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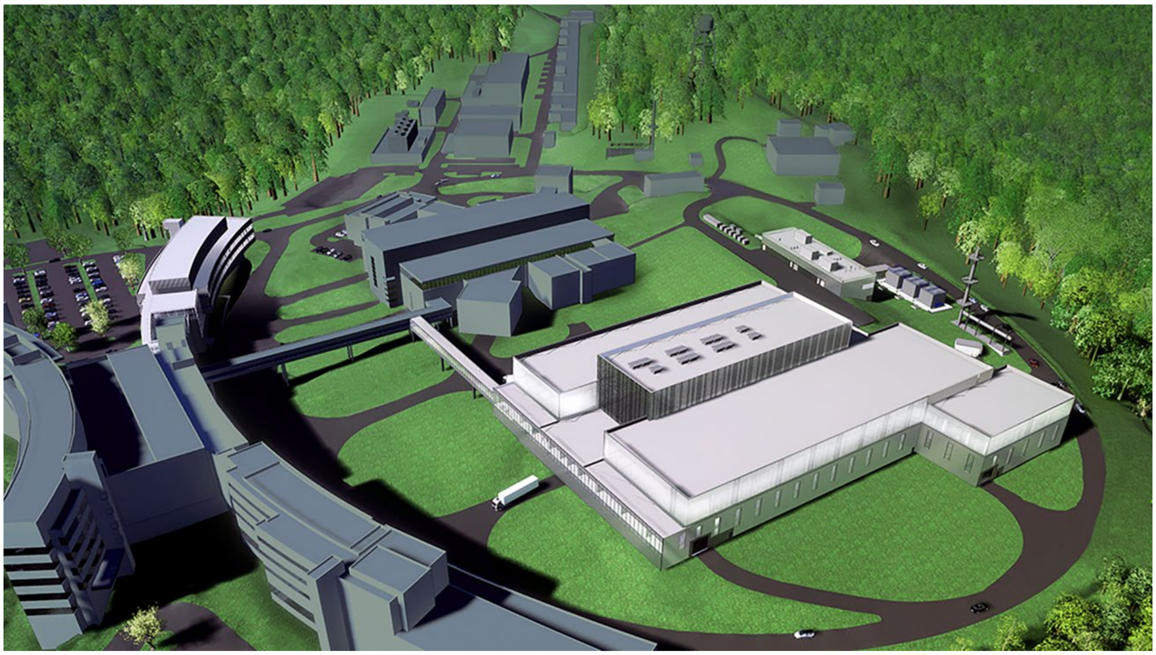
Second Target Station Project: Structural Analysis of the Moderator Reflector Assembly Hydrogen Vessels



Jim Janney

July 2026

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Second Target Station Project

STRUCTURAL ANALYSIS OF THE MODERATOR REFLECTOR ASSEMBLY HYDROGEN VESSELS

Jim Janney

July 2026

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Target Systems L2 Manager						
Configuration Authority						

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00	Initial Release

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LIST OF ACRONYMS

ASME	=	American Society of Mechanical Engineers
BPVC	=	Boiler Pressure Vessel Code
CMS	=	Cryogenic Moderator System
MKS	=	Meter Kilogram Second
MRA	=	Moderator Reflector Assembly
STS	=	Second Target Station
QA	=	Quality Assurance
OS	=	Operating System

ABSTRACT

The structural integrity of the aluminum hydrogen vessels of the Moderator Reflector Assembly of the Second Target Station is critical to the safety of the facility. The dominant load on the vessels is the 19 bara internal maximum allowable working pressure. The hydrogen vessels are designed to the intent of the ASME BPVC Section VIII, Division 2 to confirm their structural integrity. Elastic analyses were utilized to show the hydrogen vessels meet the design by analysis requirements for protection against plastic collapse, local failure, and failure from ratcheting. Fatigue screening was used to show that protection against failure from cyclic loading was assured without a full fatigue analysis. All requirements were satisfied to show that both the upper and lower hydrogen vessels meet the requirements of the ASME BPVC Section VIII, Division 2.

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 hydrogen, which flows through the upper hydrogen vessel and then through the lower vessel, is supplied to the MRA by the Cryogenic Moderator System (CMS), which pumps the hydrogen in a loop and removes heat deposited in the hydrogen to maintain temperature and pressure while also providing over pressure protection for the hydrogen vessels at 19 bara [1].

The structural integrity of the hydrogen vessels is critical to the safety of the STS facility as they are the primary boundary against hydrogen release adjacent to the spallation target in the core vessel [2]. While the hydrogen vessels fall outside the scope of the ASME Boiler and Pressure Vessel Code (BPVC) due to their small size, the hydrogen vessels are still required to be designed to the intent of the ASME BPVC Section VIII, Division 2 in order to ensure their structural integrity [3] [4]. The hydrogen vessel design has 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 hydrogen vessels' compliance with the ASME BPVC and these analyses are documented herein.

2. ASSUMPTIONS

The mass of the lower hydrogen vessel is 0.306 kg and the mass of the upper is 0.412 kg. Because of the low resulting gravitational forces, deadweight and seismic loads are considered negligible. The working fluid of the vessels is liquid hydrogen, which has a density of ~72.8 kg/m^3 [1] at the expected operating temperature and pressure, and results in a fluid mass of 0.018 kg in the upper vessel and 0.024 kg in the lower. Because of the low density of the fluid, static head and fluid live loads are considered negligible. The hydrogen vessels are operated inside a vacuum vessel where no wind or snow loads will be present. The temperature distribution during operation shows only a 3.5 K temperature range for the upper hydrogen vessel and 5 K range for the lower between minimum and maximum temperature [5]. Additionally, the coefficient of thermal expansion of Al 6061-T6 (and most other materials) is nearly zero in the operating temperature range of 18-25 K. Therefore, thermal stresses are considered negligible as well. Therefore, the only load combinations to be evaluated from Table 5.3 of [3] are cases 1, 9, and 17 and the only loads from those cases to be applied are internal pressure loads.

The hydrogen vessels are assumed to not interact structurally with their surrounding vacuum vessels. The nominal vacuum gap around the vessels is 3 mm, which is assumed to be sufficient to prevent interaction.

3. PHYSICAL MODEL DEFINITION

3.1 MATERIAL PROPERTIES

The hydrogen vessels will be constructed from hand forged Al 6061-T6 in accordance with ASME Specification SB-247. The upper hydrogen vessel can be built from less than 4” thick forgings while the lower vessel will require 4-8” forging thickness. Because the temperatures seen in the hydrogen vessels (room temperature down to 18 K) are well below the temperature at which Al 6061-T6 properties begin to change significantly (120 °C), linear material properties have been used for this analysis from ASME BPVC Code Case 2478 [6] and Aerospace Specification Metals Inc. [7], as seen in Table 3.1. The material properties used are room temperature properties as the ASME BPVC does not increase allowable stresses at cryogenic temperatures even though Al-6061-T6 increases in strength and ductility [8]. Although the hydrogen vessels are normally operated at 20 K, they are pressurized at room temperature in preparation for cooling down to operating temperature. Therefore, room temperature properties are used as they represent the worst case for the operation of hydrogen vessels. Note, no changes to the properties are made to compensate for the radiation damage effects to the vessel material throughout its lifetime.

Table 3.1 Aluminum 6061-T6 Forging Material Properties

Material	Tensile Strength (MPa)	Yield Strength (MPa)	Modulus of Elasticity (GPa)	Poisson’s Ratio	Allowable Stress (MPa)	M+B Allowable Stress (MPa)	S_{PS} Allowable Stress (MPa)
Al 6061 T6 Hand Forged <4” thick	255.1	227.5	68.9	0.33	84.8	127.2	254.4
Al 6061 T6 Hand Forged 4-8” thick	241.3	220.6	68.9	0.33	80.7	121.0	242.0
Al 6061 T6 Welded	165.5		68.9	0.33	55.2	82.7	165.5

The size of the zone of material around the welds which is required to meet the welded allowables is critical to the analysis due to the drastically different allowable stresses in the general and welded material. The upper hydrogen vessel has a weld depth of 5.1 mm while the lower hydrogen vessel has a weld depth of 2.0 mm. The upper hydrogen vessel prototyping effort revealed a maximum weld width of 5 mm [9]. Based on Figure 3.1, we expect a heat affected zone width of 1 mm or less for EB welding. The total width of the weld zone material is then 6 mm and the distance from the centerline of the weld to the edge of the weld zone material is 3 mm.

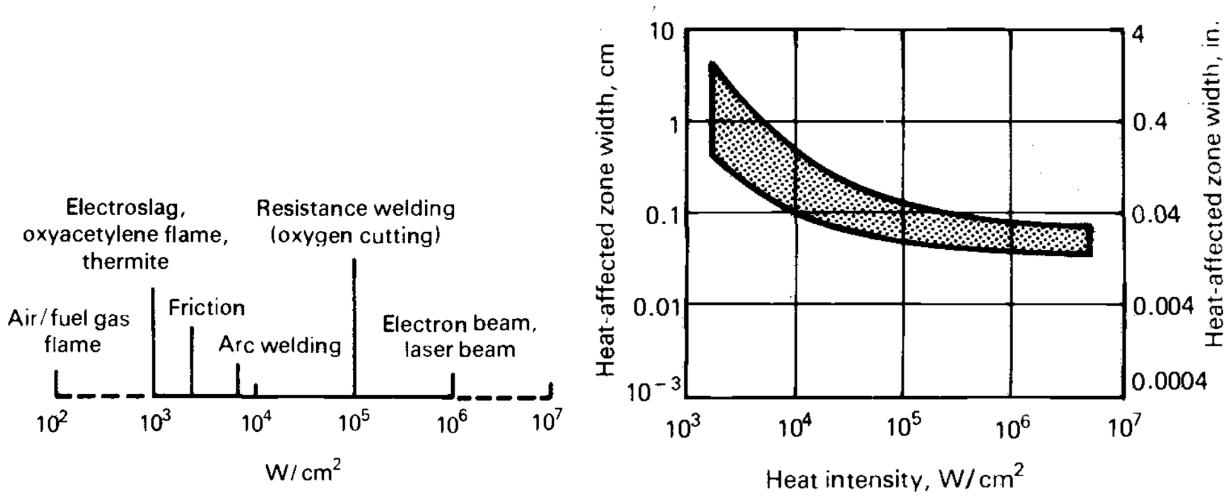

Figure 3.1 Comparison of Heat Affected Zone Width and Process Heat Intensities [9]

3.2 EXTERNAL LOADS

The maximum allowable working pressure of both hydrogen vessels is 19 bara, which corresponds to a differential pressure of 19 bar as they operate within a vacuum vessel [4].

3.3 DESIGN CRITERIA AND ACCEPTABLE VALUES

The hydrogen vessels will be evaluated against the ASME BPVC Section VIII, Division 2 design by analysis requirements.

4. UPPER HYDROGEN VESSEL

4.1 GEOMETRY

The upper hydrogen vessel structural analysis model was based on the upperhydvesselanalysis-final.prt Creo model. This model was also the basis for the Final MRA Neutronics Analysis and Thermal Hydraulic Analysis. This model was built for analysis purposes and alignment features and weld backers were not included. A quarter symmetry version of the Creo model (Figure 4.1) was imported into Ansys to allow simple extraction of the axisymmetric representation in the X-Y plane with the axis of the vessel in the Y direction. The extracted area was divided at the weld location (Figure 4.2), which was chosen in an area of low stresses, at a diameter of 68.25 mm. The coordinate system for the model is the STS global coordinate system. The internal height of the vessel is 30 mm and the inner diameter is 100 mm. The cylindrical wall thickness is 2.6 mm and the top and bottom wall thicknesses are 5.10 mm and 5.15 mm respectively. The nozzle has an inner diameter of 16 mm, a thickness of 1 mm, and a length of 79.9 mm from the top surface of the vessel. In order to maximize neutronic performance, all wall thicknesses have been optimized to be as thin as possible while still meeting structural requirements.

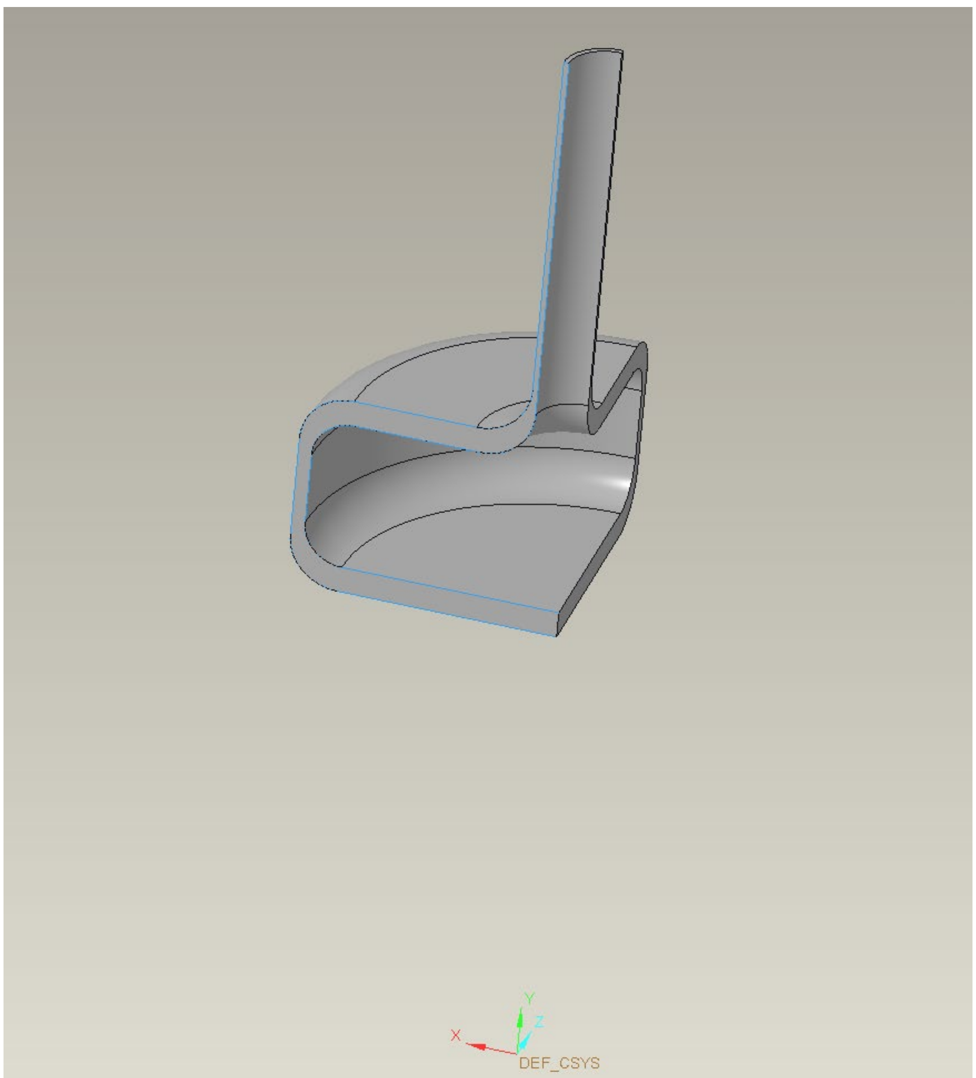

Figure 4.1 Upper Hydrogen Vessel 1/4 Symmetry Creo Model

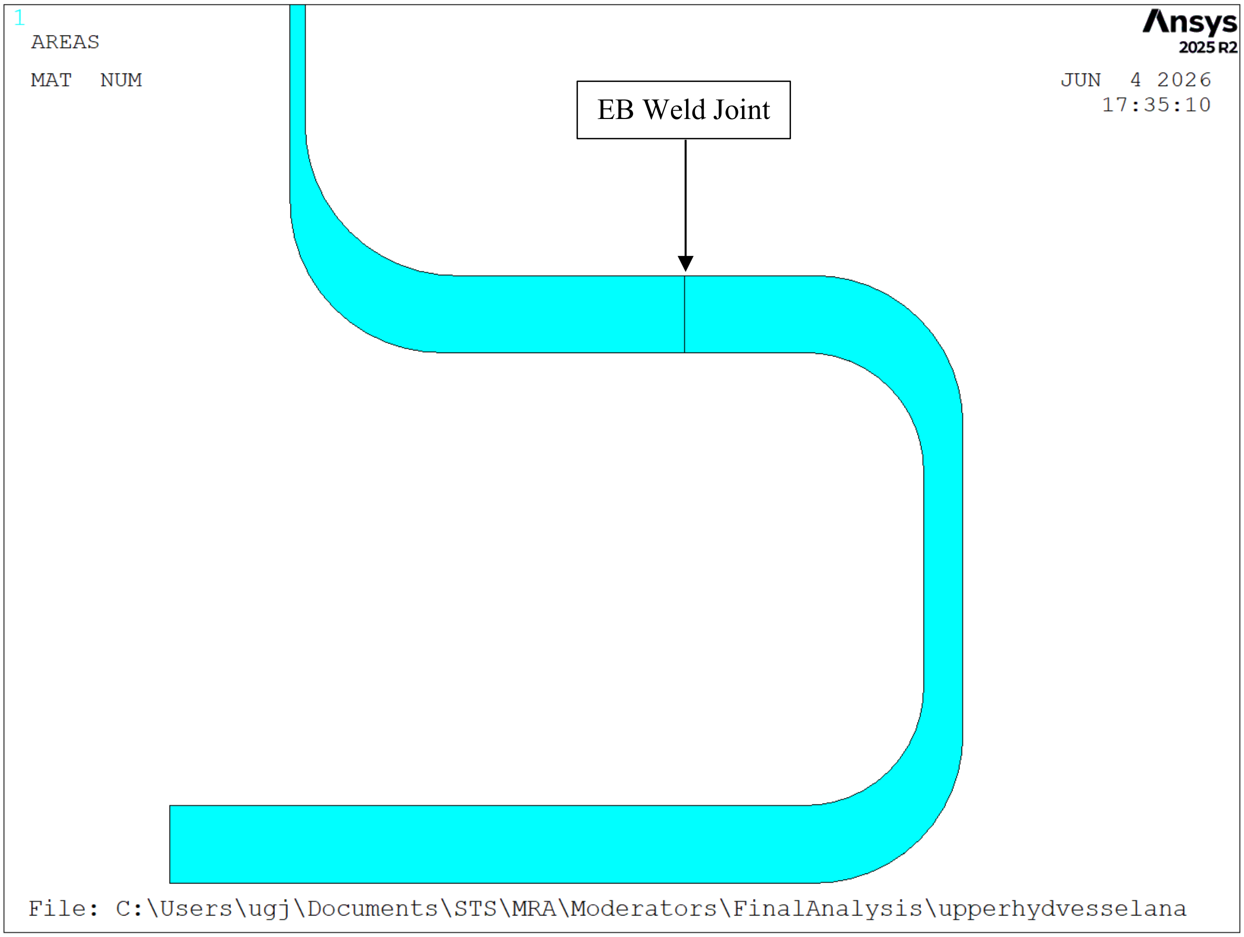

Figure 4.2 Upper Hydrogen Vessel 2-D Axisymmetric Ansys Geometry

4.2 SOFTWARE

The upper hydrogen vessel structural analysis was performed using Ansys 2025 R2 APDL Mechanical software running on PC153452 HP Z2 Tower G1i Workstation Desktop PC with an Intel Core Ultra 9 285K, 3700 MHz, 24 Core Processor with Microsoft Windows 11 Enterprise x64 operating system.

