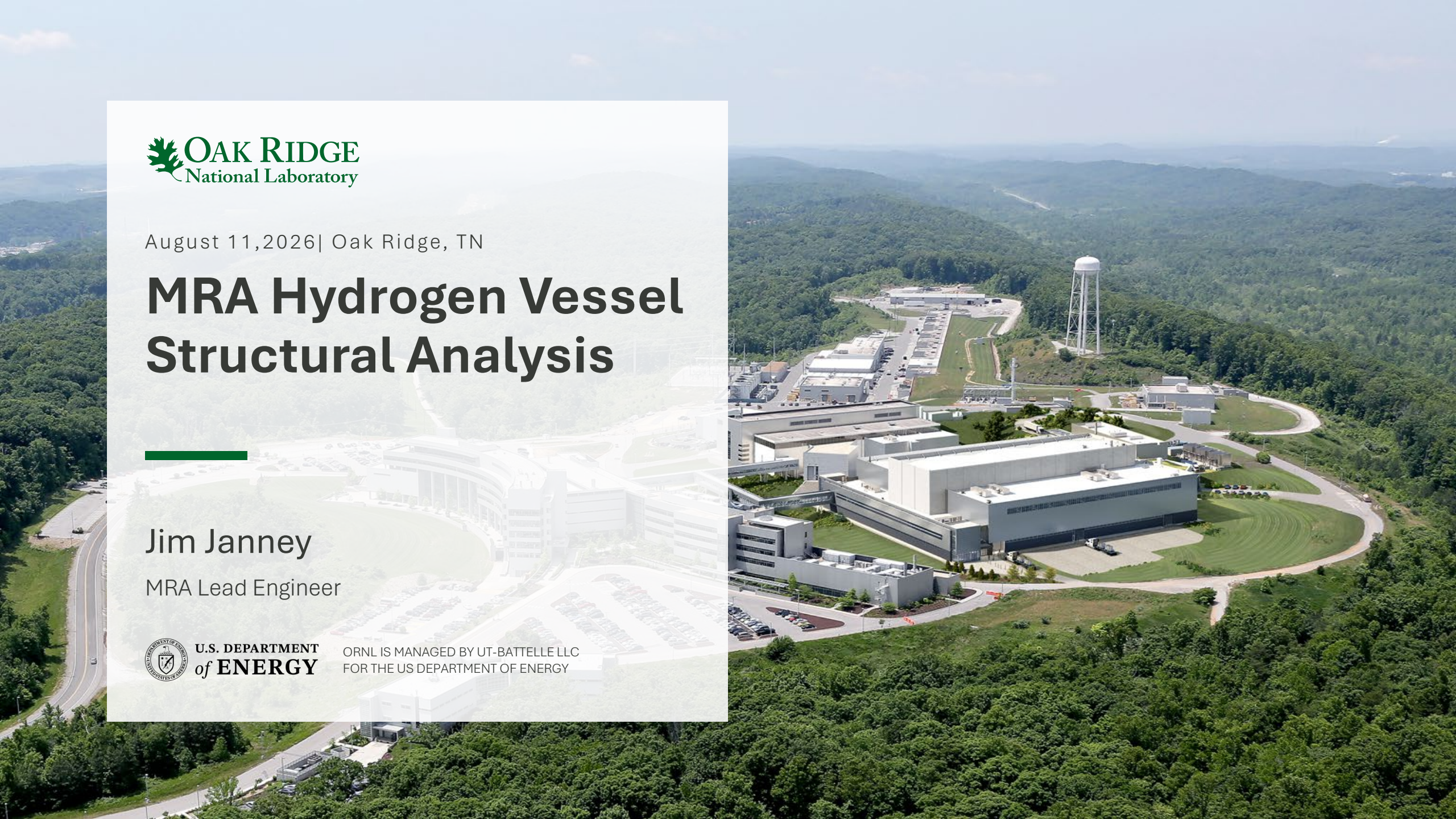

OAK RIDGE National Laboratory

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# MRA Hydrogen Vessel Structural Analysis


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U.S. DEPARTMENT of ENERGY


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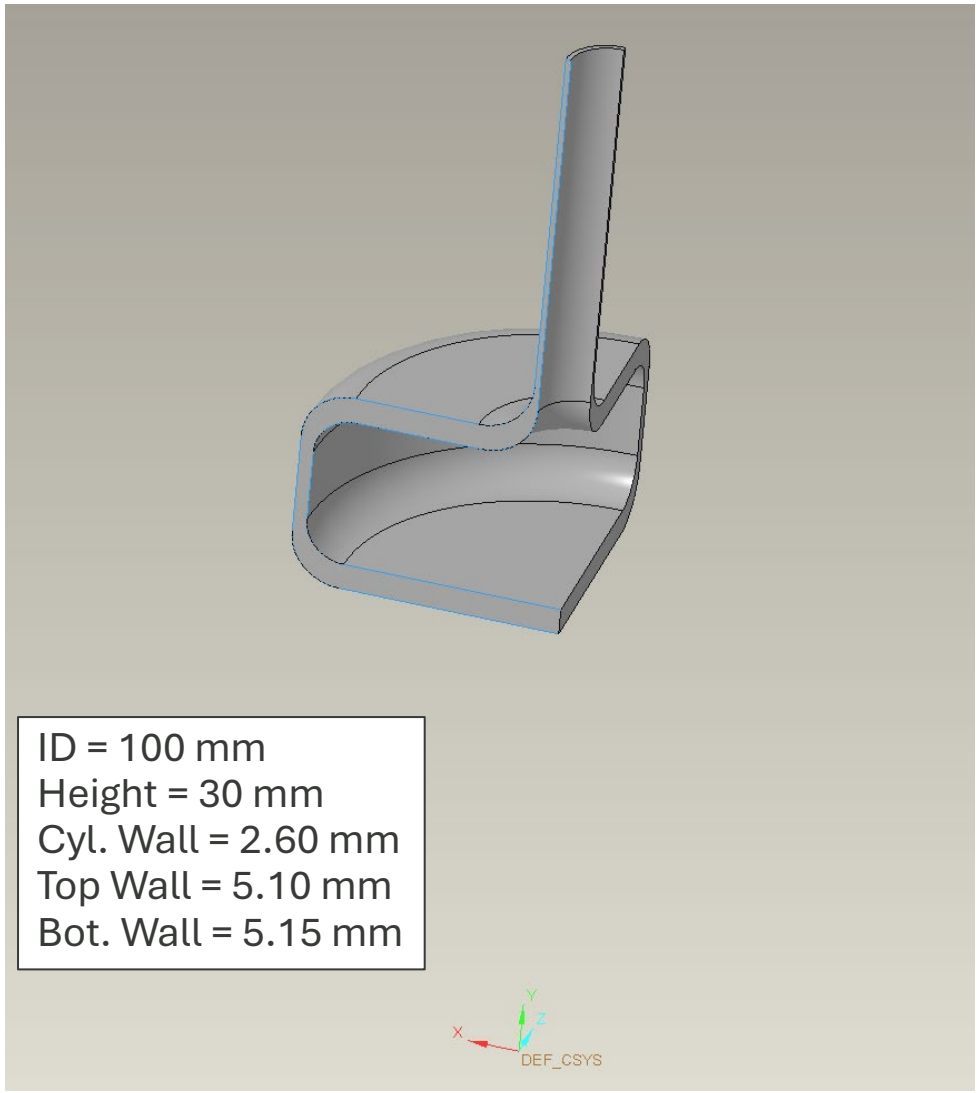
# MRA Hydrogen Vessel Structural Analysis

