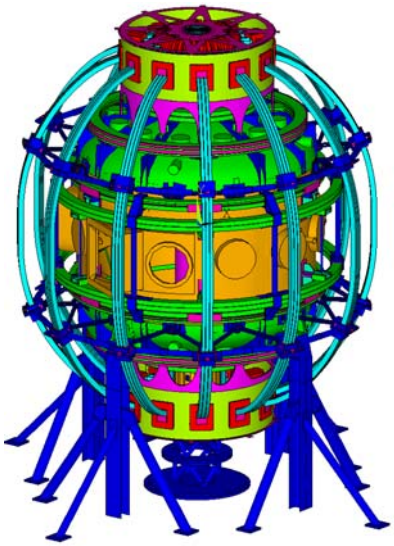
NSTX Upgrade

Global Model – Model Description, Mesh Generation, and Results

NSTXU-CALC-10-01-02

Rev 2

October 2011



Prepared By:

Peter Titus, PPPL Mechanical Engineering

Reviewed By:

Han Zhang

Phil Heitzenroeder

PPPL Calculation Form

Calculation # **NSTXU-CALC-10-01-02** Revision # **02** WP #, **1511**

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

Provide an overall simulation of the behavior of the Spherical Tokamak to qualify some components and to provide boundary conditions for other models. The global model is also used to compare with other models. The global model is also used as the model for computing influence coefficients for various parts of the machine.

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

- See the reference list in the body of the calculation (Section 6.4)

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

This global model includes varying degrees of local component model refinement. In most cases components are also treated with more detailed sub-modeling and qualified in separate calculations - this is discussed in the executive summary, section 4.0. The global model provides boundary conditions, and critical equilibria for the submodels. It is assumed that the level of modeling detail in the global model is adequate for this purpose. In a few instances the global modeling is assumed adequate to qualify individual components. This is also discussed in the executive summary (Section 4.0.

Calculation (Calculation is either documented here or attached)

Attached in the body of the calculation

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

The global model has been found adequate to provide boundary conditions, and loading conditions for more detailed modeling of sub-components. The global model has been used to cross check results in other calculations, and to survey the 96 equilibria for critical loading on some of these components.

Cognizant Engineer's printed name, signature, and date

Peter H. Titus _____

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

Checker's printed name, signature, and date

_____

2.0 Table of Contents
NSTX Center Stack Upgrade Global Model

4.0 Executive Summary

The Global model of NSTX Center Stack Upgrade (NSTX-CSU) provides a simulation of the overall behavior of the machine. It provides boundary conditions for local models and sub Models , or allows inclusion of the detailed models of components in the global model. The global model is used to compare with other models. The global model is also used as the model for computing influence coefficients for various parts of the machine.

In many cases it has been built from other available model segments – The upper and lower head sections of the vessel model come from H.M. Fan's early vessel models. The cylindrical shell that contains the mid plane ports comes from a vessel model built by Srinivasa Avasarala from the Pro–E model of the vessel. It has been updated with the latest neutral beam port frame. In some instances parts of the global model were exported to be evaluateds in more detail. Multiple scenarios from the NSTX design point are run using the global model. The design points are publised on the web and are maintained by C. Neumeyer. Loads from normal operating current sets are in general much less severe than loads that are based on worst case power supply currents. In order to compare the global model results with some of the local models that have been run, some of the "worst case" currents have been run in the global model. The outer TF reinforcements are an example of this. Results reported in sub paragraphs of section 8 have been used to qualify components, check results and guide the need for further analyses. The outer TF leg reinforcements discussed in section 8.3 and in NSTX calculation number 132-04-00 [4] include some load sets which are based on two severe current sets. These are intended to maximize the out-of-plane loading on the TF outer legs for an up-down symmetric loading and an up-down asymmetric loading that causes large net torques on the outer legs. These two current sets were included in the loading analyzed in the global model. Behavior of the global model and reference [4] is consistent. Section 8.3 discusses these results and adds a qualifiucationn of the bending related bond shear in the TF outer leg. Section 8.1 documents the acceptable stresses in the diaphram plate that replaces the gear tooth torsional connection between the centerstack and the outer umbrella structure. This analysis has been essentially superseded by reference [23].Section 8.5 provided global displacements to the detailed analysis of the flex joint [7] Section 8.6 has been expanded and split off into another calculation, ref [15]. Section 8.9 similarly profided guidance on global twist in the evaluation of the centerstack OH support details. Section 8.8 shows the stresses and loading around the I beam column attachments to the vessel and points to the need to evaluate the weld details of this connection.

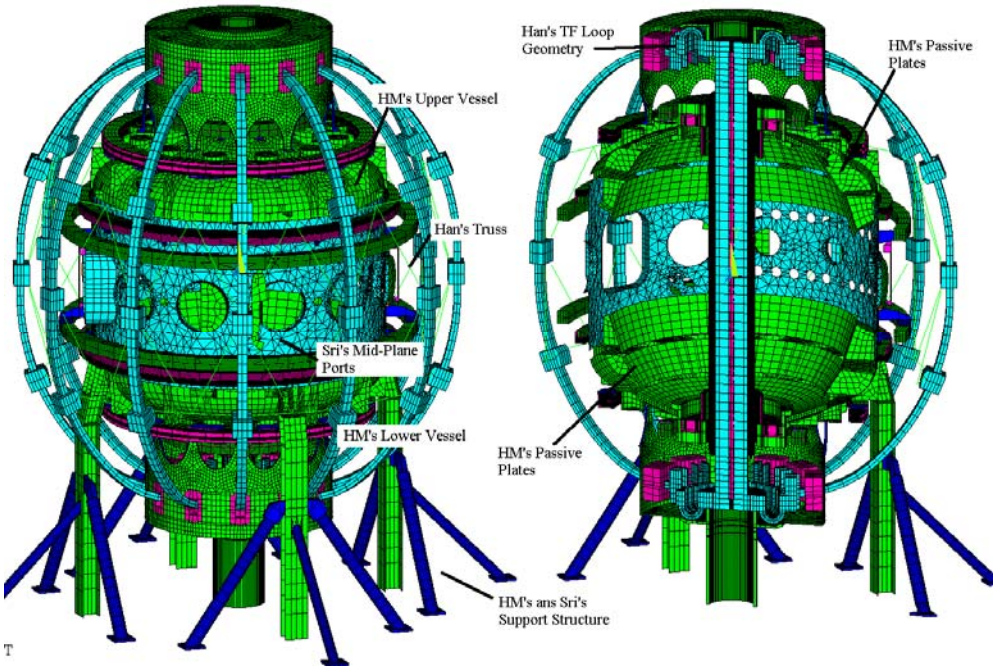


Figure 4.0-1 Global Model Status as of June 22 2009

The global model has been extensively used to investigate various alternative designs to support the out-of-plane TF loads. In October of 2010, the enlargement of the vacuum pumping duct to add the Thompson scattering diagnostic increased the vessel stresses because there was insufficient metal left between the neutral beam ports and the larger Thompson scattering port. Vessel reinforcements were investigated [25] . Also studied was an option which connected a vertically extended umbrella structure to the cell walls via long struts. The global model was used to study this and it confirmed the virtues claimed by M. Smith and T. Willard - but the hardware additions proved much more expensive that the vessel reinforcements.

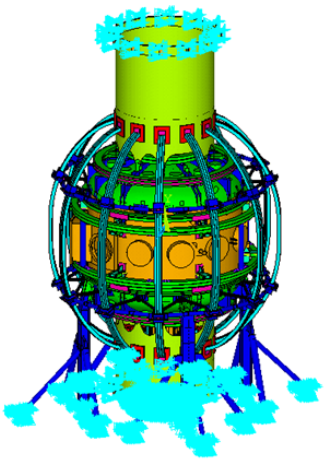


Figure 4.0-2 Extended Umbrella Structure With Restraint Provided by Struts to the Cell Wall

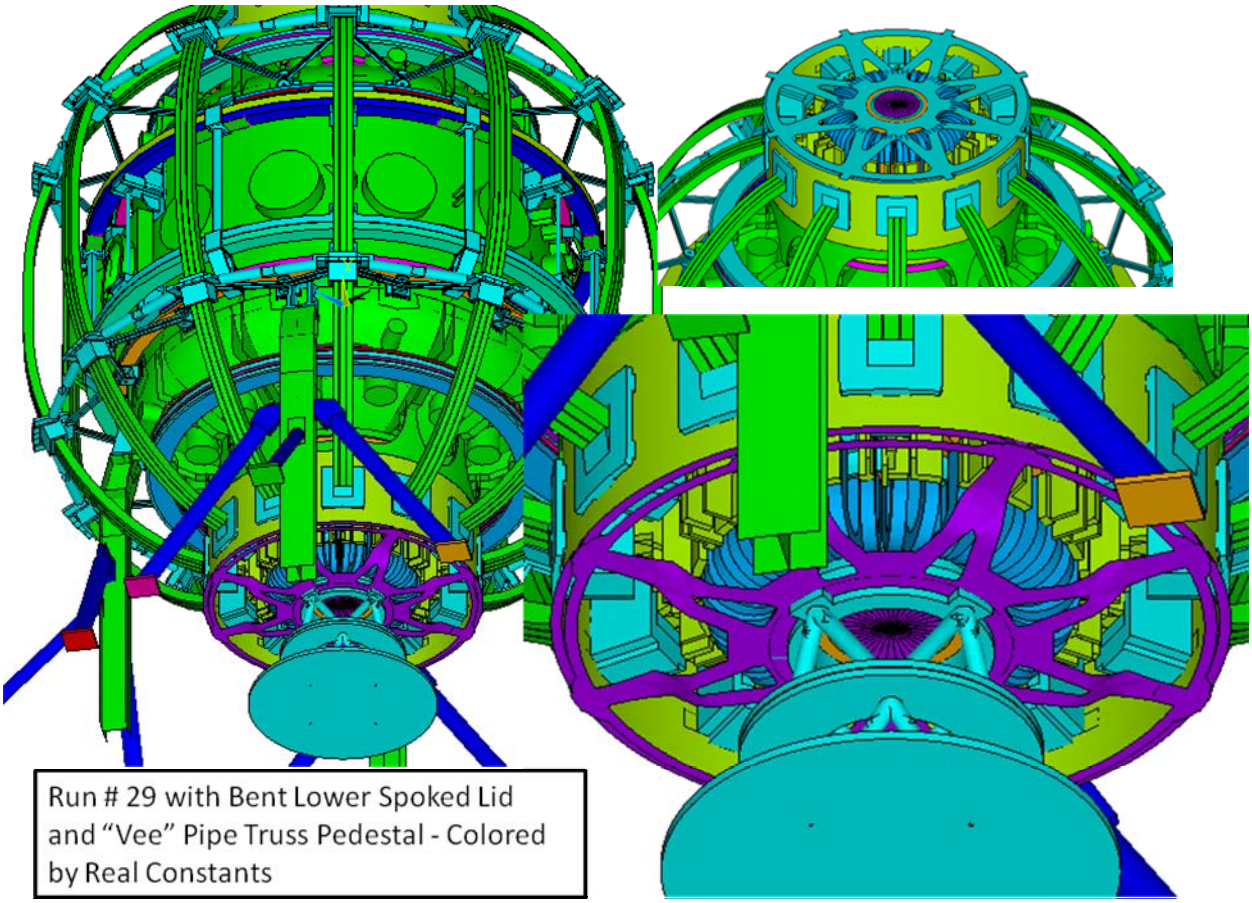


Figure 4.0-2 Global Model Status as of May 2011

The global model described in this calculation has been used to analyze a number of components and loads that are considered in separate calculations. In some instances the global model provides some of the boundary conditions. In others, like the seismic analysis, the global model is the same as the seismic analysis model. A list of calculations in which the global model is directly used follows:

NSTX Upgrade Seismic Analysis NSTXU-CALC-10-02-00 Rev 0 February 9 2011 Prepared By: Peter Titus, Reference [18]

TF Inner Leg Torsional Shear, Including Input to the DCPS, P. H. Titus NSTXU-CALC-132-07-00 Reference [15]

Umbrella Reinforcement Details, by P. Titus and H. Zhang NSTXU CALC 12-07-00, ref [19]

Analysis of Existing & Upgrade PF4/5 Coils & Supports – With Alternating Columns, NSTXU-CALC-12-05-00, Prepared By: Peter Titus, Reviewed by Irv Zatz, Cognizant Engineer: Mark Smith WBS 1.1.2. PF5 stress influence coefficients are computed by applying load files derived from using unit currents.

Lid/Spoke Assembly, Upper & Lower NSTX-CALC-12-08-00 Rev 0 May 2011 Prepared by: Peter Titus, Reference [23] In this calculation the global model is used to compare torsional load distributions for different spoked lid designs.

Analysis of the NSTX Upgrade Centerstack Support Pedestal NSTXU-CALC-12-09-00 May 2011 Prepared By: Peter Titus Reference [24] In this calculation the global model is used to compare torsional load distributions for different pedestal designs.

Calculations which utilize output from the global model as boundary conditions are:

Bellows Qualification Calc # NSTXU CALC 133-10-00, by Peter Rogoff', Reference [13] in which the global model is used to quantify the torsional moment applied on the bellows from the TF out-of plane loading

TF Flex Joint and TF Bundle Stub, T. Willard, NSTX-CALC-132-06-00, reference [7]. The differential toroidal displacements imposed on the inner and outer radius of the TF flex model come from the global model.

Structural Calculation of the TF Flag Key, NSTXU-CALC-132-08-00 , A. Zolfaghari, Reference [21] . The load at the connection of the TF flags to the upper crown and lid are derived from the global model simulations, and similar loads at the connections at the bottom flags of the TF central column are also sized using loads from the global model.

The global model uses separate model "pieces" which are brought into ANSYS as text listings similar to a CDWRITE or *.anf ANSYS file, using the /INPUT command. These segments are created in a separate program. The magnet components are meshed and the loading is computed from a model with only the magnets. Each piece is brought into ANSYS with a NUMOFF command. The last group of elements entered into the ANSYS program is the magnet model. Lorentz forces are computed in the same program used to mesh the structural components. This program is described in section 6.2. Load files are also read into ANSYS in the solution phase. This approach allows computation of loading and re-use of the load files - as long as the magnet model does not change. Structural model "pieces" may be modified and the problem re-run without alteration of the load files. This is a practical way to limit run times for the multiple current sets required by the NSTX GRD.

5.0 Input to the Digital Coil Protection System

Conceptual design, of the upgrade to NSTX, explored designs sized to accept the worst loads that power supplies could produce. Excessive structures resulted that would have been difficult to install and were much more costly than needed to meet the scenarios required for the upgrade mission, specified in the General Requirements Document (GRD). Instead the project decided to rely on a digital coil protection system (DCPS). Initial sizing was then based on the 96 scenarios in the GRD design point with some headroom to accommodate operational flexibility and uncertainty. The DCPS must control currents to limit component stresses and temperatures to acceptable levels. The digital coil protection system theory ,

hardware and software are described in other papers at this conference. The intention of this paper is to describe the generation of stress multipliers, and algorithms that are used to characterize the stresses at key areas in the tokamak,

Two approaches are used to provide the needed multipliers/algorihms:

The first is to use the loads on PF coils computed by the DCPS software and apply these to local models of components.

The second approach to calculating the stress multipliers/algorithms, is to utilize the global model that simulates the whole structure and includes an adequately refined modeling of the component in question. Unit terminal currents are applied to each coil separately, Lorentz loads are calculated, and the response of the whole tokamak and local component stress is computed. Local component stresses may then be computed in the DCPS or in a spreadsheet for the many scenarios required by the GRD.

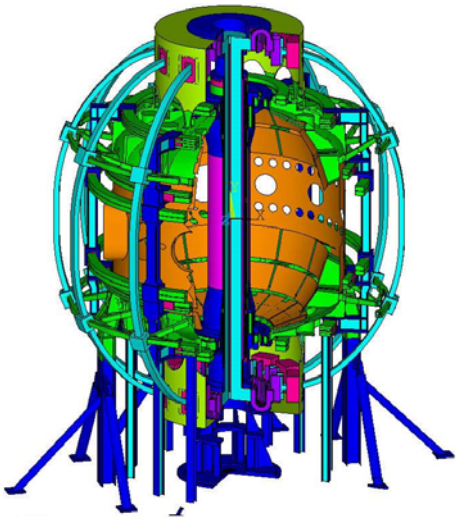


Figure 5.1 Linear Global Model Used in Calculating DCPS Stress Multipliers

Separate calculations use this global model to compute influence coefficients for components covered by the calculation. For example:

TF Inner Leg Torsional Shear, Including Input to the DCPS" NSTXU-CALC-132-07-00

6.4 References

[1] http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html Dated 2 -17- 2009
[2] Fusion Ignition Research Experiment Structural Design Criteria; Doc. No. 11_FIRE_-DesCrit_IZ_022499.doc; February, 1999
[3] "MHD and Fusion Magnets, Field and Force Design Concepts", R.J.Thome, John Tarrh, Wiley Interscience, 1982
[4] "Analysis of TF Outer Leg " Han Zhang NSTX Calculation Number 132-04-00
[5] "Estimated and Compiled Properties of Glass/101K Epoxy/Kapton Composite Properties at Room Temperature" Report to Jim Chrzanowski Princeton Plasma Physics Laboratory July 15, 2009 R. P. Reed Cryogenic Materials, Inc.Boulder, CO
[6] NSTX Structural Design Criteria Document, I. Zatz
[7] "TF Flex Joint and TF Bundle Stub" T. Willard, NSTX-CALC-132-06-00
[8] "Influence Coefficients", R. Hatcher, NSTX-CALC-13-03-00
[9] NSTX Design Point Sep 8 2009 http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html
[10] Maximum and Minimum Loads on the NSTX OH and PF Coils, and Coil Groupings" P.Titus NSTX-CALC-13-02-00
[11] ANSYS Structural Analysis Program, Revision 10.0 Swanson Analysis Systems
[12] National Spherical Torus Experiment NSTX CENTER STACK UPGRADE GENERAL REQUIREMENTS DOCUMENT NSTX_CSU-RQMTS-GRD Revision 0 March 30, 2009 Prepared By: Charles Neumeyer NSTX Project Engineering Manager
[13] Bellows Qualification Calc # NSTXU CALC 133-10-00, Peter Rogoff, Checked by I. Zatz
[14] Tile Stress Analysis (ATJ) NSTXU CALC 11-03-00, Art Brooks Used to include tile weights into th effective density of the centerstack casing, transmitted via email:
Peter, Pete: Attached are the volumes Ankita extracted from the ProE models. The density of the Center Case (inconel) is 8440 kg/m3, the tile (ATJ Graphite - www.graftech.com) is 1760 kg/m3 giving a total mass of 1138 kg and an effective density if the CS (which includes the mass of the tiles) of 12,248 kg/m3.
[15] TF Inner Leg Torsional Shear, Including Input to the DCPS, P. H. Titus NSTXU-CALC-132-07-00

[16] email from Han Zhang transmitting Strap stiffnesses from Tom Willard
Mark,

Following is the number from Tom.

> The force required to deflect the 31 lamination assembly .3" vertically is 76.2 lbf.
> The flex assembly rotates 2.57 degrees with a torque of 100 in-lbf applied.

If you want to know the E and G to use in an ANSYS model, they depends on how you model the flex strap (I used two solid arch) and the dimensions. Anyway, I can check my model and tell you the numbers. But you still need to compare with your model dimensions.

Han.

[17] TF Inner Leg Torsional Shear, Including Input to the DCPS" NSTXU-CALC-132-07-00, P. Titus

[18] NSTX Upgrade Seismic Analysis NSTXU-CALC-10-02-00 Rev 0 February 9 2011 Prepared By: Peter Titus,
[19] Umbrella Reinforcement Details, by P. Titus NSTXU CALC 12-07-00
[20] Analysis of Existing & Upgrade PF4/5 Coils & Supports – With Alternating Columns, NSTXU-CALC-12-05-00, Prepared By: Peter Titus, Reviewed by Irv Zatz, Cognizant Engineer: Mark Smith WBS 1.1.2
[21] Structural Calculation of the TF Flag Key, NSTXU-CALC-132-08-00 , A. Zolfaghari
[22] OH & PF1 & 2 Electromagnetic Stability Analyses NSTXU-CALC-133-11-00 Rev 0 March 2 2010 Prepared By: Peter Titus, Reviewed By Ali Zolfaghari, Cognizant Engineer: Jim Chrzanowski WBS 1.1.3
[23] WBS 1.1.2 Lid/Spoke Assembly, Upper & Lower NSTX-CALC-12-08-00 Rev 0 May 2011 Prepared by: Peter Titus, Reviewed By: Irving Zatz, Cognizant Engineer: Mark Smith,
[24] Analysis of the NSTX Upgrade Centerstack Support Pedestal NSTXU-CALC-12-09-00 May 2011 WBS 1.1.2 Prepared By: Peter Titus Reviewed By: Ali Zolfaghari, Cognizant Engineer: Mark Smith
[25] Vessel Rework for the Neutral Beam and Thomson Scattering Port NSTXU-CALC-24-01-00 Prepared By: T. Willard WBS 1.1.2 Reviewed by: A. Zolfaghari Cognizant Engineers: M. Smith, G. Labik, C. Priniski
[26] NSTX Upgrade Modal Analysis and Normal Operation Transient Load Effects NSTXU-CALC-133-09-00 Rev 0 June 2011, P. Titus
[27] NSTX Upgrade Centerstack Casing and Lower Skirt Stress Summary NSTXU-CALC-133-03-00 Rev 0 August 2011 Prepared By: Peter Titus
[28] "TF to Umbrella Structure Aluminum Block Connection" NSTXU-CALC-12-04-00Rev 0 December 15 2010, Prepared by Peter H. Titus
[29] Email from Art Brooks Thu 3/11/2010 8:21 AM, providing Upper and Lower design loads for the centerstack casing halo loads
[30] Halo Current Analysis of Center Stack NSTXU-CALC-133-05-00 Prepared By: Art Brooks, Reviewed by: Peter Titus, Cognizant Engineer: Jim Chrzanowski, WBS 1.1.3 Magnet Systems,
[31] SIMULATION OF TF TURN-TURN FAULTS IN NSTX CENTER STACK UPGRADE, C NEUMEYER 13-110822-CLN-01
[32] NSTX Ring Bolted Joint, NSTX-U Calc 132-11 March 2011, Peter Rogoff, Reviewed by I. Zatz
[33] NATIONAL SPHERICAL TORUS EXPERIMENT CENTER STACK RESEARCH AND DEVELOPMENT FINAL REPORT No. 13-970430-JHC Prepared By: James H. Chrzanowski April 30, 1997 PRINCETON UNIVERSITY PLASMA PHYSICS LABORATORY (PPPL)
[34] "Mechanical, Electrical and Thermal Characterization of G10CR and G11CR Glass Cloth/Epoxy Laminates Between Room Temperature and 4 deg. K", M.B. Kasen et al , National Bureau of Standards, Boulder Colorado.
[35] NSTX Upgrade OH Preload System and Belleville Springs, NSTXU-CALC-133-04-00 October 2010, P. Rogoff, Checked by test by Tom Kozub
[36] Final Test Report, PPPL Purchase Order PE010925-W Fabrication and Testing of Cyanate Ester - Epoxy /Glass Fiber/Copper Laminates, October 7 2011, Prepared for Princetoin Plasma Physics Laboratory Forrestal Campus by Composite Technology Development Inc. 2600 Campus Drive Suite D Lafayette CO 80026

7.0 Materials and Allowables

7.1Elastic Constants

In the later models, the TF insulation is discretely modeled and there is no necessity for orthotropic properties. The OH and PF coils are orthotropic and should be adjusted for coolant holes and insulation content.

```
      ! Vacuum Vessel Elastic Moduli
Ex,50,200.0e9   $ALPX,50,1.7E-5 ! HM's Model
EX,51,200.0e9   $ALPX,51,1.7E-5 ! Sri's Mid
Plane POrts
EX,52,200.0e9   $ALPX,52,1.7E-5 ! PF4 and 5
Supports attached to the vessel
EX,53,200.0e9   $ALPX,53,1.7E-5 ! Umbrella
Structure
EX,54,200.0e9   $ALPX,54,1.7E-5 ! Vessel
plates with no pressure
ex,55,200.0e9   $ALPX,55,1.7E-5 ! Neutral Beam
Port Covers
ex,60,200.0e9   $Alpx,60,1.7e-5 ! PF4/5 Plate
EX,70,1e8,  $DENS,70,2.0E3  $ALPX,70,1.7E-5
*do,mat,50,53
dens,mat,8020.0*VesDensFact
*enddo
```

7.2 Allowables

Design guidance and structural criteria are contained in the NSTX structural design criterial [6]

7.2-1 Copper Conductor Allowable:

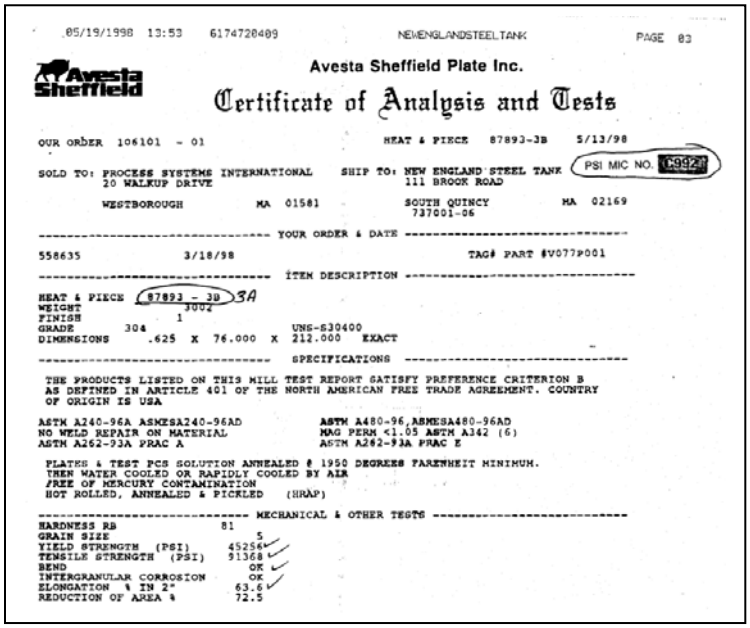
The TF copper ultimate is 39,000 psi or 270 MPa . The yield is 38ksi (262 MPa). Sm is 2/3 yield or 25.3ksi or 173 MPa – for adequate ductility, which is the case with this copper which has a minimum of 24% elongation. Note that the ½ ultimate is not invoked for the conductor (It is for other structural materials) . These stresses should be further reduced to consider the effects of operation at 100C. This effect is estimated to be 10% so the Sm value is 156 MPa.

- From: I-4.1.1 Design Tresca Stress Values (Sm), NSTX_DesCrit_IZ_080103.doc
- • (a) For conventional (i.e., non-superconducting) conductor materials, the design Tresca stress values (Sm) shall be 2/3 of the specified minimum yield strength at temperature, for materials where sufficient ductility is demonstrated (see Section I-4.1.2). *****
- It is expected that the CS would be a similar hardness to the TF so that it could be wound readily. For the stress gradient in a solenoid, the bending allowable is used. The bending allowable is 1.5*156 or 233MPa

7.2-2 Stainless Steel Allowable

Many of the calculations that address individual components include specific data on the strength of the materials used. Included in this section is some general information on the Stainless Steels used in NSTX

Material	Sm	1.5Sm
316 LN SST	183Mpa (26.6 ksi)	275Mpa (40ksi)
316 LN SST weld	160MPa(23.2ksi)	241MPa(35ksi)
304 Vessel		45 ksi



05/19/1998 13:53 6174720409 NEWENGLANDSTEELTANK PAGE 03

Avesta Sheffield

Avesta Sheffield Plate Inc.

Certificate of Analysis and Tests

OUR ORDER 106101 - 01 HEAT & PIECE 87893-3B 5/13/98

PSI MIC NO. C9924

SOLD TO: PROCESS SYSTEMS INTERNATIONAL
20 WALKUP DRIVE
WESTBOROUGH MA 01581

SHIP TO: NEW ENGLAND STEEL TANK
111 BROOK ROAD
SOUTH QUINCY MA 02169
737001-06

YOUR ORDER & DATE

558635 3/18/98 TAG# PART #V077P001

ITEM DESCRIPTION

HEAT & PIECE 87893 - 3B 3A
WEIGHT 3002
FINISH 1
GRADE 304 UNS-S30400
DIMENSIONS .625 X 76.000 X 212.000 EXACT

SPECIFICATIONS

THE PRODUCTS LISTED ON THIS MILL TEST REPORT SATISFY PREFERENCE CRITERION B AS DEFINED IN ARTICLE 401 OF THE NORTH AMERICAN FREE TRADE AGREEMENT. COUNTRY OF ORIGIN IS USA

ASTM A240-96A ASMESA240-96AD
NO WELD REPAIR ON MATERIAL
ASTM A262-93A PRAC A

ASTM A480-96,ASMESA480-96AD
MAG PERM <1.05 ASTM A342 (6)
ASTM A262-93A PRAC E

PLATES & TEST PCS SOLUTION ANNEALED @ 1950 DEGREES FARENHEIT MINIMUM. THEN WATER COOLED OR RAPIDLY COOLED BY AIR
FREE OF MERCURY CONTAMINATION
HOT ROLLED, ANNEALED & PICKLED (HRAP)

MECHANICAL & OTHER TESTS

HARDNESS RB	81
GRAIN SIZE	5
YIELD STRENGTH (PSI)	45256
TENSILE STRENGTH (PSI)	91368
BEND	OK
INTERGRANULAR CORROSION	OK
ELONGATION % IN 2"	63.6
REDUCTION OF AREA %	72.5

7.2.3 Insulation Allowables

Insulation systems used in NSTX upgrade include the existing original systems Fusifab and CTD 112P (see Appendix D), and a new Cyanate Ester - epoxy blend, CTD 425 with a Cyanate Ester Primer -CTD 450 [36]

CDR and PDR Insulation Allowable Estimates

Throughout the CDR and PDR, Test data was not available, and allowables had to be constructed from published data for similar insulation systems

From Dick Reed Reports/Conversations [5] :

Shear strength, short-beam-shear, interlaminar
Without Kapton 65 MPa (TF, PF1 a,b,c)
With Kapton 40 MPa (CS)
Estimated Strength at Copper Bond 65 MPa/2 =32.5 MPa (All Coils)

Fatigue Estimate Based on CIT/BPX Tests with BeCu

Figure 7.2.3-1 at right shows the shear compression data from CTD for 101 K and BeCu. at room and cryogenic temperatures

5ksi=34 MPa
2/3 of this is 23 MPa
C2~=.1 (not .3)

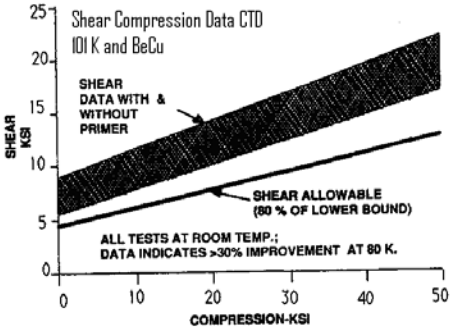


Figure 7.2.3-1

Estimate of Shear Stress Allowable Based on Published Cyanate Ester Data

For the TF, the shear stress allowable has been set by testing of the CTD 425 with-the Cyanate Ester primer. These results are included in the test report [36]. Also the shear stress allowable is considered in more detail in [15]

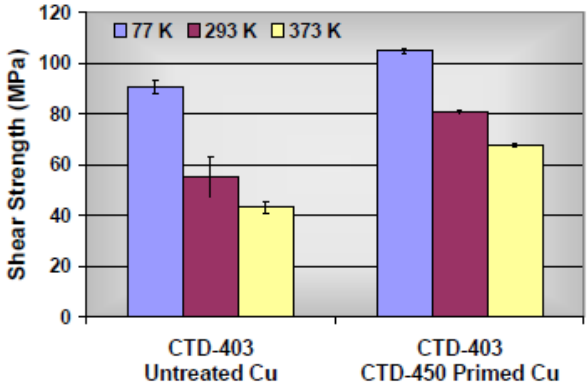


Figure 7.2.3-2 Shear Strength with binder

Estimate of Shear Stress Fatigue Allowable Based on Published Cyanate Ester Data

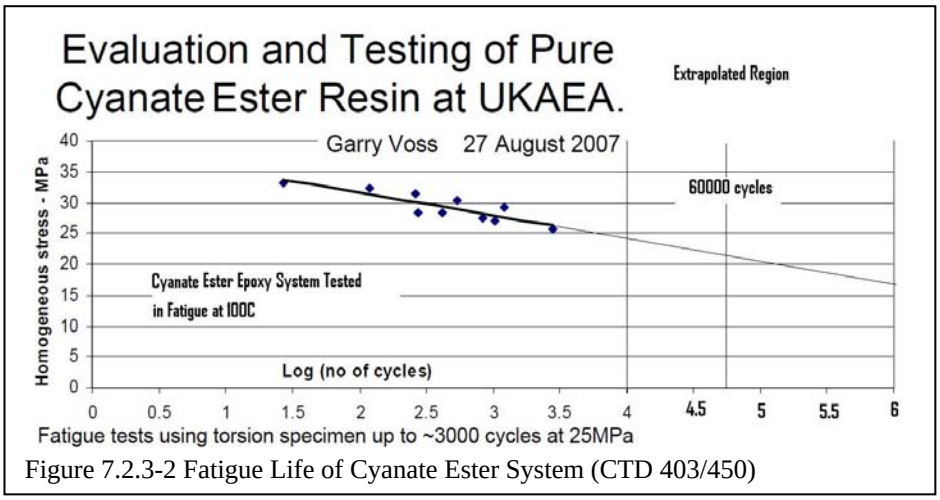


Figure 7.2.3-2 Fatigue Life of Cyanate Ester System (CTD 403/450)

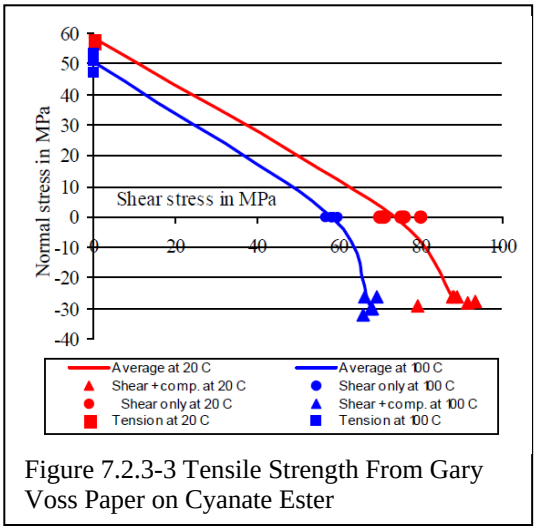


Figure 7.2.3-3 Tensile Strength From Gary Voss Paper on Cyanate Ester

The fatigue strength for the required 60000 cycles based on the Cyanate Ester primer at 100C is 21.5 MPa. The allowable without compression is 2/3*21.5= 14.33 MPa

"Homogenous" is an estimate of the average torsional shear in the torsion sample. If fully elastic, the peak shear is higher than the homogenous value. - So this plot underestimates the shear capacity unless creep or relaxation causes the shear to approach the Homogenous value.

Allowable Stress Summary from the PDR

Criteria – Stress Allowables

	Sm	Sb	
TF Copper	156 MPa	233MPa,	
OH Copper	156 MPa	233MPa	
Vessel 304 Away from weld	30 ksi 207 MPa	45 ksi 310 MPa	Mill Certs for the 304 Vessel Show a 45 ksi Yield
304 Vessel in Heat Effected Zone	20 ksi 138 MPa	30 ksi 206MPa	
316	183 MPa	275 MPa	
316 weld	160MPa	241MPa	
AISC/ASME/AWS 304 weld	20 ksi (w/PT)	14ksi (w/Visual)	

	Static	Fatigue	
TF Insulation	2/3 of 24 - 16 MPa	16 Mpa Qualified by Component Test	Existing TF Prepreg CTD 12P
CS Insulation CTD 101K	***2/3 of 32.5 MPa = 21.7 MPa***	2/3*21.5MPa=14.3 Mpa based on primer	With high temp binder CTD-450

7.0 Global Model Details

The Global model of NSTX Center Stack Upgrade (NSTX-CSU) provides a simulation of the overall behavior of the machine. It provides boundary conditions for local models and sub Models , or allows inclusion of the detailed models of components in the global model. In many cases it has been built from from other available model segments – The upper and lower head sections of the vessel model come from H.M. Fan's early vessel models. The cylindrical shell that contains the mid plane ports comes from a vessel model built by Srinivasa Avasarala from the Pro–E model of the vessel. Thermal Extremes, bake-out and operating temperatures in the centerstack casing are included as separate load steps . In another load step vacuum loads are applied. In some runs these are left on and in others they are turned off. To get the proper load balance, all the port openinngs must be closed and properly loaded. At this writing there are still some vessel shell areas that are reversed and some port openings that are not closed.

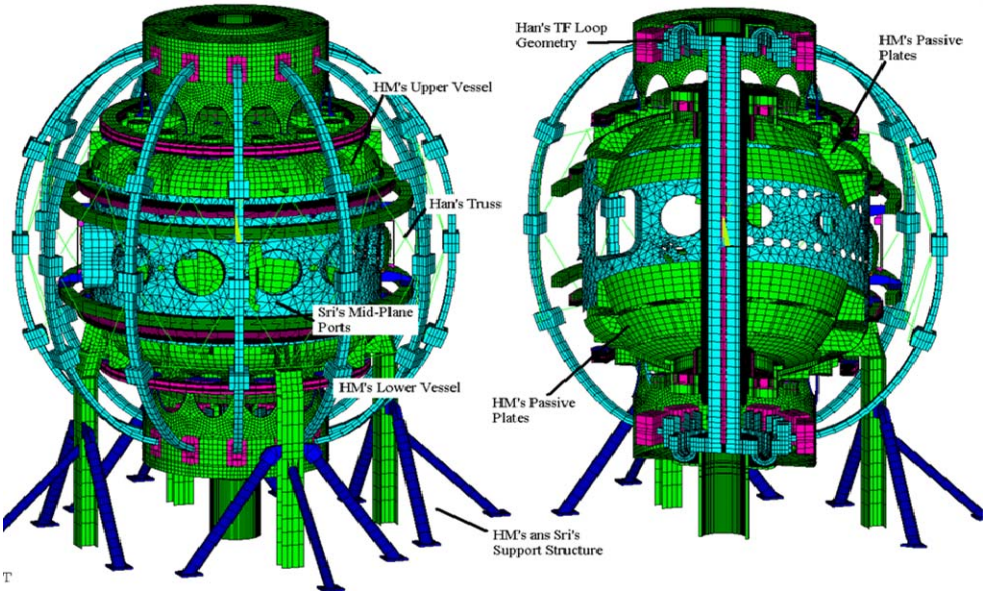


Figure 7.0-1 Global Model Status as of June 22 2009

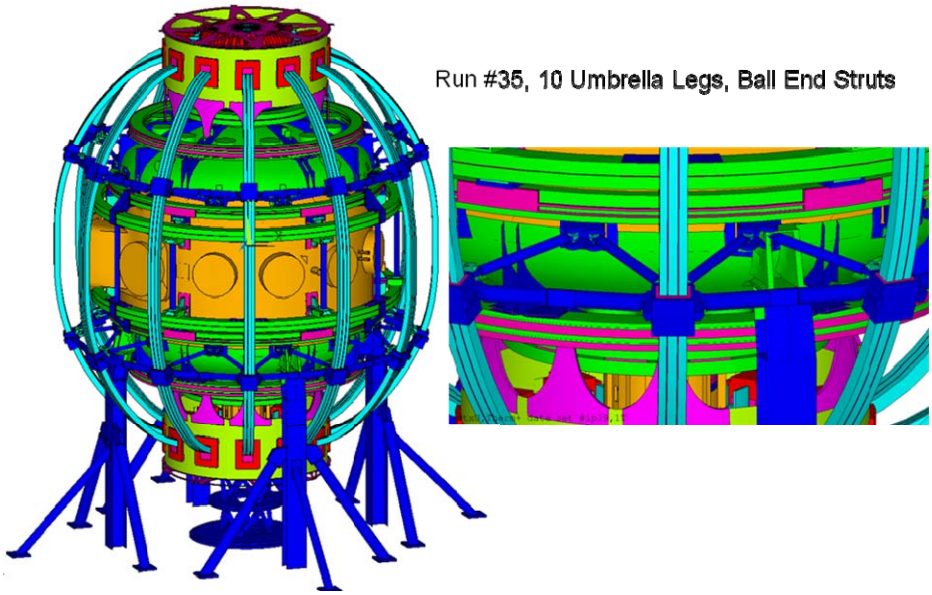


Figure 7.0-2 Global Model Status as of Sept 7 2011

7.1 Modeling Elements, Real Constants

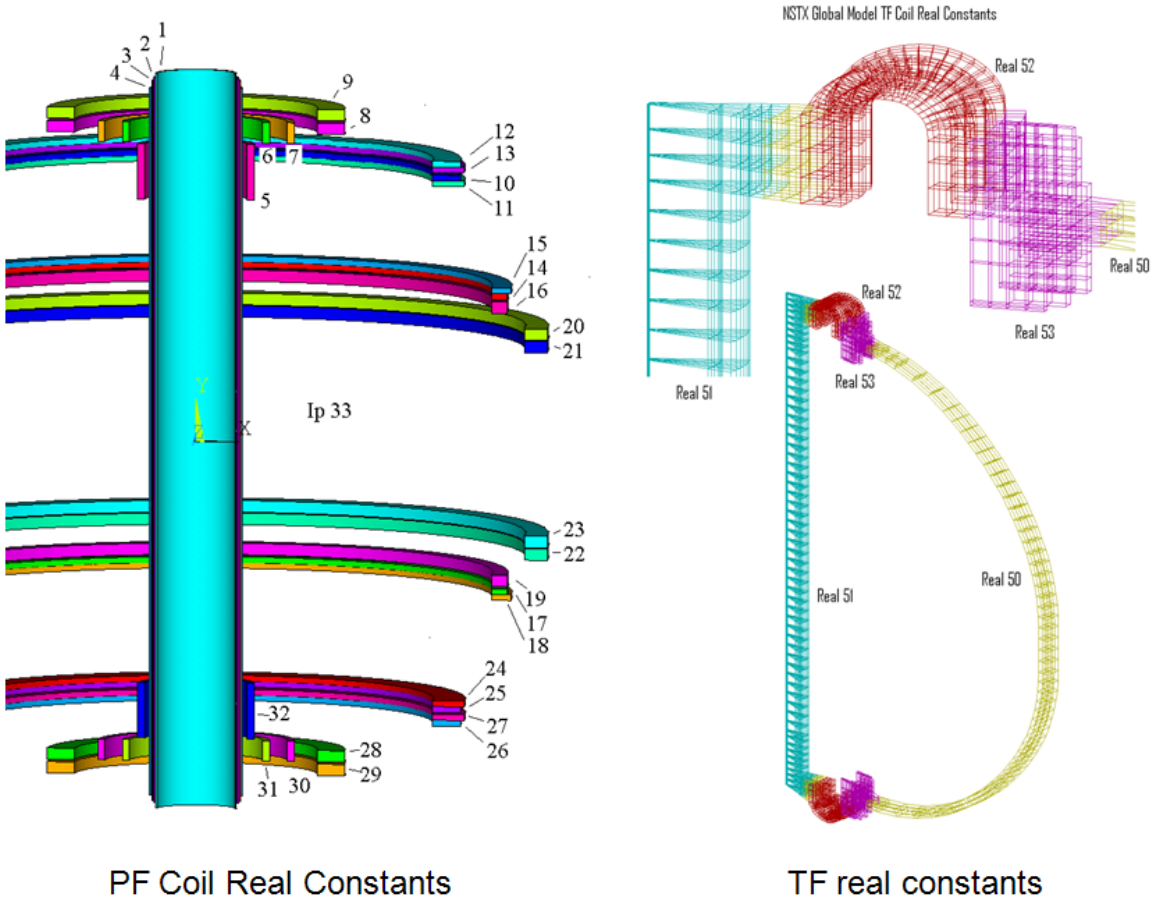


Figure 7.1-1 Model Real Constants

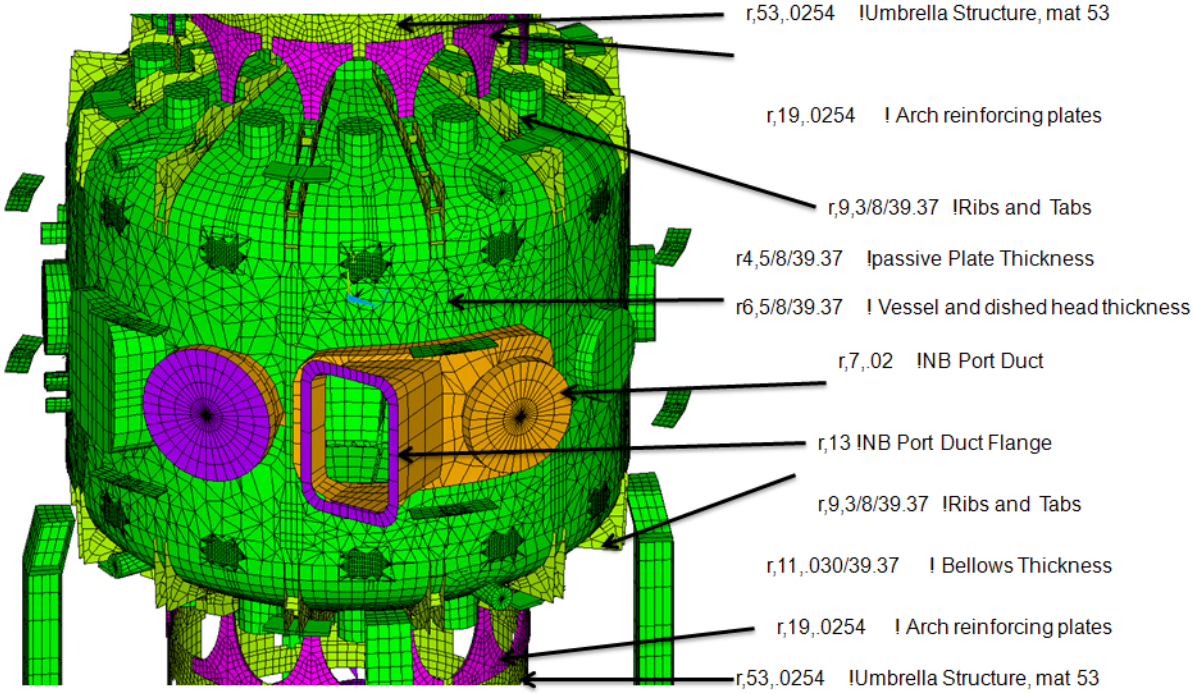


Figure 7.1-2 Model Real Constants

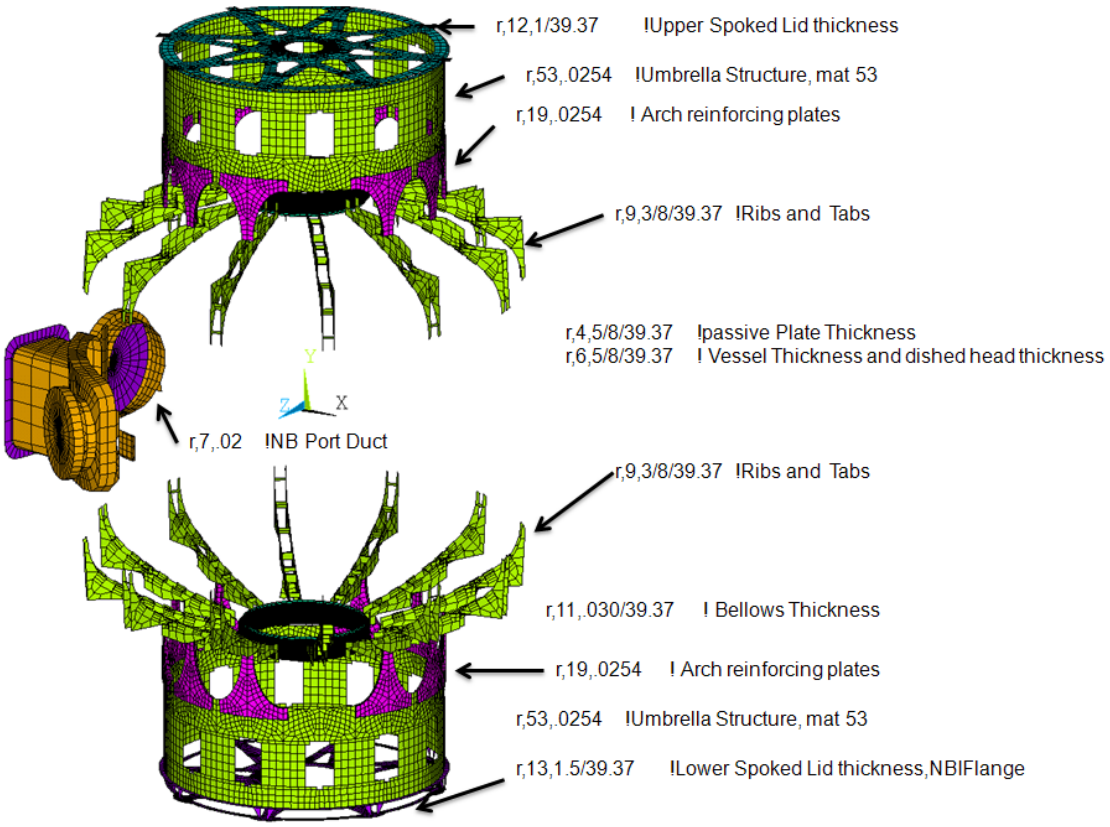


Figure 7.1-3 Model Real Constants

Figure 7.1-2 View Inside Umbrella Structure

```
!             REAL CONSTANTS
r,1,.001       !connection at the OH-TF
Spoolpiece
r,2,1e10    ! Gaps
r,2,.001
r,3,.001
r,2,.002*.002
r,4,.001    ! Mag Press Links and Cover plate
Links
r,16,.0254,   !Lid/Flex Thickness
r,17,.001   !Jack Inner Ring
r,4,5/8/39.37    !passive Plate Thickness
r,5,.001   ! PF and Ring Vertical Links
r,6,5/8/39.37    ! Vessel Thickness and dished
head thickness
r,7,.02    !NB Port Duct
r,8,.001     ! Links
r,9,3/8/39.37  !Ribs and  Tabs
r,11,.030/39.37     ! Bellows Thickness
r,12,1/39.37        !Upper Spoked Lid
thickness
r,13,1.5/39.37      !Lower Spoked Lid
thickness,NBIFlange
r,19,.0254     ! Arch reinforcing plates
r,22,.001
r,41,.001,0.0    ! Links Supporting PF
r,42,.001,.001,.01,.01,.01,.01,.01,   ! Truss
Members
r,53,.0254    !Umbrella Structure, mat 53
r,76,.01 ,-.15   ! Links Under the Tierod
r,78,.003,-.50
r,63,.05
```

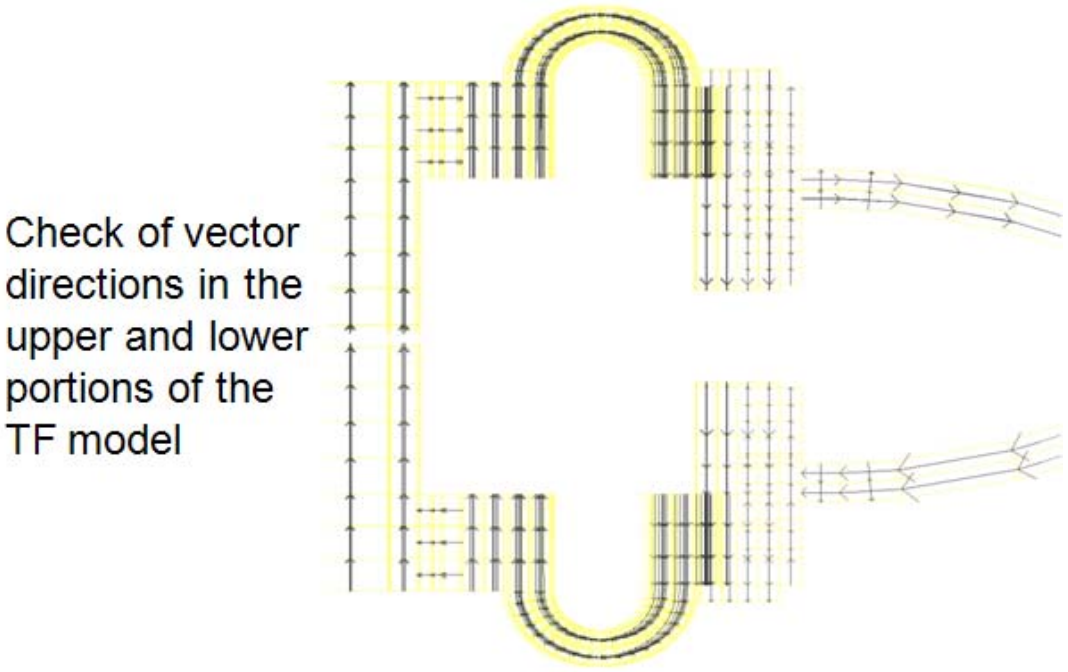


Figure 7.1-3 Current Vector Directions in the Upper and Lower Flex Joint Elements

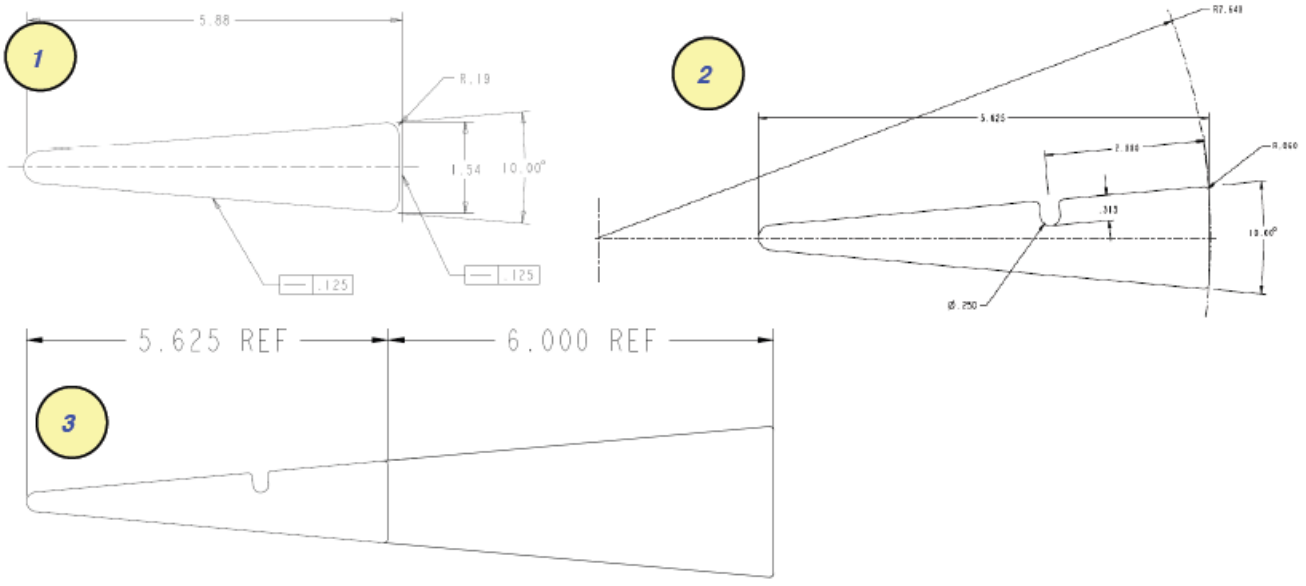


Figure 7.1-4 Inner Leg Cross Sections

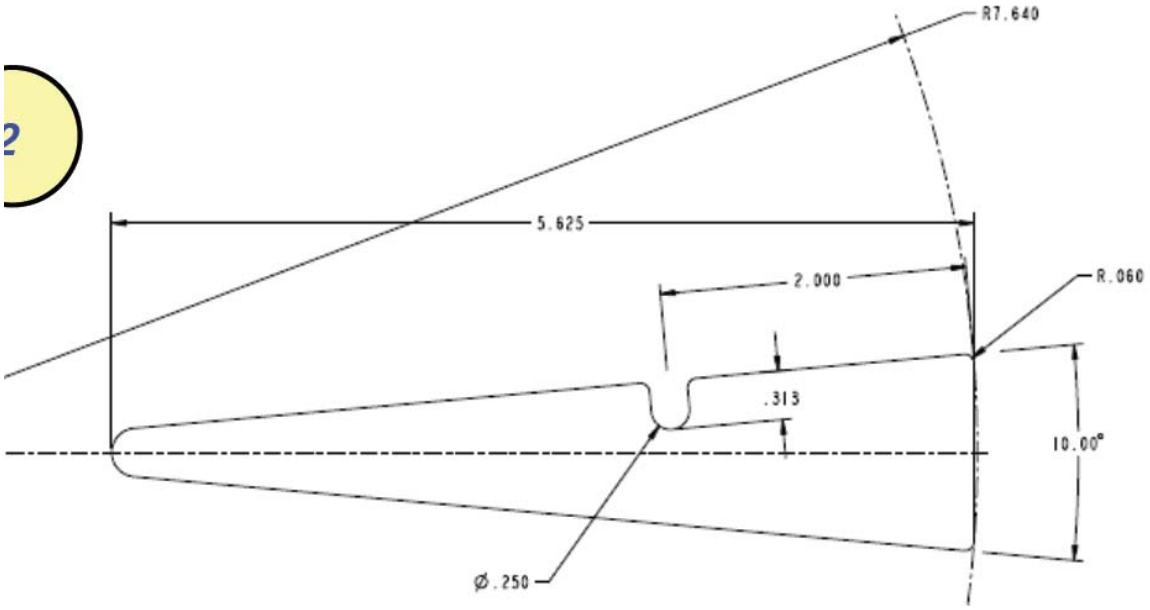


Figure 7.1-5 Inner Leg Cross Section

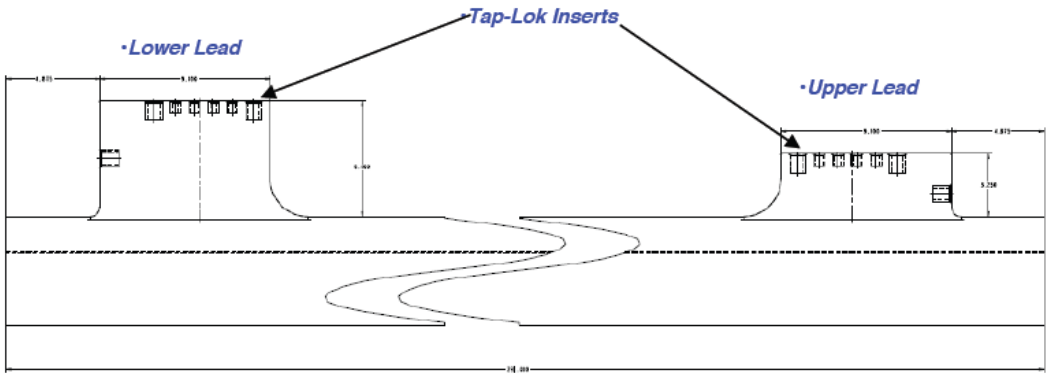


Figure 7.1-6 Inner Leg Build

TF Currents

The current in a set of TF coils may be calculated from the simple relation:

I=5e6*radius*BTat radius.

