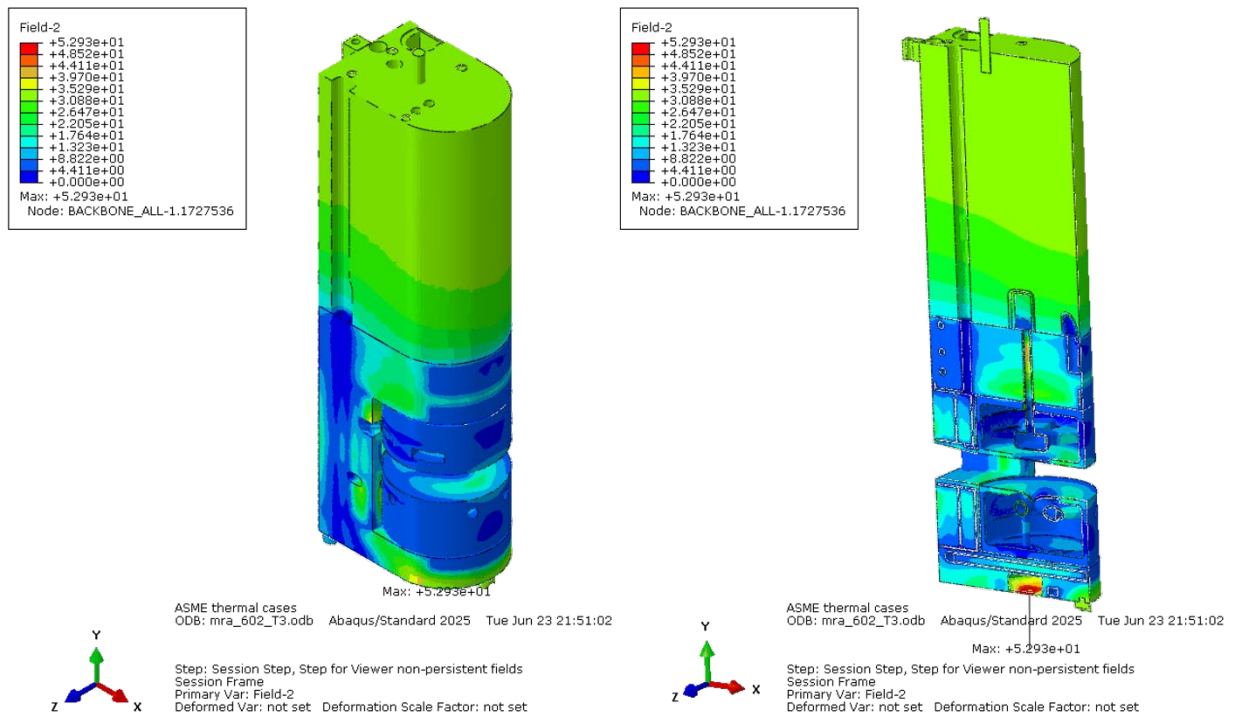


Figure 143 Temperature change (°C) from normal operation after beam trip

The overall fatigue stress is shown in Figure 144. The peak stress was artificial and in a lower mount as discussed previously. Without the mounts the peak was 245 MPa at the corner weld with 75% averaging.

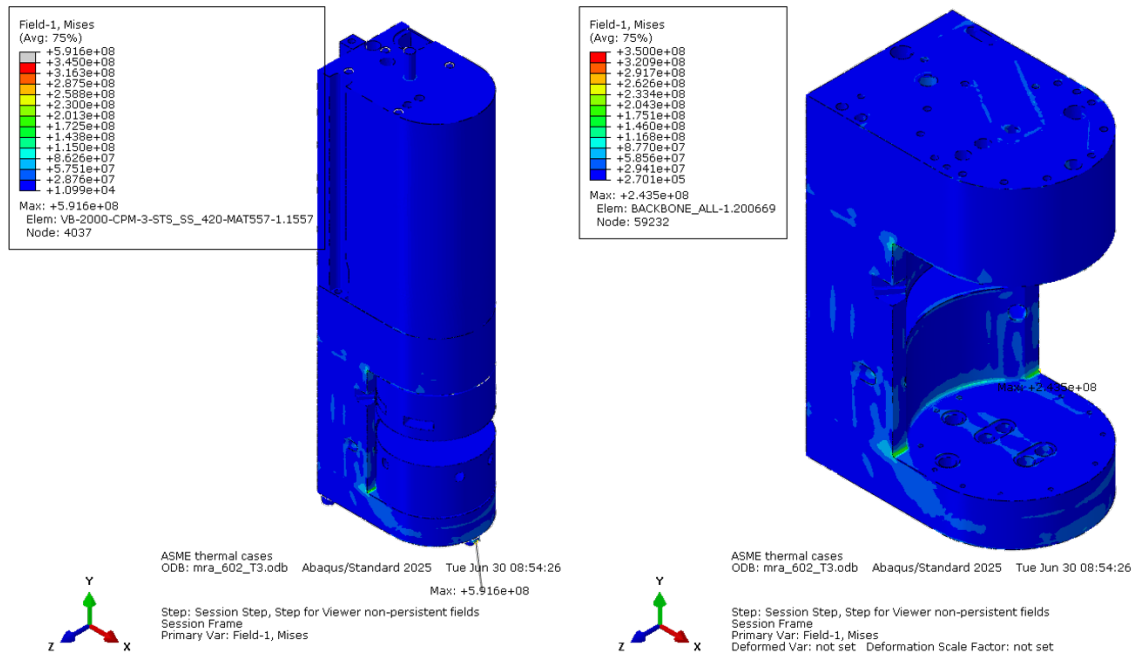


Figure 144 Assembly fatigue stress (Pa)

For fatigue analysis peak stresses were plotted. Two elements at a right-angle singularity within the backbone gave artificial peaks as shown in Figure 145. Fabrication will include a radius at this corner which will eliminate the singularity.

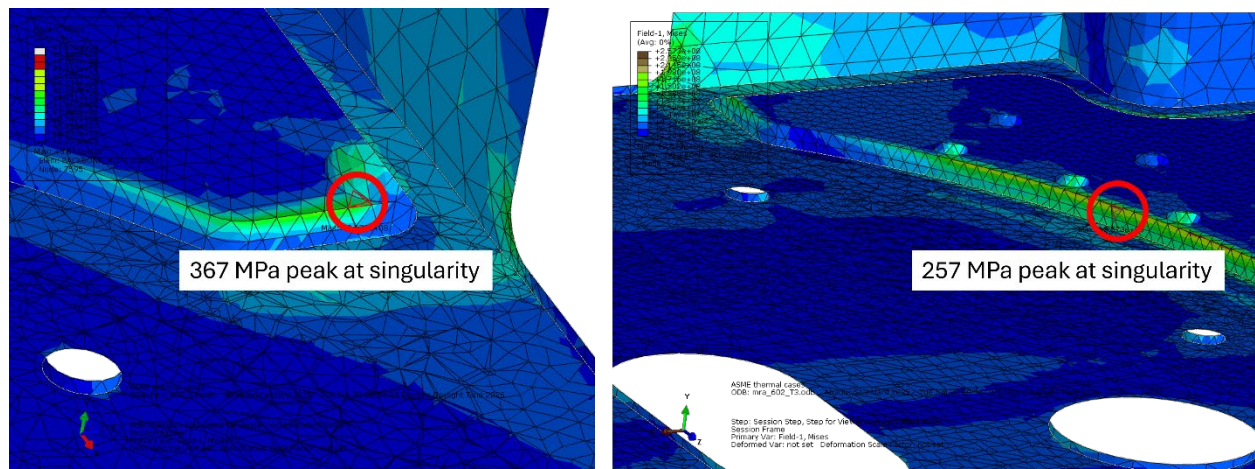


Figure 145 Fatigue peak stress (Pa) - peaks at edge corner singularity with no averaging

With the high stress elements removed from the display the peak stress was 253 MPa (no averaging) at a weld surface as shown in Figure 146 with the mesh.

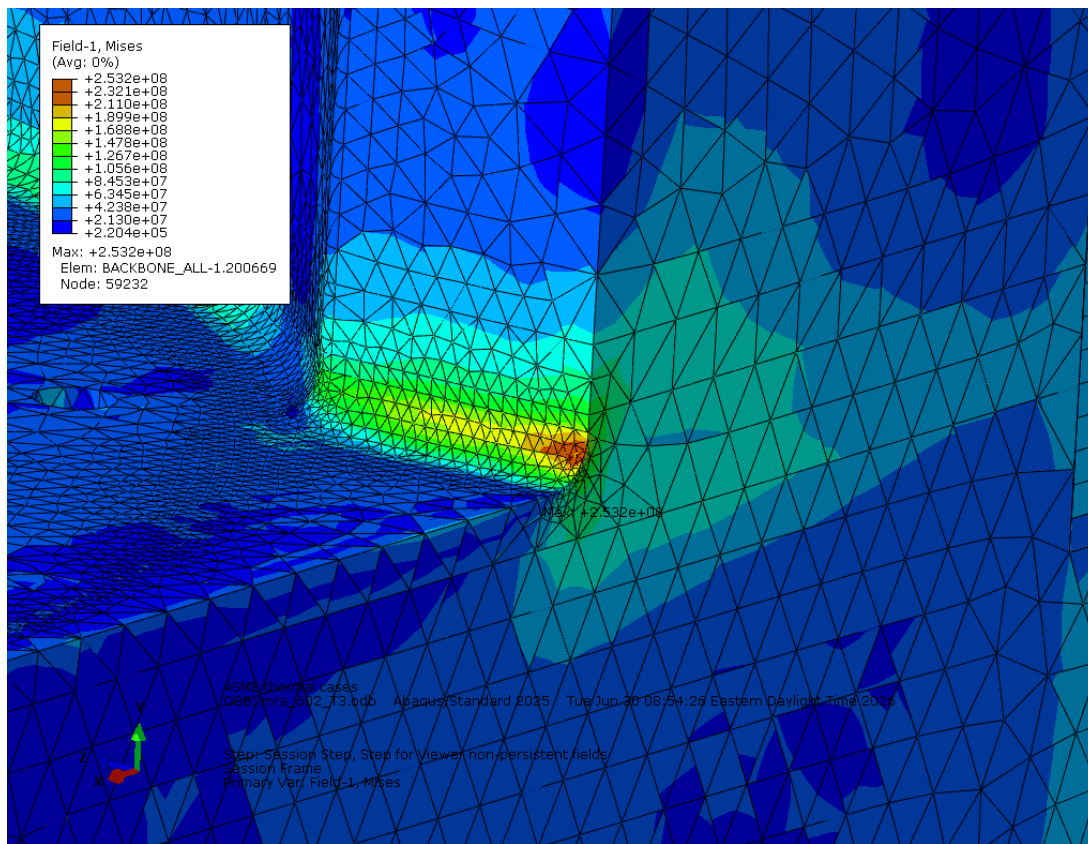


Figure 146 316L high stress (Pa) regions for fatigue without averaging - 250 MPa scale maximum

A fatigue life estimate was made using the peak value of 253 MPa which gave an estimated life of 5×10^5 cycles as shown in Figure 147. This would give a 50 year life at 10^4 cycles per year which exceeds the required lifetime of 5 years. A peak stress of approximately 420 MPa would give a 6 year life showing a large margin to the limit.

316L Peak
253 MPa
Sa = 126.5 MPa

Life $\sim 5 \times 10^5$ cycles
Life ~ 50 years

6e4 cycles $\sim$
6 years
Sa ~ 210 MPa
S ~ 420 MPa

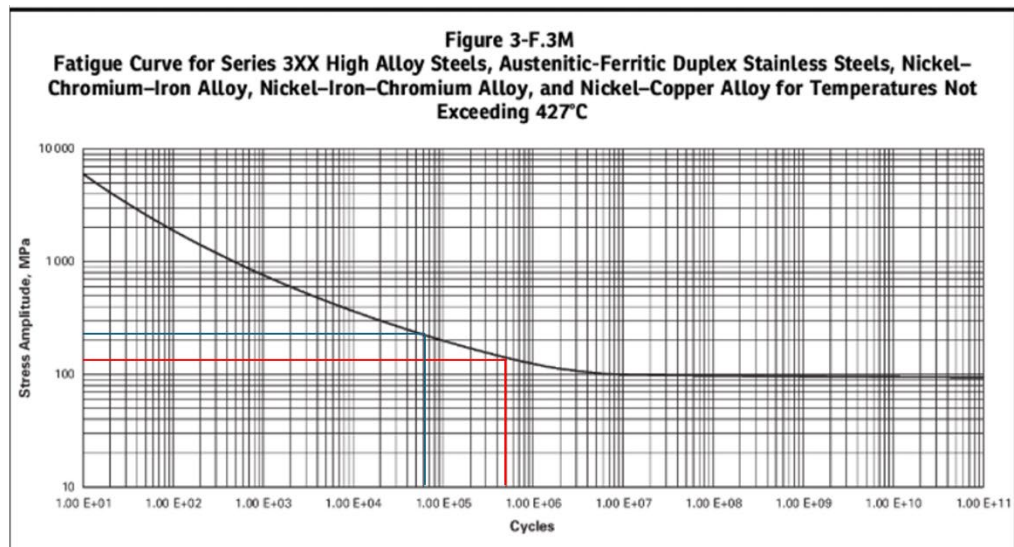


Figure 147 316L Thermal Fatigue lifetime estimate

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The fatigue stress in all Al6061T6 material is shown in Figure 148 with a peak without averaging of 81 MPa in the upper reflector.

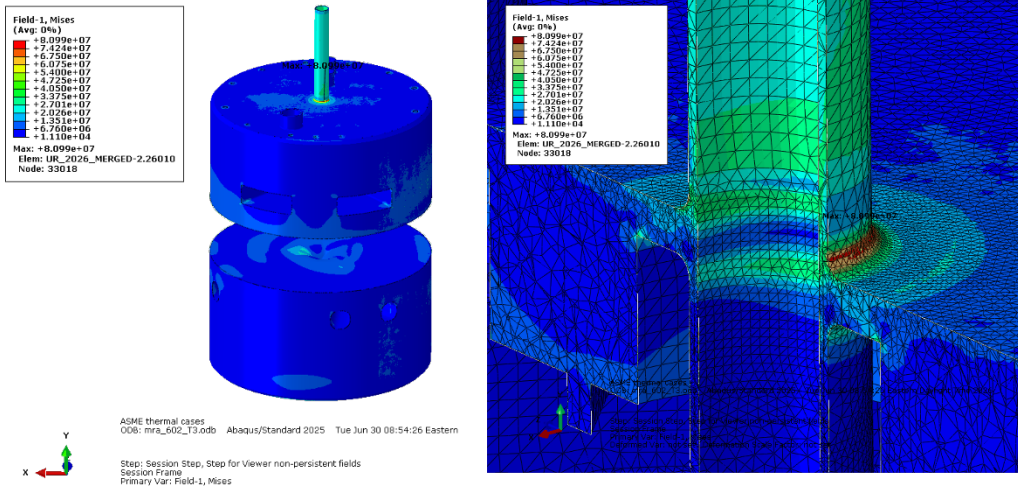


Figure 148 Thermal fatigue stress (Pa) in Al6061T6

The Lower Reflector Fatigue Stress is shown in Figure 149 with a peak of 68 MPa. The estimated fatigue lifetimes are 20 years for the upper reflector and 30 years for the lower reflector compared to the 5 year requirement as shown in Figure 150. All aluminum components meet the fatigue life requirement to exceed 5 years with 5e4 cycles.

