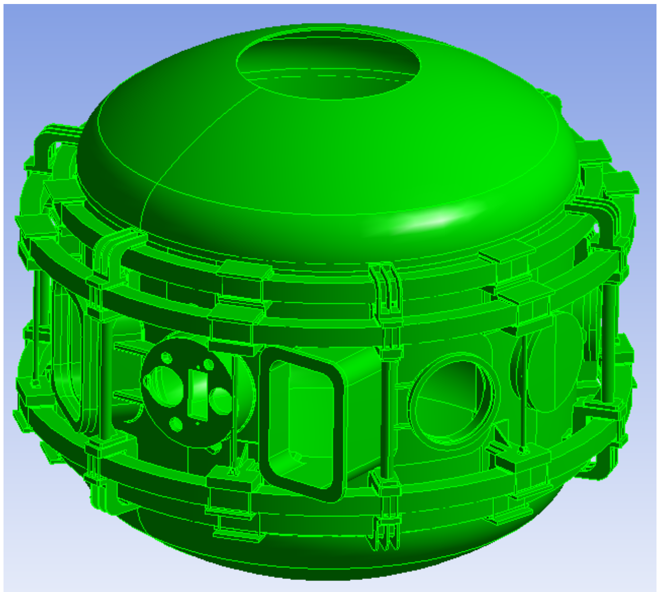
NSTX UPGRADE

Stress Analysis of the Bay L and 2nd Neutral Beam Upgrades

NSTXU-CALC-24-05-00

March 2012



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Lawrence Dudek

NSTXU-CALC-24-05-00

PPPL Calculation Form

Calculation # 24-05-00 Rev # 00 WP # 1627

Purpose of Calculation:

1. To analyze the stress on the NSTX vacuum vessel due to the vacuum pressure, the PF 4&5 Coils EM loads and the moment caused by the TFOL Coils.
2. To understand the mechanical behavior and estimate the stress in the modified vacuum vessel.
3. To validate the design of the bay L and 2nd Neutral Beam modifications.

References:

See document

Assumptions:

- The support mechanism of the NSTX Vacuum Vessel is assumed to be fixed support.
- Shape of the welds in the FEM were assumed acceptable.
- Bonded contact was assumed acceptable for welded connections.
- Coil EM loads from Maxwell based on static background fields.
- Coil current scenario 79 of the DPsheet results in the highest EM induced load inventory to the VV.
- The assumed value of vacuum pressure is 0 psi, but the actual level is 10^{-5} psi.
- The disruption load is assumed to create a 6,000 psi stress on the body of the vacuum vessel. Thus, the calculation subtracts this value from the maxumum allowable stress (shown in Table 3) and uses that as the new allowable limit.

Calculation:

Refer to the body of the report.

Conclusion:

The modified vacuum vessel meets the design criteria for the upgrades.

Inspection for fatigue cracks is required in the following locations: welds around the bay K, bay L and bay A port caps; welds around the BES diagnostics.

Cognizant Engineer's Printed Name, Signature, and Date

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Ihave reviewed this calculation and, to my proffesional satisfaction, it is properly performed and correct.

Checkers printed name, signature, and date

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Table of Contents

NSTX Upgrade Vacuum Vessel

1. Introduction

The National Spherical Torus Experiment (NSTX) is the world's highest performance ST research facility and is the centerpiece of the U.S. ST research program. Since starting operation in 1999, NSTX has established the attractiveness of the low-aspect-ratio tokomak ST concept characterized by strong intrinsic plasma and enhancing stabilizing magnetic field line curvature [1].

The NSTX is undergoing an upgrade with a cost of $94 million. As part of the upgrade a 2nd neutral beam will be added and the existing center stack will be replaced with a larger diameter. The 2nd neutral beam duct will be installed in the bay k port. This required the existing bay j, bay k and bay l ports to be redesigned.

The increased performance of the upgrade NSTX results in larger structural EM loads. Therefore, it was necessary to analyze the stress on the vacuum vessel (VV).

Stress analysis was performed at various locations of the VV and included the following: Bay K Port, Bay L Port, Beam Emission Spectroscopy (BES), Bay L FIDA, Bay F FIDA and Thomson Scattering. ANSYS Workbench Static analysis was used for calculation [2].

2. Materials

Material properties used in this calculation are shown in Table 1. Table 2 shows the actual material properties of stainless steels. Table 3 shows the maximum allowable stress and the maximum allowable bending stresses calculated based on the NSTX Criteria [3] [4].

Part Name	**Material selection**	**Yield Strength (Ksi)**	**Tensile Ultimate Strength (Ksi)**	**Young's Modulus (Ksi)**	**Density (lb in^{-3})**	**Poisson's Ratio**
PF 4 & 5 Coils	Copper Alloy	40.61	62.37	1.6E+4	0.3	0.34
All other bodies	Stainless Steel	30.02	84.99	2.8E+4	0.28	0.31

Table 1: Material properties used for calculation on Workbench

Material	Yield, 292 deg K (Ksi)	Ultimate, 292 deg K (Ksi)
316 LN SST	40 [4]	88.91 [4]
316 LN SST Weld	46.99 [4]	69.91 [4]
316 SST Sheet Annealed	39.89 [4]	86.44 [4]
316 SST Plate Annealed		83.98 [4]
304 Stainless Steel (Bar, annealed)	33.94 [4]	92.82 [4]
304 SST 50% CW	157.95 [4]	179.99 [4]

Table 2: Tensile properties of Stainless Steels

Material	Sm	1.5*Sm
316 Stainless Steel	26.7	40.03
316 Weld	23.35	34.95
304 Stainless Steel (Bar, annealed)	22.63	33.94

Table 3: Coils Structure Room Temperature (292 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield; the allowable bending stress = 1.5*Sm

3. Loading Conditions

The following loading conditions were implemented:

a) **Electromagnetic forces inside the PF 4 & 5 coils due to the current flow**: These forces are calculated for current scenario #50 using Maxwell/Ansoft. The model, which is built on Maxwell, and used to calculate the PF 4&5 loads under Scenario #50 is shown in calculation # NSTX-CALC-24-01-00 [5]. The result from Maxwell was imported to the Static Structural Analysis. The force density on the body of the PF 4&5 coils was in the range of minimum value 9.4 lbf/in^3 to a maximum value of 226.18 lbf/in^3. Refer to Figure 1.

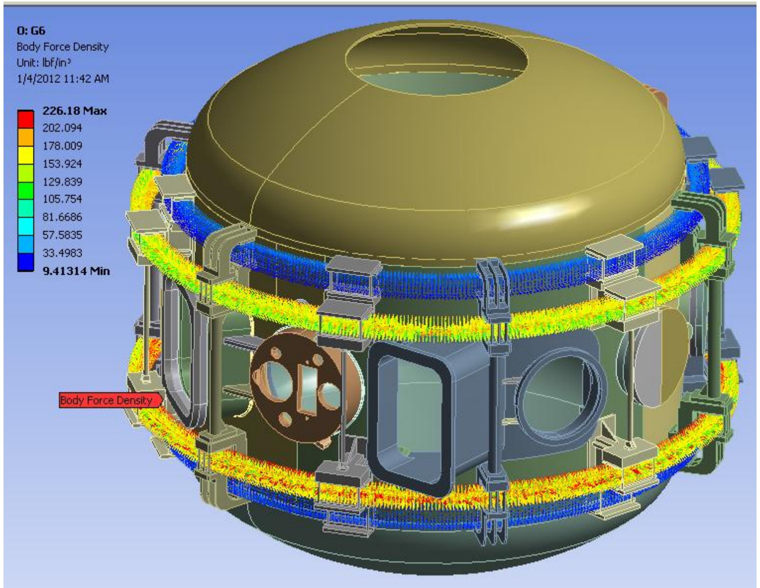


Figure 1: Electromagnetic forces in PF 4&5 Coils

b) **Vacuum Pressure**: The effect of the pressure differential between the vacuum pressure (0 psi) and the outside atmospheric pressure (14.7 psi) on the vacuum vessel has been included. Figure 2 shows the vacuum pressure applied on the vacuum vessel.