		NSTX BASE	NSTX CSU
Ro	m	0.854	0.934
A_100		1.3	1.5

Ip	MA	1.0	2.0
Bt@Ro	T	0.6	1.0
I =5e6*radius*T at Radius	Amp	2.562e6	4.67e6
I per Turn =	Amp	71166	129722

TF Outer Leg Dimensions

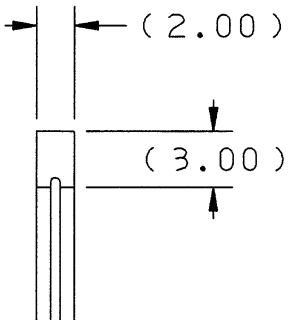


Figure 7.1-7 Single Turn Dimensions (The Outboard Leg has 3 turns

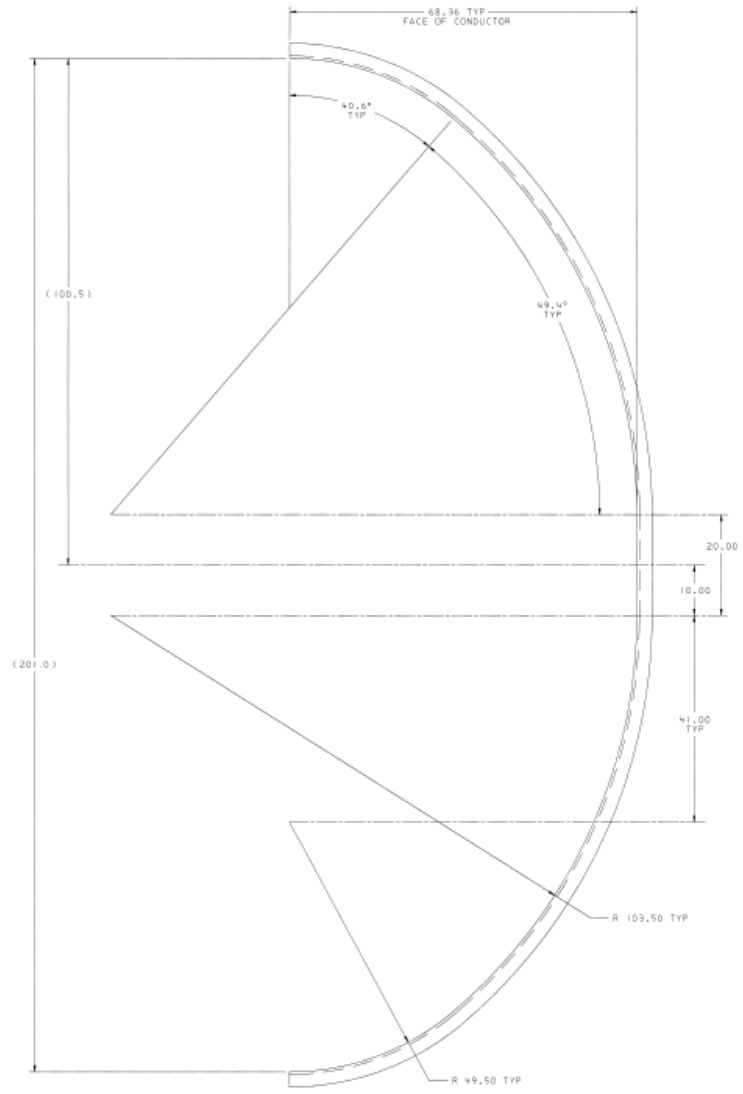


Figure 7.1-8 TF Outer Leg Dimensions

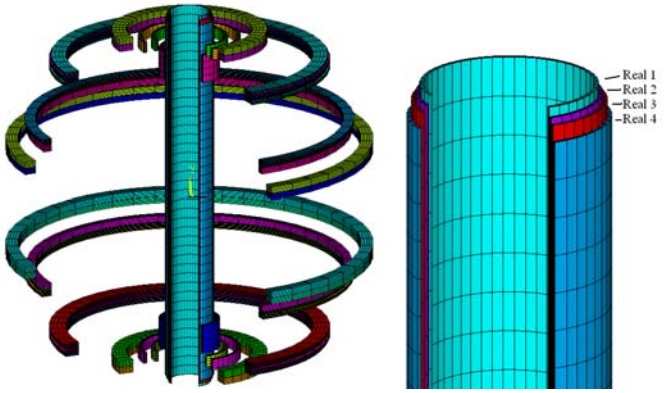


Figure 7.1-9

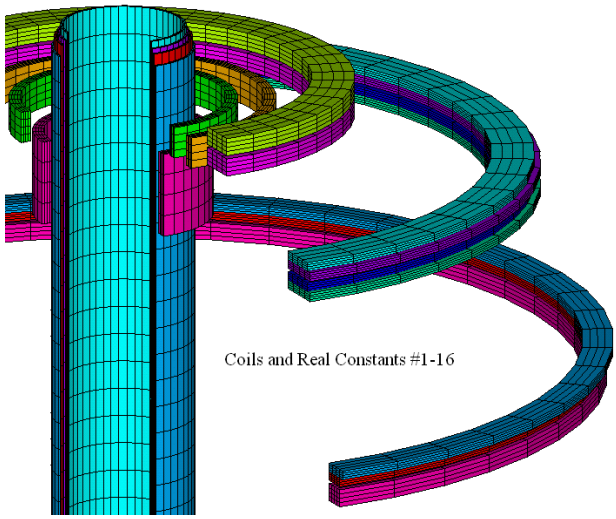


Figure 7.1-10

Coil Builds
#33 is the Plasma

#	r	z	dr	dz	nx	nz
1	.2344	.0021	.01	4.3419	2	20
2	.2461	.0067	.01	4.2803	2	20
3	.2577	.0022	.01	4.2538	2	20
4	.2693	-.0021	.01	4.1745	2	20
5	.3239	1.5906	.0413	.3265	4	4
6	.4142	1.8252	.042	.1206	4	4
7	.56	1.8252	.042	.1206	4	4
8	.7992	1.8526	.1627	.068	4	4
9	.7992	1.9335	.1627	.068	4	4
10	1.4829	1.5696	.1631	.034	4	4
11	1.4945	1.5356	.1864	.034	4	4
12	1.4829	1.6505	.1631	.034	4	4
13	1.4945	1.6165	.1864	.034	4	4
14	1.795	.8711	.0922	.034	4	4
15	1.8065	.9051	.1153	.034	4	4
16	1.7946	.8072	.0915	.068	4	4
17	1.795	-.8711	.0922	.034	4	4
18	1.8065	-.9051	.1153	.034	4	4
19	1.7946	-.8072	.0915	.068	4	4
20	2.0118	.6489	.1359	.0685	4	4
21	2.0118	.5751	.1359	.0685	4	4
22	2.0118	-.6489	.1359	.0685	4	4
23	2.0118	-.5751	.1359	.0685	4	4
24	1.4829	-1.5696	.1631	.034	4	4
25	1.4945	-1.5356	.1864	.034	4	4
26	1.4829	-1.6505	.1631	.034	4	4
27	1.4945	-1.6165	.1864	.034	4	4
28	.7992	-1.8526	.1627	.068	4	4
29	.7992	-1.9335	.1627	.068	4	4
30	.56	-1.8252	.042	.1206	4	4
31	.4142	-1.8252	.042	.1206	4	4
32	.3239	-1.5906	.0413	.3265	4	4
33	.9344	0	.5696	1	6	8

Coil Builds as of June 2011

Coil	R (center)	dR	Z (center)	dZ
	(cm)	(cm)	(cm)	(cm)
OH (half-plane)	24.2083	6.934	106.04	212.08
PF1a	32.4434	6.2454	159.06	46.3296
PF1b	40.038	3.36	180.42	18.1167
PF1c	55.052	3.7258	181.36	16.6379
PF2a	79.9998	16.2712	193.3473	6.797
PF3a	149.446	18.6436	163.3474	6.797
PF3b	149.446	18.6436	155.26	6.797
PF4b	179.4612	9.1542	80.7212	6.797
PF4c	180.6473	11.5265	88.8086	6.797
PF5a	201.2798	13.5331	65.2069	6.858
PF5b	201.2798	13.5331	57.8002	6.858

7.2 Input Currents

The most recent analyses are based on the current sets included in the design point:
http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

In addition, some earlier runs used a series of equilibria from Jon Menard and worst case currents provided by C. Neumeyer. These are shown below:

PF Scenario Currents In Mat – (Prior to 90 Design Point Scenarios)

Coil #	TFON	IM	-0.1	-0.05	0	0.05	0.1	Worst 1	Worst 2	Worst3	Worst4	Worst5
Step	2	3	4	5	6	7	8	9	10	11	12	13
	Nst1	Nst2	Nst3	Nst4	Nst5	Nst6	Nst7	Nsw3	Nsw4	Nsw5	Nsw6	Nsw7
1	0	5.88	.000	.000	.000	.000	.000	-5.88	5.88	5.88	-1.47	-1.47
2	0	5.808	.000	.000	.000	.000	.000	-5.808	5.808	5.808	-5.808	-1.452
3	0	5.76	.000	.000	.000	.000	.000	-5.76	5.76	5.76	-5.76	-1.92
4	0	5.664	.000	.000	.000	.000	.000	-5.664	5.664	5.664	-5.664	-1.416
5	0	0	7.172	7.196	7.234	7.348	7.452	0.784	0.784	0.784	0.784	0.784
6	0	0	-5.650	-4.763	-3.628	-2.331	-.946	0.12	0.12	0.12	0.12	0.12
7	0	0	-4.922	-4.014	-2.936	-1.755	-.517	0.2	0.2	0.2	0.2	0.2
8	0	0	4.484	4.307	3.941	3.401	2.772	0.168	0.168	0.168	0.168	0.168
9	0	0	4.484	4.307	3.941	3.401	2.772	0.168	0.168	0.168	0.168	0.168
10	0	0	-1.058	-1.426	-1.655	-1.720	-1.690	-0.112	-0.112	-0.112	-0.112	-0.112
11	0	0	-1.058	-1.426	-1.655	-1.720	-1.690	-0.128	-0.128	-0.128	-0.128	-0.128
12	0	0	-1.058	-1.426	-1.655	-1.720	-1.690	-0.112	-0.112	-0.112	-0.112	-0.112
13	0	0	-1.058	-1.426	-1.655	-1.720	-1.690	-0.128	-0.128	-0.128	-0.128	-0.128
14	0	0	-2.388	-1.183	-.206	.488	.923	-0.08	-0.08	-0.08	-0.08	-0.08
15	0	0	-2.388	-1.183	-.206	.488	.923	-0.1	-0.1	-0.1	-0.1	-0.1
16	0	0	-2.388	-1.183	-.206	.488	.923	-0.16	-0.16	-0.16	-0.16	-0.16
17	0	0	-2.388	-1.183	-.206	.488	.923	-0.08	-0.08	-0.08	-0.08	-0.08
18	0	0	-2.388	-1.183	-.206	.488	.923	-0.1	-0.1	-0.1	-0.1	-0.1
19	0	0	-2.388	-1.183	-.206	.488	.923	-0.16	-0.16	-0.16	-0.16	-0.16
20	0	0	-3.374	-4.340	-5.139	-5.771	-6.210	-0.384	-0.384	-0.384	-0.384	-0.384
21	0	0	-3.374	-4.340	-5.139	-5.771	-6.210	-0.384	-0.384	-0.384	-0.384	-0.384
22	0	0	-3.374	-4.340	-5.139	-5.771	-6.210	-0.384	-0.384	-0.384	-0.384	-0.384
23	0	0	-3.374	-4.340	-5.139	-5.771	-6.210	-0.384	-0.384	-0.384	-0.384	-0.384
24	0	0	-1.058	-1.426	-1.655	-1.720	-1.690	-0.112	-0.112	-0.112	-0.112	-0.112
25	0	0	-1.058	-1.426	-1.655	-1.720	-1.690	-0.128	-0.128	-0.128	-0.128	-0.128
26	0	0	-1.058	-1.426	-1.655	-1.720	-1.690	-0.112	-0.112	-0.112	-0.112	-0.112
27	0	0	-1.058	-1.426	-1.655	-1.720	-1.690	-0.128	-0.032	-0.128	-0.128	-0.128
28	0	0	4.484	4.307	3.941	3.401	2.772	0.168	0.168	0.168	0.168	0.168
29	0	0	4.484	4.307	3.941	3.401	2.772	0.168	0.168	0.168	0.168	0.168
30	0	0	-4.922	-4.014	-2.936	-1.755	-.517	0.2	0.2	0.2	0.2	0.2
31	0	0	-5.650	-4.763	-3.628	-2.331	-.946	0.12	0.12	0.12	0.12	0.12
32	0	0	7.172	7.196	7.234	7.348	7.452	0.784	0.784	0.784	0.784	0.784
33	0	0	2.000	2.000	2.000	2.000	2.000	2	2	2	2	2

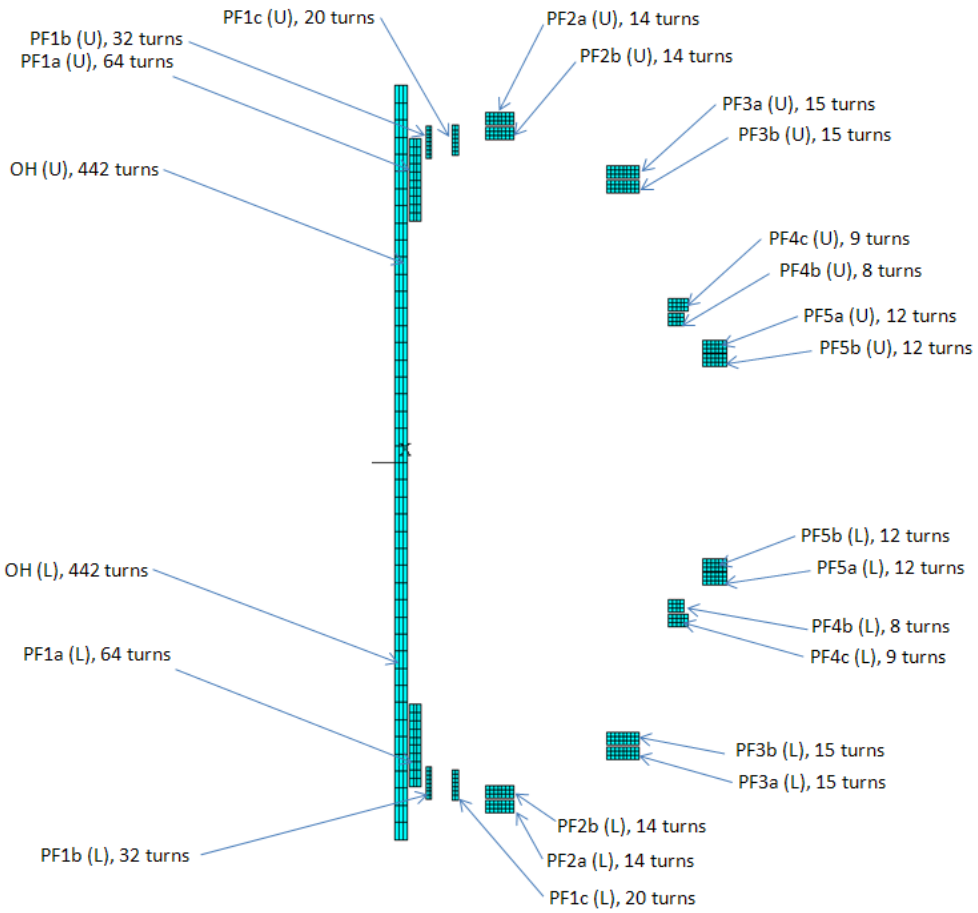


Figure 7.2-1 PF Coil Turns

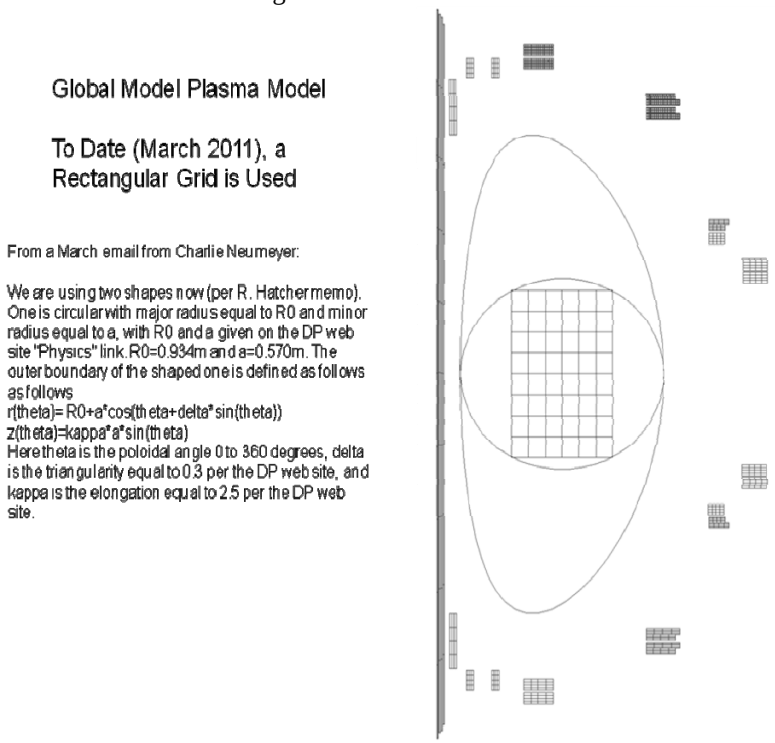


Figure 7.2-2 Plasma Modeling

7.3 Fields and Forces

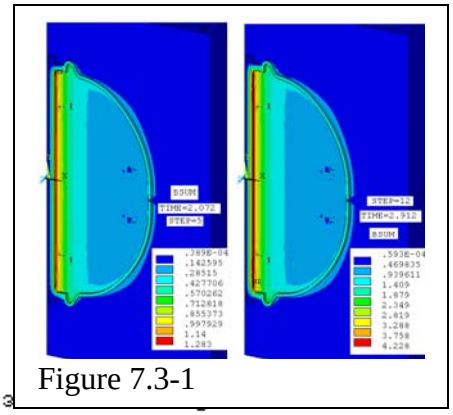


Figure 7.3-1

The peak field from the load files used in the global model is 4.9T. The peak field from the electromagnetic current diffusion model is 4.2T. They used different TF inner leg dimensions from different design point published throughout 2009

```
getn
 Node Number          21303
  Dir      Cart         Cyl
 x   -0.1824810       0.1942377
 y    1.955740        2.791884      rad    159.963148853
 z   -6.6550598E-02   1.955740
 fx    6769.650
 fy   4.7772299E-04
 fz    2463.140
 t   0.0000000E+00
 bt,bx,by,bz    4.909902       -1.681310       2.9661099E-03    4.613060
```

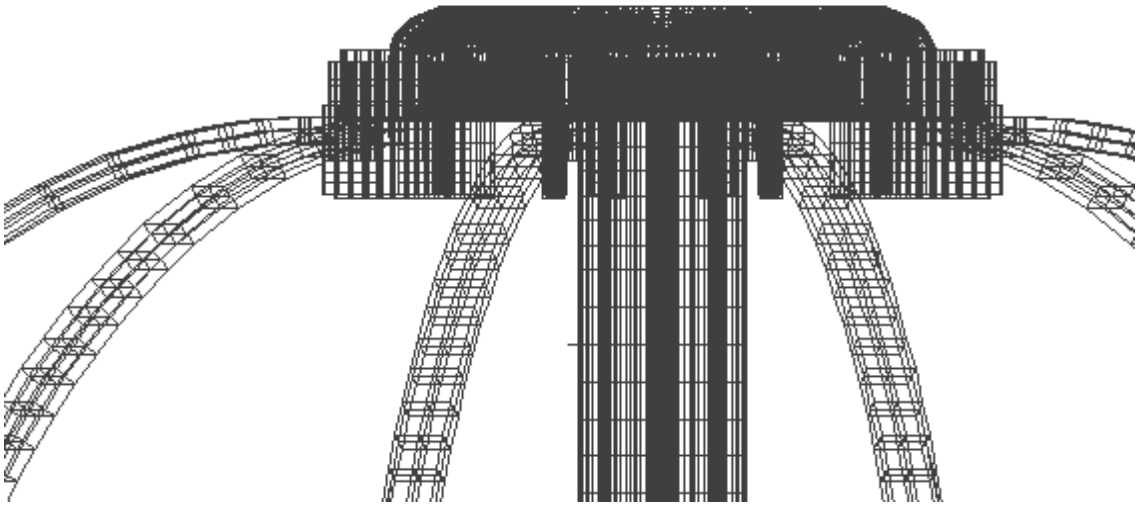


Figure 7.3-2

Fz(lbf)	(PF1AU+PF1BU+PF1BL+PF1AL+OH)	
Min w/o Plasma	-39635	
Min w/Plasma	-53445	
Min Post-Disrupt	-41843	
Min	-53445	-59436.16548
Worst Case Min	-375500	
Max w/o Plasma	20397	
Max w/Plasma	10748	
Max Post-Disrupt	19630	
Max	20397	22683.49644
Worst Case Max	375501	

Net Forces on the Outer Structures being supported by the I-Beam Columns

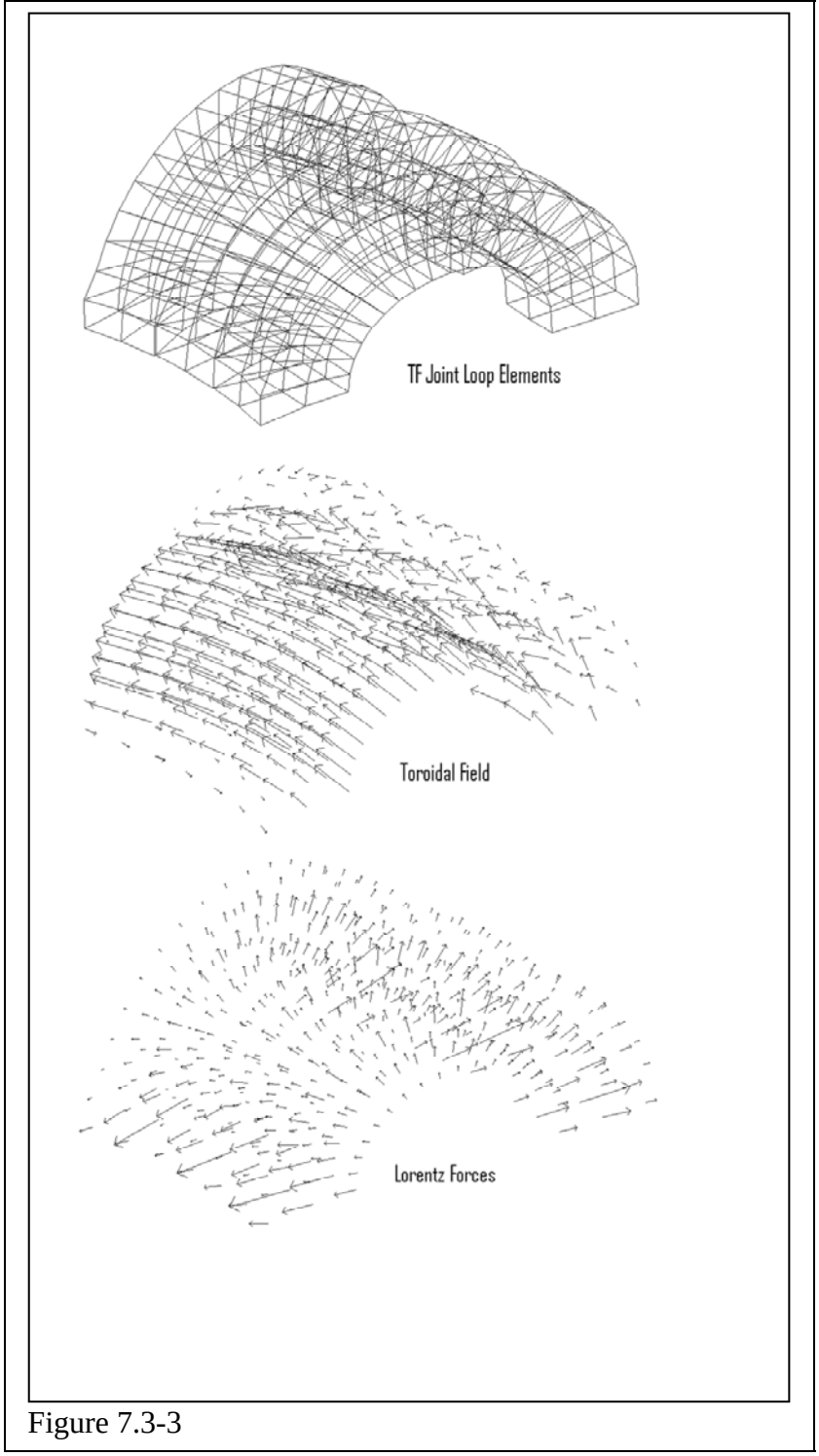


Figure 7.3-3

One of the questions that came up in the CDR is whether the multiple straps in the TF joint, are attracted to each other. They are due to their self field, but the global toroidal field is much stronger than the self fields and the Lorentz forces from the TF current crossing the TF field is

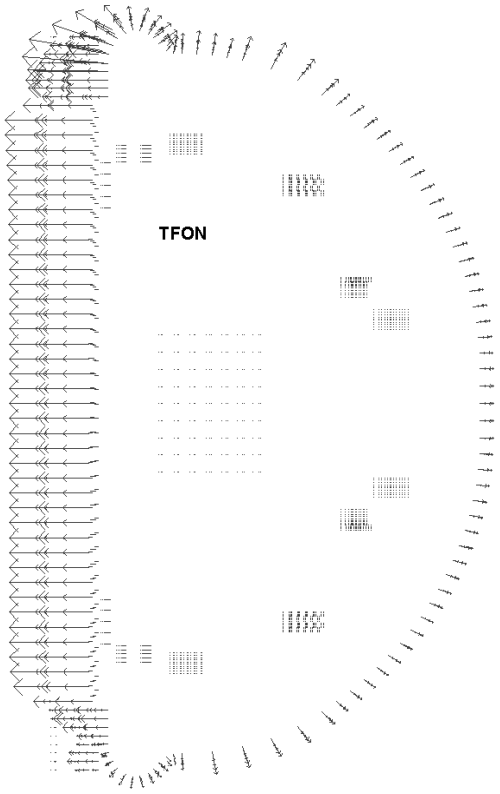


Figure 7.3-4 TFON Loading

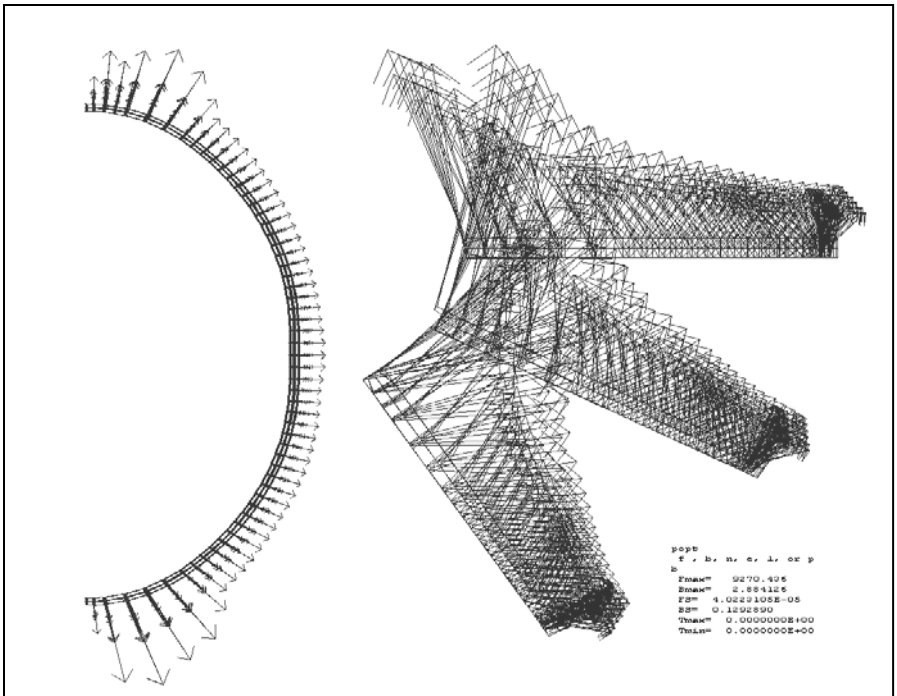


Figure 7.3-5 TFON Outer Leg Loading

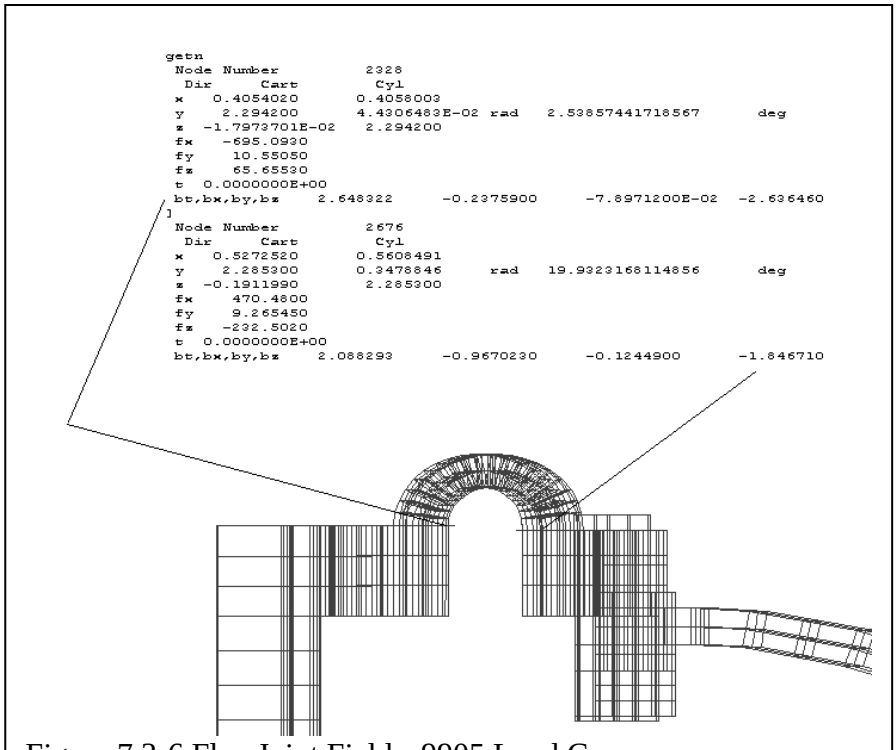


Figure 7.3-6 Flex Joint Fields, 9905 Load Case

```
getn
 Node Number          1180
  Dir      Cart        Cyl
 x    0.3241740      0.3356096
 y     2.106700      0.2617998      rad   15.0000239056614      deg
 z   -8.6862303E-02   2.106700
 fx    -1542.140
 fy     3216.290
 fz     341.2660
 t   0.0000000E+00
 bt,bx,by,bz     3.817964      -1.023640      -0.1029260      -3.676740
]
 Node Number          2791
  Dir      Cart        Cyl
 x    0.6078280      0.6309829
 y     2.106700      0.2717468      rad   15.5699468269788      deg
 z   -0.1693650       2.106700
 fx     303.1900
 fy   0.0000000E+00
 fz    -67.72940
 t   0.0000000E+00
 bt,bx,by,bz     1.067500      -0.2191660      -0.1238730      -1.037390
```

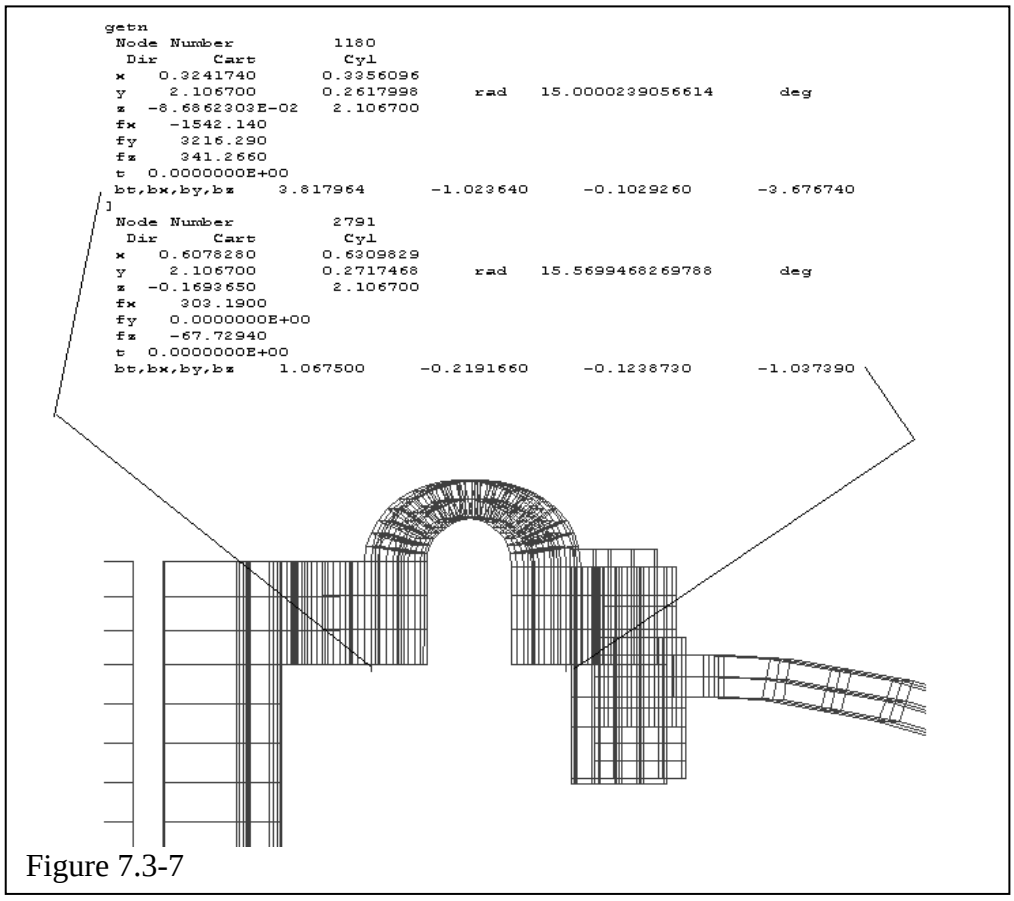


Figure 7.3-7

```
getn
 Node Number          13937
  Dir      Cart        Cyl
 x    0.4787880      0.4846534
 y     2.910690      0.1557359      rad   8.92300840227081      deg
 z   -7.5173199E-02   2.910690
 fx    0.0000000E+00
 fy    0.0000000E+00
 fz    0.0000000E+00
 t   0.0000000E+00
 bt,bx,by,bz     1.250747      -0.1735220      0.2616100      -1.210710
```

Single TF Model,
TF31 Load File

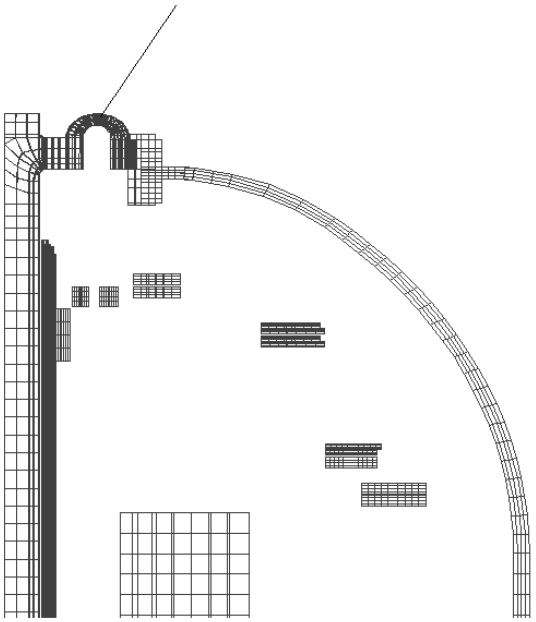


Figure 7.3-8

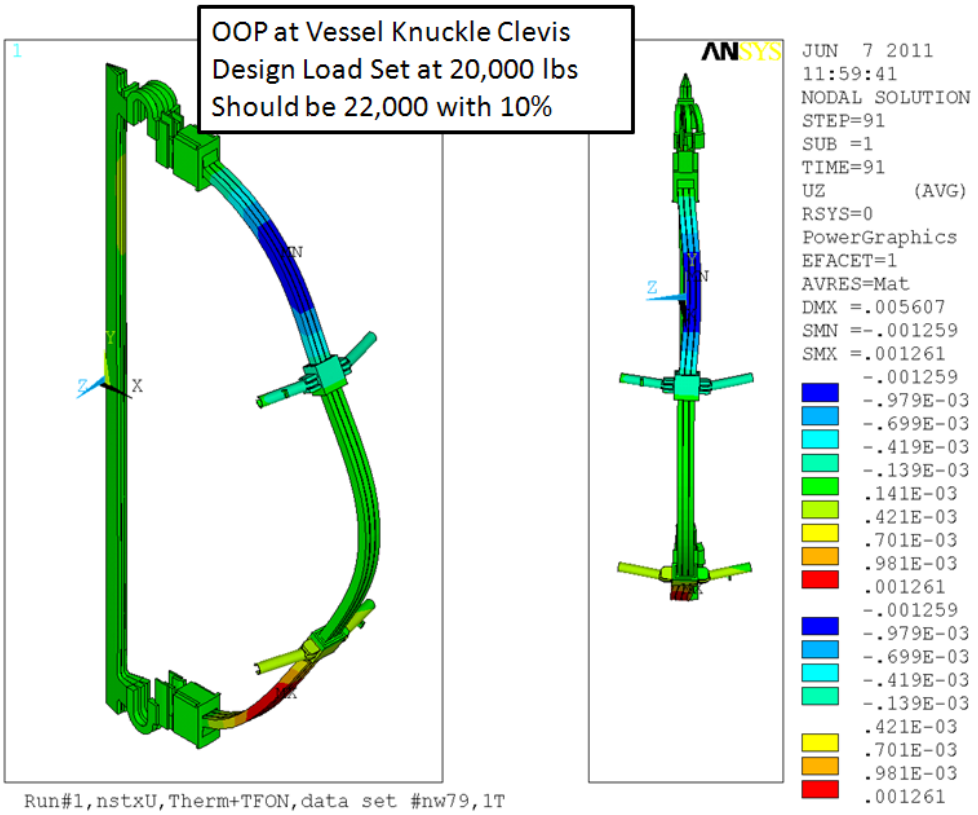


Figure 7.3-9

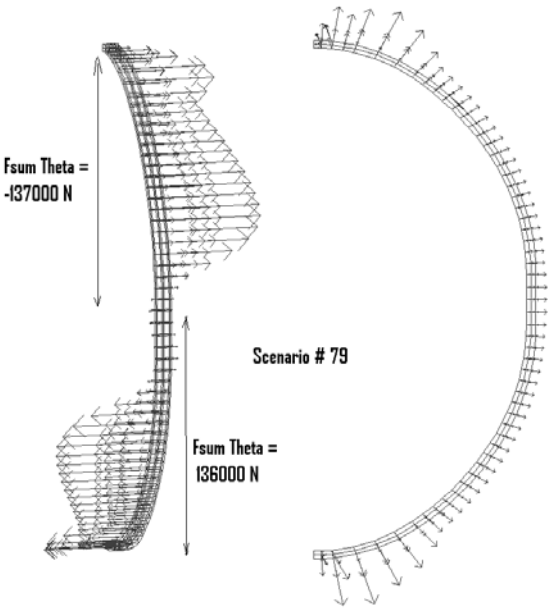
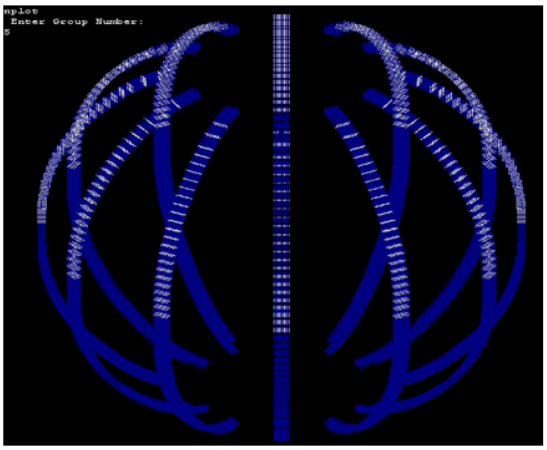


Figure 7.3-10
OOP Forces for Scenario #79 Summed from the joint flags out. From the aluminum blocks out the sum is 127000 N for the upper half.




```
input
 ENTER 4 chr FILENAME
mtot
 ENTER material and group numbers
 ENTER material and group numbers
 Cartesian Coord Select
 ENTER egroup number,xmin,xmax,ymin,ymax,zmin,zmax
 Selecting Elements By Coordinate Range To Be Group        17
       0  Elements Selected
 ENTER egrp number
 Erasing Element Group        17
 ENTER ngrp number, xmin,xmax,ymin,ymax,zmin,zmax
    12796  nodes selected
 ENTER node group for Force Summation
 FORCE SUMMARY FOR NODE GROUP=         5
 FXSUM=  -1.410431     FXMAX=   2538.220     FXMIN=  -2538.220
 FYSUM=   1894507.     FYMAX=   2612.640     FYMIN=  -512.3480
 FZSUM=  -2.274170     FZMAX=   2538.230     FZMIN=  -2538.230
 FTMAX=   3469.652     AT NODE       22586  FTMIN=  0.0000000E+00  AT NODE
       0
 MOMENTS ABOUT CENTER, XC=  0.0000000E+00 YC=  0.0000000E+00 ZC=
0.0000000E+00
 MXSUM=  -0.6482210
 MYSUM=   3718410.
 MZSUM=   2.406964
 MTOT=    3718410.
```

```
Macro mtot
Read
nw79
 smat
17,17
smat
5,17
scar
secoor
17,-1,1,-10,10,-1,1
gera
17
redu

scoo
5,-5,5,0,2.5,-5,5
fsum
5
exit
```

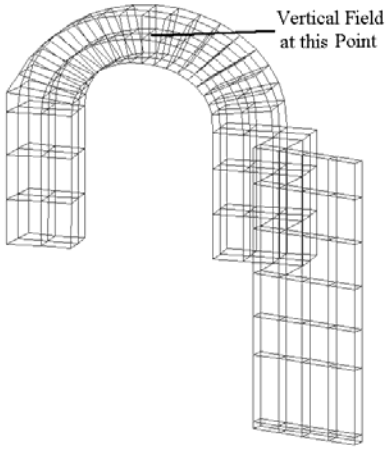
Max Moments from the Design Point

Moment (N-m)	Total TF Outer Leg Moment	Total TF Half Plane Moment
Min	-44741	-3868710

Figure 7.3 -11 TF Outer Leg Upper Half Moment Sum for EQ 79 Compared with the Design Point Spread Sheet Max.

7.3.2 TF Joint "Loop" Vertical Field

The local model of the flex joint developed by Tom Willard [6] originally employed an approximation to the poloidal field. In this section, the load files used in the global model are post processed to show the max or minimum poloidal or vertical field. The first attempt at postprocessing the files produced a max poloidal field of .1 T - different than the design maximum of .3 T provided by R. Hatcher. It was subsequently found that the script that read the fields from the load files only was reporting only the max positive poloidal field. The max absolute value resulted from the negative poloidal field. Figure 7.3-2 shows the positive and minimum extremes of the vertical field at the strap.



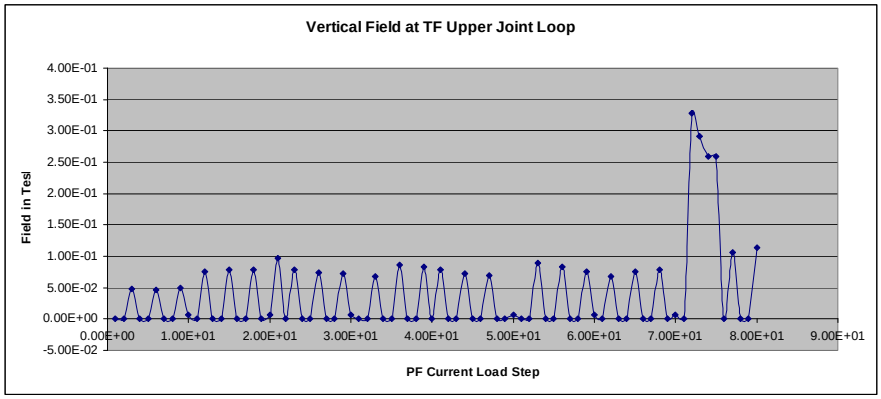


Figure 7.3.2-1 Results with only Positive Fields Reported. The .3T spike is a Worst power supply result, not one of the 96 equilibria

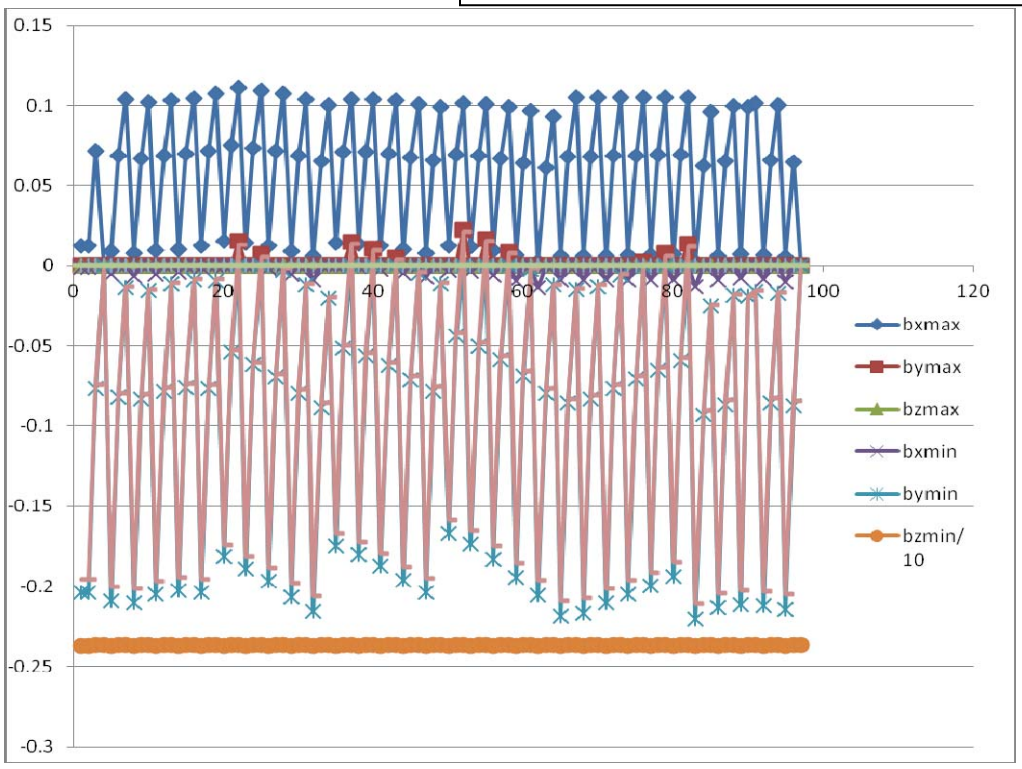


Figure 7.3.2-21 Results with Positive and Nrgative Fields Reported

```
!NTFTM snnu
Macro:
snnu
5,93395,93395,1
snnu
5,93396,93396,1
snnu
5,93521,93521,1
bsum
5
5
2,1000
zero
exit
```

```
read
nw01
macro
snnu
read
nw01
macro
snnu
read
nw02
macro
snnu
read
nw03
macro
snnu
read
nw04
```

7.4 Mesh Generation and Model Creation.

The mesh generation and calculation of the Lorentz forces is done outside of ANSYS using a code written by the author of this report. The mesh generation feature of the code is checked visually and within ANSYS during the PREP7 geometry check. . The authors code uses a Biot Savart solution for field calculations, based on single stick field calculations from Dick Thomes book [3] with some help from Pillsbury's FIELD3D code to catch all the coincident current vectors, and other singularities. The analysts in the first ITER EDA went through an exercise to compare loads calculated by the US, RF and by Cees Jong in ANSYS, and that the US analyses were "OK". Agreement was not good on net loads on coils that should net to zero – all the methods had some residuals, but summations on coil segments agreed very well. code Some information on the code, named FTM (Win98) and NTFTM2 (NT,XP), is available at: http://198.125.178.188/ftm/manual.pdf).

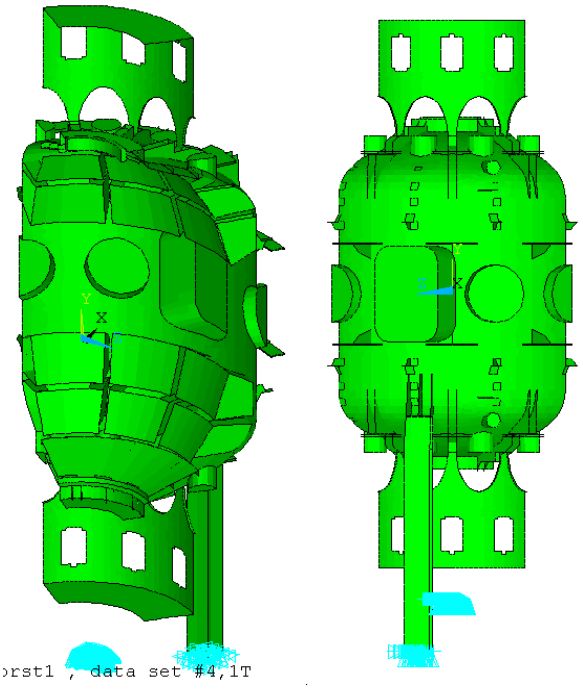


Figure 7.2-1 H.M. Fan's Quarter Symmetry Model of the Vessel and Passive Plates

The loads can be calculated within ANSYS, but the constraints on magnetic modeling vs. structural modeling make it tough to vary the structure. Coil mesh files and load files are separate in the structural model, and the support structure can be changed without changing the magnetics. The model segments and load files are input with the /INPUT command within the ANSYS batch file and look like ANSYS text commands. All the solid elements are SOLID 45's. Higher order elements are not used because the force calculations, if done outside of ANSYS, need some correction at the mid side nodes. Recent checks of the accuracy of NTFTM are included in the magnet stiffness calculation [22] in which the non-concentric loading between a misaligned OH and PF1a and b is quantified by both MAXWELL and NTFTM. Gap elements are the point-to-point type – Type 52. The use of the authors meshing tools is largely a result of wanting to control the mesh alignment at the interfaces, required by the point to point elements. Target surface elements take up too much solution time.