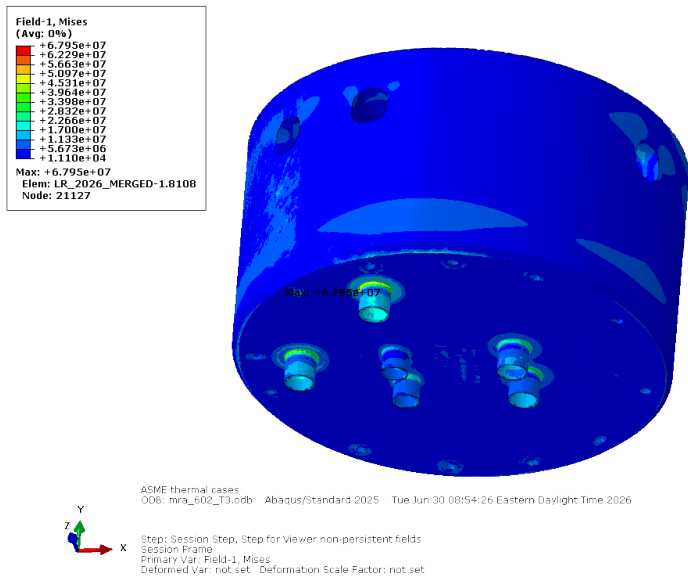


Figure 149 Lower Reflector Al6062T6 Fatigue stress (Pa)

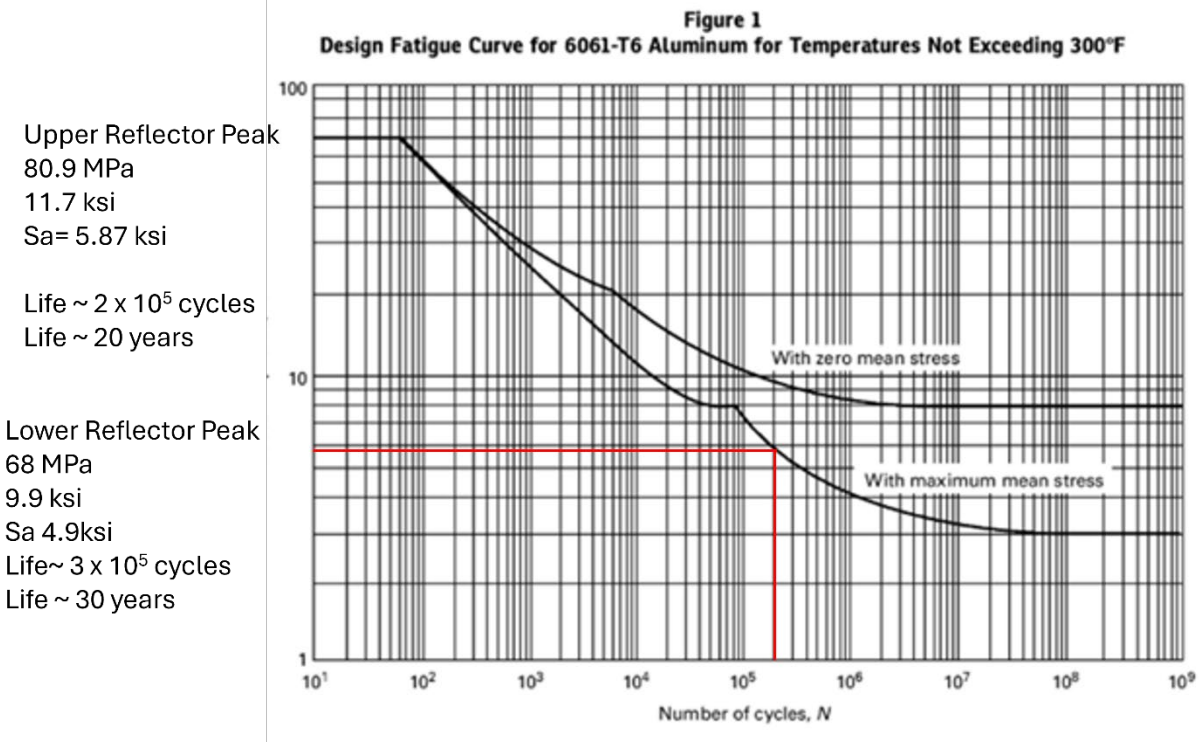


Figure 150 Al6061T6 Estimated Fatigue life of $2e5$ Cycles

5.13 PRELOAD GRAVITY WATER 3 BAR THERMAL CORE VESSEL 1 BAR (ASME CASE 3 ABAQUS CASE 10)

The core vessel 1 bar pressure was applied to the reflector vessel outer surfaces and some backbone sections with thin walls. The upper shielding and other solid regions did not have the pressure applied. The load is shown in Figure 46. Preload, gravity and thermal loads were included. The core vessel pressure reduces the deflections and stress in the reflector vessels as shown in Figure 151 and Figure 152. The stress in the cavity in the bottom of the lower backbone increased slightly but remained below 172 MPa. Figure 153 shows a comparison of the vacuum surface stress with core vessel vacuum and with 1 bar in the core vessel with an increase from 124 MPa to 131 MPa on the lower cover.

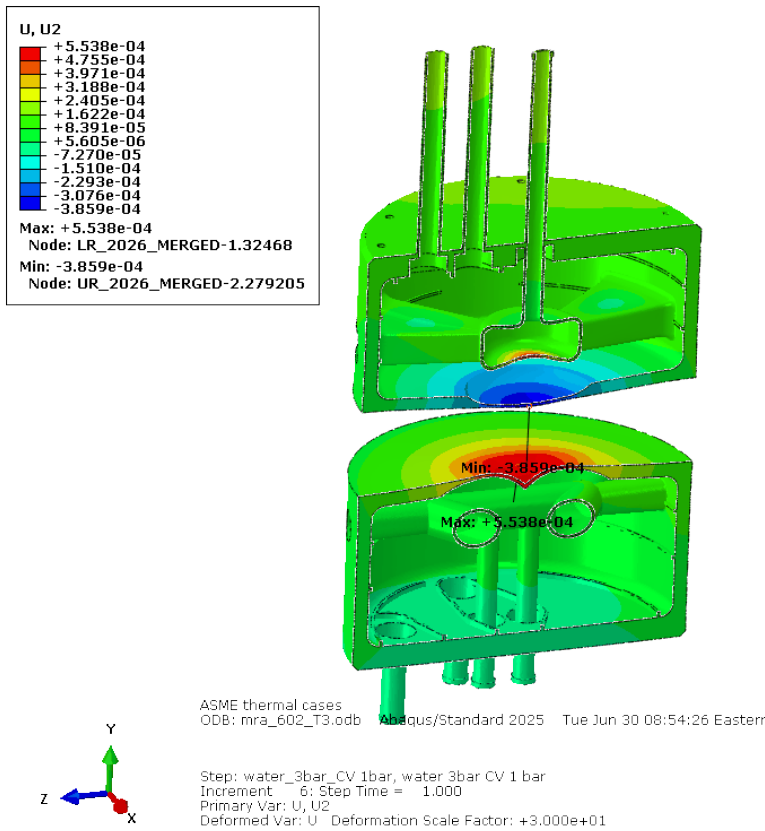


Figure 151 3bar and 1 bar CV Reflector vessel vertical displacements (m) reduced to +0.55 mm and - 0.4 mm\

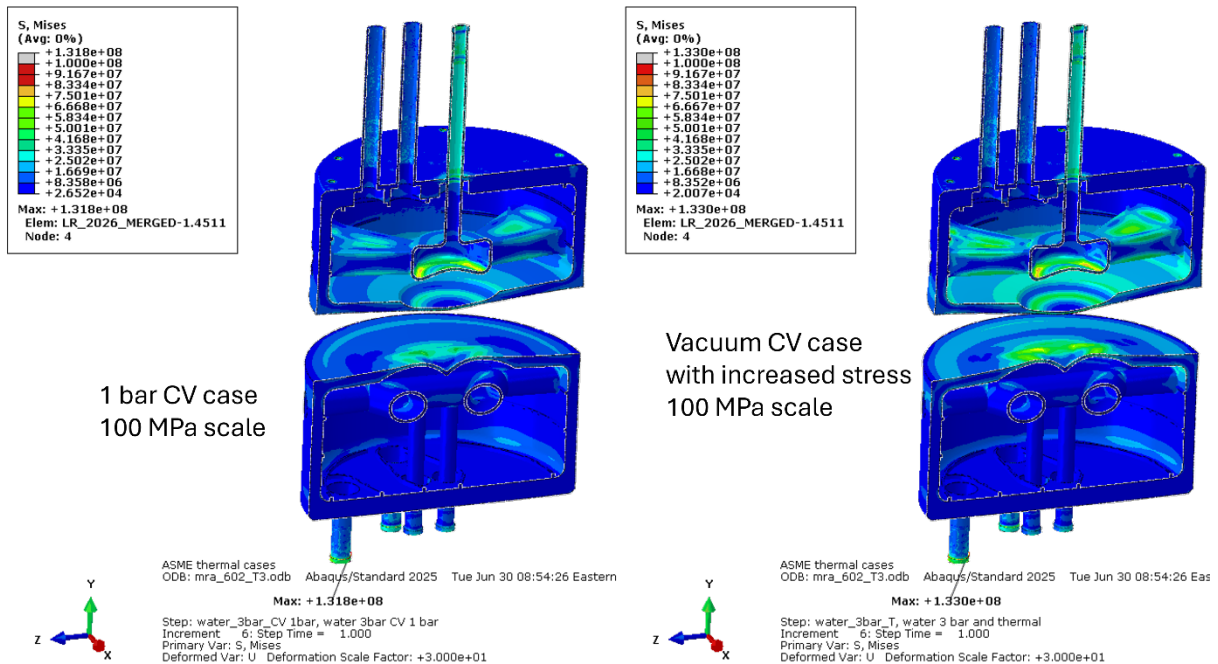


Figure 152 Reflector Vessel Stress (Pa) with 3 bar and vacuum or 1 bar Core Vessel pressure both with 100 MPa scale maximum

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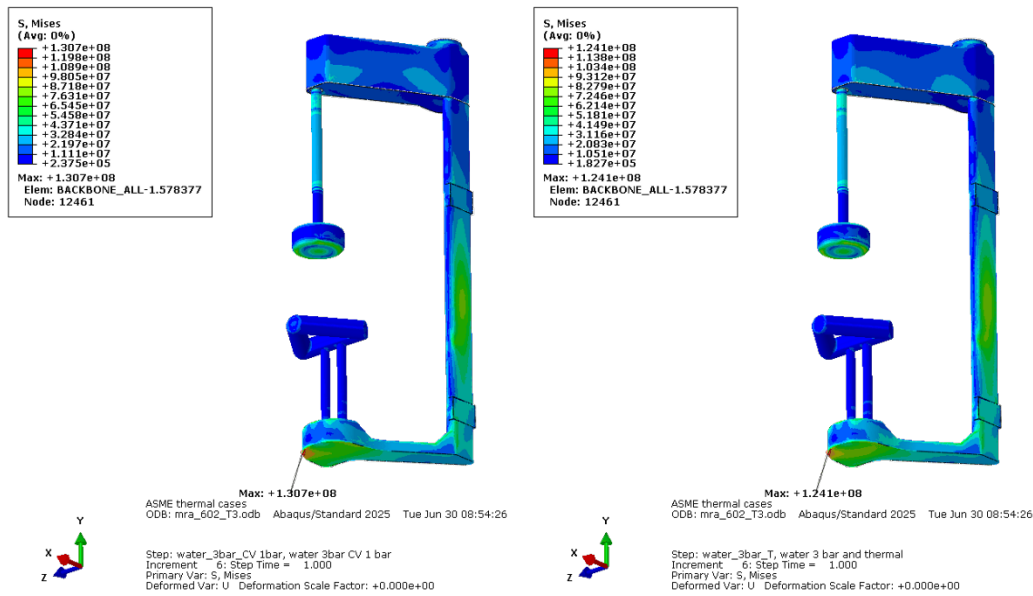


Figure 153 Vacuum surface stress (Pa) comparison with vacuum and 1 bar core vessel pressure

In general, this case with 1 bar core vessel pressure for normal operation does not produce any limiting conditions compared to vacuum operation. Overall assembly and seismic block displacements are shown in Figure 154

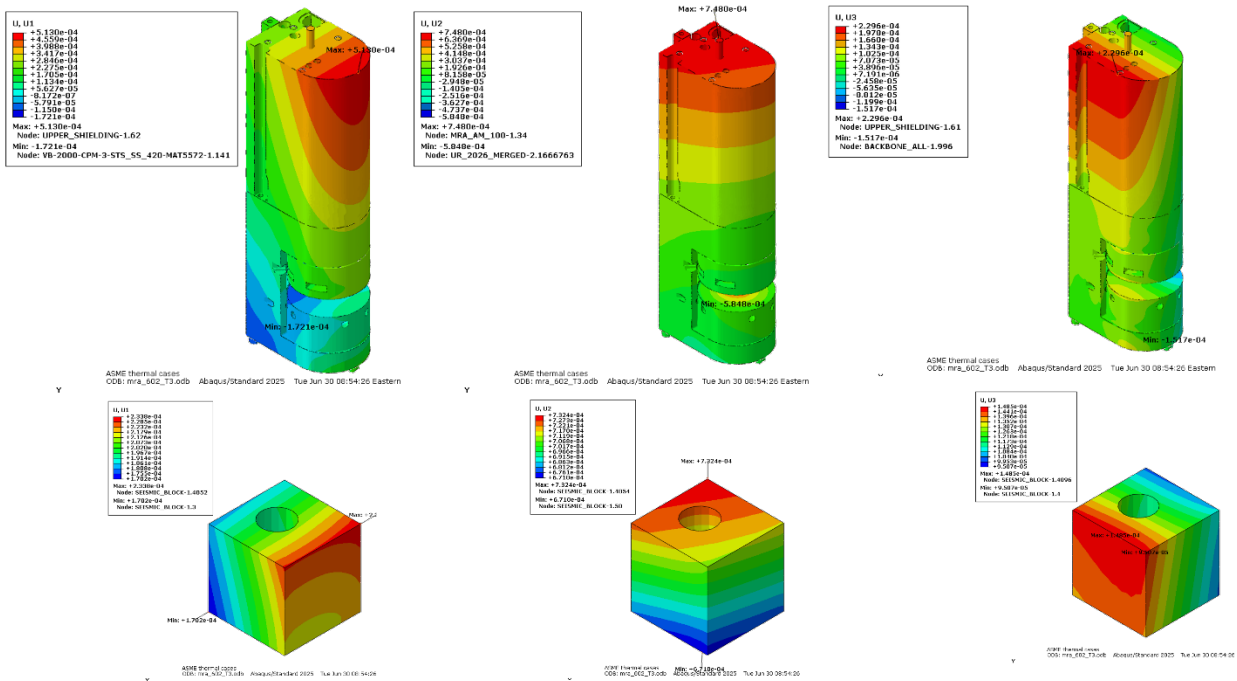


Figure 154 3bar water and 1 bar core vessel pressure overall assembly and seismic block displacements (m)

5.14 PRELOAD GRAVITY WATER 3 BAR VACUUM BOUNDARY 2 BAR (ASME CASE 3 ABAQUS CASE 11)

One case was evaluated with 2 bar pressure in the vacuum space with all other normal operation loads and temperatures. This would correspond to a hydrogen system boundary failure with vacuum boundary pressure relief at 2 bar. The vacuum boundary stress reduced slightly compared to normal operation as shown in Figure 155 with a peak of 114 MPa.

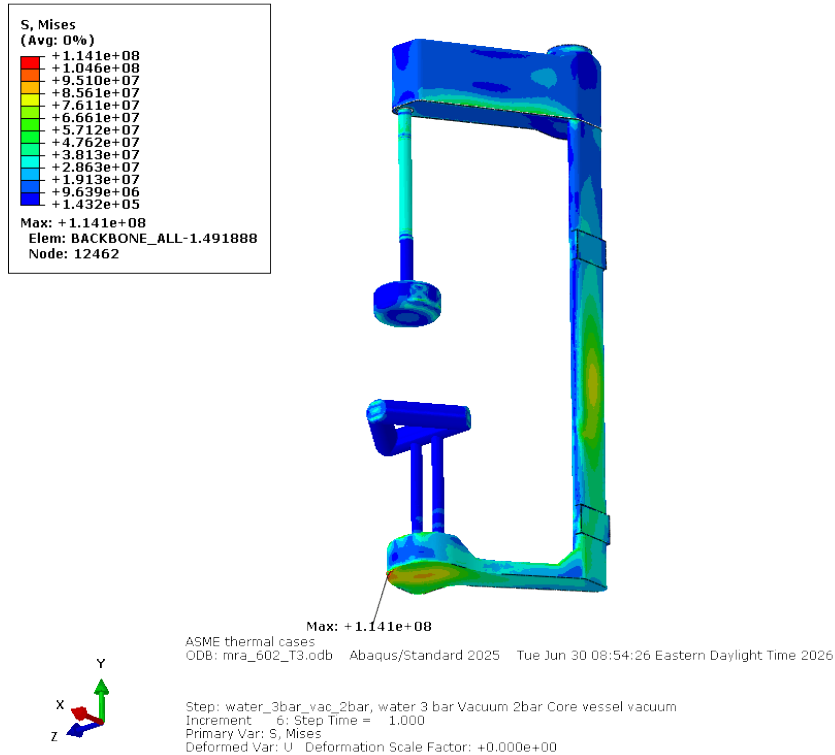


Figure 155 Vacuum boundary stress (Pa) with 2 bar pressure

Reflector vessel stresses are shown in Figure 156 with a peak of 133 MPa in a lower reflector vessel bimetal 316L tie to the backbone. Aluminum 6061 inner shell stresses are reduced by the lower differential pressure between the water pressure and the vacuum space pressure.

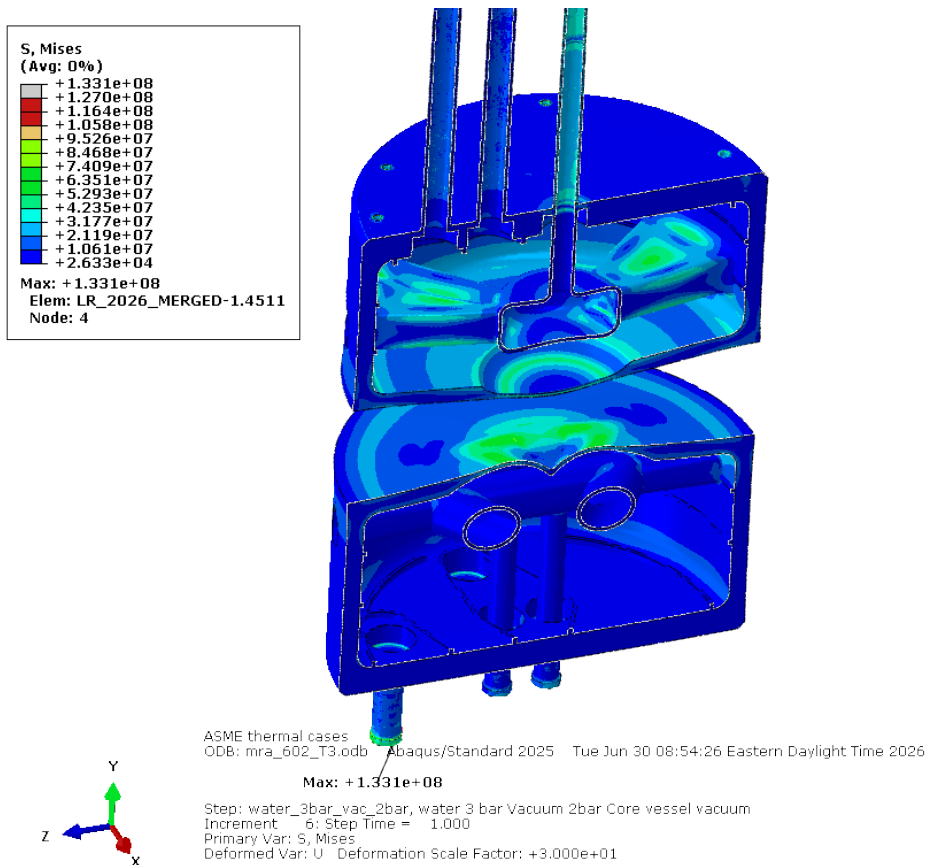


Figure 156 3 bar water and 2 bar vacuum space pressure showing Reflector Vessel Stress (Pa)

This case does not cause any additional limits.