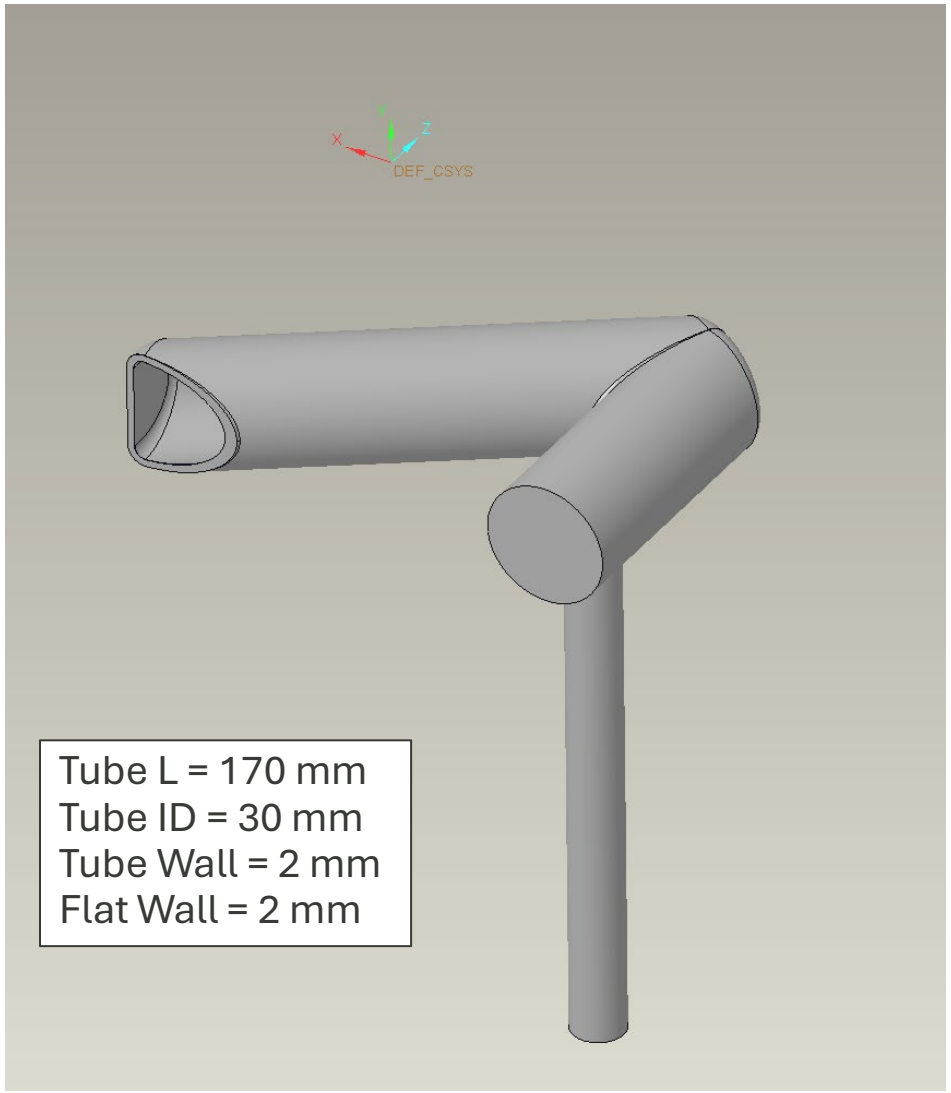
- Performed to verify MRA Hydrogen Vessel Requirement
- ASME BPVC Section VIII Division 2, Design by Analysis, Elastic Analysis Method
- Overprotection protection at 19 bara provided by CMS
    - Operated in vacuum so differential pressure is also 19 bar
- Pressure cycles defined by cyclic loading requirement

| | |
|---|---|
| MRA Hydrogen Vessel Requirement | The MRA hydrogen vessels shall be designed to the intent of the 2023 ASME BPVC. Applied seismic loads shall be derived from the NPH BOD. |
| MRA Hydrogen Boundary Pressure Requirement | The MRA hydrogen boundary MAWP shall be 19 bara. |
| 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. [...] 10000 beam trips are expected to occur each year. |

# Hydrogen Vessel Geometry




Upper Cylinder Hydrogen Vessel




Lower Tube Hydrogen Vessel

# Assumptions

- Hydrogen vessels are assumed not to interact with their surrounding vacuum vessels
  - Nominal vacuum gap of 3 mm
- Gravitational, deadweight, and seismic loads considered negligible
  - Vessel mass of 0.306 kg for lower and 0.412 kg for upper
- Fluid live loads considered negligible
  - Fluid mass of 0.024 kg for lower and 0.018 kg for upper
- Thermal stresses considered negligible
  - Only 5 K temperature range for lower and 3.5 K for upper
  - Thermal expansion coefficient nearly 0 at operating temperature range (18-25 K)

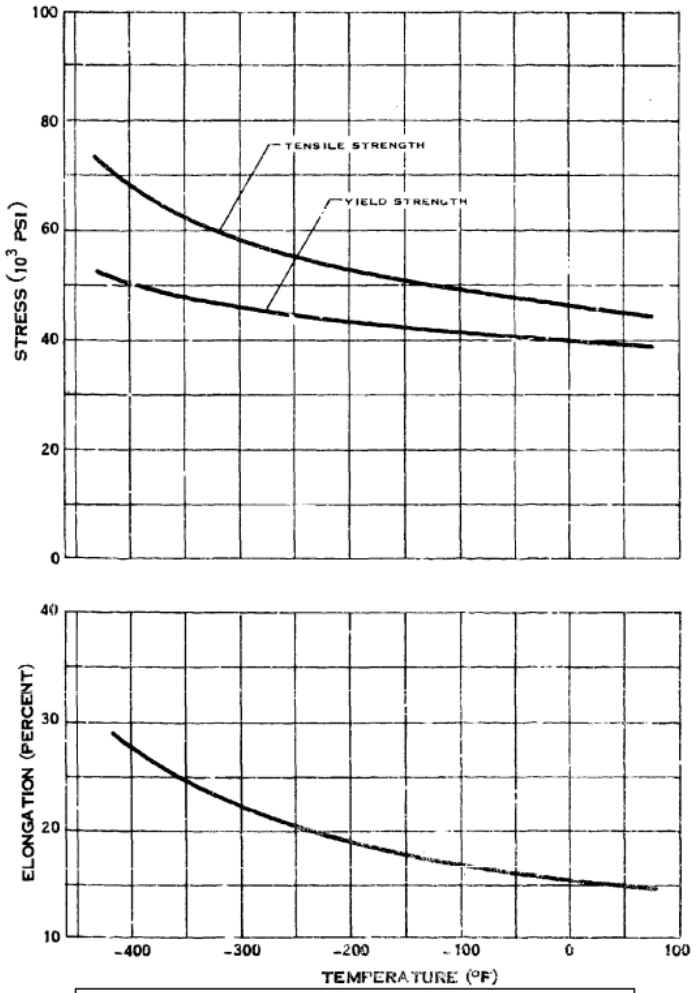
# Material Properties

- ASME BPVC Code Case 2478 properties for ASME SB-247 Al-6061 T6 Forgings
  - Room Temperature properties used
  - Al 6061 becomes stronger and more ductile at operating temperatures