The program, NTFTM was used to generate the input currents to the Biot Savart Analysis. The Subroutine that converts terminal currents to 33 coil segment real constants is included in Appendix B. Below is the input that takes the currents from the spreadsheet, and produces 8 sets of currents in the appropriate format in MAt for the 33 coil regions used in this calculation:

```
nstx
80
1,-6.5089,8.1782,11.3783,-1.8343,-10.5643,3.5565,-25.4155,-10.5643,-1.8343,11.3783,8.1782,-6.5089,-24
2,-6.07,9.4451,13.3051,2.9049,-8.822,3.482,-24.5839,-8.822,2.9049,13.3051,9.4451,-6.07,0
3,-5.848975895,10.14767773,14.37196322,5.467759425,-7.876963223,3.444231088,-24.13403753,-
7.876963223,5.467759425,14.37196322,10.14767773,-5.848975895,13.02376264
4,-1.4573,6.2247,6.7393,-2.2799,-10.2215,2.1806,-24.6842,-10.2215,-2.2799,6.7393,6.2247,-1.4573,-24
5,-1.2113,7.8008,9.0773,2.1979,-8.4659,2.071,-23.82,-8.4659,2.1979,9.0773,7.8008,-1.2113,0
6,-1.023649287,8.5927533,10.27380393,4.667965117,-7.478427463,2.025308299,-23.3866343,-
7.478427463,4.667965117,10.27380393,8.5927533,-1.023649287,13.02376264
7,2.5213,2.9327,2.1048,-0.6315,-10.2784,0.779,-23.9192,-10.2784,-0.6315,2.1048,2.9327,2.5213,-24
8,2.7448,4.6094,4.5566,3.7156,-8.4413,0.6364,-23.073,-8.4413,3.7156,4.5566,4.6094,2.7448,0
9,2.823159639,5.598229179,5.95231323,6.016518999,-7.486983792,0.5394815,-22.55753033,-
7.486983792,6.016518999,5.95231323,5.598229179,2.823159639,13.02376264
10,5.4516,-2.41,-1.2838,3.4007,-10.7211,-0.9532,-22.9857,-10.7211,3.4007,-1.2838,-2.41,5.4516,-24
11,5.5867,-0.4878,1.3408,7.5085,-8.8336,-1.1332,-22.1229,-8.8336,7.5085,1.3408,-0.4878,5.5867,0
```

12,5.652578533,0.57759805,2.776398503,9.720260491,-7.81742092,-1.232072065,-21.64661015,-
7.81742092,9.720260491,2.776398503,0.57759805,5.652578533,13.02376264
13,6.0952,-4.5714,-1.4957,5.0361,-11.0648,-2.0199,-22.348,-11.0648,5.0361,-1.4957,-4.5714,6.0952,-24
14,6.224,-2.5994,1.1551,9.0956,-9.1502,-2.2228,-21.4805,-9.1502,9.0956,1.1551,-2.5994,6.224,0
15,6.287002452,-1.524613988,2.602419889,11.29829812,-8.134292248,-2.337246314,-20.98472877,-
8.134292248,11.29829812,2.602419889,-1.524613988,6.287002452,13.02376264
16,-6.5089,8.1782,11.3783,-1.8343,-10.5643,3.5565,-25.4155,-10.5643,-1.8343,11.3783,8.1782,-6.5089,-24
17,-6.07,9.4451,13.3051,2.9049,-8.822,3.482,-24.5839,-8.822,2.9049,13.3051,9.4451,-6.07,0
18,-5.848975895,10.14767773,14.37196322,5.467759425,-7.876963223,3.444231088,-24.13403753,-
7.876963223,5.467759425,14.37196322,10.14767773,-5.848975895,13.02376264
19,7.9417,-5.4304,-4.5128,6.6264,-6.0859,-13.8375,-17.8657,-6.0859,6.6264,-4.5128,-5.4304,7.9417,-24
20,8.12,-3.6348,-2.0041,10.9091,-4.2294,-14.0221,-16.98,-4.2294,10.9091,-2.0041,-3.6348,8.12,0
21,8.214205216,-2.661328008,-0.643062538,13.23536107,-3.222934476,-14.12260004,-16.50045421,-
3.222934476,13.23536107,-0.643062538,-2.661328008,8.214150951,13.02376264
22,6.8375,-3.7565,-3.0512,5.5869,-8.0219,-6.6552,-21.2503,-8.0219,5.5869,-3.0512,-3.7565,6.8375,-24
23,7.0069,-1.9282,-0.5118,9.8623,-6.2101,-6.8201,-20.3398,-6.2101,9.8623,-0.5118,-1.9282,7.0069,0
24,7.032567666,-0.899051423,0.897859509,12.14927272,-5.21714663,-6.881637278,-19.9064343,-
5.21714663,12.14927272,0.897859509,-0.899051423,7.032567666,13.02376264
25,5.2934,-0.6884,-0.5747,3.0754,-9.176,-1.5329,-23.607,-9.176,3.0754,-0.5747,-0.6884,5.2934,-24
26,5.5062,1.0259,1.8687,7.4445,-7.3545,-1.7141,-22.6984,-7.3545,7.4445,1.8687,1.0259,5.5062,0
27,5.59872298,1.970122792,3.204232593,9.794637969,-6.351941605,-1.792296842,-22.248429,-
6.351941605,9.794637969,3.204232593,1.970122792,5.59872298,13.02376264
28,3.2088,4.0112,2.97,-1.5442,-9.5551,2.9451,-25.7056,-9.5551,-1.5442,2.97,4.0112,3.2088,-24
29,3.3477,5.6864,5.3807,2.8697,-7.746,2.8136,-24.8972,-7.746,2.8697,5.3807,5.6864,3.3477,0
30,3.478588815,6.63165384,6.713030918,5.23112523,-6.759504245,2.737410989,-24.4089717,-
6.759504245,5.23112523,6.713030918,6.63165384,3.478588815,13.02376264
31,1.1198,9.1328,6.6771,-6.9766,-8.8879,4.566,-26.5275,-8.8879,-6.9766,6.6771,9.1328,1.1198,-24
32,1.3127,10.852,9.1046,-2.5811,-7.1059,4.4469,-25.6664,-7.1059,-2.5811,9.1046,10.852,1.3127,0
33,1.432627148,11.74895739,10.39389824,-0.164106716,-6.134110244,4.392362994,-25.21632047,-6.134110244,-
0.164106716,10.39389824,11.74895739,1.432627148,13.02376264
34,12.5318,0,0,-4.5539,0.6209,0,-28.0976,-6.2196,4.4279,0,0,5.1868,-24
35,14.8637,0,0,-0.7231,2.8756,0,-27.354,-4.5944,10.3317,0,0,6.8346,0
36,16.02433431,0,0,1.481280359,3.988643315,0,-26.96502362,-
3.707861624,13.53228967,0,0,7.697044415,13.02376264
37,11.6647,0,0,-3.2872,-1.4291,0,-27.5523,-6.4409,2.5641,0,0,6.5437,-24
38,14.0991,0,0,0.5936,0.8972,0,-26.8521,-4.7988,8.6713,0,0,8.2429,0
39,15.30113903,0,0,2.796786514,2.067168011,0,-26.49112471,-
3.902982193,11.98058382,0,0,9.123143558,13.02376264
40,10.5542,0,0,-2.4708,-3.4472,0,-26.8955,-6.7315,0.9925,0,0,6.6761,-24
41,13.1991,0,0,1.4126,-0.8747,0,-26.3273,-4.8731,7.2949,0,0,8.347,0
42,14.37069598,0,0,3.737775757,0.195907555,0,-25.94961088,-
4.107736882,10.85239503,0,0,9.172001098,13.02376264
43,8.9785,0,0,-1.9873,-5.3975,0,-26.166,-7.192,-0.2176,0,0,5.9925,-24
44,11.6968,0,0,2.1751,-3.0439,0,-25.549,-5.5955,6.69,0,0,7.5064,0
45,13.03108448,0,0,4.479057877,-1.813371493,0,-25.23876312,-
4.722365246,10.4303161,0,0,8.27149179,13.02376264
46,7.4231,0,0,-1.8084,-6.809,0,-25.4852,-7.4801,-1.1423,0,0,5.0558,-24
47,10.1864,0,0,2.534,-4.5684,0,-24.8824,-6.0362,6.3657,0,0,6.327,0
48,11.67789215,0,0,4.84381857,-3.349158754,0,-24.54638692,-
5.264216469,10.44566498,0,0,7.018507531,13.02376264
49,13.1223,0,0,-9.2051,7.3022,-10,-24.3168,-1.5775,1.6799,0,0,8.057,-24
50,15.4525,0,0,-5.433,9.5636,-10,-23.5694,0.0431,7.5818,0,0,9.6899,0
51,16.60716509,0,0,-3.237085087,10.66492193,-10,-
23.18547033,0.952592758,10.76220284,0,0,10.55787951,13.02376264
52,12.2432,0,0,-7.9504,4.9892,-10,-23.6605,-1.8765,0.0851,0,0,8.6058,-24
53,14.5723,0,0,-4.0417,7.2371,-10,-22.9721,-0.2372,6.1946,0,0,10.2583,0
54,15.83858959,0,0,-1.932610171,8.461550751,-10,-
22.60059717,0.663284655,9.501224804,0,0,11.1563427,13.02376264
55,10.913,0,0,-7.0952,2.578,-10,-22.9513,-2.2509,-1.3491,0,0,8.0736,-24
56,13.5102,0,0,-3.1855,4.9843,-10,-22.2859,-0.5935,5.0808,0,0,9.7381,0
57,14.7431162,0,0,-0.97737531,6.200719431,-10,-
21.95954621,0.31458185,8.558633017,0,0,10.57834975,13.02376264
58,9.469,0,0,-6.9678,0.4749,-10,-22.1121,-2.7879,-2.5237,0,0,6.9826,-24
59,12.1474,0,0,-2.8256,2.8609,-10,-21.5096,-1.166,4.3868,0,0,8.4894,0
60,13.4459234,0,0,-0.556372156,4.128274902,-10,-21.21705373,-
0.257212696,8.114200869,0,0,9.243150263,13.02376264
61,7.5991,0,0,-7.1307,-1.3711,-10,-21.2403,-3.4971,-3.3311,0,0,5.6251,-24
62,10.4212,0,0,-2.7715,0.9349,-10,-20.6538,-2.0049,4.1764,0,0,6.9367,0
63,11.78847801,0,0,-0.403997014,2.160978722,-10,-20.36364142,-
1.198023639,8.238565834,0,0,7.580562266,13.02376264

64,5.4475,0,0,1.5575,-14.0486,0,-20.7478,-14.0486,1.5575,0,0,5.4475,-24
65,6.7105,0,0,9.2541,-12.9781,0,-19.9531,-12.9781,9.2541,0,0,6.7105,0
66,7.389852019,0,0,13.43369676,-12.39696886,0,-19.52602912,-
12.39696886,13.43369676,0,0,7.389852019,13.02376264
67,5.2595,0,0,1.1036,-12.9445,0,-21.4884,-12.9445,1.1036,0,0,5.2595,-24
68,6.5533,0,0,8.7668,-11.8341,0,-20.716,-11.8341,8.7668,0,0,6.5533,0
69,7.226248669,0,0,12.92148881,-11.19050906,0,-20.31161217,-
11.19050906,12.92148881,0,0,7.226248669,13.02376264
70,5.0804,0,0,-0.5838,-9.1702,0,-24.0195,-9.1702,-0.5838,0,0,5.0804,-24
71,6.4069,0,0,6.9654,-7.8435,0,-23.3351,-7.8435,6.9654,0,0,6.4069,0
72,7.129447498,0,0,11.06267573,-7.112378525,0,-22.98590036,-
7.112378525,11.06267573,0,0,7.129447498,13.02376264
73,5.3203,0,0,-2.1481,-5.9265,0,-26.0997,-5.9265,-2.1481,0,0,5.3203,-24
74,6.6636,0,0,5.3623,-4.5396,0,-25.4913,-4.5396,5.3623,0,0,6.6636,0
75,7.421203126,0,0,9.389247409,-3.708955272,0,-25.18345081,-
3.708955272,9.389247409,0,0,7.421203126,13.02376264
76,5.6258,0,0,-3.5564,-3.159,0,-27.8254,-3.159,-3.5564,0,0,5.6258,-24
77,7.0729,0,0,3.7634,-1.4886,0,-27.3291,-1.4886,3.7635,0,0,7.0729,0
78,7.835495568,0,0,7.746826336,-0.592782193,0,-27.05967091,-
0.592782193,7.74687207,0,0,7.835495568,13.02376264
79,6.1999,0,0,-5.5545,0.5531,0,-30.1771,0.5531,-5.5545,0,0,6.1999,-24
80,7.6648,0,0,1.7032,2.3009,0,-29.7351,2.3009,1.7032,0,0,7.6648,0
81,8.445791633,0,0,5.622430039,3.233781265,0,-
29.48998193,3.233781265,5.622430039,0,0,8.445791633,13.02376264
82,11.4306,-2.429,-2.4849,-1.4856,-10.8224,0.6765,-23.3405,-10.8225,-1.4856,-2.4849,-2.429,11.4306,-24
83,11.5553,-0.3102,0.0216,2.5998,-8.8889,0.4118,-22.439,-8.8889,2.5998,0.0216,-0.3102,11.5553,0
84,11.61591476,0.82210763,1.370536216,4.827080475,-7.819323493,0.266585047,-21.96791965,-
7.819323493,4.827080475,1.370536216,0.82210763,11.61591476,13.02376264
85,8.7772,-2.017,-1.5075,0.6635,-11.2125,1.4328,-23.7883,-11.2125,0.6635,-1.5075,-2.017,8.7772,-24
86,8.843,0.2373,1.1313,4.6913,-9.391,1.2148,-22.8358,-9.391,4.6913,1.1313,0.2373,8.843,0
87,8.886195479,1.288317645,2.461568823,6.992164734,-8.300856801,1.094004601,-22.41258198,-
8.300856801,6.992164734,2.461568823,1.288317645,8.886195479,13.02376264
88,6.8673,-0.9736,-0.6321,1.0048,-11.2862,1.9304,-24.0588,-11.2862,1.0047,-0.6321,-0.9736,6.8673,-24
89,6.995,0.9136,1.8446,5.2436,-9.3046,1.7655,-23.2991,-9.3046,5.2436,1.8446,0.9136,6.995,0
90,7.043676313,2.018611995,3.235320788,7.491935558,-8.273443593,1.665542622,-22.83843866,-
8.273443593,7.491935558,3.235320788,2.018611995,7.043676313,13.02376264
91,5.3825,0.2336,-0.2243,0.2501,-10.8655,1.9467,-24.1886,-10.8655,0.2501,-0.2243,0.2336,5.3825,-24
92,5.4882,2.2048,2.3823,4.4101,-8.986,1.7792,-23.3399,-8.986,4.4101,2.3823,2.2048,5.4882,0
93,5.559016709,3.258422398,3.783059938,6.667118066,-7.964285821,1.685049049,-22.87527727,-
7.964285821,6.667118066,3.783059938,3.258422398,5.559016709,13.02376264
94,4.1678,1.2305,-0.3909,-0.6185,-10.3518,1.6222,-24.1176,-10.3518,-0.6185,-0.3909,1.2305,4.1678,-24
95,4.3557,3.0607,2.2022,3.5535,-8.4712,1.4559,-23.2665,-8.4712,3.5535,2.2022,3.0607,4.3557,0
96,4.456905489,4.066405804,3.611262587,5.80883583,-7.44622988,1.361423455,-22.80328818,-
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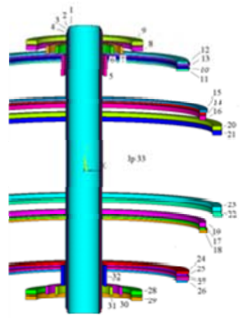
exit

Without and With Plasma Input



Influence Coefficient Input

```
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2,0,5.808,-5.808,0,5.808,-5.808,0,5.808,-5.808,0
3,0,5.76,-5.76,0,5.76,-5.76,0,5.76,-5.76,0
4,0,5.664,-5.664,0,5.664,-5.664,0,5.664,-5.664,0
5,.359832,.37722,.371112,.390576,.408816,-.359838,-.30714,-.259432,.476532,5.05088e-30
6,-.010924,.04144,-.10672,-.0833,-8.8200008e-4,.149874,.171022,.198724,-.112994,-7.3322e-31
7,.0236268,.0989048,-.094197,.007002,.0787428,.2412108,.2894778,.3373832,-.1209948,-6.84824e-31
8,.1054016,.1716824,.0994398,.1269534,.1944008,-.0277576,.0517062,.1312498,.076956,1.60325e-30
9,.1054016,.1716824,.0994398,.1269534,.1944008,-.0277576,.0517062,.1312498,.076956,1.60326e-30
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11,-.070272,-.083332,-.0888808,-.0724192,-.0889192,-.088804,-.0728804,-.0570704,-.0488816,-3.26888e-31
12,-.081488,-.0486856,-.0789467,-.0833866,-.0486866,-.0778295,-.0537441,-.0489088,-.0427839,-2.85162e-31
13,-.070272,-.083332,-.0888808,-.0724192,-.0889192,-.088804,-.0728804,-.0570704,-.0488816,-3.26888e-31
14,-.0047808,-.0051176,-.0088808,-.0098298,-.010108,.0186472,.0188812,.018810,-.0567888,-5.88548e-31
15,-.0047808,-.0051176,-.0088808,-.0098298,-.010108,.0186472,.0188812,.018810,-.0567888,-5.88548e-31
16,-.0107888,-.0119146,-.0202088,-.0214416,-.0227384,.0348612,.0380577,.0351408,-.127728,-1.28148e-30
17,-.0047808,-.0051176,-.0088808,-.0098298,-.010108,.0186472,.0188812,.018810,-.0567888,-5.88548e-31
18,-.008978,-.009397,-.011228,-.011812,-.0126323,.018434,.0184786,.0188225,-.070881,-7.11035e-31
19,-.0088816,-.0102392,-.0178816,-.0190892,-.020212,.0310944,.0311624,.031238,-.1136376,-1.139098e-30
20,-.2864436,-.2839032,-.288898,-.2571468,-.2447724,-.3083038,-.287248,-.2882444,-.214818,-2.02832e-30
21,-.2864436,-.2839032,-.288898,-.2571468,-.2447724,-.3083038,-.287248,-.2882444,-.214818,-2.02832e-30
22,-.2864436,-.2839032,-.288898,-.2571468,-.2447724,-.3083038,-.287248,-.2882444,-.214818,-2.02832e-30
23,-.2864436,-.2839032,-.288898,-.2571468,-.2447724,-.3083038,-.287248,-.2882444,-.214818,-2.02832e-30
24,-.070272,-.083332,-.0888808,-.0724192,-.0889192,-.088804,-.0728804,-.0570704,-.0488816,-3.26888e-31
25,-.081488,-.0486856,-.0789467,-.0833866,-.0486866,-.0778295,-.0537441,-.0489088,-.0427839,-2.85162e-31
26,-.081488,-.0486856,-.0789467,-.0833866,-.0486866,-.0778295,-.0537441,-.0489088,-.0427839,-2.85162e-31
27,-.070272,-.083332,-.0888808,-.0724192,-.0889192,-.088804,-.0728804,-.0570704,-.0488816,-3.26888e-31
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31,-.010924,.04144,-.10672,-.0833,-8.8200008e-4,.149874,.171022,.198724,-.112994,-7.3322e-31
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```

Data Set 11

No Plasma

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30,.0236268,.0989048,-.094197,.007002,.0787428,.2412108,.2894778,.3373832,-.1209948,-6.84824e-31
31,-.010924,.04144,-.10672,-.0833,-8.8200008e-4,.149874,.171022,.198724,-.112994,-7.3322e-31
32,1.7602667e-2,7.1781333e-2,-4.7663333e-2,6.1666666e-3,.059328,.17867467,.214428,.24686667,-.089898,-4.1824e-31
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```

2 MA Plasma

```
plcu
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2,242,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
3,240,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
4,238,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
5,0,120,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
6,0,0,108,0,0,0,0,0,0,0,0,0,0,0,0,0,0
7,0,0,0,162,0,0,0,0,0,0,0,0,0,0,0,0,0
8,0,0,0,0,14,0,0,0,0,0,0,0,0,0,0,0
9,0,0,0,0,14,0,0,0,0,0,0,0,0,0,0,0
10,0,0,0,0,0,7,0,0,0,0,0,0,0,0,0,0
11,0,0,0,0,0,8,0,0,0,0,0,0,0,0,0,0
12,0,0,0,0,0,7,0,0,0,0,0,0,0,0,0,0
13,0,0,0,0,0,8,0,0,0,0,0,0,0,0,0,0
14,0,0,0,0,0,0,4,0,0,0,0,0,0,0,0,0
15,0,0,0,0,0,0,4,0,0,0,0,0,0,0,0,0
16,0,0,0,0,0,0,8,0,0,0,0,0,0,0,0,0
17,0,0,0,0,0,0,0,0,0,0,0,0,0,4,0,0
18,0,0,0,0,0,0,0,0,0,0,0,0,0,5,0,0
19,0,0,0,0,0,0,0,0,0,0,0,0,0,8,0,0
20,0,0,0,0,0,0,0,12,0,0,0,0,0,0,0,0,0
21,0,0,0,0,0,0,0,12,0,0,0,0,0,0,0,0,0
22,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,12,0
23,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,12,0
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26,0,0,0,0,0,0,0,0,0,0,0,0,7,0,0,0
27,0,0,0,0,0,0,0,0,0,0,0,0,6,0,0,0
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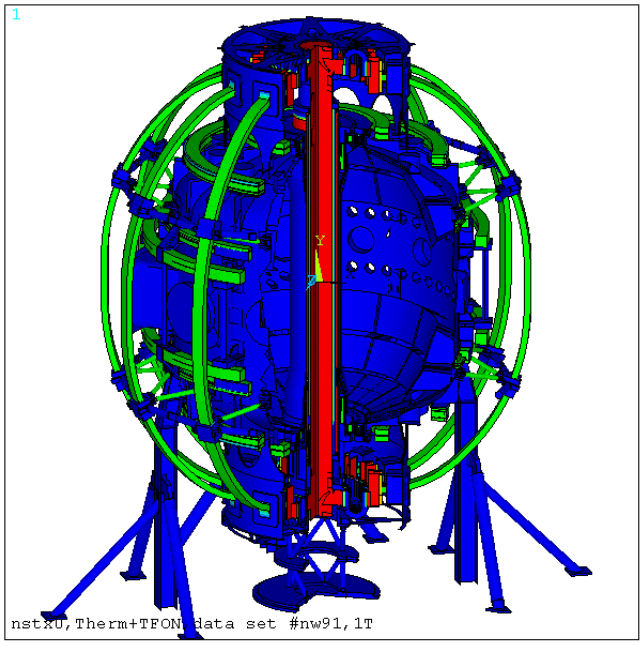
29,0,0,0,0,0,0,0,0,0,0,0,14,0,0,0,0,0
30,0,0,0,0,0,0,0,0,0,0,162,0,0,0,0,0,0
31,0,0,0,0,0,0,0,0,0,100,0,0,0,0,0,0,0
32,0,0,0,0,0,0,0,0,0,120,0,0,0,0,0,0,0
33,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1000
```

7.5 Coil Temperatures

Coil temperatures are added in a separate load step in the beginning of the run, and are not turned off in the remaining load steps. In the figure below, the coil temperatures are plotted as they remain at the end of the solution phase.