6. MESH REFINEMENT STUDY

6.1 BACKBONE WELD MESH REFINEMENT

A mesh refinement was done around the high stress weld region of the backbone. The mesh edge node spacing at the back of the full penetration weld between the middle and lower backbone regions was reduced from 3 mm to 1.5 mm as shown in Figure 157. The input file was mra_502_T2R.inp.

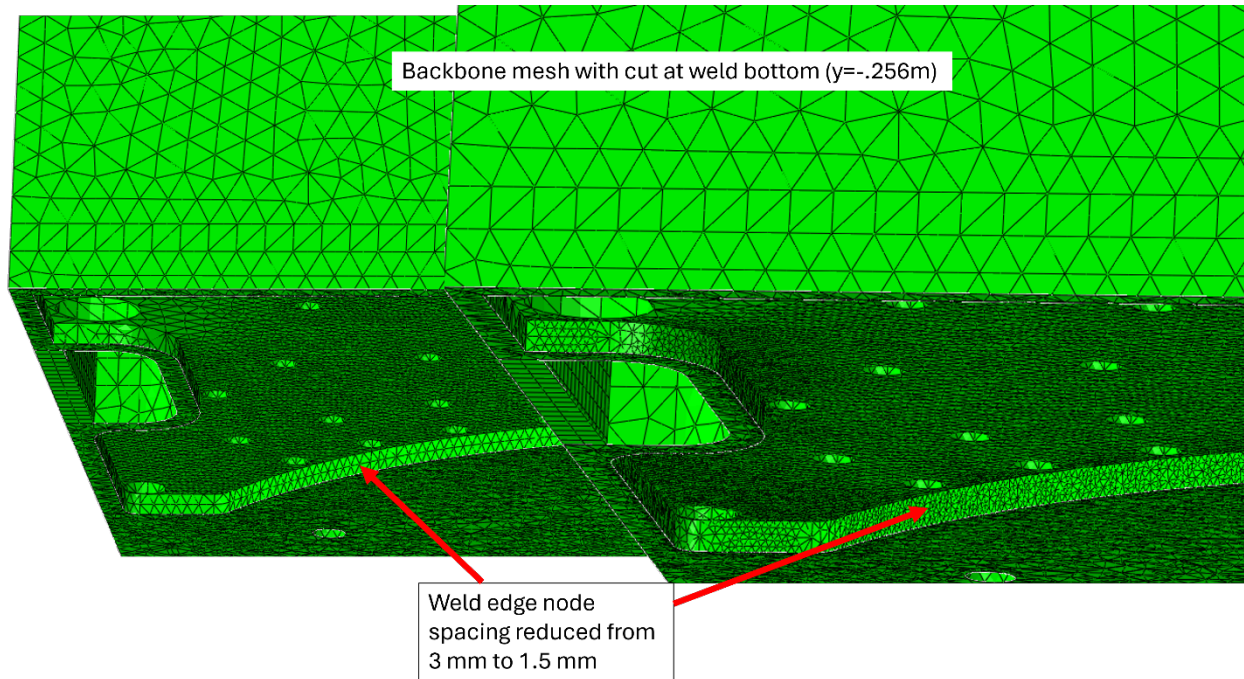


Figure 157 Mesh refinement by backbone weld inside

The mesh on the smoothed weld surface in the highest stress region was refined by reducing the node spacing on the top and bottom edges from 2 mm to 1 mm as shown in Figure 158.

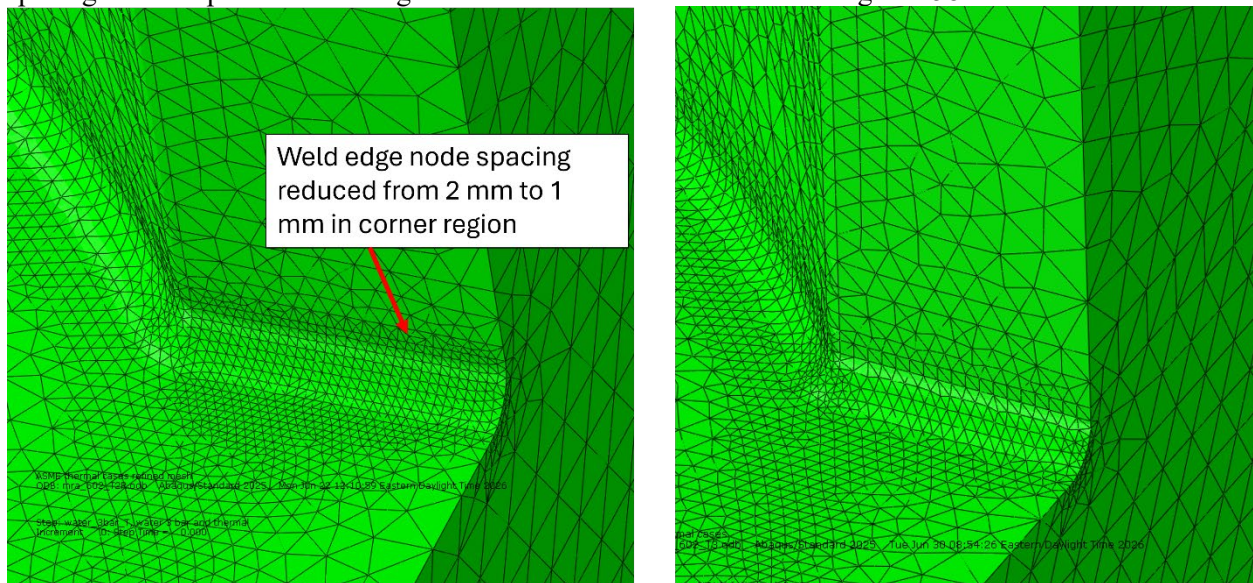


Figure 158 Corner weld mesh refinement

The peak stress in this region with 75% averaging for the 5 bar case with thermal loads reduced slightly from 260 MPa to 253 MPa as shown in Figure 159 with a scale maximum of 250 MPa for both. This indicates that the original mesh results are conservative and below the 3 Sm limit of 345 MPa.

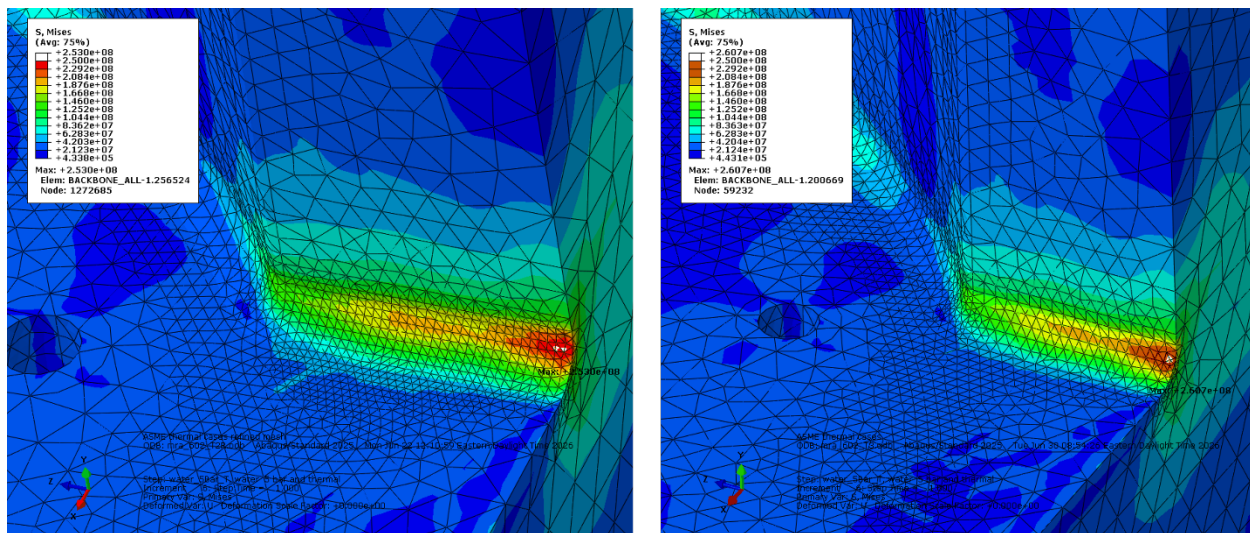


Figure 159 Corner weld stress (Pa) mesh refinement comparison showing 3% reduction with finer mesh

6.2 UPPER REFLECTOR VESSEL MESH REFINEMENT

The upper reflector peak stress region for the case with 5 bar water pressure and thermal was analyzed with a refined mesh. The edge node spacing near the peak stress was reduced from a nominal 1 mm to 0.5 mm. The peak stress with the finer mesh was nearly the same, increasing 0.8% from 130.8 MPa to 131.1 MPa as shown in Figure 160.

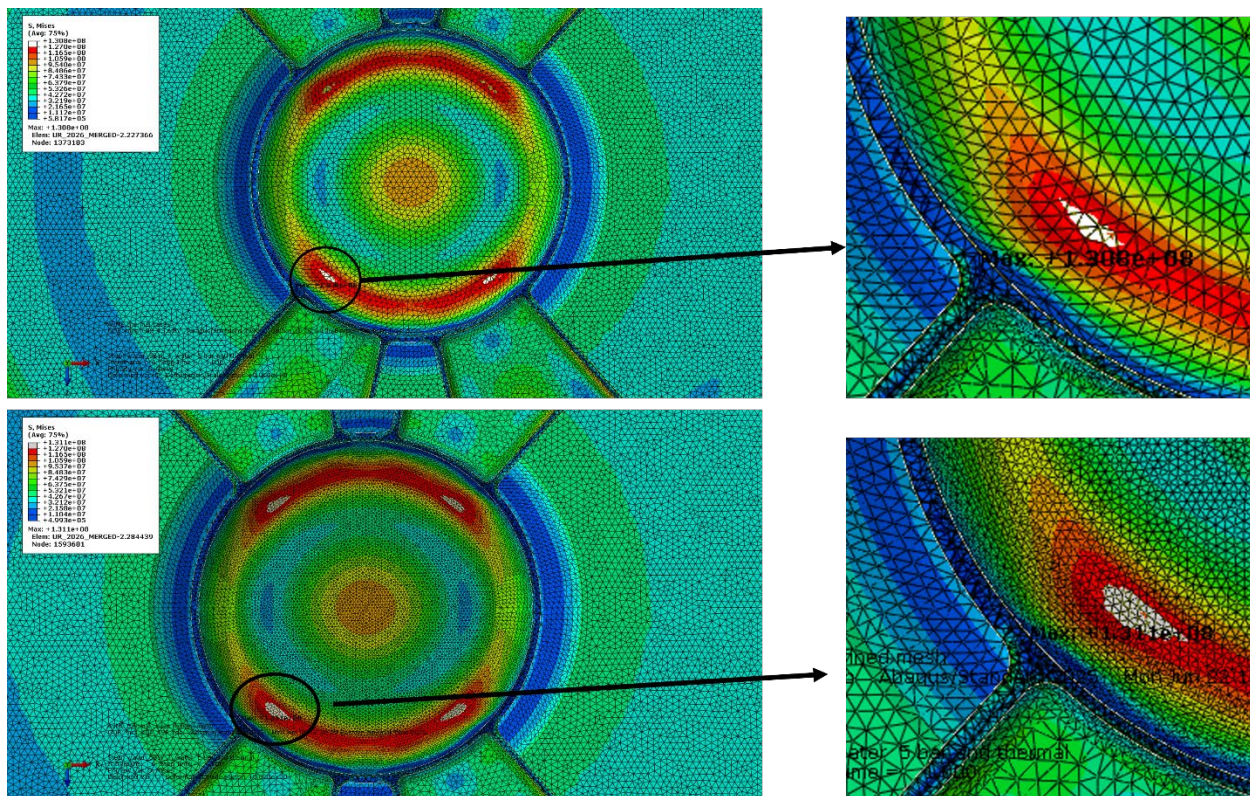


Figure 160 Upper Reflector mesh refinement stress (Pa) comparison for Abaqus case 8 (5 bar water pressure and thermal)

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The original results, which were within 1 % of the refined mode results are considered to be acceptable. The stress linearization results for the case with 5.75 bar water pressure showed primary membrane stress of 19 MPa and primary membrane plus bending of 132 MPa at the same location (Figure 82). Scaling for 5 bar water pressure the primary membrane and primary membrane plus bending would be within ASME stress intensity limits.

7. BERYLLIUM MODEL AND RESULTS

The beryllium parts rest within the upper and lower reflector vessels without any fixed connections. The beryllium was analyzed separately from the reflector vessels with only water pressure and thermal loads. The input file was mra_430_be.inp To avoid unrestrained body displacements in Abaqus, small artificial cylinders were created with a very low modulus (0.001 GPa) which could be fixed on one surface and tied to the beryllium on another without imposing any significant stress on the beryllium. The beryllium parts are shown below in Figure 161 and Figure 162,

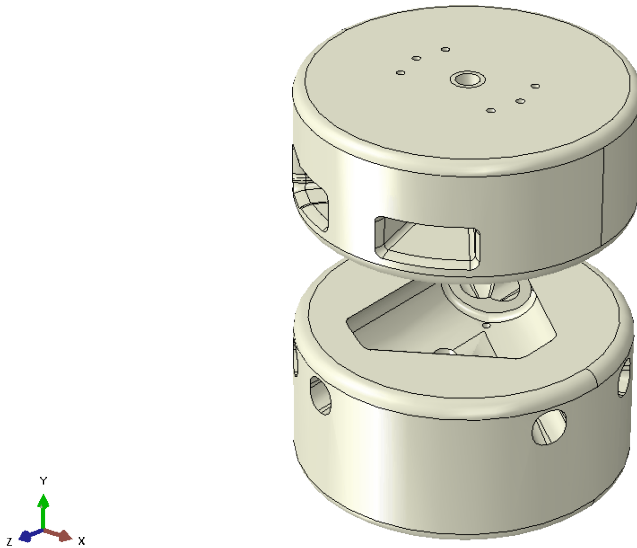


Figure 161 Beryllium upper and lower parts

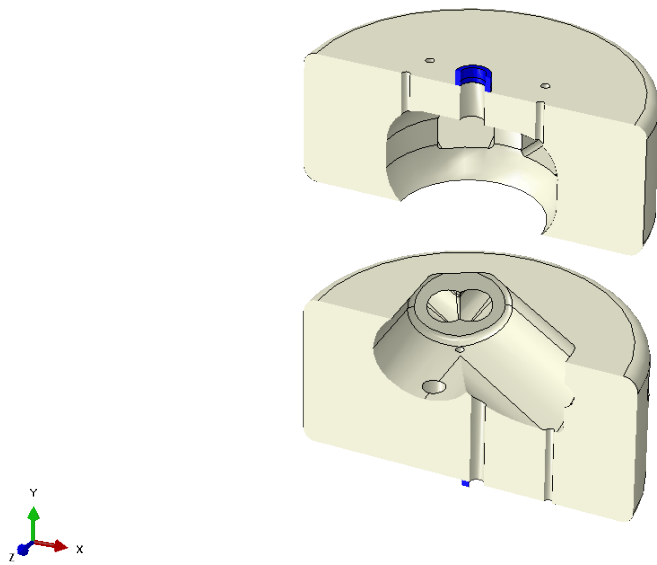


Figure 162 Section view of beryllium parts with $z=0$ cut including artificial low modulus cylinder in blue

The parts were meshed using C3D10 elements. Figure 163 shows the mesh with a group removed to show the internal mesh structure.