4.3 UNIT SYSTEM

For simplicity, all analyses were performed using MKS units.

4.4 DISCRETIZATION

The cylinder hydrogen vessel was discretized with axisymmetric plane183 elements, which is a second order 2-D quadrilateral element. The original mesh consists of 2811elements constructed from 9252 nodes with a global element sizing of 0.5 mm. The refined mesh consists of 11418 elements constructed from 35879 nodes with a global element sizing of 0.25 mm. Figure 4.3 provides a visual comparison of the 2 meshes.

Figure 4.3 Original (left) and Refined (right, zoomed to minimize moire pattern) Mesh Comparison.

4.5 BOUNDARY CONDITIONS

The cylinder hydrogen vessel has a fixed vertical constraint on the top of the nozzle (Figure 4.4). Note that the axisymmetric model also restrains the displacement of the nodes on the axis of symmetry to be only along the axis.

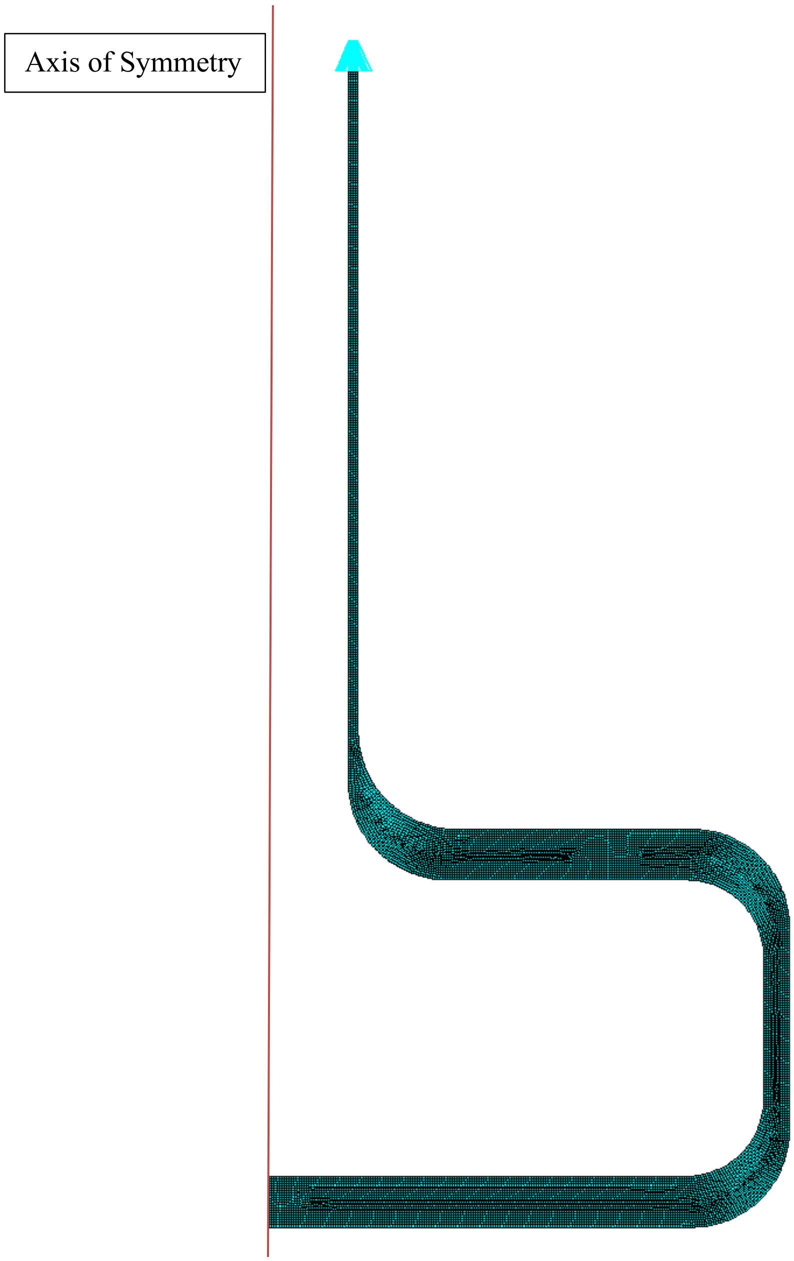

Figure 4.4 Fixed Vertical Boundary Condition on Top of the Nozzle Inlet

4.6 CONTACT CONDITIONS

No contact interactions were included in the upper hydrogen vessel analysis.

4.7 LOAD DEFINITIONS

The cylinder hydrogen vessel has an applied load of 19 bara (1.9e6 Pa) applied to all internal surfaces, as seen in Figure 4.5 [4].

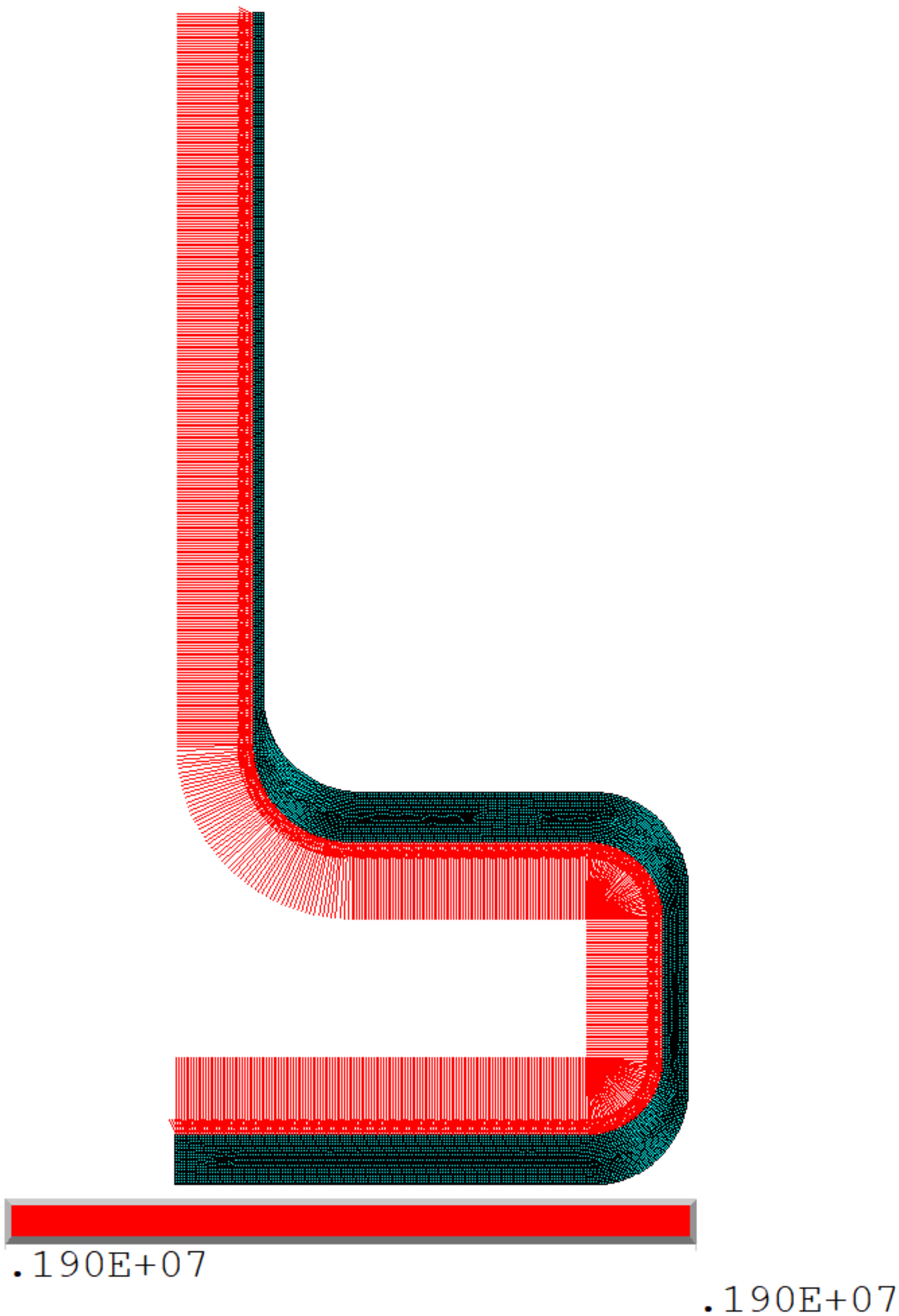

Figure 4.5 Upper Hydrogen Vessel 19 bara (1.9e6 Pa) Internal Pressure Load

4.8 SOLUTION METHODOLOGY

This analysis employed steady-state linear elastic analysis for all evaluations.

4.9 RESULTS

The results of the analysis were post processed using ANSYS APDL results viewer. The analysis shows a maximum displacement of 0.615 mm in the center of the bottom of the vessel (Figure 4.6). This maximum displacement is purely in the vertical direction. The maximum displacement is attributable about equally to displacement caused by bending of the top and bottom flat surfaces of the vessel. The bending of the flat surfaces also causes the radius of the vessel to decrease by 0.03 mm (Figure 4.7), which is not significant relative to the size of the vessel.

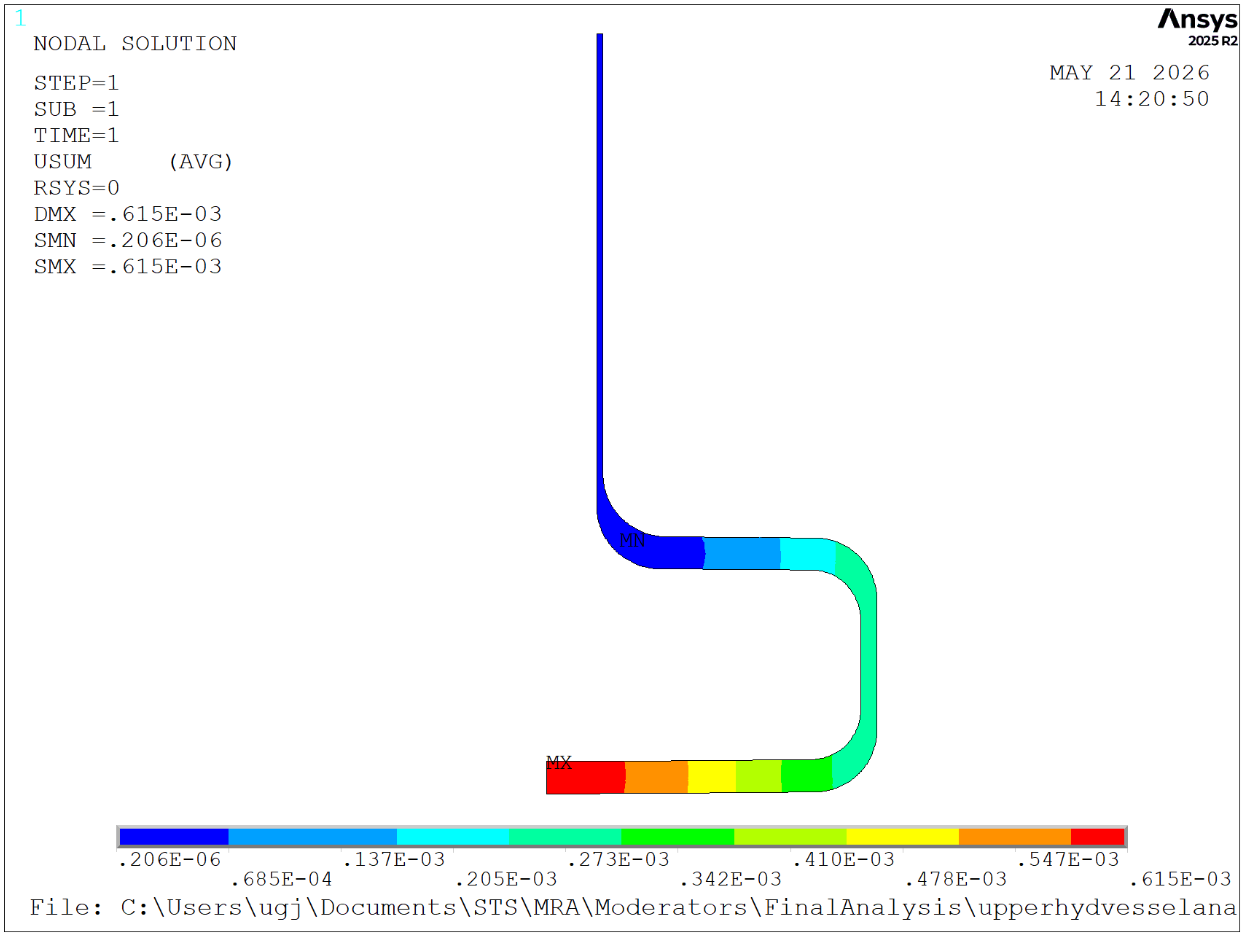

Figure 4.6 Upper Hydrogen Vessel Deflection Magnitude Contour Plot (m)

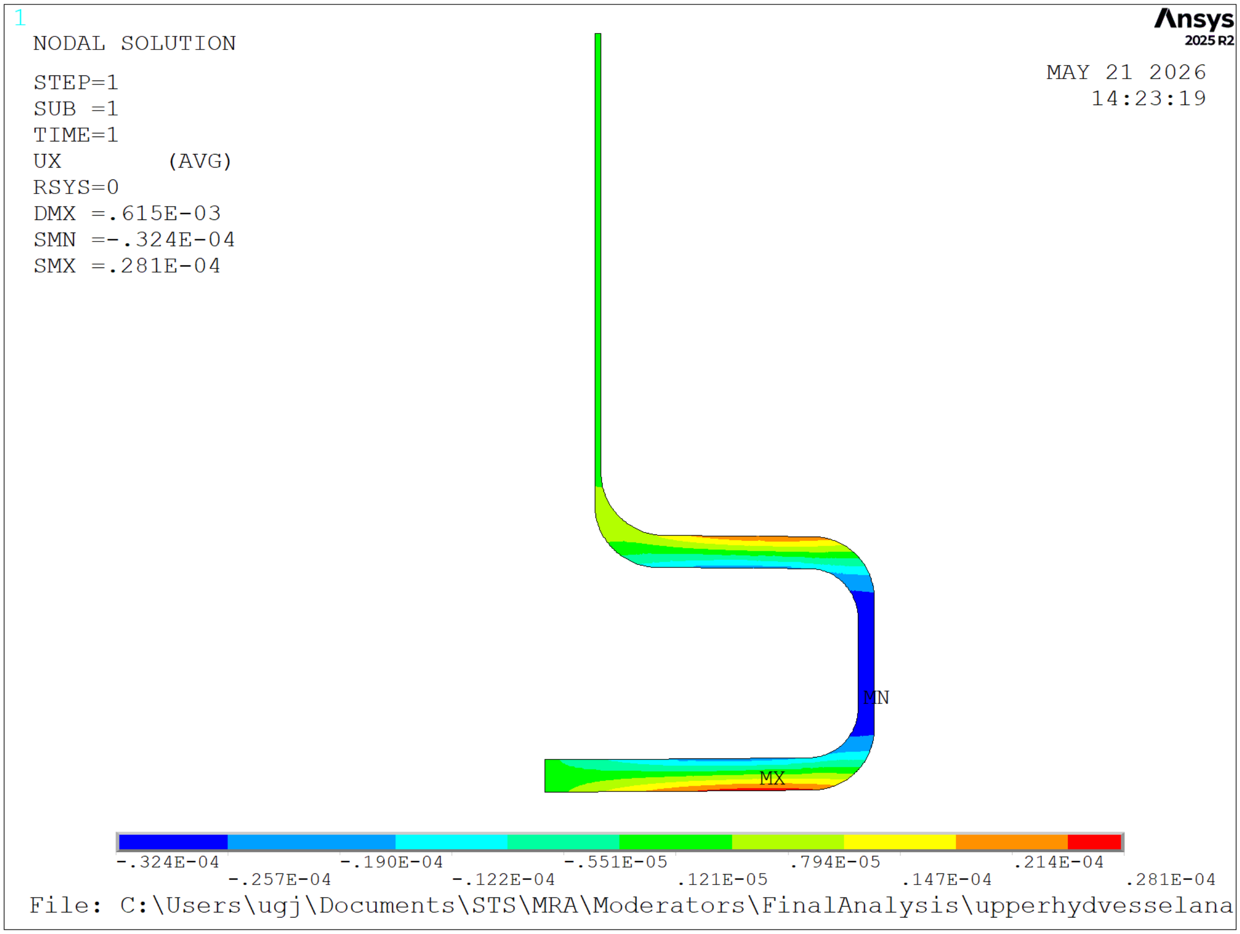

Figure 4.7 Upper Hydrogen Vessel X Direction Deflection Contour Plot (m)

4.9.1 Protection Against Plastic Collapse

Protection against plastic collapse is ensured using the Elastic Stress Analysis Method (part 5.2.2 of [3]). Load cases (2) – (8) of Table 5.3 of [3] are not evaluated due to the assumptions made previously that thermal stress, static head, fluid momentum, wind, earthquake, and snow loads are negligible. Therefore, only internal pressure will be considered. This analysis is a static analysis with no material or geometric non-linearity included.

The Von Mises stress results from 19 bar internal pressure are shown in Figure 4.8 and Figure 4.9. The maximum Von Mises stress is shown to be 127.1 MPa in the neck of the nozzle, which is just below the allowable for membrane plus bending stress of 127.2 MPa. There is also a stress of 126.4 MPa on the outside surface of the center of the bottom of the vessel and additional high stress areas on the inside surfaces of the shoulders of the vessel. The maximum Von Mises stress for the vessel below the membrane plus bending allowable indicates that all linearized stresses will also show membrane plus bending stresses below the allowable. In order to be thorough, 5 paths were chosen for stress linearization at the high stress locations of the vessel, as shown in Figure 4.10. The full results of the stress linearization are shown in Appendix A and summarized in Table 4.1, showing the maximum membrane stress was 48.5 MPa and the maximum membrane plus bending was 126.0 MPa, which are below the corresponding stress allowables of 84.8 MPa and 127.2 MPa.