```
/title Run#%runn%,nstxU DW+Hot
Coils
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easel,mat,6      $easel,mat,60
easel,mat,7,8    $nelem
bf,all,temp,300  $esel,mat,17
nelem            $bf,all,temp,350
esel,real,1,4    $ersel,mat,17
nelem            $bf,all,temp,400
csys,12          $esel,mat,1
nelem            $nrsel,x,0,.8
bf,all,temp,400  $esel,mat,1
nelem            $nrsel,x,.79,100
bf,all,temp,350
eall
nelem
solve
save
```

7.6 Global Model History

The global model has evolved through the Conceptual design activity. Early models were used to address alternate joint concepts. Variations in the outer leg support modifications were also considered. The TF outer leg support truss was modeled in the global model, and shown in Figure 4.0-1. Only the tangential radius rod results are reported in this calculation.

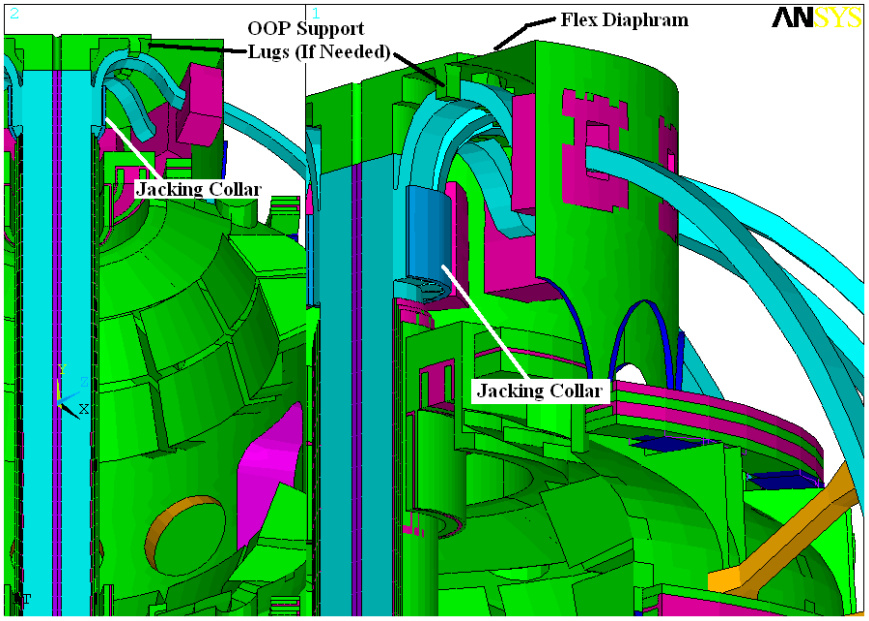


Figure 7.6 -1 Jacking ring concept

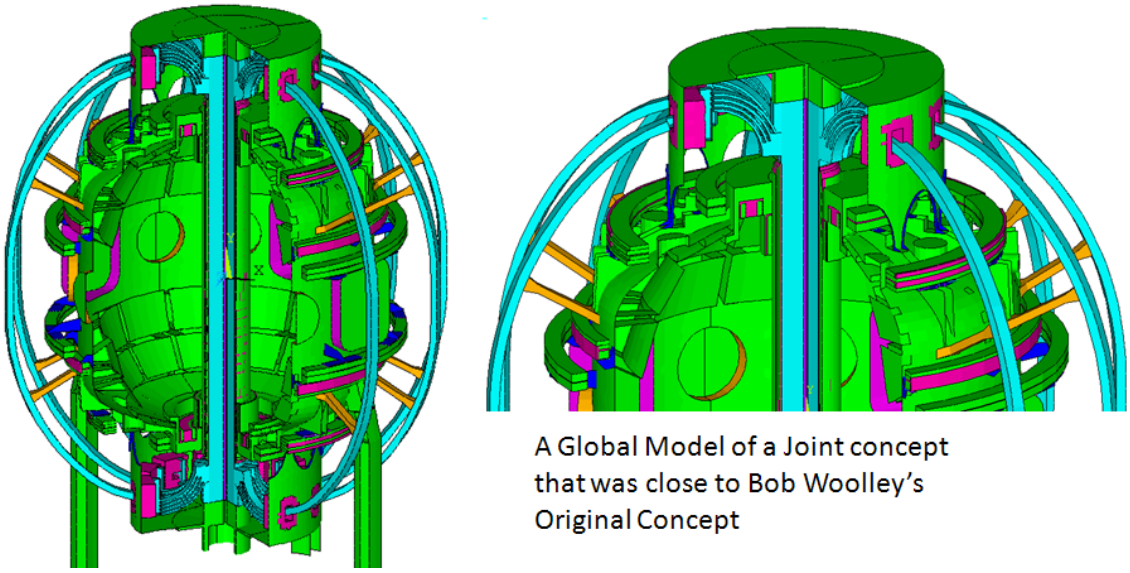


Figure 7.6 -2 Early Flex Configuration

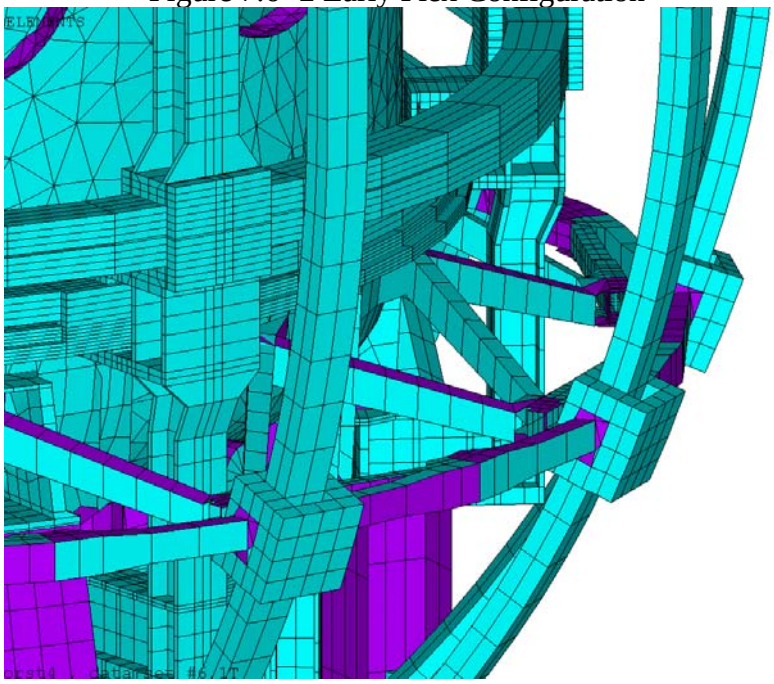


Figure 7.6-3 Details of the Tangential Radius Rod and Free Standing PF 3,4,5,u&L Support

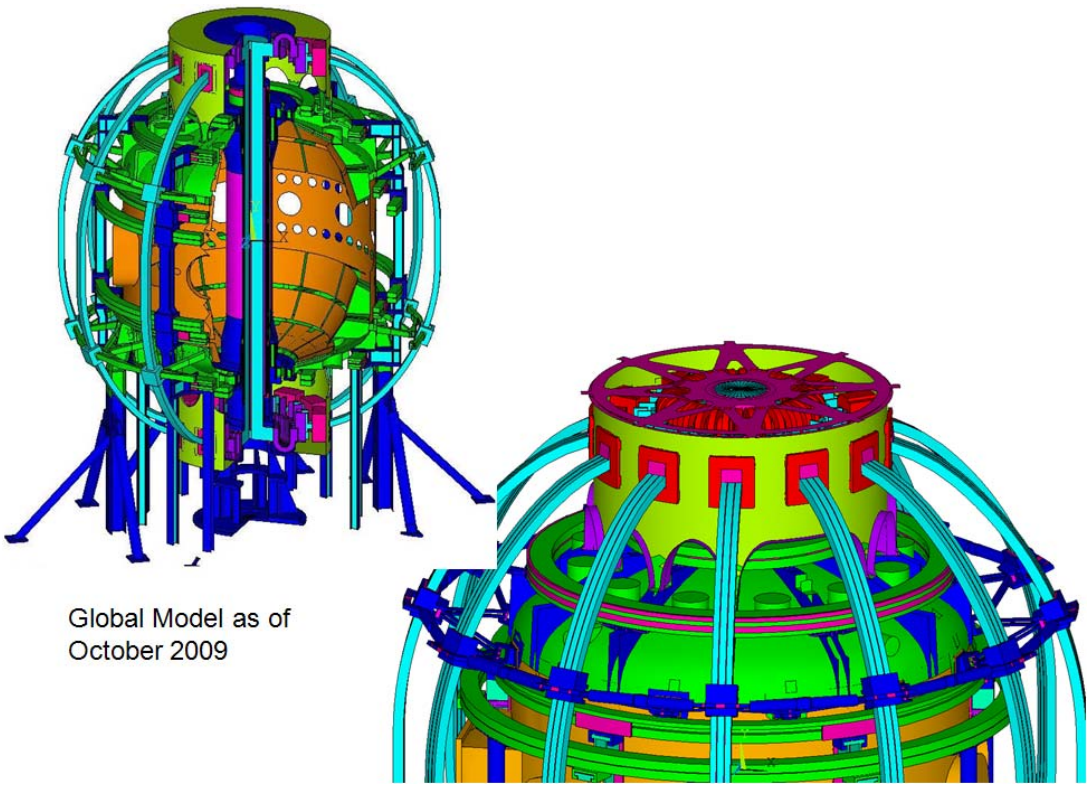


Figure 7.6-4 Global Model Status as of January 2011 compared with the October 2009 version

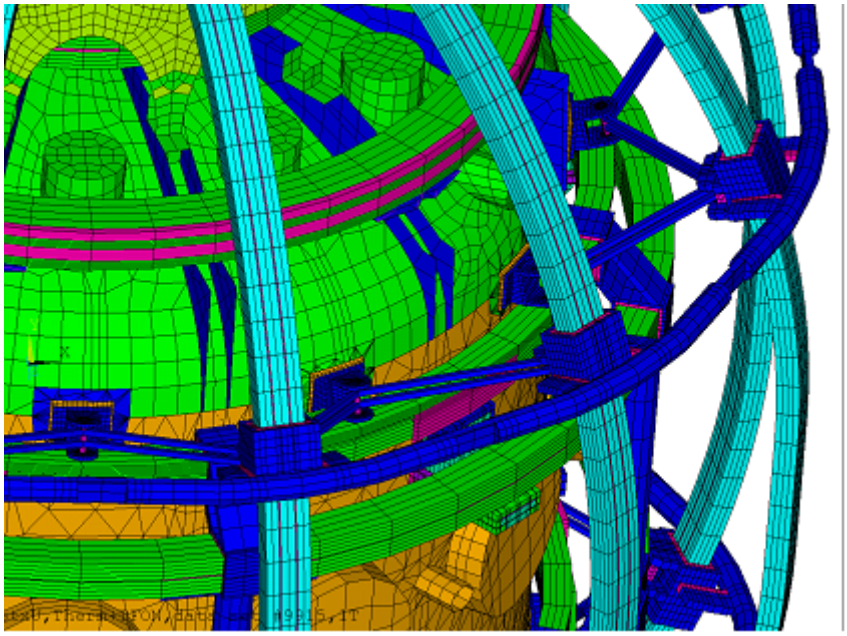


Figure 7.6-5 Concept that Employs Mostly Existing Components. Run #24

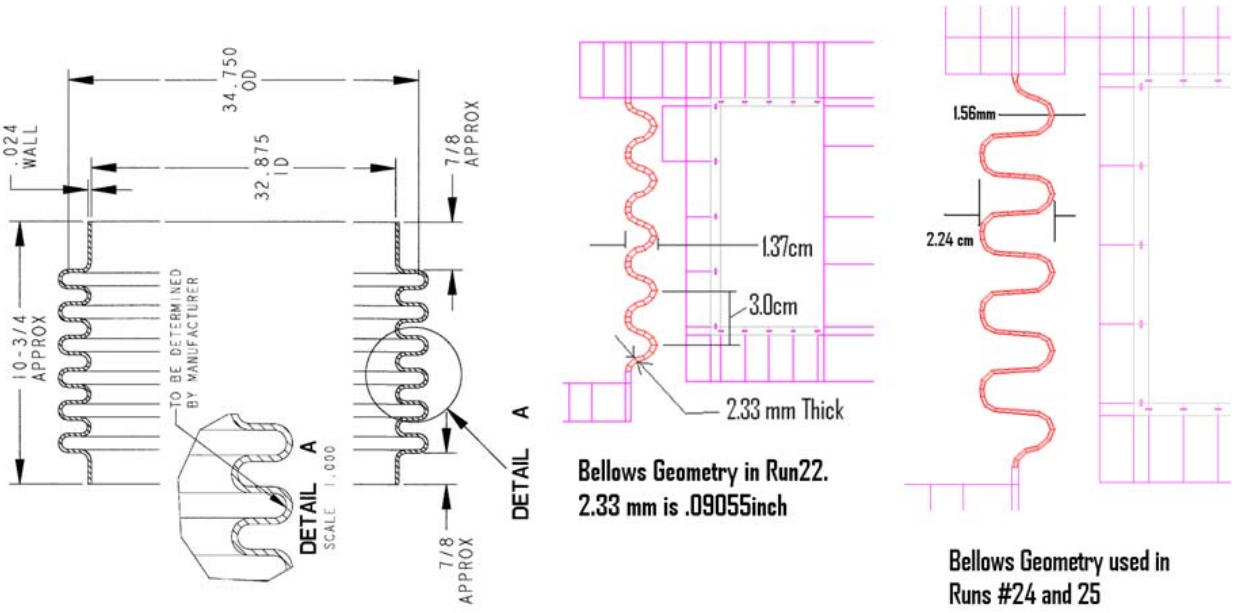


Figure 7.6-6 Run #24 and 5 Bellows Modeling

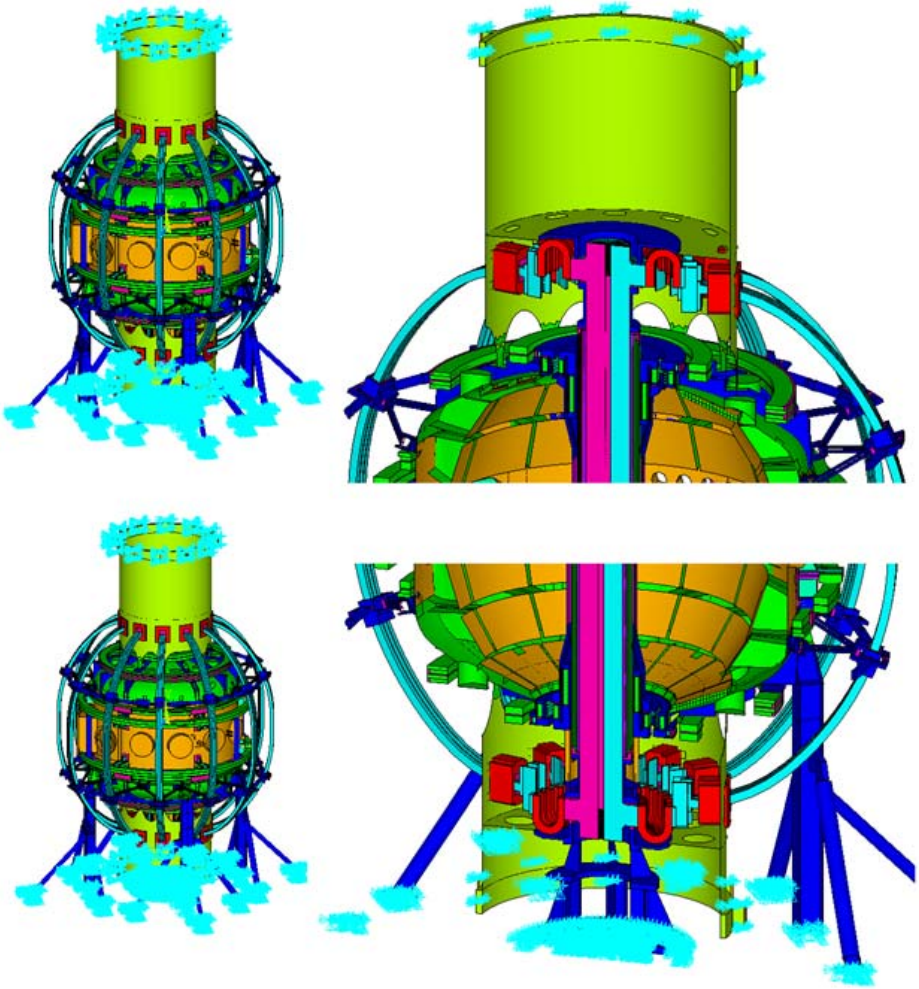


Figure 7.6-7 Run #26 Model with "Top Hat" and Lateral support Struts that go to the Walls

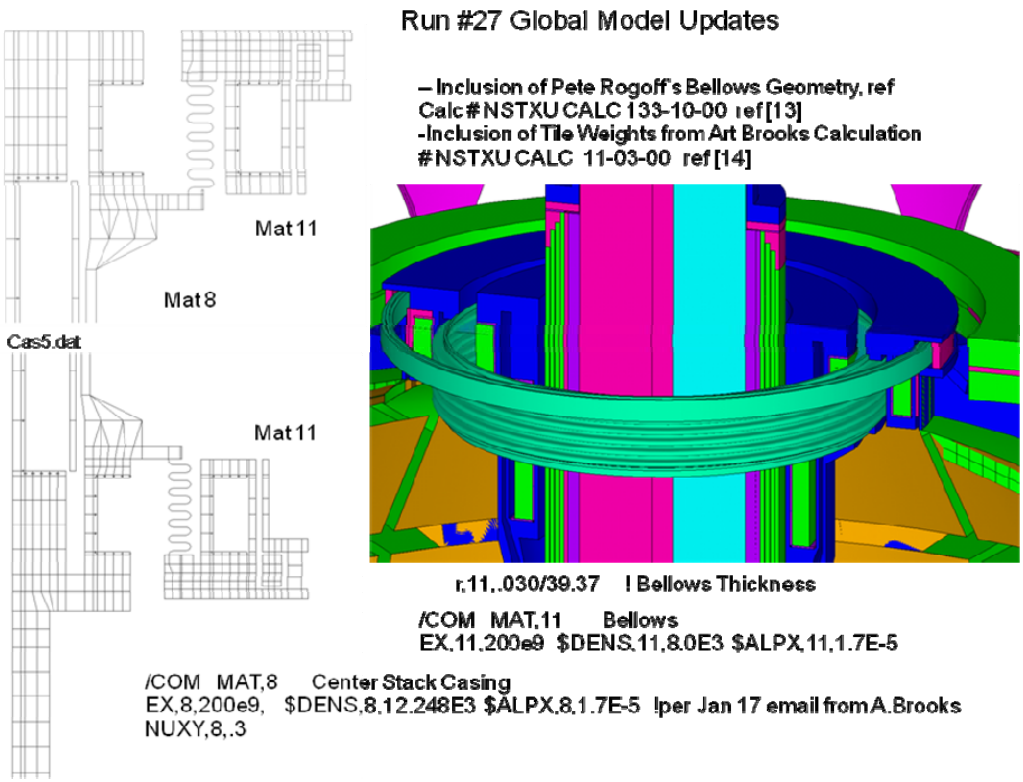


Figure 7.6-8 Run #27 Model Updates, Latest Bellows Design

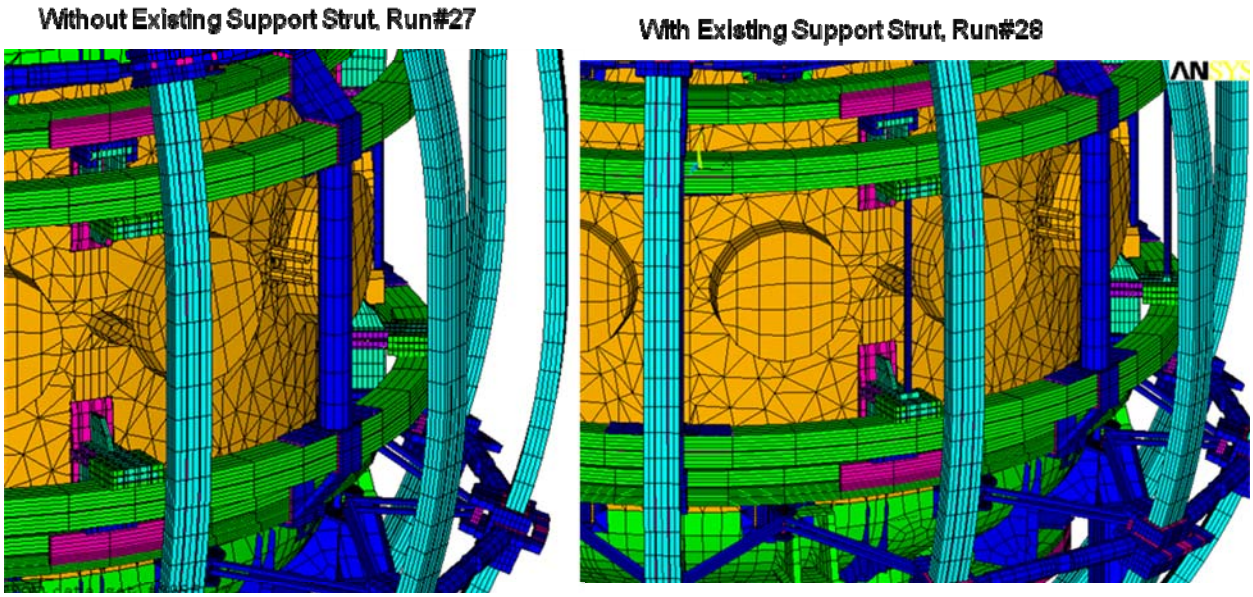


Figure 7.6-9 Run #27 and #28 PF 4/5 Support Column Details

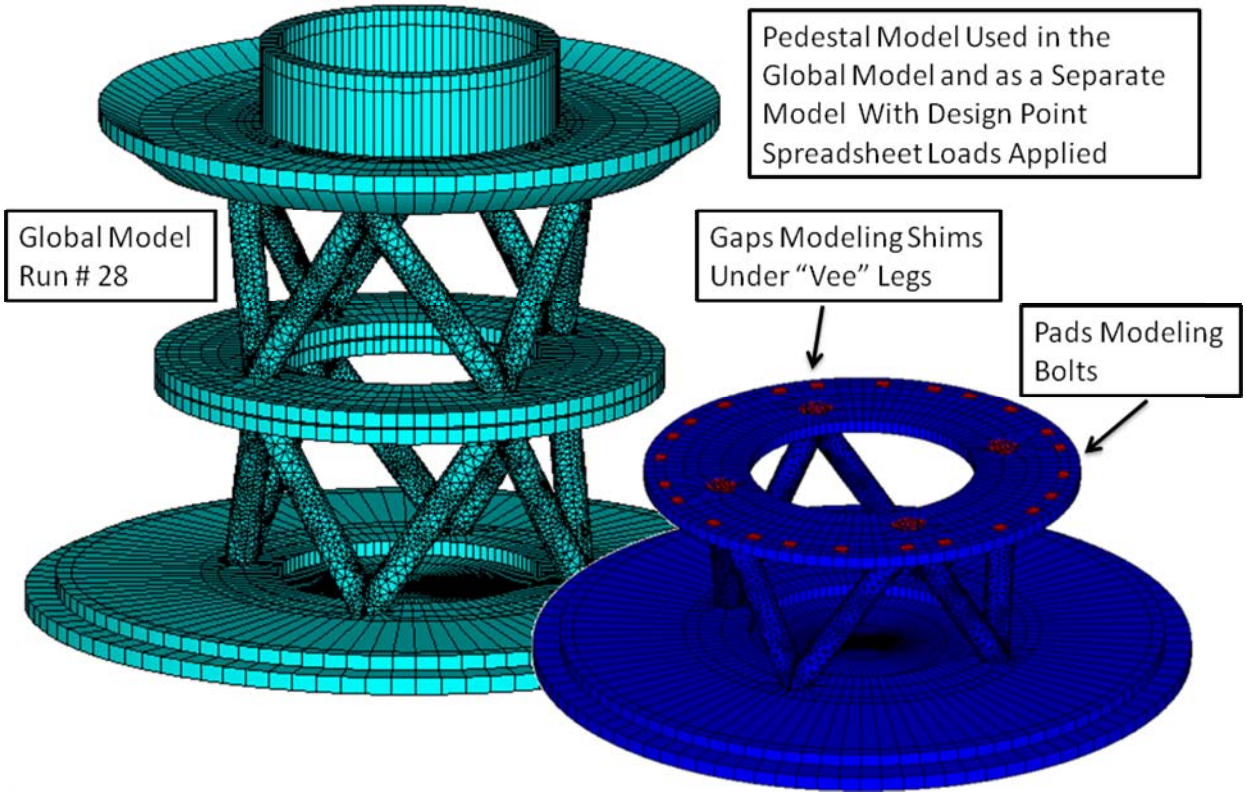


Figure 7.6-10 Run # 28 Model With "Vee" Truss Pedestal Model.

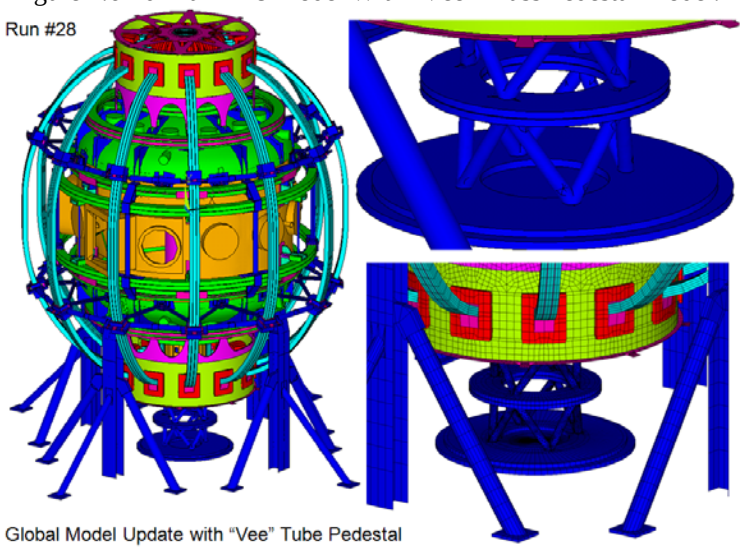


Figure 7.6-11 Global Model Status as May 2011

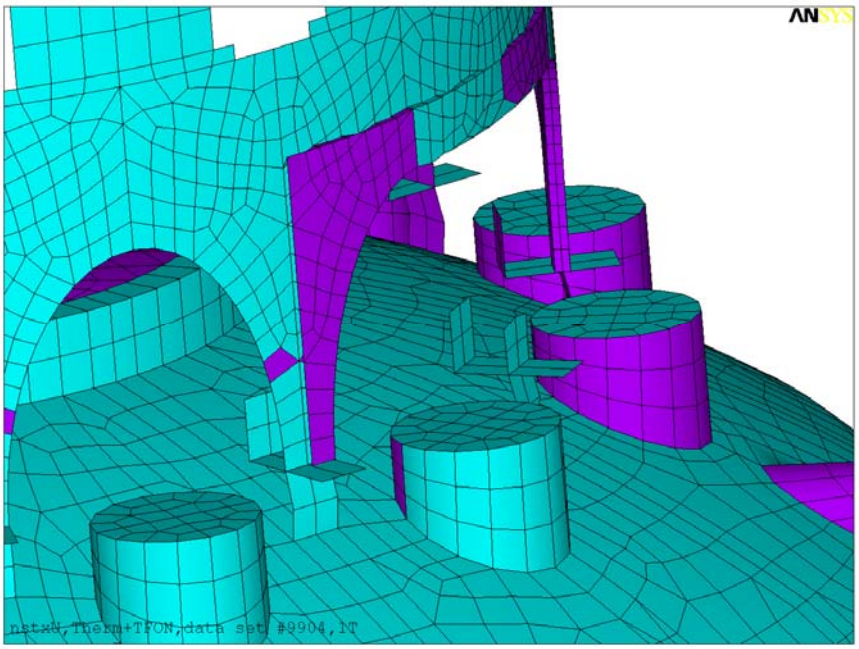


Figure 7.6-12 Umbrella Leg Cover Plate Reinforcement

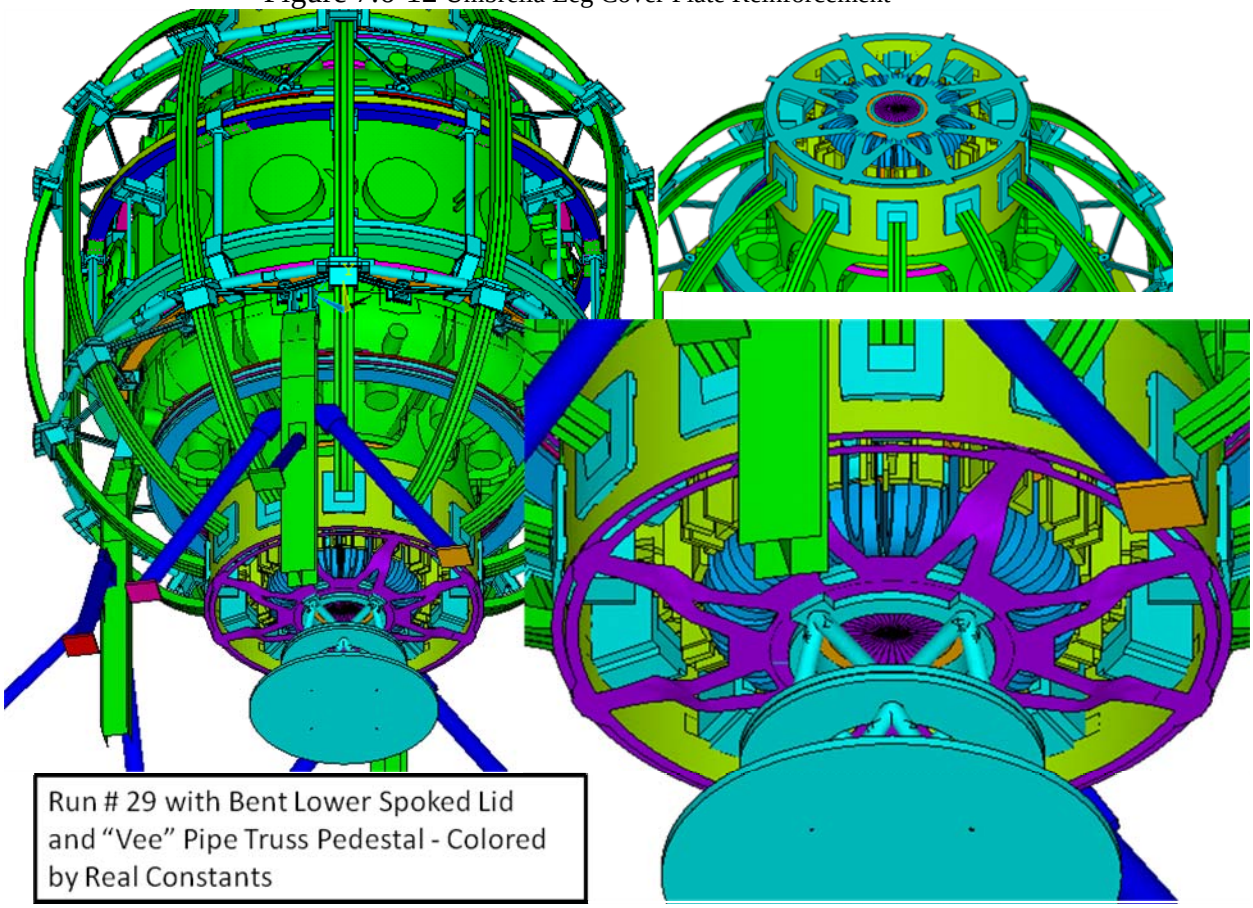


Figure 7.6-13 Global Model With Bent Lower Spoked Lid

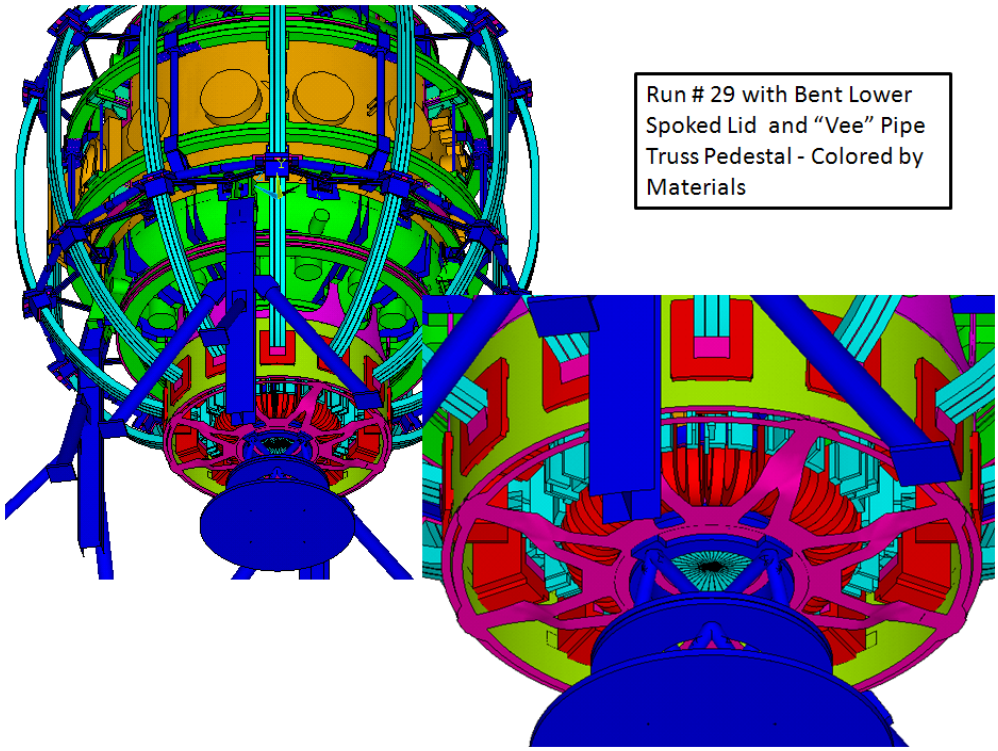


Figure 7.6-14 Global Model Status as of May 9 2011

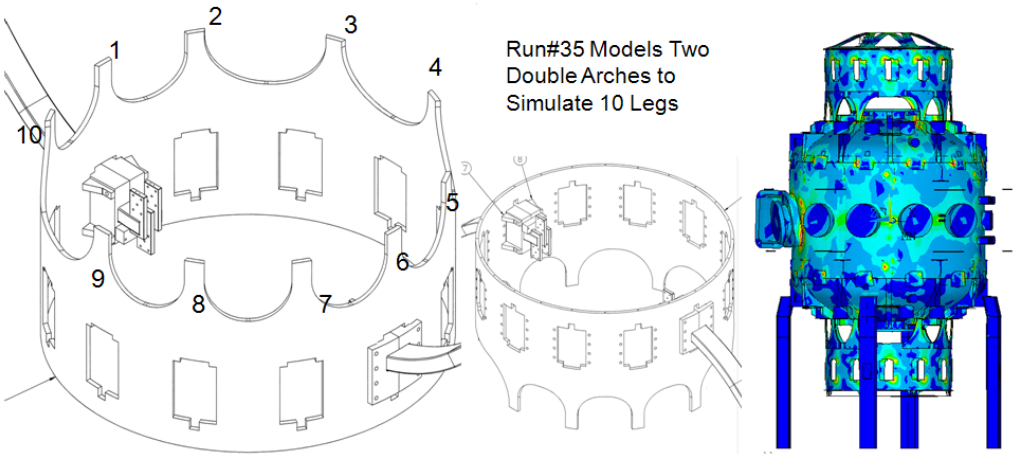


Figure 7.6-14 Run # 35 Model Simulating 10 vs 11 Umbrella Legs.

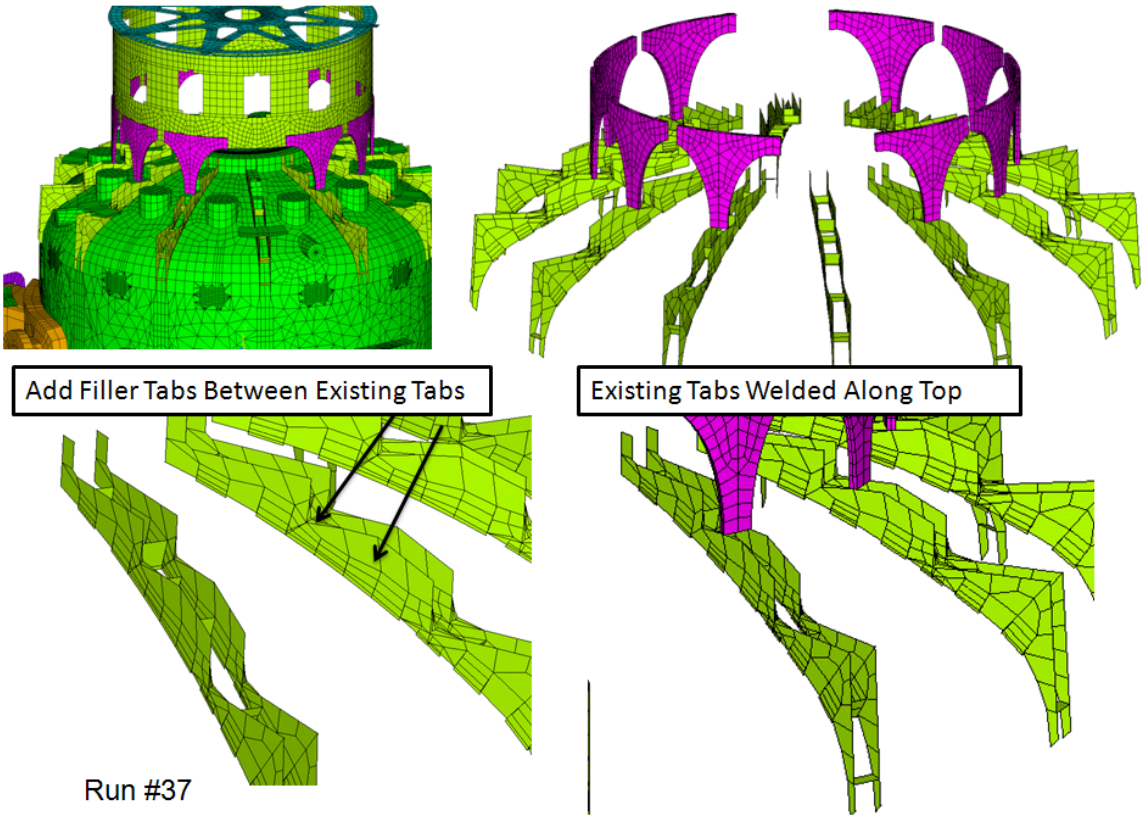


Figure 7.6-15 Run # 37 10 Umbrella Legs, Rib Welded Bridging Tabs Modeled.

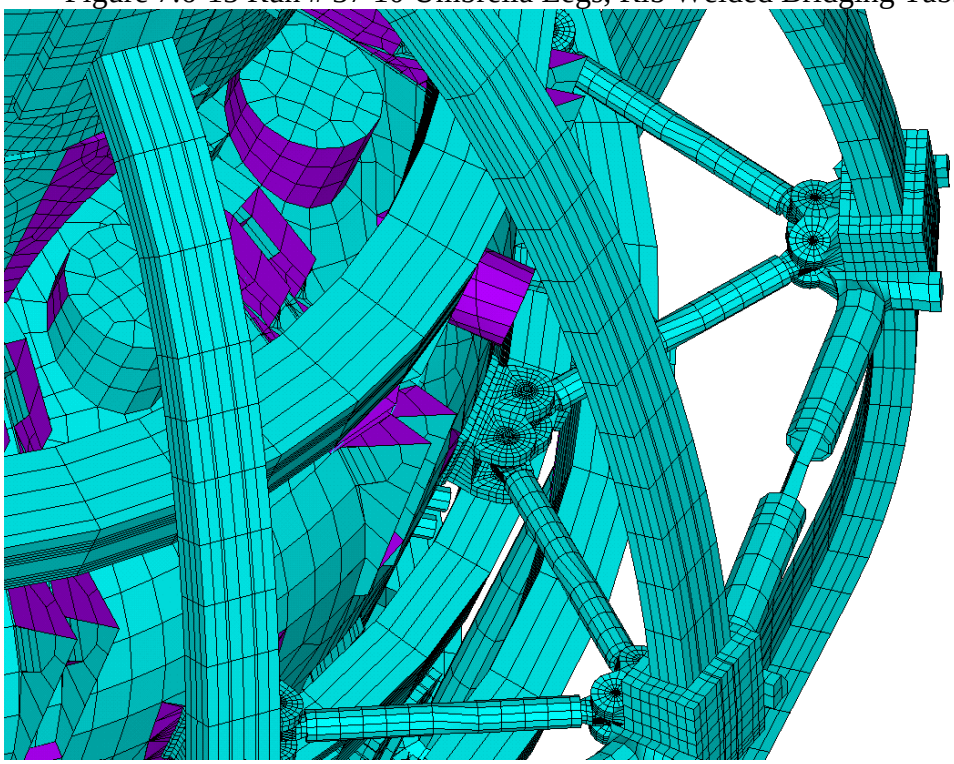


Figure 7.6-16 Run # 37 10 Umbrella Legs, Rib Tabs Outer Leg Support Truss.

7.7 Run Log

Global Model Runs

Run File	Date	Mandrel File	Coil File	Load Files	Comments
Nstx06.txt	2-2009				
Nstx17.txt	9-2009				Linear (Links Replace Gaps)
Nstx18.txt	9-2009				Non-Linear Gaps
NSTX22.txt					
NSTX24.txt					Turn insulation added to inner and outer TF conductor
RUN25.txt					Top Hat Torque Restraint, included in Ves 9.mod

Run #25

Run File	Date	Computer			
RUN25.txt		Titus 64PC			Reinforced Arches in Umbrella Structure

Titus 64PC g:\nstx\csu\global\run26
Input to vessel model sections: vsra.txt vhm9.dat, lfl2.dat

Run #26

Run File	Date	Computer			
RUN26.txt		Titus 64PC			Top Hat Torque Restraint, included in Ves9.mod

Input to vessel model sections: vhm7.dat, tha2.dat

Run #27

Run File	Date	Computer			
RUN27.txt		Titus 64PC			Spoked Lid

Titus 64PC g:\nstx\csu\global\run26
Input to vessel model sections: vsra.txt vhm9.dat, lfl2.dat

Run #29

Run File	Date	Computer			
RUN29.txt		Titus 64PC			Bent Spoked Lid

Titus 64PC g:\nstx\csu\global\run29

Run #32

Run File	Date	Computer			
RUN32.txt		Titus 64PC			Straight Lower Spoked Lid, Updated 96 Equilibrium Currents

Titus 64PC g:\nstx\csu\global\run32

Run #35

Run File	Date	Computer			
RUN35.txt		Titus 64PC			Straight Lower Spoked Lid, Updated 96 Equilibrium Currents with and without plasma 10 Umbrella Feet

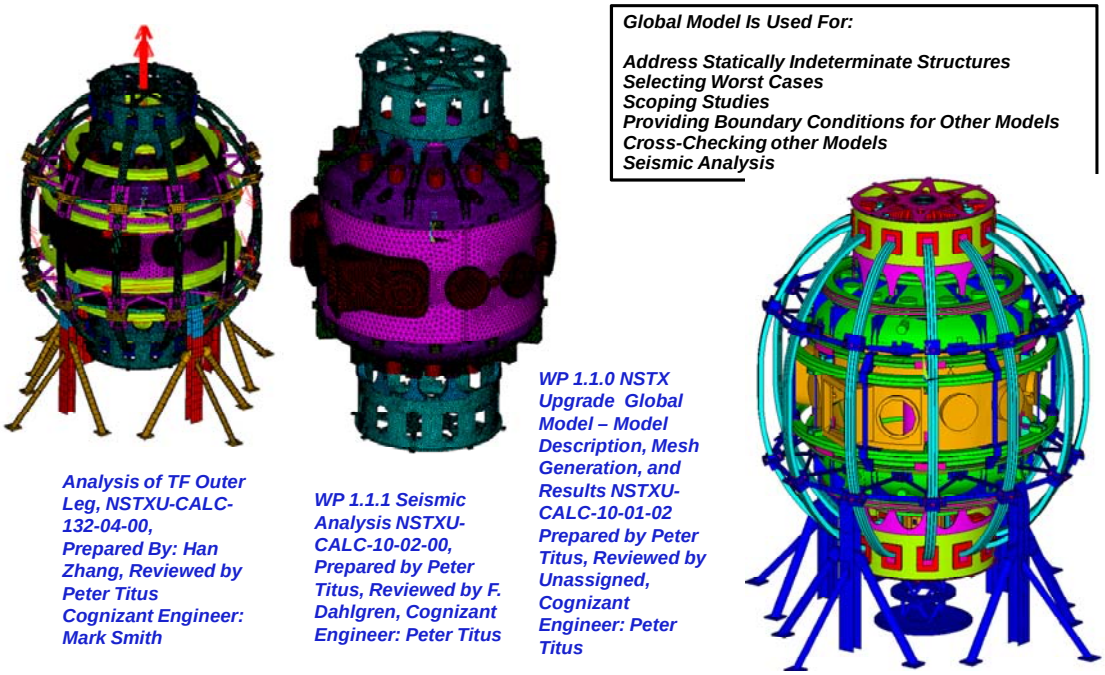
Titus 64PC g:\nstx\csu\global\run32 vese.mod radj.mod made from radk.mod

Run #37

Run File	Date	Computer			
RUN37.txt		Titus 64PC			10 Umbrella Legs, Rib Welded Bridging Tabs

Titus 64PC g:\nstx\csu\global\run37 vese.mod made from rbas and rba3.dat radj.mod made from radk.dat

8.0 Comparison with Other Global Models



Analysis of TF Outer Leg, NSTXU-CALC-132-04-00, Prepared By: Han Zhang, Reviewed by Peter Titus Cognizant Engineer: Mark Smith

WP 1.1.1 Seismic Analysis NSTXU-CALC-10-02-00, Prepared by Peter Titus, Reviewed by F. Dahlgren, Cognizant Engineer: Peter Titus

WP 1.1.0 NSTX Upgrade Global Model – Model Description, Mesh Generation, and Results NSTXU-CALC-10-01-02 Prepared by Peter Titus, Reviewed by Unassigned, Cognizant Engineer: Peter Titus

Global Model Is Used For:

Address Statically Indeterminate Structures
Selecting Worst Cases
Scoping Studies
Providing Boundary Conditions for Other Models
Cross-Checking other Models
Seismic Analysis

Figure 8.0-1 Comparison of H. Zhang's Global Model [4] and P Titus's Global Model

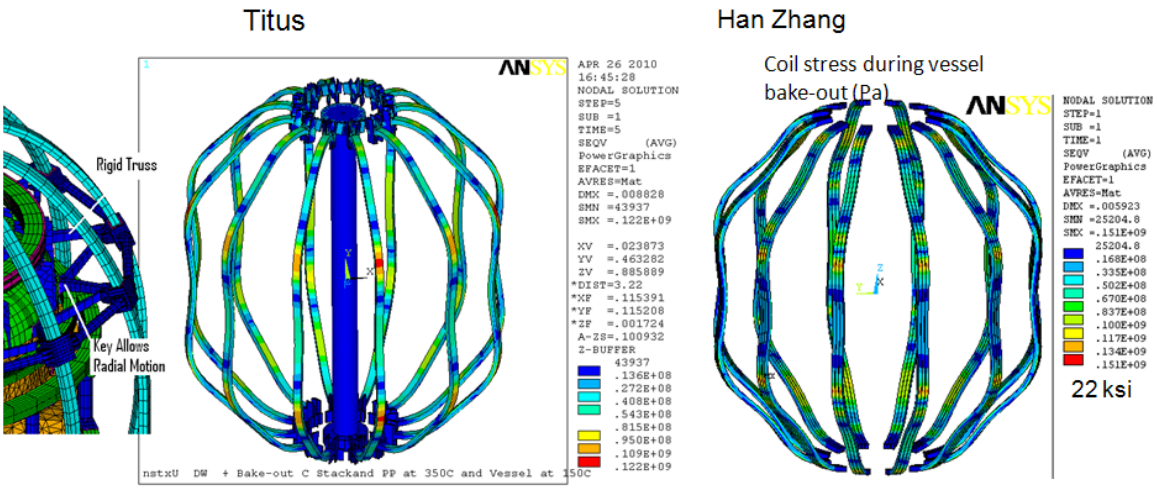


Figure 8.0-2 Comparison of Bake-Out Stress Results, This Calculation and Ref [4]

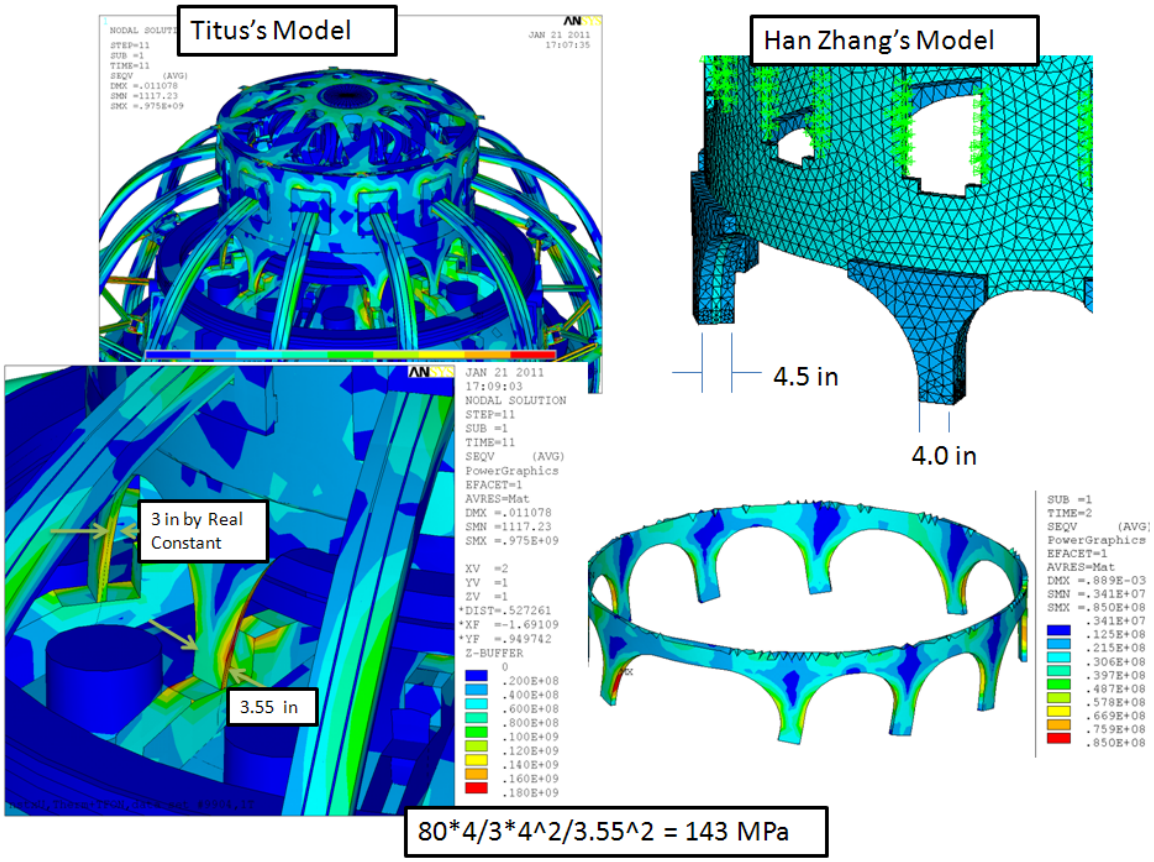
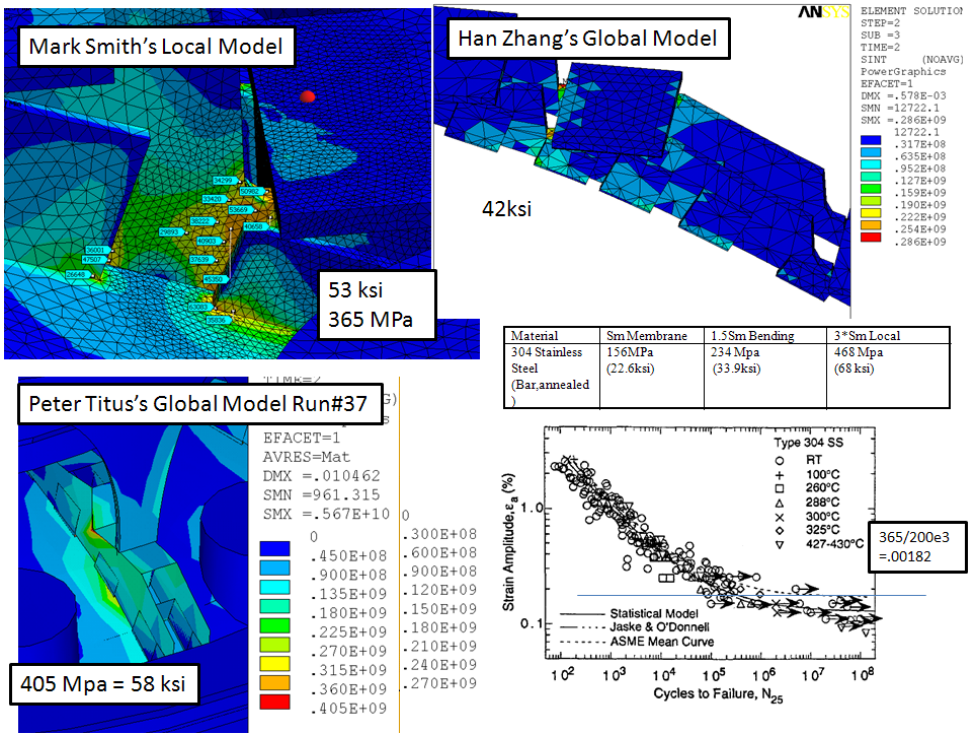


Figure 8.0-3 Comparison of Umbrella Leg Results, This Calculation and Ref [4]



Material	Sm Membrane	1.5 Sm Bending	3*Sm Local
304 Stainless Steel (Bar,annealed)	156MPa (22.6ksi)	234 Mpa (33.9ksi)	468 Mpa (68 ksi)

Figure 8.0-4 Comparison of Umbrella Support Step Radius Results, , This Calculation , M. Smith's model, and H. Zhang's Analysis [4]

9.0 TF Related Results
9.1 TF Stress Components

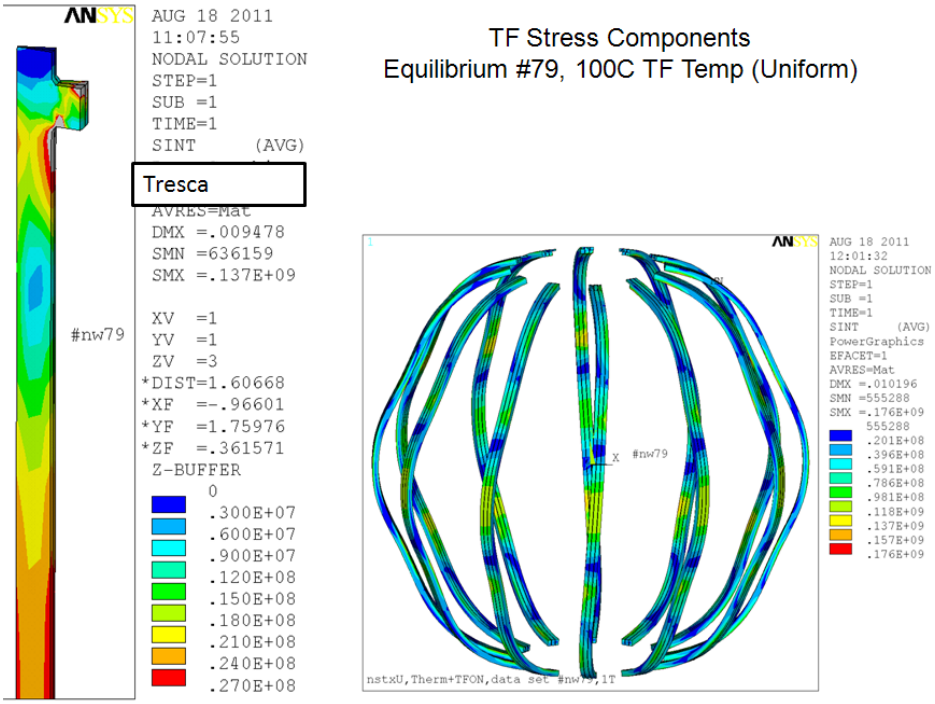
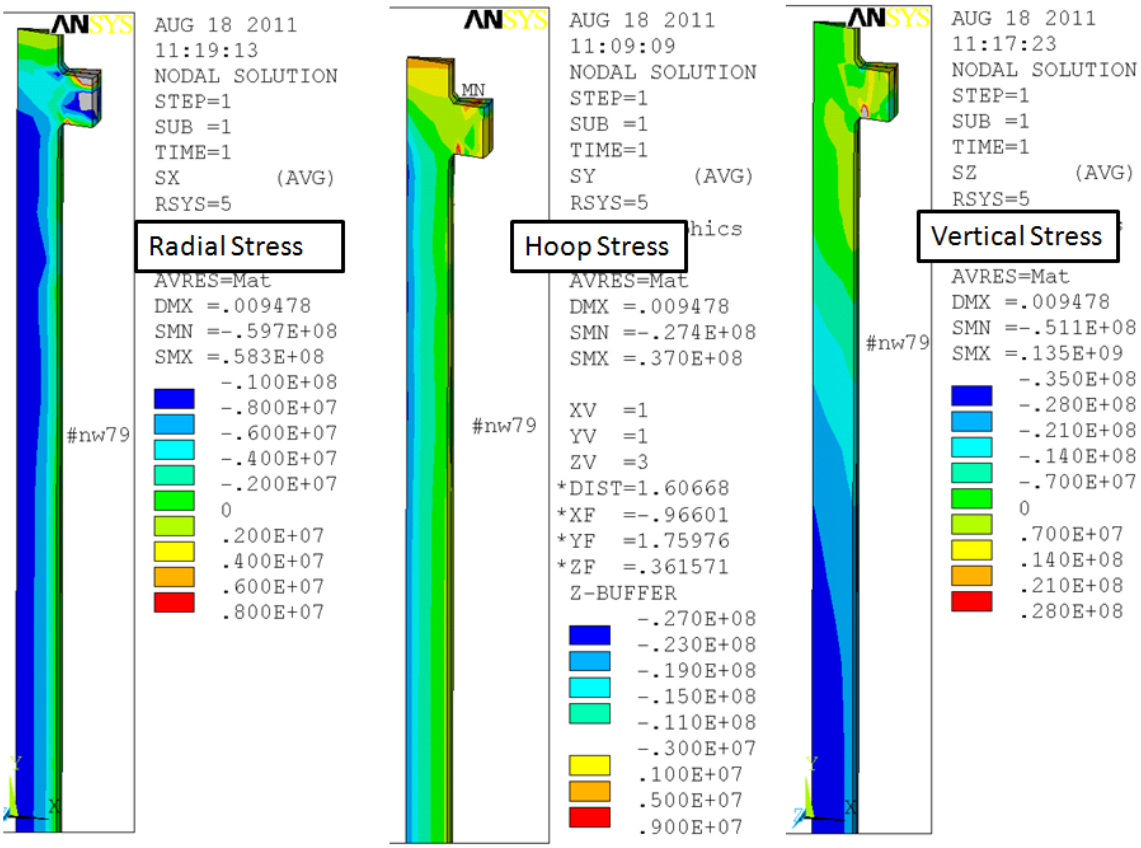


Figure 9.1-1 TF Tresca Stress



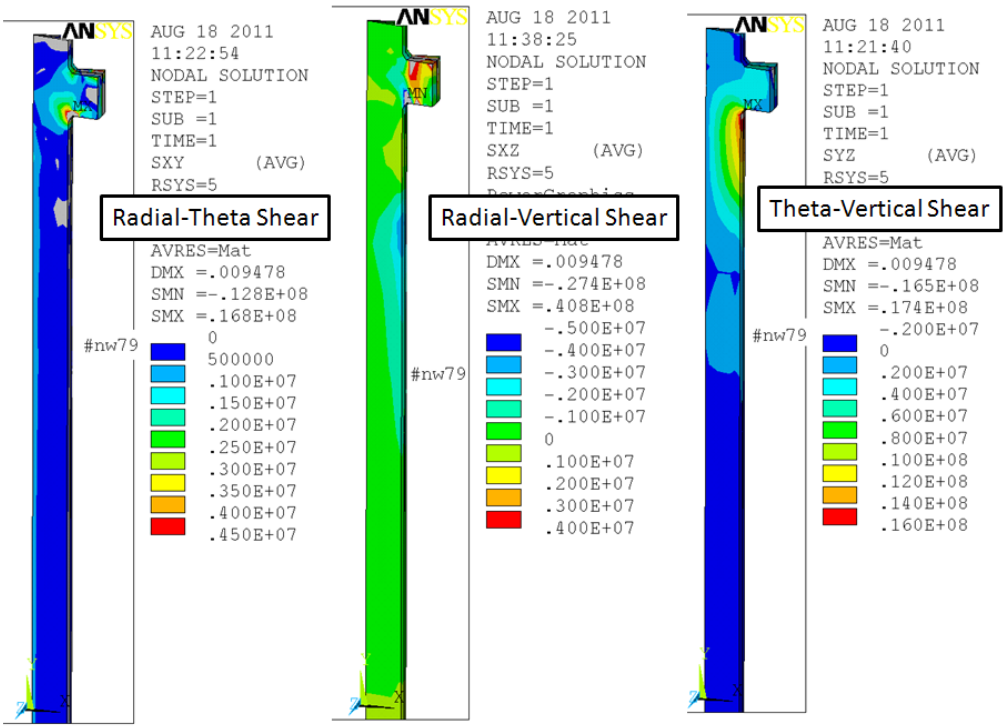


Figure 9.1-2 TF Stress Components

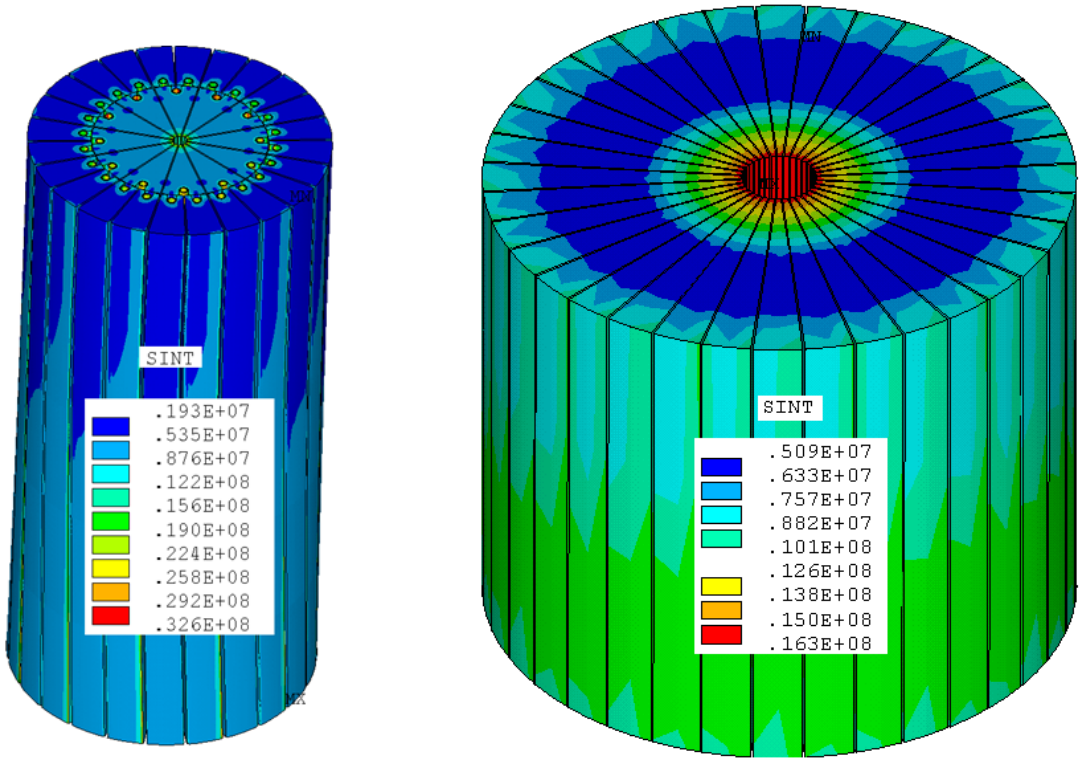
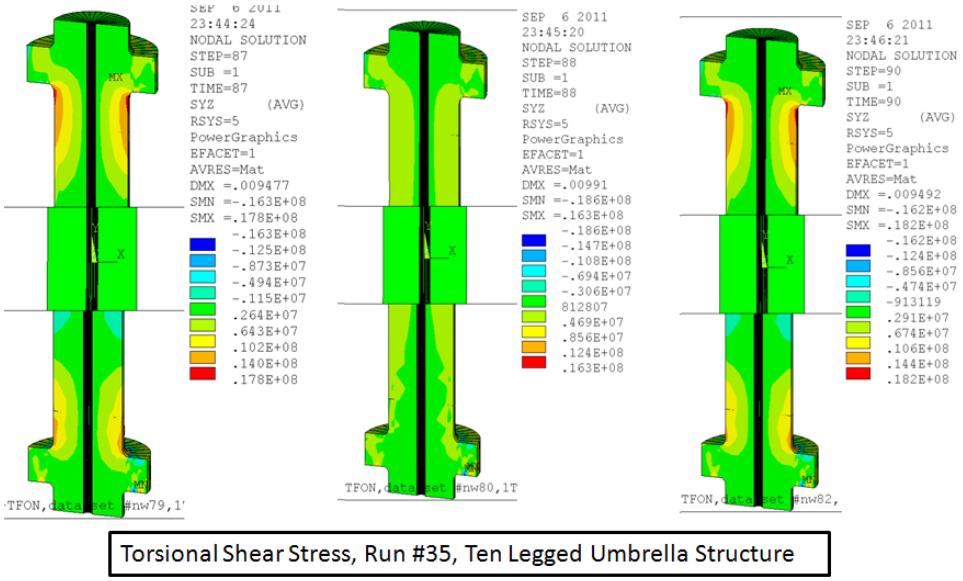


Figure 9.1-3 Comparison of Existing NSTX and NSTX-U TF Tresca Stress at the Lower End of the Inner Leg

9.2 Center Stack – TF Inner Leg Torsional Shear

Global model results of inner leg torsional shear have been split-out into another calculation, ref [15] TF Inner Leg Torsional Shear, Including Input to the DCPS NSTXU-CALC-132-07-00

Additional Discussions of torsional shear may be found in Bob Woolley's calculation NSTX-CALC-132-003-00 which provides moment calculations which are useful to find the maximums in the NSTX Design Point spreadsheet. Bob's summation of the outer leg moment is directly useful in evaluations of the up-down asymmetric case that H. Zhang ran in the diamond truss/tangential and radius rod calculations.



Torsional Shear Stress, Run #35, Ten Legged Umbrella Structure