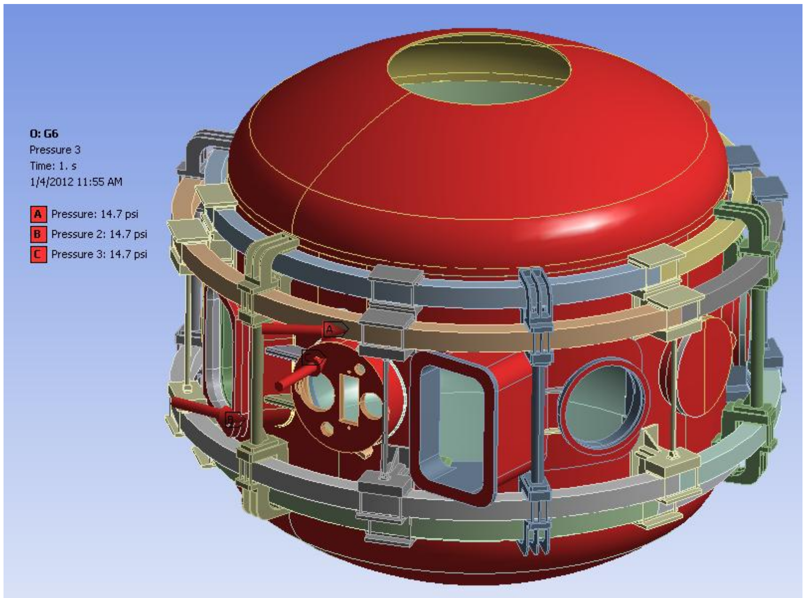


Figure 2: Vacuum pressure applied on the body of the vacuum vessel

c) **Moment**: The moment created due to the Out-of-plane (OOP) load of TF outer legs was also included in this calculation. The moment value was $3e^{+7}$ lbf-in, refer to Figure 3.

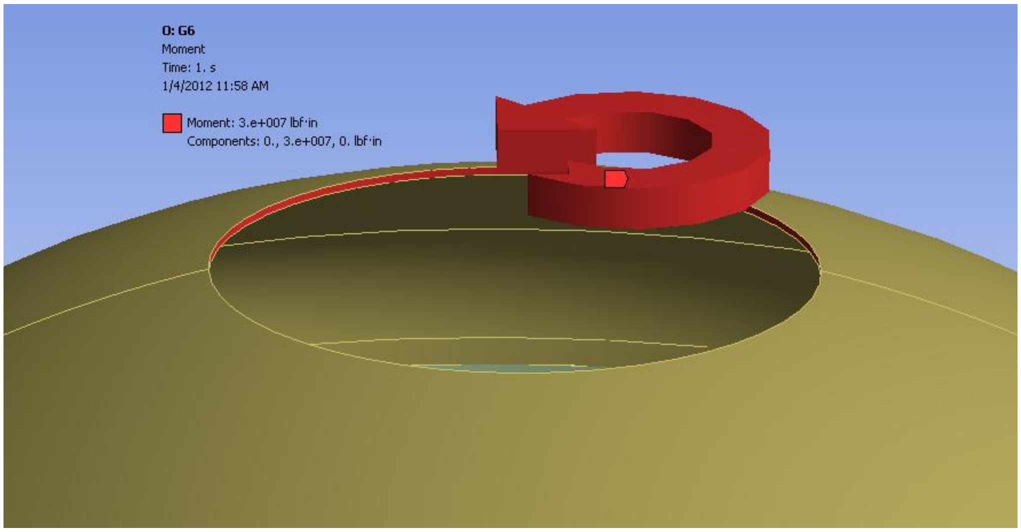


Figure 3: Moment due to the TF coils

d) **Fixed support**: The vacuum vessel was supported from the bottom. Refer to Figure 4.

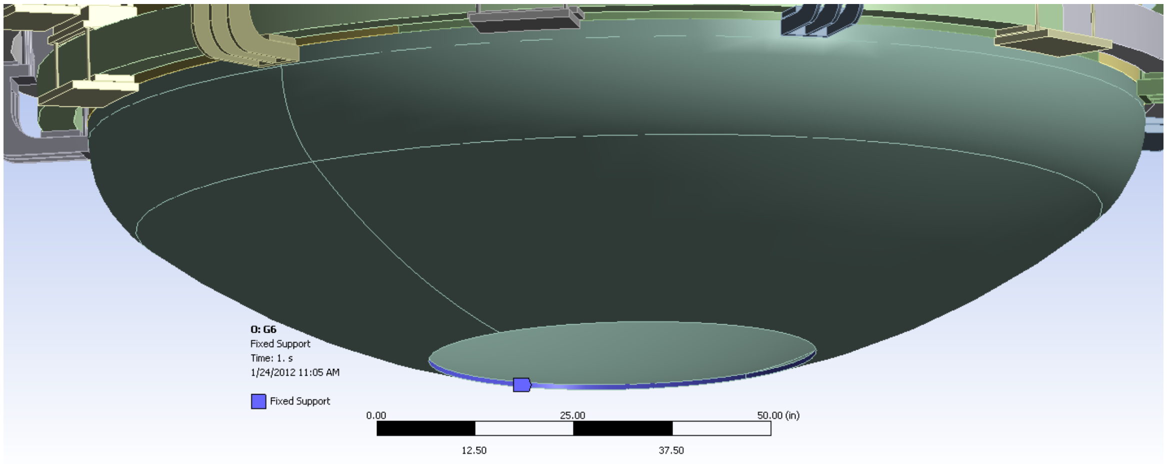


Figure 4: Fixed support applied to the lower dome

4. Geometry

Several iterations were performed by adding design modifications to improve the stress level of the vacuum vessel and other components. Most of the design changes were made in the Bay K and Bay L areas. This calculation presents only the final improved results. Figure 5 shows the final geometry used for analyses and Figure 6 shows the reinforcements.

