NSTX

Analysis of Secondary Passive Plate with Diagnostic Cutouts

NSTX-CALC-12-11-00

May 07, 2013

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PPPL Calculation Form

Calculation # **NSTXU-CALC-12-11** Revision # **00** WP #, if any **1511** (ENG-032)

Purpose of Calculation: (Define why the calculation is being performed.)

There are a few secondary passive plates with diagnostic cutouts. For the NSTX-U, due to the plasma performance increase, impact of these cutouts to the plate need to be evaluated. The purpose of this calculation is to perform disruption analysis for the secondary passive plate with diagnostic cutout to ensure stress level due to disruption forces on the plate and brazing joint interface between main body of the plate and the cylindrical cutout piece for diagnostics is within design allowable; and to add support gasket on the back of the joint interface to reduce bending stress due to disruption forces to ensure the plate cutout section is adequately supported for the upgrade.

The secondary passive plates with diagnostic cutouts are located in Bay-A, Bays F and B (see pictures in Summary). The analysis is focused on Bay-A secondary plate since it has the biggest cutout right in the middle of the plate. The plate at Bays F and B has a size of about one tile cutout, roughly a small fraction of the Bay-A cutout size. In addition, the Bay F and B cutouts are located at the bottom corner of the plate, where smaller eddy current during disruption is expected (as compare to upper part of the secondary plate). There is no brazing for the Bays F and B plates with cutouts. The situation for Bays F and B cutouts is then much less of a concern than Bay-A cutout, which is right in the middle of the plate and more than 1/3 of the plate was cut with a curved piece of the plate braze joining the two sides of the secondary plate.

References (List any source of design information including computer program titles and revision levels.)

Disruption analysis of passive plates, vacuum vessel and components, NSTXU-CALC-12-01-01, Rev 1, February, 2012

“NSTX Structural Design Criteria”, I. Zatz, NSTX-CRIT-0001-01, February, 2010.

“NSTX Center Stack Upgrade General Requirements Documents”, C. Neumeyer, NSTX-CSU-RQMTS-GRD, Rev 3, December, 2010.

“ITER IVC CuCrZr Braze Testing”, S. Jurczynski, M. Kalish, presentation (attached at end of report), 2013.

Assumptions (Identify all assumptions made as part of this calculation.)

Either fully bonded at interface of the plate with gasket support or frictional contact with 0.3 friction coefficient ?

Calculation (Calculation is either documented here or attached)

1. Eddy current induced on the secondary plate due to plasma disruption P1-P5 VDE fast (10 ms translation followed by 1 ms disruption)

2. Disruption forces on the plate and bending stress due to disruption forces
3. Stress at brazing interface with gasket support on back of the plate

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)

The results show that: 1) linearized membrane stress on secondary plate with cutout is ~25 MPa (20 MPa with gasket support); 2) the bending stress is 100 MPa (30 MPa with gasket support) 3) The total membrane plus bending stress is 108 MPa (35 MPa with gasket support).

Since the linearized stress at braze joint location (below 50 MPa) with reinforcement support on the back of the plate is much lower than either copper or CuCrZr yield strength, the modified design will meet stress allowables if the braze joint strength is higher than copper yield strength. Pull test data provided by Steve Jurczynski show that CuCrZr to CuCrZr braze joint ultimate strength is over 240 MPa (one sample with a defective joint and lower strength was believed to have oxidation on the braze surface and the braze area of the joint was probably less than 50%; which lowered its ultimate strength). The tests were conducted using induction braze method, which is worse than the vacuum braze joint method used on the Bay-A passive plates with cutout. All things considered, we should have enough stress margin in the braze joint for the Bay-A passive plate with cutouts.

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I have reviewed this calculation and, to my professional satisfaction, it is properly performed and correct.

Checker's printed name, signature, and date: Peter Titus

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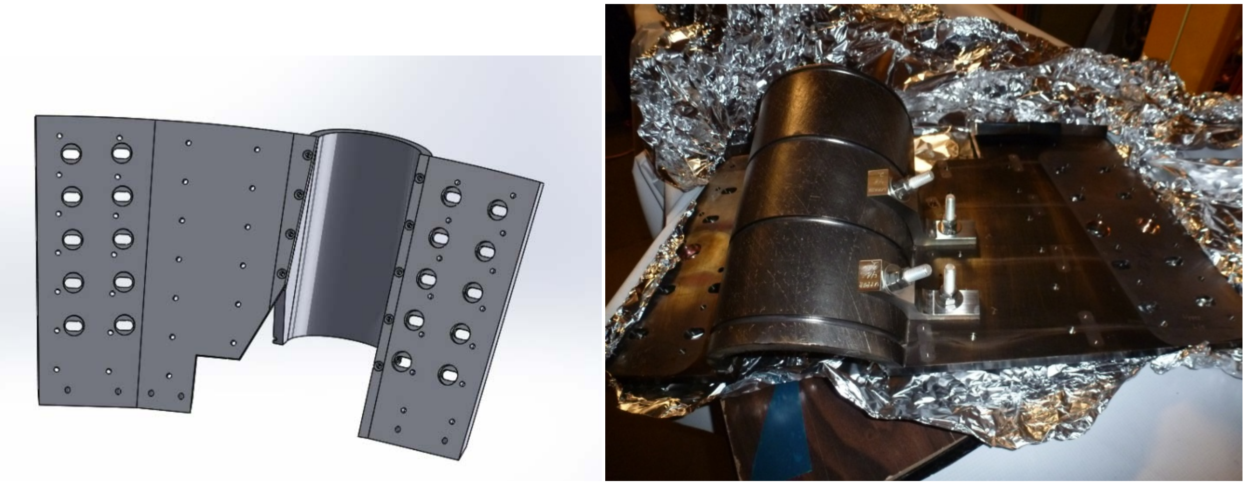
Executive Summary

The objectives of this analysis for the NSTX Upgrade bay A secondary passive plates with diagnostic cutout were: 1) to check stress level of the secondary passive plates with cutout during plasma disruptions and VDEs; 2) to check local stress level at brazing interface between main plate body and the curved cutout pieces 3) to add reinforcement gusset to ensure stress level at brazing interface is within design allowable. This report is an additional appendix to the appendix in the early report NSTXU-CALC-12-01-01 titled “Disruption Analysis of Passive Plates, Vacuum Vessel and Components”.

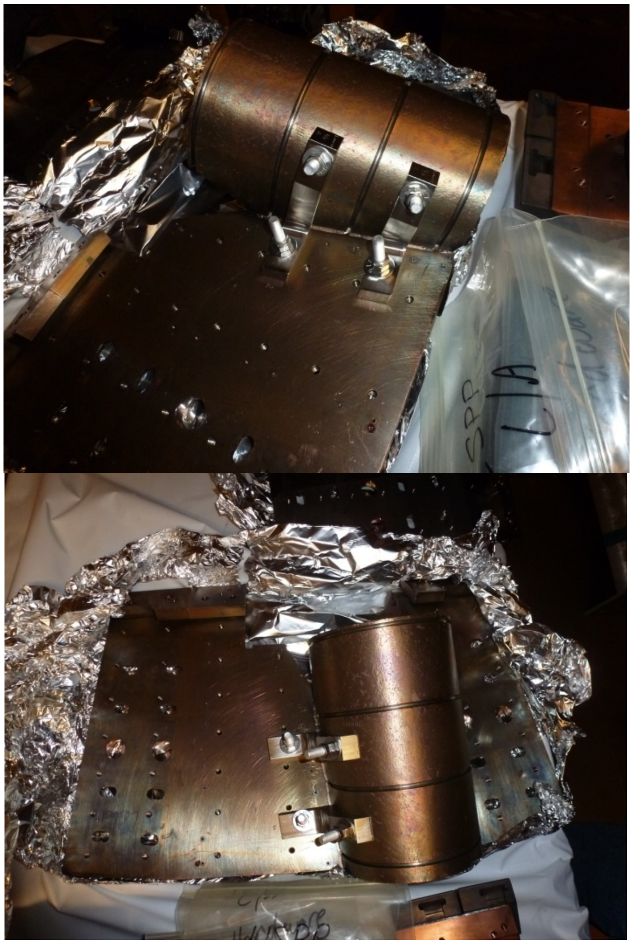
The results for the lower bay-A secondary passive plate with diagnostic cutout show that: 1) the max stress under P1 to P5 fast VDE (10 ms plasma translation and 1 ms plasma current quench at P5) is too high at brazing interface between the plate body and the cylindrical diagnostic cutout piece (beyond tested copper to copper braze joint yield strength) so gasket reinforcement is needed to reduce the stress level 2) the stress with 2 gasket supports on the back of the plate is needed and this reinforcement will bring down the stress level to within the design allowable.