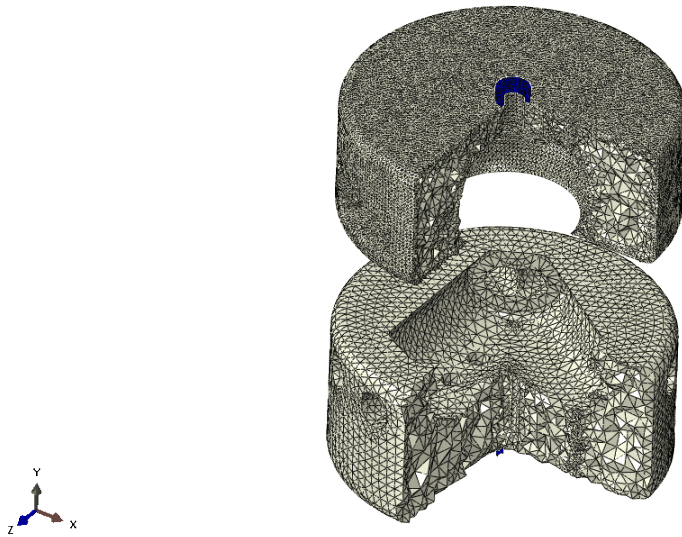
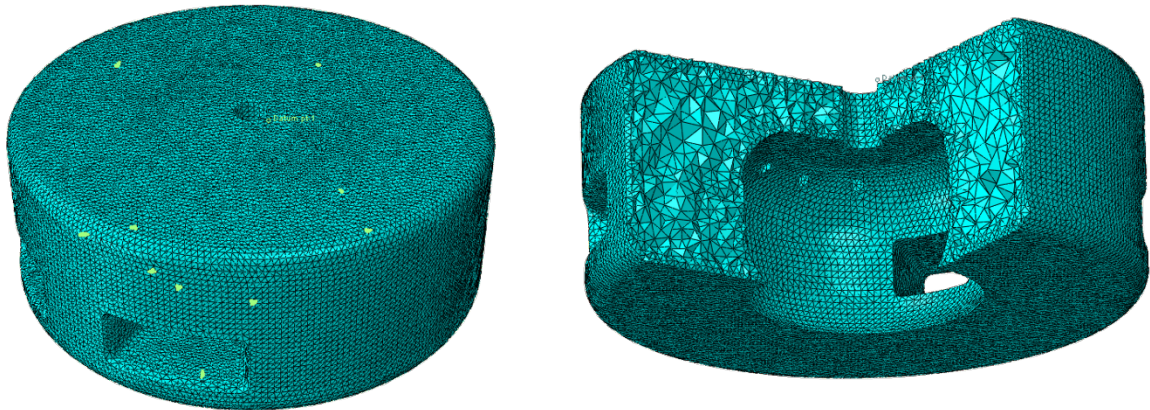


Figure 163 Beryllium parts C3D10 mesh

Figure 164 shows the upper reflector mesh with diagnostics and 18 poor elements



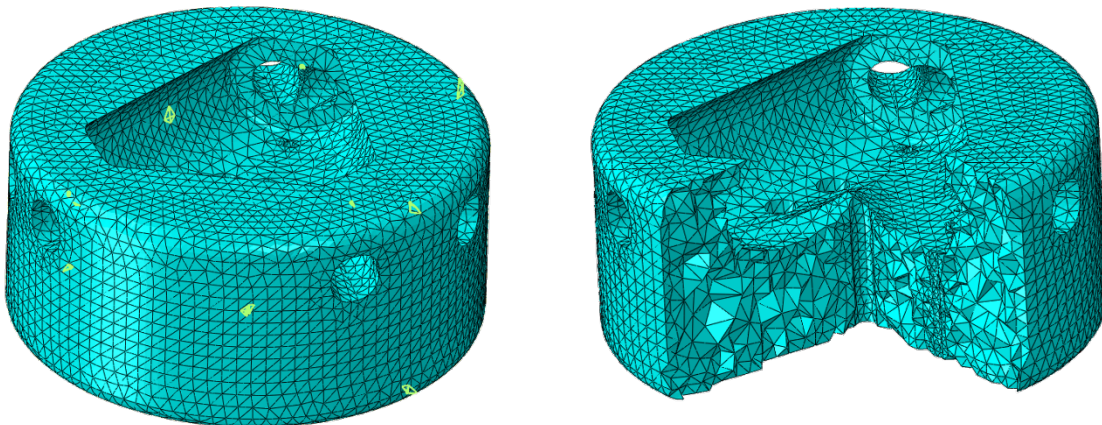
```

Min angle on Tri Faces < 5: 3 (0.00071918%)
Average min angle on tri faces: 38.10, Worst min angle on tri faces: 1.60
Max angle on Tri faces > 170: 0 (0%)
Average max angle on tri faces: 88.53, Worst max angle on tri faces: 167.48
Aspect ratio > 10: 2 (0.000479453%)
Average aspect ratio: 1.66, Worst aspect ratio: 35.86
Shape factor < 0.0001: 0 (0%)
Average shape factor: 0.659242, Worst shape factor: 0.000618
Number of elements : 417142, Analysis errors: 0 (0%), Analysis warnings: 18 (0.00431508%)
Created set 'PoorElements-2' containing 18 elements

```

Figure 164 Upper Beryllium Mesh Diagnostics

Figure 165 shows the lower reflector mesh with diagnostics and 22 poor elements.



```

Part: lower_be_1
Tet elements: 80705
Min angle on Tri Faces < 5: 6 (0.00743448%)
Average min angle on tri faces: 37.98, Worst min angle on tri faces: 2.36
Max angle on Tri faces > 170: 0 (0%)
Average max angle on tri faces: 88.41, Worst max angle on tri faces: 163.30
Aspect ratio > 10: 7 (0.00867356%)
Average aspect ratio: 1.67, Worst aspect ratio: 24.23
Shape factor < 0.0001: 0 (0%)
Average shape factor: 0.661734, Worst shape factor: 0.002454
Number of elements : 80705, Analysis errors: 0 (0%), Analysis warnings: 22 (0.0272598%)
Created set 'PoorElements-2' containing 22 elements

```

Figure 165 Lower Beryllium mesh diagnostics

Figure 166 shows the tie constraint on the upper beryllium part and the fix boundary condition on the “mush” part.

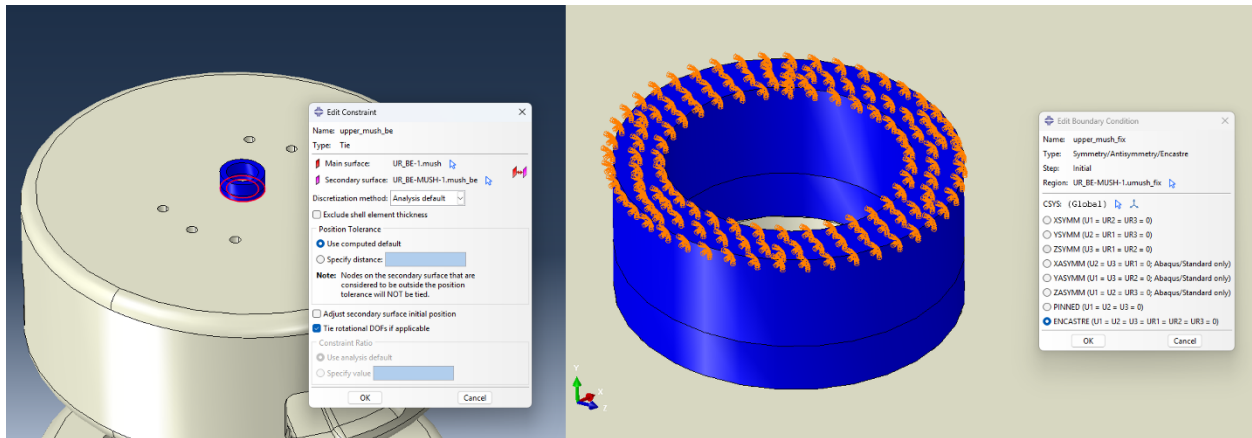


Figure 166 upper part tie and boundary condition

Figure 167 shows the tie constraint on the lower beryllium part and the fix boundary condition on the “mush” part.

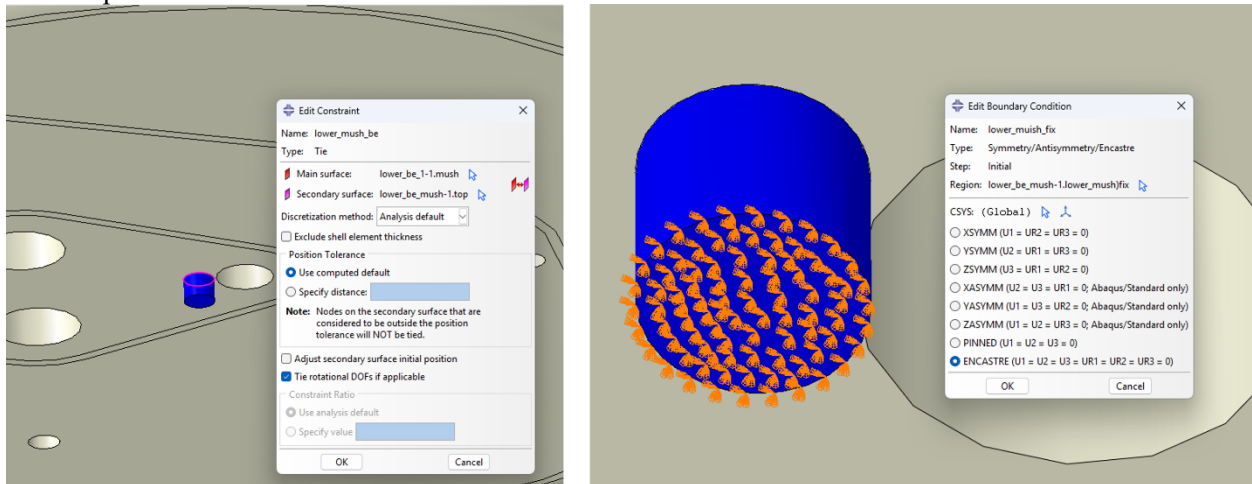


Figure 167 Lower Beryllium part tie and boundary condition

The beryllium parts see hydrostatic pressure from the water with a maximum of 5 bar.

Figure 168 shows the surfaces with the applied pressure.

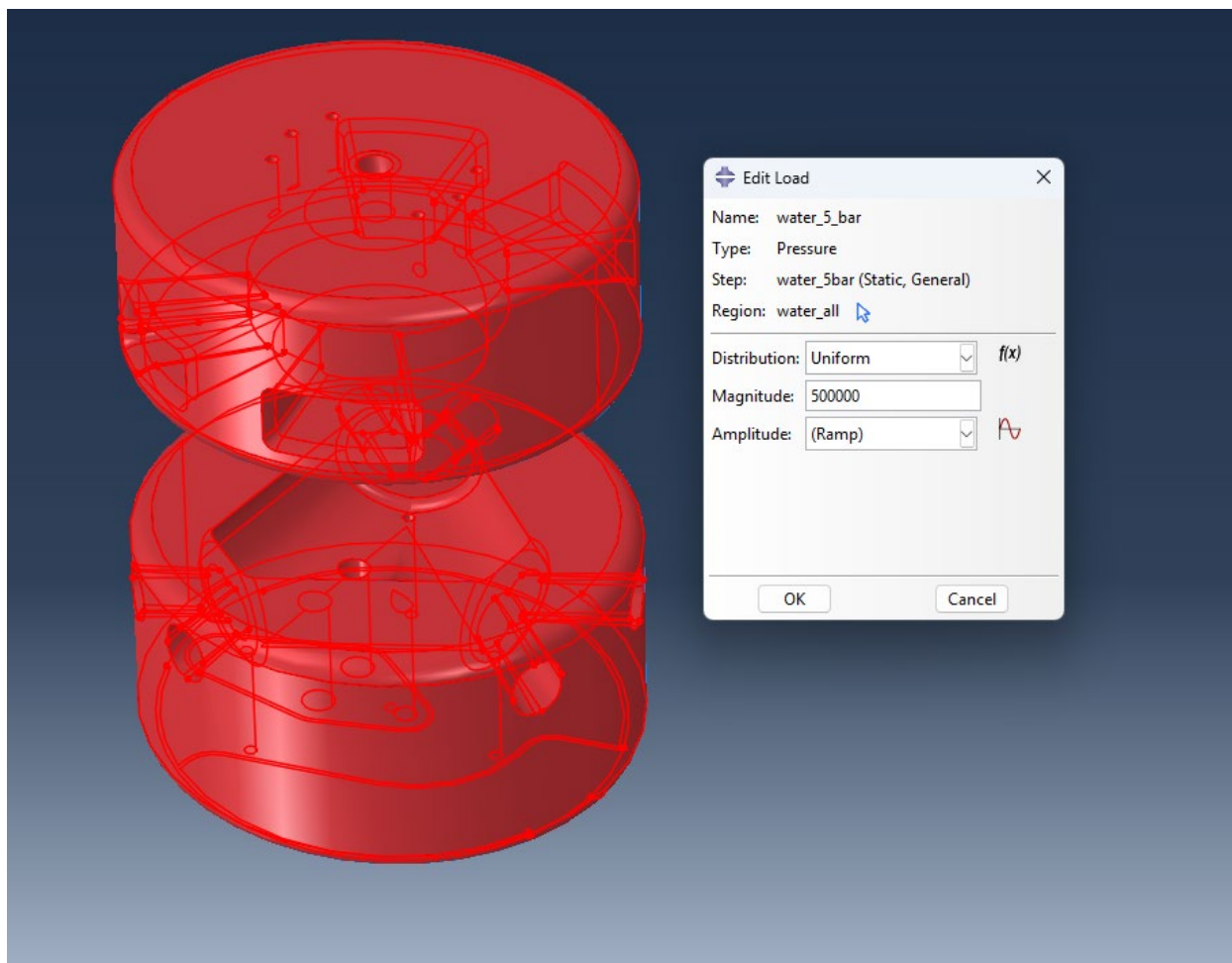


Figure 168 5 Bar Water Pressure (Pa) on Beryllium

The CFD whole model temperature data was mapped by Abaqus to the beryllium elements as shown in Figure 169, Figure 170, Figure 171 and Figure 172 with a peak of 54.7 °C. The material reference temperature was 20 °C.

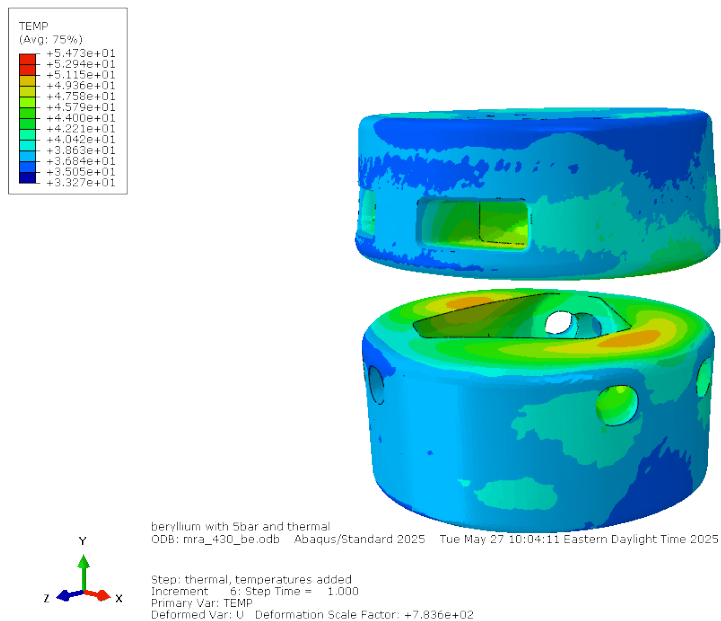


Figure 169 Beryllium Temperature (°C) with displacements x 783.6

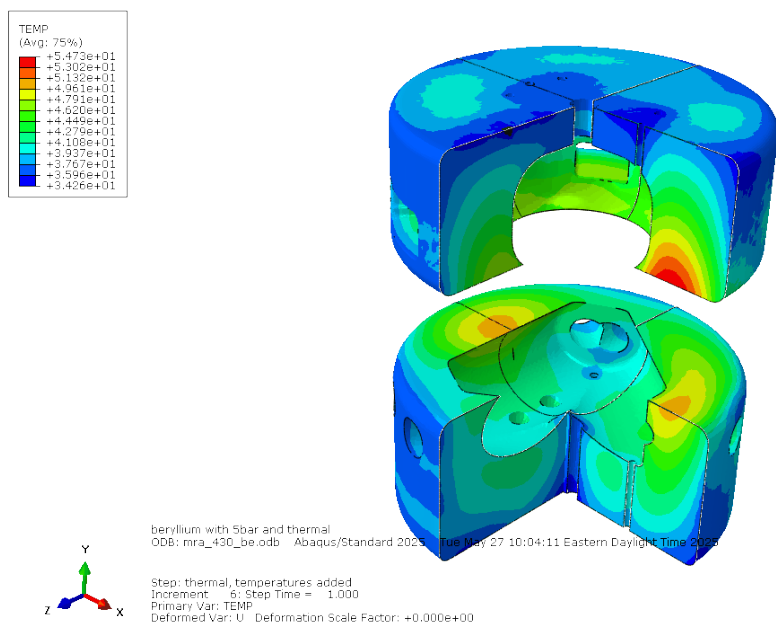


Figure 170 Berylliums temperatures(°C) with a cut view

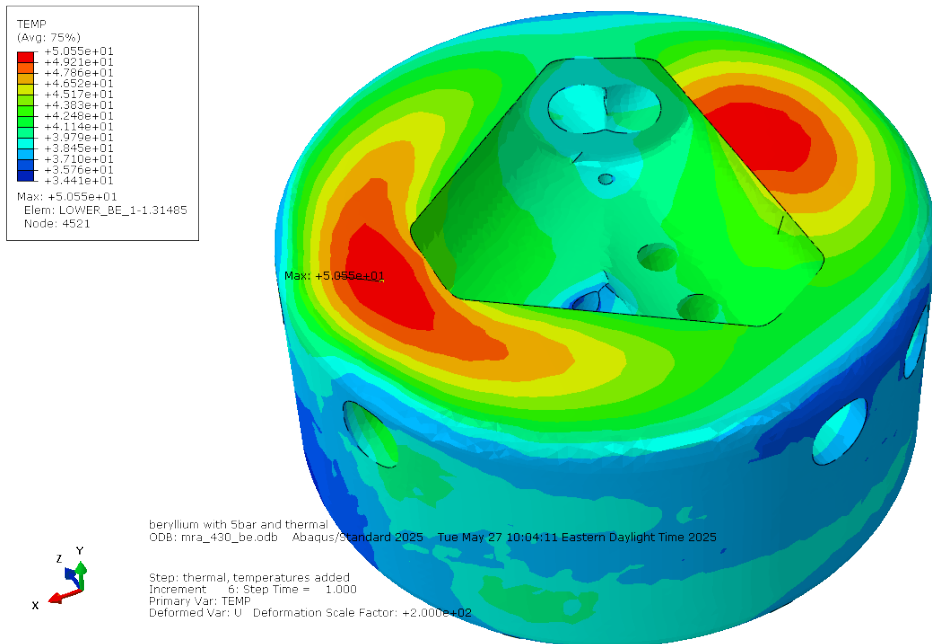


Figure 171 Lower beryllium temperature(°C) with a peak of 50.5 °C with a displacement scale factor of 200