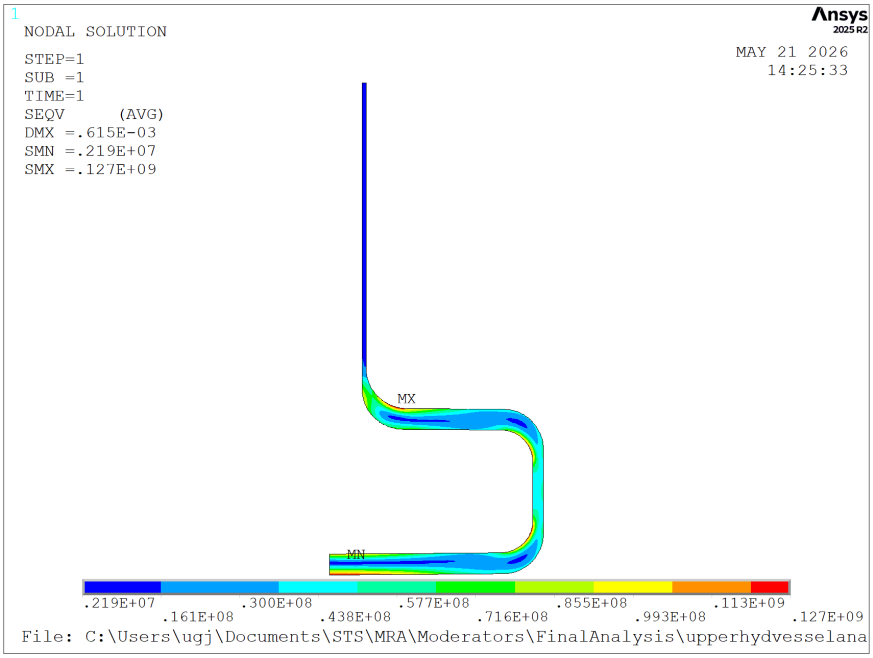

Figure 4.8 Upper Hydrogen Vessel Von Mises Stress Contour Plot (Pa)

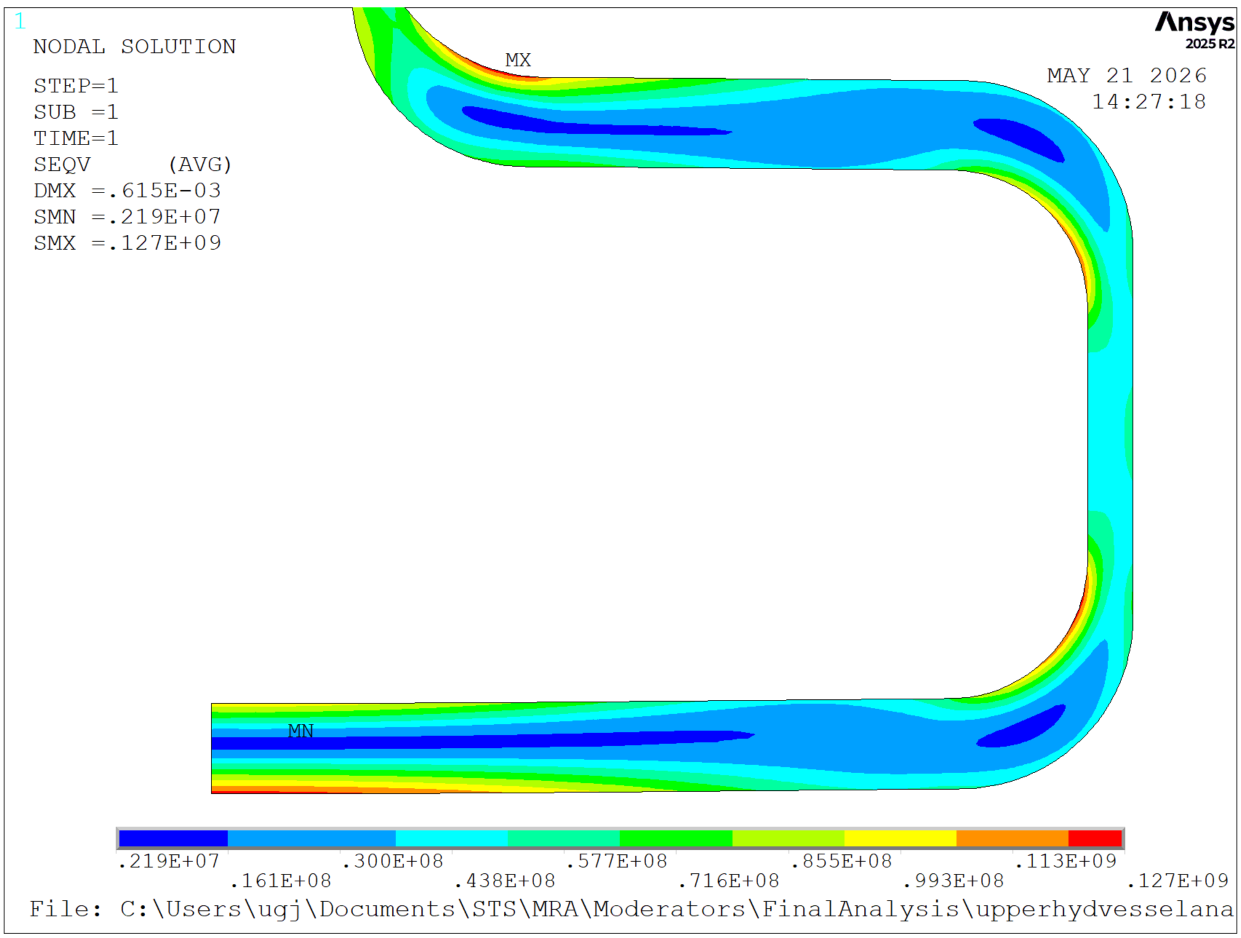

Figure 4.9 Zoomed Upper Hydrogen Vessel Von Mises Stress Contour Plot (Pa)

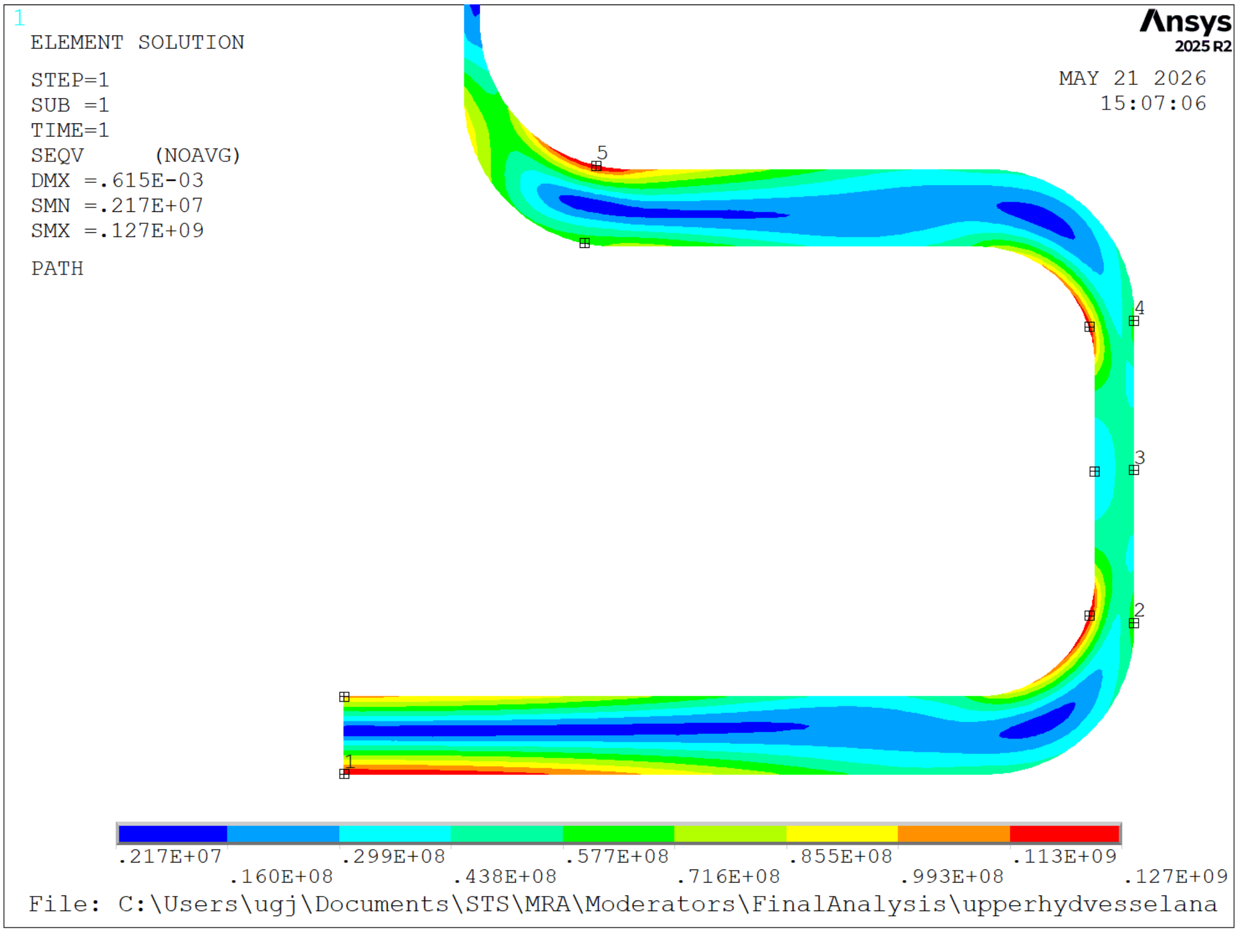

Figure 4.10 Upper Hydrogen Vessel Stress Linearization Path Definitions over Von Mises Contour Plot (Pa)

Table 4.1 Upper Hydrogen Vessel Stress Linearization Summary

	Max. Von Mises Stress (MPa)		
Path	M	M+B	Total
1	13.03	126.0	126.4
2	48.45	113.3	125.9
3	43.29	56.37	56.99
4	47.46	107.7	120.1
5	12.06	109.9	127.1

Because the hydrogen vessels are made from Al 6061-T6, the allowables are significantly reduced in the weld heat affected zone. The allowable membrane stress in the weld heat affected zone is 55.2 MPa. Note that this is greater than the maximum membrane stress found for the entire vessel of 48.5 MPa, so the weld zone membrane stress requirement is met. The allowable membrane plus bending stress for the weld heat affected is 82.7 MPa and Figure 4.11 close shows the Von Mises Stress Contour plot with the scale adjusted to this allowable stress. To ensure this requirement is met, we will measure the distance from the weld center to the nearest point where the stress exceeds the allowable. As seen in the Figure 4.12, the minimum distance from the weld center to a point exceeding the weld allowable is 8.68 mm, which exceeds the expected heat affected zone size of 3 mm.

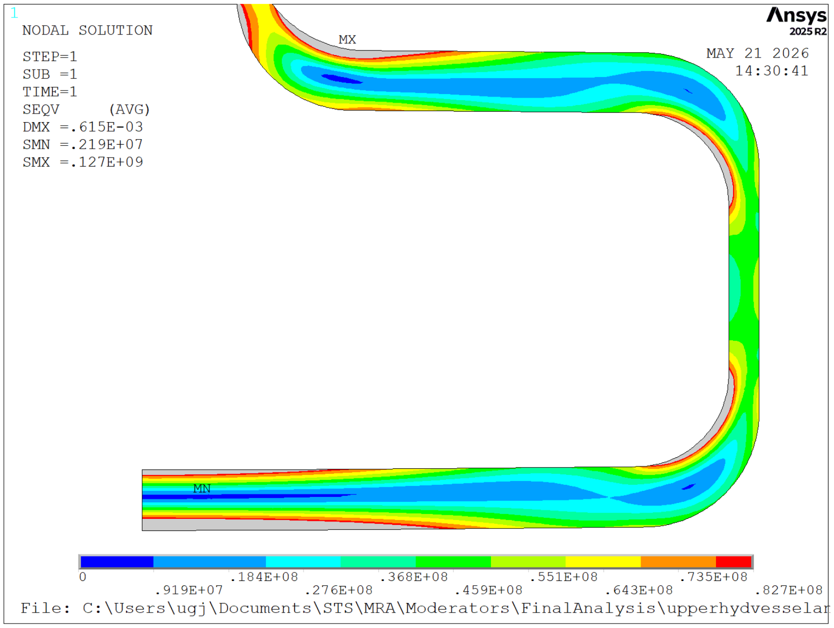

Figure 4.11 Upper Hydrogen Vessel Von Mises Stress Contour Plot Scaled to Weld Allowable (Pa)

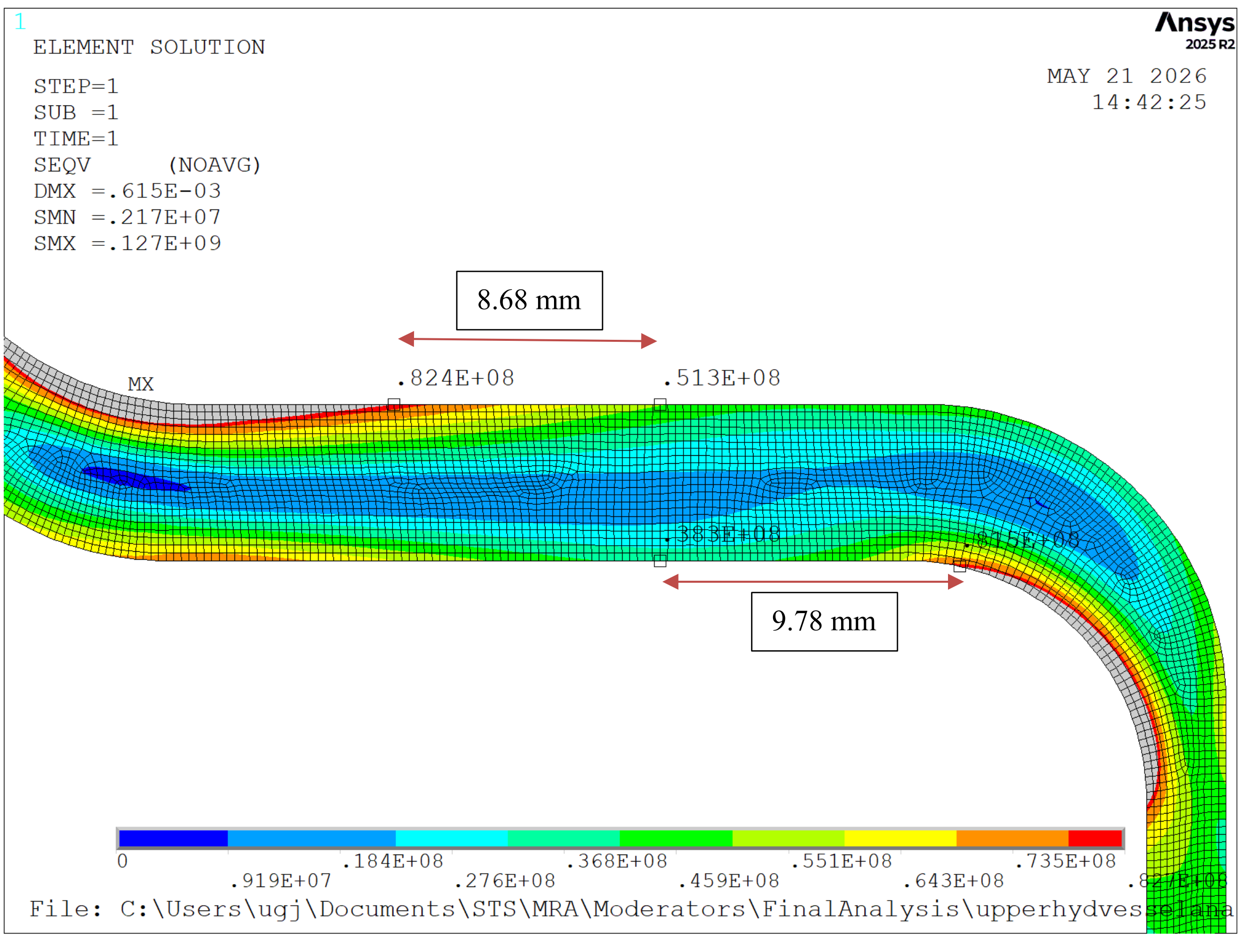

Figure 4.12 Upper Hydrogen Vessel Distance from Weld to Stress Over Weld Allowable (Pa)

The other load case to be considered is the pressure test. The pressure test will be a pneumatic pressure test at 1.15*MAWP = 21.85 bar. Because the design pressure load case was simplified to consider only internal pressure loads, we can linearly scale the results of that case by 1.15 to find the results for the pressure test, so the maximum membrane stress is 55.8 MPa and the maximum membrane plus bending stress is 144.9 MPa. The pressure test stress allowables are defined in 4.1.6.2 of [3] and for a pneumatic test are 0.8 times the yield stress, or 182 MPa. Since the membrane stresses are all less than 2/3 the yield stress, the membrane plus bending allowable is simply 1.5 times 0.8 times the yield stress, or 273 MPa. As seen in Table 4.2, a simple comparison shows that both membrane and membrane plus bending stresses are well below the allowable stresses for the pressure test.

Table 4.2 Scaled Pressure Test Maximum Stresses Compared to Pressure Test Allowable Stresses

Stress Category	Case 1 – Internal Pressure – Maximum Stress (MPa)	Scaled Case 18 – Pressure Test – Maximum Stress (MPa)	Allowable (MPa)
Membrane	48.5	55.8	182.0
Membrane + Bending	126.0	144.9	273.0

4.9.2 Protection Against Local Failure

Based on part 5.3.2 of [3], "the algebraic sum of the three linearized primary principal stresses from Design Load Combination (1) of Table 5.3 shall be used for checking this criterion. ($\sigma1 + \sigma2 + \sigma3) \leq 4S$." Therefore, a variable for the sum of the principal stresses from the internal pressure load case was plotted on a contour plot to look for areas of interest (Figure 4.13). The maximum sum of principal stresses is shown to be 242 MPa, which is significantly lower than allowable 339 MPa, and just higher than the weld zone allowable of 221 MPa. As seen in Figure 4.14, the nearest point to the weld center that exceeds the weld allowable is 15.9 mm away, which is well outside the heat affected zone. Therefore, the upper hydrogen vessel meets the requirement for protection against local failure.