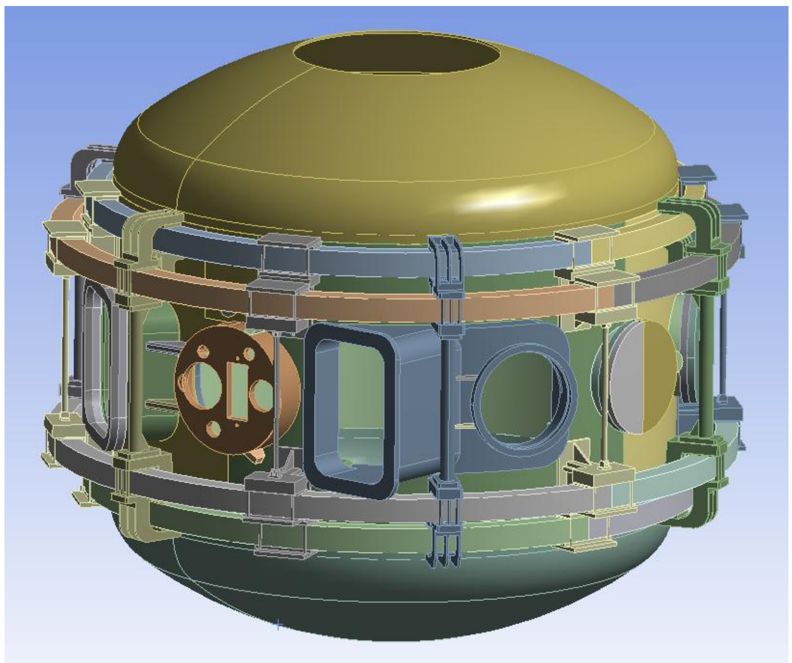


Figure 5: Global model of the NSTX Vacuum Vessel, PF 4&5 Coils and supports

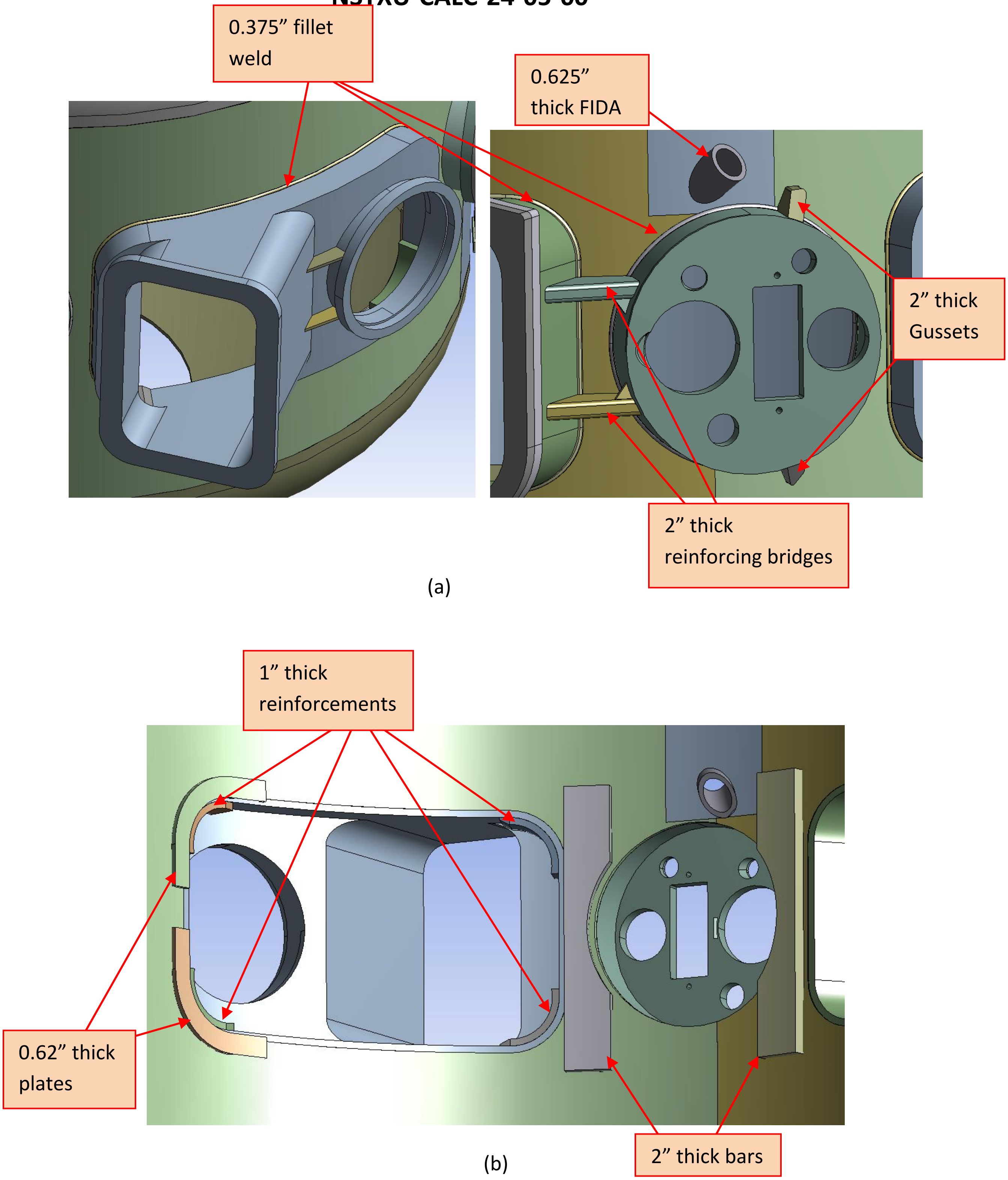


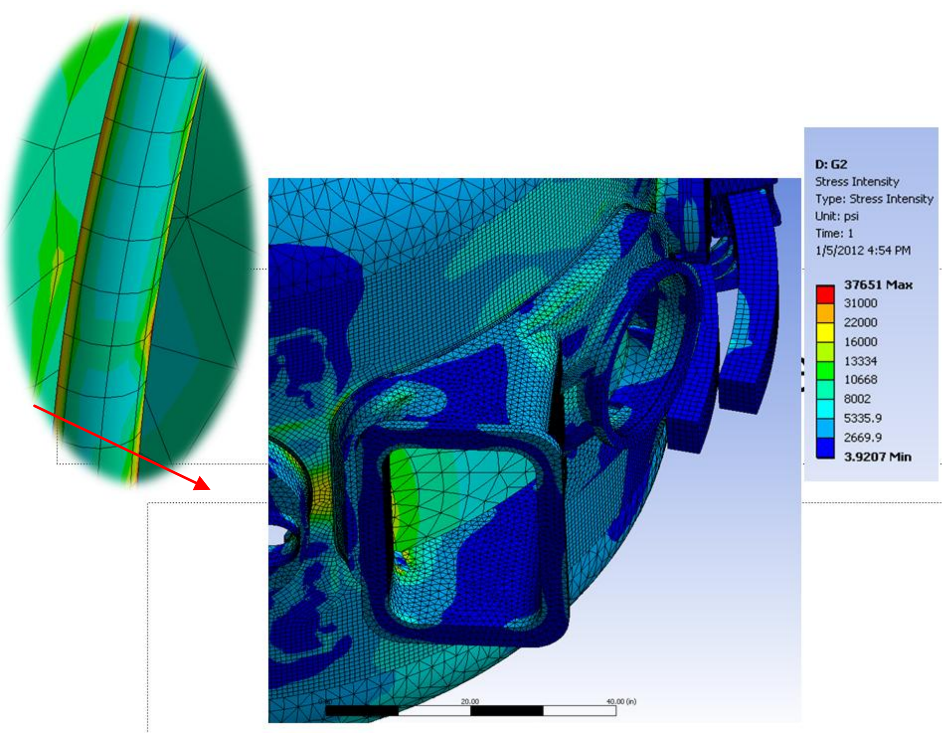
Figure 6: Reinforcements added: (a) on the outer body of the vessel; (b) inside the vacuum vessel

5. Results

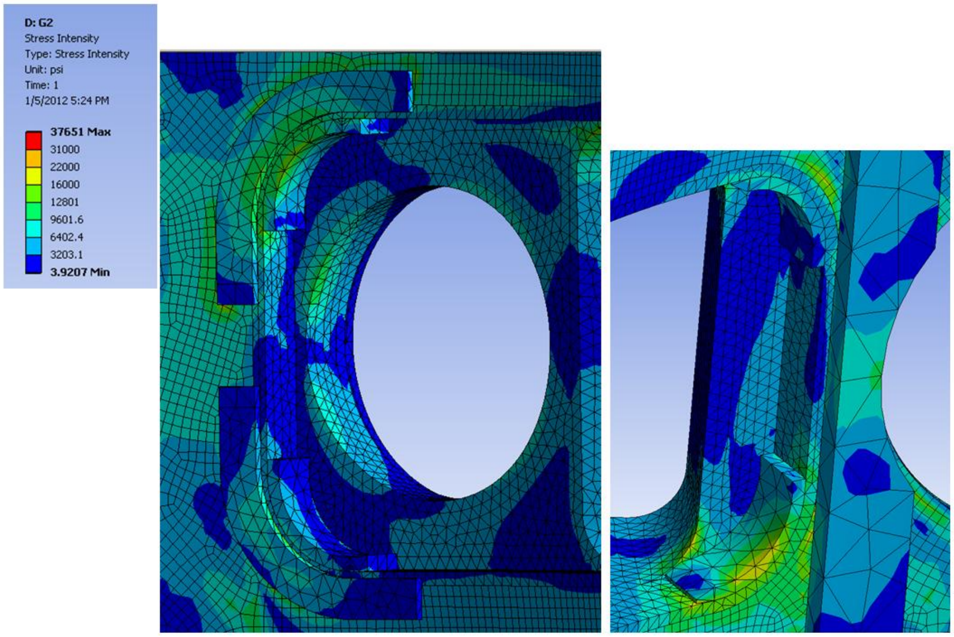
Multiple analyses, both global and sub-model, were performed on the vacuum vessel. The reinforcements added to the original model improved the stress level by a significant amount. This calculation discusses the final and improved results in the various locations where the initial analysis result showed high stress concentrations.

5.1. Bay K Port

Results from the global analysis showed high stress along the sharp edges of the fillet welds. All other parts of the port were under the allowable stress limit (22 Ksi). The global analysis result is shown in Figure 7. A sub-modeling of the Bay K Port was also analyzed. On-the sub-model: the shape of the fillet weld was improved to provide a more realistic shape; a finer element size and node to node connections were used. The sub-modeling results showed that stress on all areas of the port, including the weld, is below the allowable limit (see Figure 8 for details).