| 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 |

Al 6061-T6 Material Properties

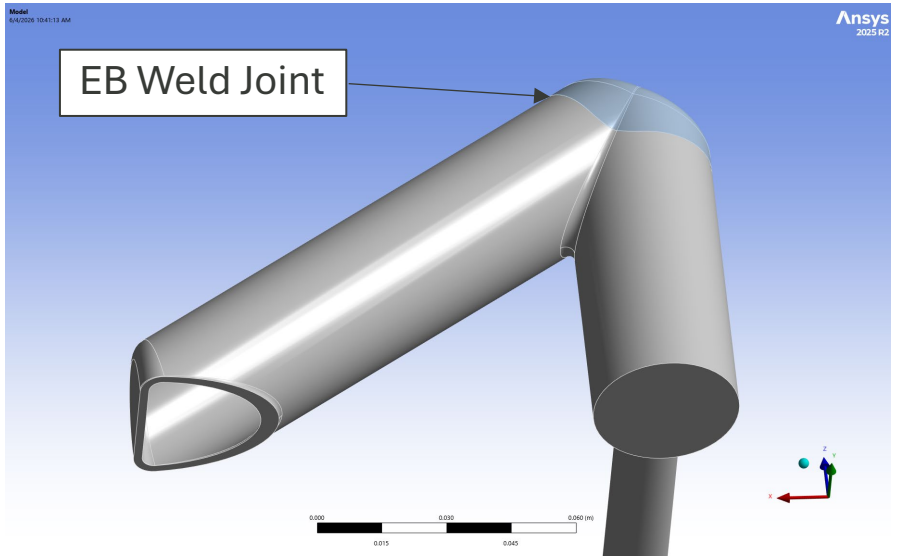
Al 6061-T6 Strength and Elongation

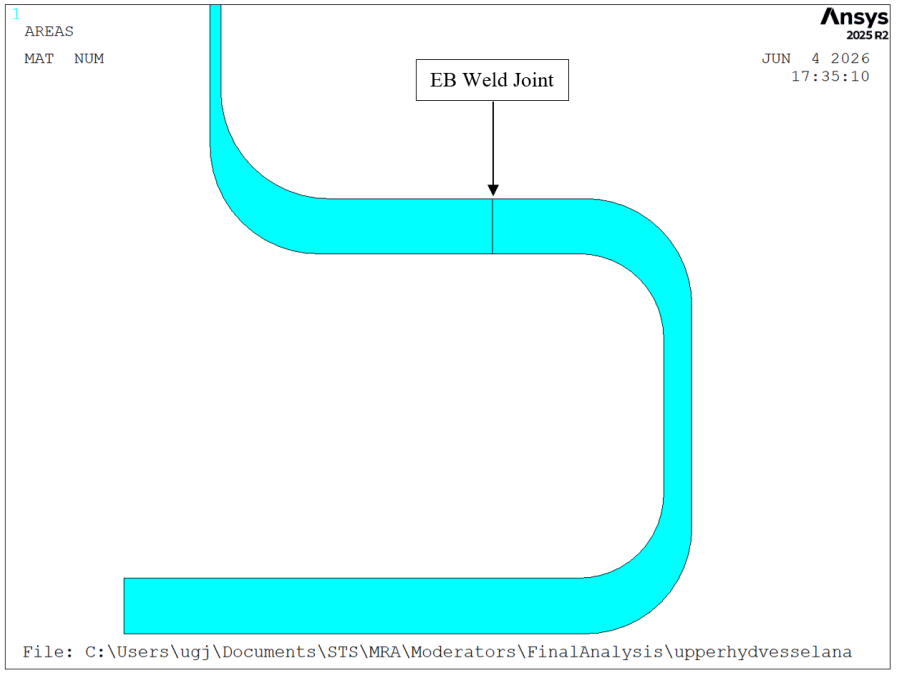



Credit: AFML-TDR-64-280

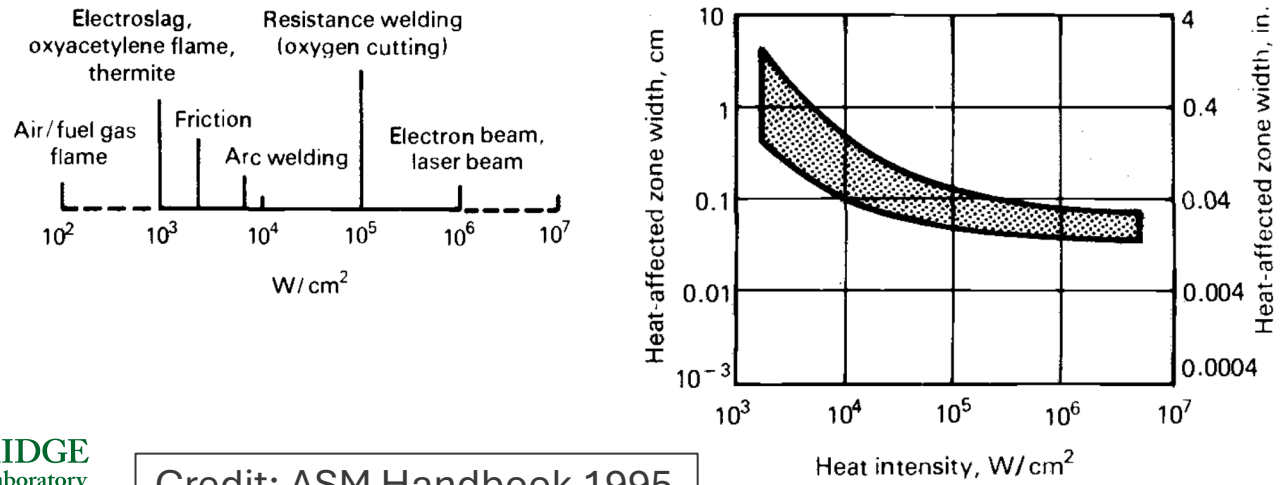
# Weld Zones with Reduced Allowables

- Hydrogen Vessels use Electron Beam Welds in low stress regions
  - Less weld distortion
  - Smaller weld and heat affected zone
- 5 mm weld width from prototyping and 1 mm heat affected zone for EB weld results in assumed 6 mm weld width