Figure 9.2-1 Torsional Shear Stress from Run #35

9.3 TF 9.4 Outer Leg Bending

Han Zhang has addressed the need for outer leg reinforcement in her calculation number NSTX CALC 132-04-00. This includes an evolutions in design concepts intended to support the outer TF legs for in-plane as well as out of plane loads. An early truss concept was eliminated from the running because of

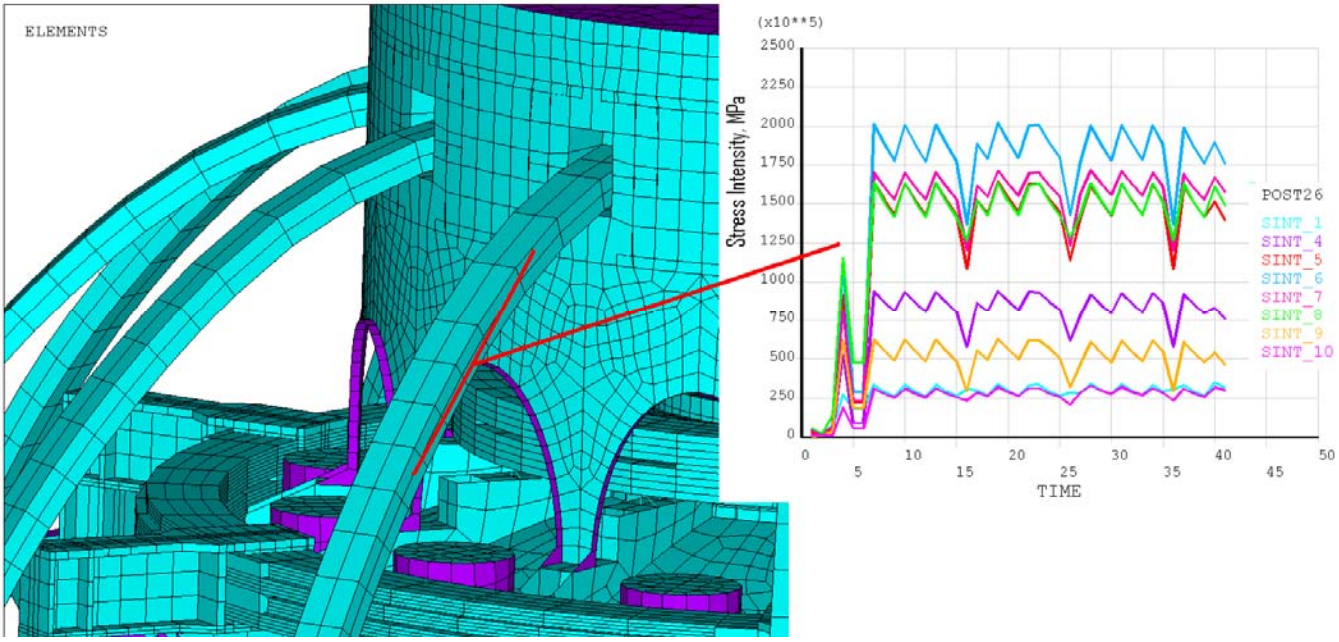


Figure 9.3-1 TF Outer Leg Bend Stress

interference problems with many diagnostics and waveguides installed in the bays. The tangential radius rod restraint concept was also considered. The truss was modeled in the global model, and shown in Figure 4.0-1. TF outer leg bending stresses are a function of the support concept used for the outer leg. The Soft spring support concept was used at the PDR and this imposed more stress on the TF leg, but off-loaded the clevises on the vessel knuckle region.

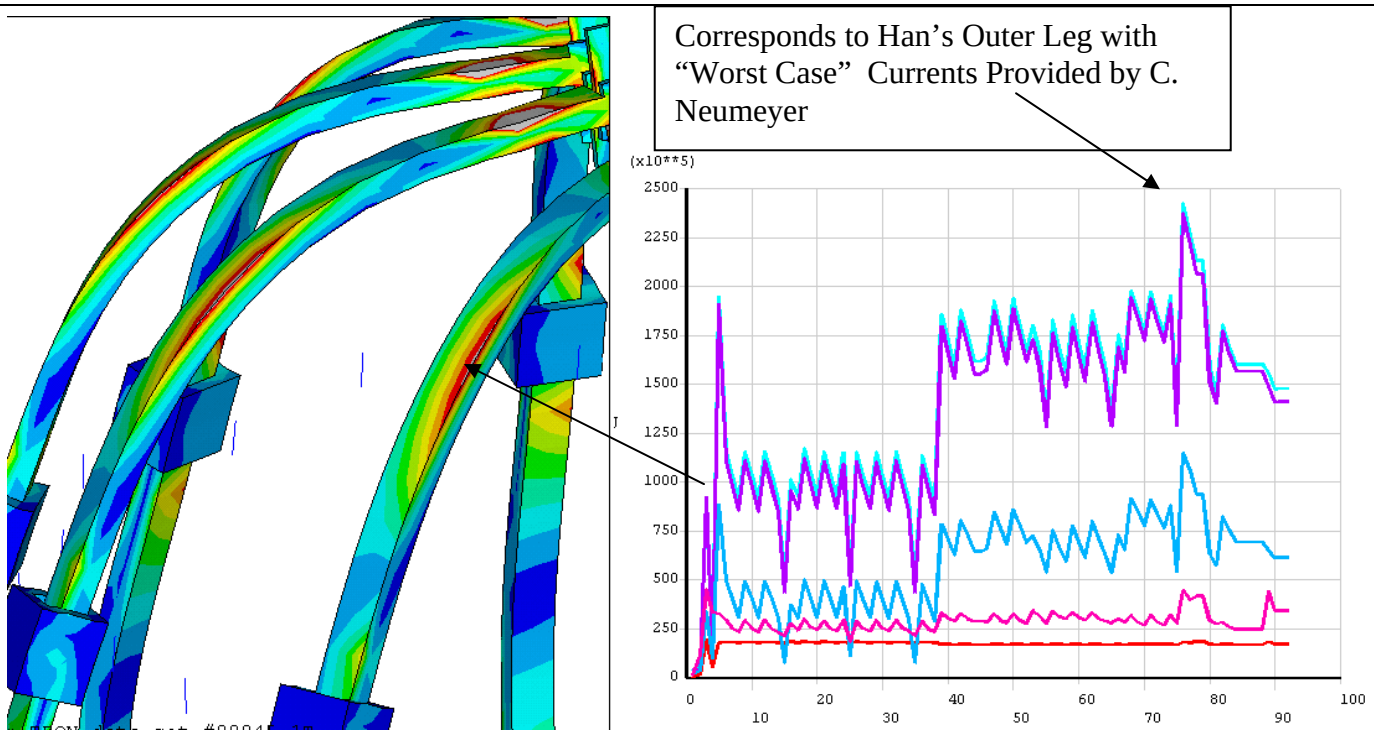


Figure 9.4-2 Figure Global Model TF Outer Leg Bending Stress

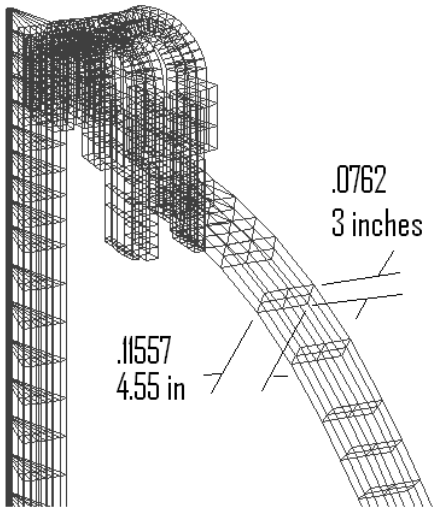


Figure 9.4-3 The Toroidal Width of the TF Outer Leg Should Be 6 inches. Stresses would scale as the section modulus or by d^3

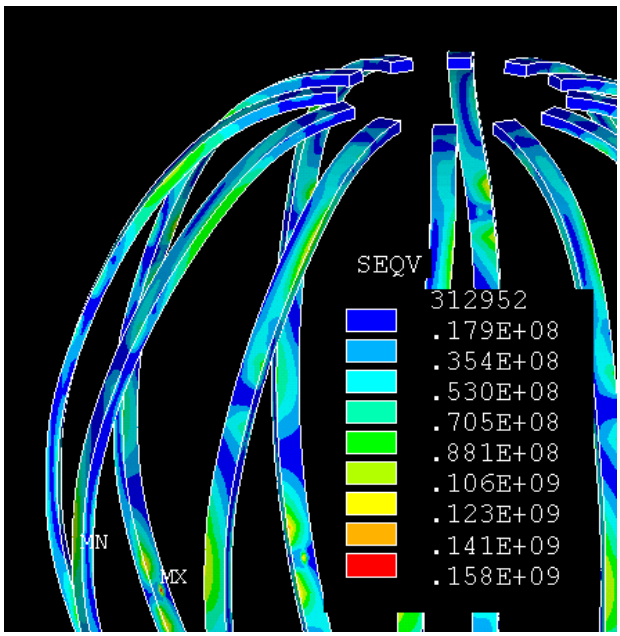


Figure 9.4-4 TF Outer Leg Bend Stress from an early version of [4]

This generation of the Global model contains an error that over-estimates the TF by leg bending stress by the ratio of section modulus or 237 MPa*(4.5/6)^3 = 100 MPa which is closer to the stress reported by Han [4]. The model was corrected in run 24 when the three individual conductors and insulation between was more accurately modeled.

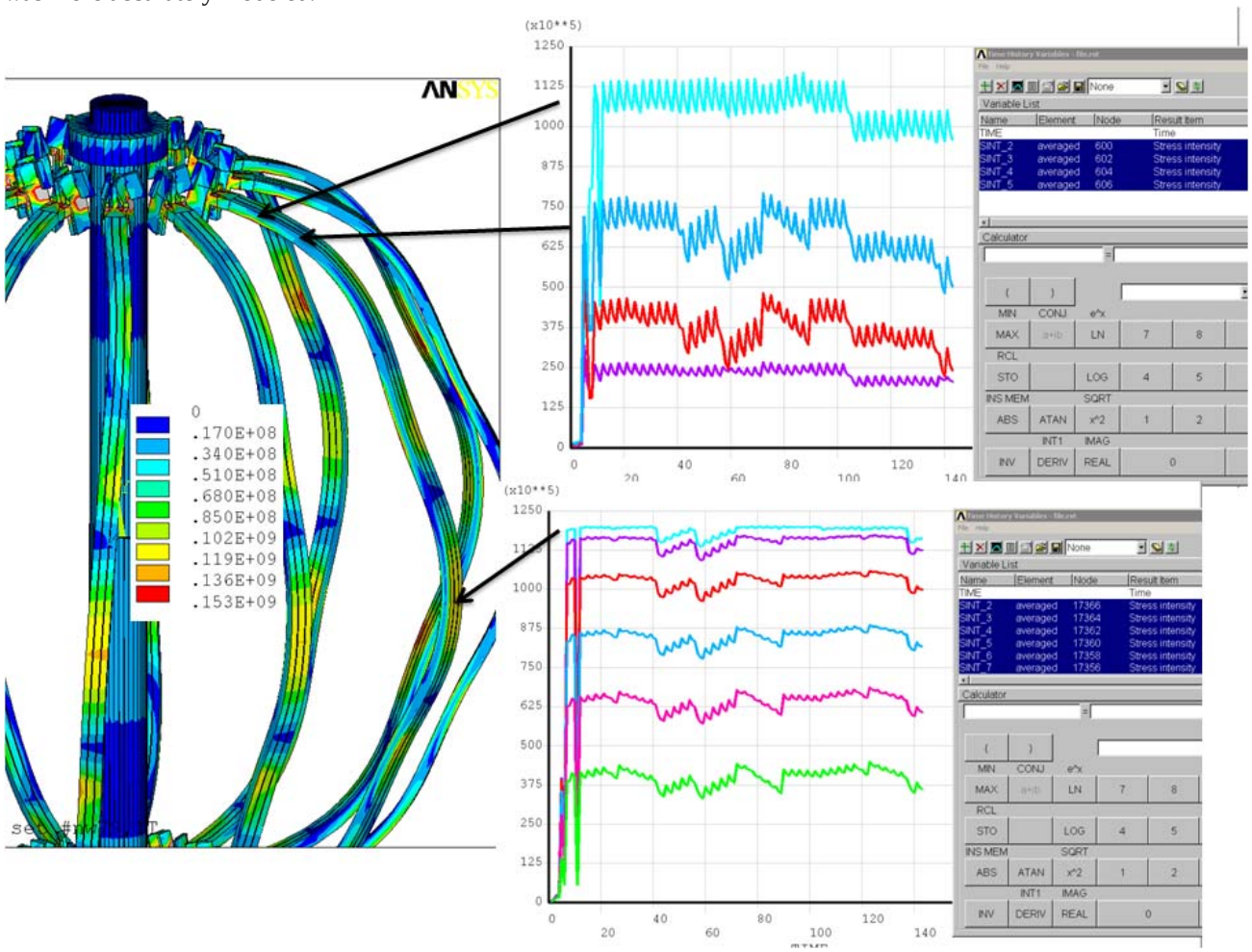


Figure 9.4-5 TF Outer Leg Metal Tresca Stress Post 26 Results for 96 Equilibria plus about 40 of the with plasma

9.5 TF Outer Leg Bond Shear

The primary qualification of the outer leg shear stress is in the outer leg support calculation, ref [4]. Results presented here are primarily intended for checking ref [4] results and addressing the 96 equilibria. Figures

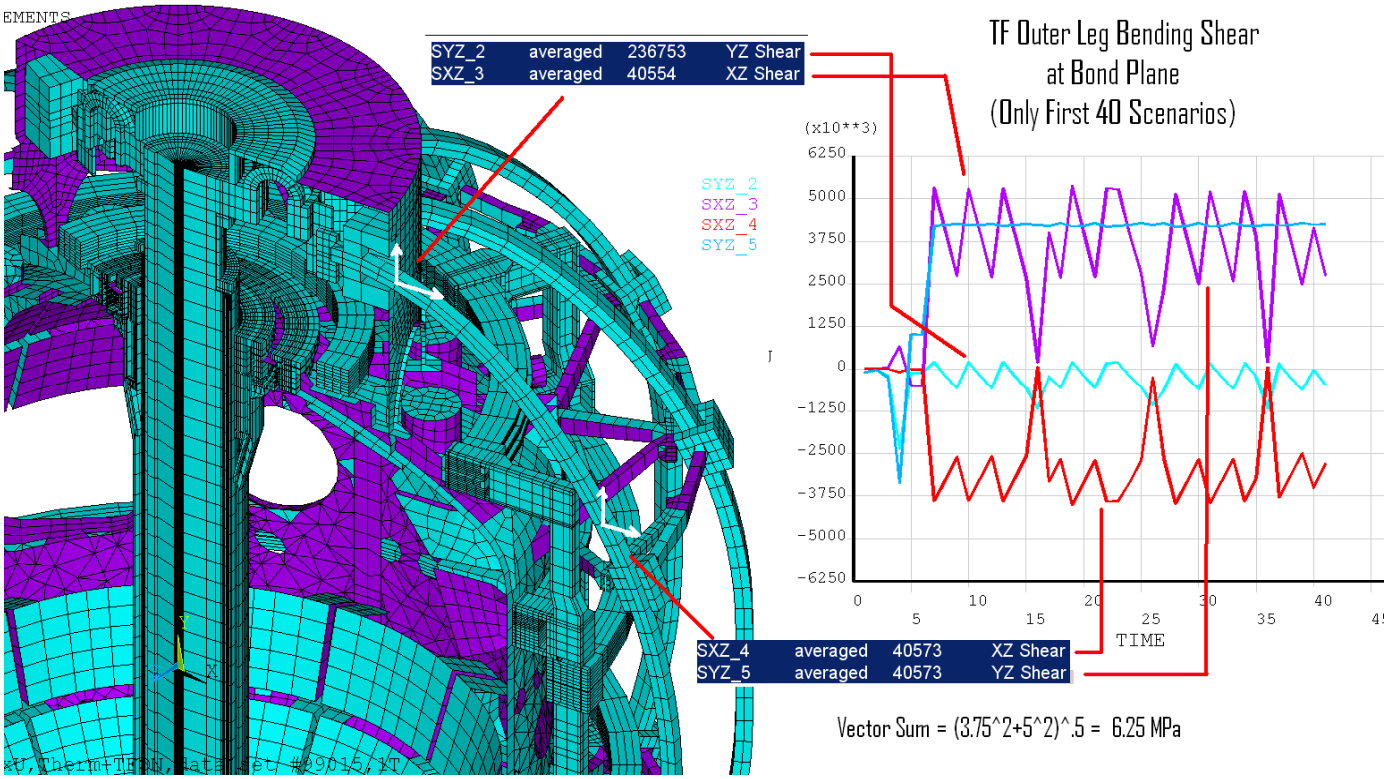


Figure 9.5-1 TF Bending Related Bond Shear Stress

9.5-1 and 2 are ANSYS POST26 plots that give an indication of which of equilibria are worst.

Outer legs are retained from the original NSTX with the exception of two new replacement outer legs. . The bending shear in the existing legs must remain below 16 MPa. to satisfy the cyclic qualification done for the insulation system. Test results are in the NSTX R&D report, ref 33, excerpts of which are included in Attachments D. The two new TF outer legs will use the Cyanate ester blend, CTD 425 system with the Cyanate Ester primer, CTD 450. Ref [15], the TF torsional shear stress calculation, includes results of more complete testing of the CTD 425 system. These tests qualify the insulation system for up to 25 MPa shear stress.

Figure 9.5-2 is the stress intensity in the insulation. The insulation stress includes shear and direct stress components contributing to the equivalent or Tresca stress. The total shear stress in the insulation must be less than 1/2 the Tresca. In the upper portion of the leg, the Tresca is 25 MPa and the shear can be no more than 12.5 MPa. and the vector sum of the shears on the bond face must be less than that. In figure 7 of [4], the insulation shear is reported as 10 MPa. In figures Figure 9.5-3 to 5, the shear stresses are below 10 MPa, again, consistent with [4]

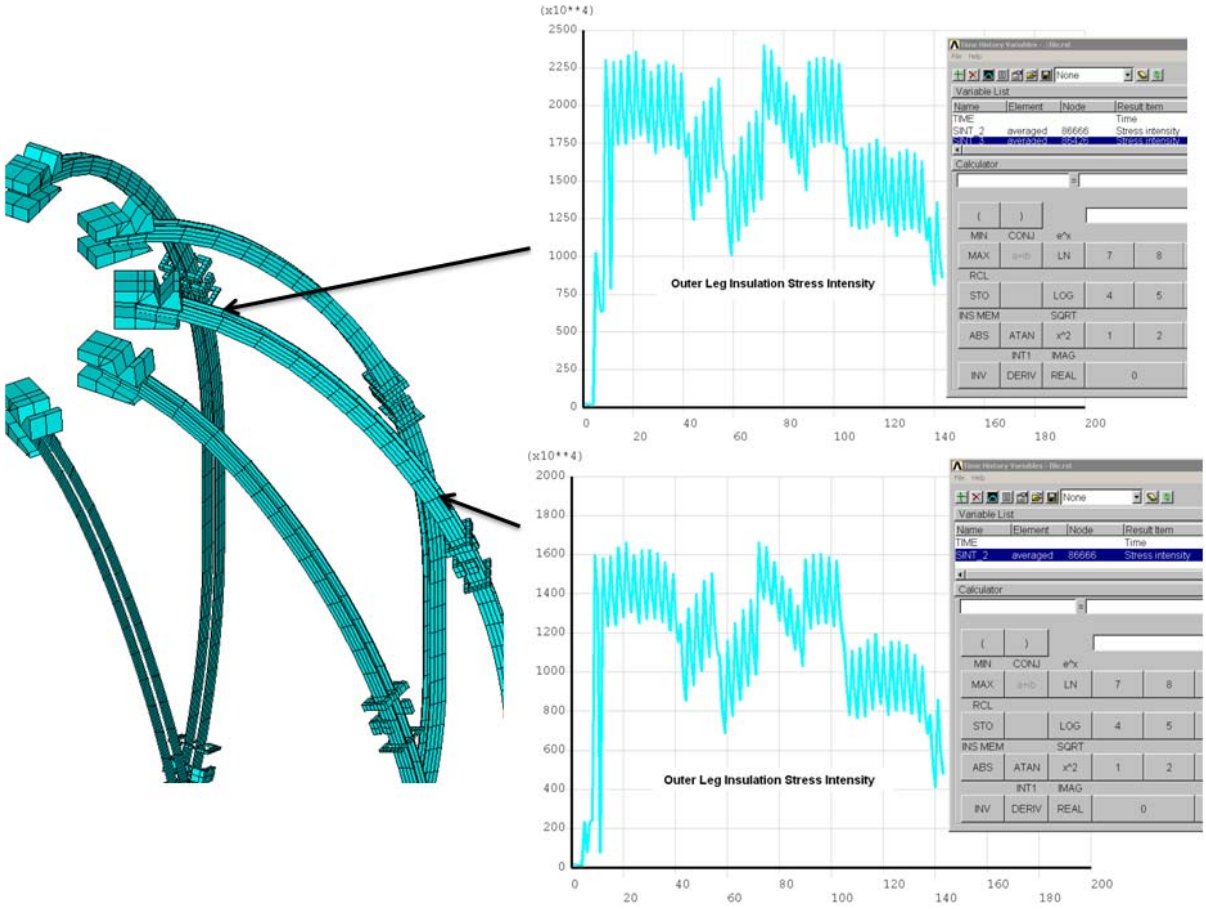


Figure 9.5-2 Outer Leg Insulation Stress Intensity from run #37

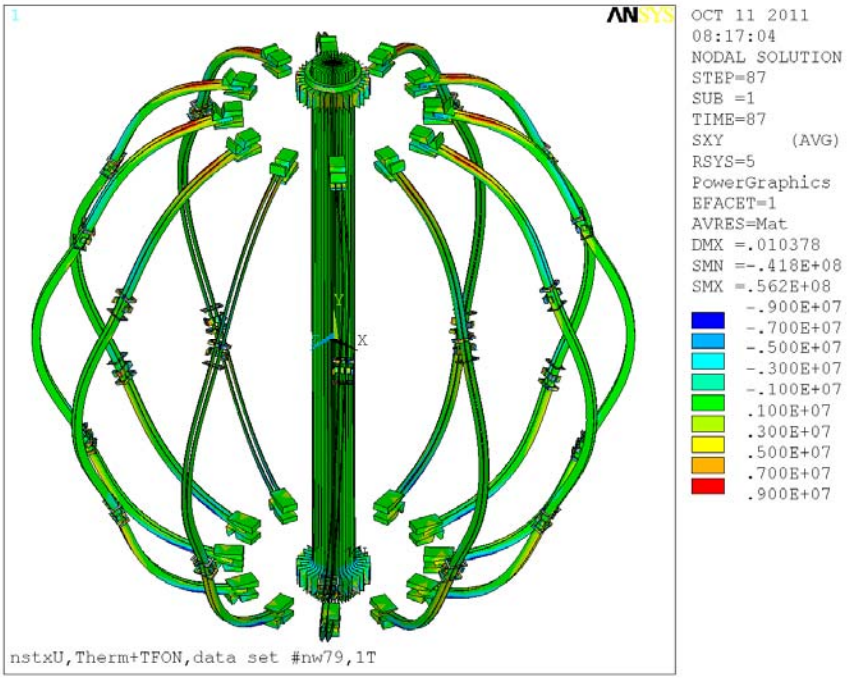


Figure 9.5-3 Outer Leg Insulation Radial-Theta Shear Stress from run #37

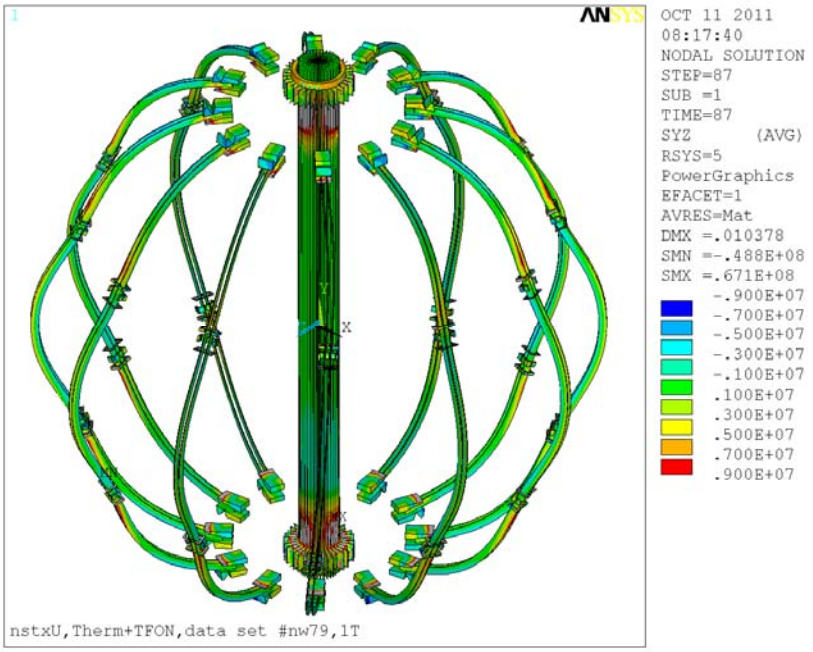


Figure 9.5-4 Outer Leg Insulation Vertical -Theta Shear Stress from run #37

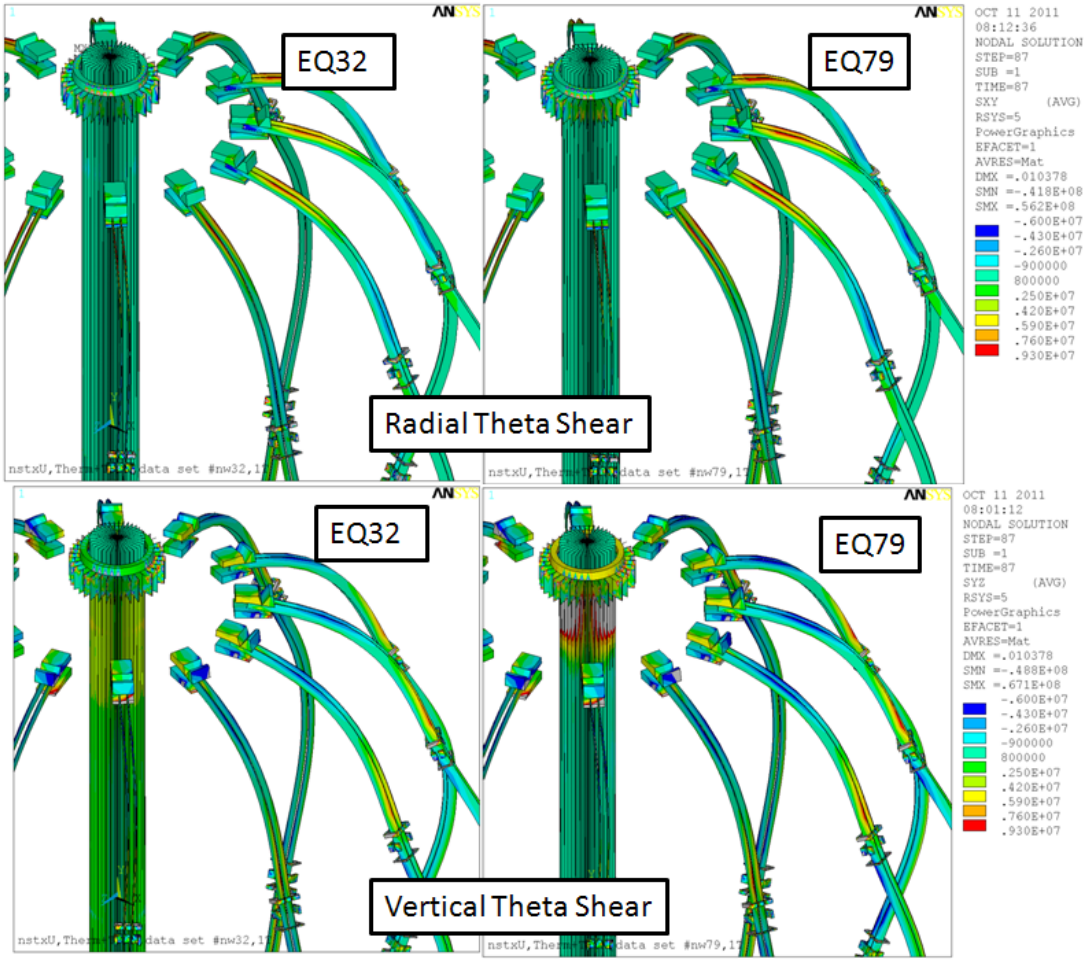


Figure 9.5-5 Outer Leg Insulation Shear Stress from run #37

9.6 Aluminum Block and Bolting Stresses

Greater detail in the analysis of these components may be found in "TF to Umbrella Structure Aluminum Block Connection" NSTXU-CALC-12-04-00Rev 0 December 15 2010[28]. Loads shown below were extracted from the global model by selecting mat, 14, then selecting the nodes connected to mat,14, then selecting the upper half of these nodes then graphically "reselecting" the pad nodes that are connected to the umbrella shell. A summation point at the center of the TF leg at the surface of the umbrella structure was selected using the SPOINT command. RSYS,5 was used, Then the FSUM,RSYS command was issued.

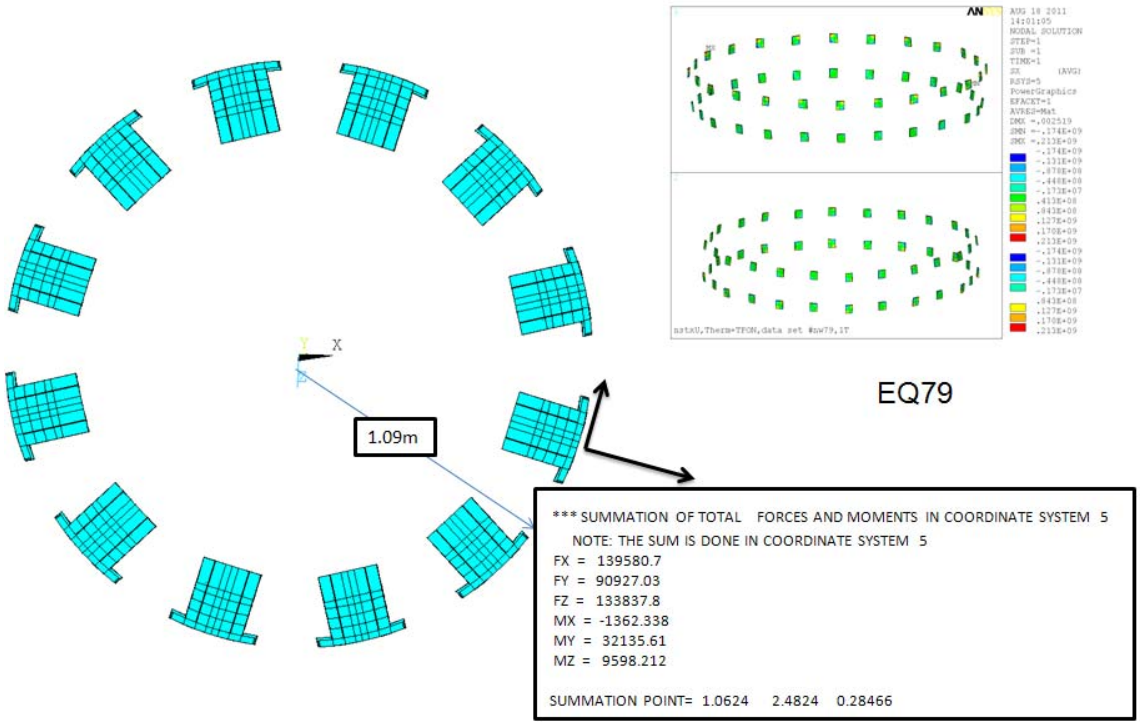
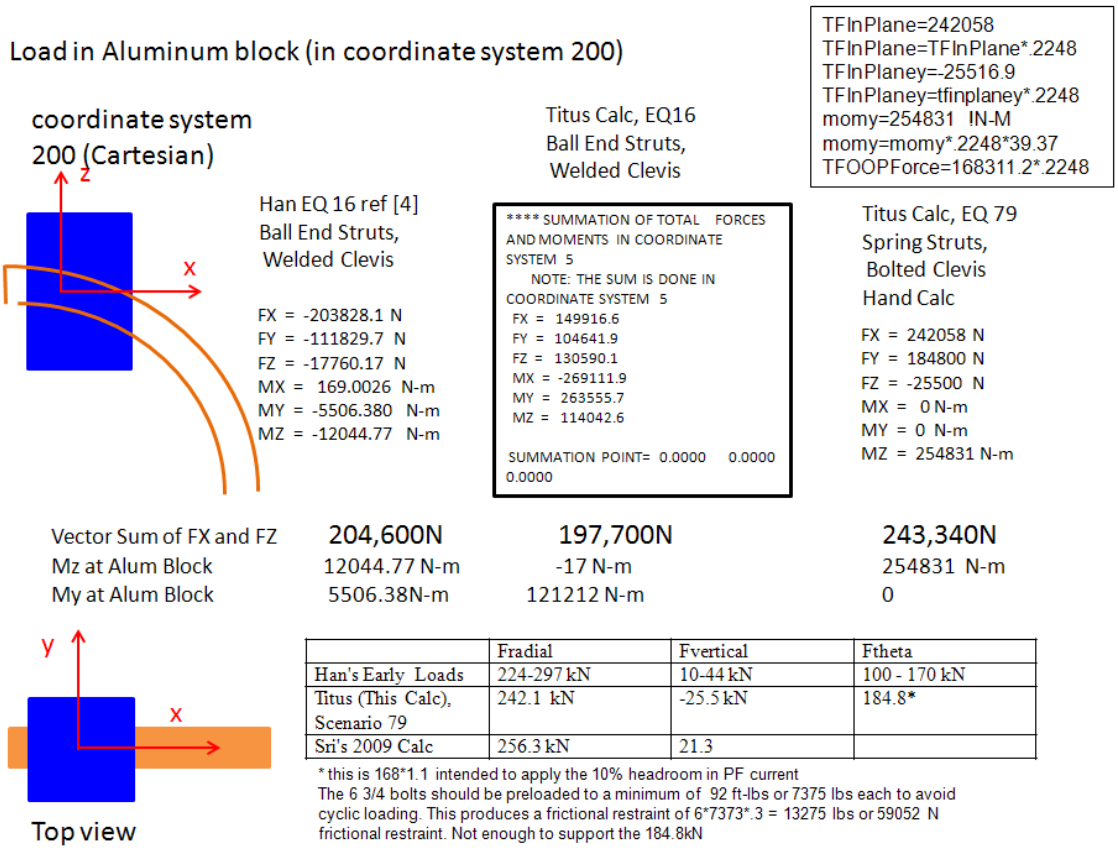


Figure 9.6-1 EQ 79 Aluminum Block Loading

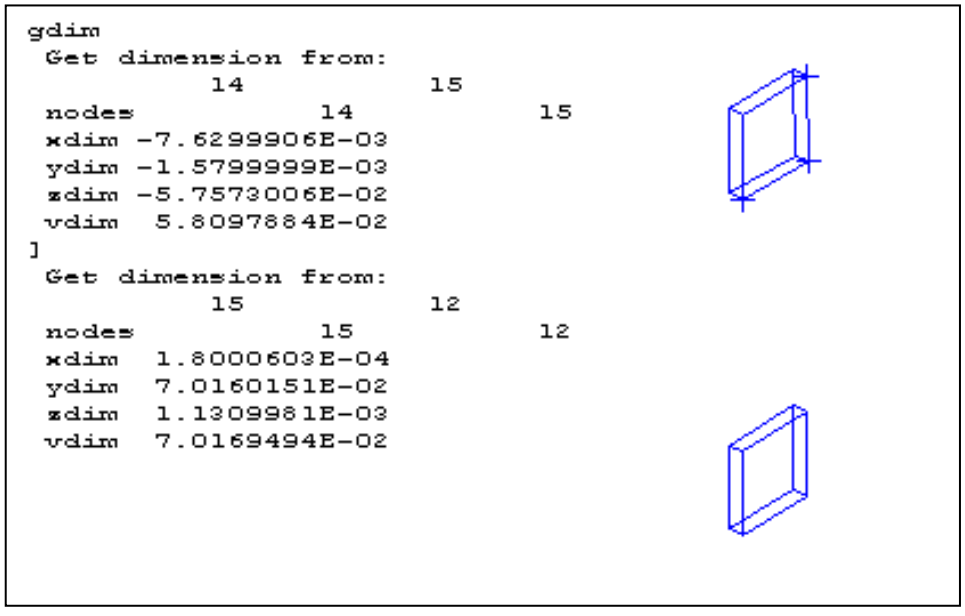


	Fradial	Fvertical	Ftheta
Han's Early Loads	224-297 kN	10-44 kN	100 - 170 kN
Titus (This Calc), Scenario 79	242.1 kN	-25.5 kN	184.8*
Sri's 2009 Calc	256.3 kN	21.3	

* this is 168*1.1 intended to apply the 10% headroom in PF current
The 6 3/4 bolts should be preloaded to a minimum of 92 ft-lbs or 7375 lbs each to avoid cyclic loading. This produces a frictional restraint of 6*7373*.3 = 13275 lbs or 59052 N frictional restraint. Not enough to support the 184.8kN

Figure 9.6-2 Aluminum Block Loading Comparison with Ref [4] for EQ 16 and the Earlier Estimate of EQ 79 loads for the Soft Spring Trusses.

The alignment of the outward load on the aluminum blocks is different between H. Zhangs' calculation [4] and this global model analysis, but the magnitude of the outward load is similar for the two EQ 16 loads. This calculation includes the effects of



10.0 PF Coil Results
10.1 PF Coil Hoop Stresses

10.2 PF Coil Hoop Stresses

PF coil hoop stresses(exclusive of the OH coil) are small for all the postulated coil currents, including the worst case power supply currents. The OH coil is the most severely loaded and continues to push the allowable stress.

Figure 10.2-1 shows the “smeared” hoop stresses. is representative of the PF coil hoop stress exclusive of the effects of cooling holes. Figure 10.2.4 shows the maximum and minimum hoop stresses based on Ron Hatcher’s influence coefficients..

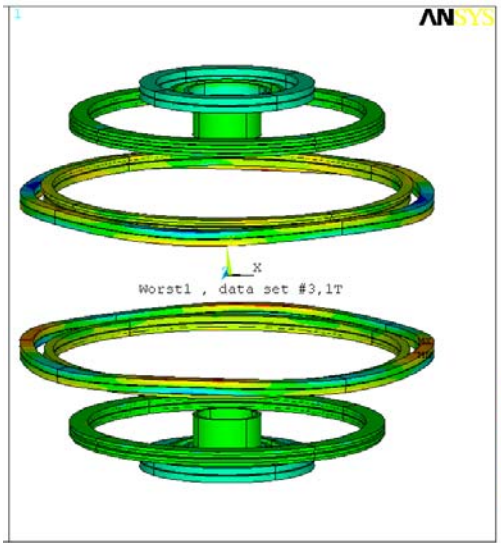


Figure 10.2-1.-. Representative PF coil Hoop Stress

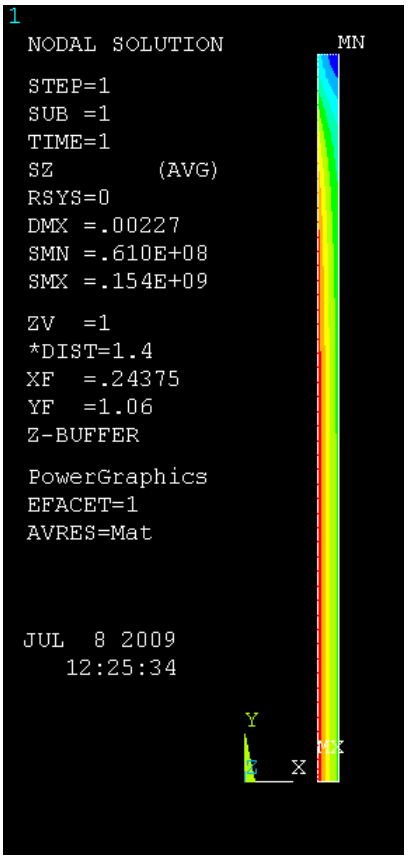


Figure 10.2-2 - OH “Smeared” Hoop Stress

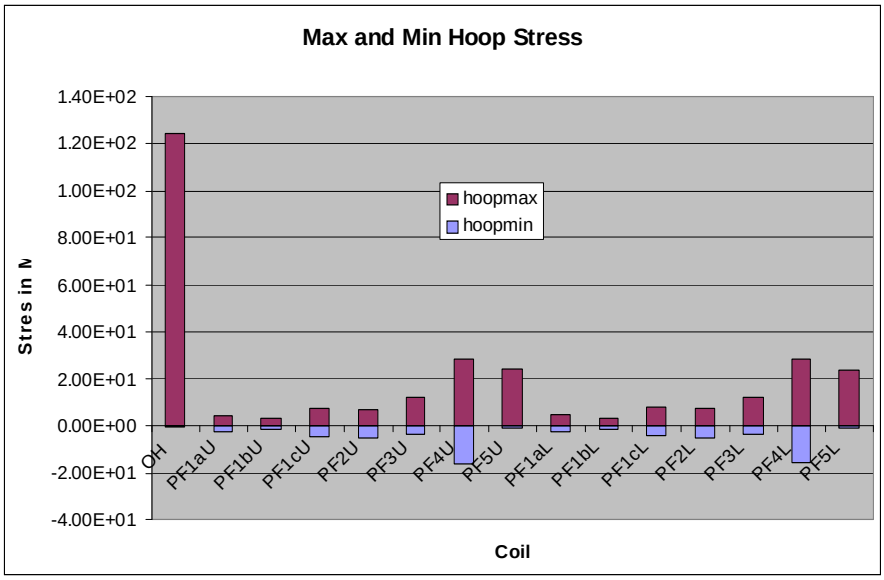


Figure 10.2-3 – Maximum and Minimum Hoop Stress

A couple of the coils, like PF4 and 5, maybe 3, are limited by vertical bending due to the span from support to support. Rigorously the hoop tension should be added to this.Hoop tension produces a load at the in the PF4 and 5 fixed support and changes the bending stress when they go oval - These effects are considered in the following sections that address the coils and their supports.