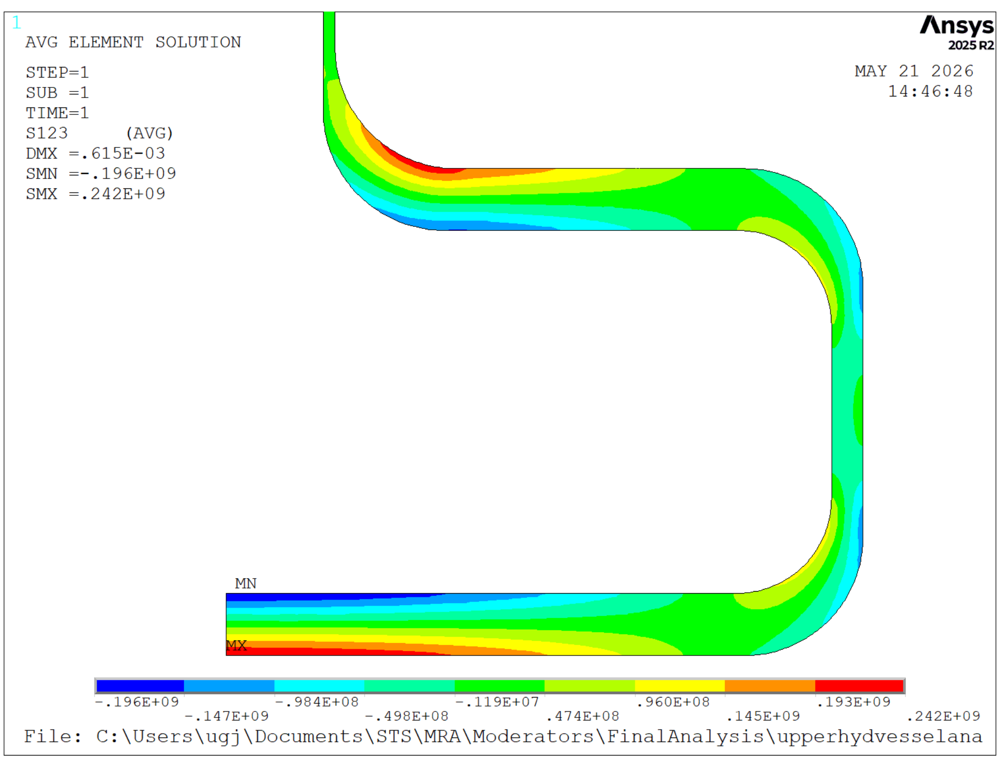

Figure 4.13 Upper Hydrogen Vessel Sum of Principal Stress Contour Plot (Pa)

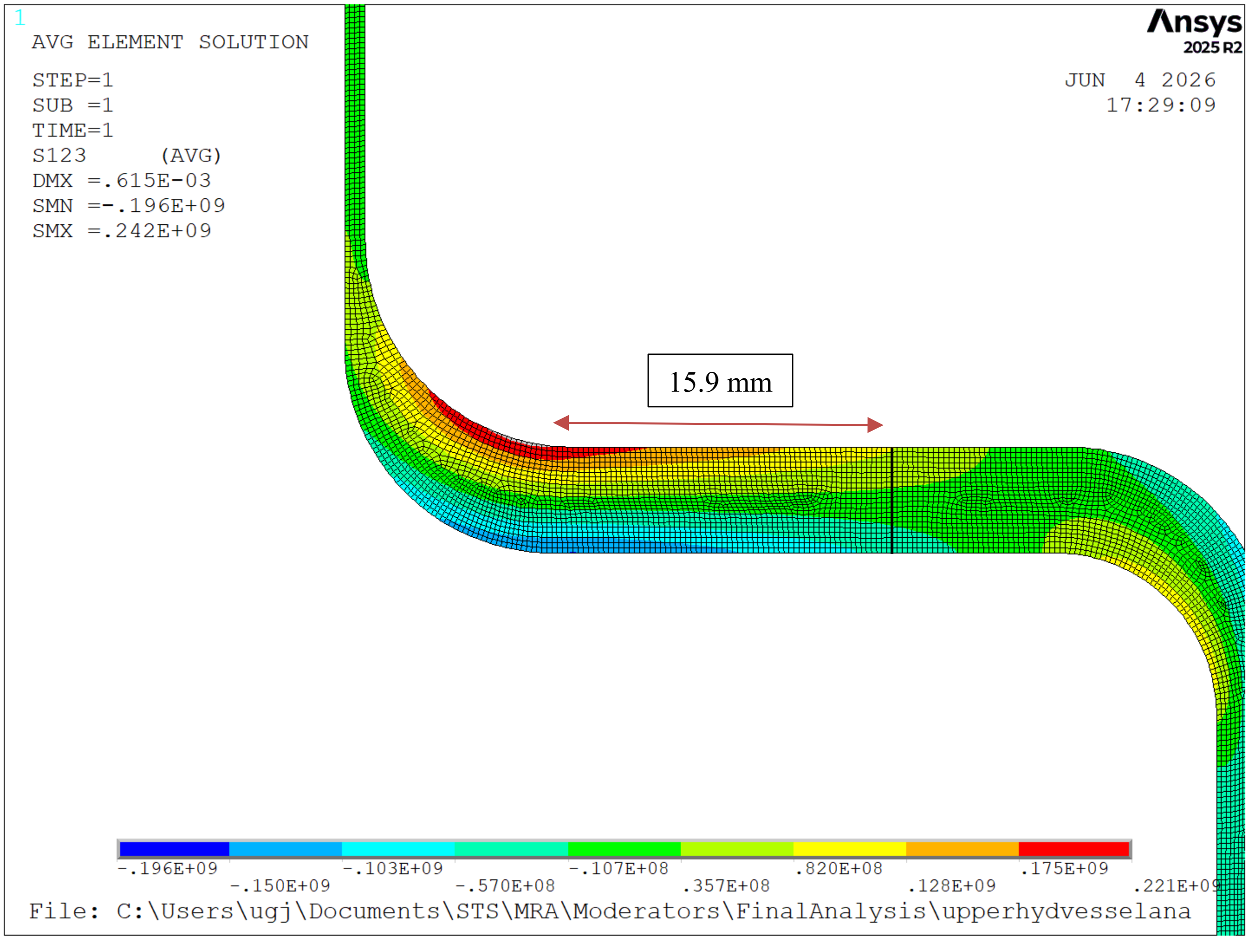

Figure 4.14 Upper Hydrogen Vessel Weld Distance from Over Sum of Principal Stress Allowable (Pa)

4.9.3 Protection Against Failure from Cyclic Loading

Fatigue analysis screening method A of part 5.5.2 of [3] will be satisfied to show that no fatigue analysis is required for the upper hydrogen vessel. First, with a minimum tensile strength of 255 MPa, the 6061-T6 aluminum meets the material requirement for method A of a tensile strength less than 552 MPa. There are expected to be 100 full range pressure cycles in the lifetime of the hydrogen vessel. The pressure response from beam trips is required to be +/- 1 bar from nominal pressure [1], for a total difference of 2 bar. Because this pressure response is less than 20% of design pressure of 19 bara, the pressure responses from beam trips are not counted as pressure cycles for the upper hydrogen vessel. During 700 kW beam operations, the temperature of the upper hydrogen varies from 19.6 to 23.1 K [5], which is below the 28 C threshold shown in table 5.8 of [3] and results in a temperature fatigue cycle factor of 0 from beam trips. Additionally, no thermal cycles are associated with warm up and cool down of the vessel due to the slow temperature change rates and high thermal conductivity of the vessel. Summing the pressure cycles and thermal cycles gives a total number of cycles of 100, which is less than the fatigue screening allowable of 1000 in Table 5.9 of [3]. Therefore, full fatigue analysis is not required for the upper hydrogen vessel.

4.9.4 Protection Against Failure from Ratcheting

Protection against ratcheting is ensured using the Elastic Ratcheting Analysis Method (part 5.5.6.1 of [3]). Load cases (10) – (17) of Table 5.3 of [3] are not evaluated due to the assumptions made previously that thermal stress, static head, fluid momentum, wind, earthquake, and snow loads are negligible. Therefore, only the stress range caused by internal pressure will be considered.

The operating range to be considered for the ratcheting analysis is the pressure cycle from no internal pressure to the MAWP, or 19 bara. While not every operating cycle will reach the MAWP, some will as the result of loss of pressure control of the hydrogen loop. Conveniently, this pressure cycle is represented by the load case analyzed in section 4.9.1. Therefore, the primary plus secondary stress range is represented by the contour plot shown in Figure 4.8 and the maximum primary plus secondary stress range is 127.1 MPa, which is well below the allowable 254.4 MPa for the general material and even below the 165.5 MPa allowable for the weld material.

4.9.5 Mesh Sensitivity

In order to evaluate the mesh sensitivity of the results, the Von Mises stress results between the original (Figure 4.15) and refined mesh (Figure 4.9) were compared. The maximum Von Mises stress for the fine mesh was 127.104 MPa compared to 126.940 MPa for the coarse mesh, for a 0.13% difference. The peak stress in the maximum membrane plus bending stress location, the center of the bottom of the vessel, was also compared showing 126.431 MPa for the fine mesh and 126.425 MPa for the coarse mesh, for a 0.0047% difference. The very low difference in peak Von Mises stresses in the critical areas of the vessel confirms that the mesh density is adequate to resolve the results.

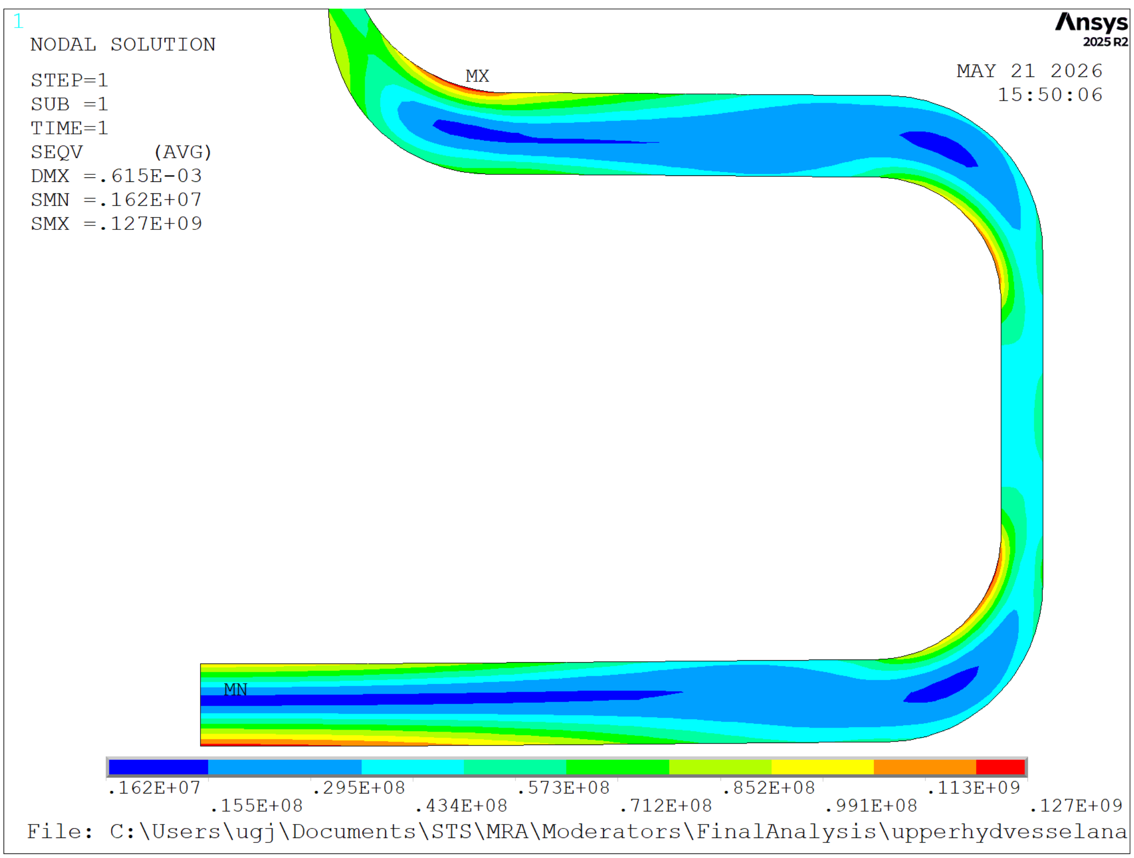

Figure 4.15 Zoomed Upper Hydrogen Vessel Original Mesh Von Mises Stress Contour Plot (MPa)

5. LOWER HYDROGEN VESSEL

5.1 GEOMETRY

The lower hydrogen vessel structural analysis model was based on the lowerhydvesselanalysis-final.prt Creo model and is an arrangement of 3 tubes to form a triangle. This model was also the basis for the Final MRA Neutronics Analysis and Thermal Hydraulic Analysis. This model was built for analysis purposes and alignment features and weld backers were not included. A half symmetry version of the Creo model was imported into Ansys (Figure 5.1). The model was segmented along the weld centerline so that the location of the weld was known (Figure 5.2). The weld location was chosen to allow access for machining and to maximize distance to high stress zones. The coordinate system for the model is the STS global coordinate system. The internal diameter of the tubes is 30 mm and the longest tube length is 170 mm. All vessel wall thicknesses were set to 2 mm to allow for EB welding of the vessel and for sufficient robustness. The nozzle has an inner diameter of 13 mm, a wall thickness of 1 mm, and extends 160.5 mm from the centerline of the vessel.

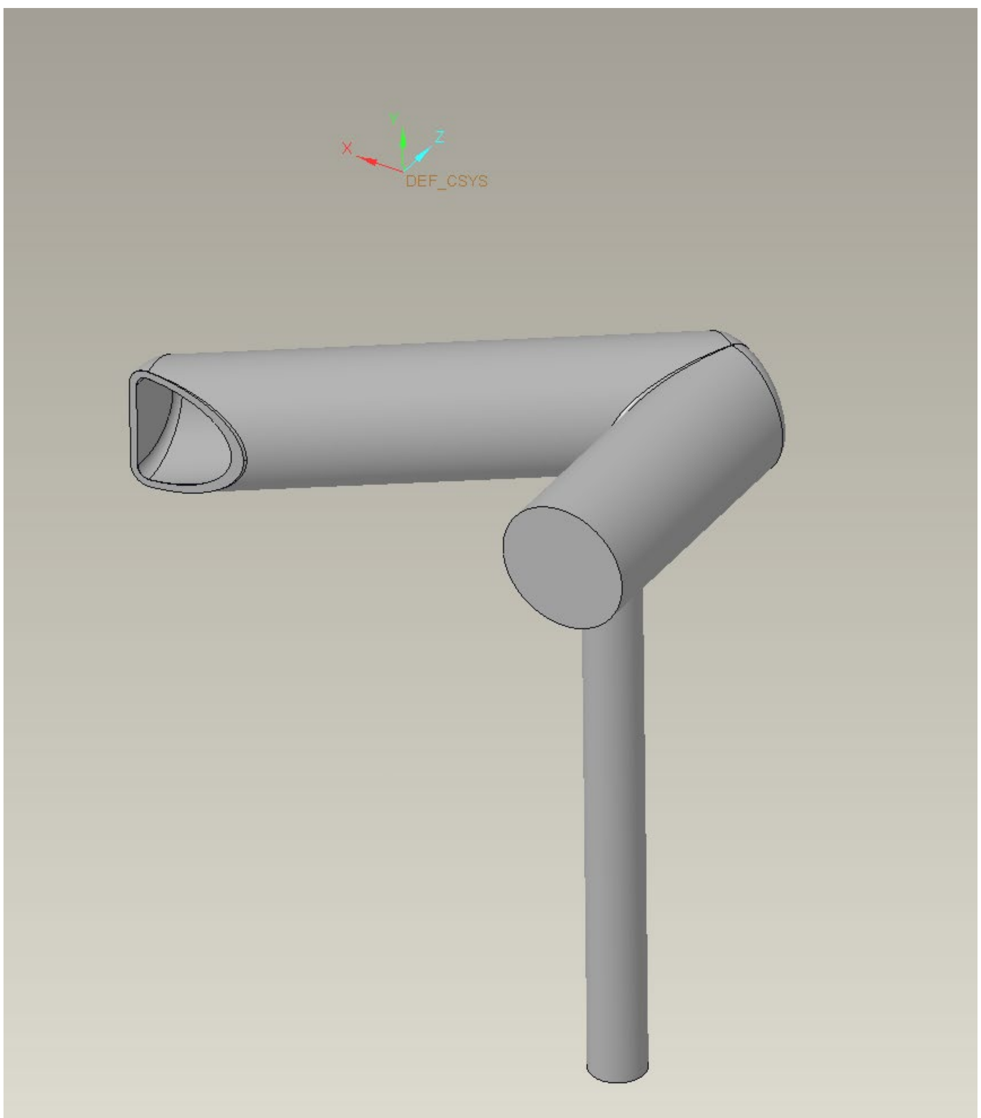

Figure 5.1 Lower Hydrogen Vessel Half Symmetry Creo Model

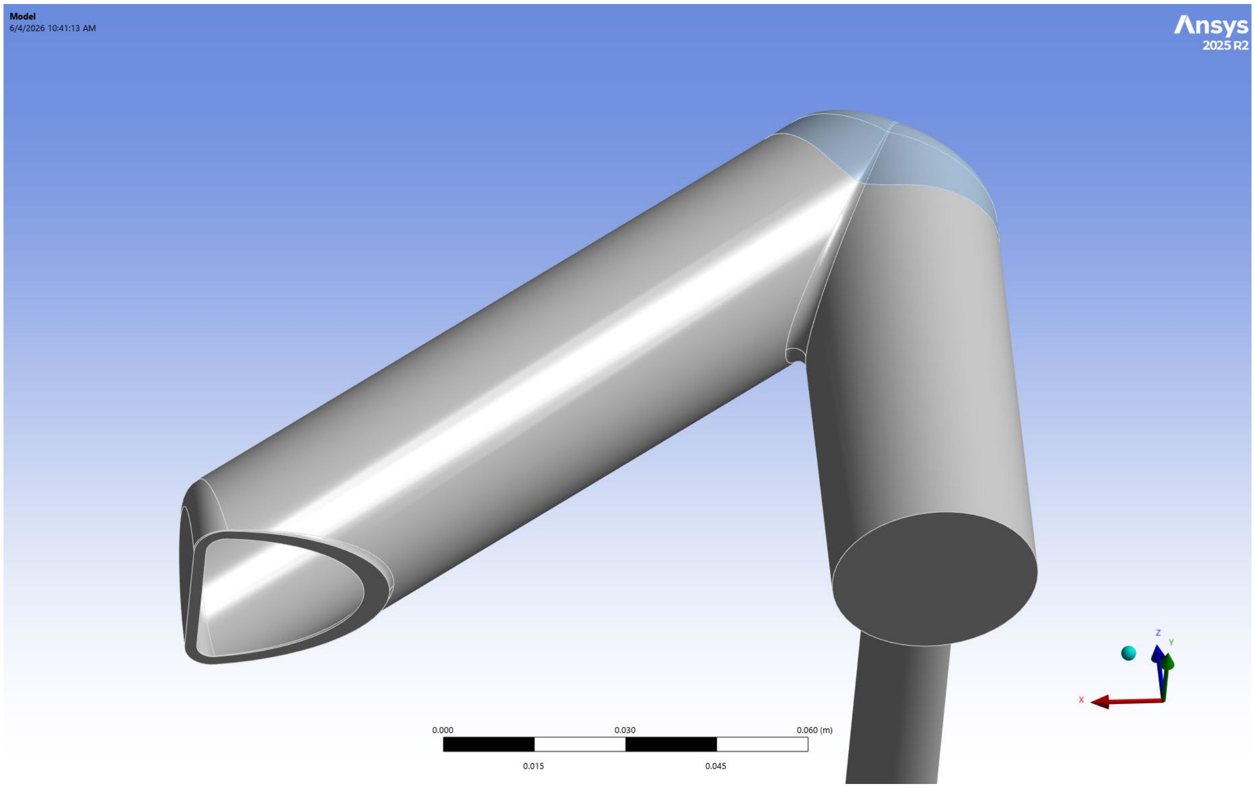

Figure 5.2 Ansys Solid Geometry Model Showing Volume Divided on EB Weld Joint

5.2 SOFTWARE

The lower hydrogen vessel structural analysis was performed using Ansys 2025 R2 Workbench Mechanical software running on PC153452 HP Z2 Tower G1i Workstation Desktop PC with an Intel Core Ultra 9 285K, 3700 MHz, 24 Core Processor with Microsoft Windows 11 Enterprise x64 operating system.

5.3 UNIT SYSTEM

For simplicity, all analyses were performed using MKS units.

5.4 DISCRETIZATION

The tube hydrogen vessel was discretized with tet10 elements, which is a second order 3-D tetrahedral element. The original mesh consists of 457458 elements constructed from 749333 nodes with a global element sizing of 1 mm (Figure 5.3). The refined mesh consists of 1501832 elements constructed from 2309346 nodes with a global element sizing of 0.67 mm (Figure 5.4).