There is an equivalent upper secondary plate with cutout as the mirror image of the lower plate with cutout analyzed in this report. The upper bay-A secondary plate with cutout will have the same level of stress at joint interface as the lower one, assuming the upward plasma disruption/VDEs are the same as the downward ones. We will need to add reinforce gaskets at the brazing interface in the mid of the plate the same as the lower plate.

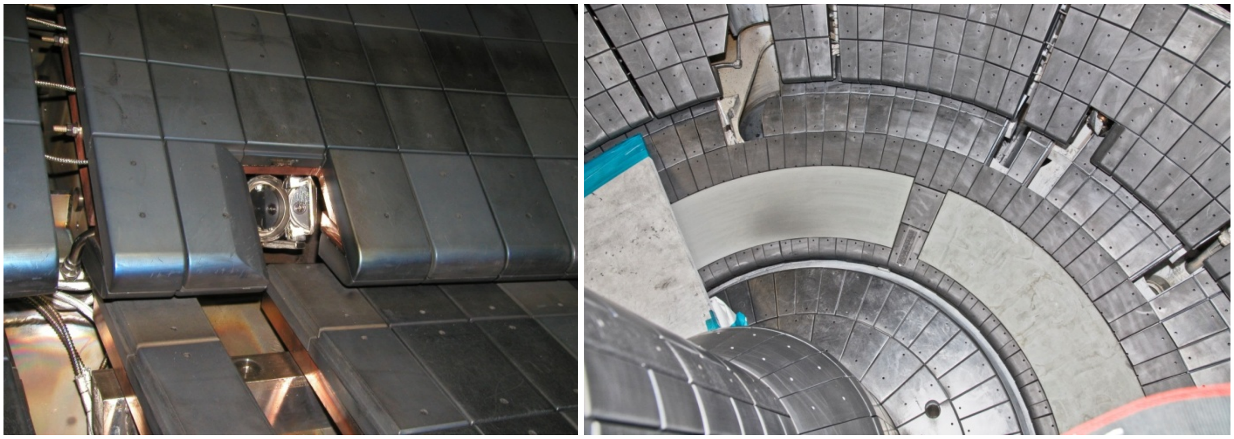
Below are the pictures of the Bay A, Bays F and B cutouts. Bay A cutout is large and significant impact is expected on the plate during plasma disruption. Bays F and B cutouts, on the other hand, they are almost identical with a size of about one tiles-worth of cutout in the secondary passive plate, in two separate locations. The cutouts are located at the bottom of the secondary plate, where smaller disruption loads (than the upper half of the plate) are expected in the P1-P5 fast disruption case.



Bay A secondary passive plate with large cutout and the plate with reinforcement



Photos of Bay A secondary passive plate with reinforcement



Bays F and B secondary passive plate with cutout about one tile size

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1. OPERA 3D Model and NSTX Coil Magnetic Fields

The NSTX PF, OH and TF coils in OPERA 3D model are shown in Figure 1.1. The small fringe fields of TF flex joints are neglected for the purpose of this magnetic shielding analysis. All TF, PF and OH coils are treated as Biot-Savart conductors in OPERA to extract magnetic field distribution of coils anywhere in 3D space without involving finite element analysis. The model with PF and OH coils only have been used for benchmark the model against Woolley Design Sheet to ensure that the Opera model produces the same background fields as the Design Sheet.

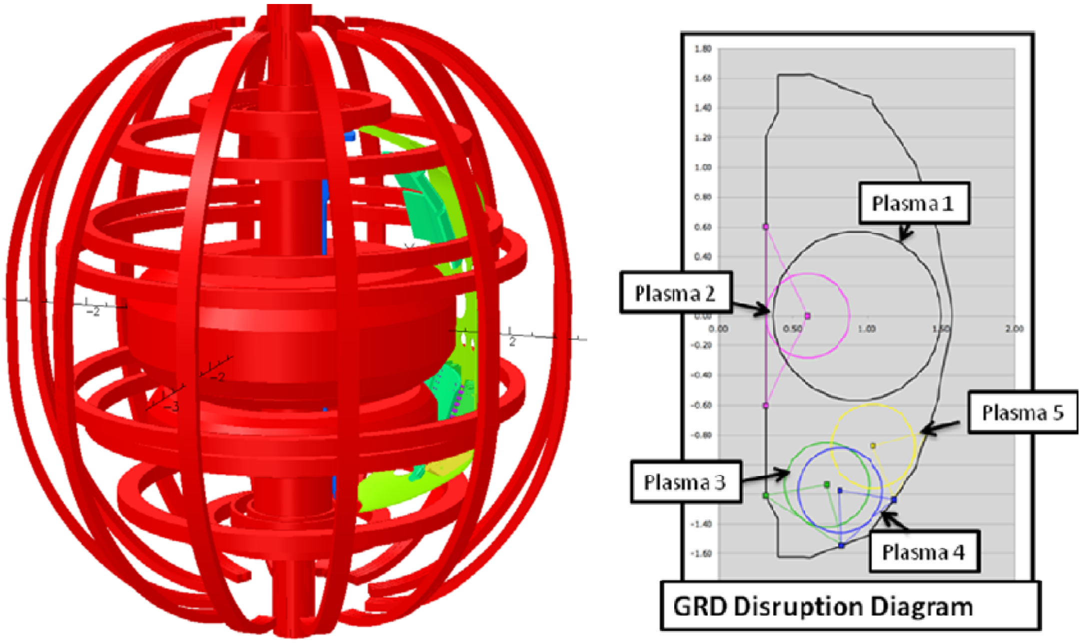


Figure 1.1 - NSTX PF, OH, TF coils and P1 and P5 plasma modeled as Biot-Savart conductors; green shows the passive structures (VV, passive plates), blue is the CS casing. The right figure shows plasma disruption cases

The NSTX coil magnetic fields (total field distribution from all coils – TF, PF and OH) for current scenario #79 is used in OPERA 3D. Figures 1.2 presents the DC current flow models where the effective bracket resistivity is calculated based on matching the NSTX measured passive plate conductivity.