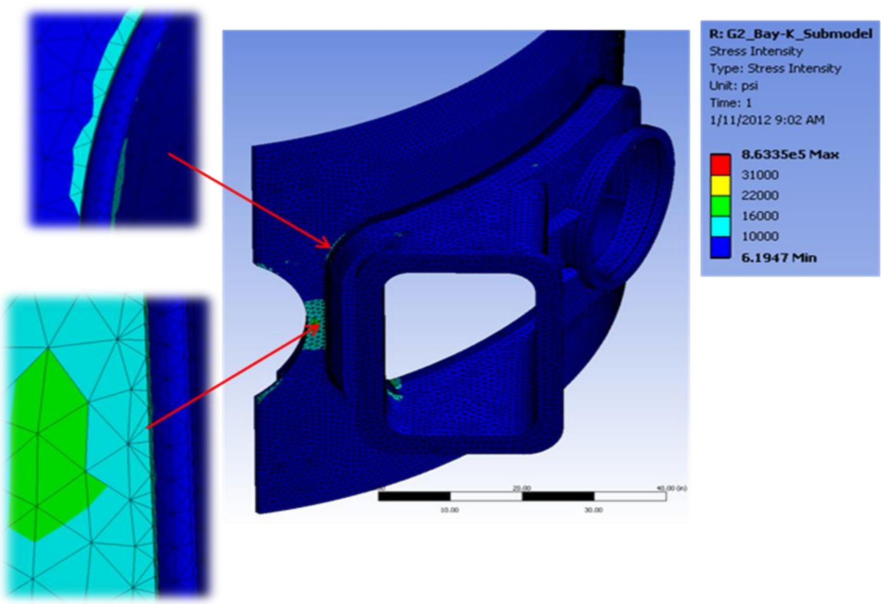


(a)

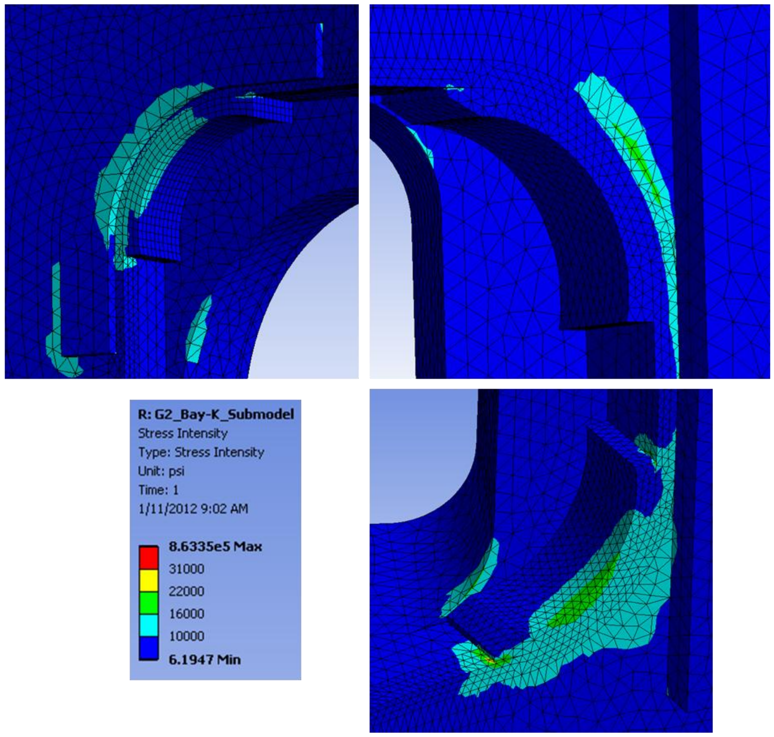


(b)

Figure 7: Global stress results around Bay K port: (a) view from outside; (b) view from inside the vacuum vessel



(a)



(b)

Figure 8: Sub-modeling stress results around Bay K Port: (a) view from outside the vessel; (b) view from inside the vacuum vessel

5.2. Bay L Port

As shown if Figure 9, the global analyses results show high stresses in areas of the Bay L Port, especially around the weld. The sub-model of the Bay L port was prepared by incorporating better geometry for the fillet welds, node to node connections and finer mesh element sizes. As shown in Figure 10, the sub-modeling results showed that the stress on the body of Bay L port is below the allowable (22 ksi).