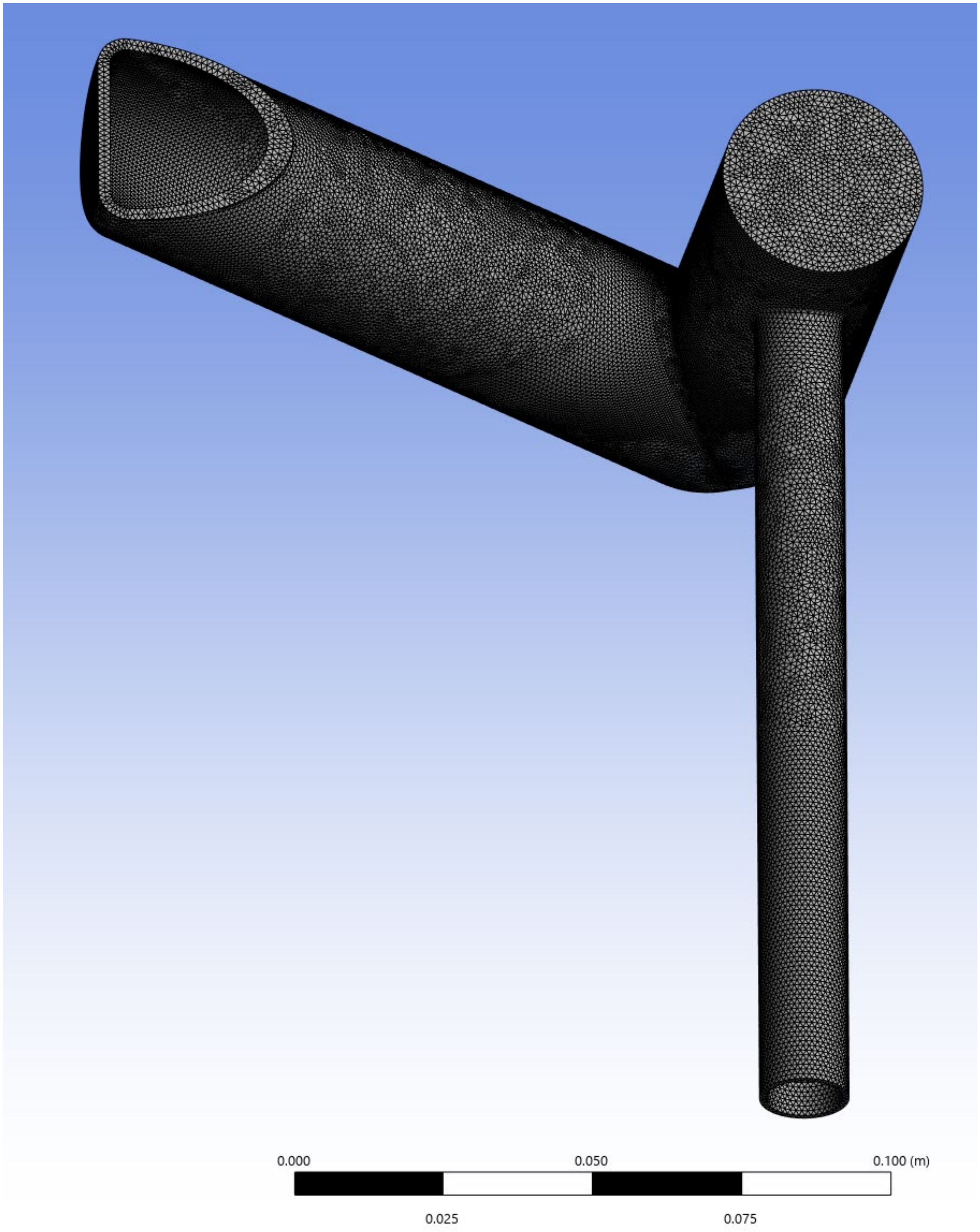

Figure 5.3 Lower Hydrogen Vessel Original Mesh

Figure 5.4 Lower Hydrogen Vessel Refined Mesh

5.5 BOUNDARY CONDITIONS

The tube hydrogen vessel has a fixed x and y constraint, where displacement in the x and y directions are set to 0, on the top of the nozzle. A symmetry boundary condition, where displacement in the z direction is set to 0, has been applied to the symmetry plane of the vessel (Figure 5.5)

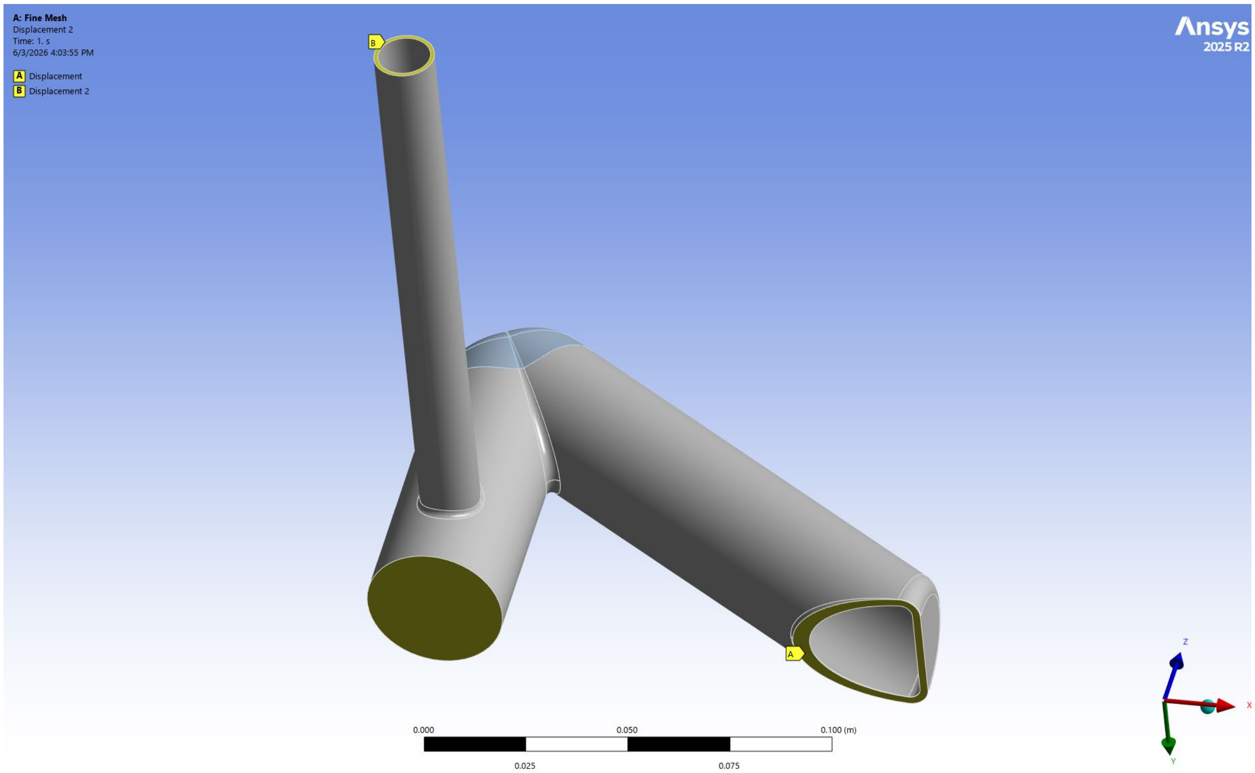

Figure 5.5 Lower Hydrogen Vessel Boundary Conditions

5.6 CONTACT CONDITIONS

No contact interactions were included in the lower hydrogen vessel analysis.

5.7 LOAD DEFINITIONS

The tube hydrogen vessel has an applied load of 19 bara (1.9e6 Pa) applied to all internal surfaces (Figure 5.6) [4].

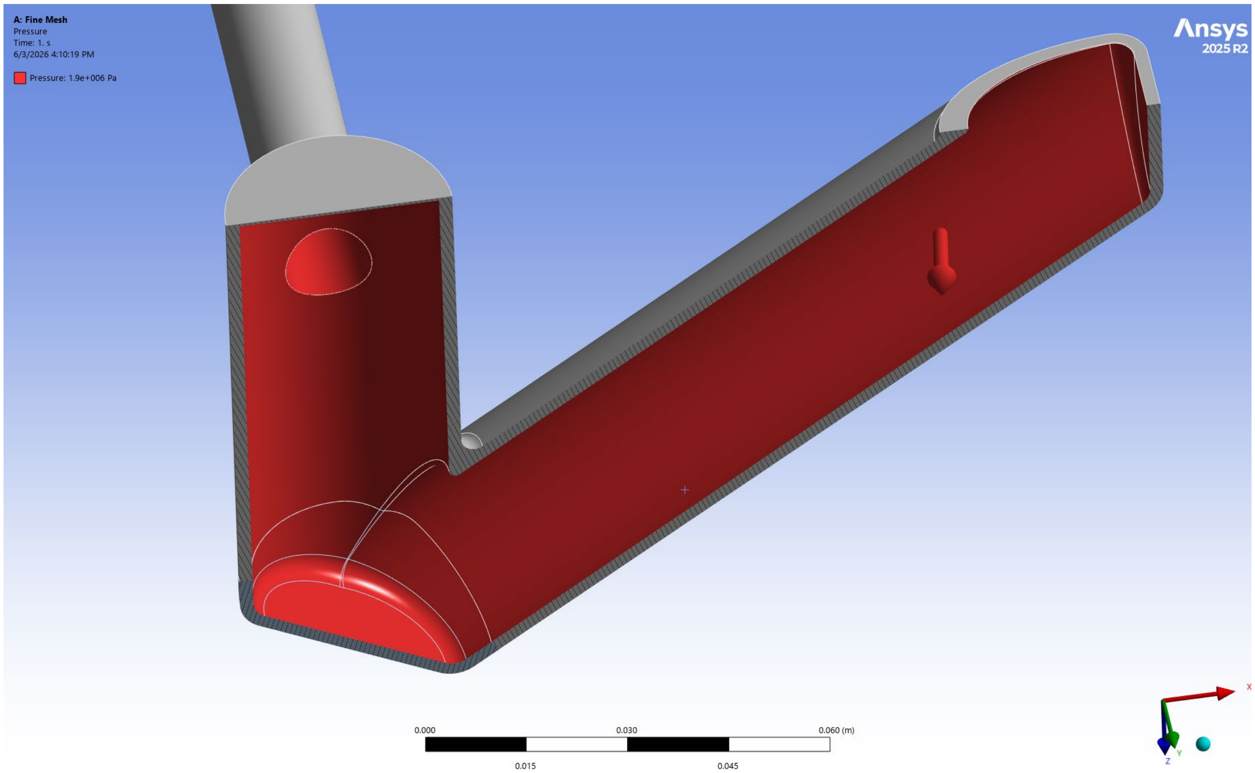

Figure 5.6 Lower Hydrogen Vessel 19 bara (1.9e6 Pa) Internal Pressure Loading (Cross Section for Clarity)

5.8 SOLUTION METHODOLOGY

This analysis employed steady-state linear elastic analysis for all evaluations.

5.9 RESULTS

The results of the analysis were post processed using ANSYS Workbench. The lower hydrogen vessel shows very low deflection resulting from the 19 bar internal pressure loading (Figure 5.7). The maximum deflection is 0.056 mm in the center of the flat vessel surface opposite the nozzles. The deflection of the center of the other two flat surfaces is also above 0.05 mm. The low deflection of the lower hydrogen vessel is due to the inherent stiffness of the tube structure.

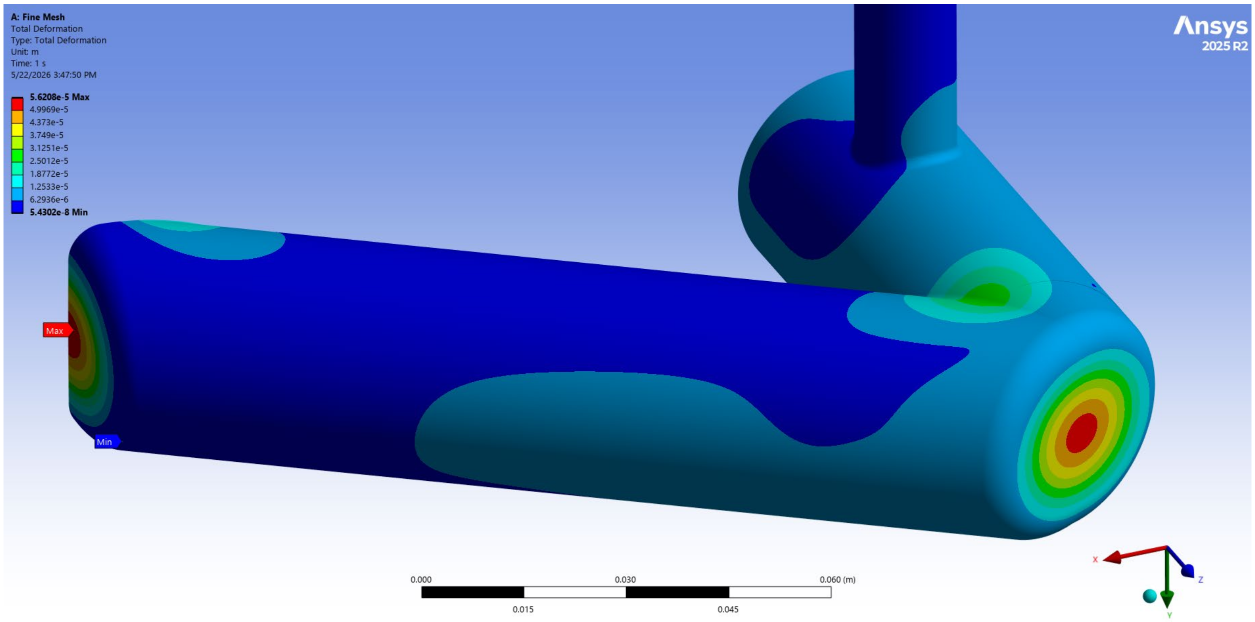

Figure 5.7 Lower Hydrogen Vessel Displacement Contour Plot (m)

5.9.1 Protection Against Plastic Collapse

Protection against plastic collapse is ensured using the Elastic Stress Analysis Method (part 5.2.2 of [3]). Load cases (2) – (8) of Table 5.3 of [3] are not evaluated due to the assumptions made previously that thermal stress, static head, fluid momentum, wind, earthquake, and snow loads are negligible. Therefore, only internal pressure will be considered. This analysis is a static analysis with no material or geometric non-linearity included.

The Von Mises stress results from internal pressure are shown in Figure 5.8 and Figure 5.9. The maximum Von Mises stress is shown to be 117.6 MPa in the radius where the flat surface opposite the nozzles meets the tubes, which below the allowable for membrane plus bending stress of 121.0 MPa. There are also additional high stress areas in the radii where the other flat surfaces meet the tubes and in the inside corners of the tube intersections. The maximum Von Mises stress for the vessel below the membrane plus bending allowable indicates that all linearized stresses will also show membrane plus bending stresses below the allowable. In order to be thorough, 4 paths were chosen for stress linearization at the high stress locations of the vessel, as shown in Figure 5.9 and Figure 5.10. The full results of the stress linearization are shown in appendix B and summarized in Table 5.1, showing the maximum membrane stress was 48.6 MPa and the maximum membrane plus bending was 94.1 MPa, which are below the corresponding allowables of 80.7 MPa and 121.0 MPa. Note that path 2 is in the weld zone and has lower allowables, as discussed in the next paragraph.

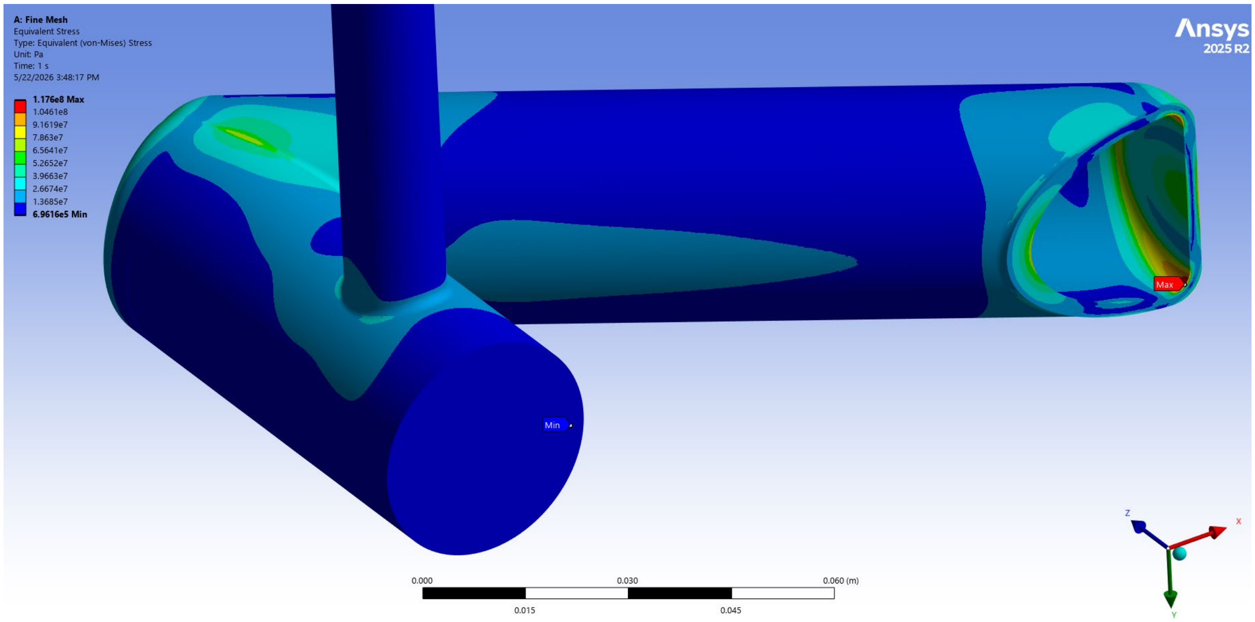

Figure 5.8 Lower Hydrogen Vessel Von Mises Stress Contour Plot (Pa)