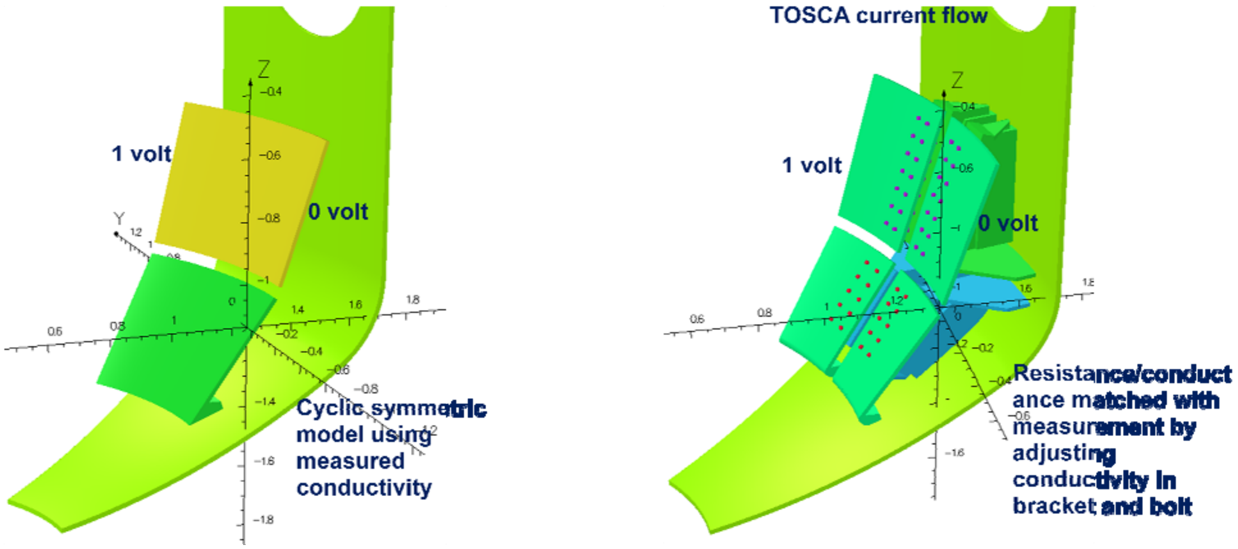


Figure 1.2 – DC current flow models for extracting equivalent bracket conductivity

Table 1.1 – Electrical conductivity used for disruption analysis (bracket conductivity extracted from DC current flow models that matches NSTX measurement of plate conductivity)

Electrical conductivity (S/m) - Matched

Passive Plate	5.07x10^7 (85% Cu)
LPP Bracket/bolt	3.35x10^5
LSP Bracket/bolt	3.12x10^5
VV	1.389x10^6 (SS)
CS Casing	0.7576x10^6 (Inconel)

Electrical conductivity - Measured

upper primary PP	**8.387x10^5**
upper secondary PP	**6.113x10^5**
lower primary PP	**8.207x10^5**
lower secondary PP	**6.668x10^5**

2. Eddy current during disruptions

The eddy current distribution on the passive plate for P1 to P5 VDE fast (10 ms plasma translation followed by 1 ms plasma disruption) shown in Figure 2.1. The secondary plate with diagnostic cut out is show and red arrows indicate the eddy current flow direction.

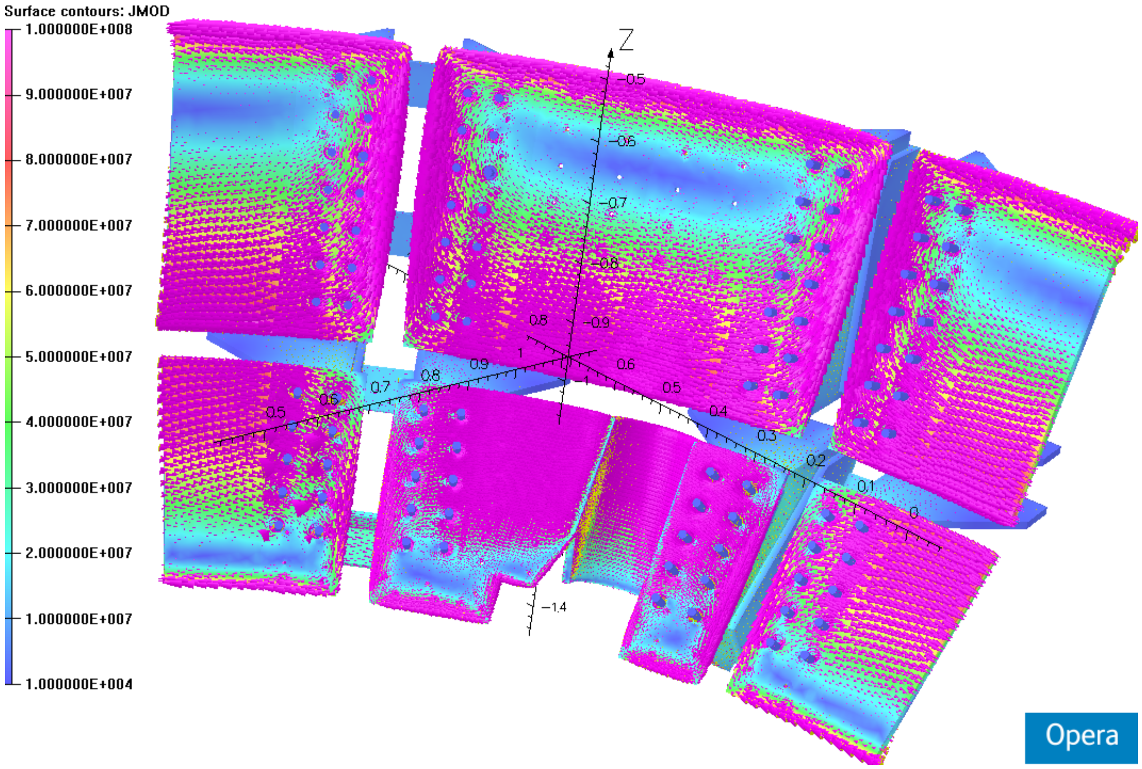


Figure 2.1 – Eddy current distribution at 10 ms end of plasma translation for P1 to P5 VDE fast

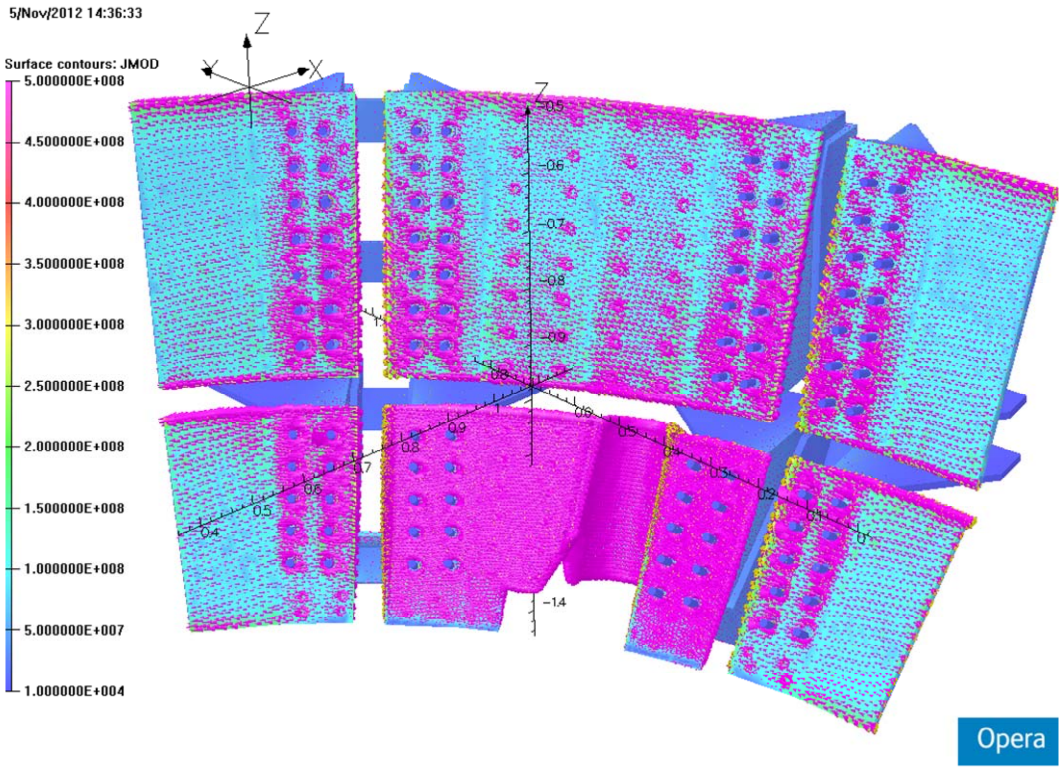


Figure 2.2 – Eddy current distribution at 11 ms end of plasma quench for P1 to P5 VDE fast (higher density of red arrows is mainly due to higher mesh density of the plate with cut out)