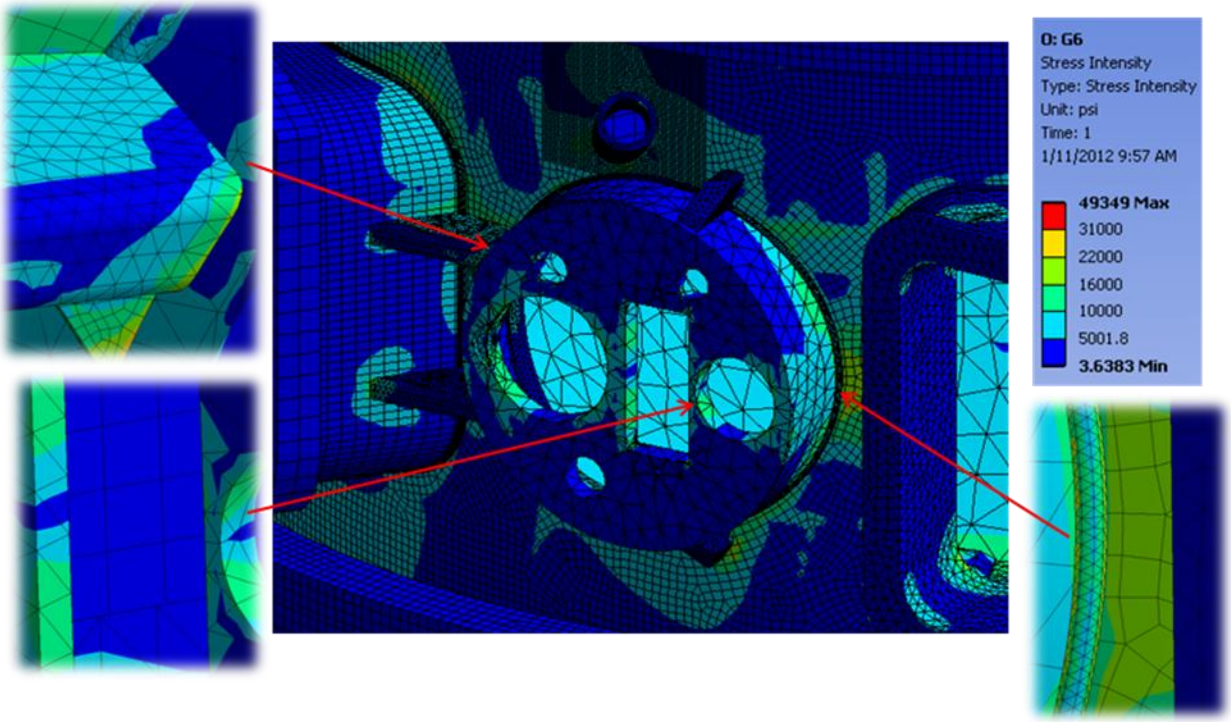


Figure 9: Global stress analysis results near Bay L Port

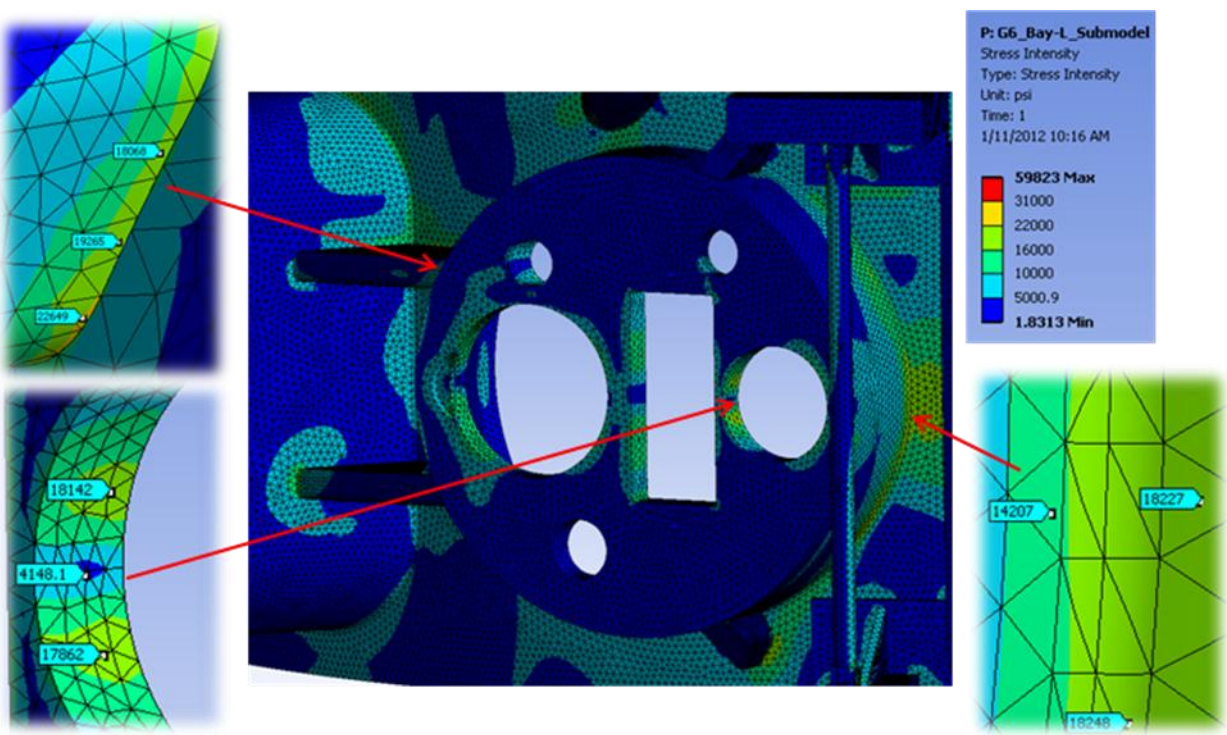
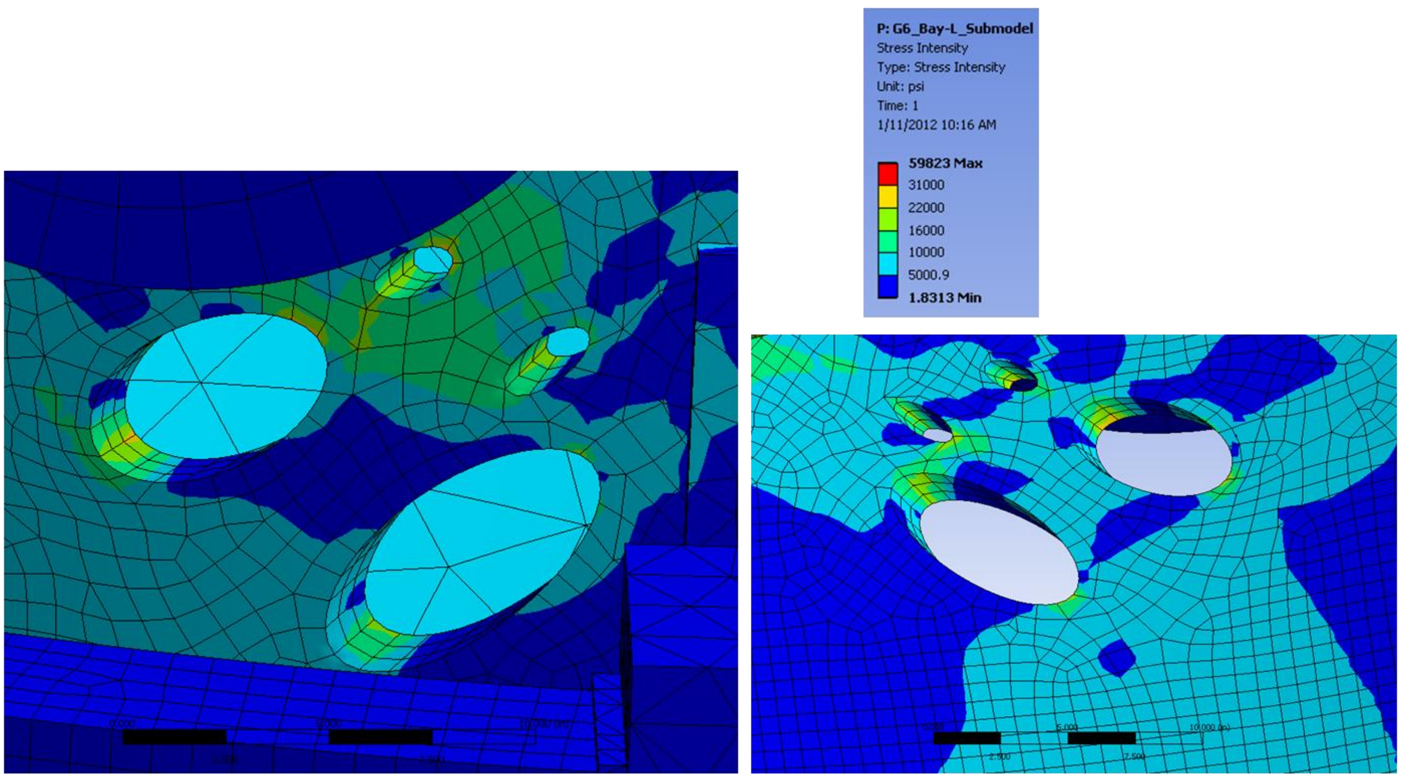


Figure 10: Sub-modeling analysis results near Bay L Port

5.3. Beam Emission Spectroscopy (BES)

The BES diagnostic is located between Bay A and Bay B near to the lower dome. VV penetrations for this diagnostic are installed elliptical. For a very conservative perspective, stress analysis on the vessel was performed by cutting out the tubes. In reality, the existence of the tubes would provide more stiffness. The stress result, as shown in Figure 11, is below the yield limit; but it is above the allowable limit (22 ksi). The stress results for these holes are accepted considering that the actual result would be lower if the tubes were installed. But periodic (may be once a year) inspection will be required.



(a) (b)

Figure 11: Stress results for BES diagnostics holes: (a) view from outside; (b) view from inside the vacuum vessel

5.4. Bay L FIDA

Analysis revealed stresses exceeding the design limits on the FIDA Tube near bay L. Design and analysis iterations were performed. The final design was improved by removing and replacing the existing tube with a thicker tube, 5.03” OD and 0.625” thick. Full penetration welds will be used to join the new tube to the vessel. The stress on the new FIDA tube, as shown in the Figure 12, is in the allowable limit.

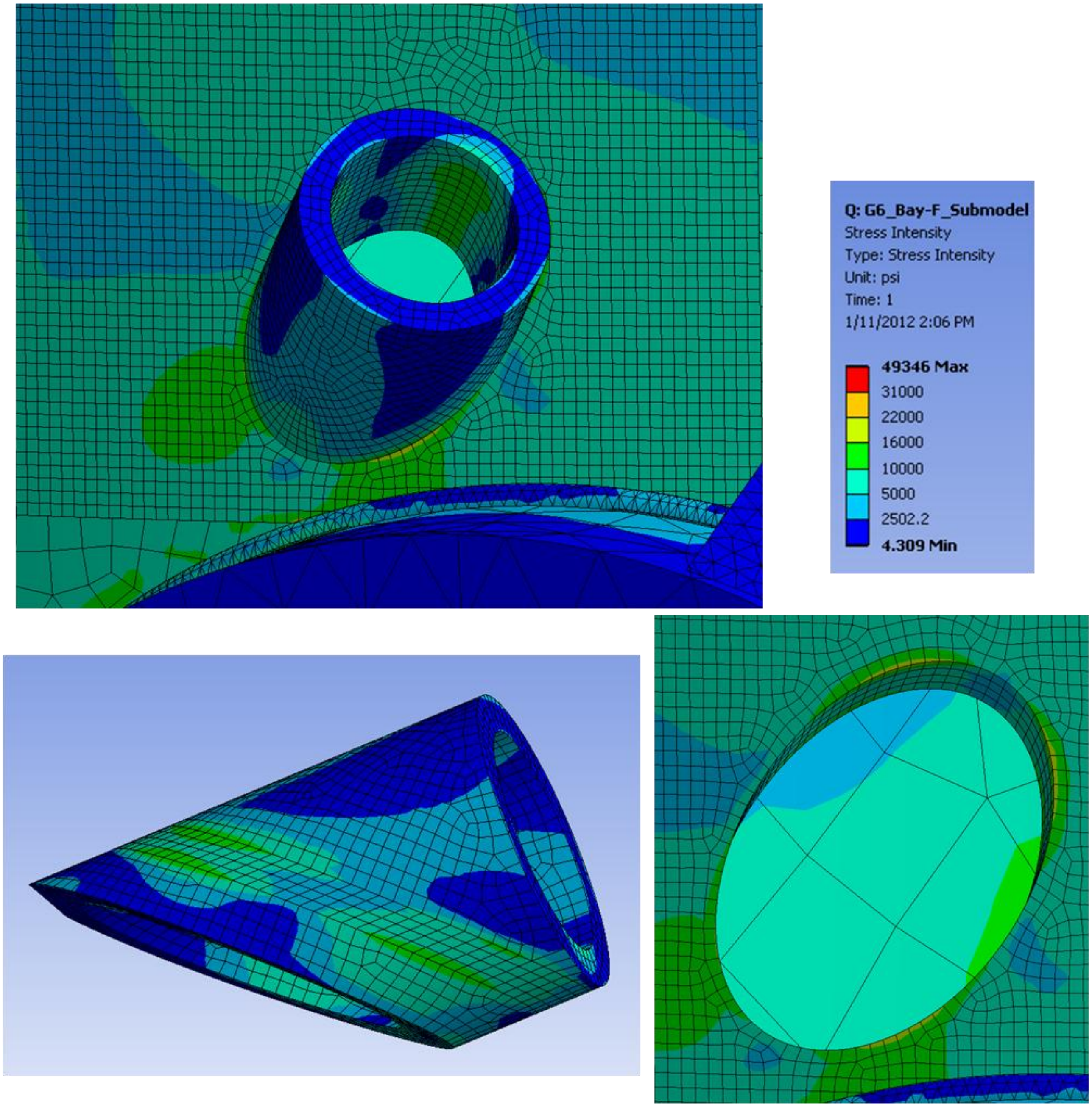


Figure 12: Stress results of the FIDA tube near Bay L

5.5. Bay F FIDA

This FIDA is located above the Bay F port close to Bay G. Analyses result, as shown in Figure 13, confirmed that the elliptical penetration is OK.