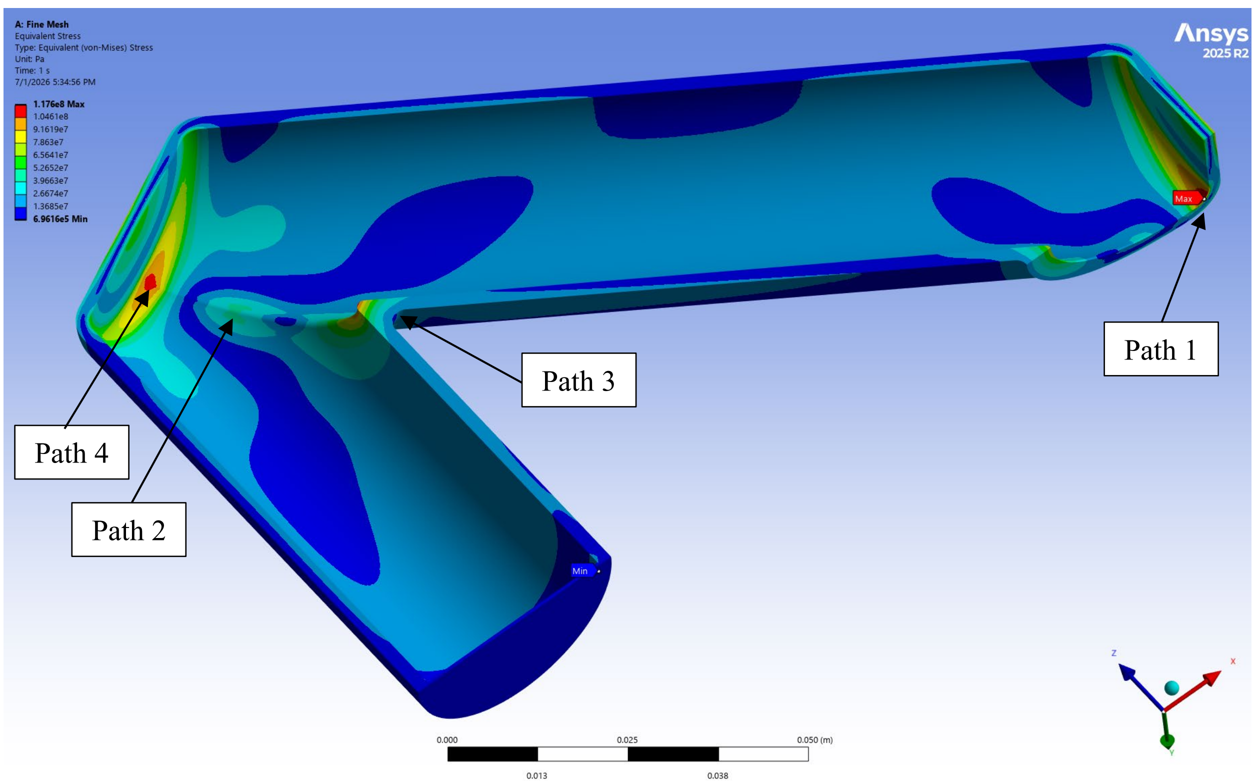

Figure 5.9 Lower Hydrogen Vessel Von Mises Stress Contour Plot, Cross Section (Pa)

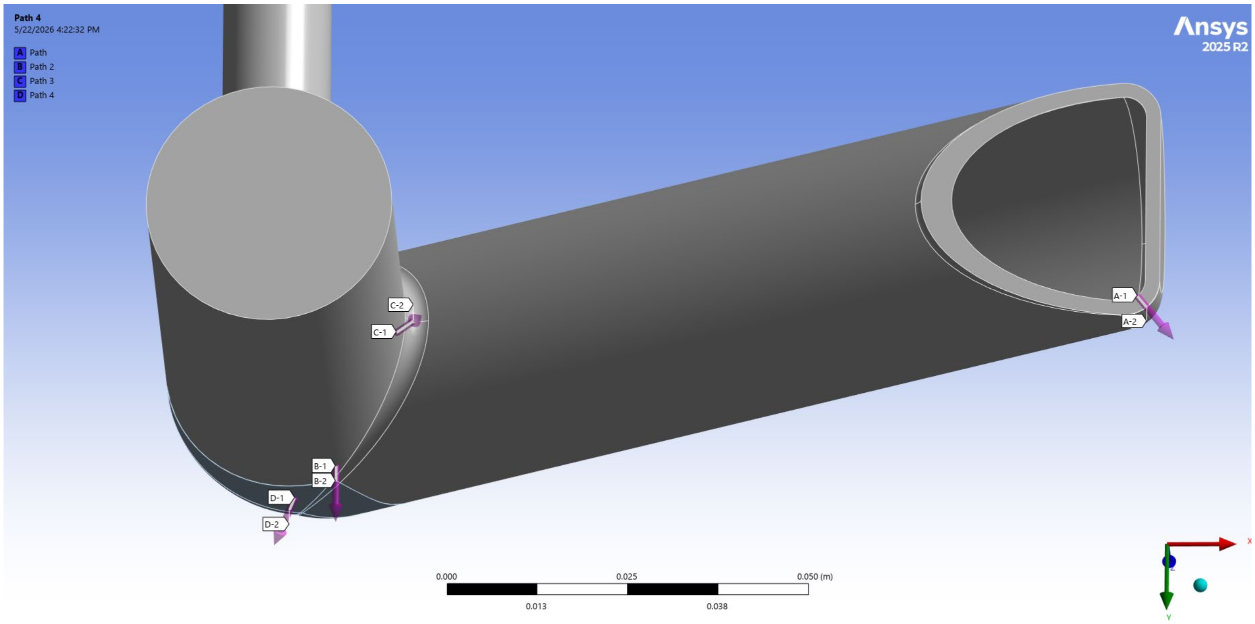

Figure 5.10 Lower Hydrogen Vessel Stress Linearization Path Definition

Table 5.1 Lower Hydrogen Vessel Stress Linearization Summary

	Max. Von Mises Stress (MPa)		
Path	M	M+B	Total
1	16.3	94.1	117.6
2	11.0	52.6	71.3
3	48.6	93.9	109.3
4	16.1	89.6	112.0

Because the hydrogen vessels are made from Al 6061-T6, the allowables are significantly reduced in the weld heat affected zone. The allowable membrane stress in the weld heat affected zone is 55.2 MPa. Note that this is greater than the maximum membrane stress found for the entire vessel of 48.6 MPa, so the weld zone membrane stress requirement is met. The allowable membrane plus bending stress for the weld heat affected is 82.7 MPa, and the Von Mises stresses are compared to this threshold in Figure 5.11 and Figure 5.12. To ensure this requirement is met, we will measure the distance from the weld center to the nearest point where the stress exceeds the allowable. As seen in the Figure 5.13, the minimum distance from the weld center to a point exceeding the weld allowable is 9.75 mm, which exceeds the expected weld affected material size of 3 mm. As mentioned previously, path 2 was selected through the highest stress region of the weld zone. The maximum von Mises stresses from path 2 are 11.0 MPa for membrane and 52.6 MPa for membrane plus bending, which are well below the allowables of 55.2 MPa and 82.7 MPa, respectively.

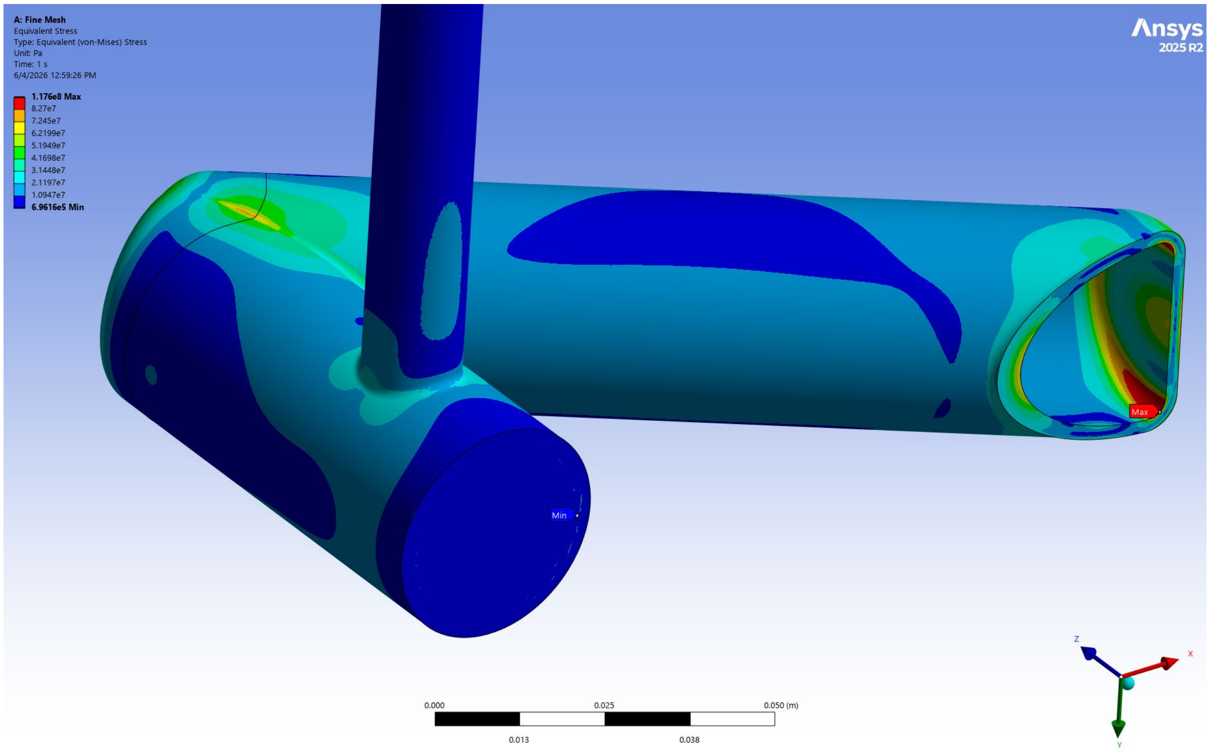

Figure 5.11 Lower Hydrogen Vessel Von Mises Stress Contour Plot with Stresses Over Weld Allowable Shown in Red (Pa)

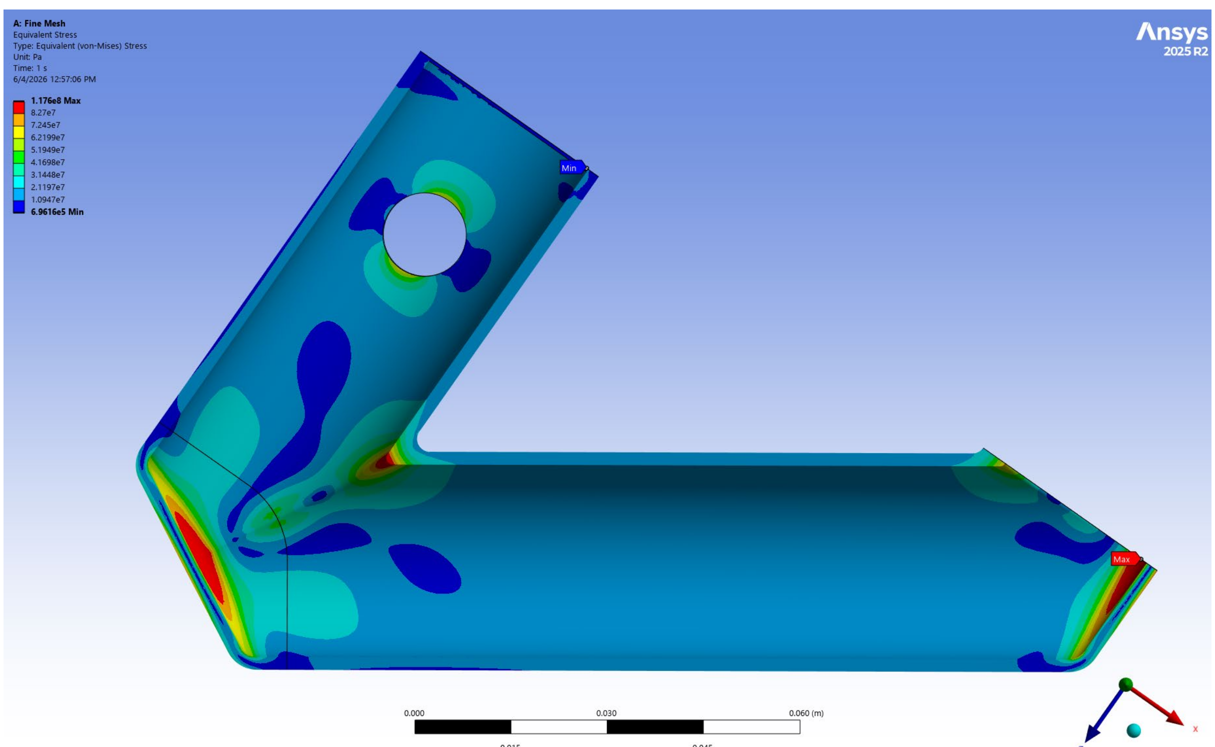

Figure 5.12 Lower Hydrogen Vessel Von Mises Stress Contour Plot Cross Section with Stresses Over Weld Allowable Shown in Red (Pa)

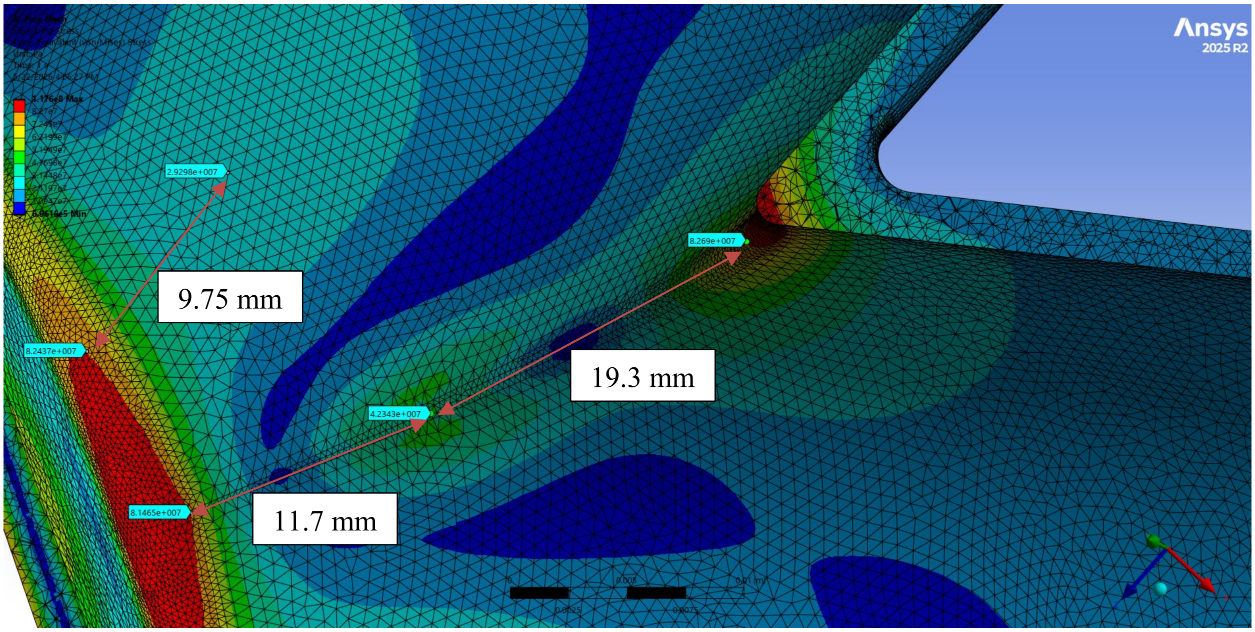

Figure 5.13 Distance from Weld Joint to Regions with Stresses Over Weld Allowable (Pa)

The other load case to be considered is the pressure test. The pressure test will be a pneumatic pressure test at 1.15*MAWP = 21.85 bar. Because the design pressure load case was simplified to consider only internal pressure loads, we can linearly scale the results of that case by 1.15 to find the results for the pressure test, so the maximum membrane stress is 55.9 MPa and the maximum membrane plus bending stress is 108.2 MPa. The pressure test allowables are defined in 4.1.6.2 of [3] and for a pneumatic test are 0.8 times the yield stress, or 177 MPa. Since the membrane stresses are all less than 2/3 the yield stress, the membrane plus bending allowable is simply 1.5 times 0.8 times the yield stress, or 265 MPa. As seen in Table 5.2, a simple comparison shows that both membrane and membrane plus bending stresses are well below the allowable stresses for the pressure test.

Table 5.2 Scaled Pressure Test Maximum Stresses Compared to Pressure Test Allowable Stresses

Stress Category	Case 1 – Internal Pressure – Maximum Stress (MPa)	Scaled Case 18 – Pressure Test – Maximum Stress (MPa)	Allowable (MPa)
Membrane	48.6	55.9	176.5
Membrane + Bending	94.1	108.2	264.8

5.9.2 Protection Against Local Failure

Based on part 5.3.2 of [3], "the algebraic sum of the three linearized primary principal stresses from Design Load Combination (1) of Table 5.3 shall be used for checking this criterion. $(\sigma 1 + \sigma 2 + \sigma 3) \leq 4S$." Therefore, a variable for the sum of the principal stresses from the internal pressure load case was plotted on a contour plot to look for areas above the allowable (Figure 5.14). The maximum sum of principal stresses is shown to be 166 MPa, which is significantly lower than allowable 323 MPa, and still lower than the weld zone allowable of 221 MPa. Therefore, the upper hydrogen vessel meets the requirement for protection against local failure.

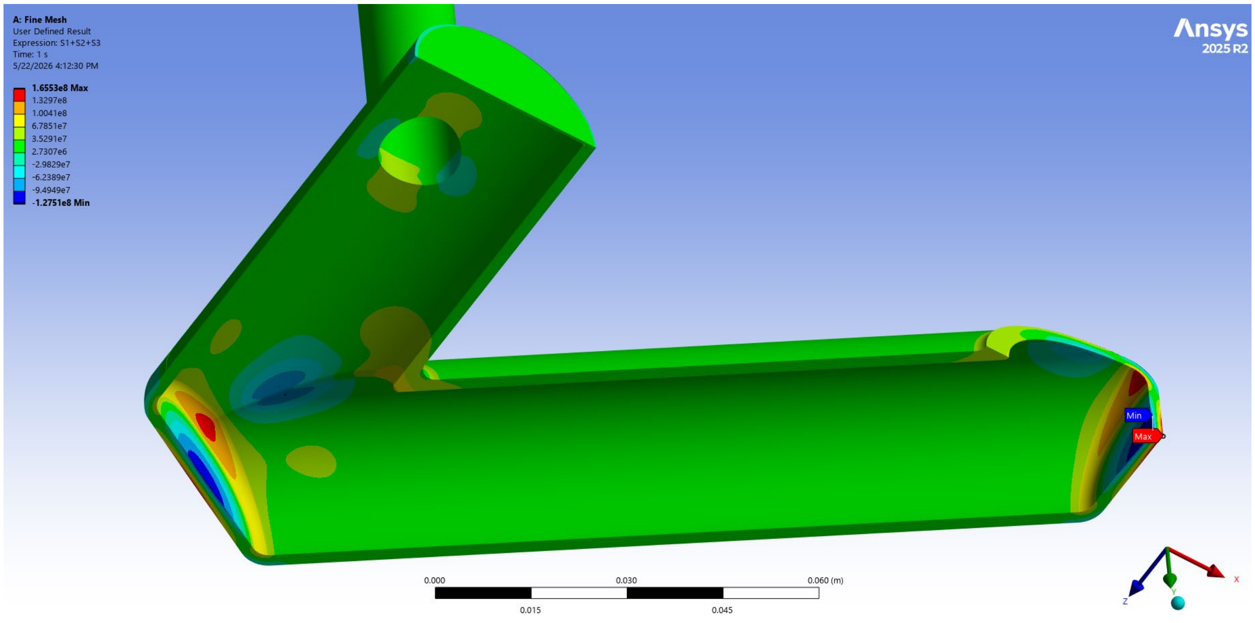

Figure 5.14 Lower Hydrogen Vessel Sum of Principal Stresses Contour Plot (Pa)

5.9.3 Protection Against Failure from Cyclic Loading

Fatigue analysis screening method A of part 5.5.2 of [3] will be satisfied to show that no fatigue analysis is required for the upper hydrogen vessel. First, with a minimum tensile strength of 255 MPa, the 6061-T6 aluminum meets the material requirement for method A of a tensile strength less than 552 MPa. There are expected to be 100 full range pressure cycles in the lifetime of the hydrogen vessel. The pressure response from beam trips is required to be +/- 1 bar from nominal pressure, for a total difference of 2 bar [1]. Because this pressure response is less than 20% of design pressure of 19 bara, the pressure responses from beam trips are not counted as pressure cycles for the lower hydrogen vessel. During 700 kW beam operations, the temperature of the lower hydrogen vessel ranges from 19.6 to 24.6 K [5], which is below the 28 C threshold shown in table 5.8 of [3] and results in a temperature fatigue cycle factor of 0 from beam trips. Additionally, no thermal cycles are associated with warm up and cool down of the vessel due to the slow temperature change rates and high thermal conductivity of the vessel. Summing the pressure cycles and thermal cycles gives a total number of cycles of 100, which is less than the fatigue screening allowable of 1000 in Table 5.9 of [3]. Therefore, full fatigue analysis is not required for the lower hydrogen vessel.