3. Disruption Forces on the plate

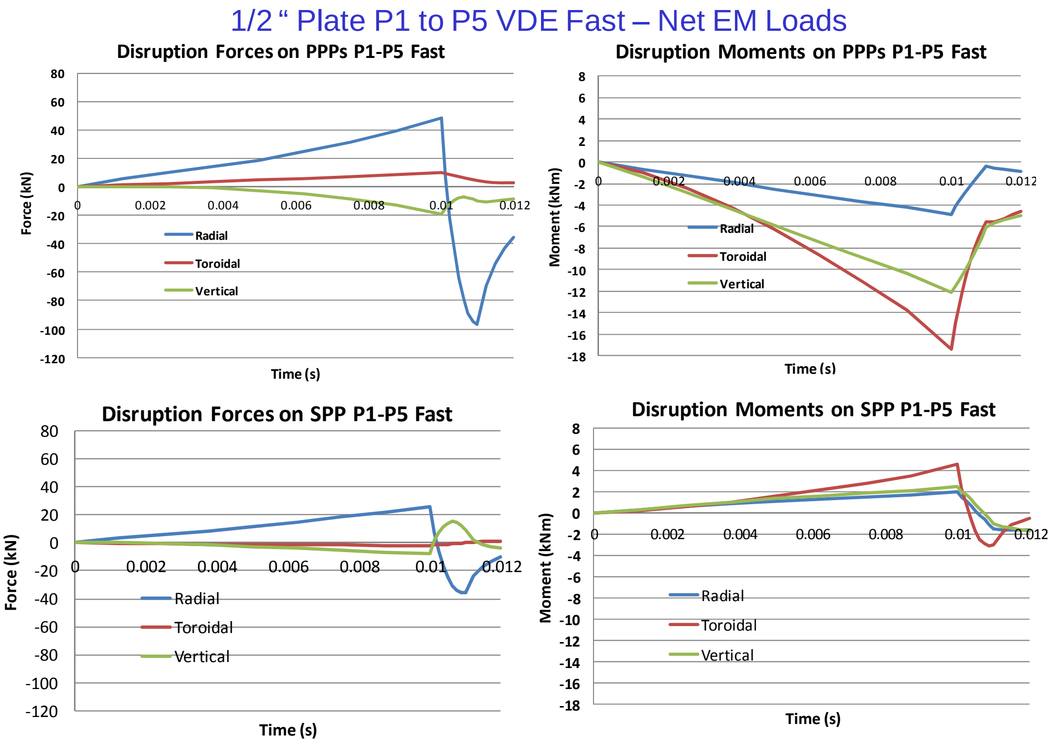
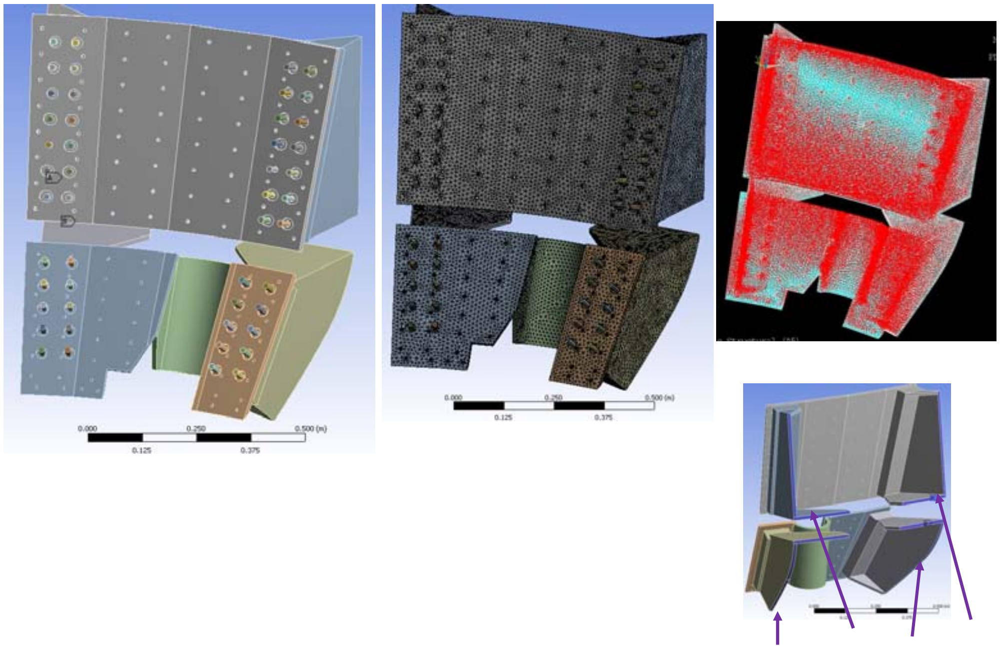


Figure 3.1 – Transient disruption forces on the primary and secondary plate

4. Stress Analysis of the Plate with Cutout

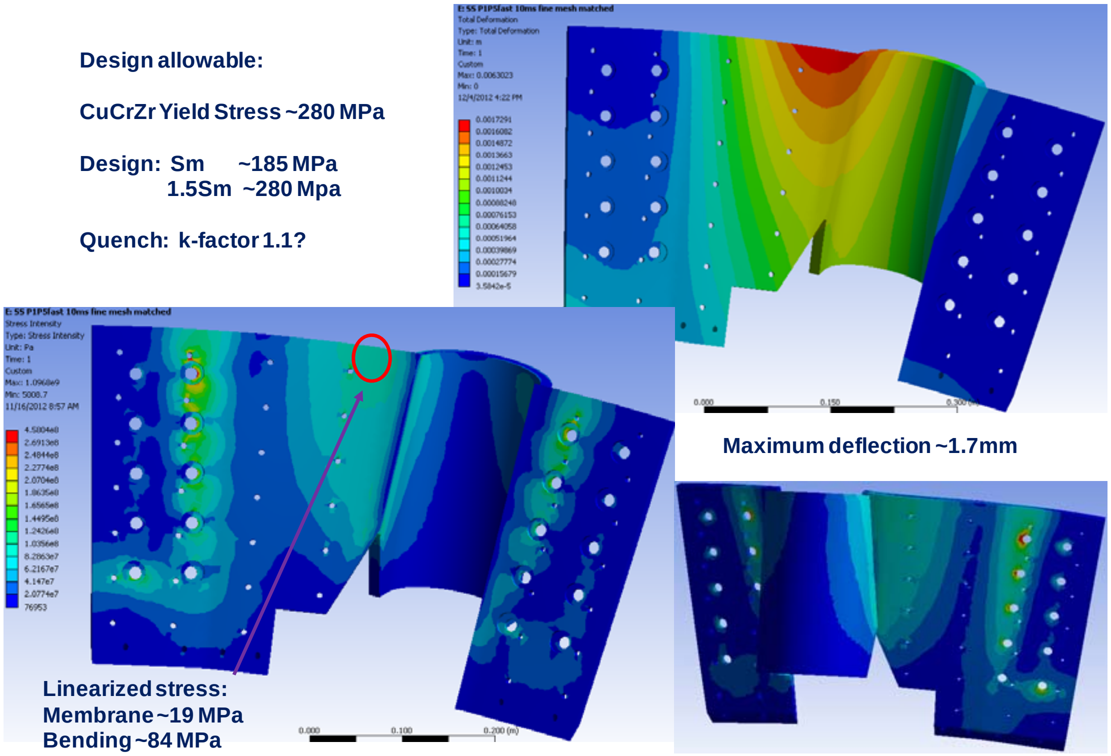
The elemental forces on the plate during disruption are mapping onto ANSYS static structural analysis in Workbench.