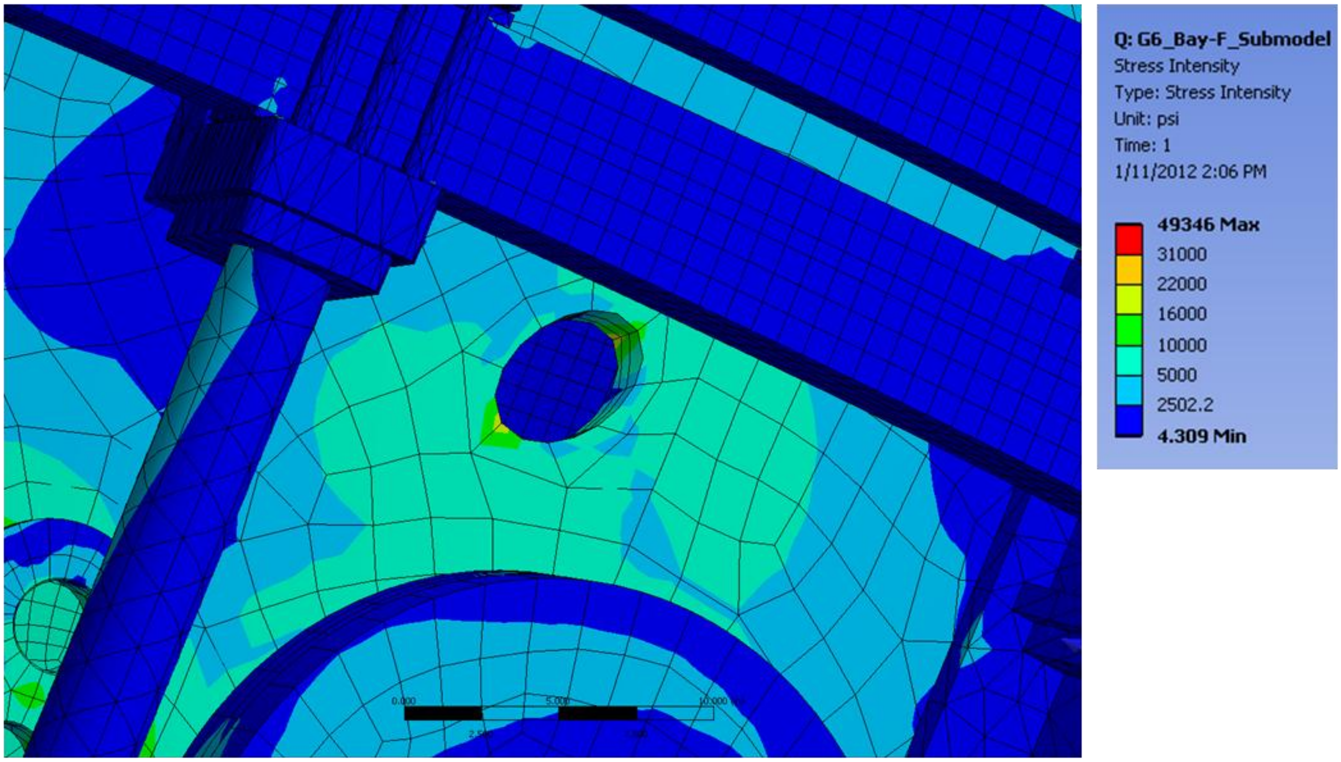


Figure 13: Stress results of the FIDA tube near Bay F

5.6. Thomson Scattering

This diagnostic is installed between Bay F and Bay G, in the mid-plane region. The stress in this region is also acceptable (see Figure 14).

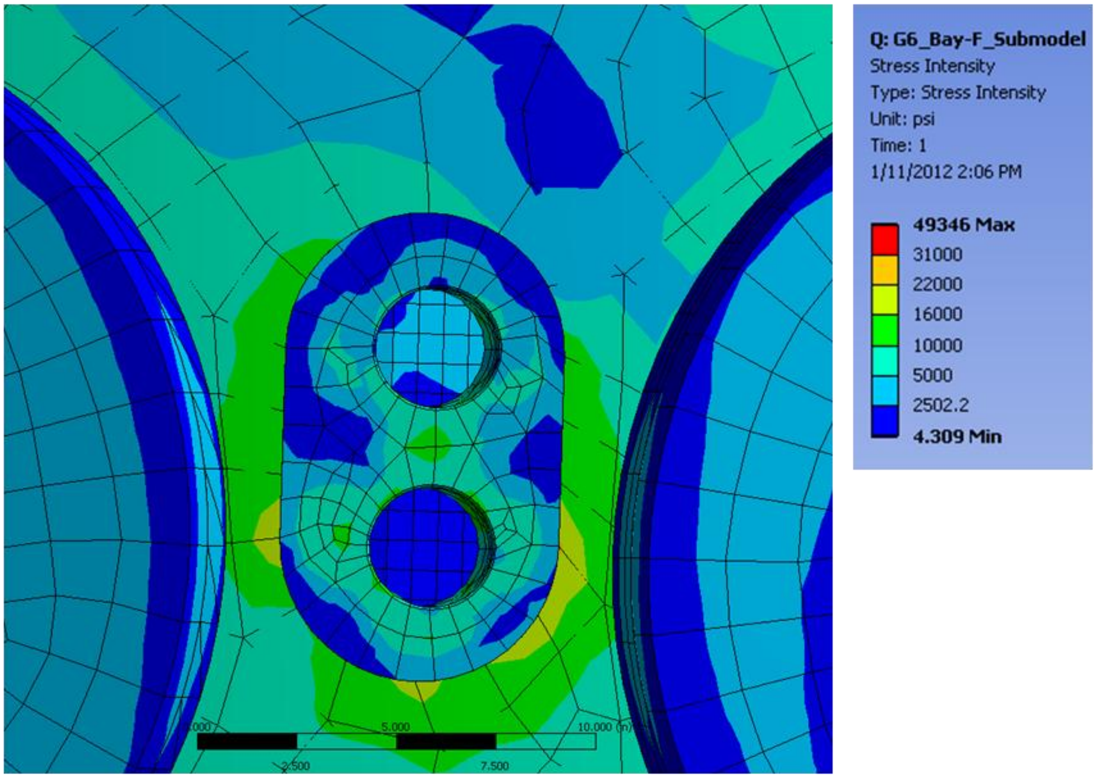


Figure 14: Stress results of the Thomson Scattering, between Bay F and Bay G

6. Conclusion

- The stress intensity on the vacuum vessel caused due to the three forces (Vacuum Pressure, TF Coils and PF 4&5 Coils Current) was analyzed.
- The reinforcements added to the bay k and bay l ports reduced the stress level to below the allowable limits.
- Using a larger and thicker tube, the stress on the FIDA tube near bay k was improved.
- VV stress under the given load conditions is acceptable.

7. Recommendation: Fatigue Inspection

- The welds around Bay-K, Bay-L and Bay-A ports should be inspected, at least, every year during the long maintenance period.
- Once a year inspection is also required on the welds around the BES diagnostics.

References

1. GRD (http://nstx-upgrade.pppl.gov/Engineering/Overall_Project_Information/GRD/NBI_Rev0/NSTX_2nd_NB_GRD-R0.pdf)
2. Ansys Work Bench (http://www.ansys.com/Products/Simulation+Technology/Structural+Mechanics)
3. PF4 and PF5 Support Analysis, NSTXU-CALC-12-05-00 (http://nstx-upgrade.pppl.gov/Engineering/Calculations/1_Torus_Systems/1_2_VV/CALC-12-005/NSTXU-CALC-12-05-00-signed.pdf)
4. Design Point Spreadsheet (DPsheet), NSTX-CALC-10-03-00
5. Maxwell Results, NSTX-CALC-24-01-00
6. Design criteria document, NSTX-CRIT-0001-01

Appendix 1

The Displacement of the NSTX Vacuum Vessel

June 28, 2012

Prepared By:

Han Zhang

Comparison of Neway's result and Han Zhang's

When I conducted TF outer leg analysis, I had the vessel model included. To compare with Neway's result, I extracted the vessel model and applied the same torque as his. In his model, he has the load from PF4 and 5, and vacuum pressure which I don't have and too hard to add them to my model. So I remove these loads in his workbench model, also increase the torque he used from 3E7 lbf-in to 3.2E7 lbf-in which is same as mine, and re-run it. My previous model has outer TF load (radial, toroidal and vertical) and clevis load (radial, toroidal and vertical). Figures 2-4 compare the results from these three models.