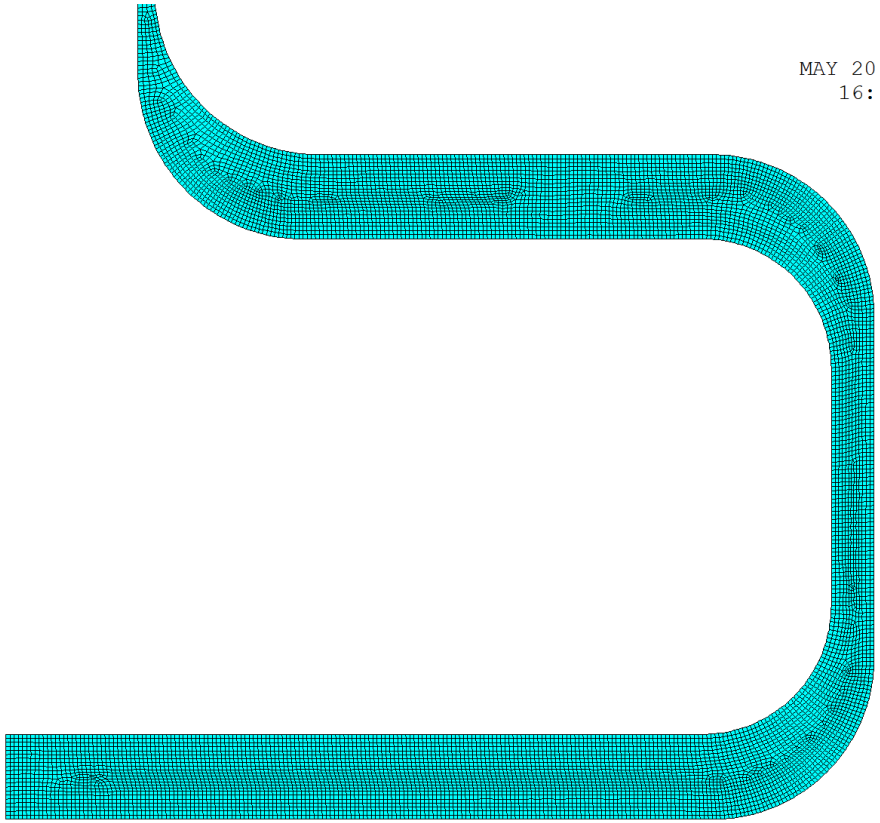




Heat Affected Zone Widths for Various Weld Types

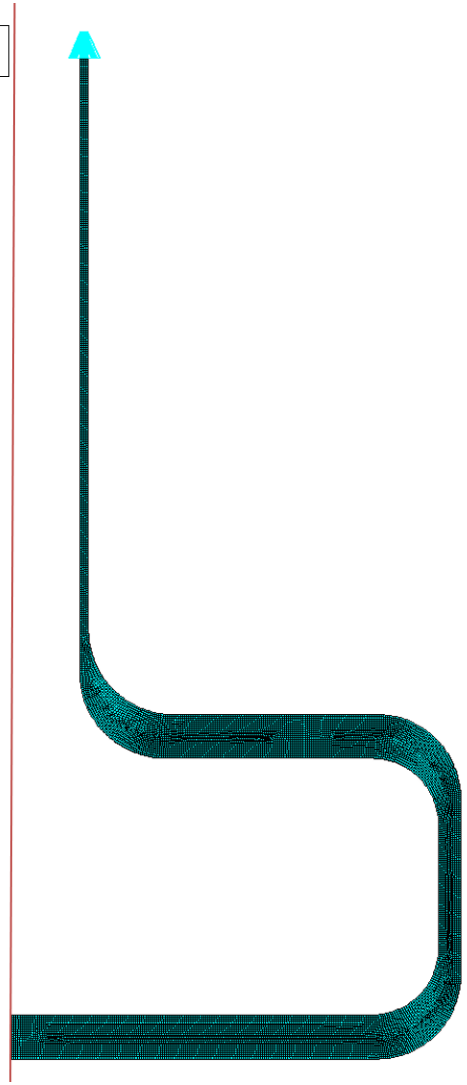



Credit: ASM Handbook 1995

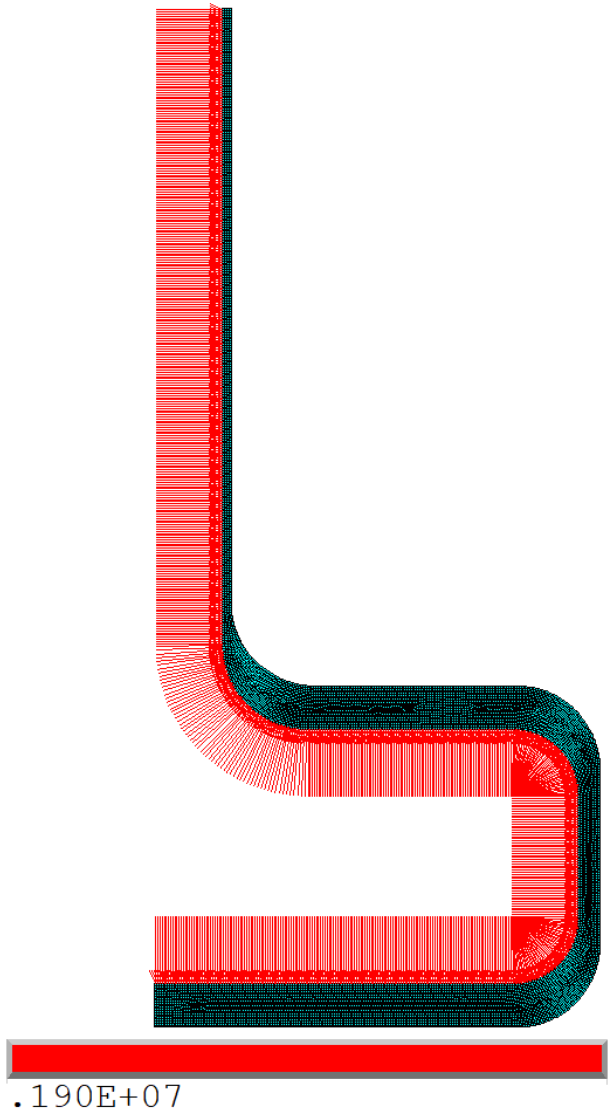
# Upper Hydrogen Vessel Mesh and Boundary Conditions