Fixed displacement B.C.

Figure 4.1 – Model of structural analysis for the plate with fixed displacement at back of bracket on the vessel

Deflection on Lower SP (no support) at 10 ms (End of P1-P5 Trans)



Design allowable:

CuCrZr Yield Stress ~280 MPa

Design: Sm ~185 MPa
1.5Sm ~280 Mpa

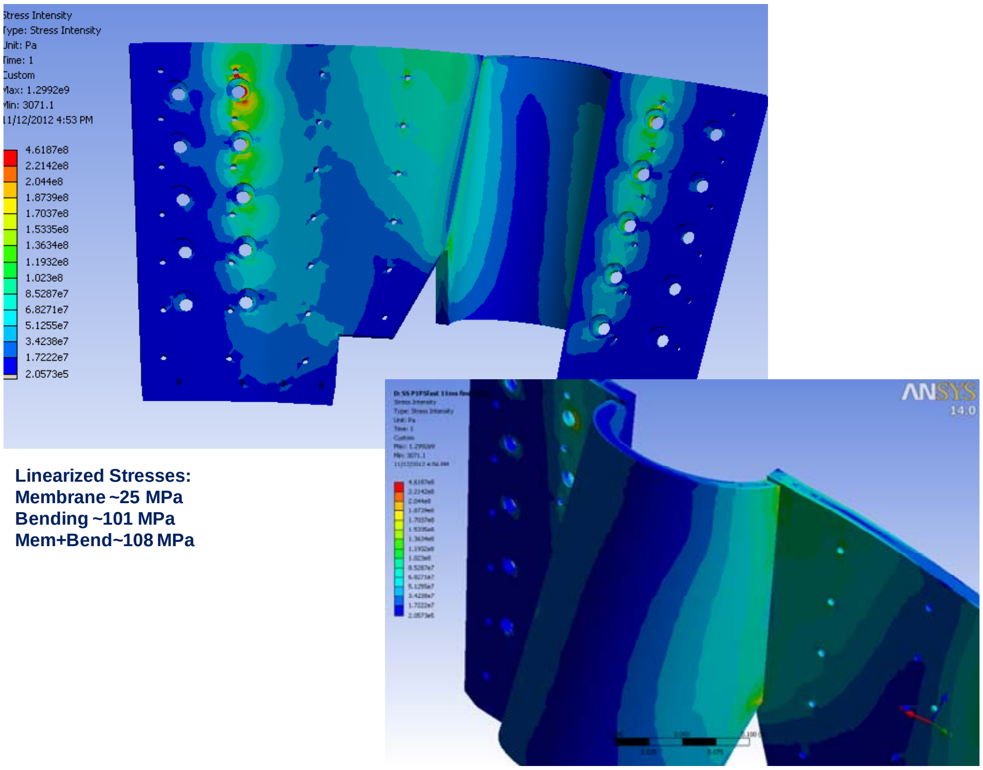
Quench: k-factor 1.1?

Maximum deflection ~1.7mm

Linearized stress:
Membrane ~19 MPa
Bending ~84 MPa
Mem+bend ~87 MPa

Figure 4.2 – Stress and bending deflection of the plate of interest with no additional support

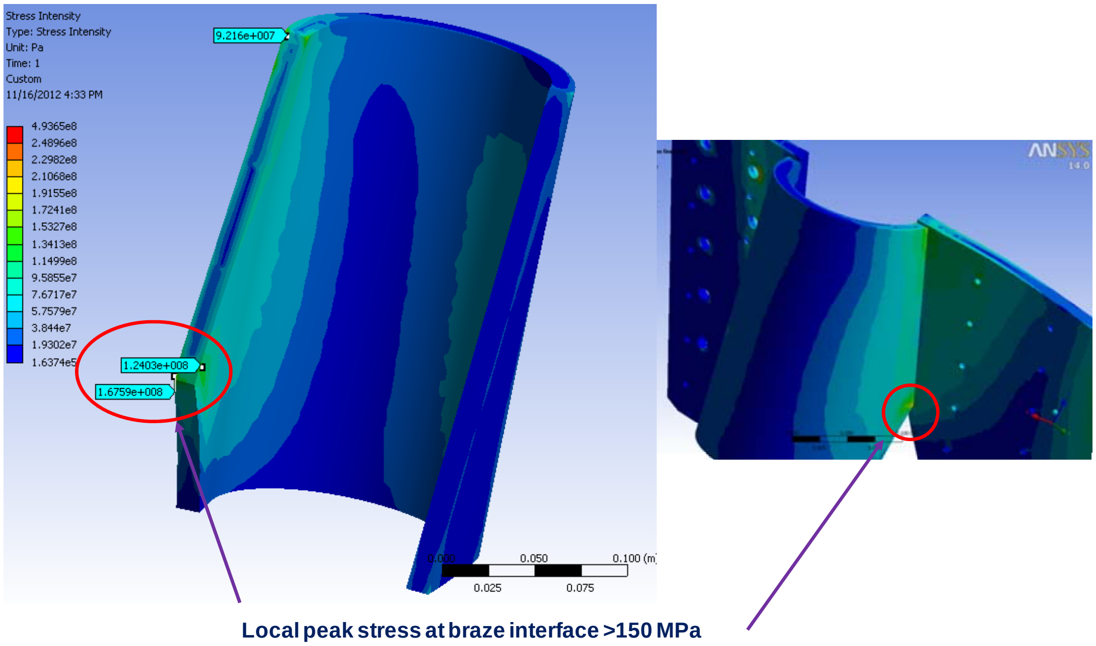
Stresses on Lower SP (no support) at 11 ms (End of Quench)



Linearized Stresses:
Membrane ~25 MPa
Bending ~101 MPa
Mem+Bend~108 MPa

Figure 4.3 – Stress concentration at interface of braze joint between plate side piece and cylindrical cut out piece

Stresses on Lower SP (no support) at 11 ms (End of Quench)



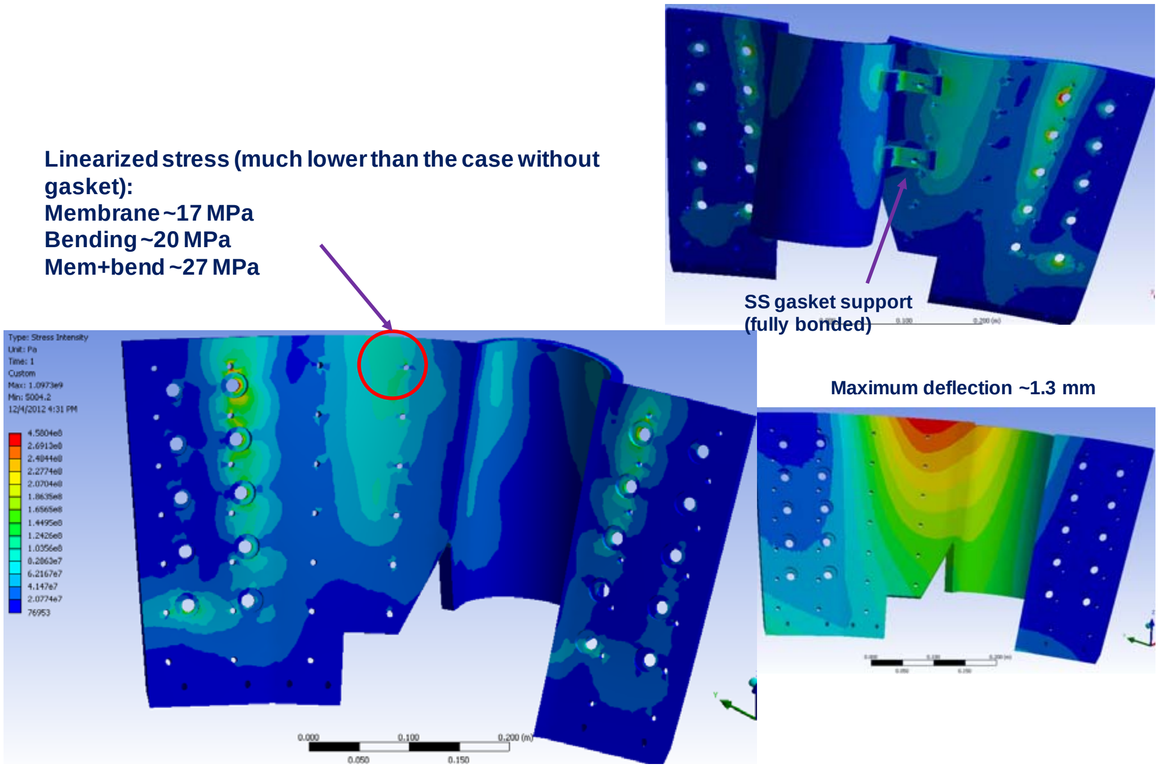
Local peak stress at braze interface >150 MPa
Need to check yield strength at braze joint