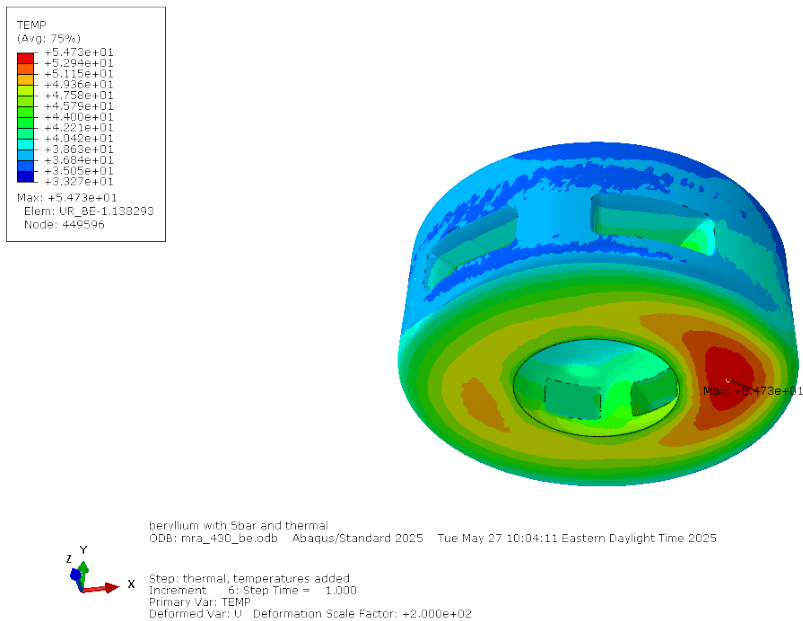


Figure 172 Upper beryllium lower surface peak temperature of 54.7 °C with a displacement scale factor of 200

The stresses with both temperature and pressure are given below with a peak Von Mises stress of 51.5 MPa on the lower beryllium part near a beam channel hole.

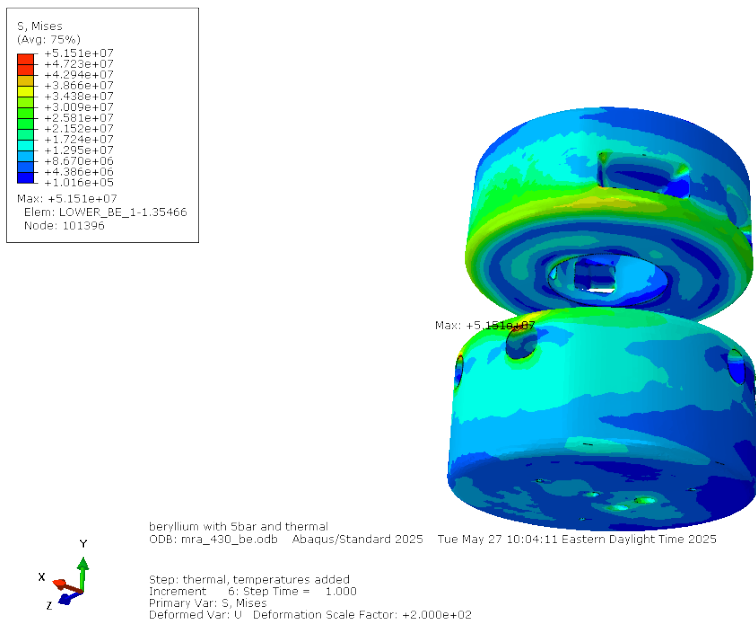


Figure 173 Upper and lower beryllium Stress (Pa) with a displacement scale factor of 200

The peak stress in the upper part is 49.3 MPa by a beam window corner (Figure 174).

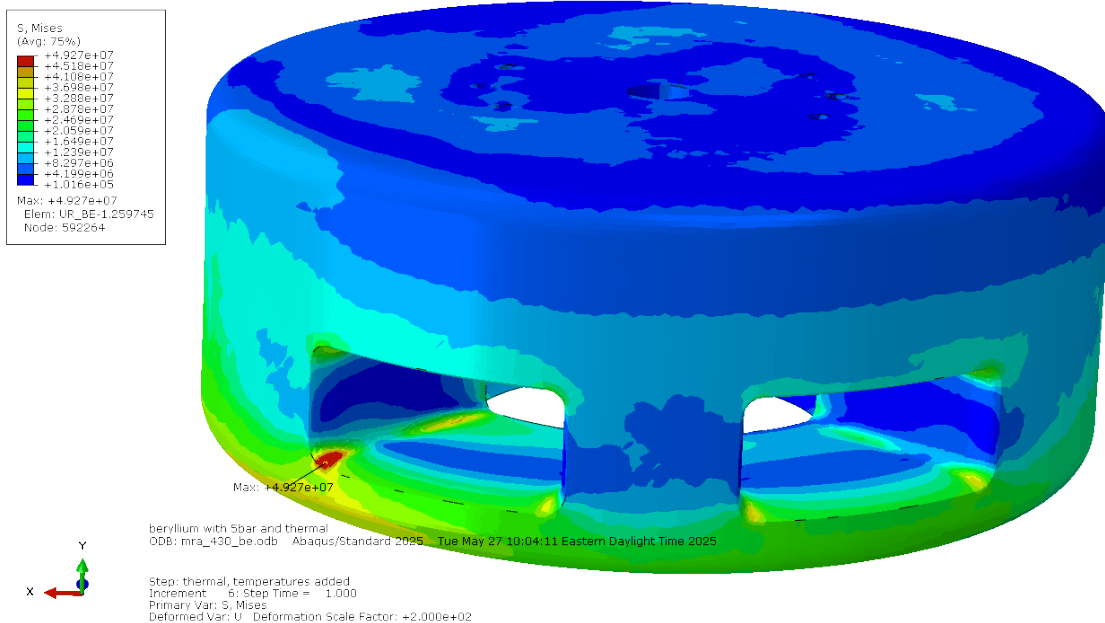


Figure 174 Upper beryllium stress (Pa) with a peak of 49.3 MPa

The lower part stress is shown in Figure 175.

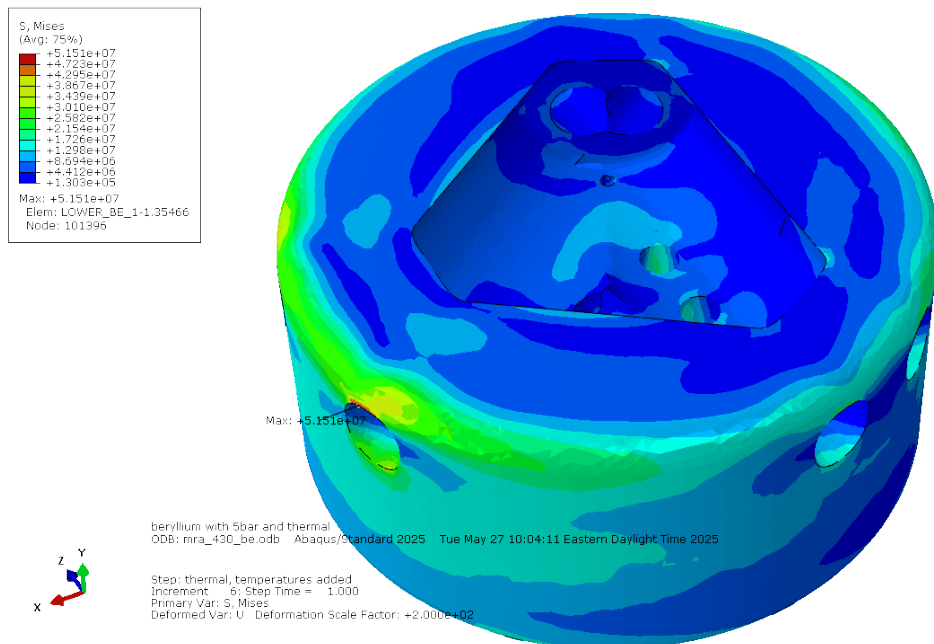


Figure 175 Lower beryllium Von Mises stress (Pa) with a peak of 51.5 MPa

The beryllium could behave as a brittle material so that the Maximum Principal Stress should also be evaluated. This is shown in Figure 176 with a peak of 52 MPa in the lower beryllium part.

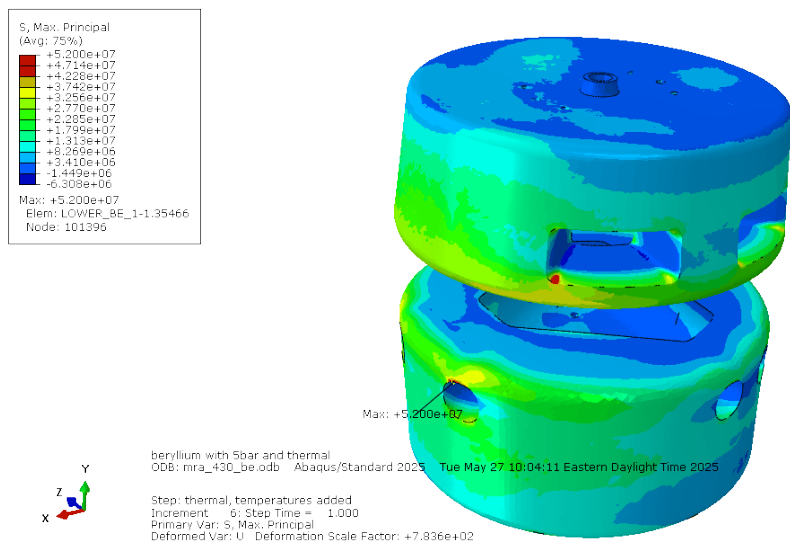


Figure 176 Beryllium assembly Max Principal stress (Pa)- peak 52 MPa – displacement x783.6

These stresses are well below the nominal beryllium yield of 241 MPa (35 ksi) and ultimate strength of 324 MPa (47 ksi)/ [5].. The peak displacements for the upper and lower beryllium parts with pressure and

temperatures was .06 mm as shown in Figure 177

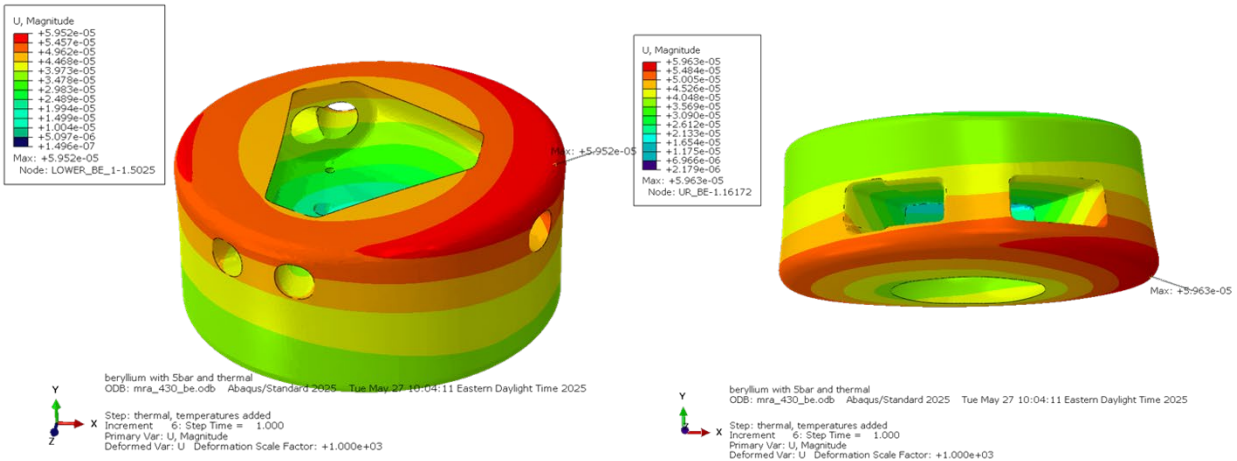
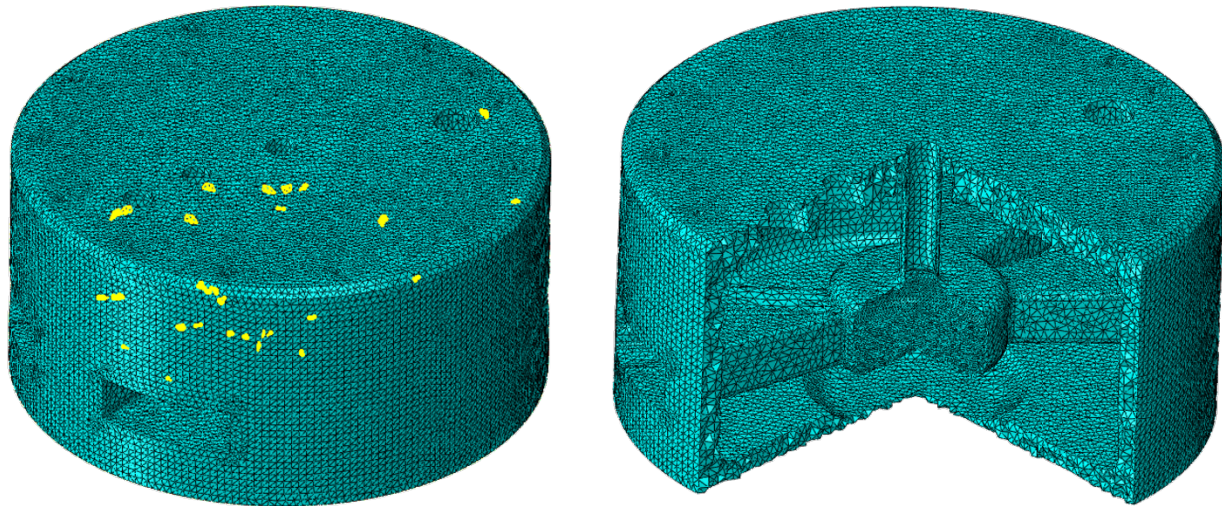


Figure 177 Upper and Lower Beryllium displacements (m) with 1000 x scale factor

8. UPPER AND LOWER REFLECTOR VESSEL BUCKLING ANALYSIS BY ASME METHOD B SECTION 5.4.3

8.1 UPPER REFLECTOR VESSEL MODEL AND EIGENVALUES

The upper vessel was separately analyzed. Only the internal vessel would see a compressive load, so a modified model was used with the external tubing cut off. Also, the mesh was changed from the full model to reduce the number of elements and decrease analysis memory requirements. The nominal C3D10 mesh size was increased to 5 mm but the bottom surface of the inner vessel kept a 2 mm nominal size. A partition was also made on the bottom surface to allow base 6061T6 to be used on the bottom plate with the rest of the vessel conservatively assumed to be welded in the second plastic buckling analysis. The mesh model for the eigenvalue analysis is shown in Figure 178 along with mesh diagnostics. The Abaqus input file was UR_2026_modes.inp.



```

Part: UR_2026_merged_buckling
Tet elements: 431547
Min angle on Tri Faces < 5: 24 (0.00556139%)
Average min angle on tri faces: 37.71, Worst min angle on tri faces: 2.43
Max angle on Tri faces > 170: 0 (0%)
Average max angle on tri faces: 88.94, Worst max angle on tri faces: 165.74
Aspect ratio > 10: 13 (0.00301242%)
Average aspect ratio: 1.67, Worst aspect ratio: 14.22
Shape factor < 0.0001: 0 (0%)
Average shape factor: 0.652973, Worst shape factor: 0.000739
Number of elements : 431547, Analysis errors: 0 (0%), Analysis warnings: 61 (0.0141352%)
Created set 'PoorElements-2' containing 64 elements

```

Figure 178 Upper Reflector vessel Eigenvalue mesh model with approximately 430,000 C3D10 elements

Fixed boundary conditions were applied to the hole surface nodes where bolts would be attached as shown below.

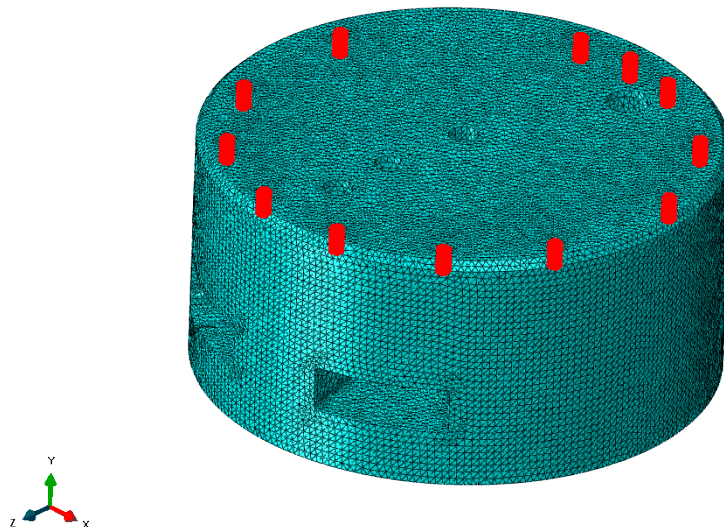


Figure 179 Fixed nodes boundary condition on bolt tie regions

The nominal pressure load was applied to the interior surface which would contact water as shown in Figure 180.