Axisymmetric Mesh

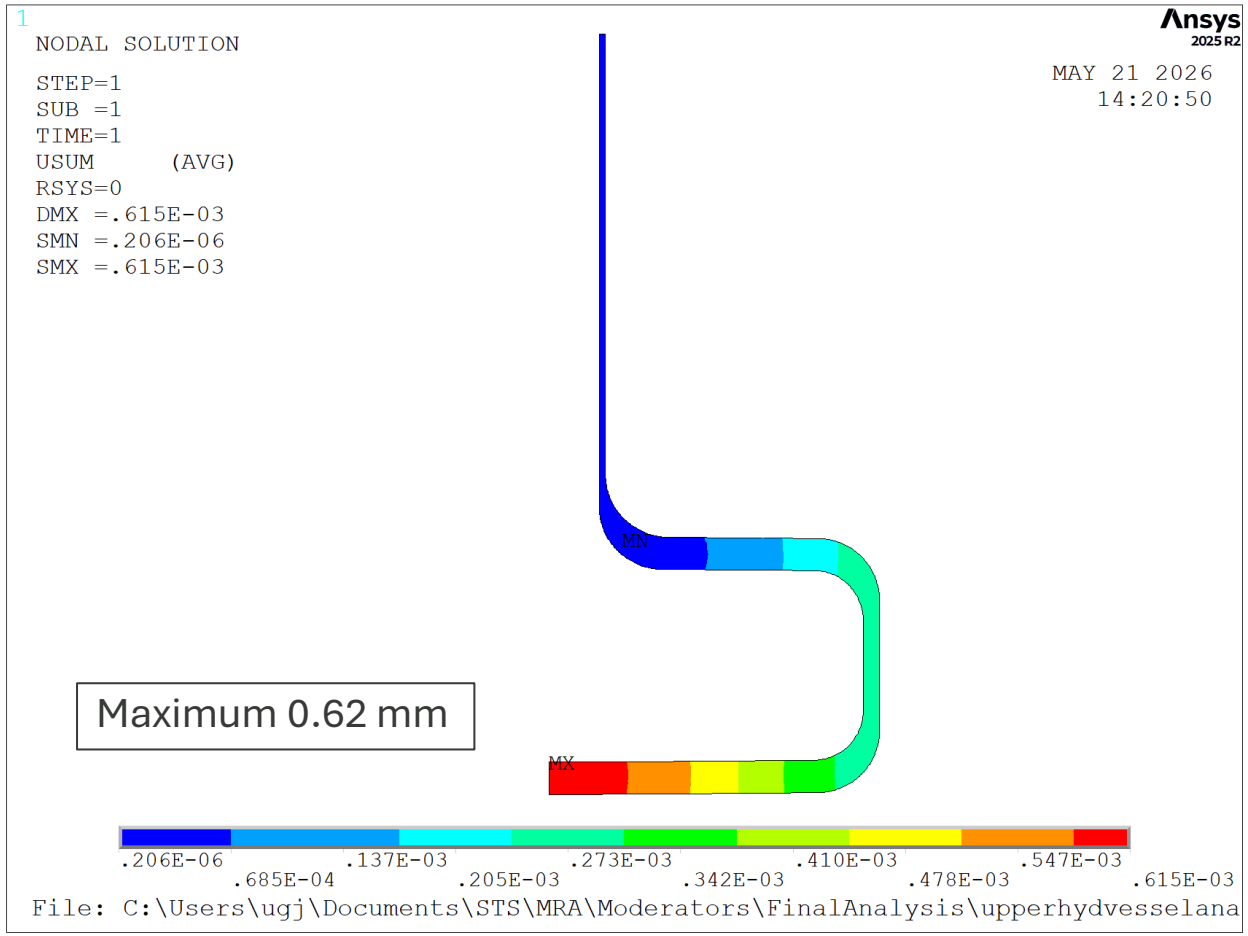



Boundary Conditions



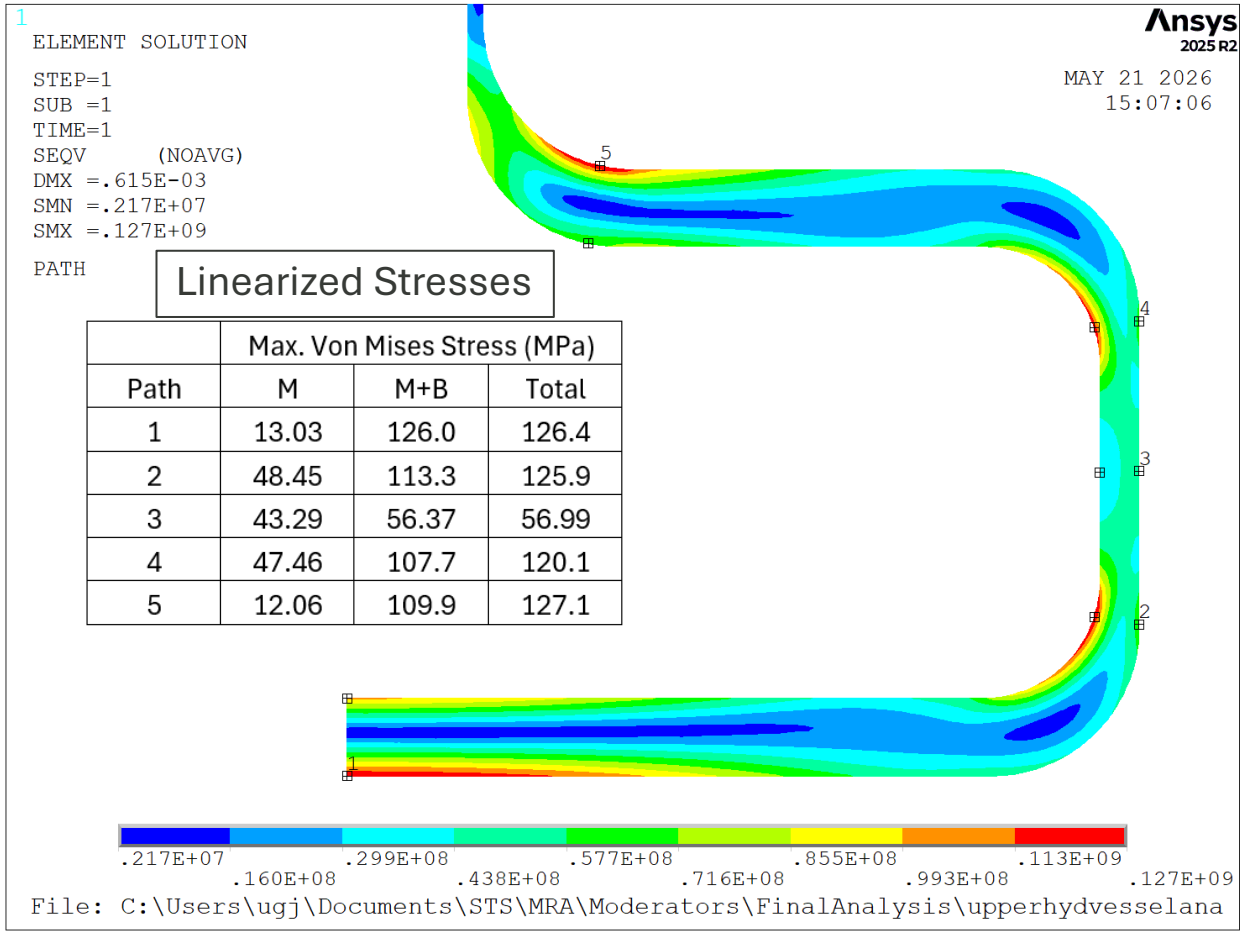

Pressure Loading

# Upper Hydrogen Vessel Deflection and Stress Results




Maximum 0.62 mm

Upper Hydrogen Vessel Deformation Contour Plot (m)