Figure 4.4 – Local stress at top and bottom brazing joint interface exceed test copper to copper braze joint strength

5.1 Stress Analysis with Gasket Support

Two additional gasket support were added in the back of the plate (only the side of interface in the middle of the plate; not the side closer to the bracket support of the plate) to reduce stress level at braze interface between side pieces of the plate and the cylindrical piece with diagnostic cutout. Figure 5.1 shows that this greatly reduce the stress level at bottom of the interface from >150 MPa to <90 MPa. Figures 5.2-5.3 show the detailed stress distribution at the back of the plate. The stress level at the other interface is much closer to the support of the plate and thus stress level is much lower (no additional gasket support is needed).

Stresses on Lower SP (with support) at 10 ms (End of Quench)



Linearized stress (much lower than the case without gasket):
Membrane ~17 MPa
Bending ~20 MPa
Mem+bend ~27 MPa

SS gasket support (fully bonded)

Maximum deflection ~1.3 mm

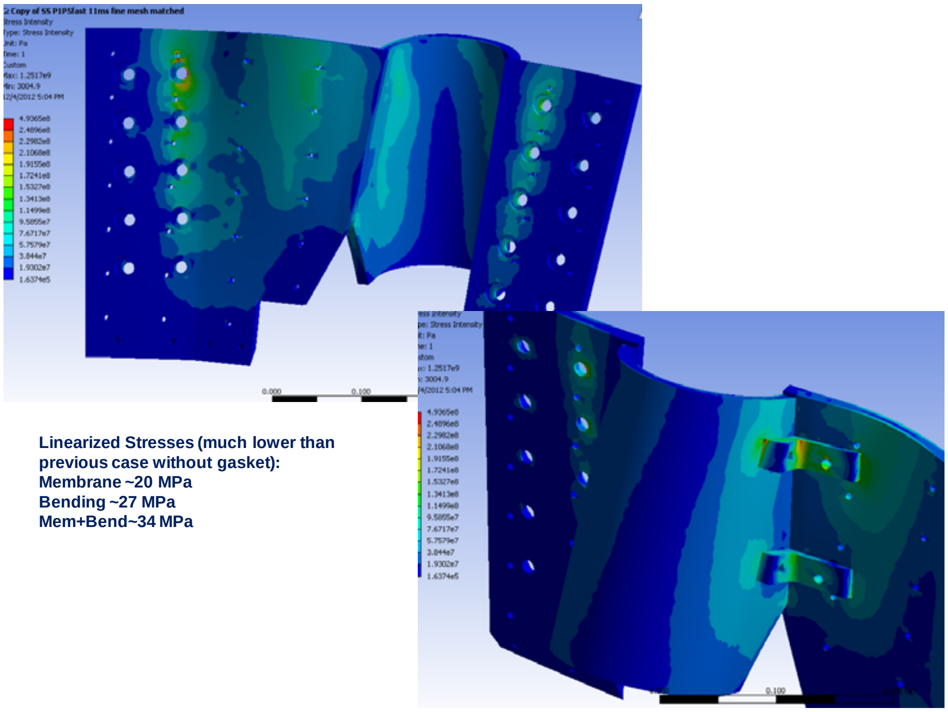
Figure 5.1 – Stress and bending deflection of the plate of interest with 2 additional gasket supports

5.2 Yield Strength of Copper to Copper Braze Joint

The yield strength of copper to copper braze joint can be lower than the CuCrZr yield strength. It is not clear what the braze strength is but the linearized stress at braze joint location of the secondary passive plate with reinforcement is < 50 MPa, which is much lower than both copper and CuCrZr base metal yield strength. The modified design will meet the stress allowable if the braze joint strength is higher than copper yield strength.

Peter Titus also pointed out during the design review of the Bay A Secondary Passive Plate Modification that the particular plate with cutouts and braze joint were not age hardened properly (after brazing with the curved piece the CuCrZr became softer) and this will significantly reduce CuCrZr yield strength. The age hardening temperatures for the Cu is in the 300-400 C range so it is well below the braze temperature. Larry pointed out after the review that we should be able to easily age the material with just some SS strap to support the plates with cutout and ensure the Bay A secondary plate with cutout is properly age hardened with the right CuCrZr strength.

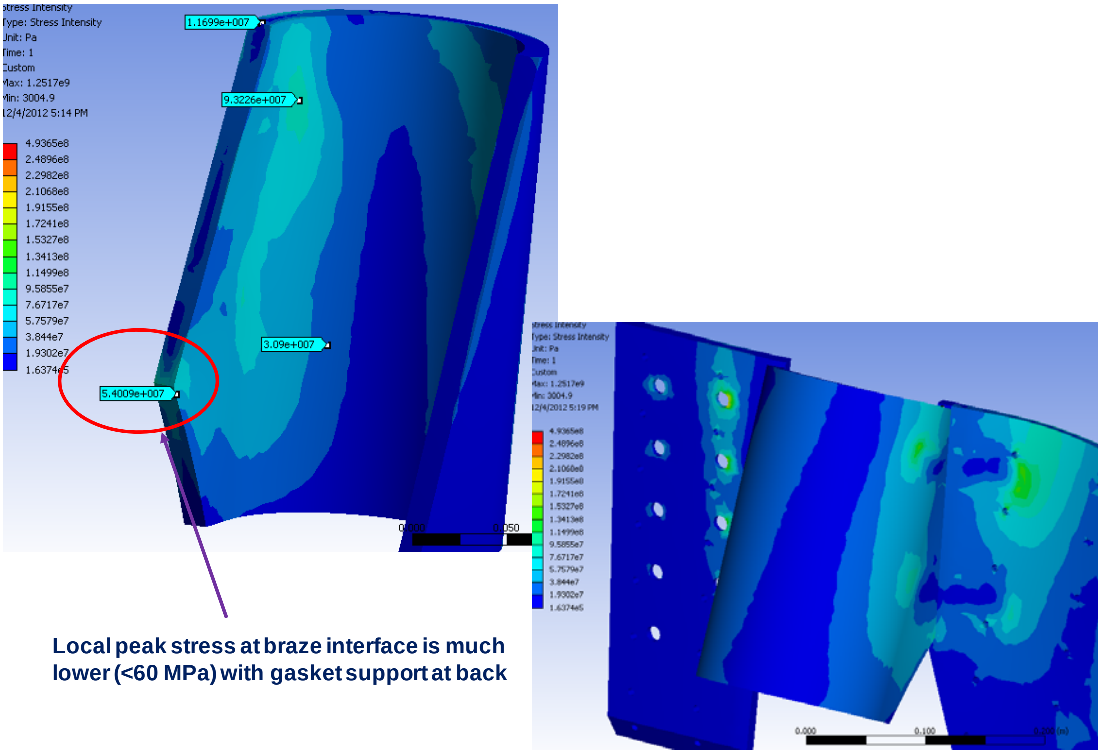
Stresses on Lower SP (with support) at 11 ms (End of Quench)