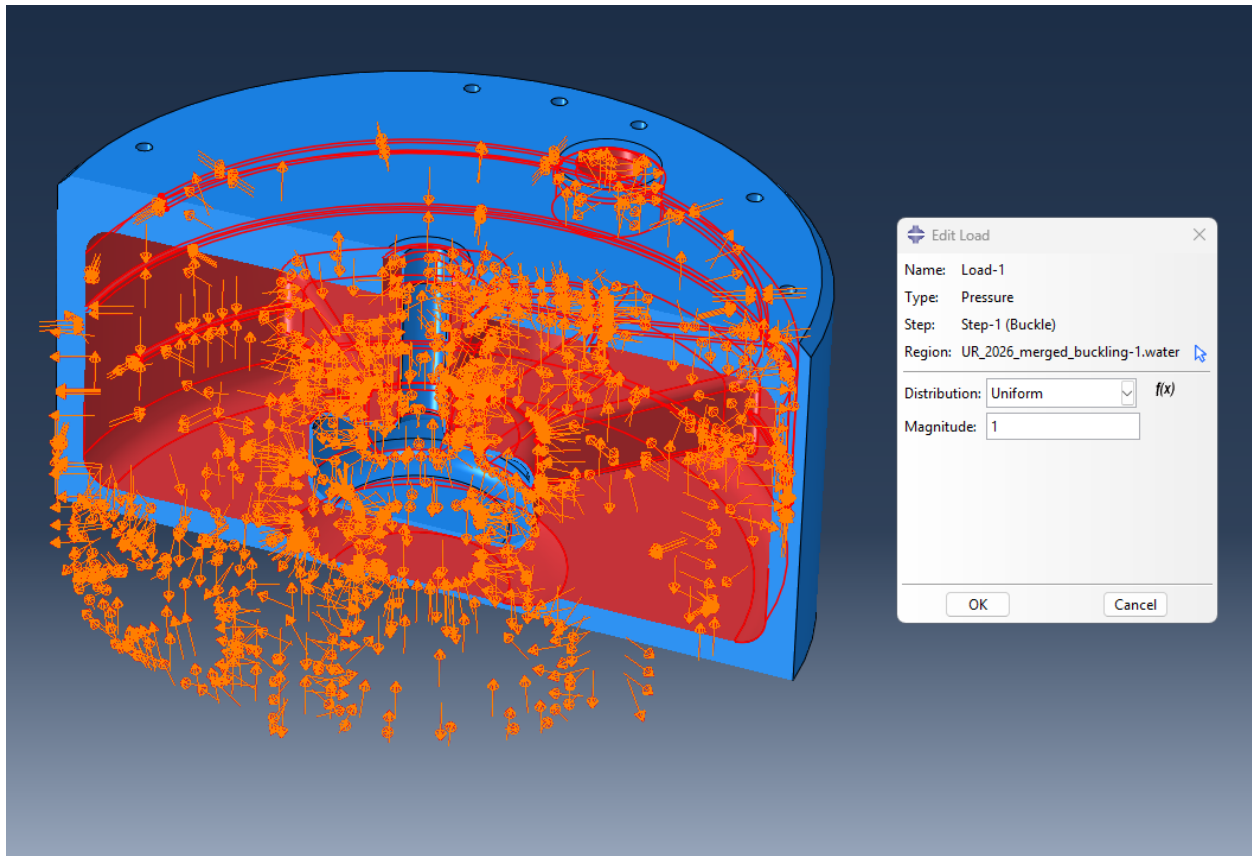


Figure 180 Upper Vessel pressure load (Pa) on all internal surfaces for eigenvalue analysis

The first 10 eigenvalues were requested and a data file for nodal displacement for the first two modes was also requested. Table 7 gives the first 10 Eigenvalues and a factor of safety compared to 5 bar pressure.

Table 7 Upper Reflector first 10 Eigenvalues

Mode	Eigenvalue	FOS 5 bar
1	7.46736E+06	14.9
2	1.11582E+07	22.3
3	1.44570E+07	28.9
4	1.47749E+07	29.5
5	1.74690E+07	34.9
6	1.79560E+07	35.9
7	1.80531E+07	36.1
8	1.93045E+07	38.6
9	1.94791E+07	39.0
10	2.00320E+07	40.1

Figure 181 shows the first 4 mode shapes for the upper reflector

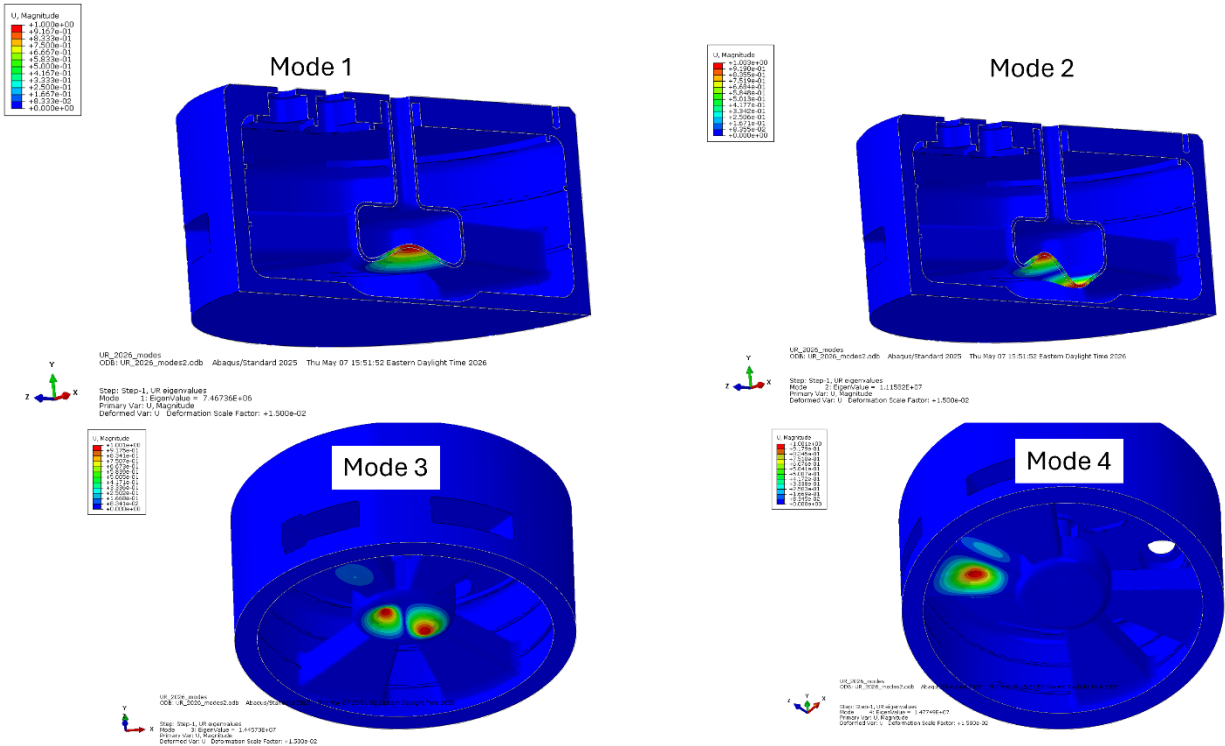


Figure 181 First four upper reflector mode shapes

The deformed mode shape file created was UR_2026_modes2.fil.

8.2 UPPER REFLECTOR BUCKLING ANALYSIS

The method B analysis requires the use of true stress strain material curves based on material yield and ultimate strength. As described previously, the methodology of Section 3-D.3 was used to obtain stress strain curves for Al6061T6 and Al6061T6 as welded. ASME case 2478-1 defined yield and tensile strengths of 33 ksi (227.5MPa) and 37 ksi (255.1 MPa) respectively for the T6 condition with hand T6 up to 4 inch thickness. The welded condition had a tensile strength of 24 ksi (165.5 MPa) but no yield strength was defined. As discussed in section 3.2.3, a conservative bounding case assumption of 8 ksi (55.2 MPa) was used for the welded yield strength.

The eigenvalue Abaqus model was copied for the buckling evaluation. The bottom plate had T6 material assigned, and the balance was assumed to be welded material. This is shown in Figure 182. The lower corners would be out of the heat affected zone but were conservatively assumed to be welded material.

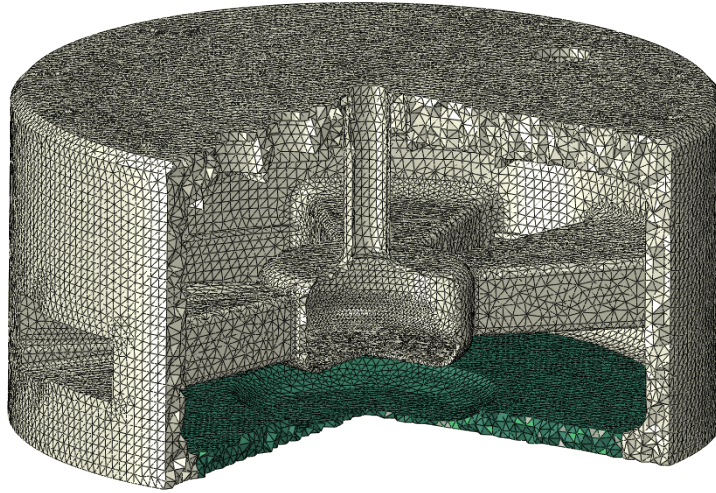


Figure 182 Upper Reflector Vessel with T6 material in green and welded material silver

The buckling analysis will use the load cases from ASME Table 5.15 with a Method B analysis. Only cases 1,2 and 5 were applicable.

5.14

ASME BPVC.VIII.2-2023

Table 5.14 Load Case Combinations for Method A and Method B Buckling Analysis	
Load Case, k	Load Combination [Notes (1) and (2)]
(1)	$\beta_b(P + P_s + D)$
(2)	$0.88 \beta_b(P + P_s + D + T) + 1.13 \beta_b L + 0.36 \beta_b S_s$
(3)	$0.88 \beta_b(P + P_s + D) + 1.13 \beta_b S_s + \beta_b(0.71L \text{ or } 0.36W)$
(4)	$0.88 \beta_b(P + P_s + D) + 0.71 \beta_b W + 0.71 \beta_b L \text{ or } 0.36 \beta_b S_s$
(5)	$0.88 \beta_b(P + P_s + D) + 0.71 \beta_b E + 0.71 \beta_b L \text{ or } 0.14 \beta_b S_s$
(n) [Note (3)]	Per the UDS

NOTES:

(1) The load combinations in this column are defined in Table 5.2.

(2) These load combinations shall be considered to act in combinations that produce the most unfavorable effect (i.e., highest compressive stress) in the component being considered. The effects of one or more loads not acting shall be considered. Effects of loads acting alone shall also be considered.

(3) n is the total number of load combinations.

Figure 183 ASME Table 5.14 Load Combinations

The MRA does not have significant snow, wind or live loads. The load combinations will use the deformed shape from the eigenvalue mode analysis with a scale factor of 0.25 mm which is the planned machining tolerance.

Factors to be used with pneumatic testing:

$$\beta_b = 1.67$$

$$P+P_s = 5e5$$

$$E_x=E_z=.308g$$

$$E_y=0.1g$$

Al6061T6 CTE for thermal analysis adjusting in case 2 to apply load factor

$$CTE_{\text{adjusted}} = 0.88 * \beta_b * CTE = 1.47 * 23.6e-6 = 34.7e-6$$

The Abaqus input file (UR_2026_buckling2.inp) had to be modified to read the nodal displacement from the Eigenvalue output file. The text change made by keyword modifications is shown below with the .25 mm offset applied only to mode 1.