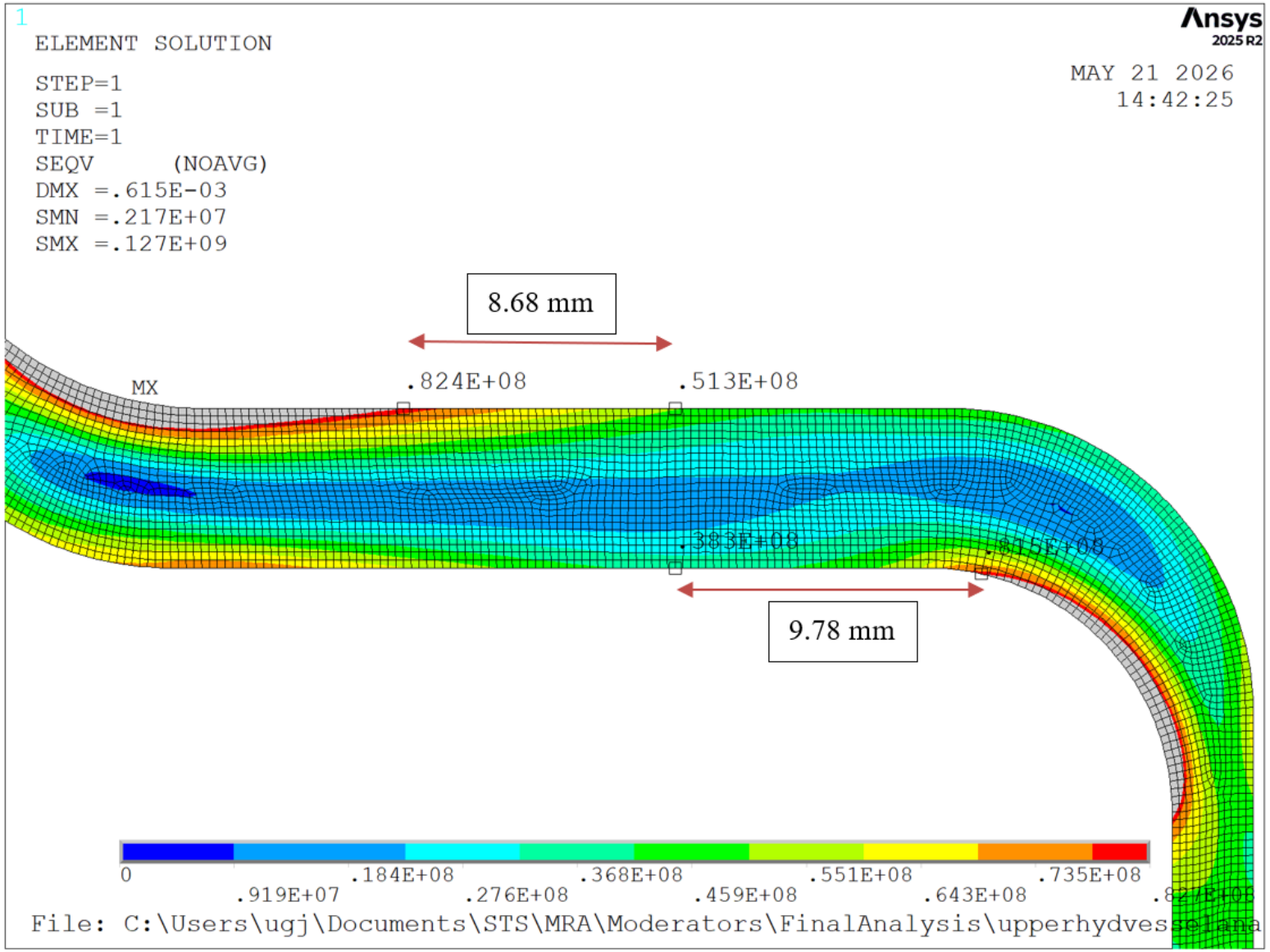



Linearized Stresses

| | 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 |

Upper Hydrogen Vessel Von Mises Stress Contour Plot (MPa)

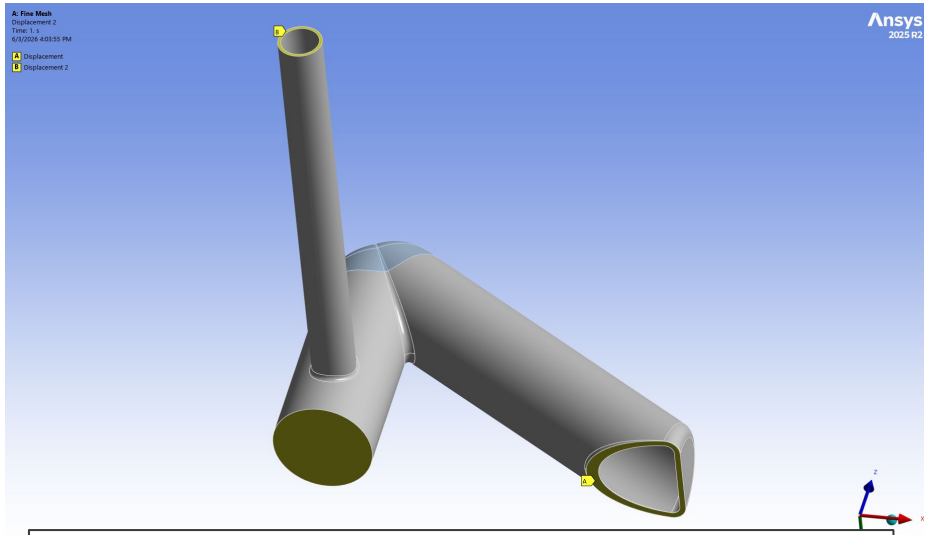
# Upper Hydrogen Vessel Weld Stress Results



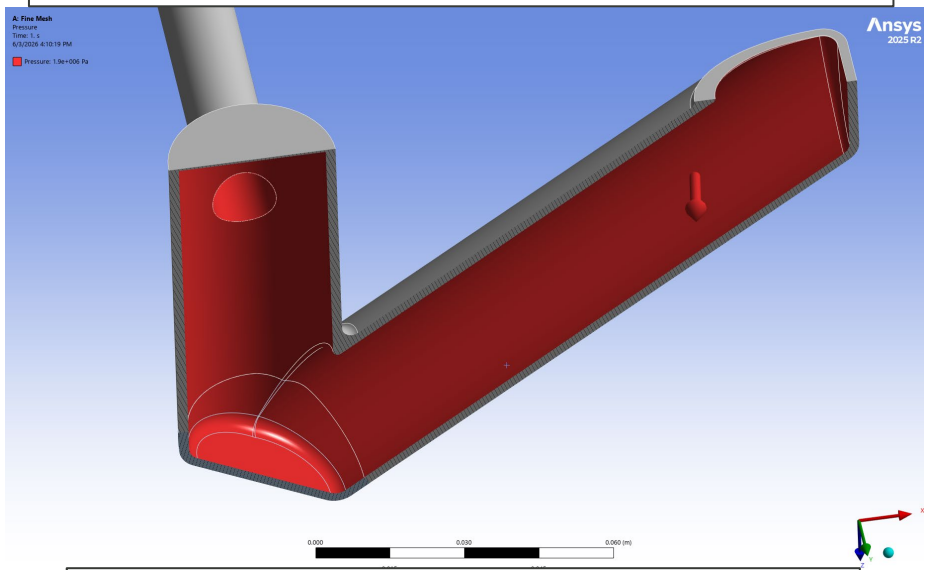

Upper Hydrogen Vessel Von Mises Stress Contour Plot Scaled to Weld M+B Allowable Stress(MPa)