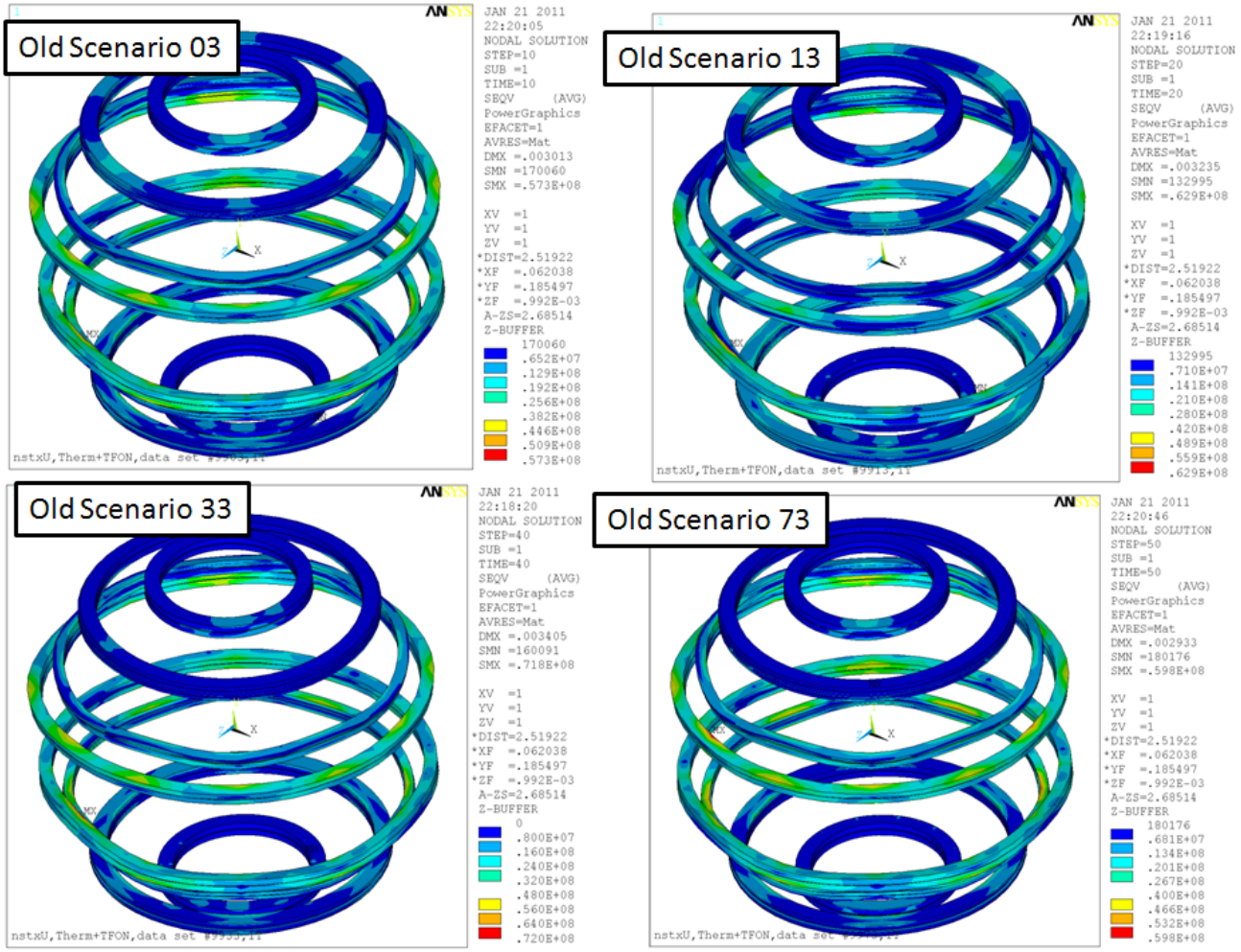


Figure 10.2-4 PF Coil Von Mises Stress

It may be possible to have hoop compression and stability issues in some coils that we might need to be precluded in the DCPS.

11.0 Vessel Results

11.1 Vessel Displacements

Results for a few evolutions of the model are presented. Results from this calculation include all loads - PF vacuum, TF in-plane and out-of plane. For comparison sake, also included are results from [4] which only has the OOP torques applied.

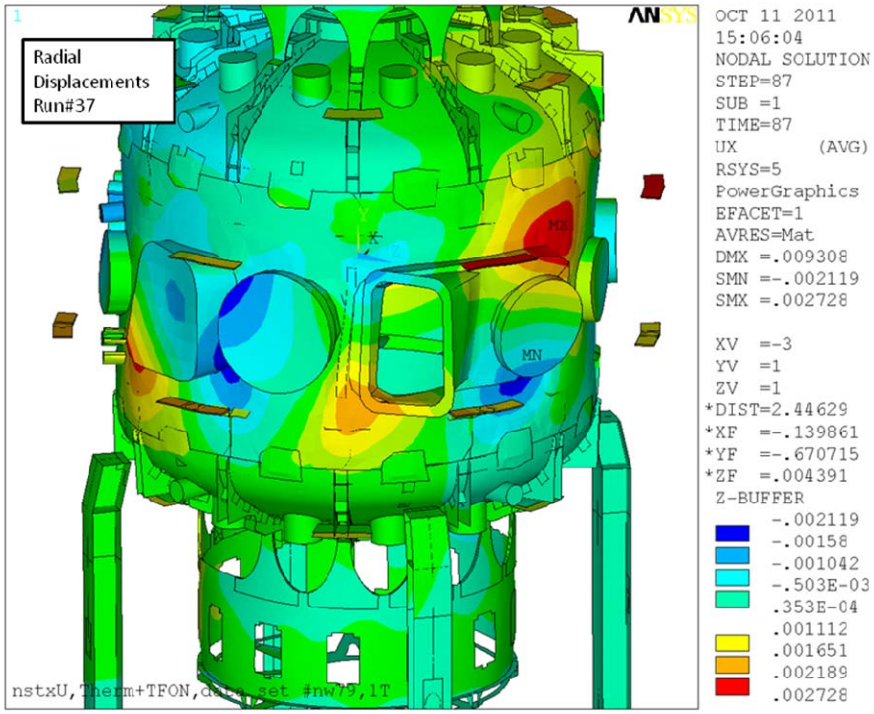


Figure 11.1-1Radial Displacements from This Global Model Analysis EQ 79

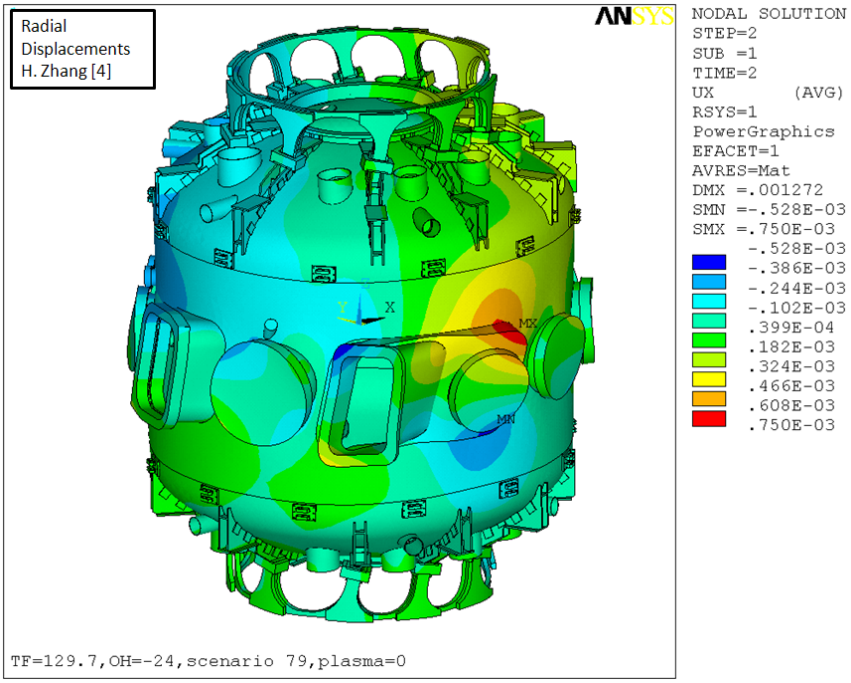


Figure 11.1-2 EQ 79 Radial Displacements from H. Zhang's Analysis of Just the OOP loads [4]

Displacements from the global model are almost 4 times larger than from [4] with only OOP loads applied. This may be a consequence of the other load components applied in the global model and not in [4]. The displacement shape is similar.

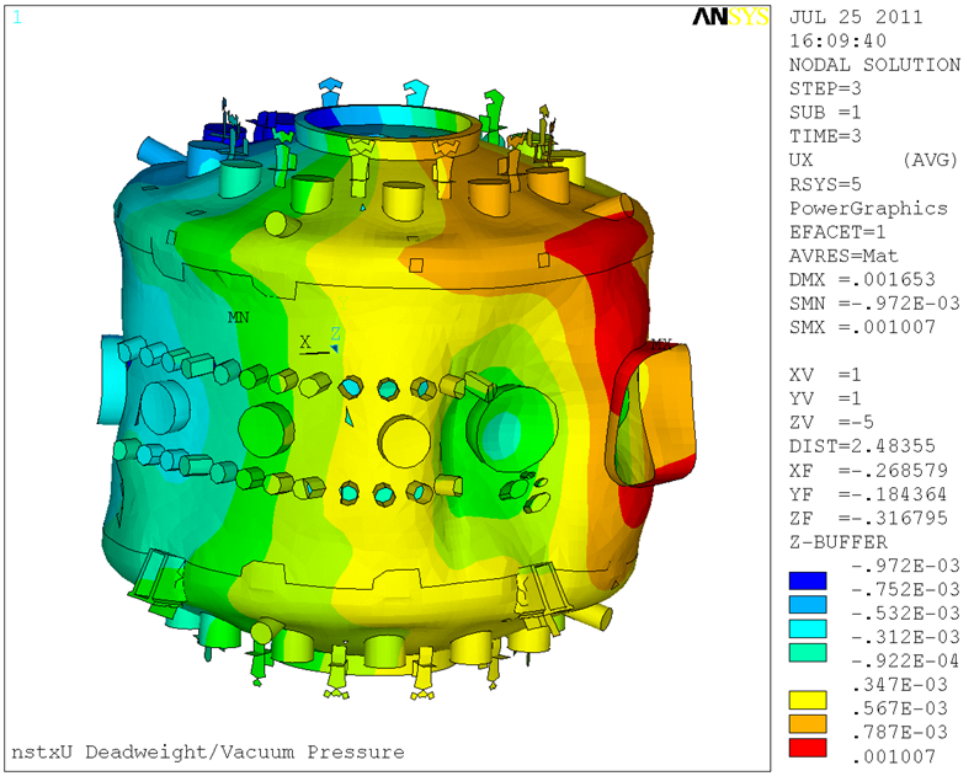


Figure 11.1-3 Radial Displacements in the Vessel for Vacuum and Deadweight

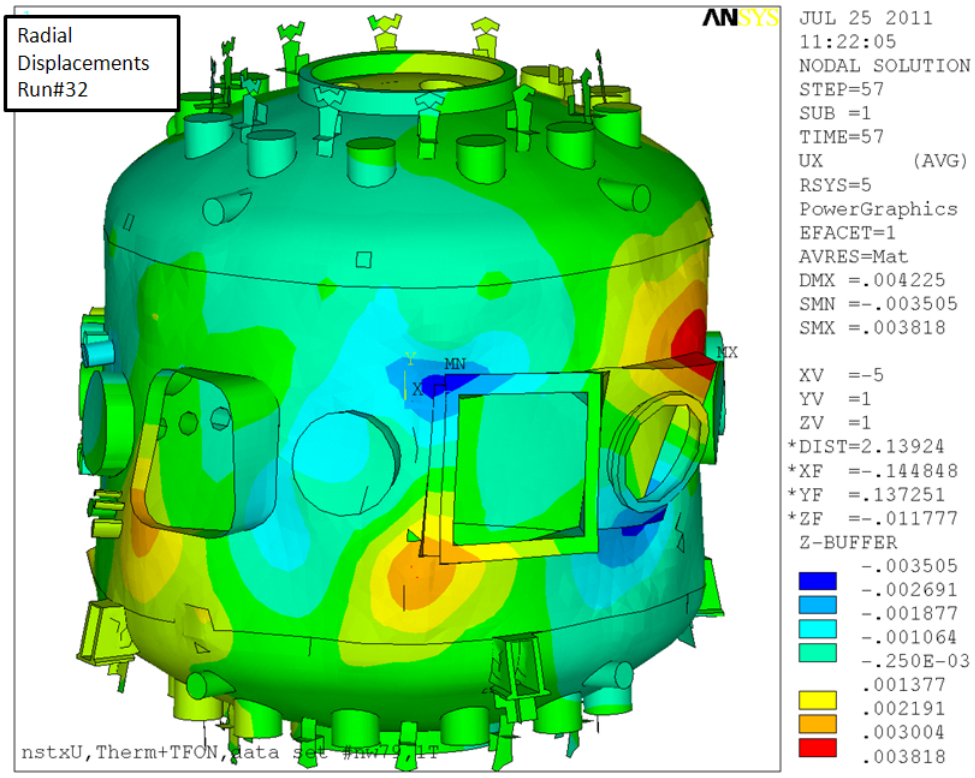


Figure 11.1-4 Radial Displacements in the Vessel EQ #79

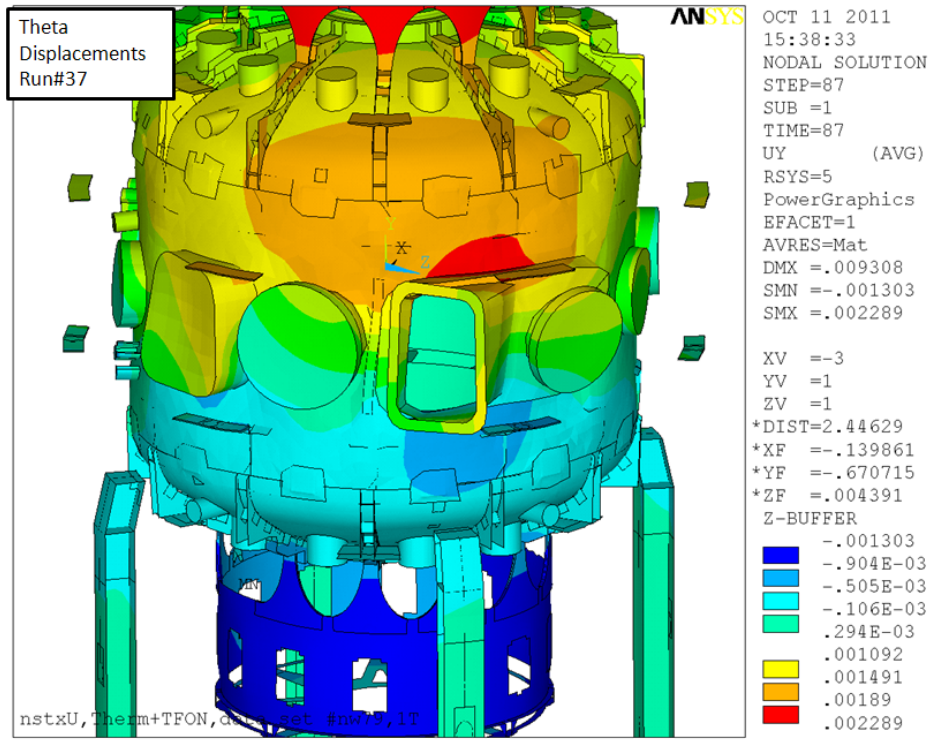


Figure 11.1-5 Theta Displacements in the Vessel EQ #79 All Loads

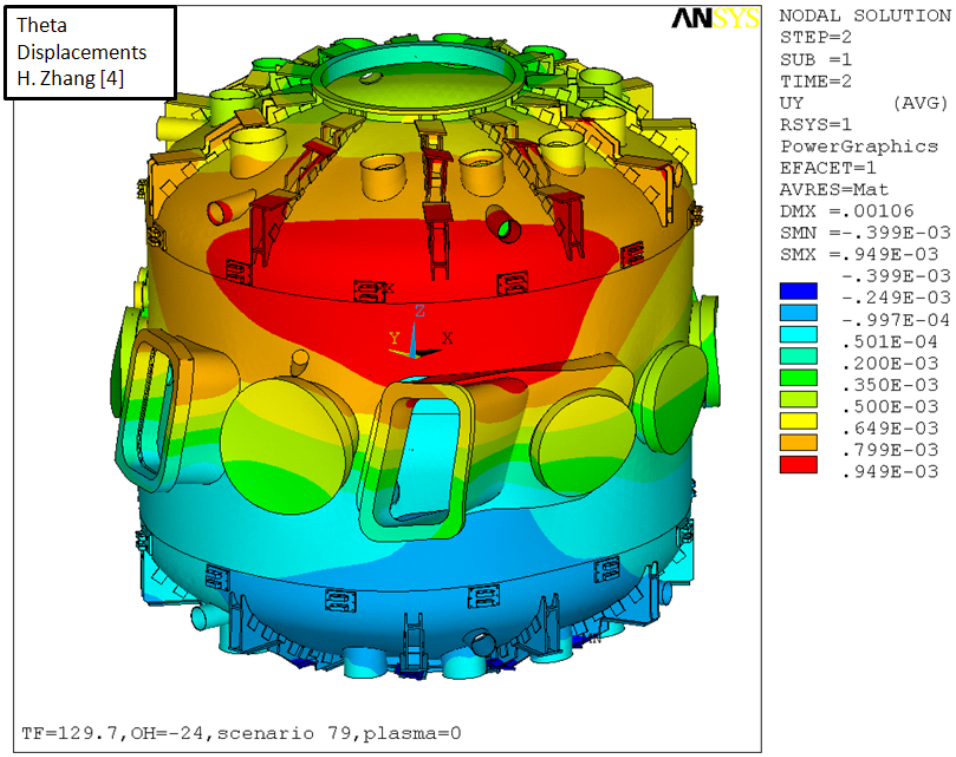


Figure 11.1-6 Theta Displacements in the Vessel EQ #79 Only Hoop [4]

Differential displacement across the port region

This Calculation 2.289-(-.904) = 3.193 mm

[4] .949 +.2 = 1.149

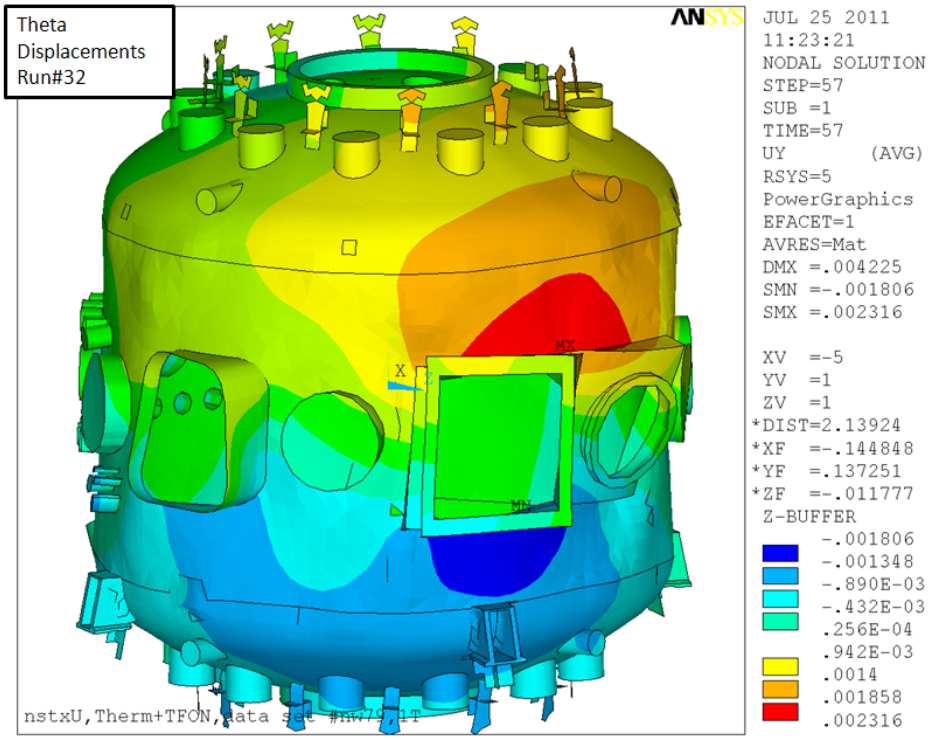


Figure 11.1-2 Toroidal or Theta Displacements in the Vessel EQ #79

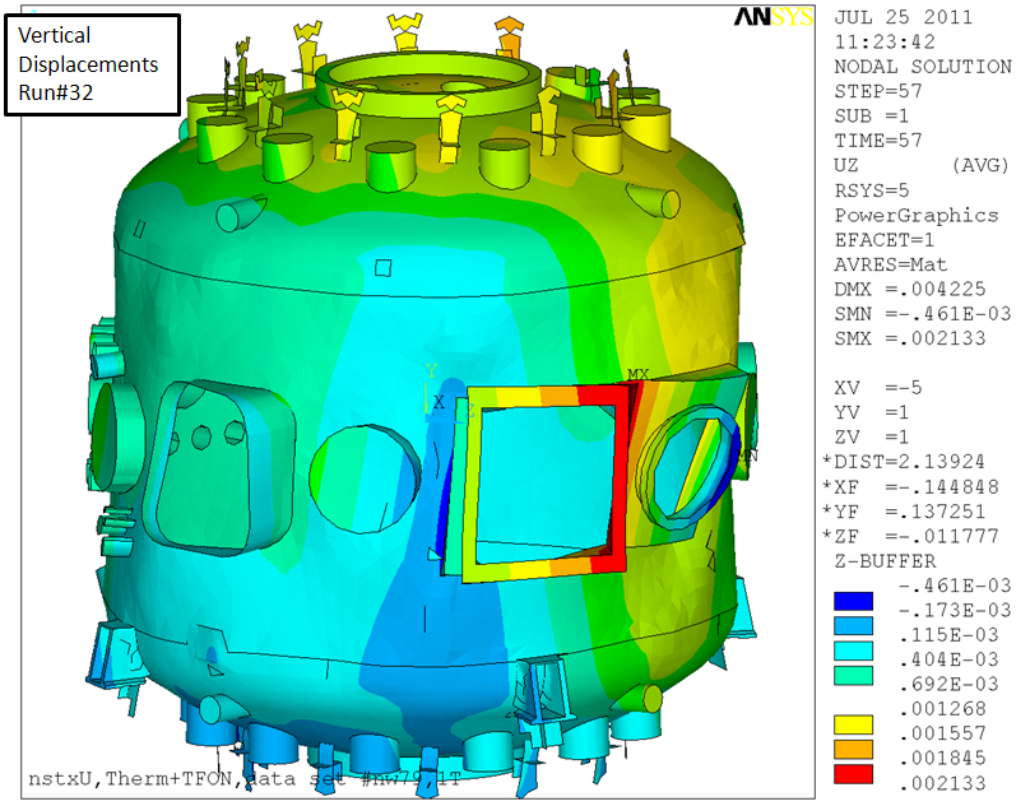


Figure 11.1-3 Vertical Displacements in the Vessel EQ #79

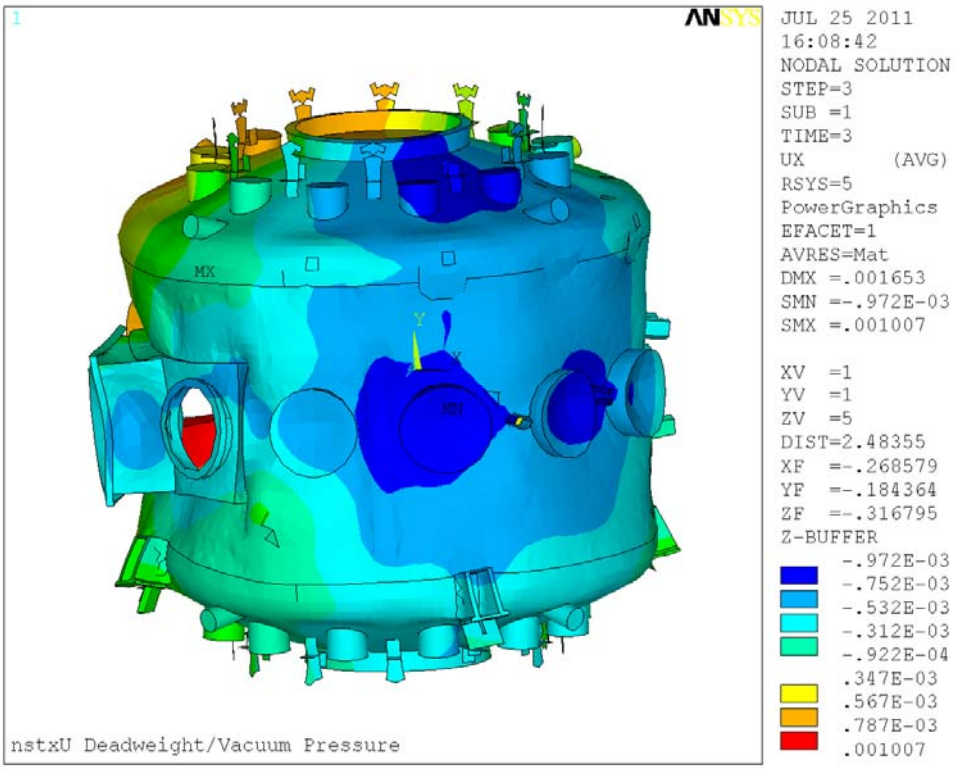


Figure 11.1-4 Radial Displacements in the Vessel for Vacuum and Deadweight

11.2 Vessel Stresses

The primary responsibility for qualification of the vessel is with ref ??? - M Smith and N. Atnafu calculation #. Also ref [4] includes vessel stresses.

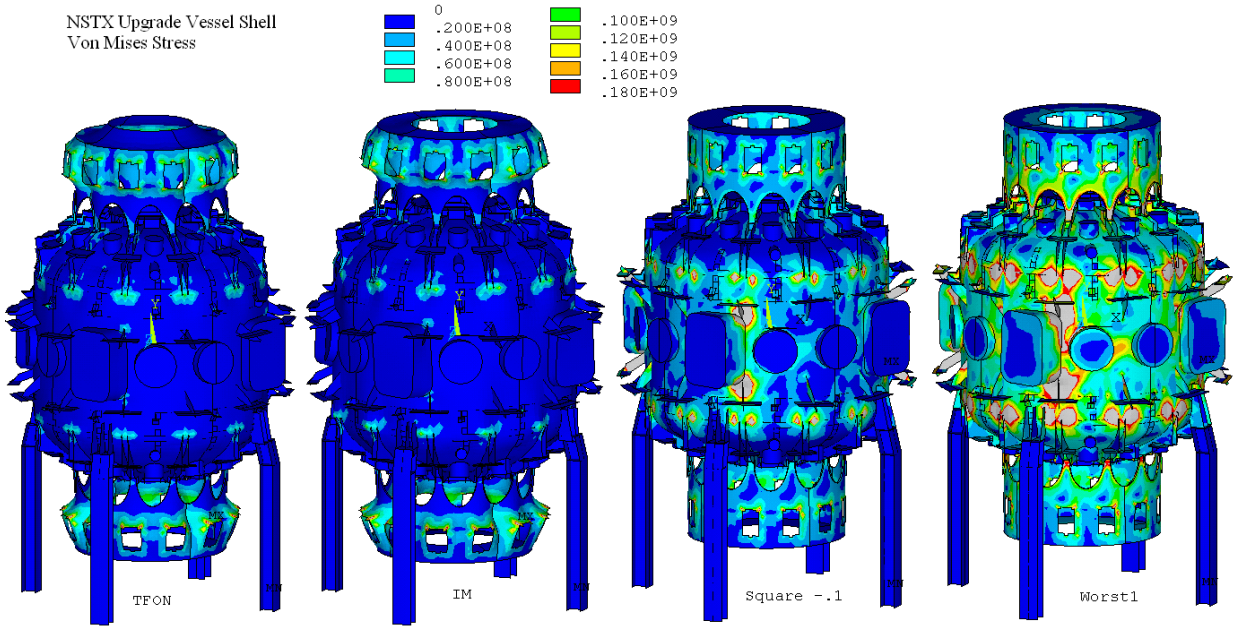


Figure 11.2-1 Vessel Stresses for Normal and "Worst" Loading

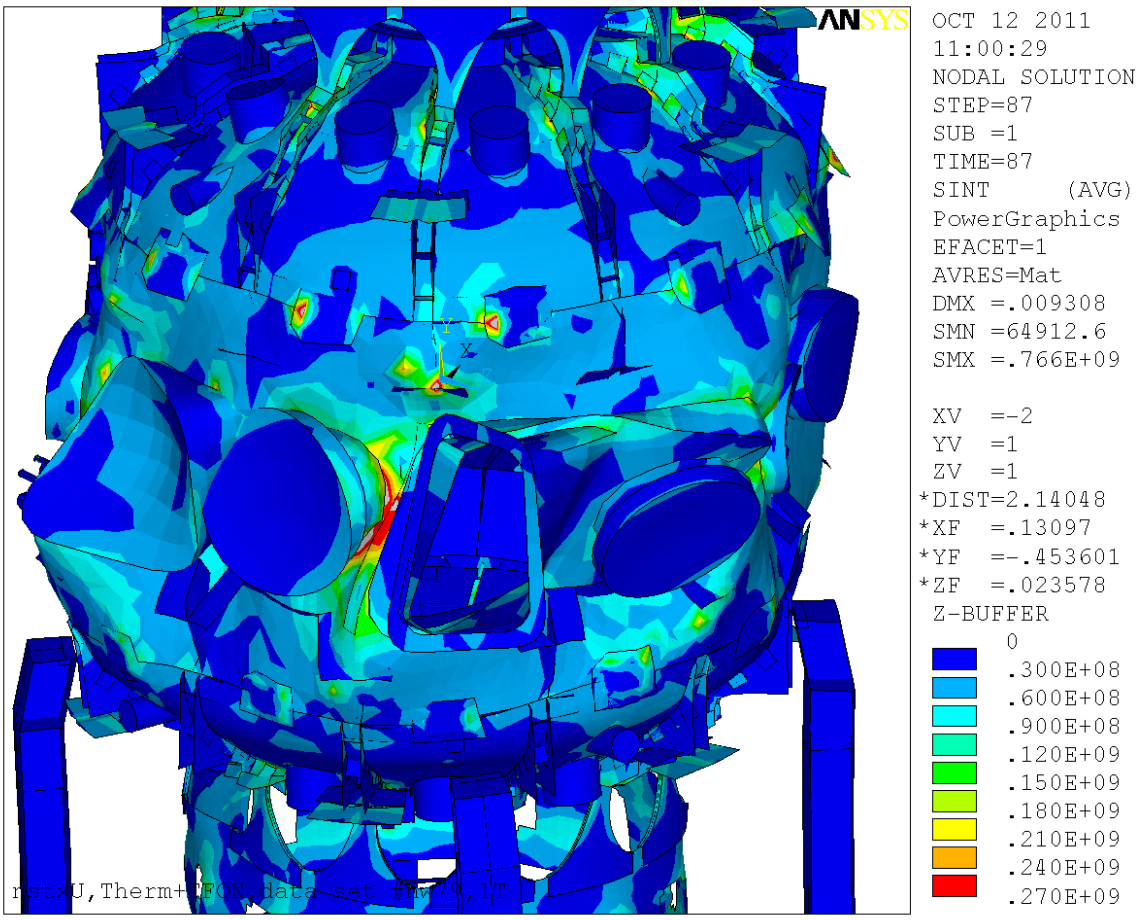


Figure 11.2-2 Vessel Stress for EQ 79 Max is ~300 MPa

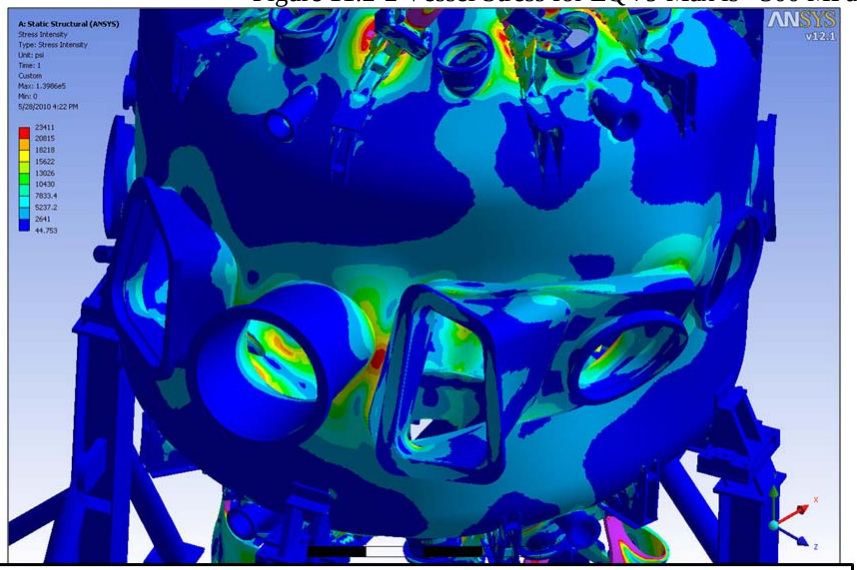


Figure 21 – Port 'L' Upgrade, 30" Dia. x ¾" Wall Tube: Stress Intensity 2
Current Scenario 79

Figure 11.2-2 Vessel Stress for EQ 79, Willard/Smith Result - Probably Soft Truss Rods, Max is 161 MPa

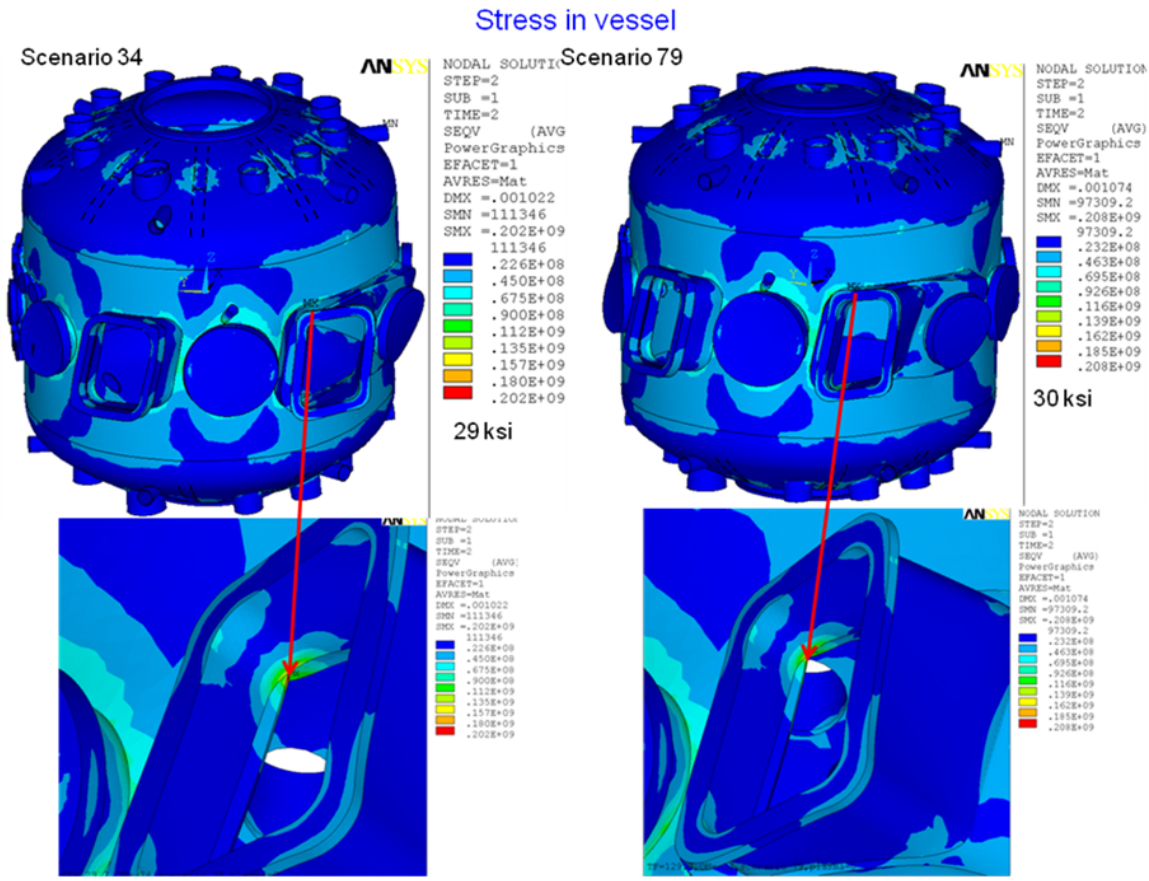


Figure 11.2-3 Vessel Stress for EQ 34, and79, H. Zhang Result - Max Between Port is 92 MPa

12.0 Global Structure Results

12.1.1 Global Structure Displacements

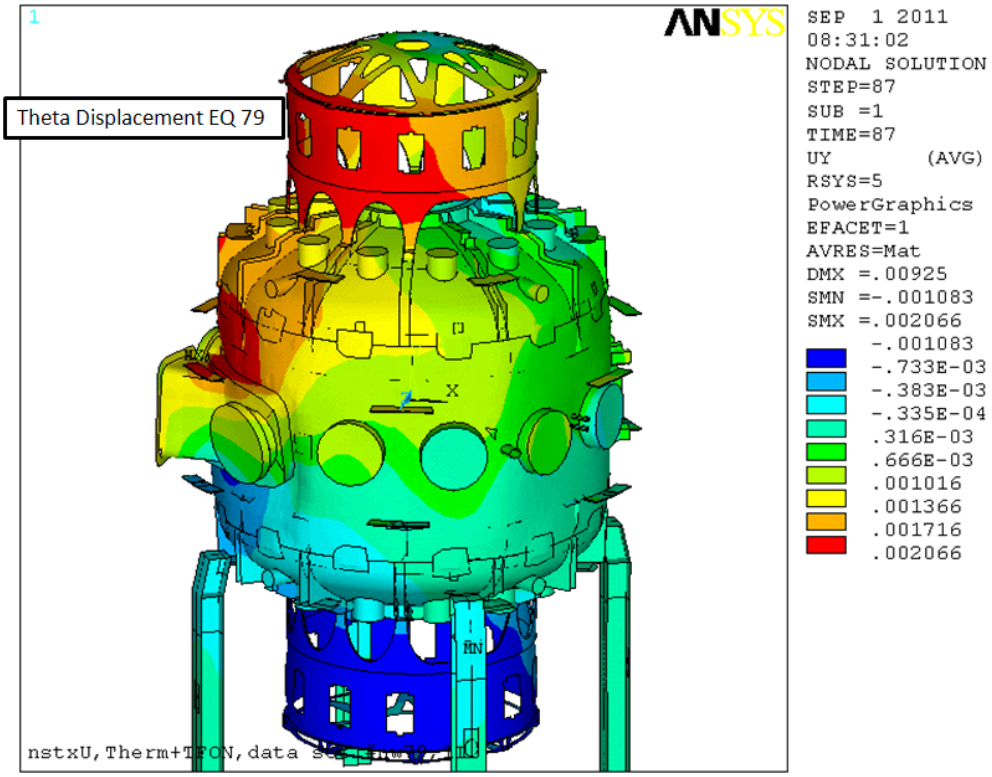


Figure 12.1.1-1 Torsional Displacement ion the Major Shell Structures EQ 79

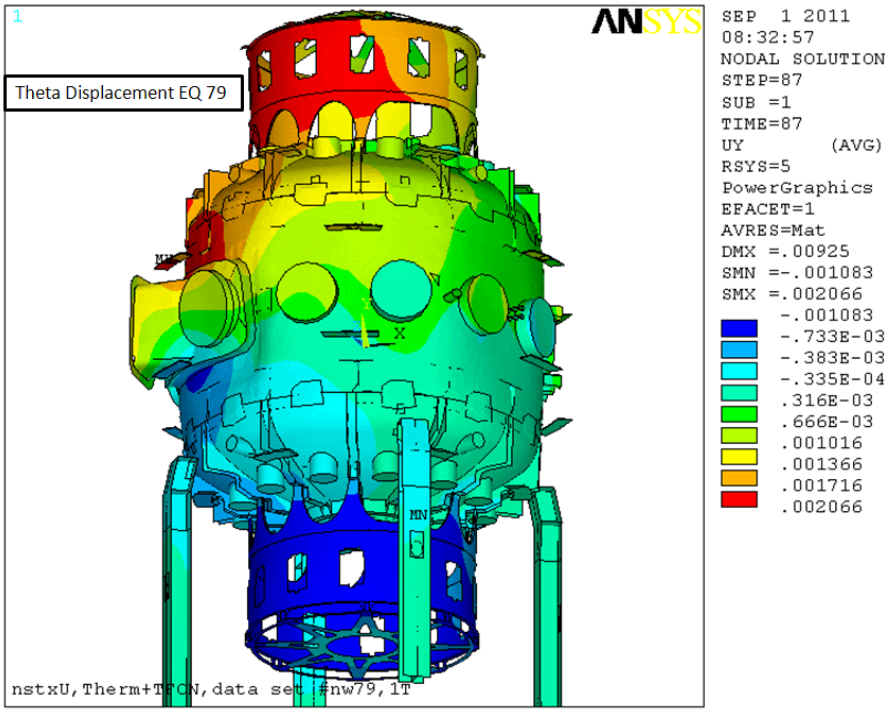


Figure 12.1.1-2 Torsional Displacement ion the Major Shell Structures EQ 79

12.1.2 Toroidal Displacements at TF Flex Joint

Early in the CDR, estimates were made of the relative motion of the inner and outer connections of teh TF strap. During the PDR the latest global model was post processed to obtain an updated value for the displacement. It had all the 96 current sets plus some with plasma. The enveloped relative displacement is less than 1 mm, down from the 2.4mm reported last year for the worst power supply loads. Aside from the 96 current set results vs max power supply currents, there were a few upgrades to the model.

The umbrella structure thickness was updated to 3/4 inch from 5/8, but arch reinforcement was removed.
The proposed reinforcement around the two neutral beams was updated to the latest frame design
port covers were added on most ports.
The build of the outer TF coil was corrected
Bellows were thinned and convolutions widened - but they still are too stiff. But:
This model does not have Danny's latest TF outer leg support
The trusses do not have the soft springs. (consistent with the FDR design)
The scenarios are last year's and have not been updated.
The cover/lid is modeled as merged with the inner and outer connections points.

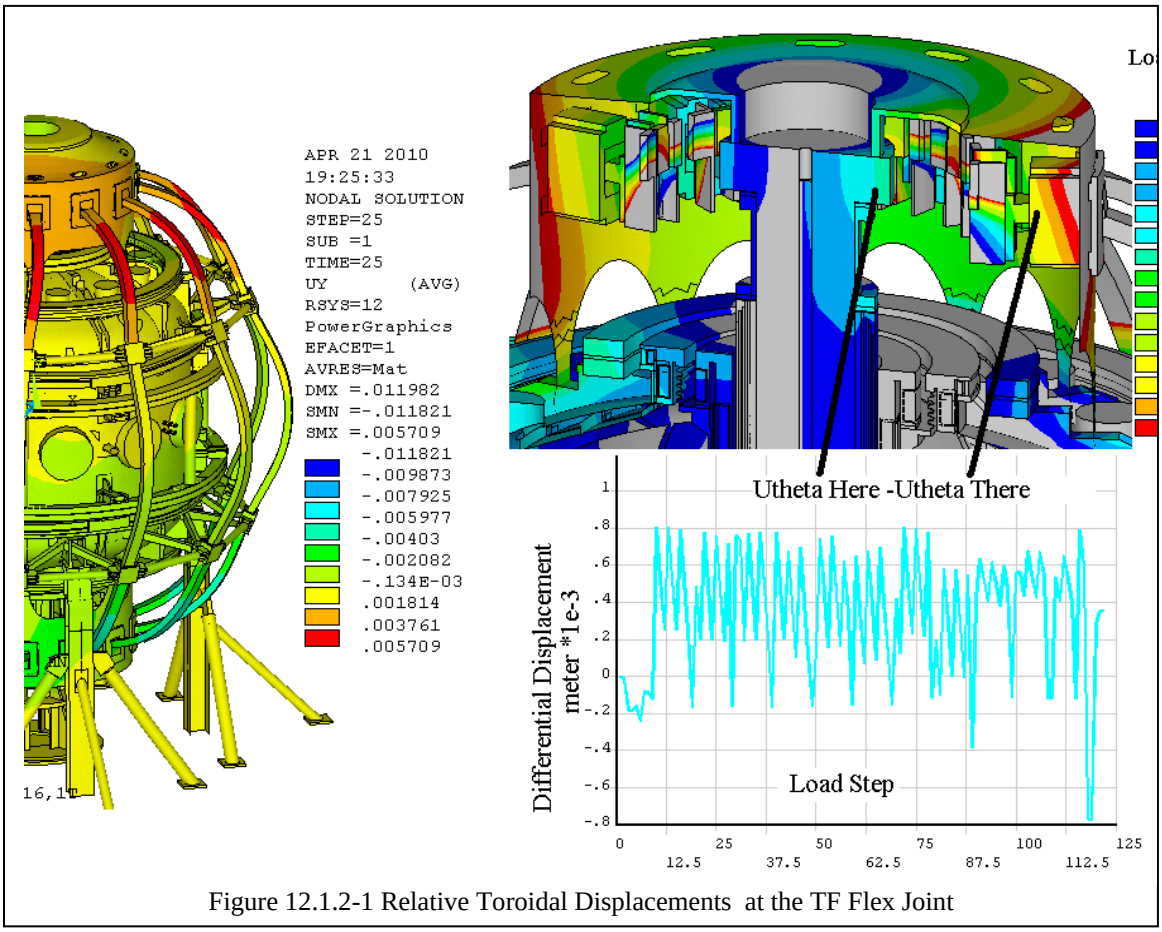


Figure 12.1.2-1 Relative Toroidal Displacements at the TF Flex Joint

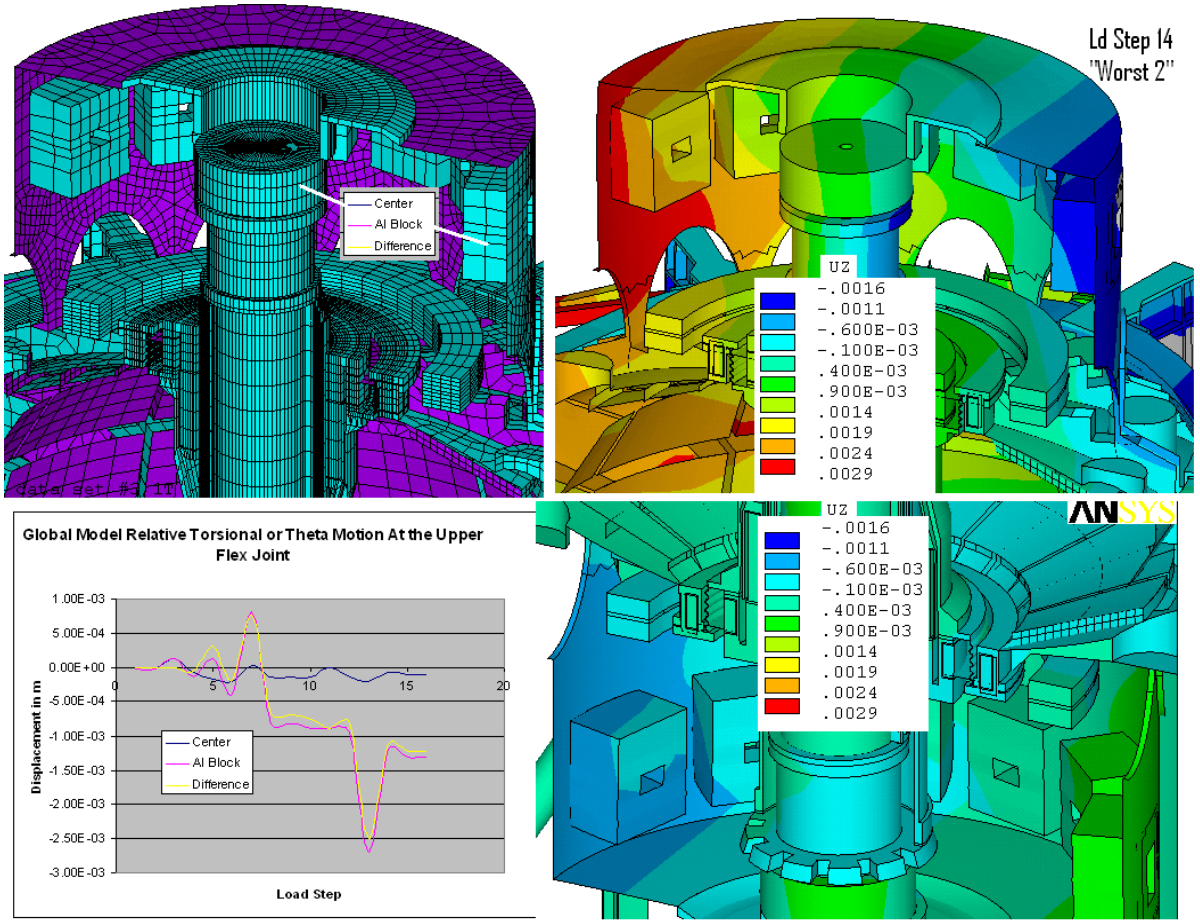


Figure 12.1.2-2 Relative Toroidal Displacements at the TF Flex Joint

12.2 Upper and Lower Umbrella Lids

Shown in this section, first, is the CDR concept that utilized a continuous plate that would flex vertically to accommodate the vertical growth of the central column. This offered no access to the TF joints and flags unless the lid was removed. Access openings were added and the design evolved into spoked wheel design that is addressed in reference [23]. Many of the global model results for the lids are shown in Lid/Spoke Assembly, Upper & Lower NSTX-CALC-12-08-00 [23]. In Section 12.16, the torques transmitted through the lids and spoked lids are quantified for design of the inner connections to the inner TF legs. In this calculation the global model is used to compare torsional load distributions for different lid designs.

12.2.1 Upper Flex Plate/Diaphragm (Replaces the Gear Tooth Connection)

- Vessel at 150C during Bake-Out RT Central Column
- Vessel Expands +8mm

In figure 12.2-1, the Flex/Diaphram Stress is 135 MPa. Note Uniform Stress at Edge. This would have required a large number of bolts at the plate to umbrella structure flange to lid bolt circle. This was another motivation for the spoked lid solution.

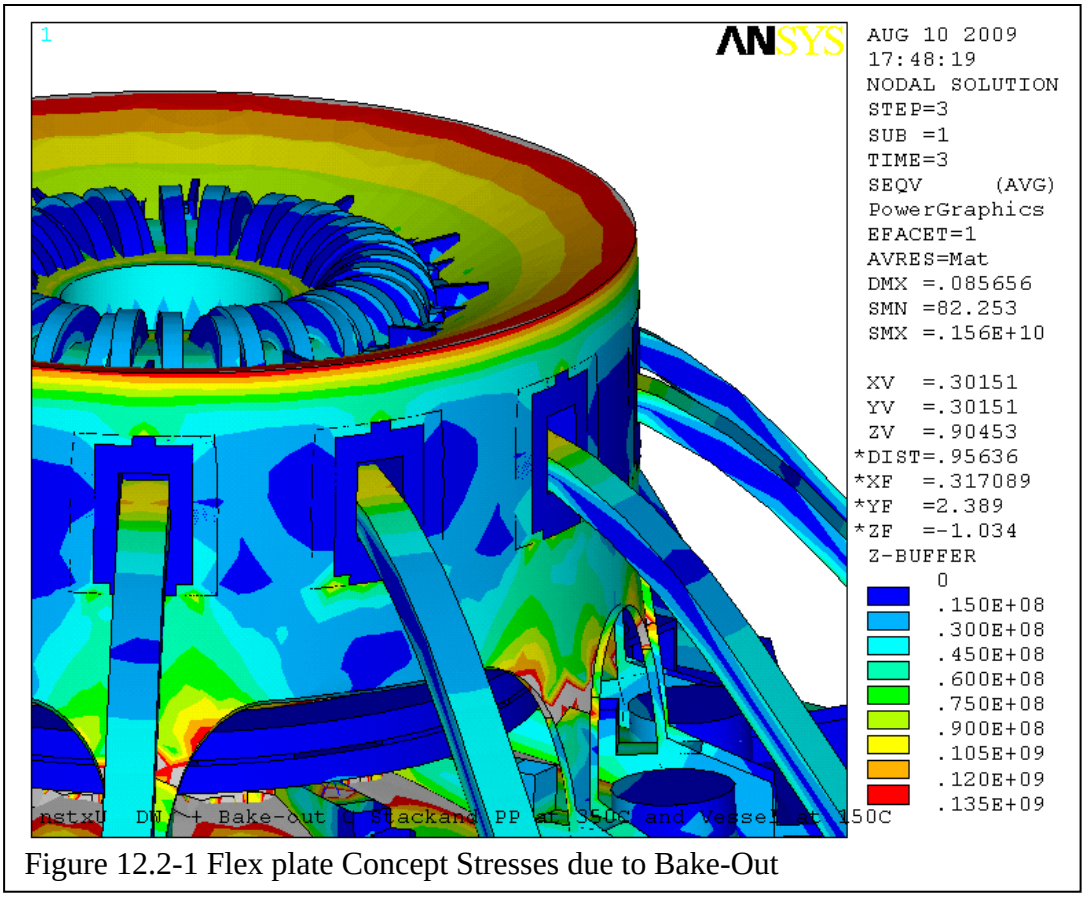
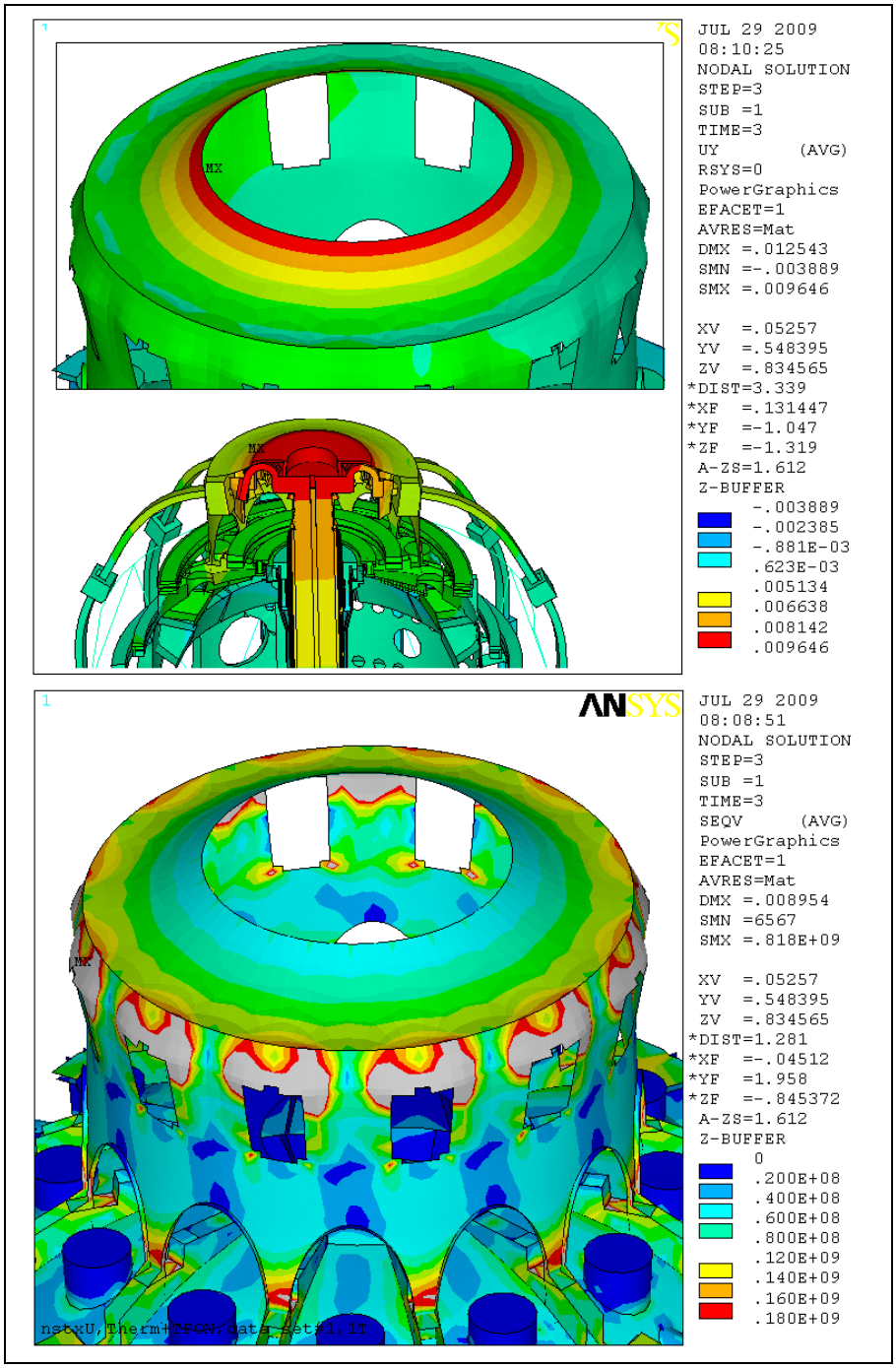


Figure 12.2-1 Flex plate Concept Stresses due to Bake-Out

Hot Central Column, Cold Vessel

Central Column Expands 9mm



5/8” Flex/Diaphram, 150 MPa
Note Non-Uniform Stress when TF Expands

12.2.2 Spoked Lid and Lower "Bent" Spoked Lid Solution

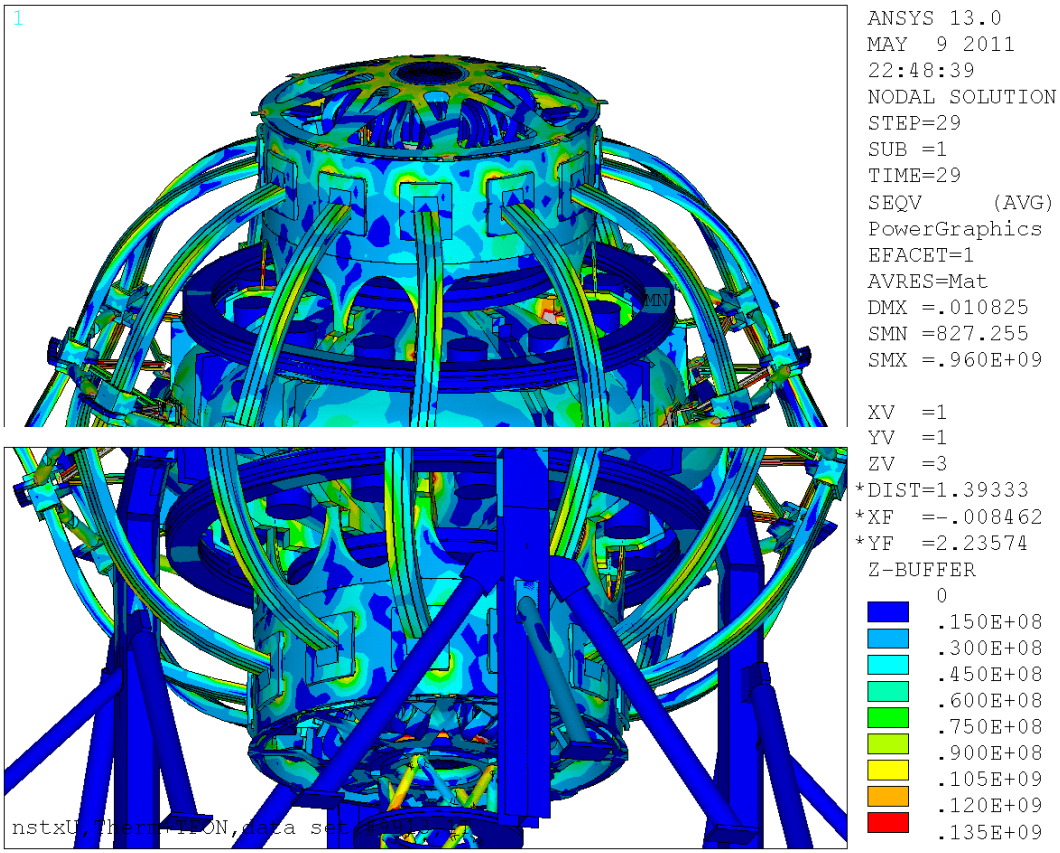


Figure 12.2.2-1 Spoked Lid Stress

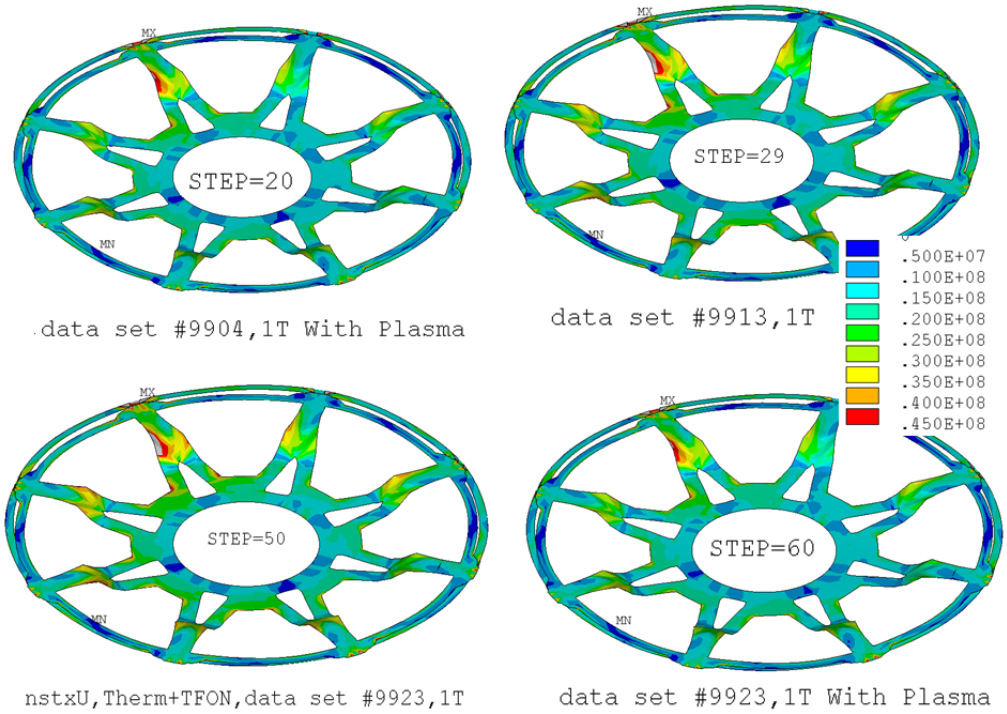
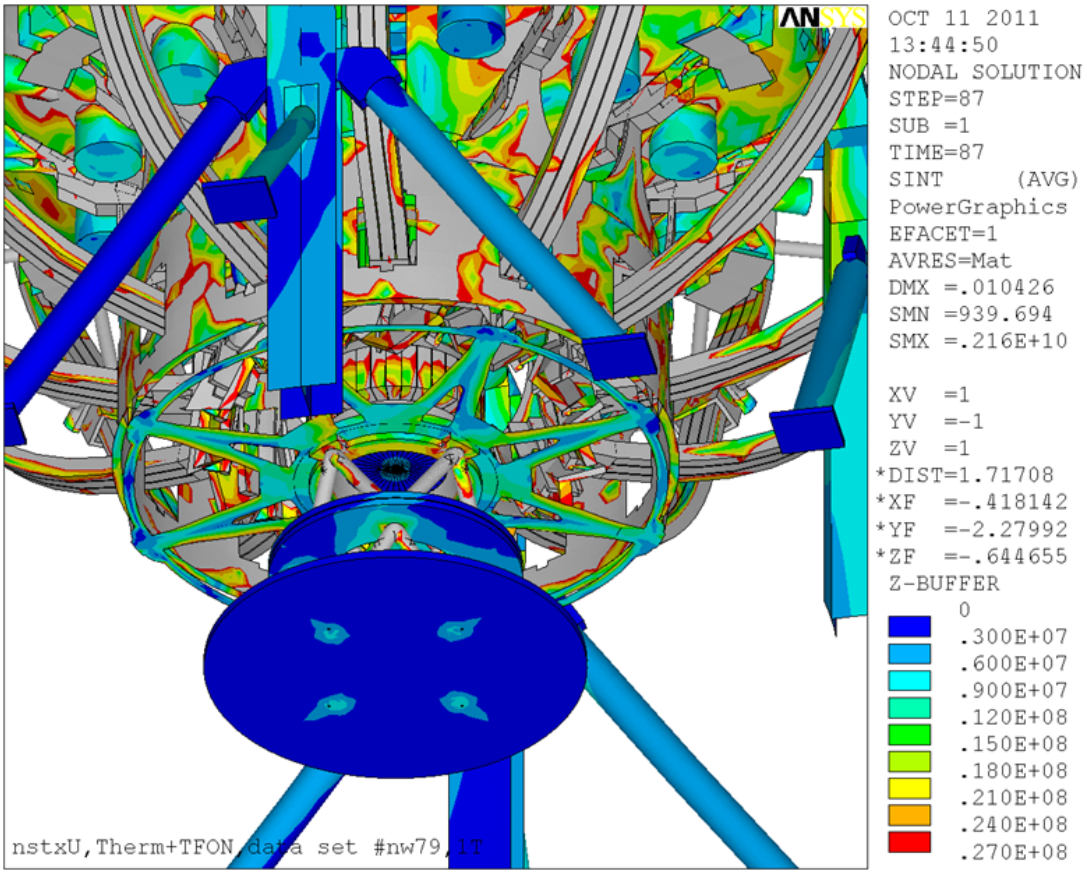


Figure 12.2.2-2 Bent Spoked Lid Stresses

12.2.3 Spoked Lid and Lower "Flat" Spoked Lid

This the representation of the lower spoked lid as it appears in the final design. More details of this design are evaluated in [23]. The "bent" spoke caused the load to be torsionally soft and potentially more of the machine torque could appear at the bellows.



12.3 Stand Alone Outer PF Support Structure