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```

** PREDEFINED FIELDS
**
** Name: Predefined Field-1   Type: Temperature
*Initial Conditions, type=TEMPERATURE
All_nodes, 20.
** -----
**
**
*Imperfection,
file=UR_2026_modes2,step=1
1,.00025
2,0
**
** STEP: Step-1
**
*Step, name=Step-1, nlgeom=YES, inc=500, solver=ITERATIVE
8_35 bar 1.67G
*Static
0.1, 1., 1e-06, 1.
**

```

Figure 184 Imperfection edit made to .inp file

The Abaqus model used 5 steps as shown in Table 7.

Table 8 ASME Buckling Cases versus Abaqus Step for Upper and Lower Reflector vessels

ASME Case	Abaqus Step	Water Pressure (P bar)	Core Vessel pressure (bar)	Weight (D)	Vacuum Space Pressure (bar)	Seismic load (E)	Thermal T
1	1	8.35		1.67*D			
5	2	7.348		1.47*D		1.186 Ex	
5	3	7.348		1.47*D		1.186 Ez	
5	4	7.348		1.47*D		1.186 Ey	
2	5	7.348		1.47*D			T with 1.47*CTE

The pressure load was applied to all internal surfaces as shown in Figure 180.

8.2.1 Upper Reflector Vessel Buckling results

The criterion for showing a stable configuration is met if the solutions converge. Results for the upper vessel for all 5 steps did converge, meeting the criteria. Figure 185 shows Abaqus step 1 stress and displacement.

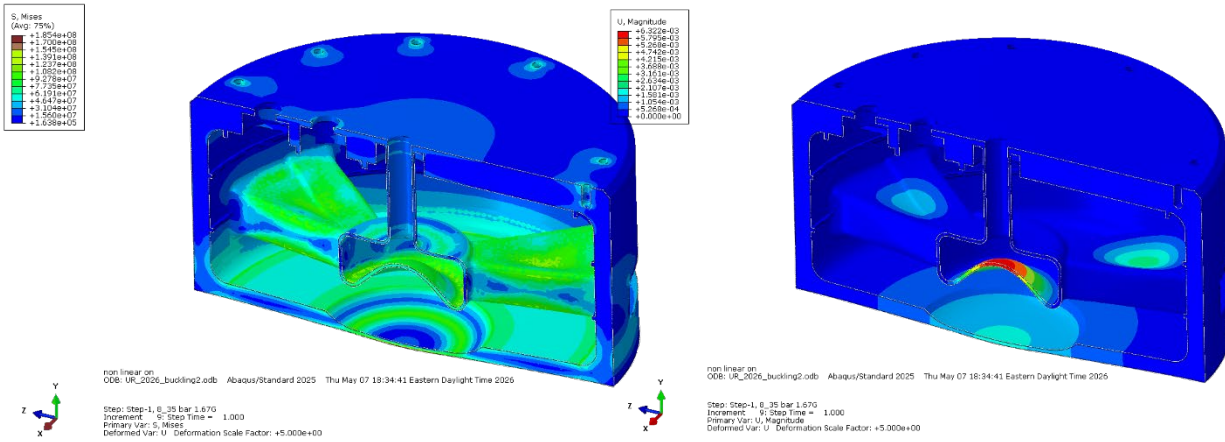


Figure 185 Abaqus buckling step1 stress (Pa) and displacement (m)

Figure 186 shows the equivalent plastic stress PEEQ for Abaqus steps 1 through 4 and Figure 187 shows step 5 PEEQ and temperature.

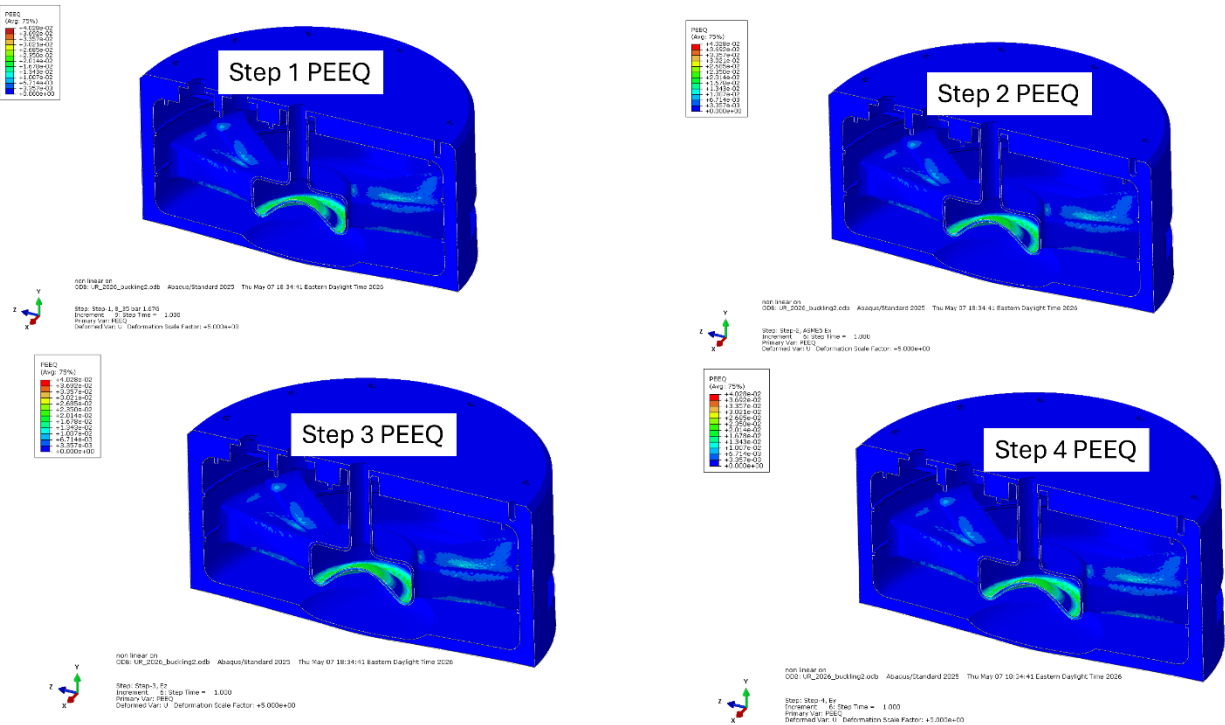


Figure 186 Abaqus steps 1,2,3 and 4 PEEQ

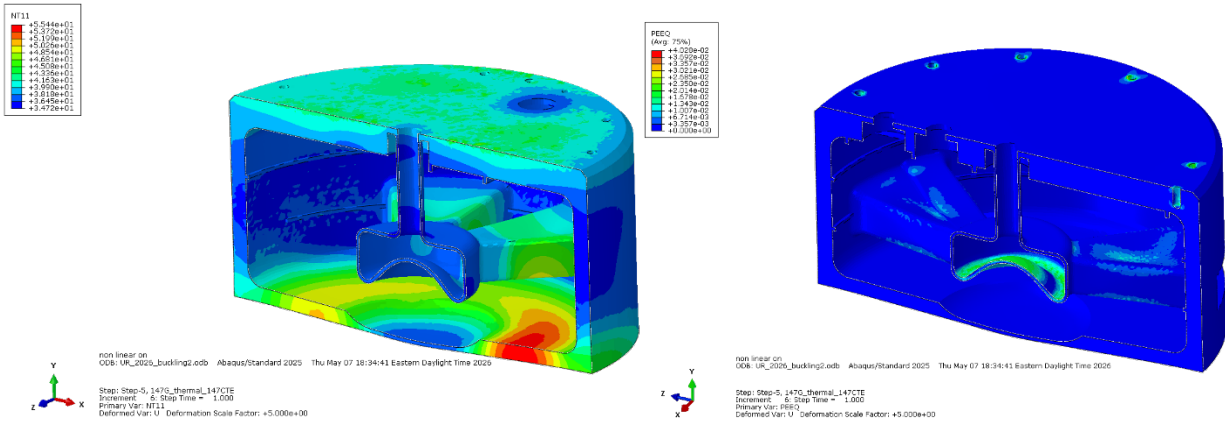


Figure 187 Abaqus step 5 NT11 (°C) and PEEQ

9. LOWER REFLECTOR VESSEL BUCKLING ANALYSIS

9.1 LOWER REFLECTOR MODEL

The 2026 Lower Reflector model was nearly unchanged from the 2025 model. The only change was a small chamfer on the edge of the thick lower plate. This would have no effect on the buckling modes or analysis results. The 2025 model and buckling analysis results will be presented here. Figure 188 shows the mesh model and diagnostics with approximately 1.6e6 C3D10 elements.

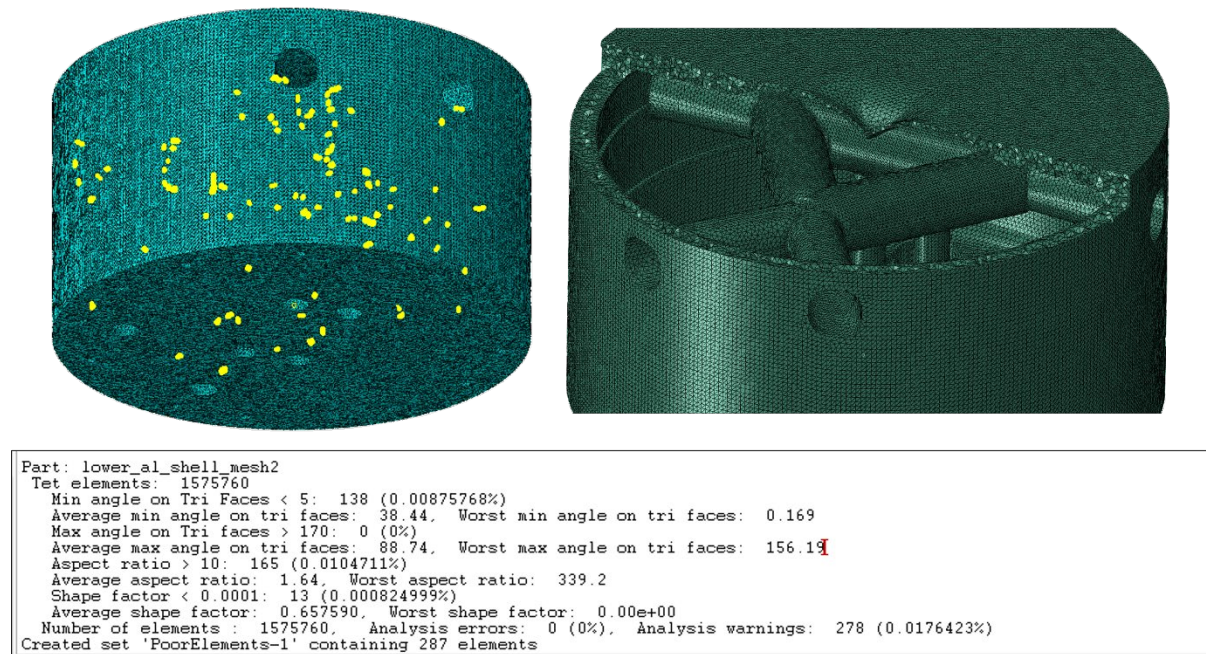


Figure 188 2025 Lower Reflector mesh model and diagnostics

The part model was partitioned to make a separate cell for the top plate. This was done so that after the eigenvalue analysis with all elastic Al6061T6 material, the buckling analysis could be done with elastic plastic materials with T6 properties on the top plate section and welded properties on the rest while keeping the same mesh as used for the eigenvalue analysis. The deformed shape nodal displacements

could then be imported into buckling analysis. The mesh model for the two regions is shown in Figure 189 . The mesh is contiguous for the part so no tie condition is needed between the cells.

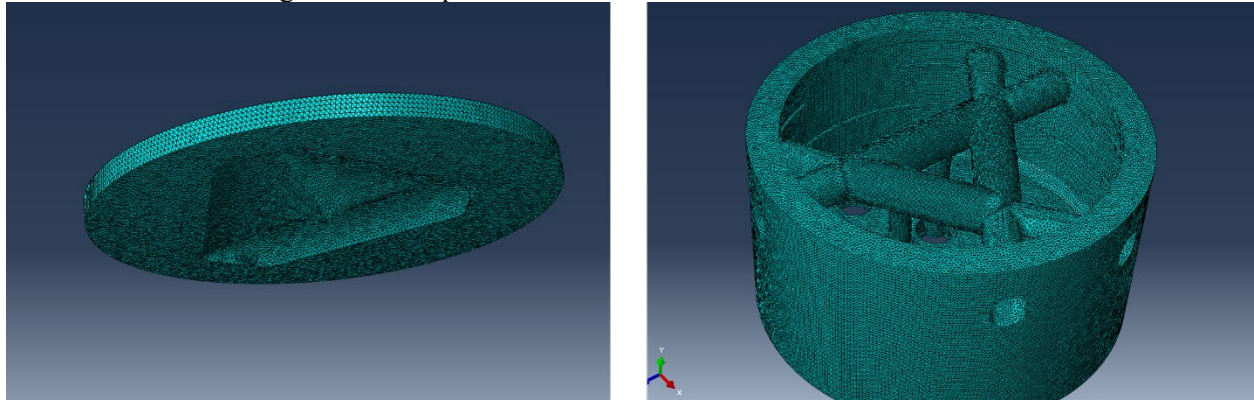


Figure 189 Lower Reflector Vessel mesh in the two cell regions

The tubes below the bottom surface were not included in the model and the nodes on the surface of the bolt holes were fixed as a boundary condition as shown in Figure 190.

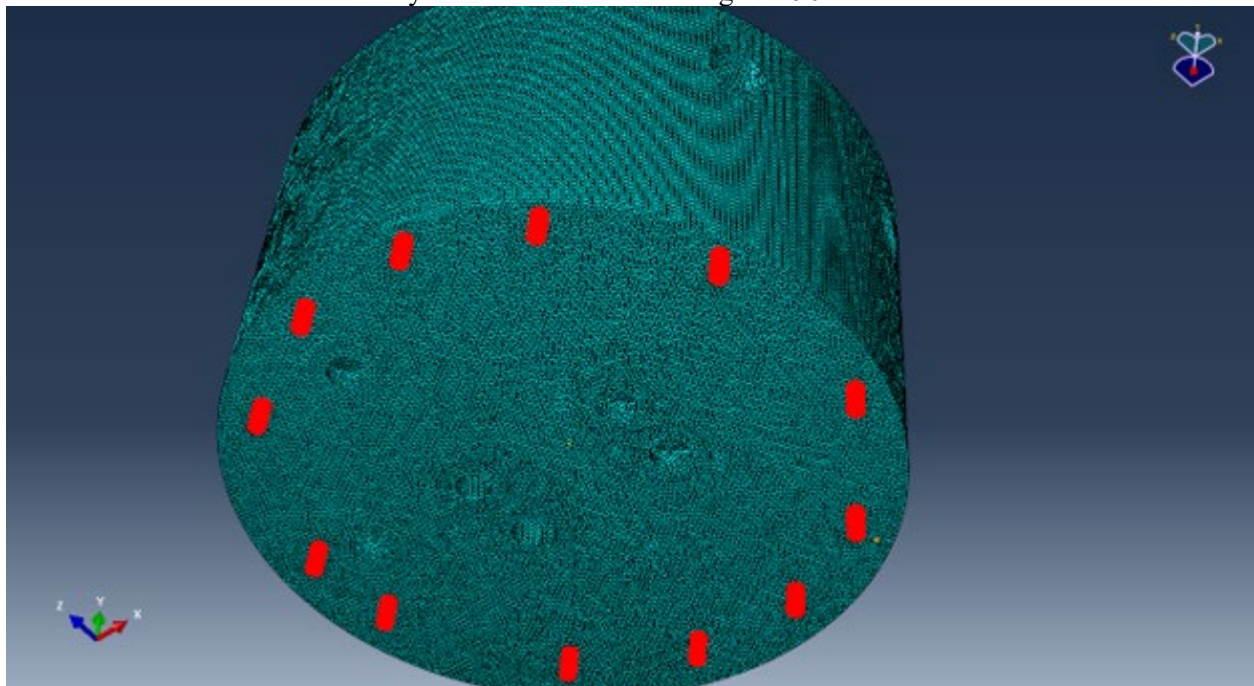


Figure 190 Fixed bolt hole nodes on bottom of Lower Reflector Vessel

The water pressure was applied to the surfaces shown in Figure 191. The upper and lower plates which would give negative pressure modes were not included. The input file for the eigenvalue analysis was LR_buckling_3.inp.

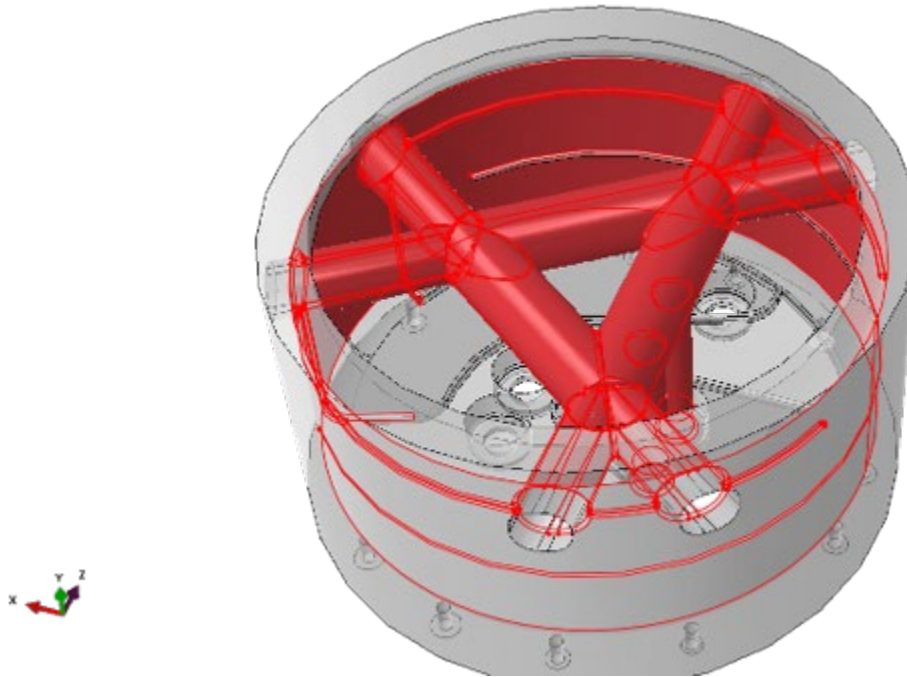


Figure 191 Lower Reflector Surfaces with applied pressure of 1 for Eigenvalue analysis

9.1.1 Lower Reflector Vessel Eigenvalue Results

The first 10 Eigenvalues were calculated and the nodal displacements for the first four modes were recorded in the file LR_buckling_3.fil. The first mode is shown in Figure 192 with an Eigenvalue of 2.92×10^7 . The widow which is deformed did not have pressure applied on either side.

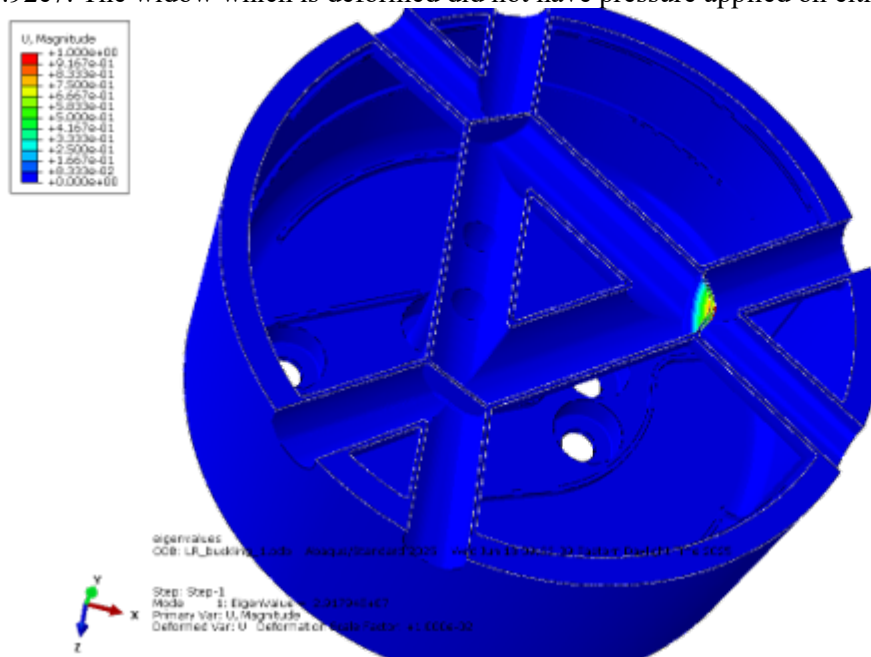


Figure 192 First lower Reflector Vessel buckling mode

The next two mode shapes are shown in Figure 193. Higher modes had similar shapes.

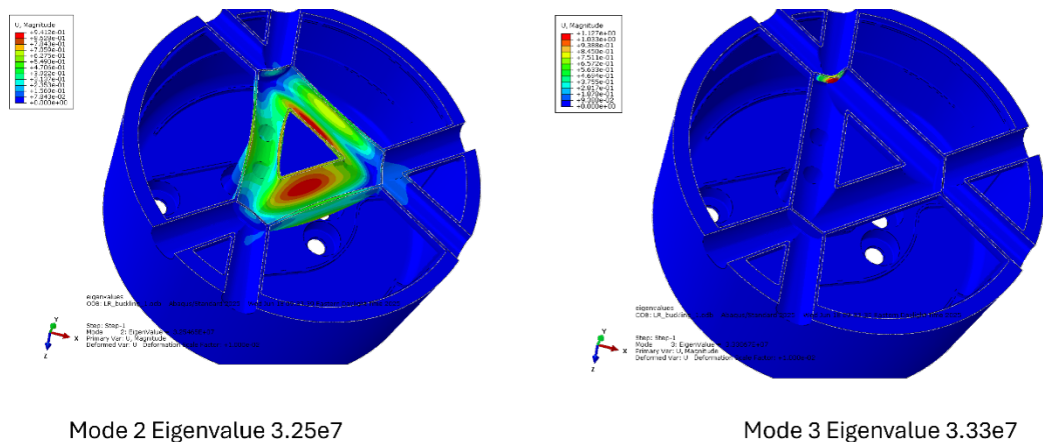


Figure 193 Lower Reflector Vessel Modes 2 and 3.

9.1.2 Lower Reflector Vessel Buckling model evaluation

The same 5 Abaqus analysis steps as given in Table 8 were done. The deformed shape for mode 1 was imported with a scale factor of 0.25 mm corresponding to the part machining tolerance. The keyword edit before Step 1 to import the data is given below.