# Lower Hydrogen Vessel Mesh and Boundary Conditions

Lower Hydrogen Vessel Mesh

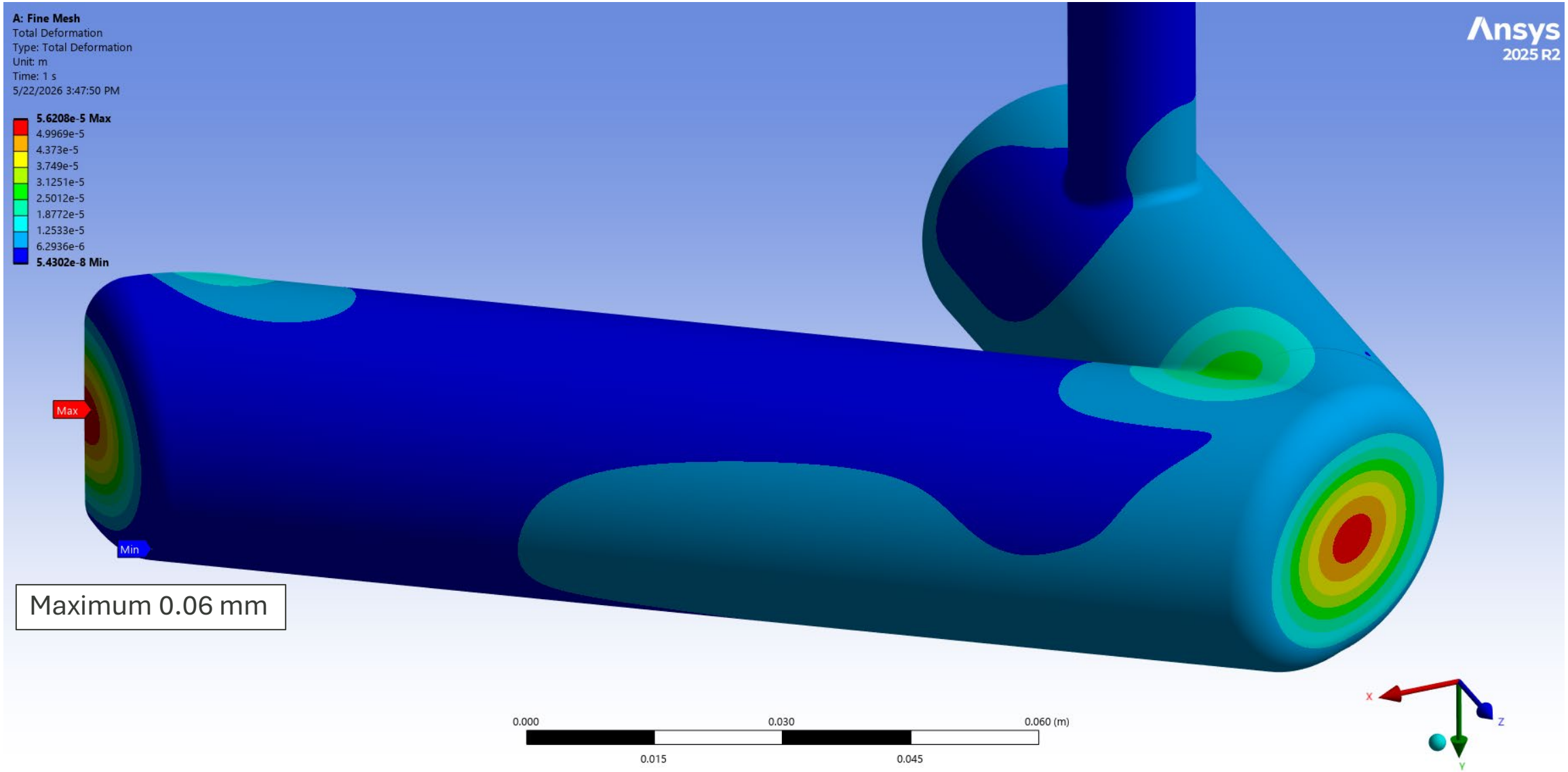



Lower Hydrogen Vessel Boundary Conditions




Lower Hydrogen Vessel Pressure Loading

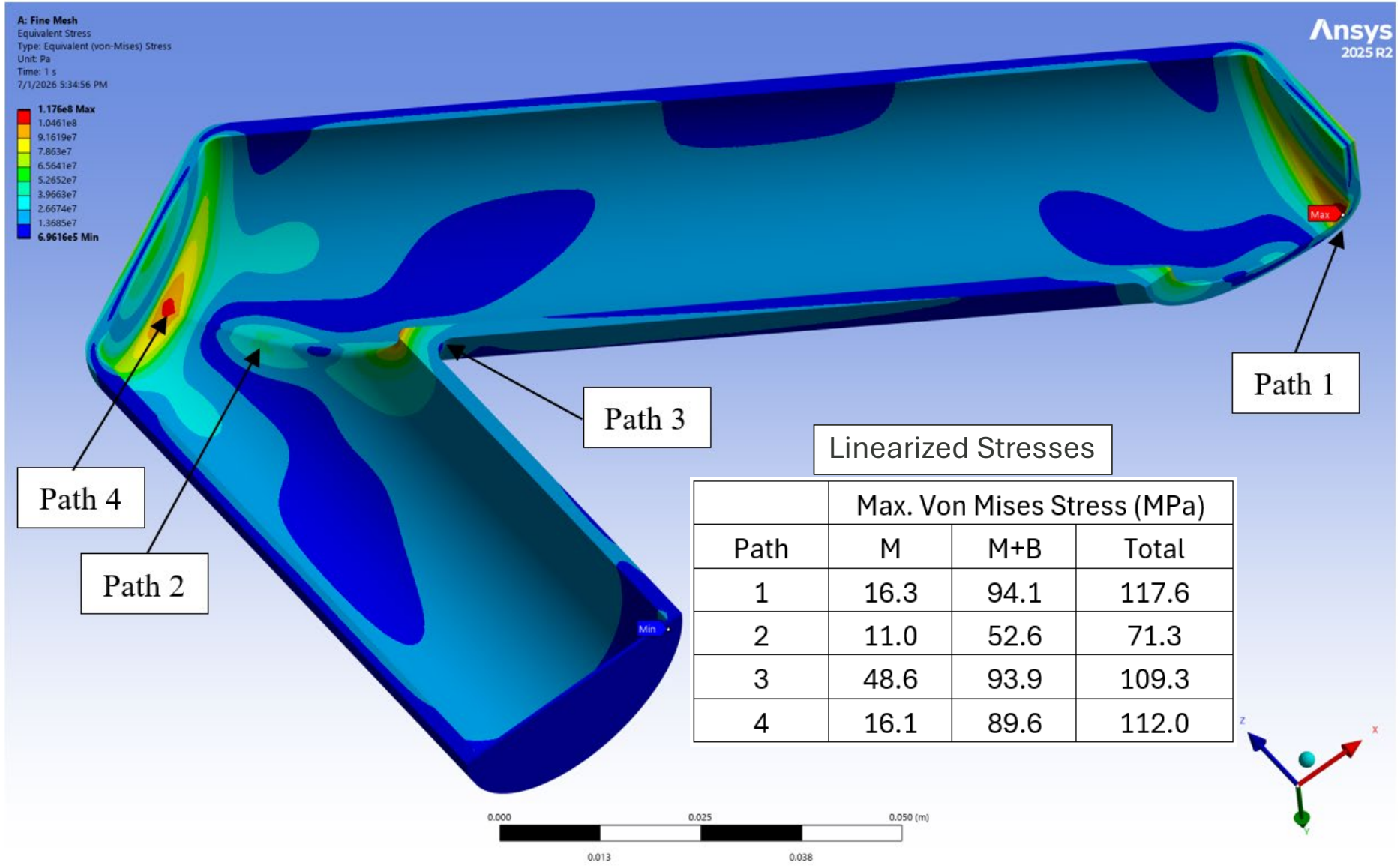
# Lower Hydrogen Vessel Deflection Results