5.9.4 Protection Against Failure from Ratcheting

Protection against ratcheting is ensured using the Elastic Ratcheting Analysis Method (part 5.5.6.1 of [3]). Load cases (10) – (17) of Table 5.3 of [3] are not evaluated due to the assumptions made previously that thermal stress, static head, fluid momentum, wind, earthquake, and snow loads are negligible. Therefore, only the stress range caused by internal pressure will be considered.

The operating range to be considered for the ratcheting analysis is the pressure cycle from no internal pressure to the MAWP, or 19 bara. While not every operating cycle will reach the MAWP, some will as the result of loss of pressure control of the hydrogen loop. Conveniently, this pressure cycle is represented by the load case analyzed in section 5.9.1. Therefore, the primary plus secondary stress range is represented by the contour plot shown in Figure 5.8 and Figure 5.9 and the maximum primary plus secondary stress range is 117.6 MPa, which is well below the allowable 242.0 MPa for the general material and even below the 165.5 MPa allowable for the weld material.

5.9.5 Mesh Sensitivity

In order to evaluate the mesh sensitivity of the results, the Von Mises stress results between the coarse and fine mesh were compared. The maximum Von Mises stress for the refined mesh was 117.60 MPa (Figure 5.8) compared to 116.96 MPa for the original mesh (Figure 5.15), for a 0.55% difference. The low difference in peak Von Mises stresses in the critical areas of the vessel confirms that the mesh density is adequate to resolve the results.

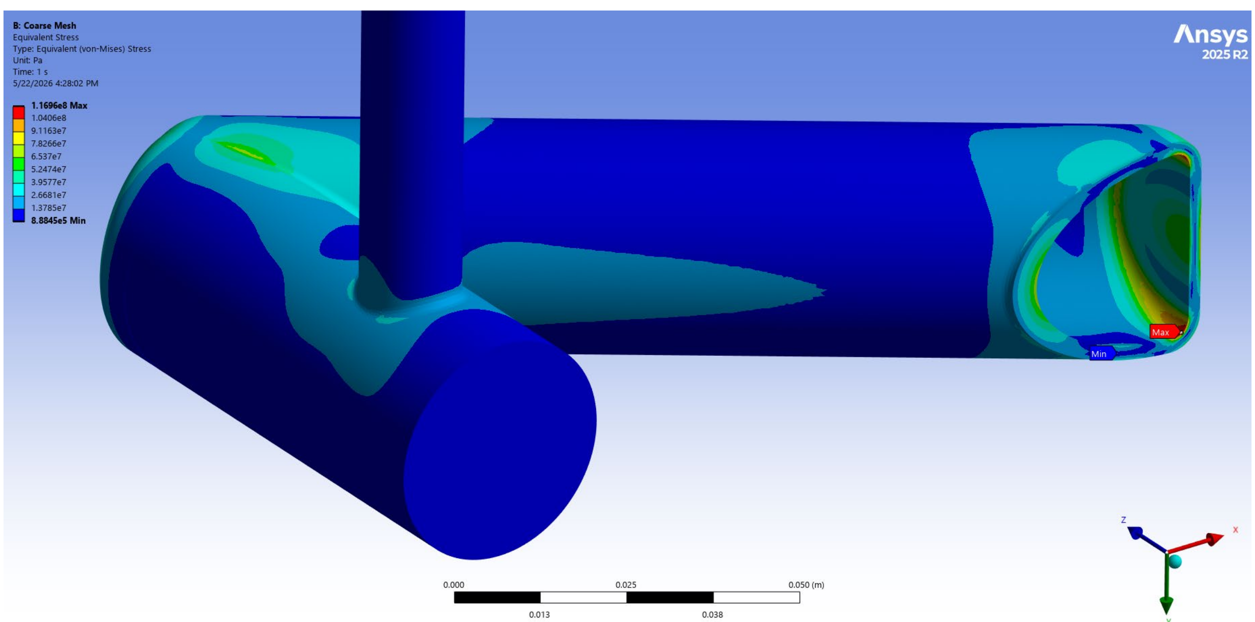

Figure 5.15 Lower Hydrogen Vessel Original Mesh Von Mises Stress Contour Plot (Pa)

6. CONCLUSIONS

The upper and lower hydrogen vessels were evaluated using the design by analysis elastic methods of the ASME BPVC Section VIII, Division 2 to ensure structural integrity under specified design loads. As seen in Table 6.1. and Table 6.2, both vessels meet the requirements for protection from plastic collapse, local failure and ratcheting. Both vessels also met the fatigue screening requirements to demonstrate protection from fatigue failure without a full fatigue analysis. Mesh sensitivity studies were performed for both analyses to show that the stress results are independent of the model discretization. Therefore, the upper and lower hydrogen vessels meet the requirements of the ASME BPVC Section VIII, Division 2.

Table 6.1 Upper Hydrogen Vessel BPVC Requirements Summary

Evaluation	Criterion	Allowable	Result	Acceptable
Plastic Collapse - Case 1 – Internal Pressure	Membrane	84.8 MPa	48.5 MPa	Yes
	Membrane + Bending	127.2 MPa	126.0 MPa	Yes
	Weld Distance from Stress over Allowable	3 mm	8.68 mm	Yes
Plastic Collapse - Case 18 – Pressure Test	Membrane	182.0 MPa	55.8 MPa	Yes
	Membrane + Bending	273.0 MPa	144.9 MPa	Yes
Local Failure – Internal Pressure	Triaxial Stress	339.2 MPa	242.0 MPa	Yes
	Weld Distance from Stress over Allowable	3 mm	15.87 mm	Yes
Fatigue Screening	Cycles	1000	100	Yes
Ratcheting – Internal Pressure	Primary Plus Secondary Stress Range	254.4 MPa	127.1 MPa	Yes

Table 6.2 Lower Hydrogen Vessel BPVC Requirements Summary

Evaluation	Criterion	Allowable	Result	Acceptable
Plastic Collapse - Case 1 – Internal Pressure	Membrane	80.7 MPa	48.6 MPa	Yes
	Membrane + Bending	121.0 MPa	94.1 MPa	Yes
	Weld Distance from Stress over Allowable	3 mm	9.75 mm	Yes
Plastic Collapse - Case 18 – Pressure Test	Membrane	176.5 MPa	55.9 MPa	Yes
	Membrane + Bending	264.8 MPa	108.2 MPa	Yes
Local Failure – Internal Pressure	Triaxial Stress	322.7 MPa	166.0 MPa	Yes
Fatigue Screening	Cycles	1000	100	Yes
Ratcheting – Internal Pressure	Primary Plus Secondary Stress Range	242.0 MPa	117.6 MPa	Yes

7. REFERENCES

[1] S01020500-IST10148, "Interface Sheet for Cryogenic Moderator System and Moderator Reflector Assembly".

[2] S01030000-ESH10002, "Second Target Station: Hazard Analysis Report".

[3] American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Section VIII, Division 2, 2023.

[4] S03040000-SR0001, "System Requirements Document for Target Systems Moderator Reflector Assembly (MRA)".

[5] S03040000-DAC10011, "Thermohydraulic Analysis for the Moderator Reflector Assembly (MRA)".

[6] American Society of Mechanical Engineers, "Boiler and Pressure Vessel Code, Code Case 2478," 2023.

[7] Aerospace Specification Metals Inc., "Aluminum 6061-T6; 6061-T651," 2026. [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6.

[8] Air Force Material Laboratory, AFML-TDR-64-280 Volume 1, Cryogenic Materials Data Handbook, 1970.

[9] ASM International, "Energy Sources Used for Fusion Welding," in *ASM Handbook*, 1995.

APPENDIX A. UPPER HYDROGEN VESSEL STRESS LINEARIZATION RESULTS

```
PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= 1          DSYS=  0

          ***** POST1 LINEARIZED STRESS LISTING *****
         INSIDE NODE =  12229     OUTSIDE NODE =  11885

 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000           LOAD CASE=  0

THE FOLLOWING X,Y,Z STRESSES ARE IN THE GLOBAL COORDINATE SYSTEM.

             ** MEMBRANE **
     SX          SY          SZ          SXY          SYZ          SXZ
 0.1208E+08 -0.9500E+06  0.1208E+08  -7.016       0.000        0.000
     S1          S2          S3          SINT         SEQV
 0.1208E+08  0.1208E+08 -0.9500E+06  0.1303E+08  0.1303E+08

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY          SYZ          SXZ
I -0.1141E+09 -0.1140E+07 -0.1141E+09   244.9        0.000        0.000
C   0.000       0.000       0.000       0.000        0.000        0.000
O  0.1141E+09  0.1140E+07  0.1141E+09  -244.9        0.000        0.000
     S1          S2          S3          SINT         SEQV
I -0.1140E+07 -0.1141E+09 -0.1141E+09  0.1130E+09  0.1130E+09
C   0.000       0.000       0.000       0.000        0.000
O  0.1141E+09  0.1141E+09  0.1140E+07  0.1130E+09  0.1130E+09

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY          SYZ          SXZ
I -0.1020E+09 -0.2090E+07 -0.1020E+09   237.9        0.000        0.000
C  0.1208E+08 -0.9500E+06  0.1208E+08  -7.016        0.000        0.000
O  0.1262E+09  0.1901E+06  0.1262E+09  -251.9        0.000        0.000
     S1          S2          S3          SINT         SEQV
I -0.2090E+07 -0.1020E+09 -0.1020E+09  0.9993E+08  0.9993E+08
C  0.1208E+08  0.1208E+08 -0.9500E+06  0.1303E+08  0.1303E+08
O  0.1262E+09  0.1262E+09  0.1901E+06  0.1260E+09  0.1260E+09

             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY          SYZ          SXZ
I -0.2671E+06  0.1878E+06 -0.2678E+06  -494.3        0.000        0.000
C   151.6       13.54       13.22       29.43        0.000        0.000
O  0.2676E+06 -0.1873E+06  0.2679E+06  -300.0        0.000        0.000
     S1          S2          S3          SINT         SEQV
I  0.1878E+06 -0.2671E+06 -0.2678E+06  0.4556E+06  0.4553E+06
C   157.6       13.22       7.528       150.1        147.3
O  0.2679E+06  0.2676E+06 -0.1873E+06  0.4552E+06  0.4550E+06

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY          SYZ          SXZ
I -0.1023E+09 -0.1902E+07 -0.1023E+09  -256.5        0.000        0.000
C  0.1208E+08 -0.9500E+06  0.1208E+08   22.41        0.000        0.000
O  0.1264E+09   2769.      0.1264E+09  -551.9        0.000        0.000
     S1          S2          S3          SINT         SEQV         TEMP
I -0.1902E+07 -0.1023E+09 -0.1023E+09  0.1004E+09  0.1004E+09   0.000
C  0.1208E+08  0.1208E+08 -0.9500E+06  0.1303E+08  0.1303E+08
O  0.1264E+09  0.1264E+09   2769.      0.1264E+09  0.1264E+09   0.000
```

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PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= 2          DSYS=  0

  RADIUS OF CURVATURE =  0.51300E-01

        ***** POST1 LINEARIZED STRESS LISTING *****
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 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000          LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =  0.51300E-01
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX          SY          SZ          SXY         SYZ         SXZ
 0.3678E+07  0.1688E+08 -0.3395E+08  0.9320E+07   0.000       0.000
     S1          S2          S3          SINT        SEQV
 0.2170E+08 -0.1142E+07 -0.3395E+08  0.5565E+08  0.4845E+08

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I -0.2643E+07  0.9350E+08  0.2957E+08   0.000       0.000       0.000
C -0.4133E+07  0.9003E+06  0.2875E+06   0.000       0.000       0.000
O -0.5623E+07 -0.9169E+08 -0.2900E+08   0.000       0.000       0.000
     S1          S2          S3          SINT        SEQV
I  0.9350E+08  0.2957E+08 -0.2643E+07  0.9614E+08  0.8475E+08
C  0.9003E+06  0.2875E+06 -0.4133E+07  0.5033E+07  0.4757E+07
O -0.5623E+07 -0.2900E+08 -0.9169E+08  0.8607E+08  0.7709E+08

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  0.1034E+07  0.1104E+09 -0.4383E+07  0.9320E+07   0.000       0.000
C -0.4556E+06  0.1778E+08 -0.3367E+08  0.9320E+07   0.000       0.000
O -0.1946E+07 -0.7482E+08 -0.6295E+08  0.9320E+07   0.000       0.000
     S1          S2          S3          SINT        SEQV
I  0.1112E+09  0.2457E+06 -0.4383E+07  0.1155E+09  0.1133E+09
C  0.2170E+08 -0.4376E+07 -0.3367E+08  0.5537E+08  0.4798E+08
O -0.7725E+06 -0.6295E+08 -0.7599E+08  0.7522E+08  0.6962E+08

             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I -0.5821E-09  0.1061E+08  0.2008E+07  0.9331E+07   0.000       0.000
C  0.6018E+07 -0.3627E+07 -0.7250E+06 -0.2202E+07   0.000       0.000
O -0.4657E-09  0.4459E+07  0.8444E+06  0.2212E+07   0.000       0.000
     S1          S2          S3          SINT        SEQV
I  0.1604E+08  0.2008E+07 -0.5429E+07  0.2147E+08  0.1888E+08
C  0.6497E+07 -0.7250E+06 -0.4106E+07  0.1060E+08  0.9381E+07
O  0.5370E+07  0.8444E+06 -0.9114E+06  0.6282E+07  0.5614E+07