Linearized Stresses (much lower than previous case without gasket):
Membrane ~20 MPa
Bending ~27 MPa
Mem+Bend~34 MPa

Figure 5.2 – Detailed stress distribution at back of the plate with additional gasket support

Stresses on Lower SP (with support) at 11 ms (End of Quench)



Local peak stress at braze interface is much lower (<60 MPa) with gasket support at back

Figure 5.3 – Local stress concentration is much smaller with the gasket support on the back of the plate

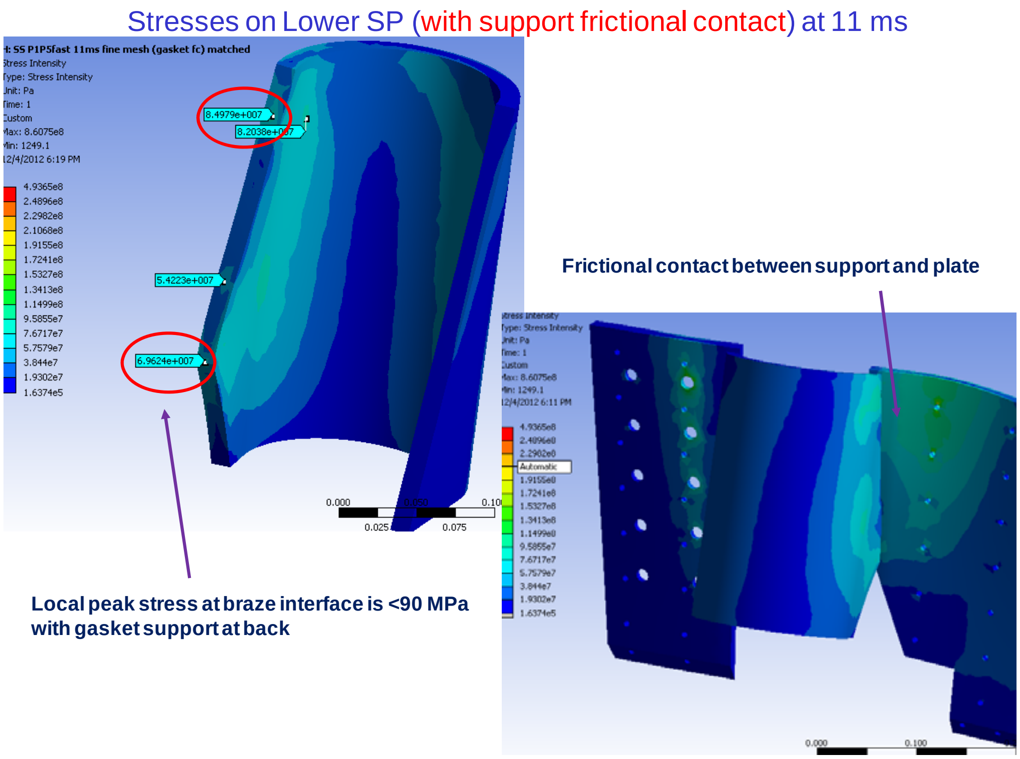


Figure 5.4 – Local stress distribution with gasket support and assumed 0.3 frictional coefficients (the frictional contact is between the PP and gasket support while the support remains bonded to the cylindrical curved piece)

6. Summary and Conclusions

The results for the lower bay-A secondary passive plate with diagnostic cutout show that: 1) the max stress under P1 to P5 fast VDE (10 ms plasma translation and 1 ms plasma current quench at P5) is too high at brazing interface between the plate body and the cylindrical diagnostic cutout piece (beyond tested copper to copper braze joint yield strength) so gasket reinforcement is needed to reduce the stress level 2) the stress with 2 gasket supports on the back of the plate is needed and this reinforcement will bring down the stress level to within the design allowable.

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References:

"Disruption analysis of passive plates, vacuum vessel and components", P. Titus, NSTXU-CALC-12-01-01, Rev 1 February 2012.

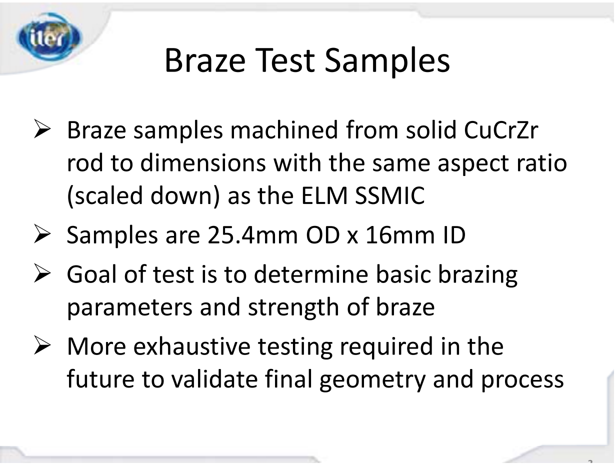
"NSTX Structural Design Criteria", I. Zatz, NSTX-CRIT-0001-01, February, 2010.

“NSTX Center Stack Upgrade General Requirements Documents”, C. Neumeyer, NSTX-CSU-RQMTS-GRD, Rev 3, December, 2010.

Attached slides below are from “ITER IVC CuCrZr Braze Testing”, S. Jurczynski and M. Kalish

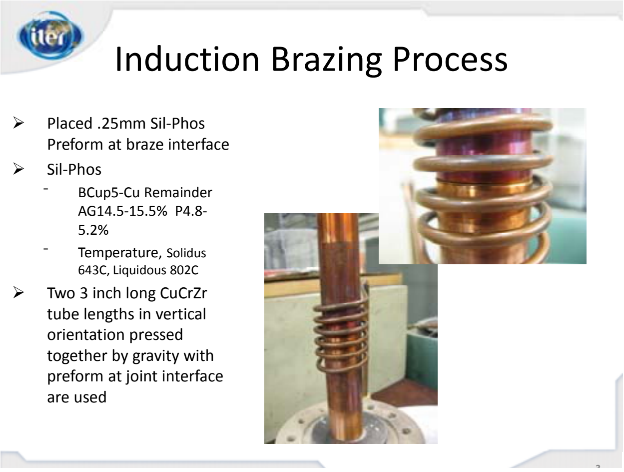
ITER IVC
CuCrZr Braze Testing

Steve Jurczynski
Mike Kalish



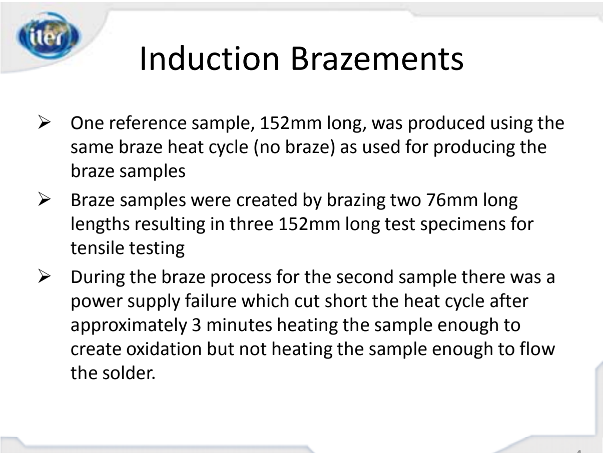
Braze Test Samples

- Braze samples machined from solid CuCrZr rod to dimensions with the same aspect ratio (scaled down) as the ELM SSMIC
- Samples are 25.4mm OD x 16mm ID
- Goal of test is to determine basic brazing parameters and strength of braze
- More exhaustive testing required in the future to validate final geometry and process