This PF support concept was developed to support large worst case power supply PF loads during the conceptual design portion of the project. The idea was to add a separate dedicated structure to support the huge loads that could develop if the maximum power supply currents were applied in a worst case manner. The expense and difficulty of implementing this large "cage" was considered extreme and led to the reliance on the digital coil protection system to limit loads such that the existing PF support hardware could be used.

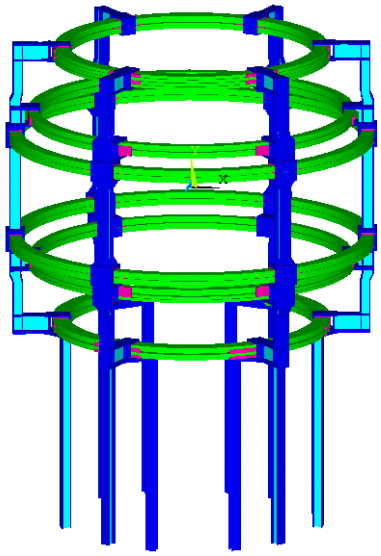


Figure 12.3-2 Six Column CDR Support

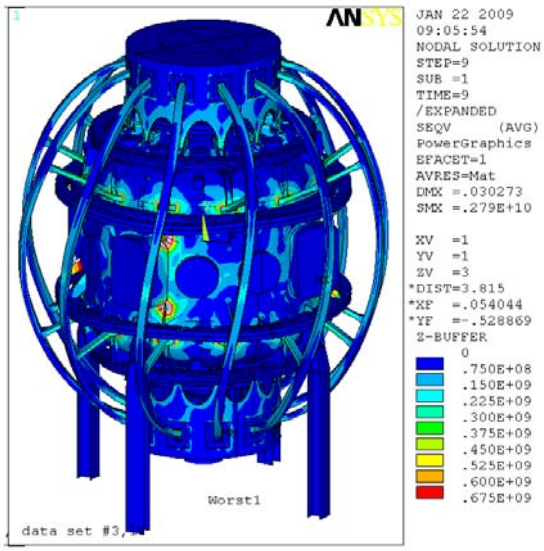


Figure 12.3-1 From an early run, the stresses at the PF4/5 support attachments to the vessel were excessive

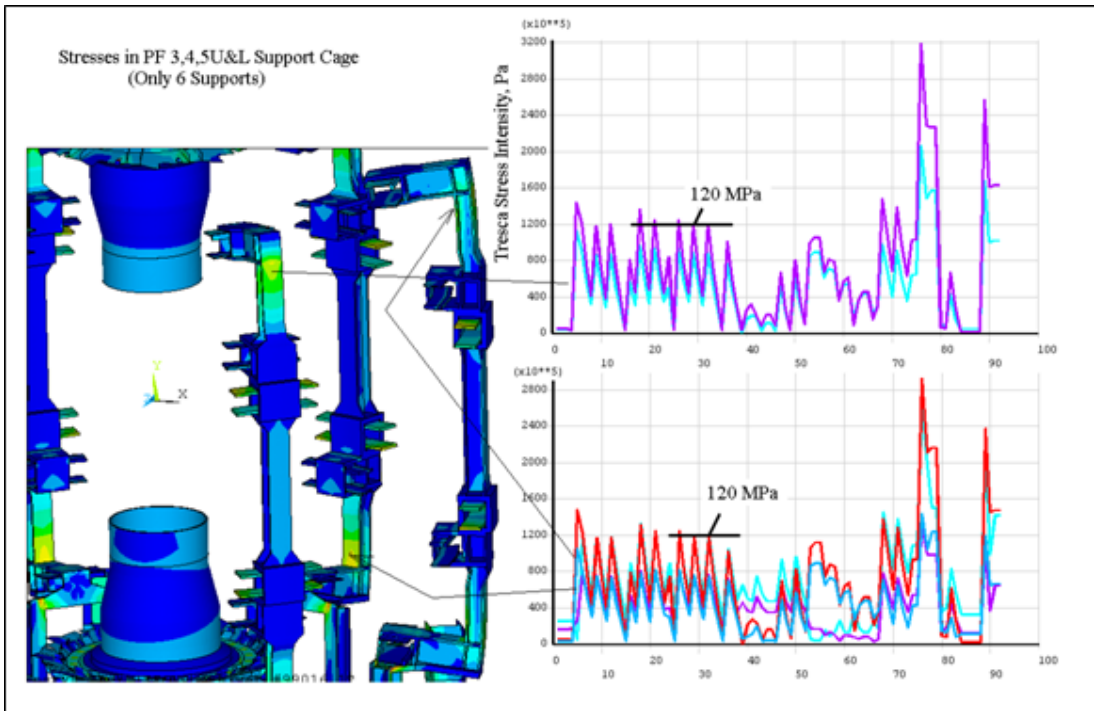


Figure 12.3-3 Stand Alone Outer PF Support Stress

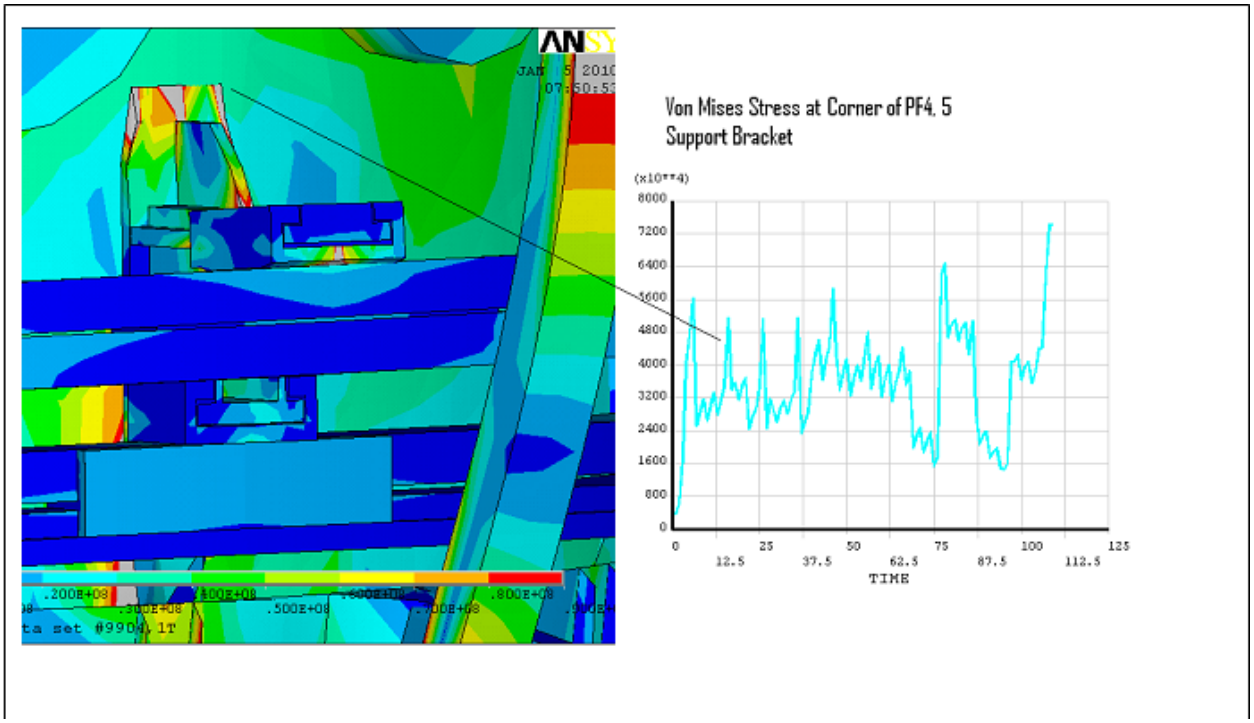


Figure 12.3-4 Stress around Existing Support

12.4 Main Support Column to Vessel Connection

These attachments or "chairs" connect the main support I beam columns to the vessel. The main beam gusset plates are 1.5 inches thick . Visually scaling the welds, they are about 2 inches long and maybe 3/8 fillets.

From an email from L. Dudek
Joe Winston indicates that the weld seems to be about 3/8", definitely less than ½ " and more than ¼ ".
He will measure to confirm.

There are 3 on each outside edge and 3 inside- maybe more on the underside

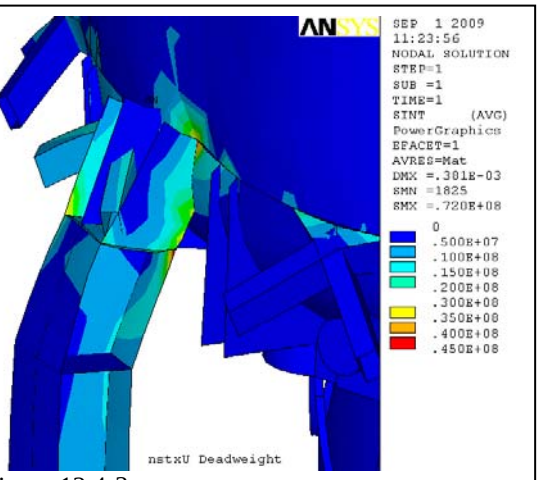


Figure 12.4-3

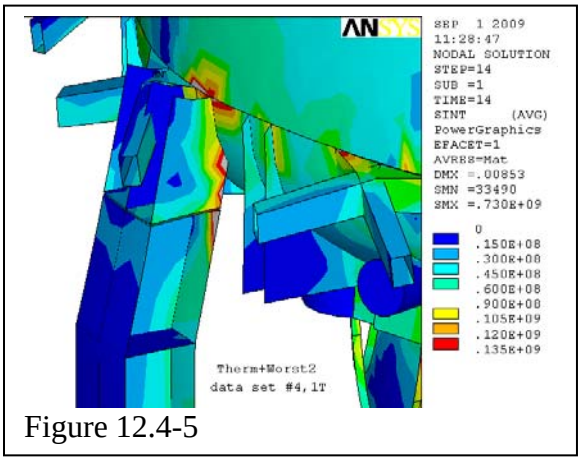
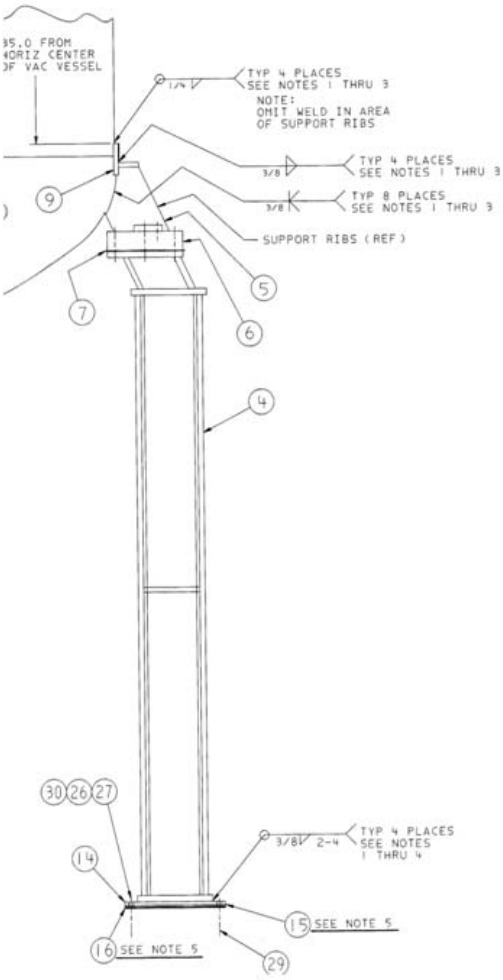


Figure 12.4-5


Figure 12.4-2 Bay B-C


Figure 12.4-6



Bay B-C

Figure 12.4-7

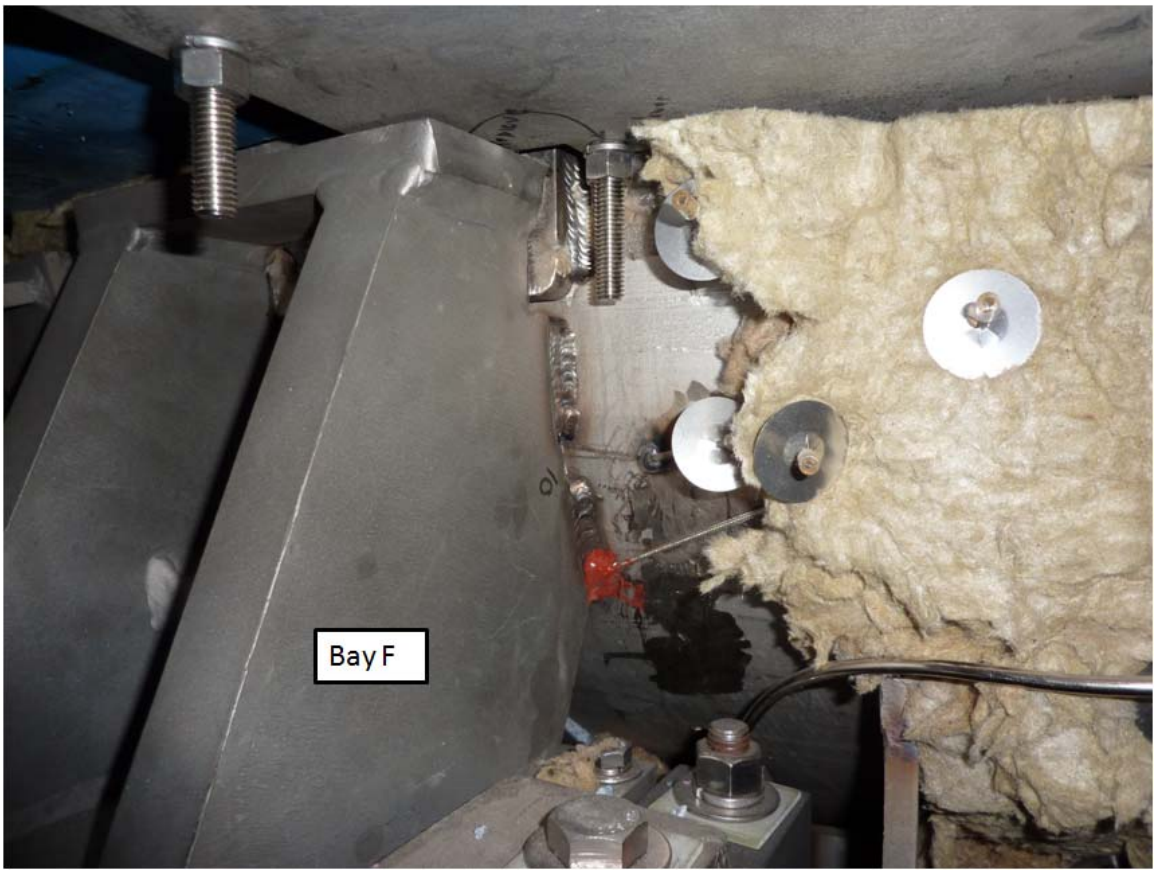


Figure 12.4-7

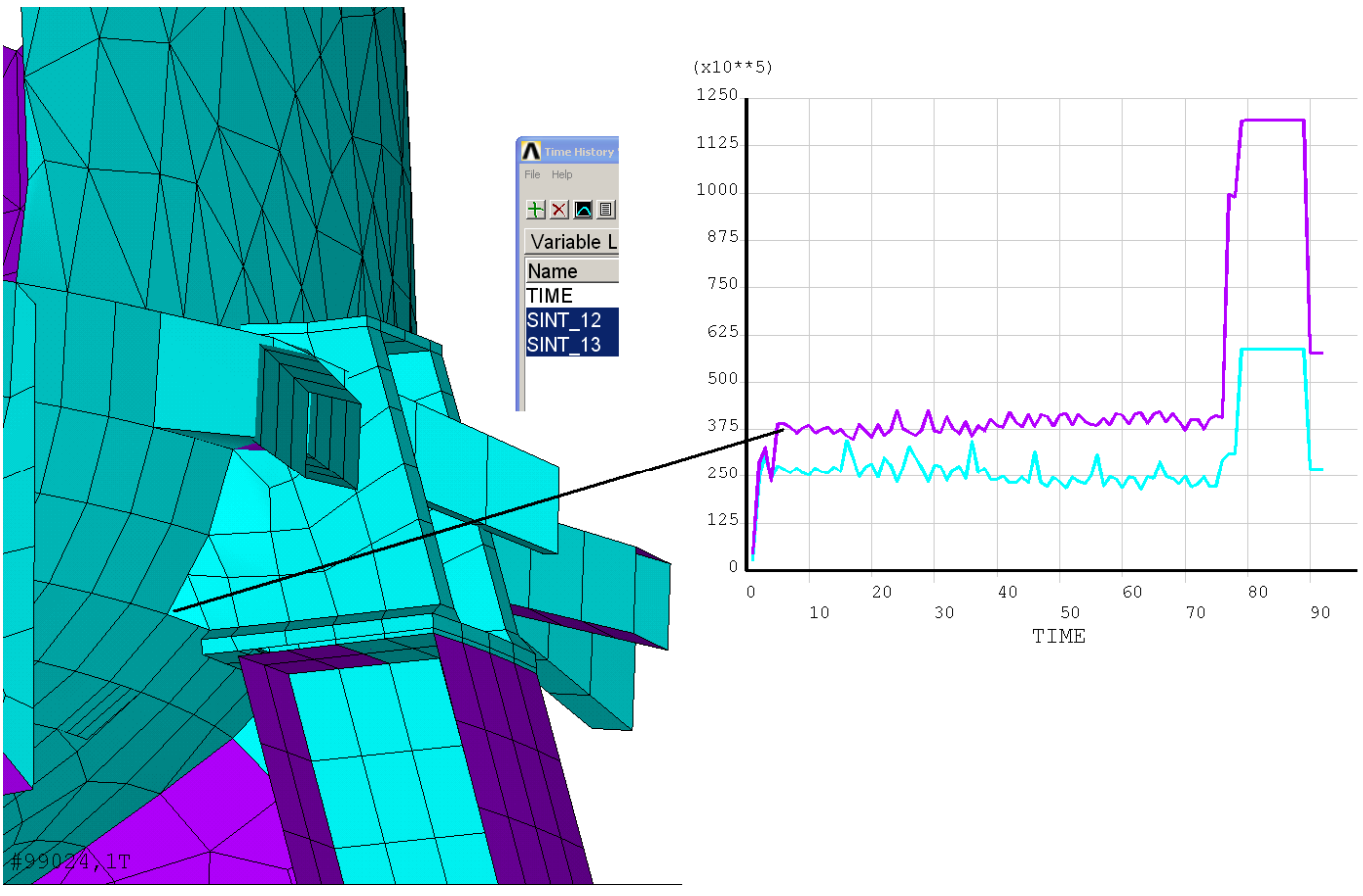
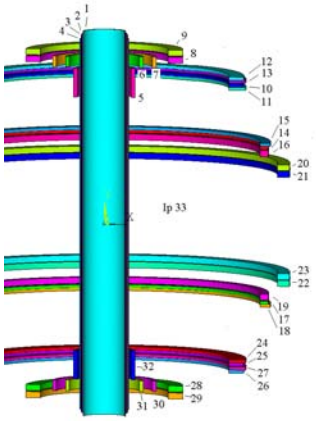
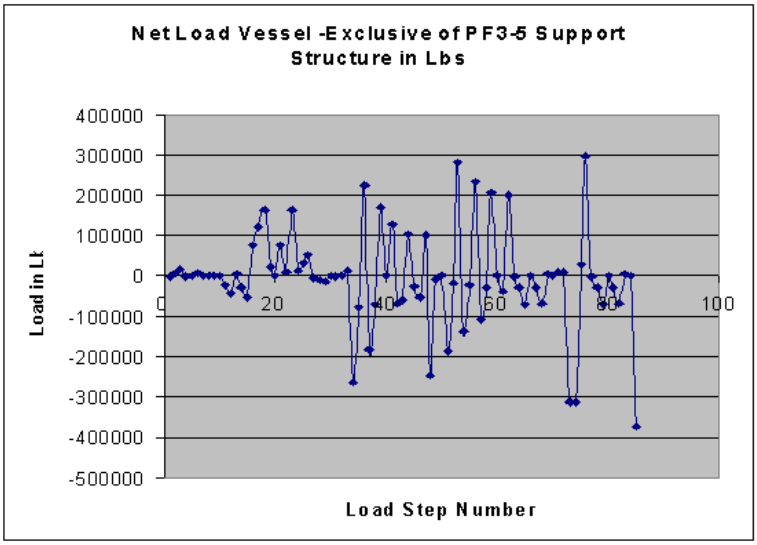


Figure 12.4-8 Stresses in the vessel at the I-Beam Connection (Fully Bonded)

Where the outer PF's are supported on a separate frame, the only PF loads on the vessel result from PF1c and PF2 upper and lower. Summing these loads provides one major component of the loads that are supported by the vessel support column.



PF Coil Real Constants



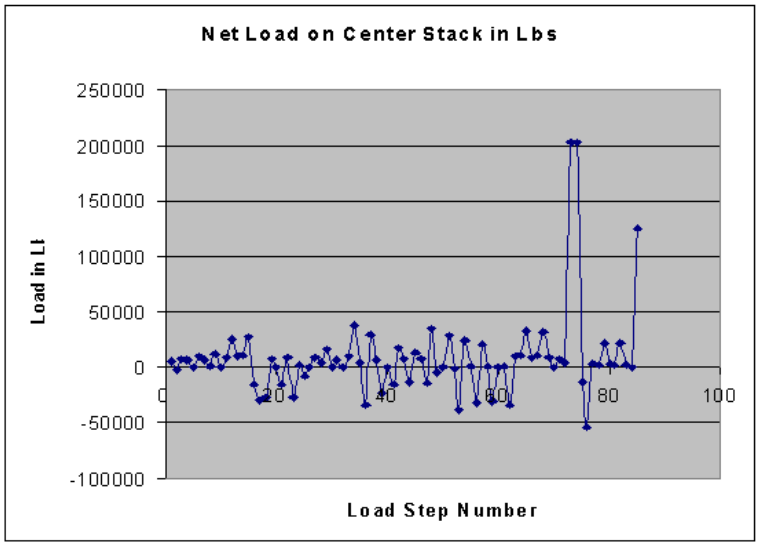


Figure 12.4-9 Net Loads from the PF's that must be Reacted by the I-Beam Connection Welds

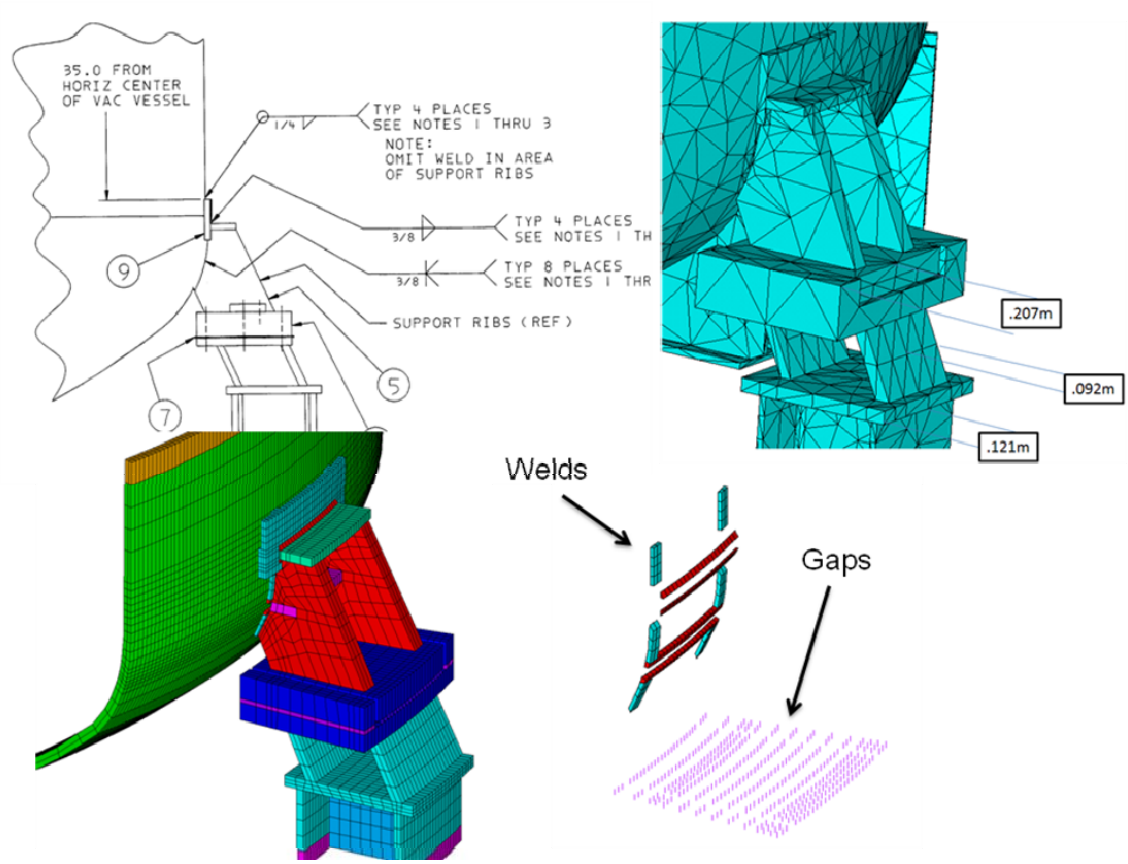


Figure 12.4-9 Separate Sub Model of the "chair" or Support Column Connection to the Vessel

Fz(lbf)	(PF1AU+PF1BU+PF1BL+PF1AL+OH)
Min w/o Plasma	-39635
Min w/Plasma	-53445
Min Post-Disrupt	-41843
Min	-53445
Worst Case Min	-375500
Max w/o Plasma	20397
Max w/Plasma	10748
Max Post-Disrupt	19630
Max	20397
Worst Case Max	375501

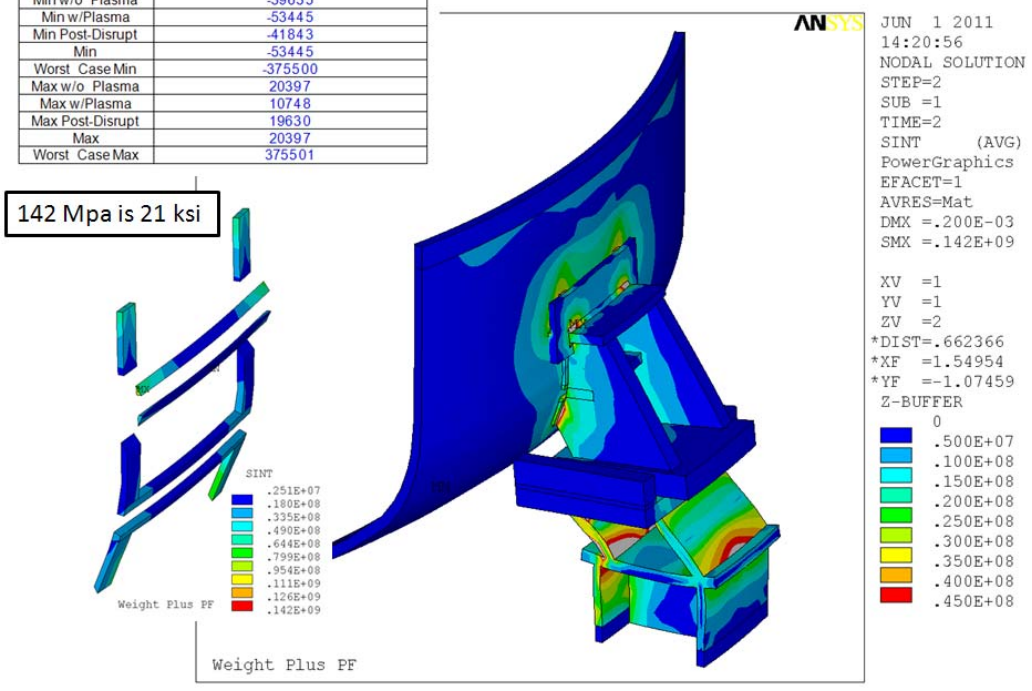


Figure 12.4-10

In the global model, There isn't a strong side-to-side variation from the normal operating equilibria. There are variations that result from interactions with neighboring structures, like the one chair/foot that interferes with the clevis attachment and the loads are additive. A special design will be needed here. The side-to-side variation would result from the support columns carrying some of the machine torque down through the floor and pedestal - the effects of the torque in the pedestal are visible but the larger radius of the columns must reduce the torque loading at the columns so that it is overwhelmed by other loading. If the pedestal was torsionally flexible, and the upper and lower lids were stiff, then the torque would be internally reacted, and the columns would not see any of the torque. The stiffer lower lid is in the global model - so the torque going through the columns and pedestal is small compared with other loads.

For most of the equilibria, the shell stresses are below 40 MPa/6ksi.

The more detailed model assumed that the primary loading on the chair was the deadweight and net PF loads. If the columns don't participate in the torque very much, then the more detailed model captures the primary loading adequately. Strains in the shell due to internal machine loads will add to fatigue damage. The loads in the global model include these effects, and the stresses at the chair/shell interface are about 40 to 90 MPa, maybe twice the stress in the more detailed model. There is margin in the welds except in the starts and stops of the welds. That is why the chair welds have been added to the inspection plan.

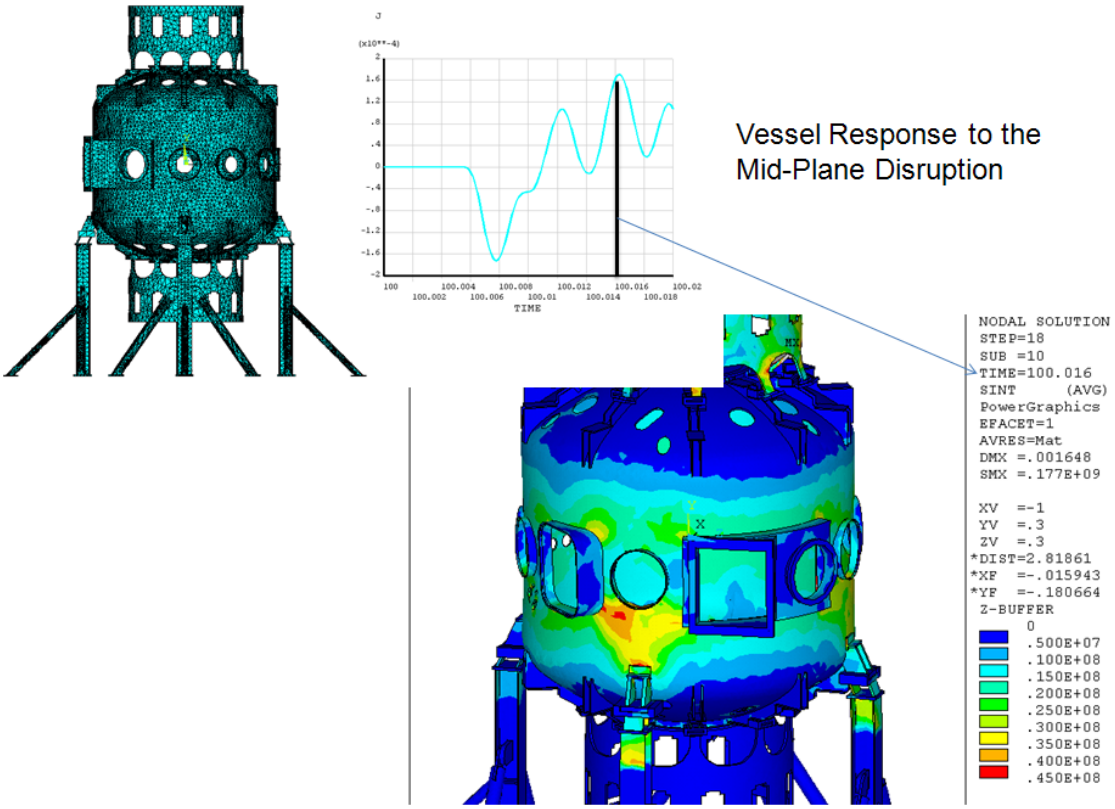


Figure 12.4-11

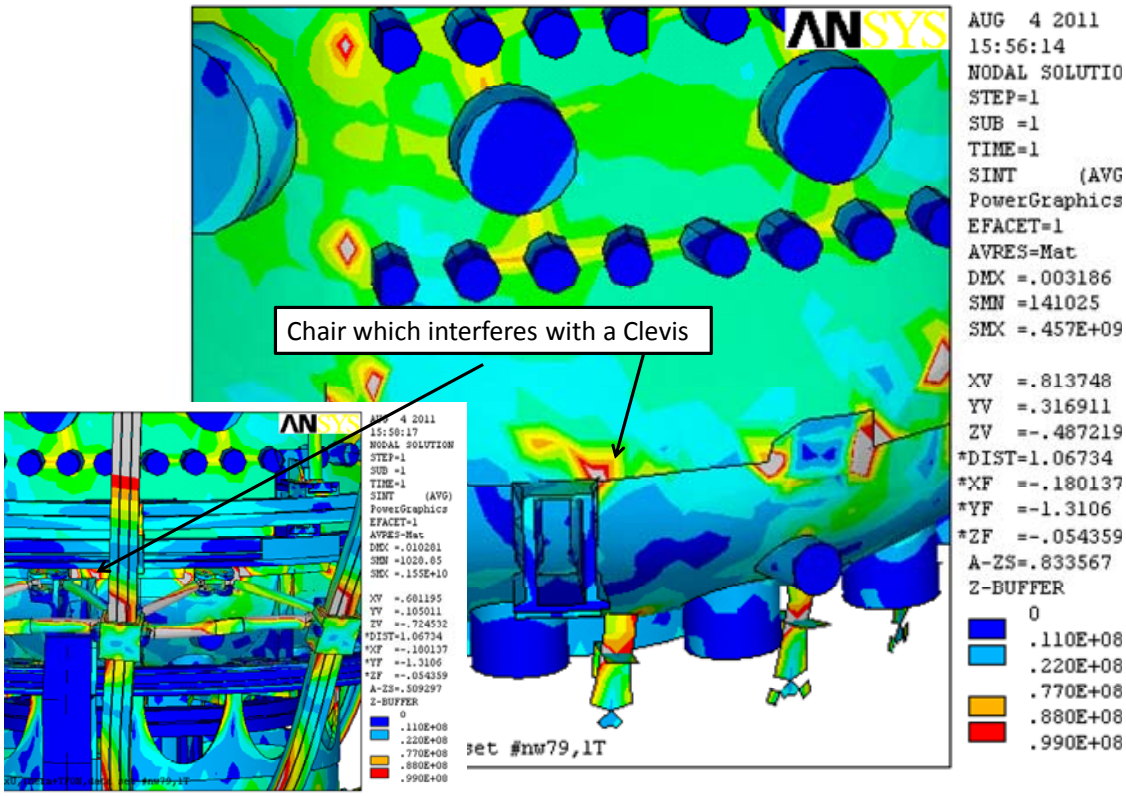


Figure 12.4-12

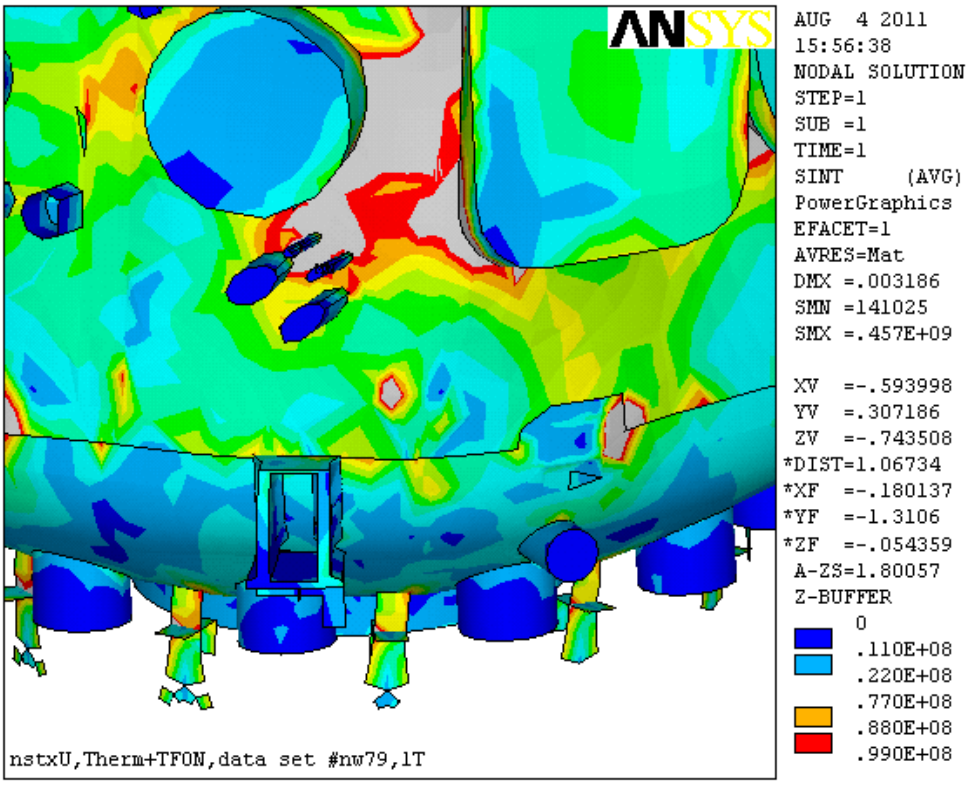


Figure 12.4-13

In the chair/foot slides, I used two sets of /contour ranges. These are linear scales with the gray areas representing stress values outside the contour range. In the first 5 slides, The 0 to 99 MPa range captured the EQ 79 shell stresses around the chair/foot except where the clevis interference loads added to the local chair stress. I shifted to a 0 to 45 MPa scale to compare all the load cases consistently. Most load cases/locations remained below the 45 MPa - some were higher for example bake-out was higher. Also there are areas where the PF bracket attachments and clevis attachments show stresses higher than 45 MPa - The modeling is coarse in this global model, connectivity is not always perfect - to get better resolution and model the weld details and local hardware, I shift to local models, and don't rely on just the global model.
The question at hand was the stress around the chair/foot for all loads, all four chairs and all equilibria. I selected contour ranges to represent these well. -Peter

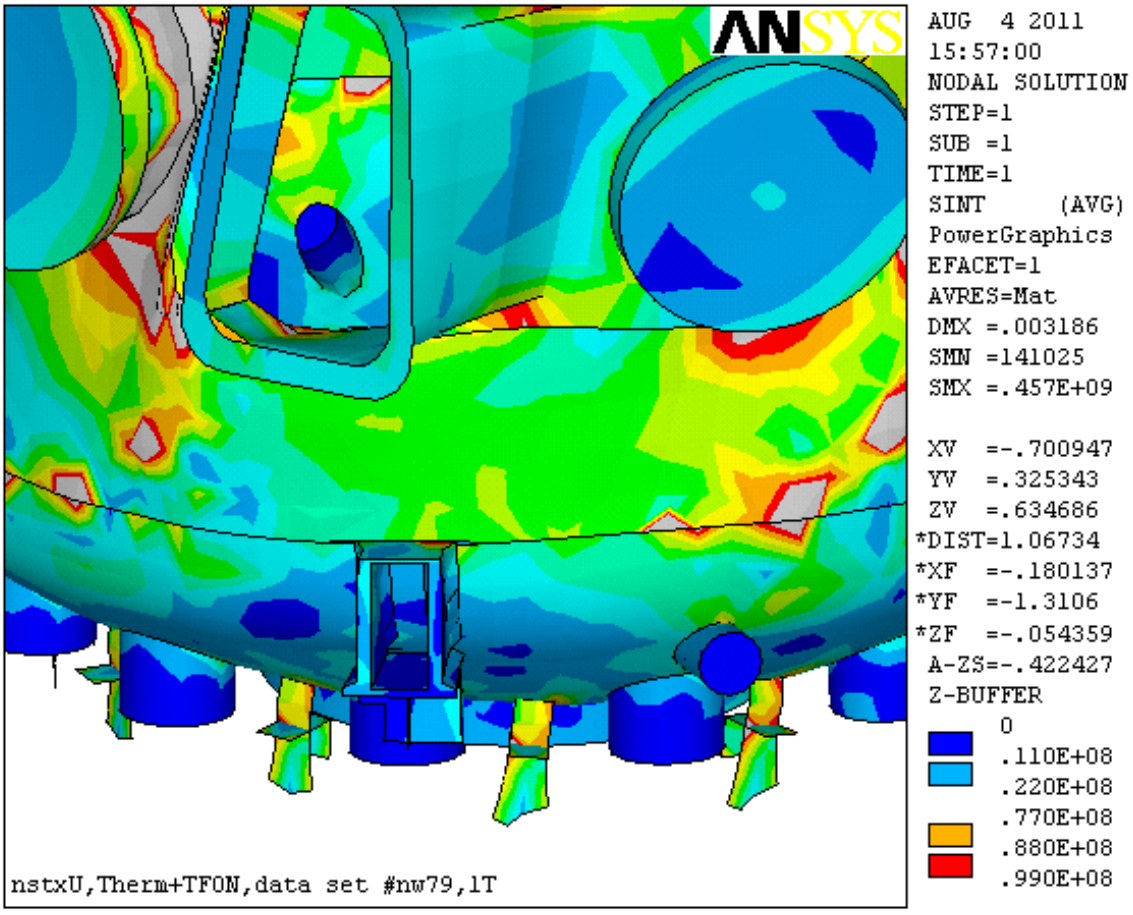


Figure 12.4-14

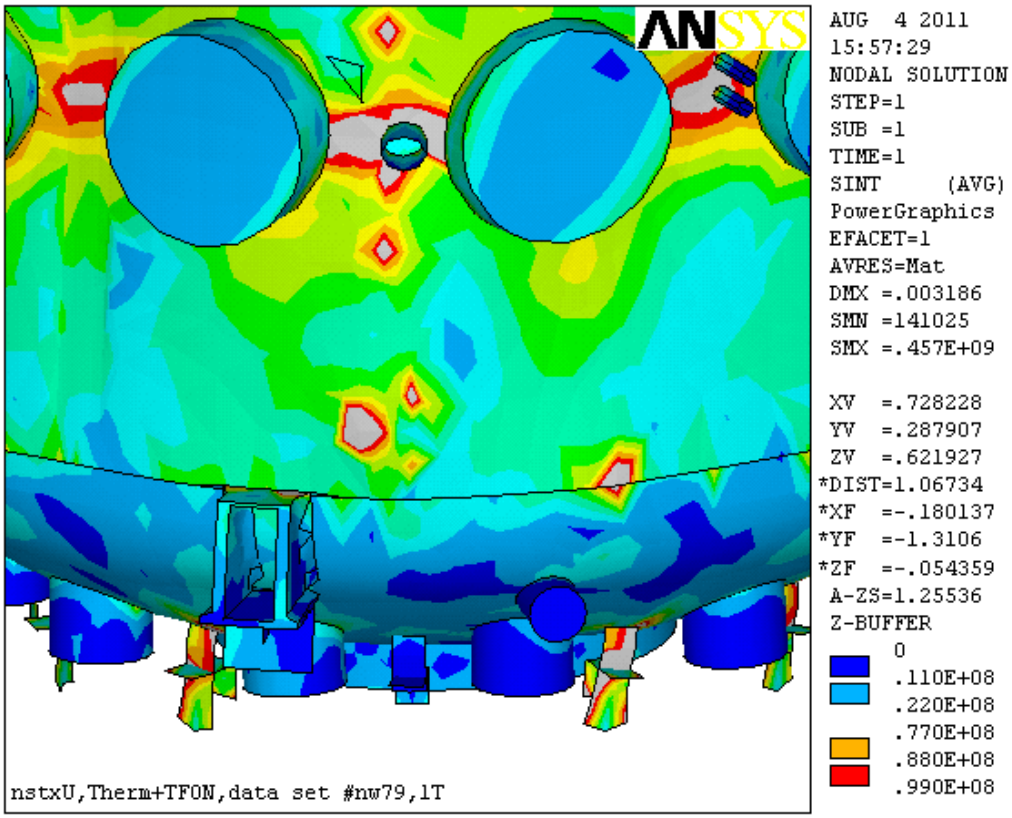


Figure 12.4-15

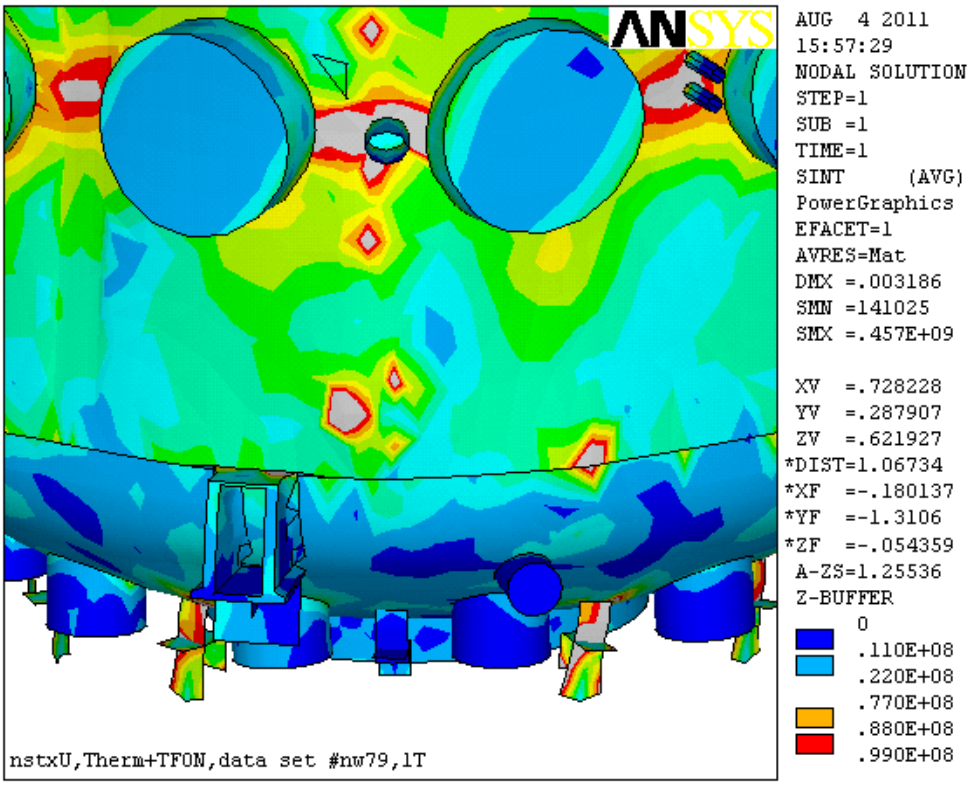


Figure 12.4-16

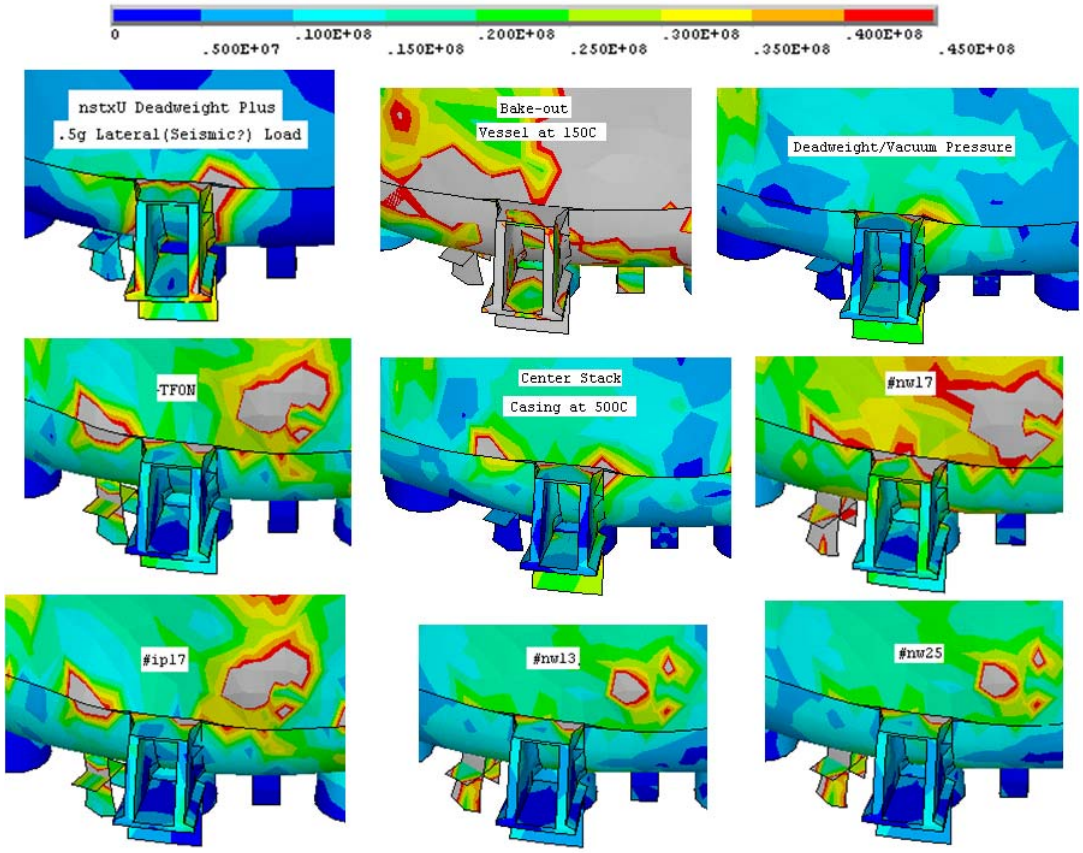


Figure 12.4-17

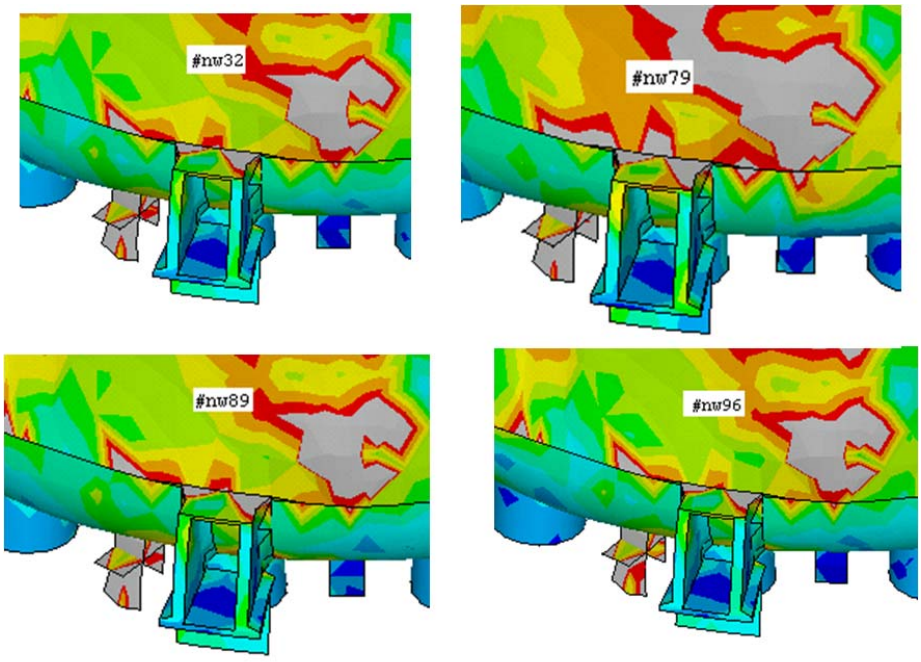


Figure 12.4-18

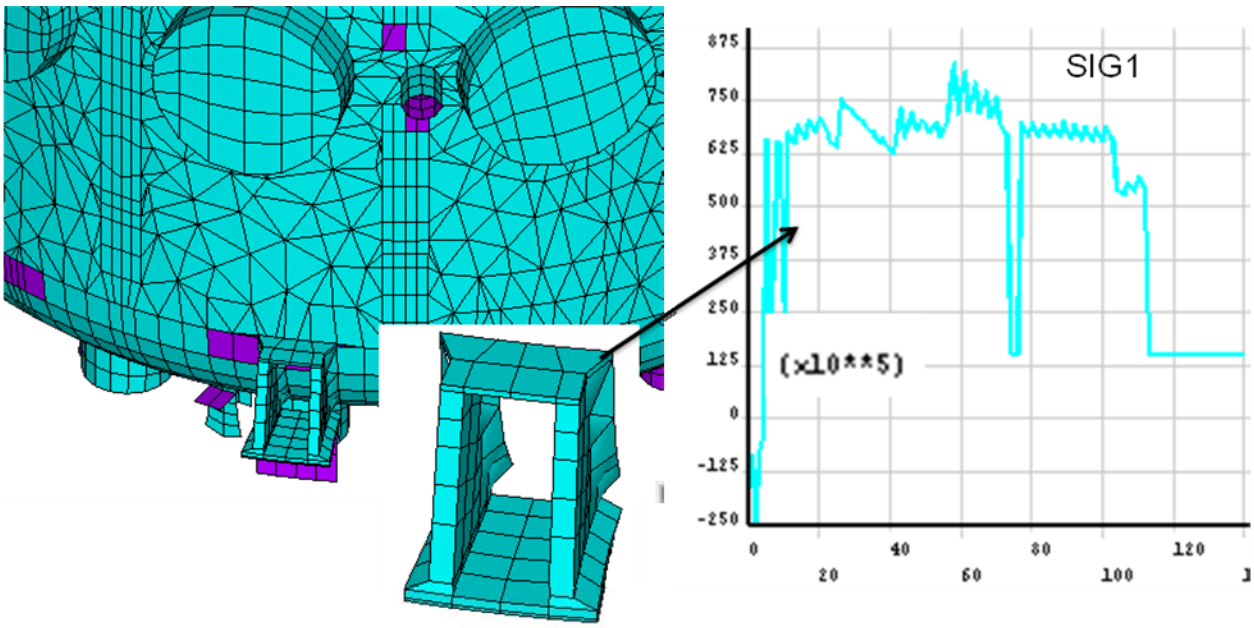


Figure 12.4-19

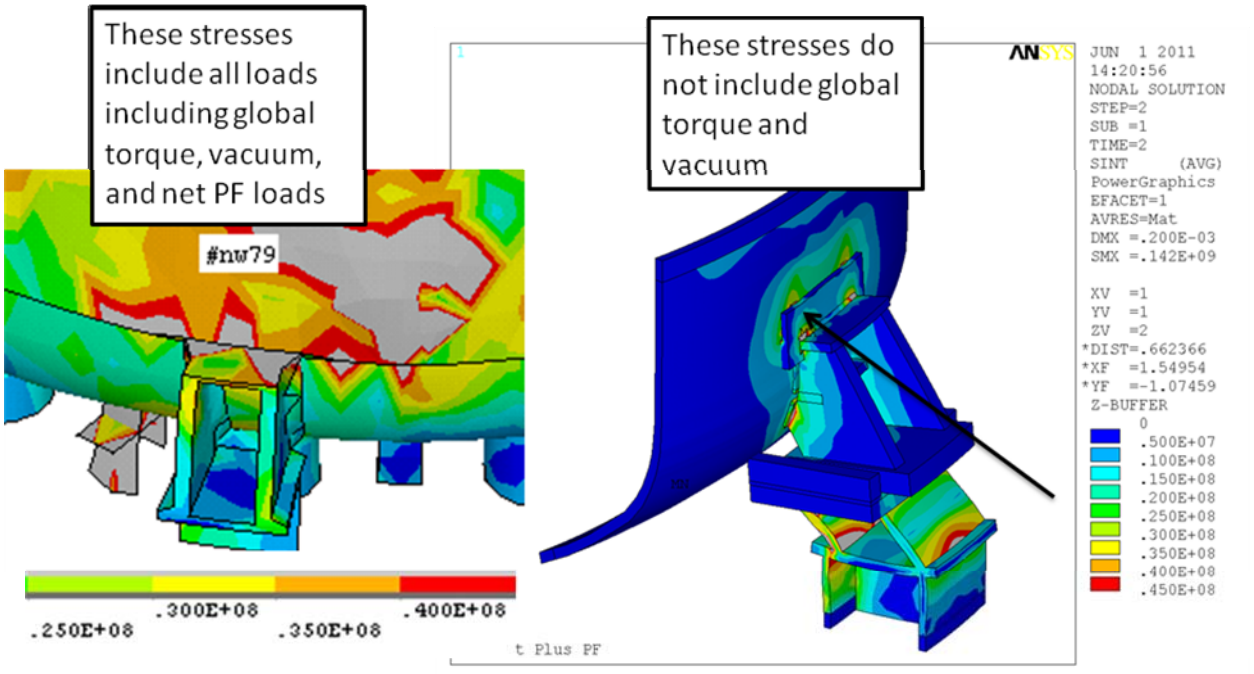


Figure 12.4-20

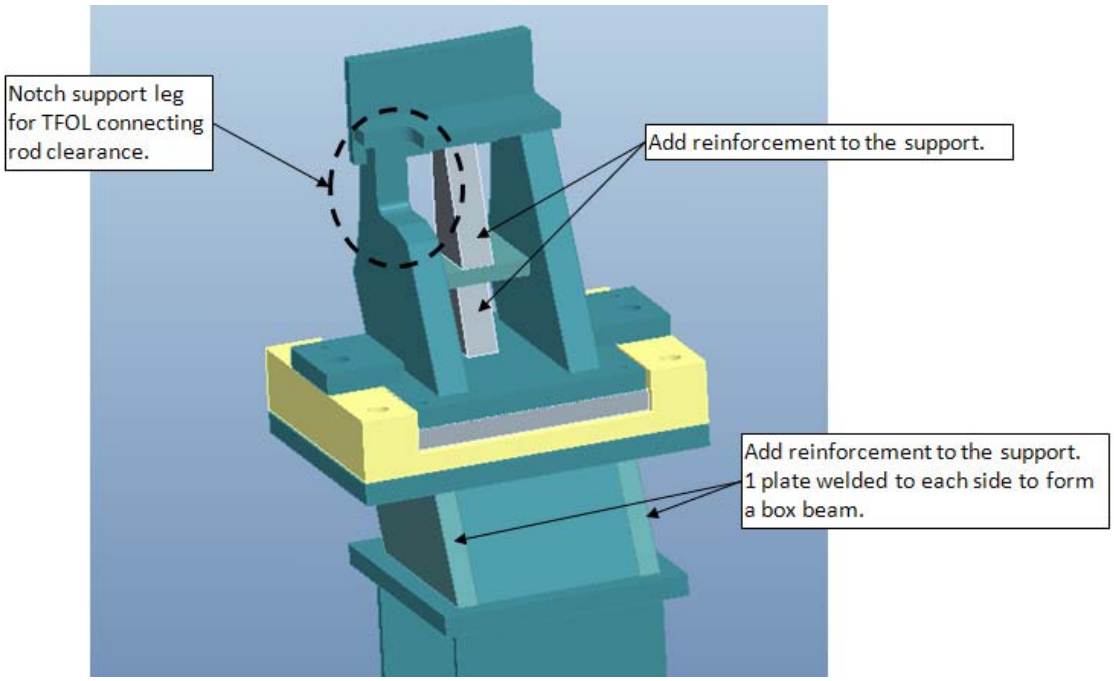


Figure 12.4-21 Special "Chair" Design Where the TF Clevis interferes with the Chair

12.5 Centerstack Torsional Displacement at OH Bellevilles

The inner leg of the TF coil twists under the OOP loading from the interaction with the PF field. The OH and TF inner leg are connected via the OH preload system. Vertical preloads on the OH are reacted by the TF flags. The OH does not experience any twisting motion, and this introduces, potentially, a differential motion between the OH and TF that would be imposed on the preload system of Bellevilles and pins.

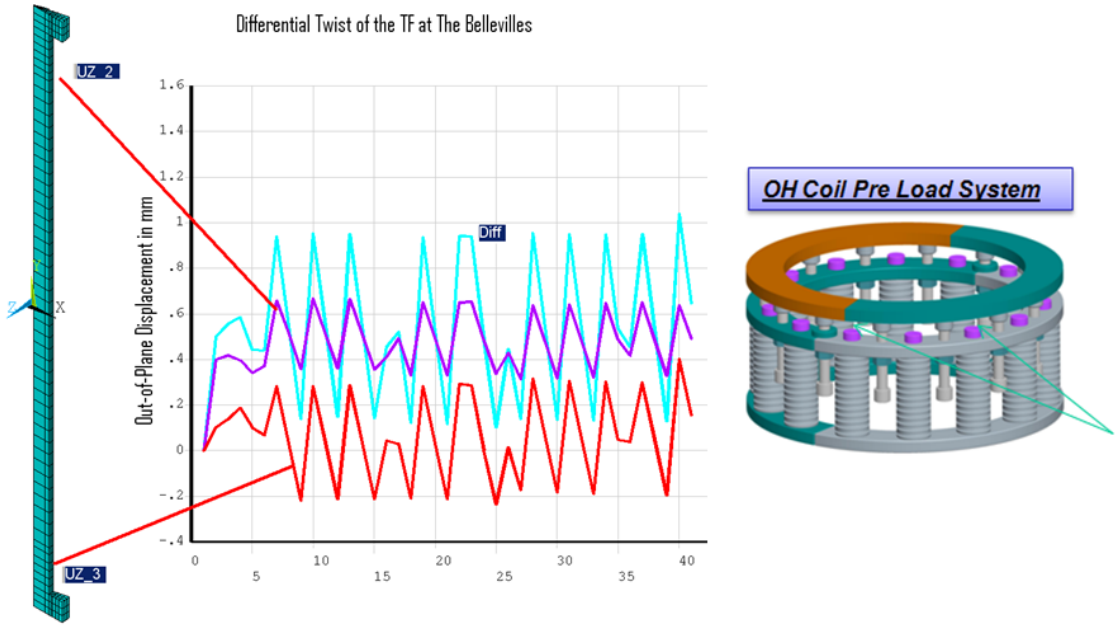
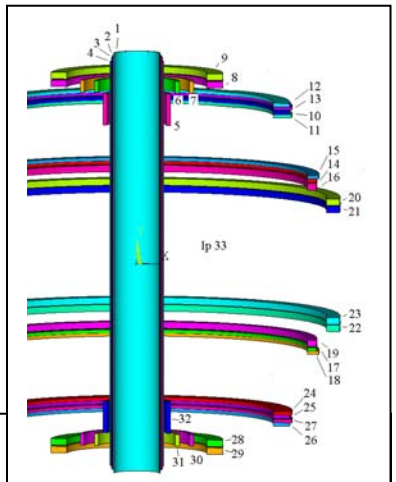


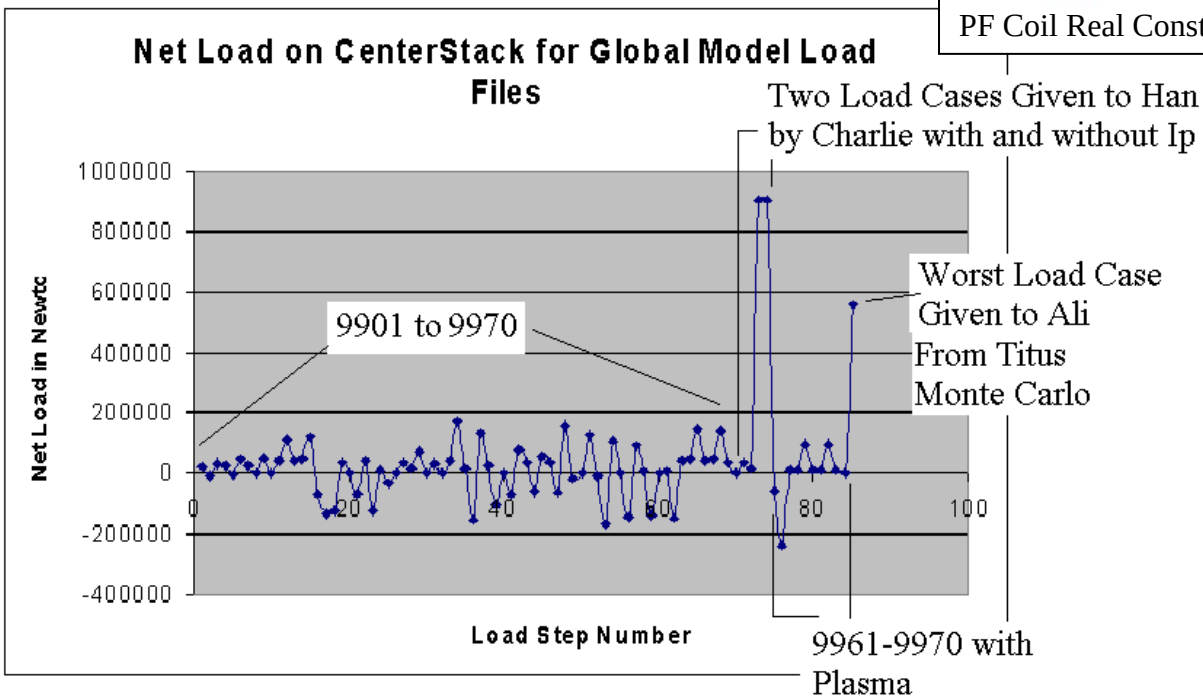
Figure 12.5-1 Relative Torsional Displacements that must be allowed by the OH Belleville Precompression System