```

**
*Imperfection,
file=LR_buckling_3,step=1
1,2.5e-4
2,0
3,0
4,0
** STEP: Step-1

```

Figure 194 Lower Reflector Vessel Buckling input keyword edit

The Eigenvalue model was copied and the elastic plastic material models as shown in Figure 11 Al6061T6 True Stress – Strain were used. Figure 195 shows the mesh model with the T6 material in tan for the top plate and the welded material with an assumed yield strength of 8 ksi otherwise in red.

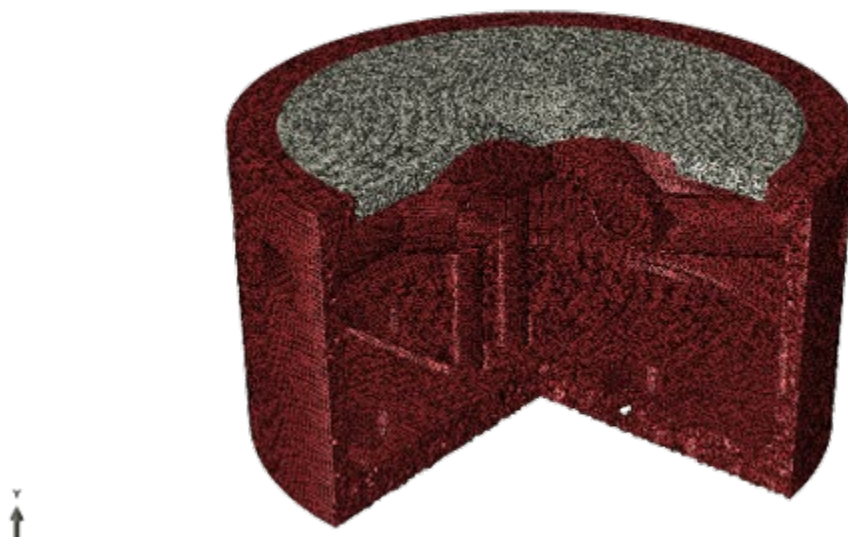


Figure 195 LR_buckling_stress_3 model showing T6 and welded materials

The loads for the 5 steps based on Table 7 from the input file LR_buckling_3_stress21 are shown in Figure 196.

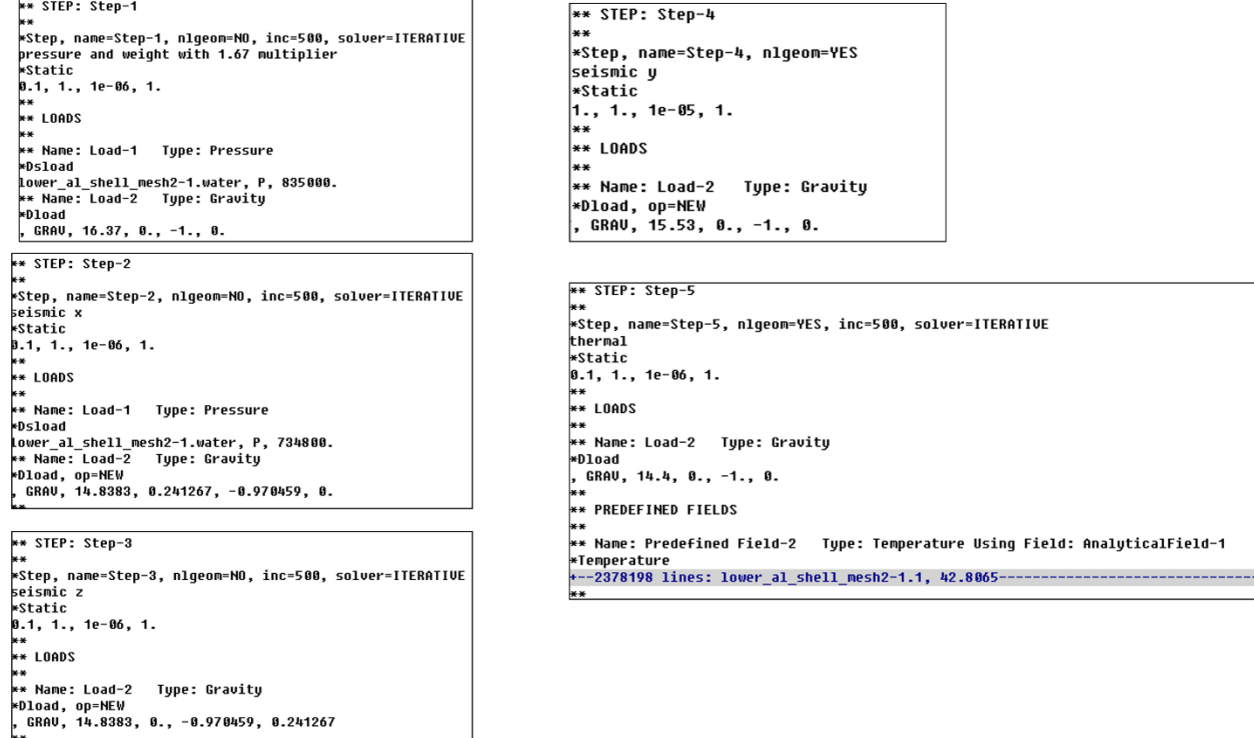


Figure 196 Lower Reflector Vessel buckling step loads – note step2 pressure load (Pa) is maintained for steps 3,4 and 5

The input file for buckling evaluation was LR_buckling_3_stress21.inp

9.1.3 Lower Reflector Vessel Buckling Results

The results converged for all 5 load steps. The PEEQ equivalent plastic strain for step 1 with 8.35 bar water pressure and 1.67 g vertically are shown in Figure 197.

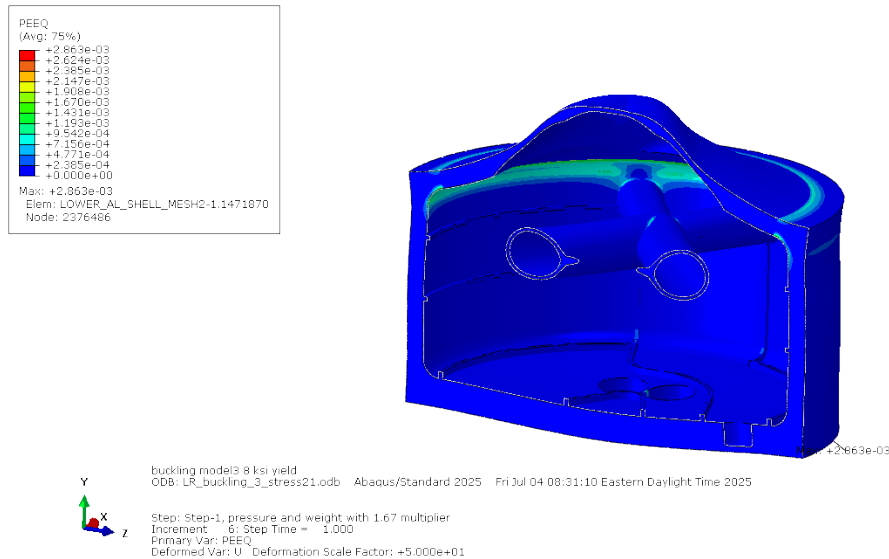


Figure 197 Lower Reflector Vessel buckling Step 1 PEEQ showing convergence

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Figure 198 shows PEEQ for all 5 steps and the temperature for step 5 demonstrating that all cases converge, satisfying the buckling criteria with elastic plastic properties.

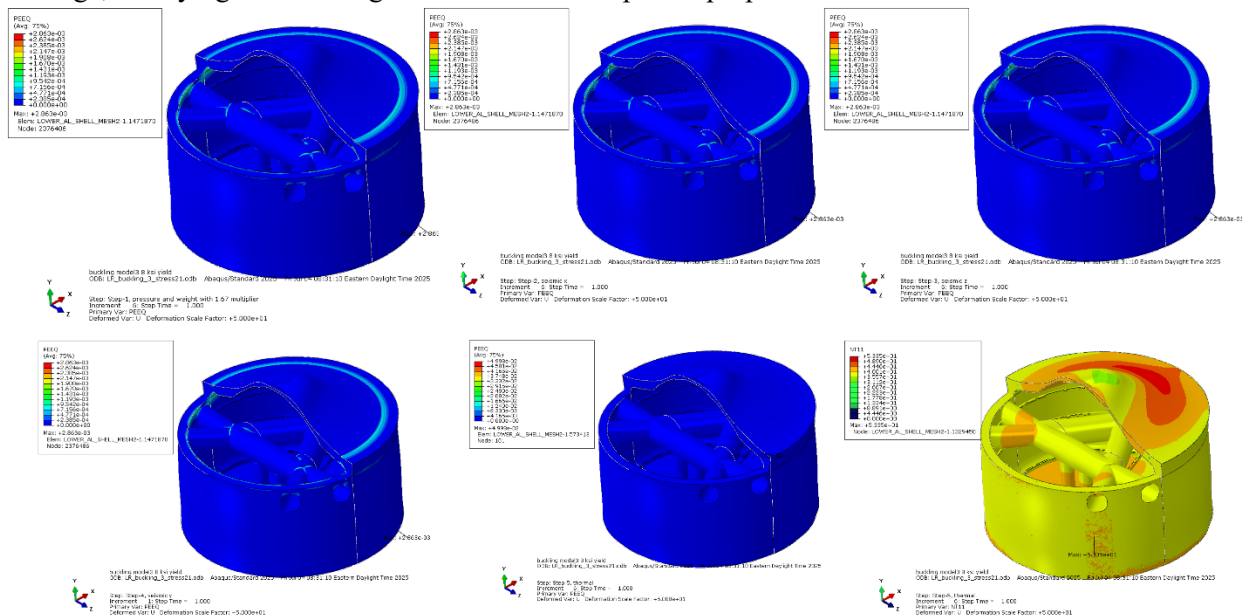


Figure 198 Lower Reflector Assembly PEEQ for all 5 steps and temperature for step 5

10. CONCLUSIONS

The applicable ASME BPVC cases were analyzed.

Table 9 Load Case summary and peak stresses is a summary of the load cases as described in Table 5 with the peak stresses found in the 316L materials and the Al6061T6 and overall assembly maximum displacements. Bolt and tie rod stresses were not included because the peaks in tied regions were at singularities and not realistic. The lower 3 mounting blocks were also omitted because of unrealistic peaks at singularities by grooves, especially when thermal stresses were included.

Table 9 Load Case summary and peak stresses

ASME Case	Abaqus case	Water Pressure (bar)	Core Vessel (bar)	Weight	Vac (bar)	Seismic load	Thermal	SS S max (MPa)	Al S max (MPa)	U Max (mm)
1	1	5	0	D				127	126	0.99
1	3	3	0	D	2			126	121	0.61
3	10	3	1	D			T	258	113	0.84
3	8	5	0	D			T	261	139	1.11
						.7E overturn				0.61
5	7	3	0	.6D				126	122	
6	4	3	0	D		.7 Ex		126	124	0.61
6	5	3	0	D		.7 Ez		126	120	0.61
6	6	3	0	D		.7 Ey		126	121	0.61
9	9	3	0	D			T	259	114	0.85
18	2	5.75	0	D				128	145.5	1.13
	11	3	0	D	2		T	259	114	0.85

Without thermal loads, the peak 316L stresses were in the bottom region where lower bolt preload was reacted and the values were below the 172 MPa 1.5 Sm limit. With thermal loads the peak was below the 3Sm limit of 345 MPa. Coolant channel covers had low stresses with primary membrane and membrane plus bending well below Sm of 115 MPa.

The aluminum peak stresses without thermal were adjacent to bolt tie connections and below the 1.5 Sm limit of 127 MPa, not including the test pressure case with 5.75 bar. The test pressure case was shown to meet the ASME BPVC limit for test pressure. With thermal the peak was 139 MPa and below the 3 Sm limit of 254 MPa. Stress linearization for the test pressure case showed the for up to 5 bar pressure the primary membrane and membrane plus bending meet stress intensity limits.

All displacements were below the 1.5mm requirements.

Fatigue life was estimated for the backbone and aluminum reflector vessels. The minimum life was 20 years (2e5 cycles) for the upper reflector vessel which exceeds the lifetime 5 year (5e4 cycle) limit. The lower reflector vessel life was 30 years and the backbone 50 years.

Separate analysis of the beryllium parts completed with stresses well below yield.

Buckling analysis using ASME Method B section 5.4.3 was completed and the results for the upper and lower vessels converged and shown to be stable against collapse from buckling.

All MRA requirements identified in S03040000-SR0001-R02 have been satisfied.

Table 10 Requirements Status after analysis

Summary	Description	Results
MRA cyclic loading Requirement	The MRA shall be designed for a lifetime of 5 years (25000 hours of 700 kW beam power operation) or more with respect to cyclic loading. The hydrogen boundaries are expected to experience 50 full pressure cycles during commissioning and 10 full pressure cycles per year during operation. Hydrogen pressure is expected to fluctuate 2 bar or less during beam trips and ramps. The water boundaries are expected to experience 20 pump start cycles during commissioning and 4 pump start cycles per year during operation. A pump start cycle is expected to produce an MRA water pressure change of 1 bar or less. No full pressure cycles are expected for the water boundaries. 10000 beam trips are expected to occur each year.	2339 Pass – 50 year life backbone 20 year upper reflector and 30 year lower reflector
MRA Vacuum Vessel Requirement	The MRA vacuum vessels shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	2893 Pass
MRA Reflector Vessel Requirement	The MRA backbone shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	2355 Pass
MRA Backbone Requirement	The MRA reflector vessels shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD.	10921 Pass
MRA Vacuum Boundary Pressure Requirement	The MRA vacuum boundary MAWP shall be 2 bara.	2358 Pass
MRA Water Boundary Pressure Requirement	The MRA water boundaries shall have a MAWP of 5 bara	2361 Pass
MRA Deflection Requirement	The MRA outside surfaces shall not deflect more than +/- ~ 1.5 mm from their installed locations under any expected loading conditions.	2994 Pass Peak 1.1 mm
MRA Moderator Operational Displacement Requirement	The MRA moderators shall have a displacement of 0.3 mm or less relative to the MRA mounting points from installation to 700 kW operation.	2892 Pass peak .25mm

Summary – all requirements have been met.

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11. APPENDIX A SEISMIC LOADS

The seismic loads were developed by Excel Spreadsheet (Siesmic_loads) included in data files

Table 1: STS SSCs using ASCE-7-16 Chap. 13 - Seismic Requirements for Nonstructural Components (Equivalent Static Method)

Base or grade elevation = 1073.52' (Level 1 or Instrument Floor)

W_p = Component Operating Weight

a_p = Component amplification factor from Table 13.6-1 (mechanical & electrical equip.)

S_{DS} = Short period spectral acceleration

S_{DS} = 0.485 from USGS, Risk Category IV & Soil Class D at SNS

R_p = Component response modification factor from Table 13.6-1

z = Height above base where attached

h = Average Roof Height, top of level 3 (elev. 1108.0', = 34.48' above base

I_p = Importance = 1.0 (non-hazardous content), =1.5 (hazardous content)

Level	Elevaton	z
1	1073.52	0
2	1094	20.48
3	1108	34.48
4	1137.5	63.98
Roof	1157.67	84.15

(Note: elevations preliminary from
Building Sections AR301-D, 12/20/23

	EQ #	Equation
Basic Horizontal Seismic Force	13.3-1	$F_p = 0.4a_p S_{DS} I_p W_p / R_p * (1 + 2z/h)$
Maximum Horizontal Seismic Force	13.3-2	$F_p = 1.6 S_{DS} I_p W_p$
Minimum Horizontal Seismic Force	13.3-3	$F_p = 0.3 S_{DS} I_p W_p$
Vertical Seismic Force	13.3.1.2	$E_v = +/- 0.2 S_{DS} W_p$

SSC	F_p/W_p (Eq.13.3-1)	F_p/W_p max (Eq.13.3-2)	F_p/W_p min (Eq.13.3-3)	E_v (Eq.13.3.1.2)	S_{DS} (USGS)	I_p	a_p	R_p	z	h
Moderator Reflector Assembly (Conservative Attachment Height)	0.308	1.16	0.22	0.10	0.49	1.5	1.0	1.5	10.1	34.5
Moderator Reflector Assembly (Bottom Attachment Height)	0.246	1.16	0.22	0.10	0.49	1.5	1.0	1.5	4.6	34.5

Load Calculations for Buckling

Buckling Method B case6						
Bb	1.67					
.71BbE		m/s ²				
horizontal	0.365256055	3.579509				
Vertical	0.1150129	1.127126				
0.88						
p	5	bar				
.88*1.67P	7.348	bar				
.88*1.67D	14.40208	m/s ²				
vertical	15.52920642	m/s ²				
CTE 0-100 C MatWeb						

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2.36E-05						
For Method B case 2						
Bb	1.67					
Bb*CTE	3.941E-05		Increased for load factor on thermal			

12. DATA FILES

The data folder for this analysis includes all the Abaqus input files, CFD Temperatures, Step files, Excel worksheets for Seismic load and Aluminum elastic-plastic properties. Also included are the .fil mode shape files for the upper and lower reflector vessels and report files for the attachment point displacements. The files are at:

[mra_2026_DAC_data](#)

13. REFERENCES

- [1] American Society of Mechanical Engineers, "Boiler and Presssure Vessel Code Section VIII, Division 2," 2023.
- [2] A. S. o. M. Engineers, "Boiler and Presssure Vessel Code Case 2478," 2023.
- [3] "S07070200-TRT10000-R00".
- [4] M.-T. Kao, "No. S03020000-DAC10003-A.7, "Target Assembly Thermo-Fluid Analysis,"," 2026.
- [5] M. Lyttle, "106030101-TS001-R00 Technical Specifications Beryllium Material Specification for Inner Reflector Plug Reflectors," Oak Ridge, 2018.

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