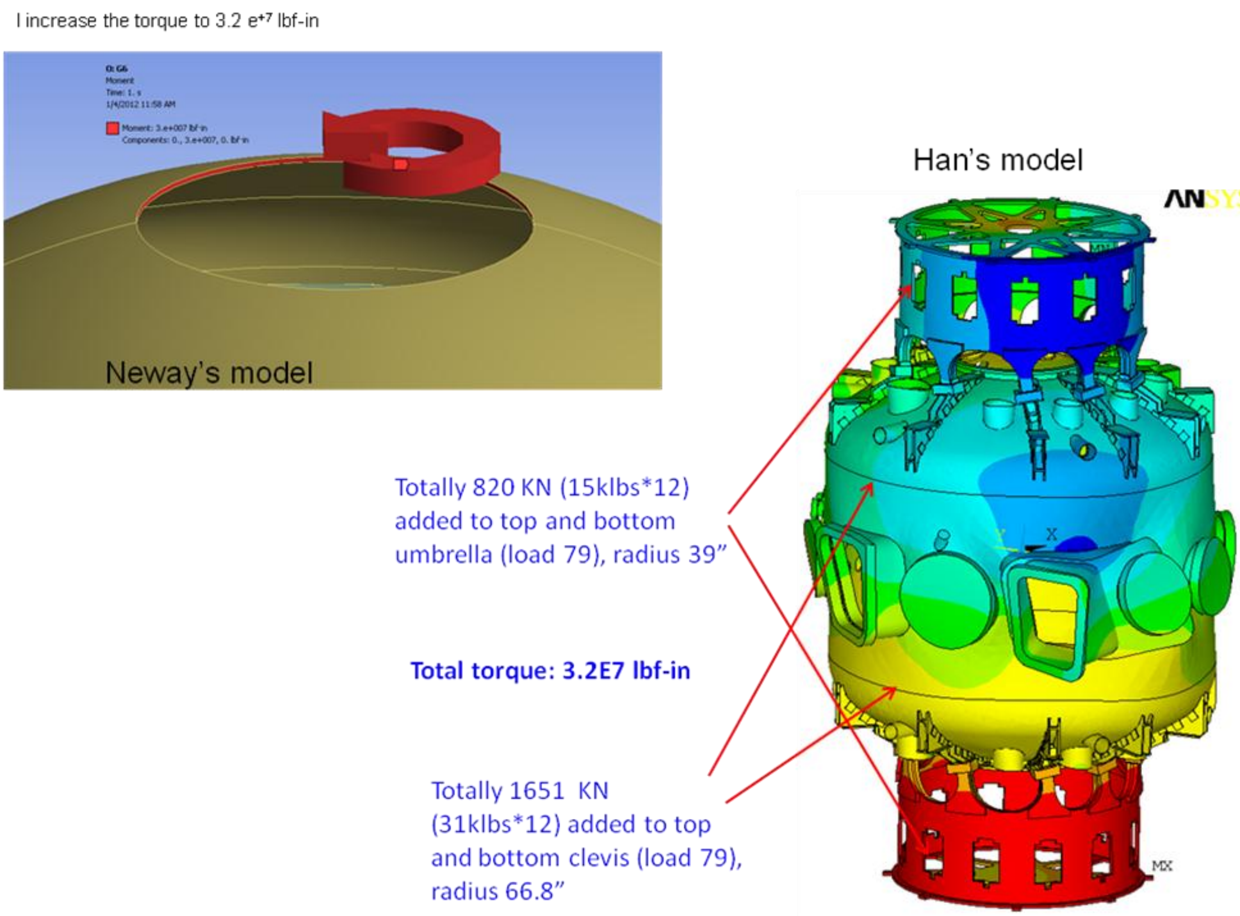


Figure 1: Neway's model and mine.

Neway's model has all the latest reinforcement but my model has only some of them. According to NSTXU-CALC-24-05-00 Fig. 6(a), the 2" thick reinforcing bridges and 2" thick gussets are missing in my model. And same document Fig. 6(b), the 0.62" thick plates, 1" thick reinforcements and one of the 2" thick bars are missing in my model. Some ports, e.g. BES diagnostics holes and Thomson scattering, are missing in my model. In Neway's model, he fixed the bottom of the vessel. But my model has the four supporting legs and thus the bottom is not fixed. When comparing the vessel displacement, only the difference between max and min is calculated and compared with Neway's.

Comparing vessel displacement results, Neway's model has less radial displacement, 1mm, than mine, 2.4mm (Figure 2). Theta (or circumferential) displacements are similar, all within 2.2~2.6mm (Figure 3). In his model, left side of 2^{nd} NBI port have lower stress than mine probably because he added the new reinforcement bars but I didn't. With pure torque applied to vessel, stress intensity at the right side of 2^{nd} NBI port is 21% higher in my model, 165MPa (membrane 150MPa), than Neway's, 130 MPa (Figure 4). With outer TF and clevis load, I got 200MPa (membrane 190 MPa) in my previous model. According to NSTXU-CALC-24-05-00, the allowable of ss 316 is 26.7 ksi, i.e 184 MPa. Stress in my model is just the upper limit of the allowable.

Peter Titus has his own vessel model. In his model, vessel displacement is similar to mine, but both a little higher than Neway's result in radial direction. It is probably because Neway's model has much more reinforcement than ours, but I am not sure about this. Also we are wondering if the vessel displacement is within calculation benchmark or DCPS input.

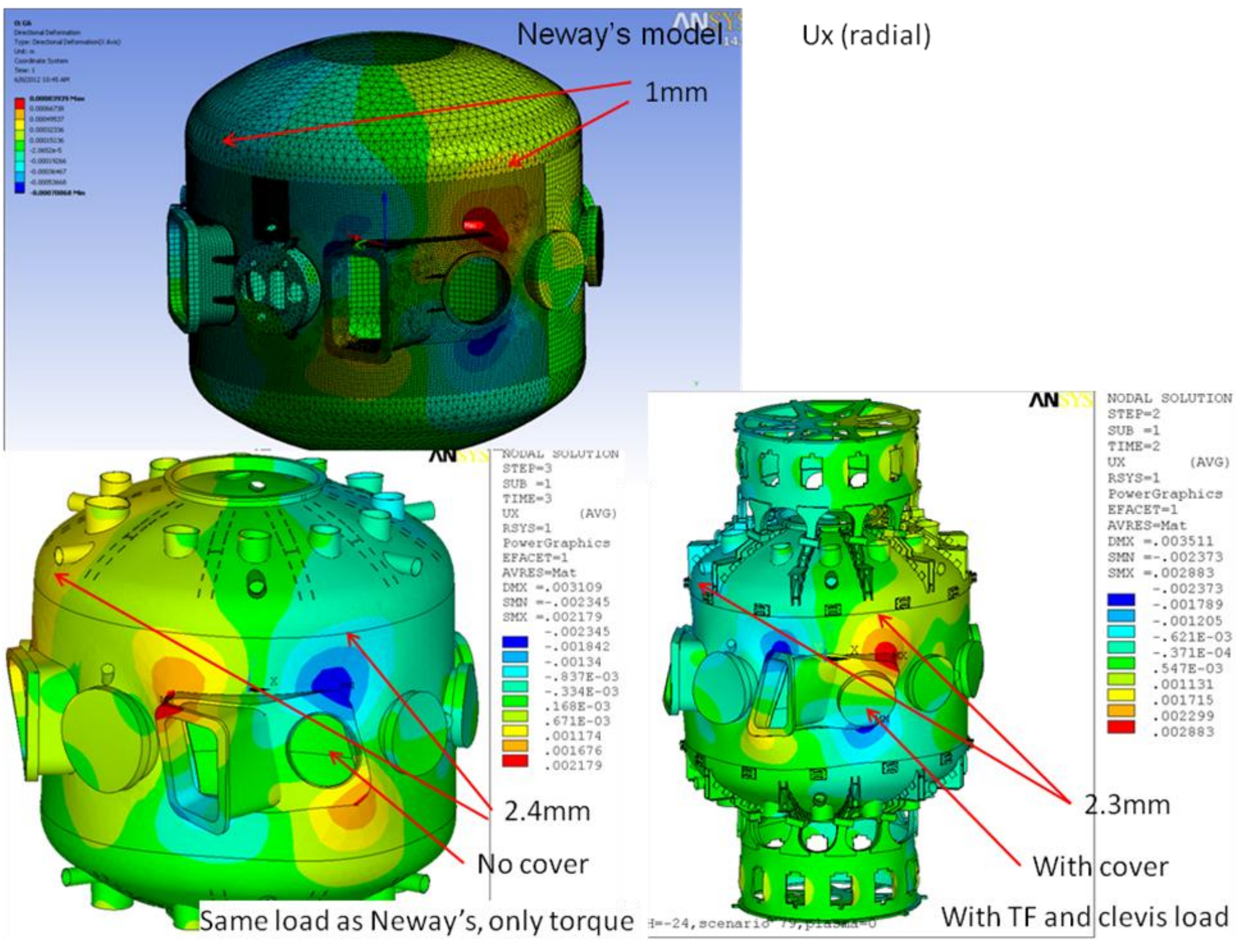


Figure 2: vessel displacement in radial direction.