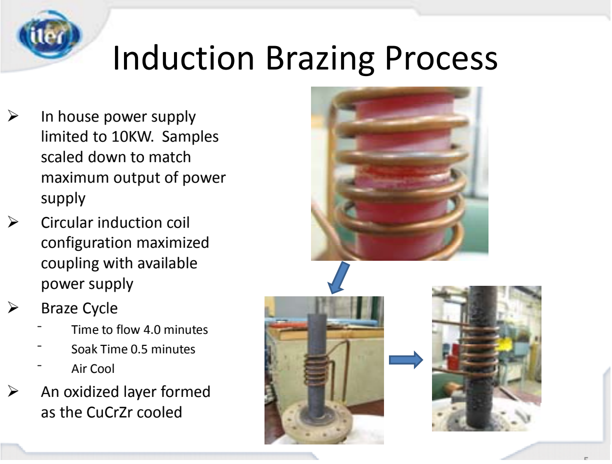
Induction Brazing Process

- Placed .25mm Sil-Phos Preform at braze interface
- Sil-Phos
  - BCup5-Cu Remainder AG14.5-15.5% P4.8-5.2%
  - Temperature, Solidus 643C, Liquidous 802C
- Two 3 inch long CuCrZr tube lengths in vertical orientation pressed together by gravity with preform at joint interface are used



Induction Brazements

- One reference sample, 152mm long, was produced using the same braze heat cycle (no braze) as used for producing the braze samples
- Braze samples were created by brazing two 76mm long lengths resulting in three 152mm long test specimens for tensile testing
- During the braze process for the second sample there was a power supply failure which cut short the heat cycle after approximately 3 minutes heating the sample enough to create oxidation but not heating the sample enough to flow the solder.

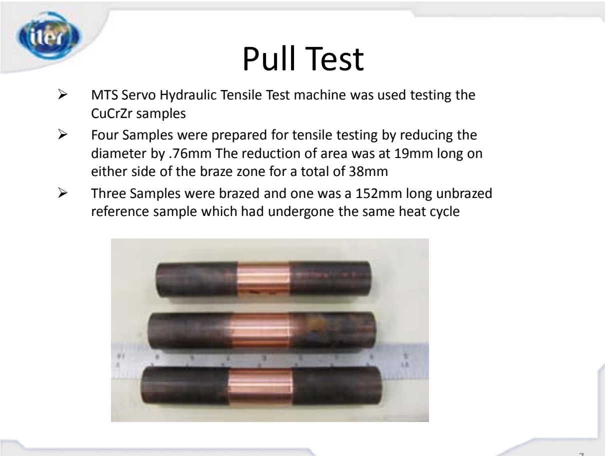


Induction Brazing Process

- In house power supply limited to 10KW. Samples scaled down to match maximum output of power supply
- Circular induction coil configuration maximized coupling with available power supply
- Braze Cycle
  - Time to flow 4.0 minutes
  - Soak Time 0.5 minutes
  - Air Cool
- An oxidized layer formed as the CuCrZr cooled

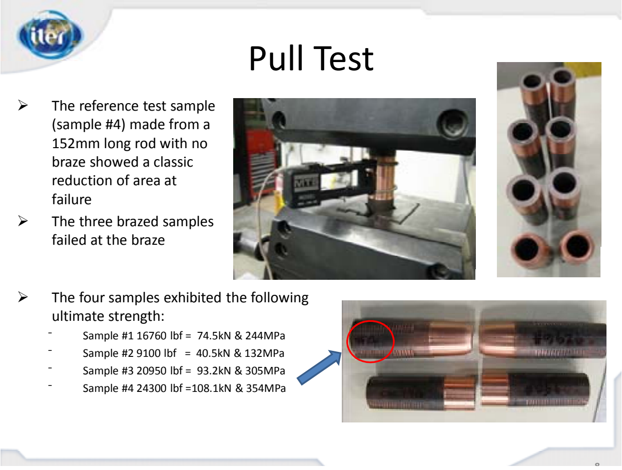
Hardness Testing

- CuCrZr hardness tested before and after brazing
- As received Hardness Consistently HRB=79
- Braze samples After Brazing
  - HRB= 68 to 71 on either side 51mm from center braze heat affected zone
  - HRB= 56 to 62 at braze heat affected zone
- Reference Samples After Identical Braze Heat Cycle
  - HRB=59 at center at potential braze location
  - HRB= 63 to 64 at 25mm away on either side of braze location



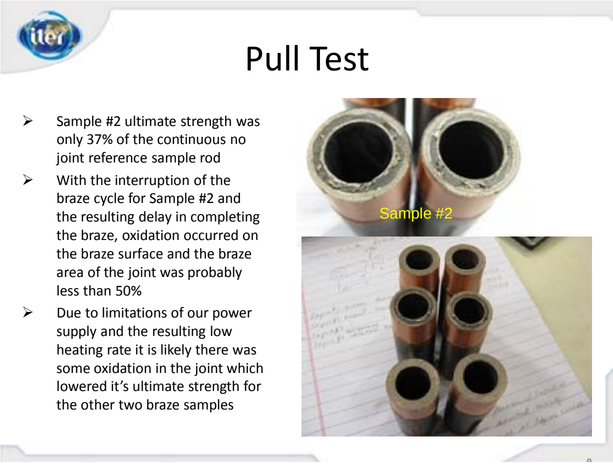
Pull Test

- MTS Servo Hydraulic Tensile Test machine was used testing the CuCrZr samples
- Four Samples were prepared for tensile testing by reducing the diameter by .76mm The reduction of area was at 19mm long on either side of the braze zone for a total of 38mm
- Three Samples were brazed and one was a 152mm long unbrazed reference sample which had undergone the same heat cycle



Pull Test

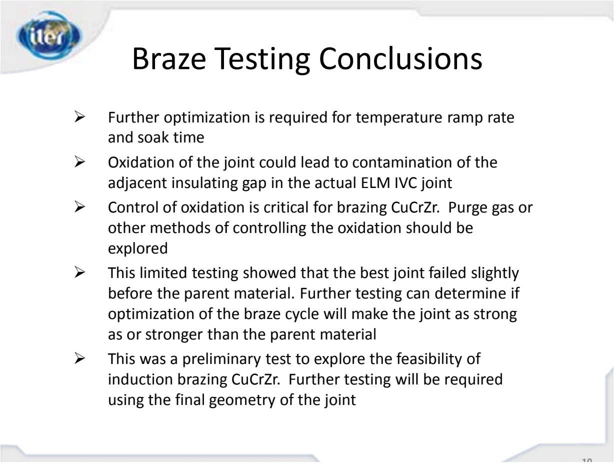
- The reference test sample (sample #4) made from a 152mm long rod with no braze showed a classic reduction of area at failure
- The three brazed samples failed at the braze
- The four samples exhibited the following ultimate strength:
  - Sample #1 16760 lbf = 74.5kN & 244MPa
  - Sample #2 9100 lbf = 40.5kN & 132MPa
  - Sample #3 20950 lbf = 93.2kN & 305MPa
  - Sample #4 24300 lbf =108.1kN & 354MPa



Pull Test

- Sample #2 ultimate strength was only 37% of the continuous no joint reference sample rod
- With the interruption of the braze cycle for Sample #2 and the resulting delay in completing the braze, oxidation occurred on the braze surface and the braze area of the joint was probably less than 50%
- Due to limitations of our power supply and the resulting low heating rate it is likely there was some oxidation in the joint which lowered it's ultimate strength for the other two braze samples

Sample #2



Braze Testing Conclusions

- Further optimization is required for temperature ramp rate and soak time
- Oxidation of the joint could lead to contamination of the adjacent insulating gap in the actual ELM IVC joint
- Control of oxidation is critical for brazing CuCrZr. Purge gas or other methods of controlling the oxidation should be explored
- This limited testing showed that the best joint failed slightly before the parent material. Further testing can determine if optimization of the braze cycle will make the joint as strong as or stronger than the parent material
- This was a preliminary test to explore the feasibility of induction brazing CuCrZr. Further testing will be required using the final geometry of the joint