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  0.1034E+07  0.1210E+09 -0.2374E+07  0.1865E+08   0.000       0.000
C  0.5562E+07  0.1415E+08 -0.3439E+08  0.7118E+07   0.000       0.000
O -0.1946E+07 -0.7036E+08 -0.6211E+08  0.1153E+08   0.000       0.000
     S1          S2          S3          SINT        SEQV        TEMP
I  0.1238E+09 -0.1799E+07 -0.2374E+07  0.1262E+09  0.1259E+09   0.000
C  0.1817E+08  0.1544E+07 -0.3439E+08  0.5256E+08  0.4653E+08
O -0.5390E+05 -0.6211E+08 -0.7225E+08  0.7219E+08  0.6770E+08   0.000
```

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PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= 3          DSYS=  0

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 TIME=    1.0000          LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =  0.51300E-01
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX          SY          SZ          SXY          SYZ          SXZ
-0.9894E+06  0.1778E+08 -0.3171E+08  0.7849E+06   0.000       0.000
     S1          S2          S3          SINT         SEQV
 0.1781E+08 -0.1022E+07 -0.3171E+08  0.4952E+08  0.4329E+08

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY          SYZ          SXZ
I -0.9315E+06 -0.2443E+08 -0.9555E+07   0.000        0.000        0.000
C  0.6673E+05 -0.2047E+06 -0.8010E+05   0.000        0.000        0.000
O  0.1065E+07  0.2402E+08  0.9395E+07   0.000        0.000        0.000
     S1          S2          S3          SINT         SEQV
I -0.9315E+06 -0.9555E+07 -0.2443E+08  0.2350E+08  0.2059E+08
C  0.6673E+05 -0.8010E+05 -0.2047E+06  0.2714E+06  0.2353E+06
O  0.2402E+08  0.9395E+07  0.1065E+07  0.2296E+08  0.2013E+08

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY          SYZ          SXZ
I -0.1921E+07 -0.6657E+07 -0.4126E+08  0.7849E+06   0.000        0.000
C -0.9227E+06  0.1757E+08 -0.3179E+08  0.7849E+06   0.000        0.000
O  0.7551E+05  0.4180E+08 -0.2231E+08  0.7849E+06   0.000        0.000
     S1          S2          S3          SINT         SEQV
I -0.1794E+07 -0.6784E+07 -0.4126E+08  0.3947E+08  0.3722E+08
C  0.1760E+08 -0.9559E+06 -0.3179E+08  0.4939E+08  0.4321E+08
O  0.4182E+08  0.6075E+05 -0.2231E+08  0.6413E+08  0.5637E+08

             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY          SYZ          SXZ
I   0.000     -0.7343E+06 -0.2143E+06 -0.9925E+06   0.000        0.000
C -0.9691E+05  0.2707E+05  0.4732E+05  0.2858E+05   0.000        0.000
O  0.5821E-10  0.6105E+06  0.1792E+05  0.8351E+06   0.000        0.000
     S1          S2          S3          SINT         SEQV
I  0.6911E+06 -0.2143E+06 -0.1425E+07  0.2117E+07  0.1839E+07
C  0.4732E+05  0.3334E+05 -0.1032E+06  0.1505E+06  0.1440E+06
O  0.1194E+07  0.1792E+05 -0.5839E+06  0.1778E+07  0.1567E+07

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY          SYZ          SXZ
I -0.1921E+07 -0.7391E+07 -0.4148E+08 -0.2076E+06   0.000        0.000
C -0.1020E+07  0.1760E+08 -0.3174E+08  0.8135E+06   0.000        0.000
O  0.7551E+05  0.4241E+08 -0.2229E+08  0.1620E+07   0.000        0.000
     S1          S2          S3          SINT         SEQV         TEMP
I -0.1913E+07 -0.7399E+07 -0.4148E+08  0.3956E+08  0.3713E+08   0.000
C  0.1763E+08 -0.1055E+07 -0.3174E+08  0.4937E+08  0.4318E+08
O  0.4247E+08  0.1360E+05 -0.2229E+08  0.6477E+08  0.5699E+08   0.000
```

```
PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= 4          DSYS=  0

  RADIUS OF CURVATURE =  0.51300E-01

         ***** POST1 LINEARIZED STRESS LISTING *****
        INSIDE NODE =  12845     OUTSIDE NODE =  13347

 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000          LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =  0.51300E-01
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX           SY           SZ           SXY          SYZ          SXZ
 0.3733E+07  0.1671E+08 -0.3303E+08 -0.9229E+07   0.000        0.000
     S1           S2           S3           SINT         SEQV
 0.2150E+08 -0.1060E+07 -0.3303E+08  0.5453E+08  0.4746E+08

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX           SY           SZ           SXY          SYZ          SXZ
I -0.2239E+07  0.8774E+08  0.2782E+08   0.000        0.000        0.000
C -0.3719E+07  0.8449E+06  0.2698E+06   0.000        0.000        0.000
O -0.5200E+07 -0.8605E+08 -0.2728E+08   0.000        0.000        0.000
     S1           S2           S3           SINT         SEQV
I  0.8774E+08  0.2782E+08 -0.2239E+07  0.8998E+08  0.7934E+08
C  0.8449E+06  0.2698E+06 -0.3719E+07  0.4564E+07  0.4306E+07
O -0.5200E+07 -0.2728E+08 -0.8605E+08  0.8085E+08  0.7238E+08

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX           SY           SZ           SXY          SYZ          SXZ
I  0.1494E+07  0.1045E+09 -0.5210E+07 -0.9229E+07   0.000        0.000
C  0.1351E+05  0.1755E+08 -0.3276E+08 -0.9229E+07   0.000        0.000
O -0.1467E+07 -0.6934E+08 -0.6031E+08 -0.9229E+07   0.000        0.000
     S1           S2           S3           SINT         SEQV
I  0.1053E+09  0.6732E+06 -0.5210E+07  0.1105E+09  0.1077E+09
C  0.2151E+08 -0.3948E+07 -0.3276E+08  0.5427E+08  0.4703E+08
O -0.2346E+06 -0.6031E+08 -0.7058E+08  0.7034E+08  0.6581E+08

             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX           SY           SZ           SXY          SYZ          SXZ
I  0.4657E-09  0.9791E+07  0.1862E+07 -0.1036E+08   0.000        0.000
C  0.5442E+07 -0.3331E+07 -0.6684E+06  0.2031E+07   0.000        0.000
O   0.000       0.3821E+07  0.7380E+06 -0.4042E+06   0.000        0.000
     S1           S2           S3           SINT         SEQV
I  0.1635E+08  0.1862E+07 -0.6559E+07  0.2291E+08  0.2007E+08
C  0.5889E+07 -0.6684E+06 -0.3779E+07  0.9667E+07  0.8548E+07
O  0.3863E+07  0.7380E+06 -0.4230E+05  0.3905E+07  0.3579E+07

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX           SY           SZ           SXY          SYZ          SXZ
I  0.1494E+07  0.1142E+09 -0.3348E+07 -0.1958E+08   0.000        0.000
C  0.5455E+07  0.1422E+08 -0.3343E+08 -0.7198E+07   0.000        0.000
O -0.1467E+07 -0.6552E+08 -0.5957E+08 -0.9633E+07   0.000        0.000
     S1           S2           S3           SINT         SEQV         TEMP
I  0.1175E+09 -0.1811E+07 -0.3348E+07  0.1209E+09  0.1201E+09   0.000
C  0.1827E+08  0.1411E+07 -0.3343E+08  0.5169E+08  0.4566E+08
O -0.4968E+05 -0.5957E+08 -0.6694E+08  0.6689E+08  0.6353E+08   0.000
```

```
PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= 5          DSYS=  0

  RADIUS OF CURVATURE =  0.16395E-01

         ***** POST1 LINEARIZED STRESS LISTING *****
        INSIDE NODE =    242     OUTSIDE NODE =   1534

 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000          LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =  0.16395E-01
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX          SY          SZ          SXY         SYZ         SXZ
 0.5768E+07  0.1966E+08  0.1346E+08   5455.       0.000       0.000
     S1          S2          S3          SINT        SEQV
 0.1966E+08  0.1346E+08  0.5768E+07  0.1389E+08  0.1206E+08

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I -0.7852E+07 -0.1054E+09 -0.8591E+08   0.000       0.000       0.000
C -0.6345E+07 -0.8038E+06 -0.4319E+07   0.000       0.000       0.000
O -0.4837E+07  0.1038E+09  0.7727E+08   0.000       0.000       0.000
     S1          S2          S3          SINT        SEQV
I -0.7852E+07 -0.8591E+08 -0.1054E+09  0.9752E+08  0.8939E+08
C -0.8038E+06 -0.4319E+07 -0.6345E+07  0.5541E+07  0.4856E+07
O  0.1038E+09  0.7727E+08 -0.4837E+07  0.1086E+09  0.9807E+08

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I -0.2084E+07 -0.8571E+08 -0.7245E+08   5455.       0.000       0.000
C -0.5767E+06  0.1886E+08  0.9137E+07   5455.       0.000       0.000
O  0.9310E+06  0.1234E+09  0.9072E+08   5455.       0.000       0.000
     S1          S2          S3          SINT        SEQV
I -0.2084E+07 -0.7245E+08 -0.8571E+08  0.8362E+08  0.7785E+08
C  0.1886E+08  0.9137E+07 -0.5767E+06  0.1943E+08  0.1683E+08
O  0.1234E+09  0.9072E+08  0.9310E+06  0.1225E+09  0.1099E+09

             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  0.4657E-09  0.1508E+08  0.1674E+07 -0.3697E+07   0.000       0.000
C  0.8941E+07 -0.8124E+07 -0.8177E+06 -0.1813E+07   0.000       0.000
O  0.2328E-09  0.2065E+08  0.1839E+07  0.1132E+08   0.000       0.000
     S1          S2          S3          SINT        SEQV
I  0.1594E+08  0.1674E+07 -0.8578E+06  0.1679E+08  0.1568E+08
C  0.9131E+07 -0.8177E+06 -0.8315E+07  0.1745E+08  0.1516E+08
O  0.2565E+08  0.1839E+07 -0.4997E+07  0.3065E+08  0.2787E+08

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I -0.2084E+07 -0.7063E+08 -0.7078E+08 -0.3692E+07   0.000       0.000
C  0.8364E+07  0.1073E+08  0.8319E+07 -0.1807E+07   0.000       0.000
O  0.9310E+06  0.1441E+09  0.9256E+08  0.1133E+08   0.000       0.000
     S1          S2          S3          SINT        SEQV        TEMP
I -0.1886E+07 -0.7078E+08 -0.7083E+08  0.6894E+08  0.6891E+08   0.000
C  0.1171E+08  0.8319E+07  0.7388E+07  0.4322E+07  0.3940E+07
O  0.1450E+09  0.9256E+08  0.4013E+05  0.1449E+09  0.1271E+09   0.000
```

APPENDIX B. LOWER HYDROGEN VESSEL STRESS LINEARIZATION RESULTS

Path 1

Column1	SX	SY	SZ	SXY	SYZ	SXZ	S1	S2	S3	SINT	SEQV
Membrane	1.3823e+007	1.221e+007	3.1482e+006	-7.4587e+006	-19207	96694	2.0519e+007	5.5151e+006	3146800	17372000	16317000
Bending (Inside)	5.295e+007	3.8679e+007	2.9484e+007	-4.4127e+007	16162	1.0609e+005	9.0515e+007	2.9484e+007	1114500	89401000	79127000
Bending (Outside)	-5.295e+007	-3.8679e+007	-2.9484e+007	4.4127e+007	-16162	-1.0609e+005	-1.1145e+006	-2.9484e+007	-90515000	89401000	79127000
Membrane+Bending (Inside)	6.6773e+007	5.0889e+007	3.2632e+007	-5.1586e+007	-3044.7	2.0279e+005	1.1102e+008	3.2633e+007	6637000	104390000	94122000
Membrane+Bending (Center)	1.3823e+007	1.221e+007	3.1482e+006	-7.4587e+006	-19207	96694	2.0519e+007	5.5151e+006	3146800	17372000	16317000
Membrane+Bending (Outside)	-3.9128e+007	-2.647e+007	-2.6336e+007	3.6668e+007	-35368	-9399.3	4.4118e+006	-2.6336e+007	-70009000	74421000	64774000
Peak (Inside)	8.569e+006	1.982e+006	-6.1558e+005	-1.2758e+007	-1.3949e+005	1.5893e+005	1.8454e+007	-6.1789e+005	-7900500	26354000	23572000
Peak (Center)	-1.5076e+006	-1.8248e+006	4.4793e+005	4.3598e+006	53502	-21897	2.6967e+006	4.4817e+005	-6029300	8725900	7847100
Peak (Outside)	4.3814e+006	2.2774e+006	-9.0371e+005	-7.9795e+006	-2.1863e+005	8031.	1.138e+007	-8.9892e+005	-4725800	16106000	14574000
Total (Inside)	7.5342e+007	5.2871e+007	3.2017e+007	-6.4343e+007	-1.4253e+005	3.6171e+005	1.2942e+008	3.2016e+007	-1210700	130640000	117600000
Total (Center)	1.2315e+007	1.0385e+007	3.5962e+006	-3.099e+006	34295	74797	1.4596e+007	8.1055e+006	3594900	11001000	9578500
Total (Outside)	-3.4746e+007	-2.4192e+007	-2.7239e+007	2.8689e+007	-2.54e+005	-1368.3	-2.9778e+005	-2.724e+007	-58640000	58342000	50575000

Path 2

Column1	SX	SY	SZ	SXY	SYZ	SXZ	S1	S2	S3	SINT	SEQV
Membrane	5.5343e+006	5.3415e+006	-9.8352e+005	1.0334e+006	-1.579e+006	4.7731e+006	8.0678e+006	5.7113e+006	-3886800	11955000	10968000
Bending (Inside)	-5.0039e+007	-3.2796e+006	-4.8056e+007	3.319e+006	-7.6776e+006	-6.3747e+005	-1.7633e+006	-4.9328e+007	-50283000	48520000	48049000
Bending (Outside)	5.0039e+007	3.2796e+006	4.8056e+007	-3.319e+006	7.6776e+006	6.3747e+005	5.0283e+007	4.9328e+007	1763300	48520000	48049000
Membrane+Bending (Inside)	-4.4505e+007	2.0619e+006	-4.9039e+007	4.3524e+006	-9.2566e+006	4.1356e+006	3.9526e+006	-4.2073e+007	-53362000	57315000	52587000
Membrane+Bending (Center)	5.5343e+006	5.3415e+006	-9.8352e+005	1.0334e+006	-1.579e+006	4.7731e+006	8.0678e+006	5.7113e+006	-3886800	11955000	10968000
Membrane+Bending (Outside)	5.5574e+007	8.6211e+006	4.7072e+007	-2.2855e+006	6.0985e+006	5.4106e+006	5.8211e+007	4.5579e+007	7476400	50735000	45746000
Peak (Inside)	1.8969e+007	-7.3448e+006	6.9641e+006	1.0928e+006	-7.9062e+005	7.2194e+006	2.237e+007	3.7035e+006	-7485000	29855000	26124000
Peak (Center)	-7.1238e+006	1.6475e+006	-3.7641e+006	-2.9688e+005	-44691	-2.4361e+006	1.6578e+006	-2.4871e+006	-8411100	10069000	8765200
Peak (Outside)	2.1352e+007	-6.5791e+006	1.1293e+007	-6.5253e+005	-1.6225e+006	6.6605e+006	2.4724e+007	8.0679e+006	-6725300	31449000	27251000
Total (Inside)	-2.5535e+007	-5.2829e+006	-4.2075e+007	5.4452e+006	-1.0047e+007	1.1355e+007	-2.4061e+006	-1.9763e+007	-50725000	48319000	42395000
Total (Center)	-1.5895e+006	6.989e+006	-4.7476e+006	7.3655e+005	-1.6237e+006	2.337e+006	7.2302e+006	-3.497e+005	-6228600	13459000	11687000
Total (Outside)	7.6926e+007	2.042e+006	5.8365e+007	-2.9381e+006	4.476e+006	1.2071e+007	8.2877e+007	5.2974e+007	1482400	81395000	71311000

Path 3

Column1	SX	SY	SZ	SXY	SYZ	SXZ	S1	S2	S3	SINT	SEQV
Membrane	4.9066e+006	5.4043e+007	5.9848e+006	-1.0045e+005	-1.9034e+005	-6.9219e+005	5.4044e+007	6.3227e+006	4567800	49476000	48622000
Bending (Inside)	-2.9561e+006	4.3556e+007	-2.4882e+005	1.1239e+005	1.0265e+005	-2.0303e+006	4.3557e+007	8.3764e+005	-4043100	47600000	45357000
Bending (Outside)	2.9561e+006	-4.3556e+007	2.4882e+005	-1.1239e+005	-1.0265e+005	2.0303e+006	4.0431e+006	-8.3764e+005	-43557000	47600000	45357000
Membrane+Bending (Inside)	1.9505e+006	9.7599e+007	5.736e+006	11941	-87688	-2.7224e+006	9.7599e+007	7.1589e+006	527490	97072000	93932000
Membrane+Bending (Center)	4.9066e+006	5.4043e+007	5.9848e+006	-1.0045e+005	-1.9034e+005	-6.9219e+005	5.4044e+007	6.3227e+006	4567800	49476000	48622000
Membrane+Bending (Outside)	7.8628e+006	1.0487e+007	6.2336e+006	-2.1285e+005	-2.9299e+005	1.3381e+006	1.0547e+007	8.5587e+006	5477100	5070000	4424700
Peak (Inside)	-9.9708e+005	1.1579e+007	-6.8251e+006	-1.1942e+005	80615	4.239e+006	1.158e+007	1.2324e+006	-9055800	20636000	17871000
Peak (Center)	9.865e+005	-3.366e+006	2.8296e+006	55983	1538.6	-1.2912e+006	3.4945e+006	3.2239e+005	-3366700	6861200	5947600
Peak (Outside)	-6.1355e+006	3.2072e+006	-5.6957e+006	-1.3206e+005	95942	-2.1971e+005	3.2102e+006	-5.607e+006	-6227200	9437400	9143100
Total (Inside)	9.5342e+005	1.0918e+008	-1.0891e+006	-1.0748e+005	-7073.3	1.5165e+006	1.0918e+008	1.7604e+006	-1896200	111070000	109290000
Total (Center)	5.8931e+006	5.0677e+007	8.8144e+006	-44471	-1.888e+005	-1.9834e+006	5.0678e+007	9.8165e+006	4890200	45788000	43534000
Total (Outside)	1.7273e+006	1.3694e+007	5.3792e+005	-3.4491e+005	-1.9705e+005	1.1184e+006	1.3708e+007	2.3853e+006	-134060	13842000	12770000

Path 4

Column1	SX	SY	SZ	SXY	SYZ	SXZ	S1	S2	S3	SINT	SEQV
Membrane	4.2375e+006	1.1016e+007	1.1398e+007	3.071e+006	-5.9738e+006	-4.9818e+006	1.936e+007	5.6088e+006	1682900	17677000	16078000
Bending (Inside)	2.9686e+007	4.4945e+007	3.9444e+007	1.9541e+007	-3.7614e+007	-6.6264e+006	8.627e+007	2.6339e+007	1466800	84803000	75505000
Bending (Outside)	-2.9686e+007	-4.4945e+007	-3.9444e+007	-1.9541e+007	3.7614e+007	6.6264e+006	-1.4668e+006	-2.6339e+007	-86270000	84803000	75505000
Membrane+Bending (Inside)	3.3924e+007	5.5961e+007	5.0842e+007	2.2612e+007	-4.3588e+007	-1.1608e+007	1.0546e+008	2.8022e+007	7245700	98213000	89649000
Membrane+Bending (Center)	4.2375e+006	1.1016e+007	1.1398e+007	3.071e+006	-5.9738e+006	-4.9818e+006	1.936e+007	5.6088e+006	1682900	17677000	16078000
Membrane+Bending (Outside)	-2.5449e+007	-3.3929e+007	-2.8046e+007	-1.647e+007	3.164e+007	1.6446e+006	4.3772e+006	-2.4655e+007	-67146000	71523000	62305000
Peak (Inside)	2.5526e+006	1.9746e+006	5.7862e+006	5.746e+006	-1.1477e+007	-2.3992e+006	1.7602e+007	1.2799e+006	-8568100	26170000	22894000
Peak (Center)	-1.162e+006	-1.7775e+006	-2.083e+006	-2.6232e+006	5.001e+006	6.3408e+005	3.5643e+006	-8.3908e+005	-7747700	11312000	9876300
Peak (Outside)	1.1668e+006	2.8361e+006	3.0223e+006	3.7358e+006	-6.9164e+006	-1.2341e+006	1.1107e+007	5.5422e+005	-4636200	15743000	13895000
Total (Inside)	3.6476e+007	5.7936e+007	5.6628e+007	2.8358e+007	-5.5065e+007	-1.4007e+007	1.2288e+008	2.9297e+007	-1136100	124020000	111950000
Total (Center)	3.0755e+006	9.2385e+006	9.3152e+006	4.4778e+005	-9.7282e+005	-4.3477e+006	1.1966e+007	8.819e+006	843830	11122000	9930200
Total (Outside)	-2.4282e+007	-3.1093e+007	-2.5023e+007	-1.2735e+007	2.4724e+007	4.1053e+005	-1.8117e+005	-2.4103e+007	-56114000	55933000	48608000

APPENDIX C. REVIEW DOCUMENTATION

Method of Advanced Review used
X In-Depth Calculation Review
__ Alternate Calculation
__ Qualification Test

Technical Review Checklist:

	Yes	No	N/A
Is the calculation well organized, legible, and complete?	X		
If excerpts from other sources are included in the calculation package, are the excerpts legible and properly referenced?	X		
Do the calculations cover the expressed purpose?	X		
Are all necessary elements included?	X		
Is the method used appropriate considering the purpose and type of analysis and the use and acceptability of the results (i.e. margin to limits)?	X		
Is the method in accordance with codes, standards, and regulatory requirements?	X		
Has the method been employed similarly elsewhere in industry?	X		
Are assumptions necessary to perform the analysis adequately described, justified, and reasonable?	X		
Are there any Unverified Assumptions (UVAs)?		X	
Were UVAs justified?			X
Are the inputs sufficiently documented considering the purpose of the analysis?	X		
Is all the software used identified correctly (name, version, manual reference, OS, and compilers are documented)?	X		
Are the computer codes suitable for the present analysis?	X		
Does the model adequately represent the physical systems?	X		
Is the magnitude of the result reasonable?	X		
Are the directions of trends reasonable?	X		

Independent Review Verification:

	Yes	No
Did you perform the original calculation?		X
Did you specify a single analytical approach?		X
Did you rule out certain analytical considerations?		X
Did you establish any input to the calculation being verified?		X

Justification for any "Yes" to an Independent Review Verification question above:

Does the independent review support the calculation findings? What differences were observed?

Yes, the independent review supports the calculation findings.

Additional comments:

This DAC is well written and structured. The stress analysis of hydrogen vessels is evaluated by the ASME BPVC Section VIII, Division 2 Code for structural integrity. The author applied conservative allowable stress of UTS/3, which will be replaced by UTS/2.4 in the 2025 version ASME Code . Elastic analyses were utilized to show the hydrogen vessels meet the design by analysis requirements for protection against plastic collapse, local failure, and failure from ratcheting by satisfying conservative allowable stresses. Fatigue screening was used to show that protection against failure from cyclic loading was assured without a full fatigue analysis. The author has done good job documenting the whole analysis.

Hao Jiang Digitally signed by Hao Jiang
Date: 2026.07.02 11:13:11 -04'00'

Reviewer Date