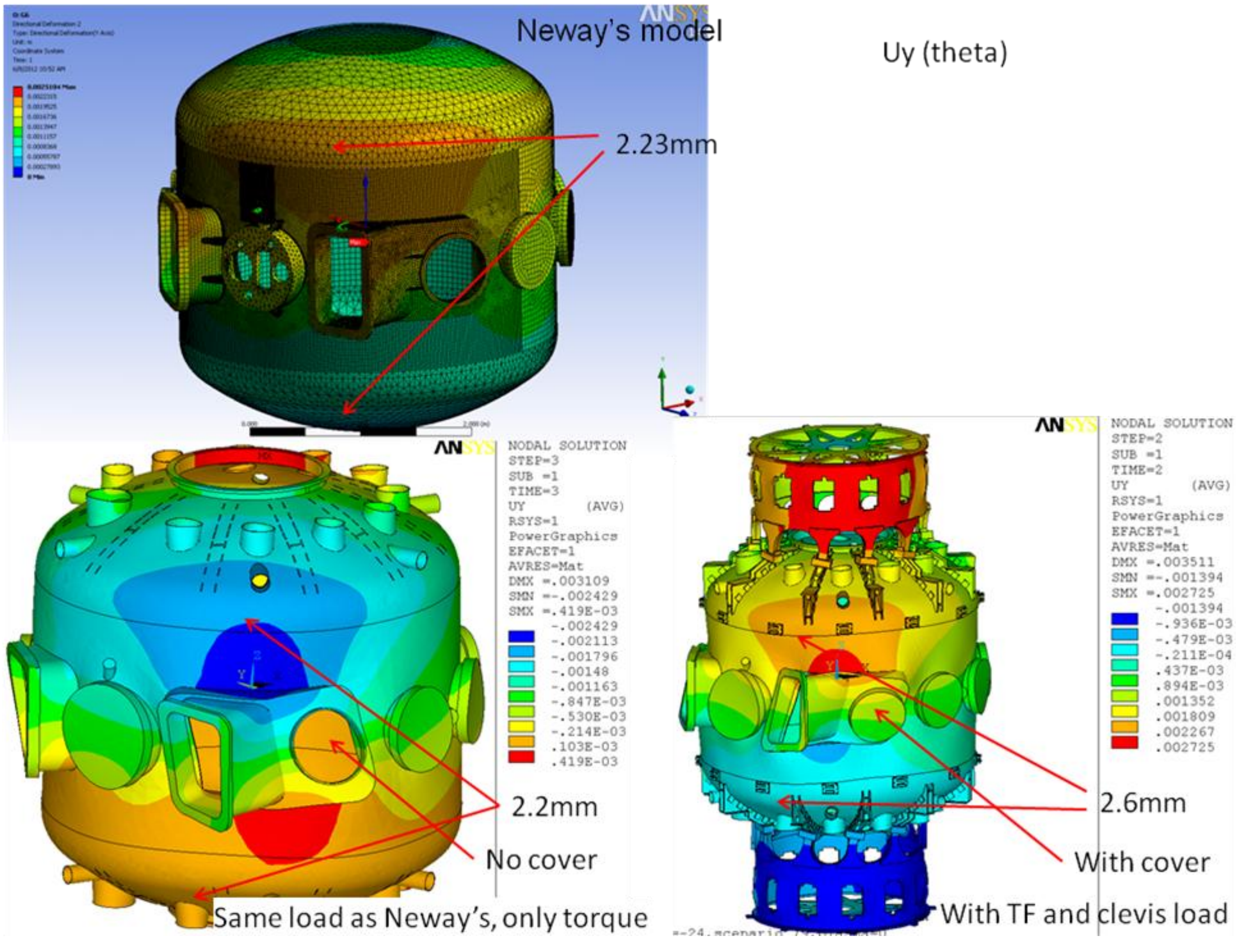


Figure 3: vessel displacement in circumferential direction.

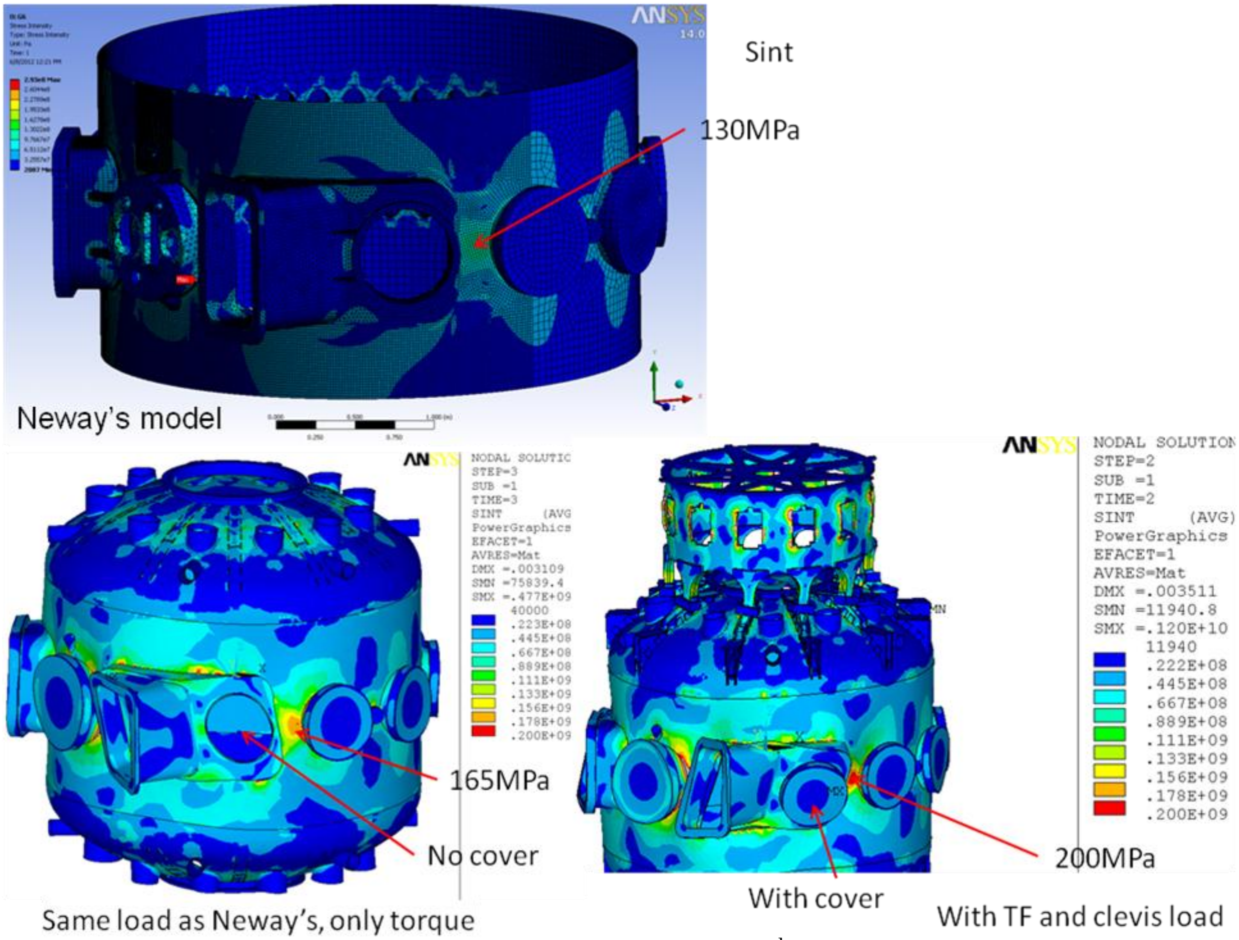


Figure 4: stress intensity around 2nd NBI port.