Maximum 0.06 mm

Lower Hydrogen Vessel Deformation Contour Plot (m)

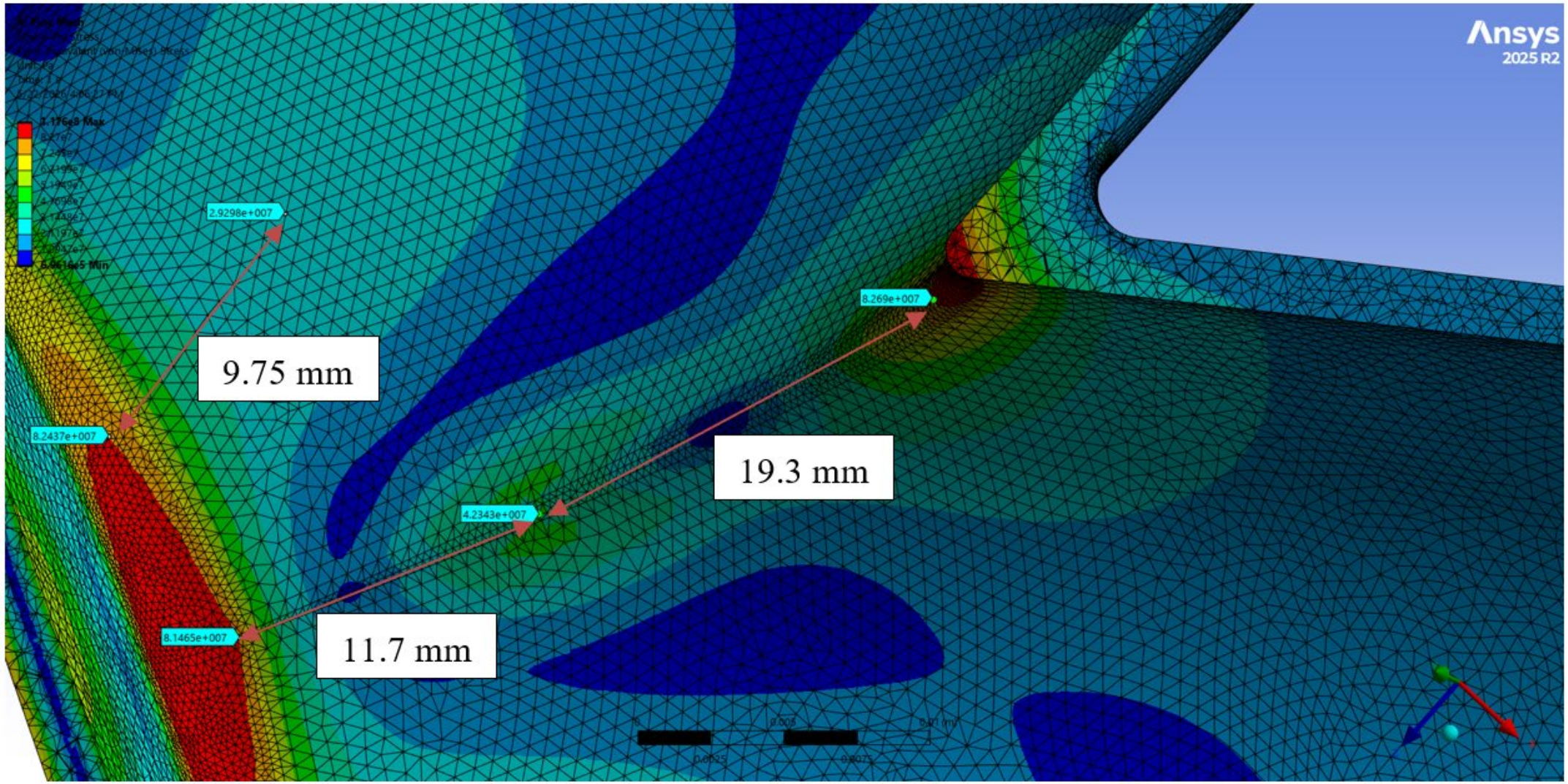
# Lower Hydrogen Vessel Stress Results




Linearized Stresses

| | 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 |

Lower Hydrogen Vessel Von Mises Stress Contour Plot (MPa)




Lower Hydrogen Vessel Von Mises Stress Contour Plot Scaled to Weld M+B Allowable Stress(MPa)

# Fatigue Screening

- Al-6061 T6 meeting the requirements for Fatigue Screening Method A
    - Yield strength of 255 Mpa is less than required 552 MPa
- 50 full pressure cycles for commissioning and 10/year during operations
    - 100 full pressure cycles over 5 year minimum lifetime
- Beam trip driven pressure cycles are less than 10.5% of MAWP
    - Pressure cycles less than 20% of MAWP are not counted in fatigue screening
- Temperature range during operation less than 28 °C
    - Temperature fatigue cycle factor is 0
- Hydrogen vessels have 100 total fatigue cycles over 5 years, which meets the requirement of less than 1000 fatigue cycles
    - Fatigue screening requirement would be met for lifetime of up to 95 years

# Conclusions

- Both hydrogen vessels meet the design requirements of ASME BPVC Section VIII, Division 2, Design by Analysis, Elastic Method for minimum required lifetime of 5 years
  - Maximum design lifetime of 95 years by Fatigue Screening Method A
  - M+B Stress in bottom center of upper hydrogen vessel is 126.0 MPa compared to allowable stress limit of 127.2 MPa

Upper Cylinder Hydrogen Vessel Results

| 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 |

Lower Tube Hydrogen Vessel Results

| 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 |

# Thank You