These displacements were transmitted to the preload mechanism analysis: NSTX Upgrade OH Preload System and Belleville Springs, NSTXU-CALC-133-04-00 [35

12.6 Net Load on Centerstack



PF Coil Real Constants



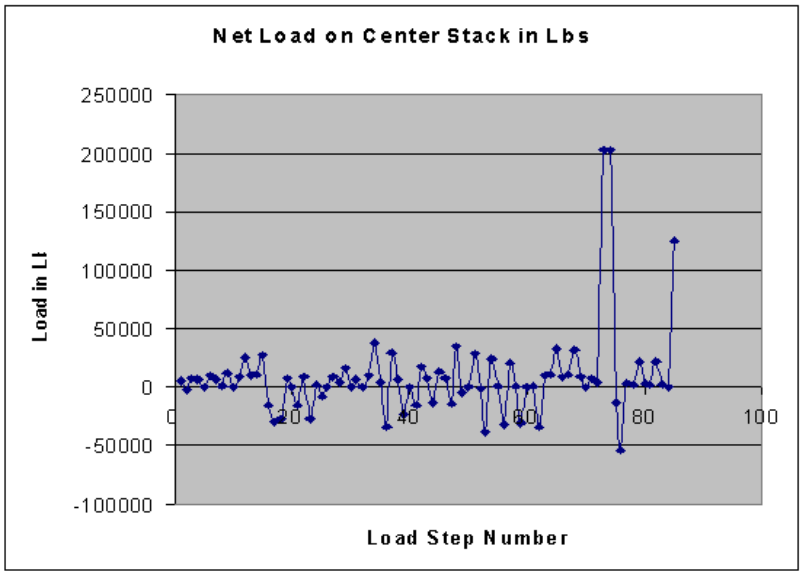


Figure 8.10-1 Net Loads on the Centerstack Assembly – See also the Monte Carlo Calculation, [10]

8.11 Vessel Shell Stresses

Vessel and umbrella structure stresses are considered in more detail in Han's outer leg calculation [4]. Note she used the vessel segment model from the global model in her analyses.

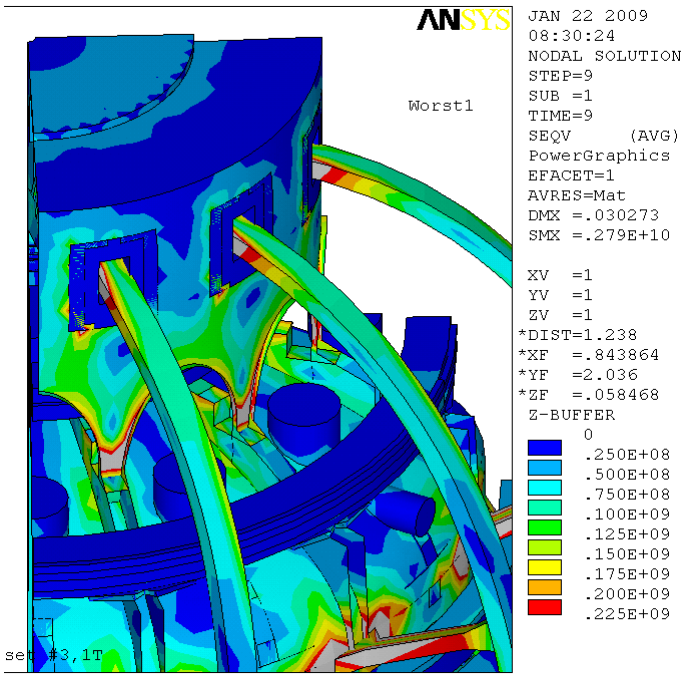


Figure 8.11-2 Umbrella Structure Stress

12.8 Center Stack Casing Thermal Stress

- 500C During Plasma Operation Ref: Art Brooks Original Calculation
- Yield of 625 at 600C is 410 MPa
- From Len's Presentation:
- For good fatigue resistance the peak stresses in the Incoloy structure should be kept below ~380 MPa.

540MPa for 500C Plasma Operation and 400MPa for 350C Bake-Out

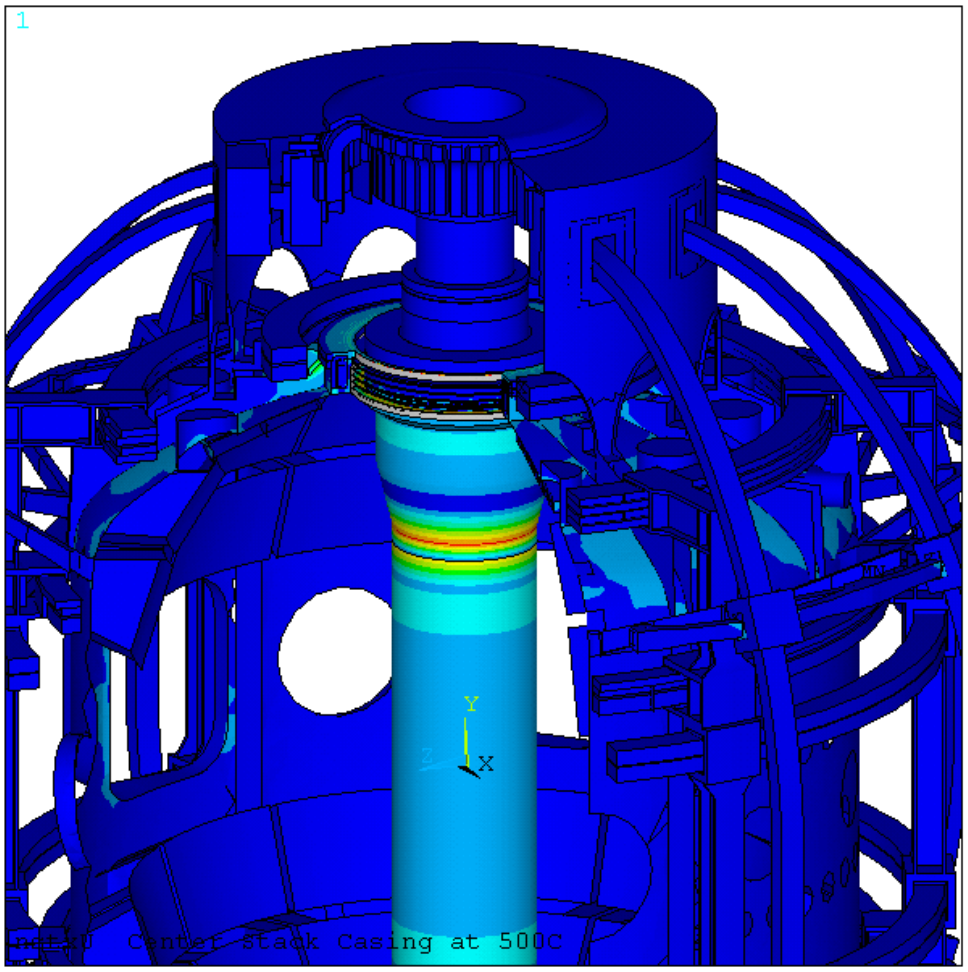


Figure 8.12-1

12.9 Bake-Out

These results were presented and the 350 C bake out temperature was questioned. It is actually 150C for the vessel and 350C for the passive plates. This analysis showed the action of the tangential radius rods allowing the growth of the vessel without disconnection of the support links.

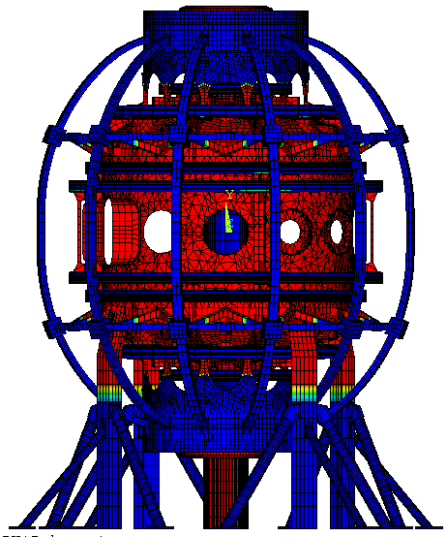


Figure 8.13-1 350C Bake-Out Temp

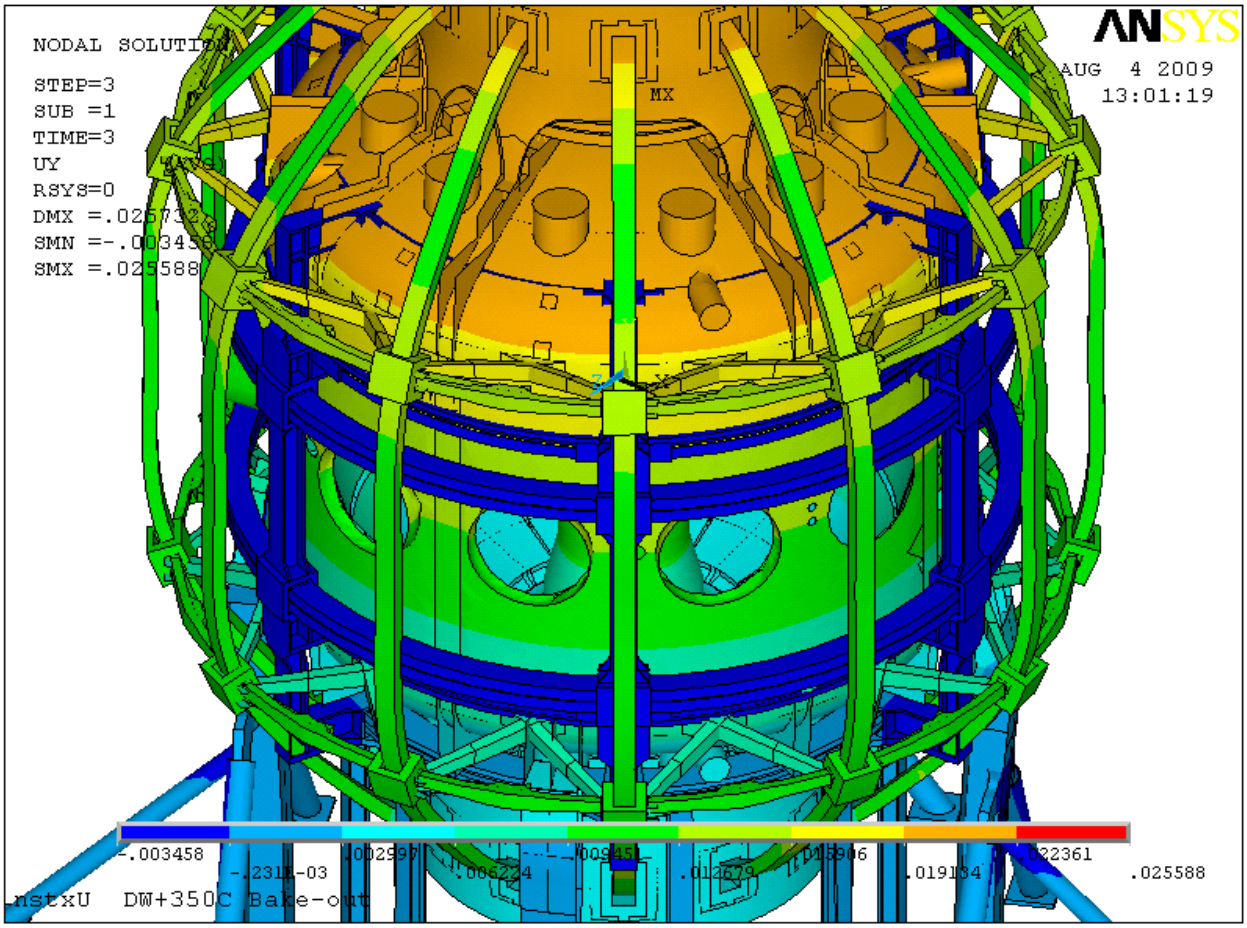
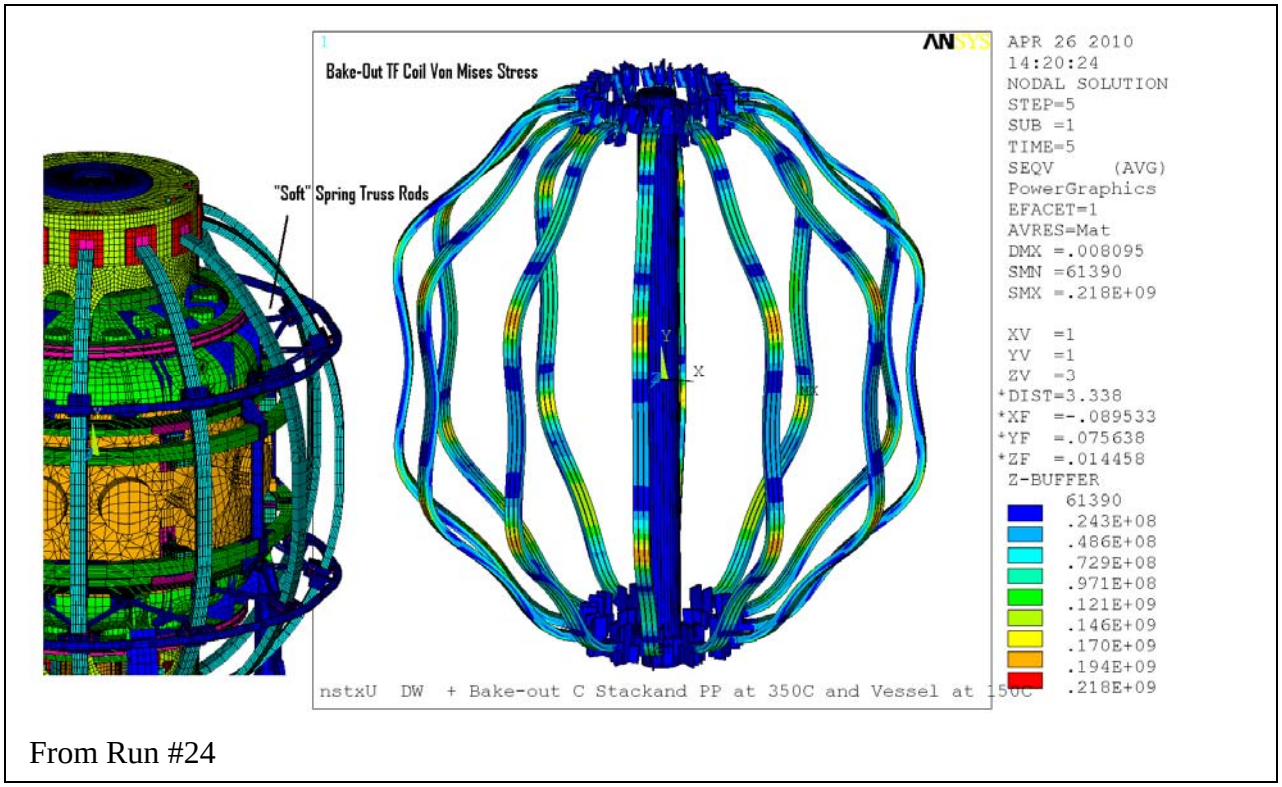


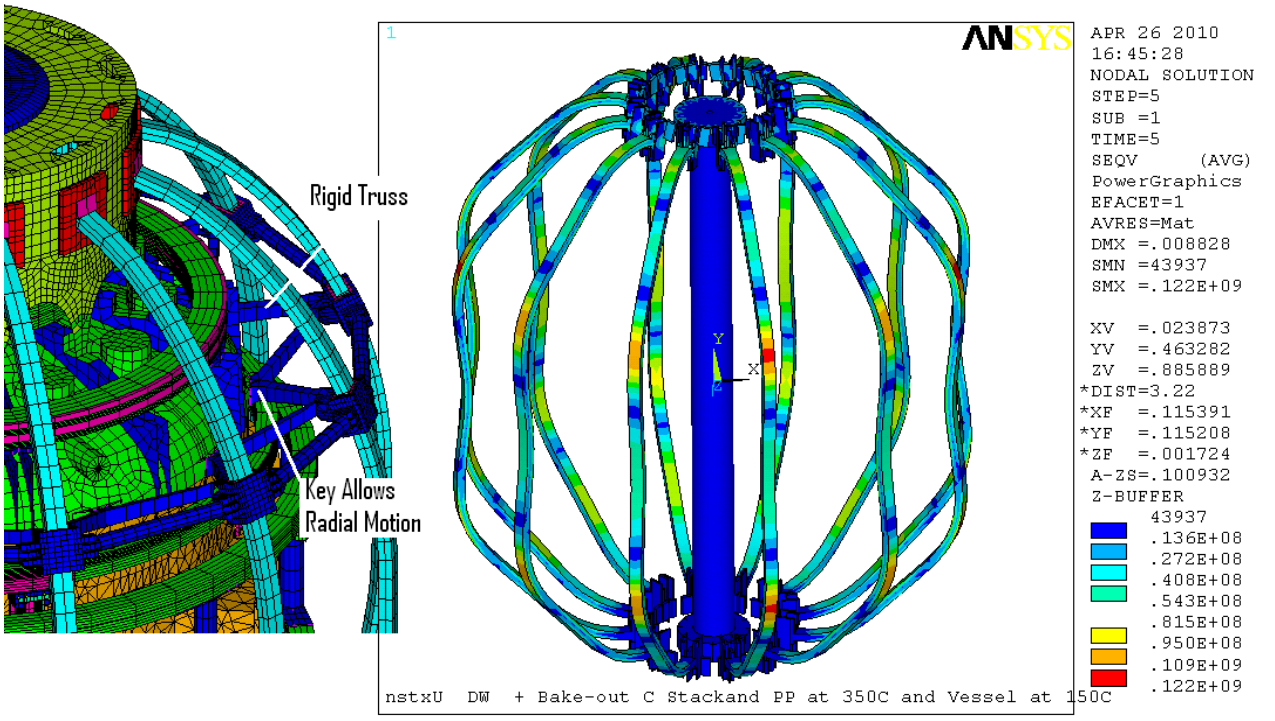
Figure 8.13-2 Outer PF Support "Cage" is Not Connected to the Vessel During Normal Operation or Bake-Out

TF Bending Stress Due to Bake-Out

TF bending stress at the umbrella structure is about the same for the soft spring truss and the tangential radius rod. The rings that are supposed to take the in-plane loads are stiff radially and do not allow radial motion of the coils for either support concept. The vertical stretch of the vessel bends the TF coils pretty much in the same way for both support concepts. The loads at the vessel attachment points obviously will be very different, so the motivation for the tangential radius rods is to avoid breaking the 3/8 bolts that hold the clevises to the vessel. The soft spring truss elements will have to be soft enough not to break the 6 bolts. They have a .0773 square inch stress area each. The yield could be 60 ksi or more if we replaced the bolts.



From Run #24



From Run #22

12.10 TF OOP Load Support from the Vacuum Vessel
12.11.1 Radius Rod Stresses and Loads

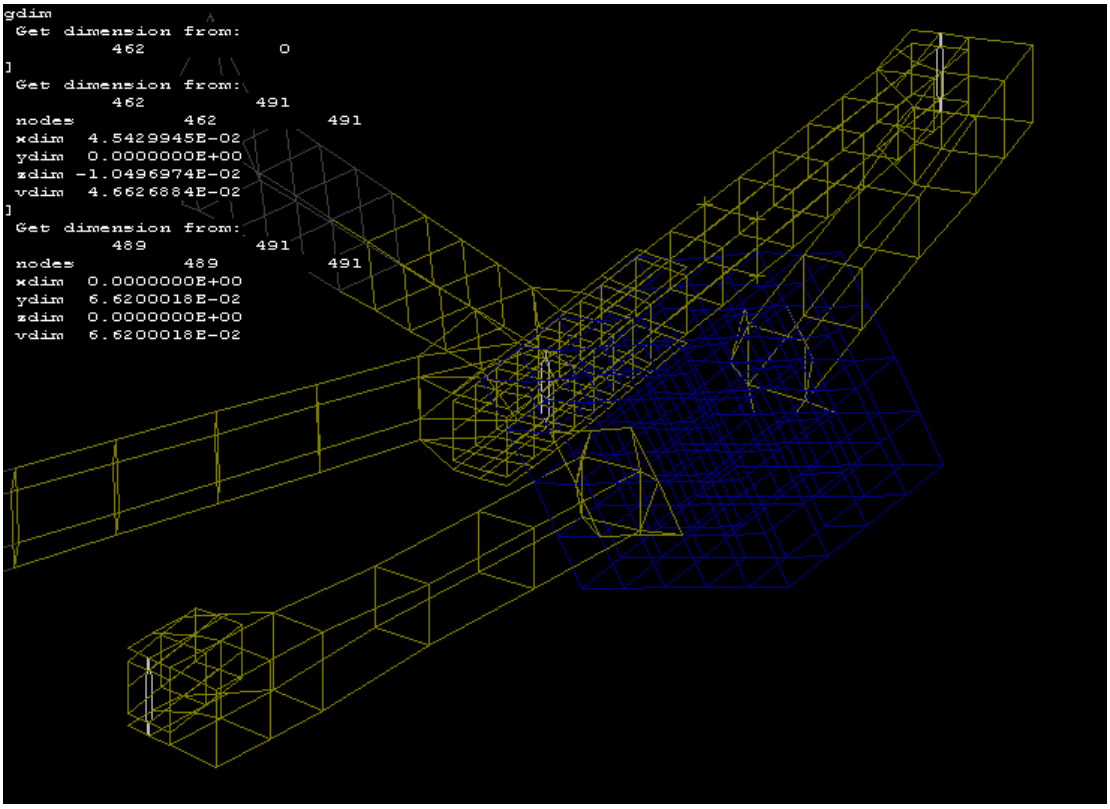
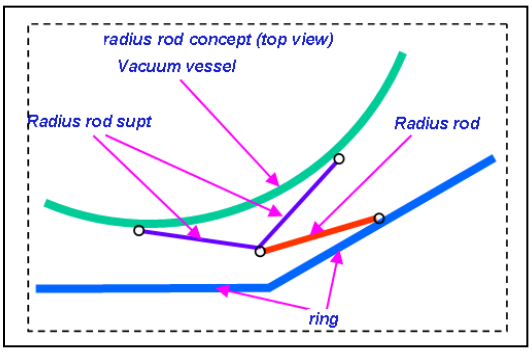
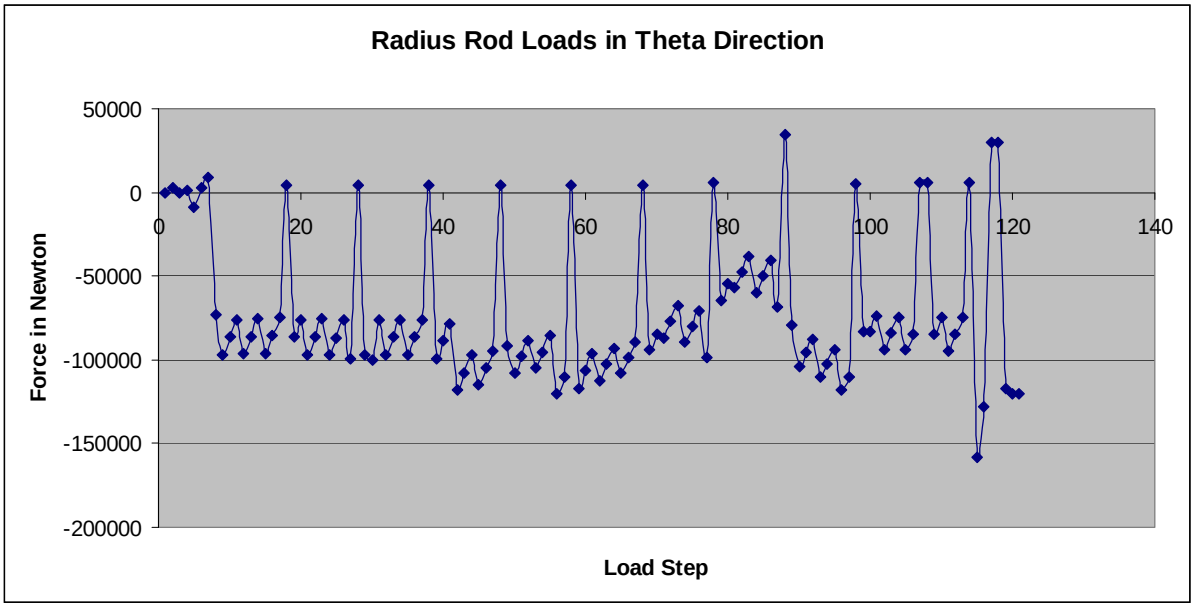
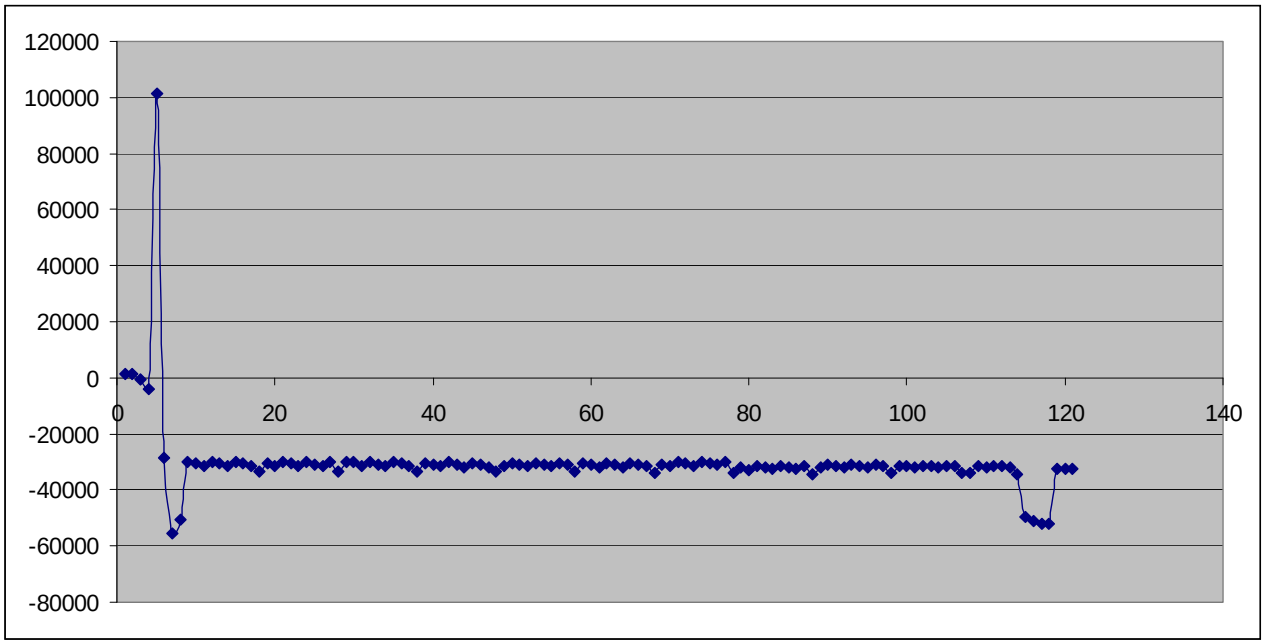


Figure Global Model approximation to the truss and radius rod.



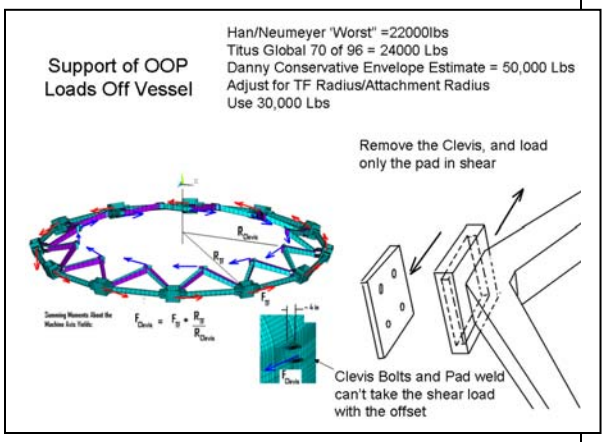


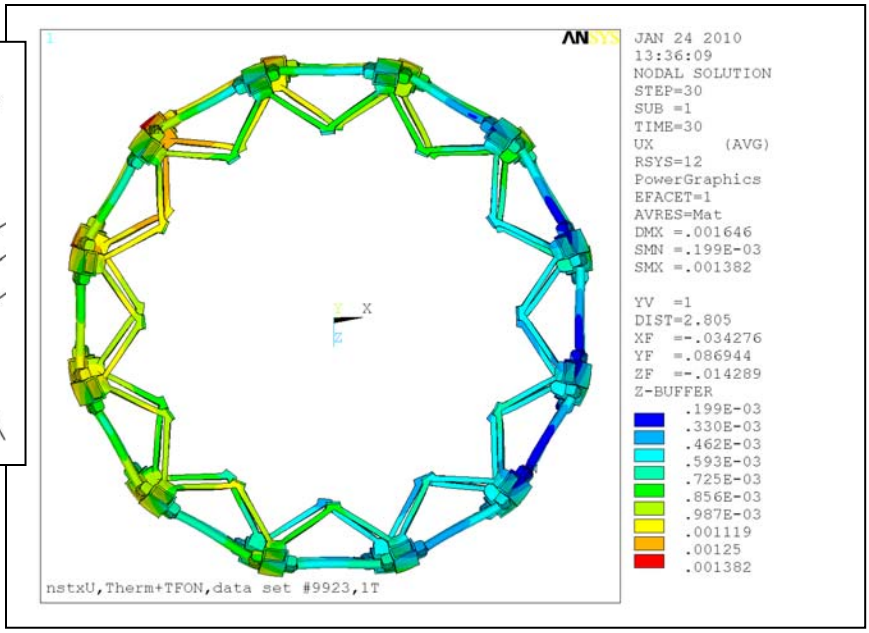
Radius Rod Loads for the Tangential Radius Rod Concept

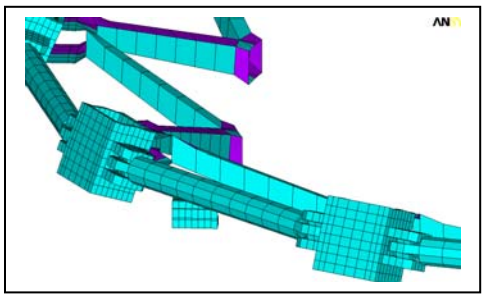


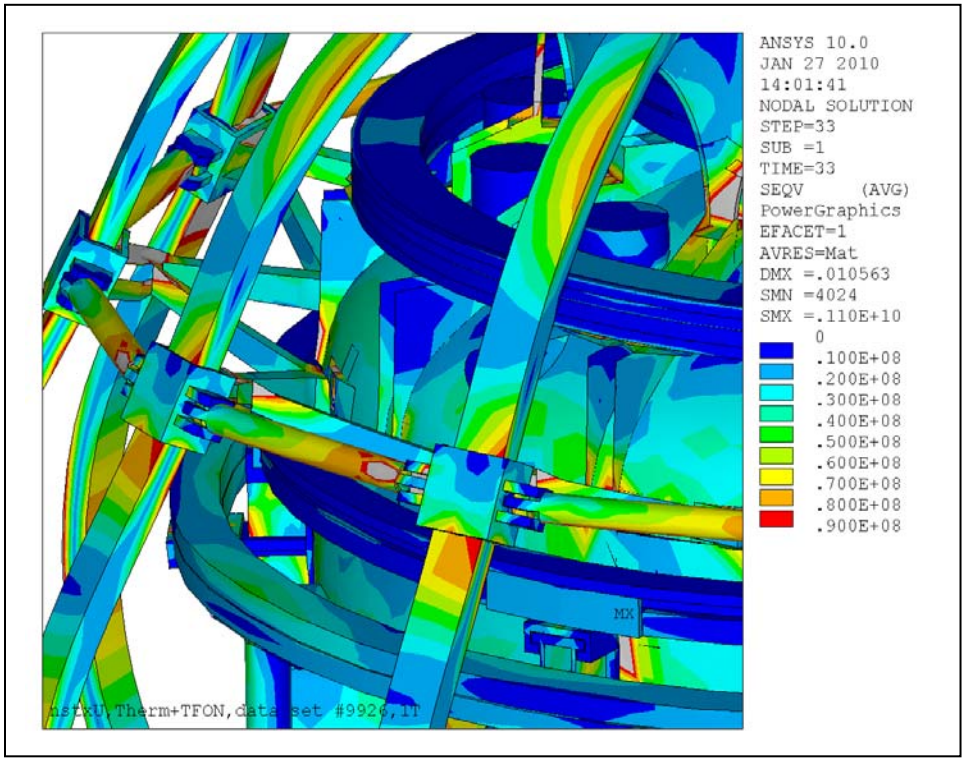
I am not sure what this is Radius Rod Loads for the Tangential Radius Rod Concept

12.10 TF OOP Support with the Clevis Modified Into Shear Key

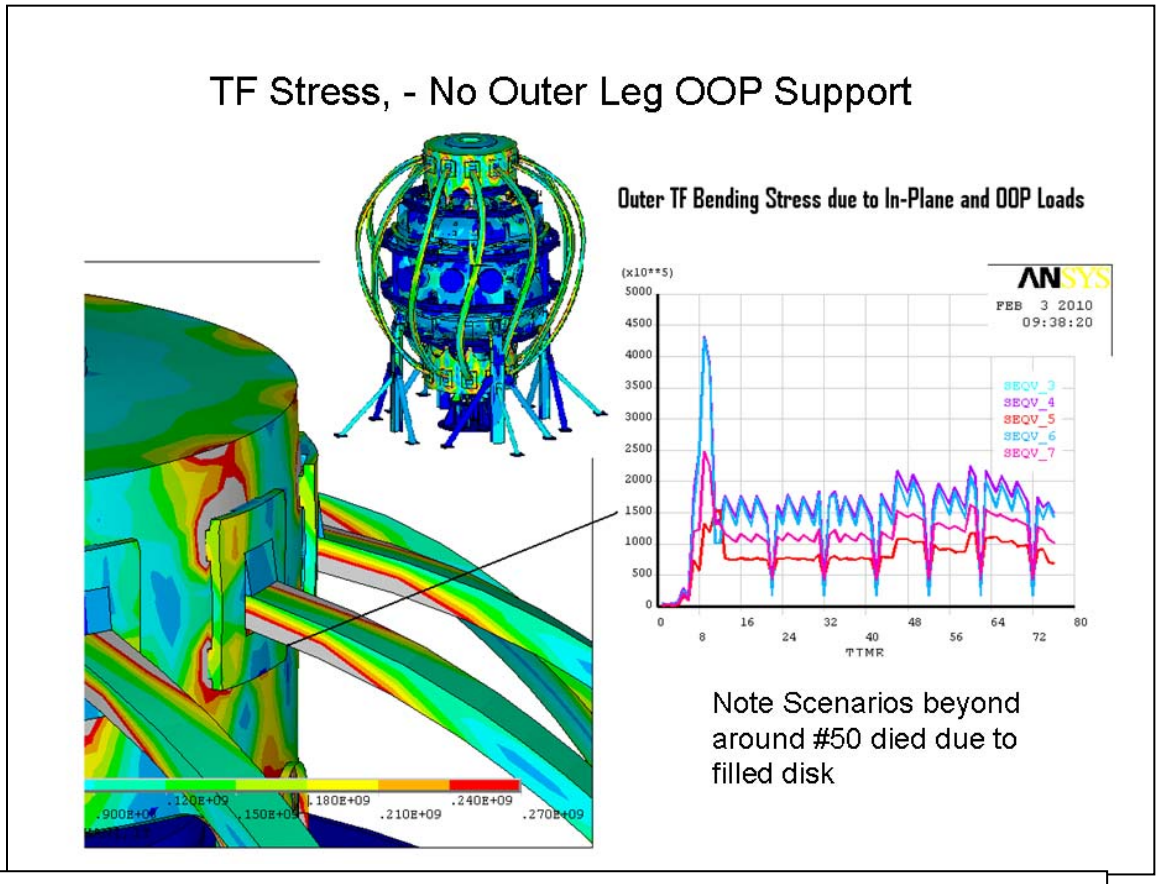


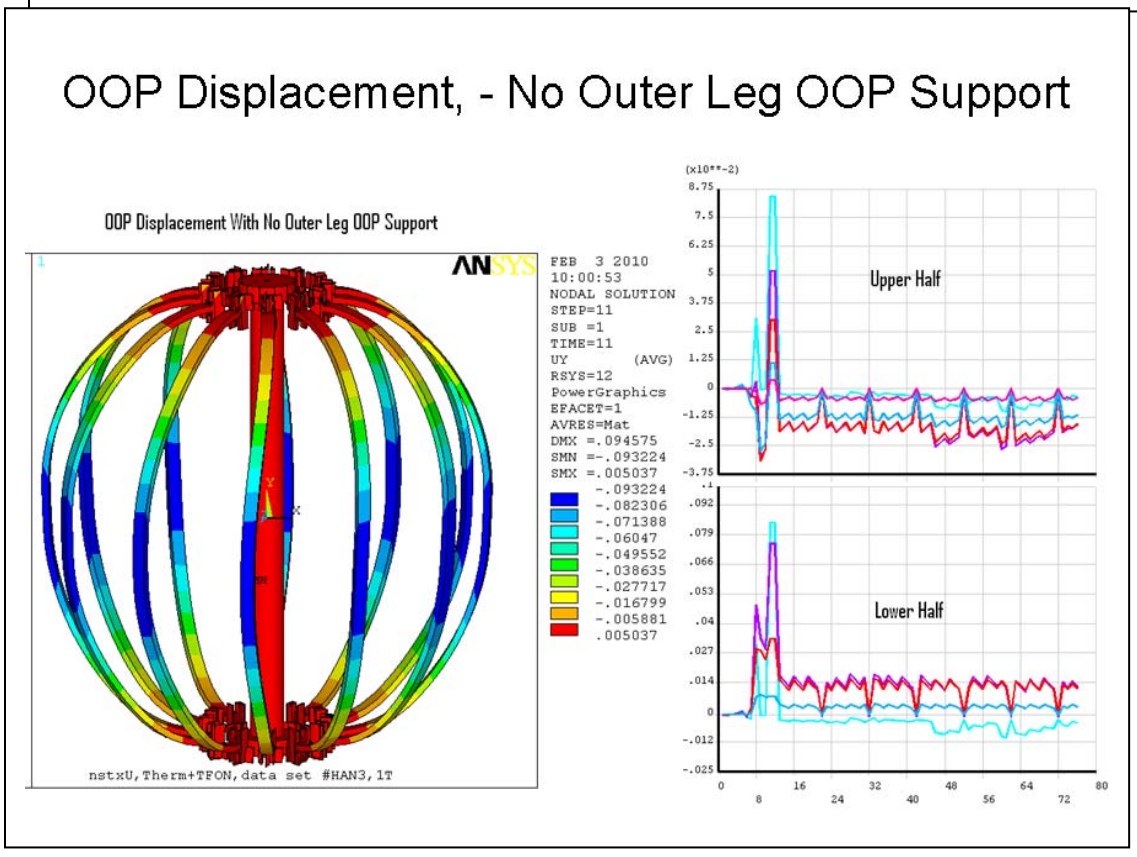




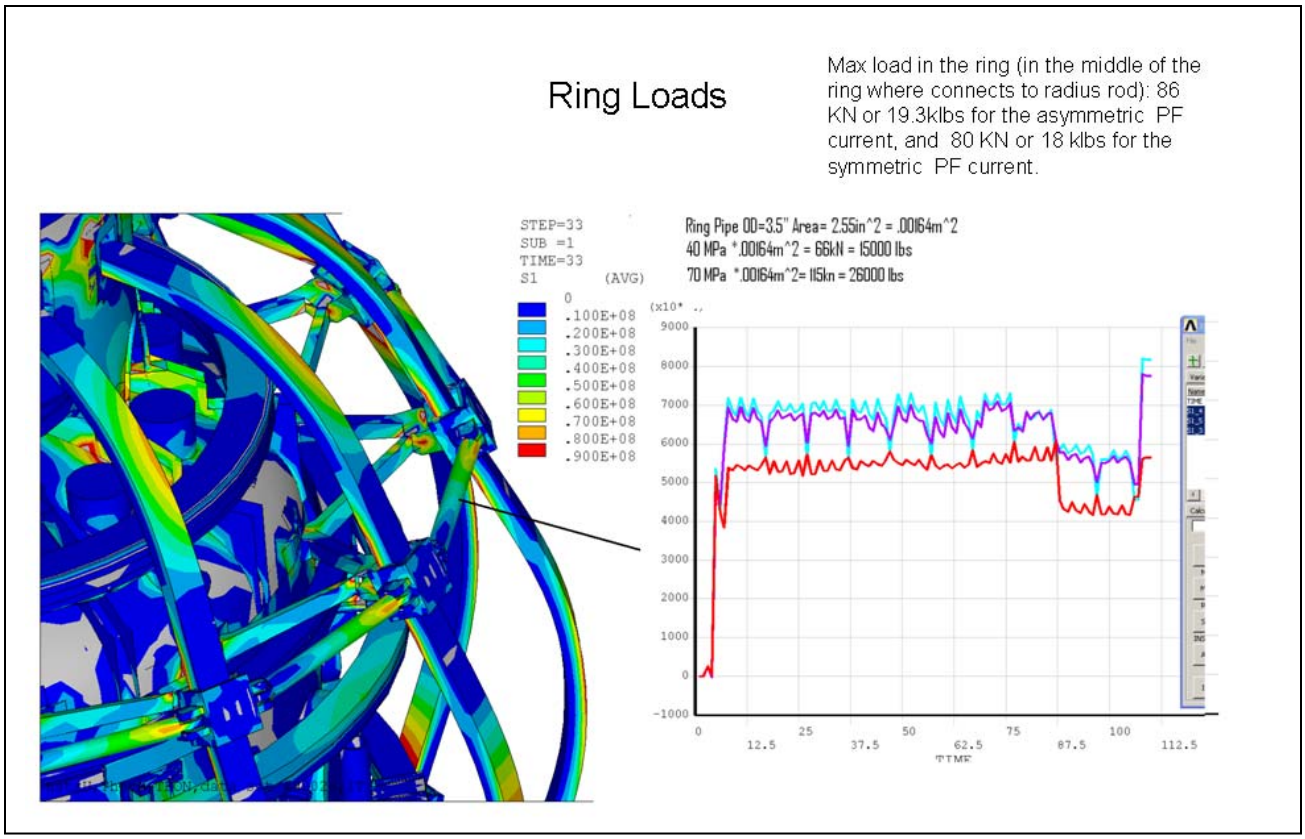


12.11.3 Soft Spring Truss Support
12.11.4 No TF Outer Leg Support





12.12 Outer TF Support Ring



12.13 Umbrella Leg Stress

The Umbrella structure legs have gone through a number of design iterations and modeling details. Originally the model was based on a quarter symmetry model developed by H.M. Fan and modeled 12 legs. These models were useful for initial scoping analyses and showed a need for an improved leg cross section.

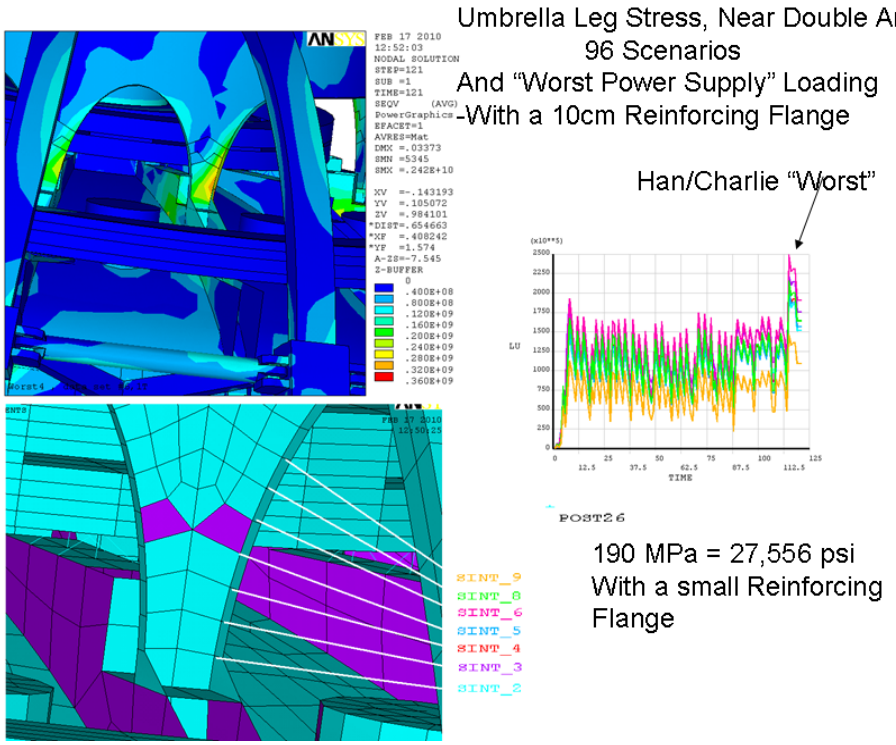


Figure 12.13-1 Early Results with One-Sided Flange Reinforcement

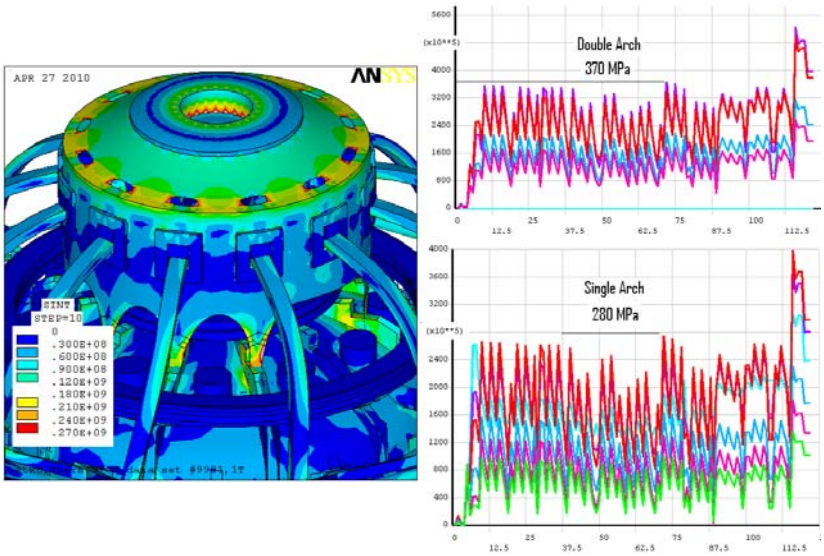


Figure 12.13-2 Early Results with One-Sided Flange Reinforcement Showing Stress in Nominal and Double Arches

The umbrella legs are actually distributed in a non-uniform way. One arch was "missing" a leg and the load inventory concentrated on either side of the double arch. The model that included the double arch was used to evaluate subsequent reinforcements. These models have 12-1 or 11 arch "feet". However there are actually only 10 legs. The distribution of the supporting ribs is irregular. To address the actual ten legged

configuration, the global model was modified to have two double arch regions, so that the global stiffness was modeled appropriately and the local stresses at the umbrella feet are conservatively treated.

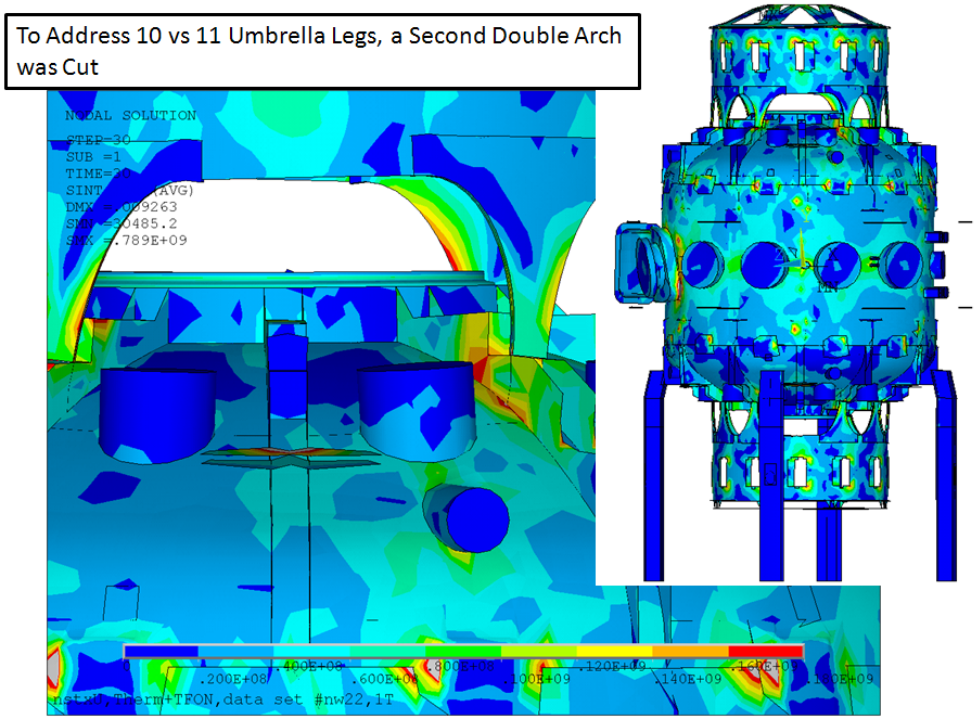


Figure 12.13-3 Ten Legged Configuration, Run 35

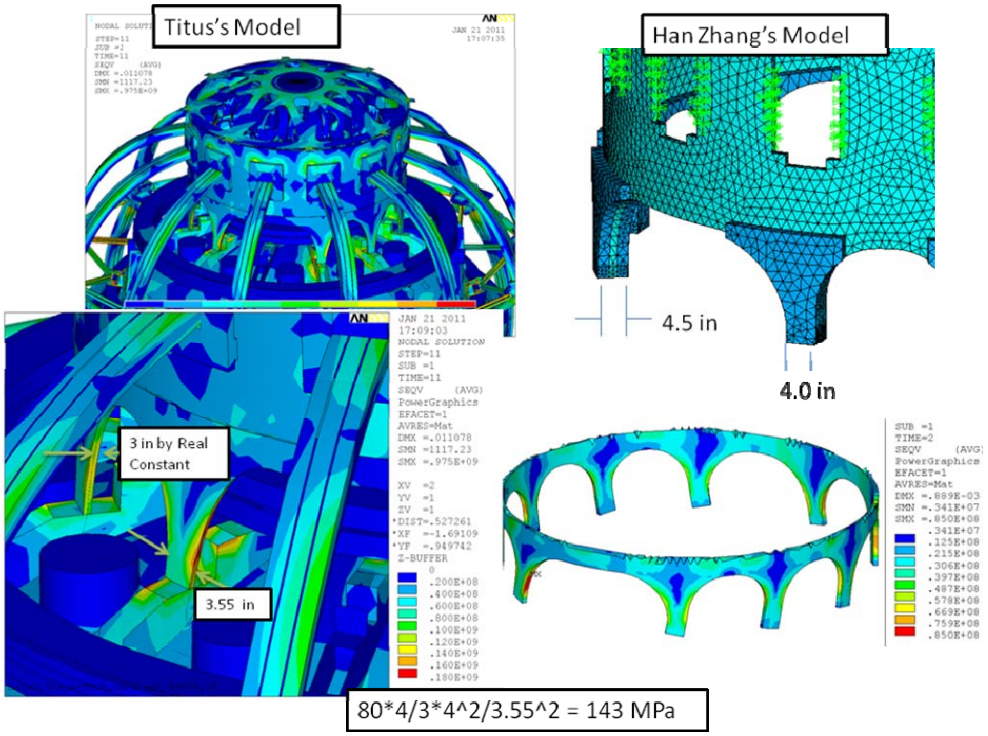


Figure 12.13-4 Comparison of Global Model Results

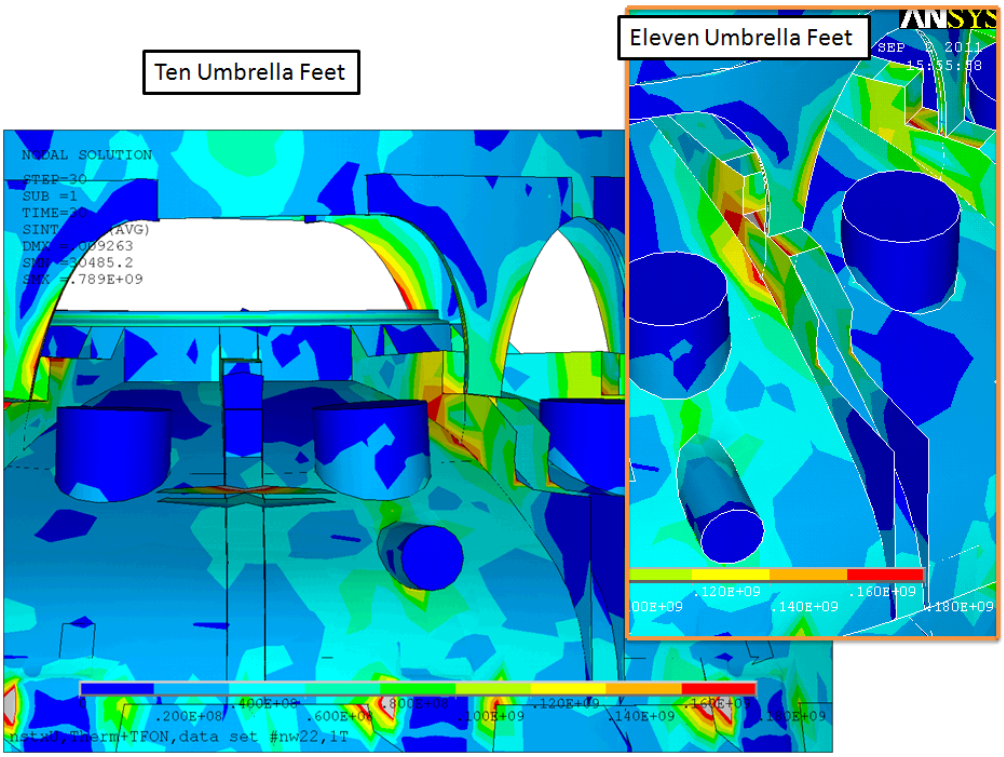


Figure 12.13-4 Comparison of Global Model Results Stress Results for Run #35 with a View that shows the Two Double Arches that Form the Ten Legged Model

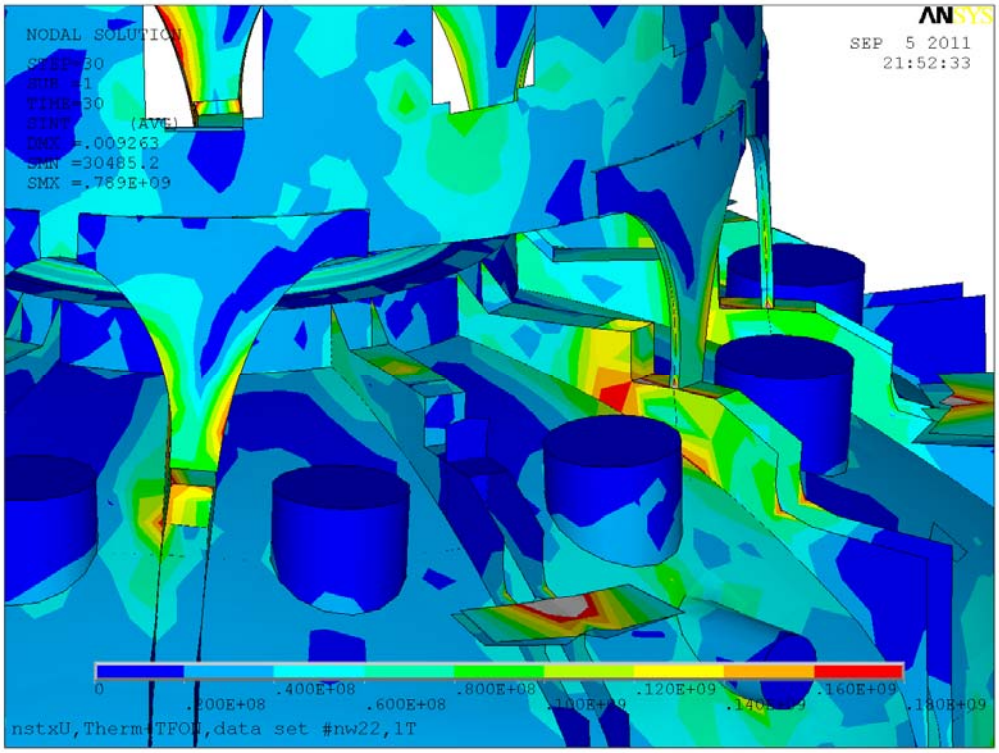


Figure 12.13-5 EQ 22 Run #35 10 Legged Umbrella Structure, Tresca Stress, Contoured to a max of 180MPa

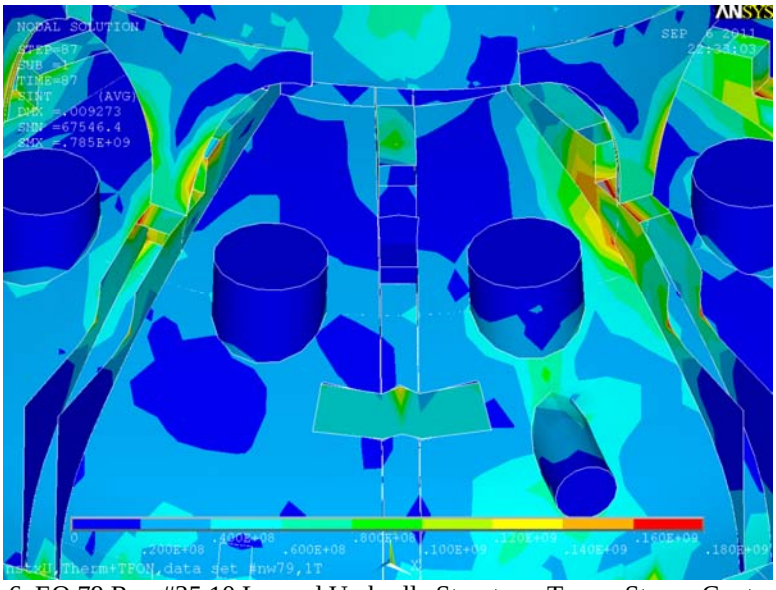


Figure 12.13-6 EQ 79 Run #35 10 Legged Umbrella Structure, Tresca Stress, Contoured to a max of 180MPa

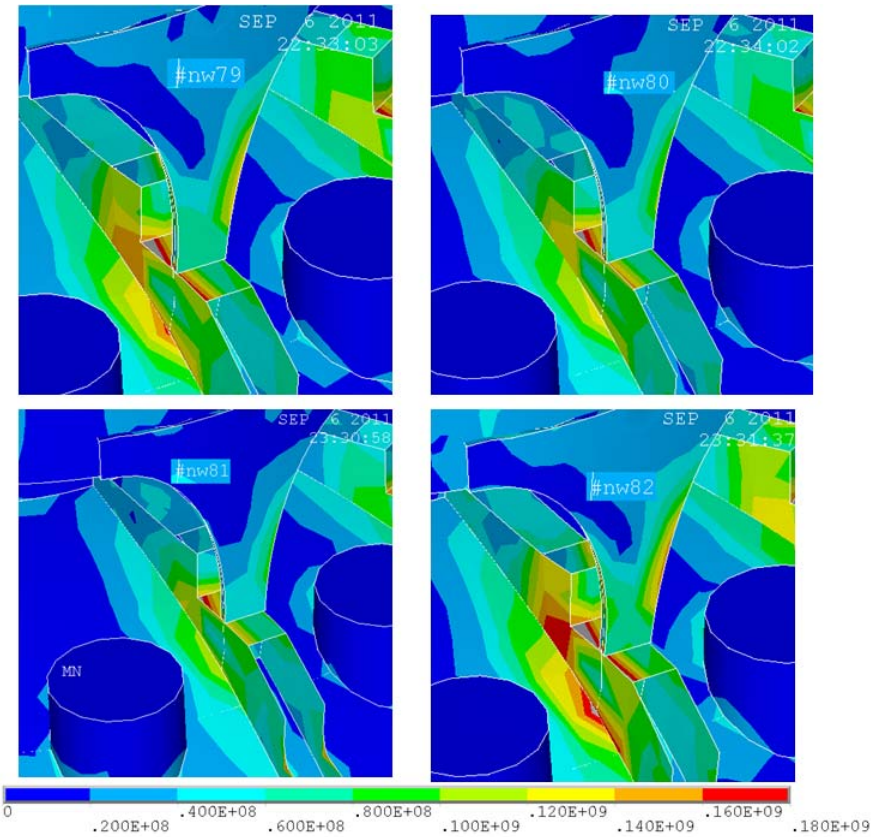
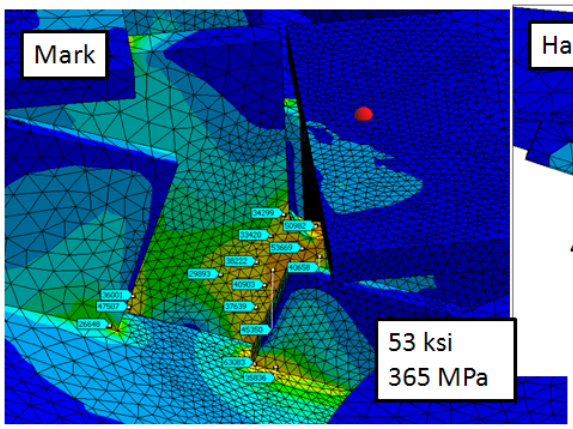
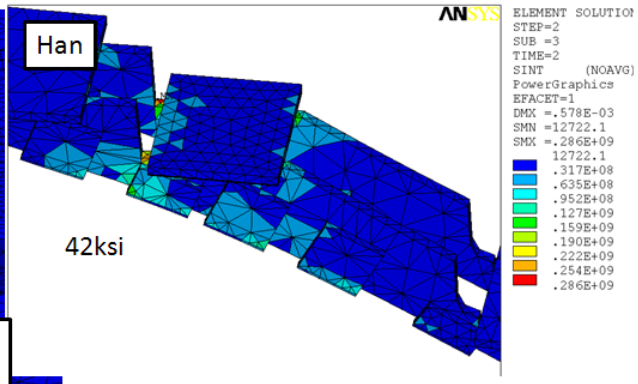


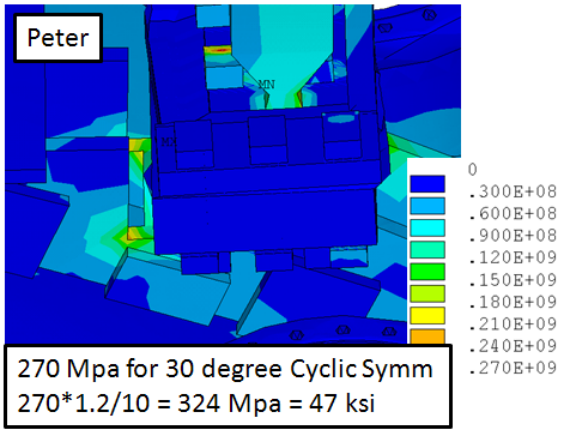
Figure 12.13-7 EQ 79,80,81,and 83 Run #35 10 Legged Umbrella Structure, Tresca Stress, Contoured to a max of 180MPa

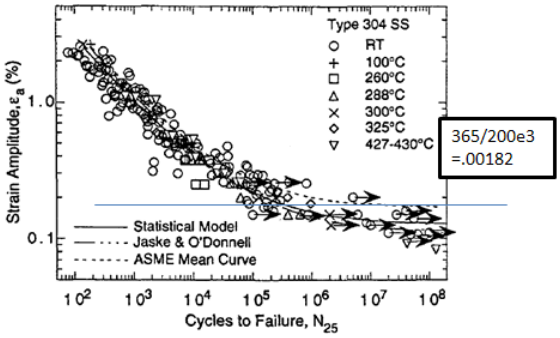
EQ 82 looks a bit worse than 79. The small gray triangular area is above 180 MPa

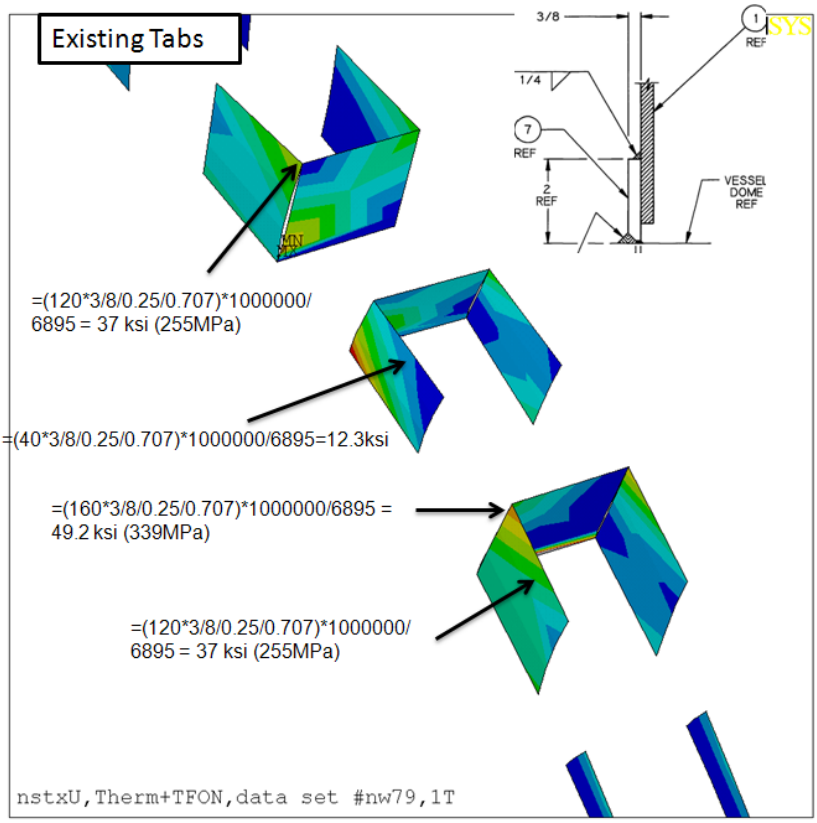




Material	Sm Membrane	1.5Sm Bending	3*Sm Local
304 Stainless Steel (Bar,annealed)	156MPa (22.6ksi)	234 Mpa (33.9ksi)	468 Mpa (68 ksi)

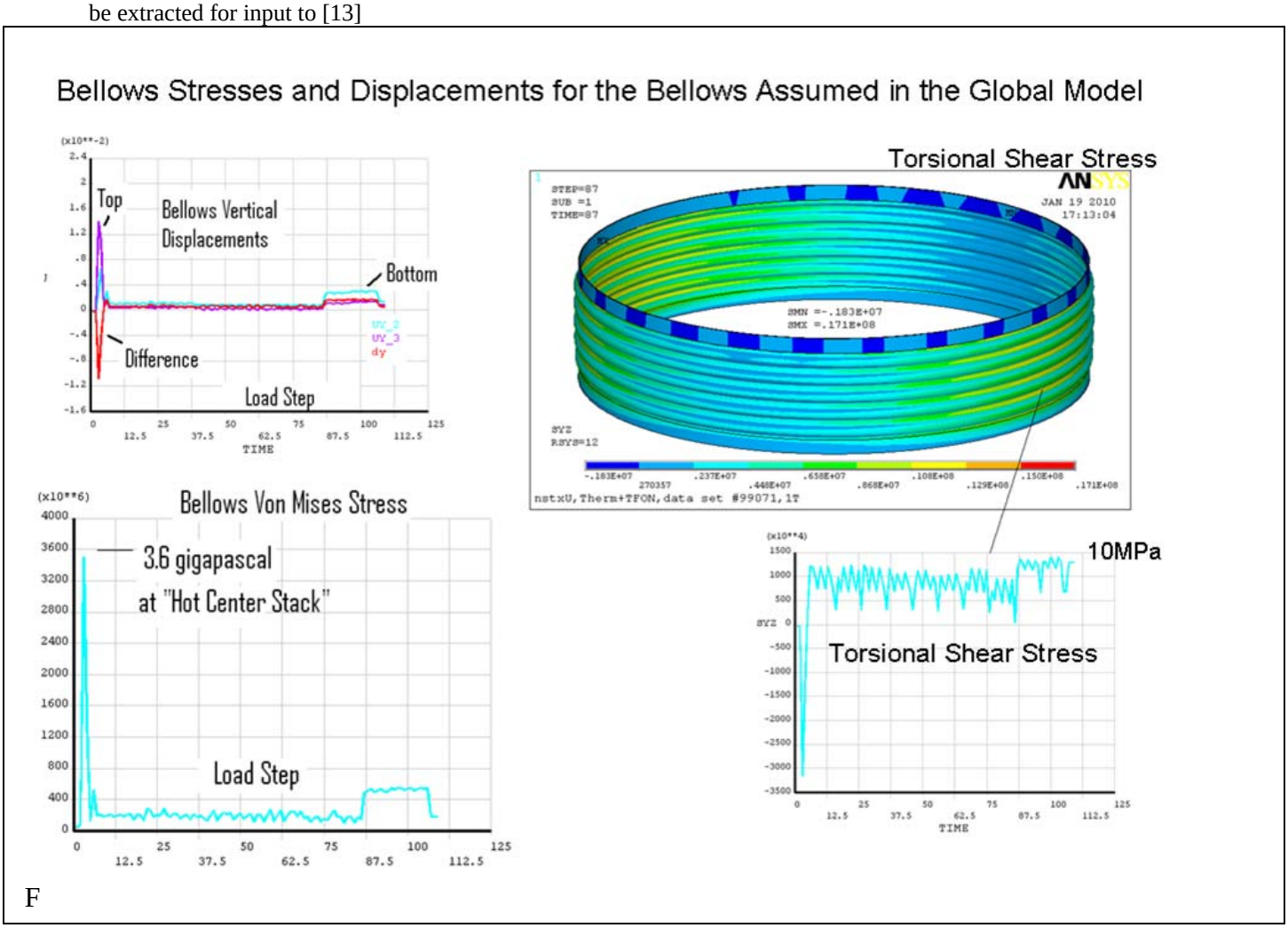




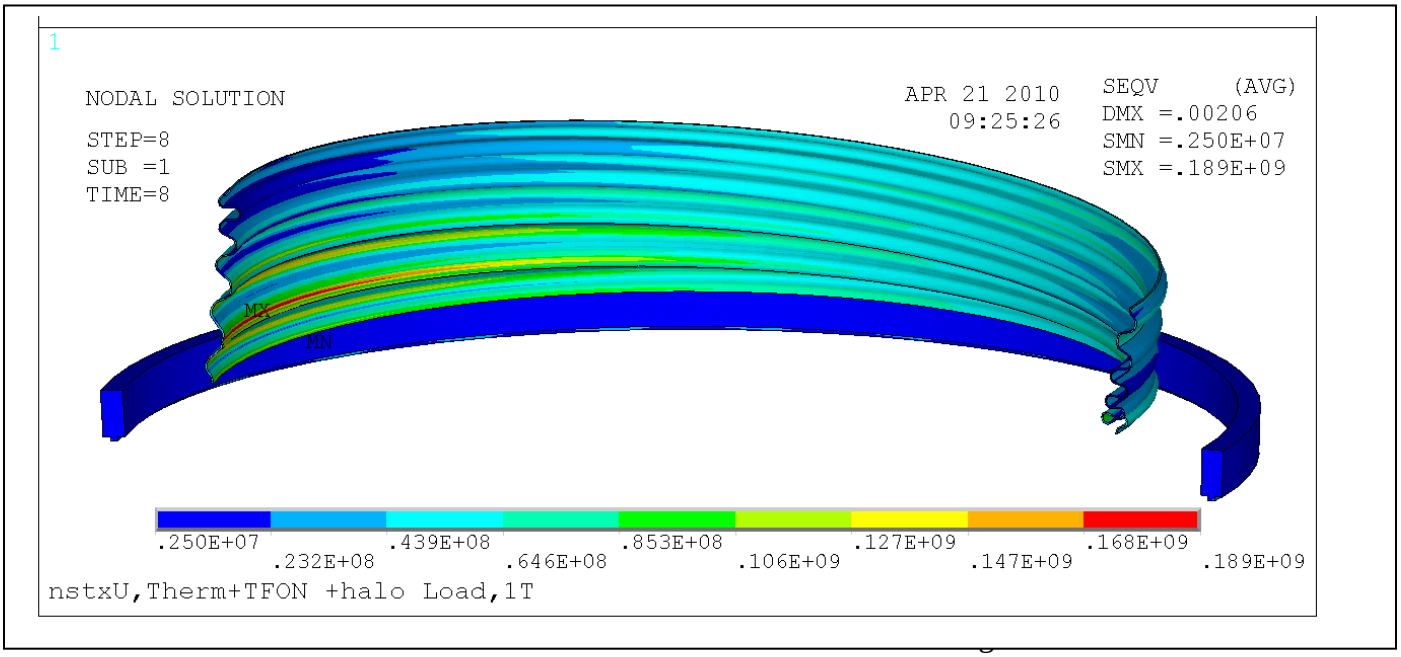


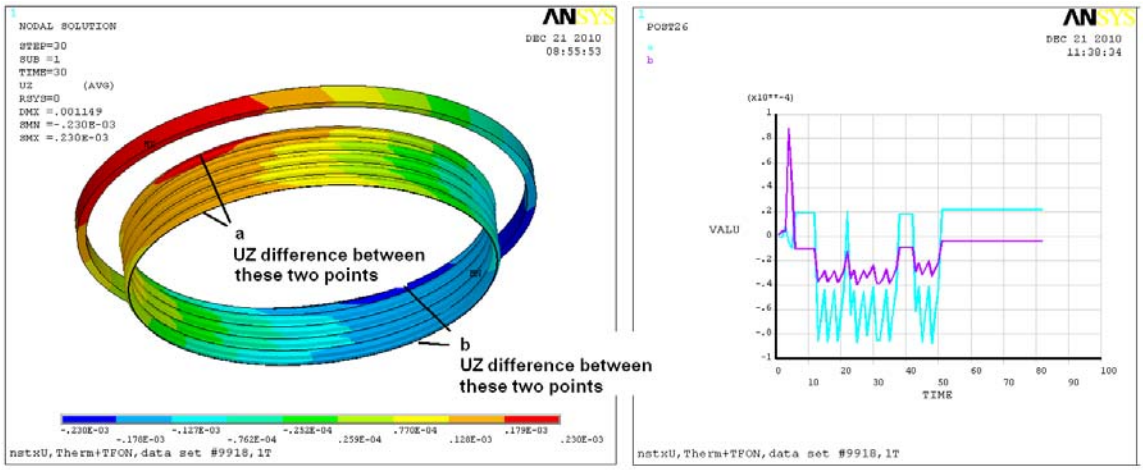
12.14 Bellows

The bellows have been considered in detail in a separate calculation [13] prepared by P. Rogoff. The global model includes models of the bellows from which torsional displacements and lateral loading may be extracted for input to [13]



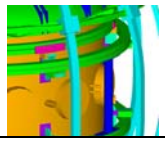
F





Run#24 Twist OOP Displacements for the Upper Bellows First 50 load files.

12.15 Brace Pad Embedment Loads



The load files include bake-out vacuum, including the net side-load from the NB port, 90 of the 96 Current files and some of the extreme loads from Han's OOP truss/radius rod analyses. No seismic side loading is applied at this time .

The global model was updated in late December 2009 to include the existing PF4 and 5

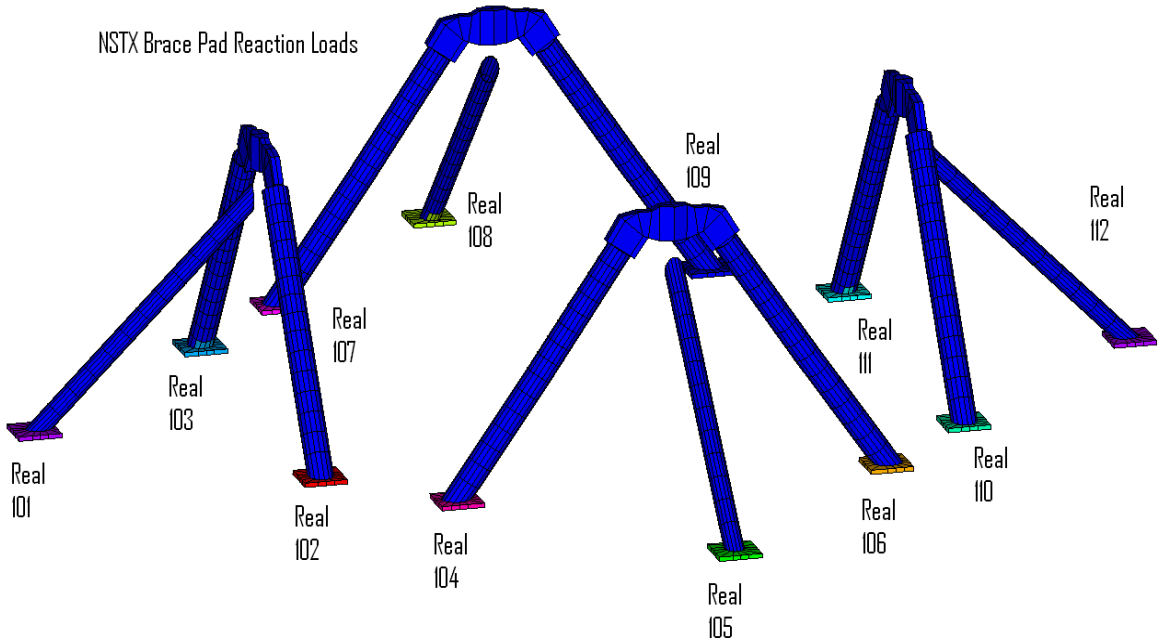
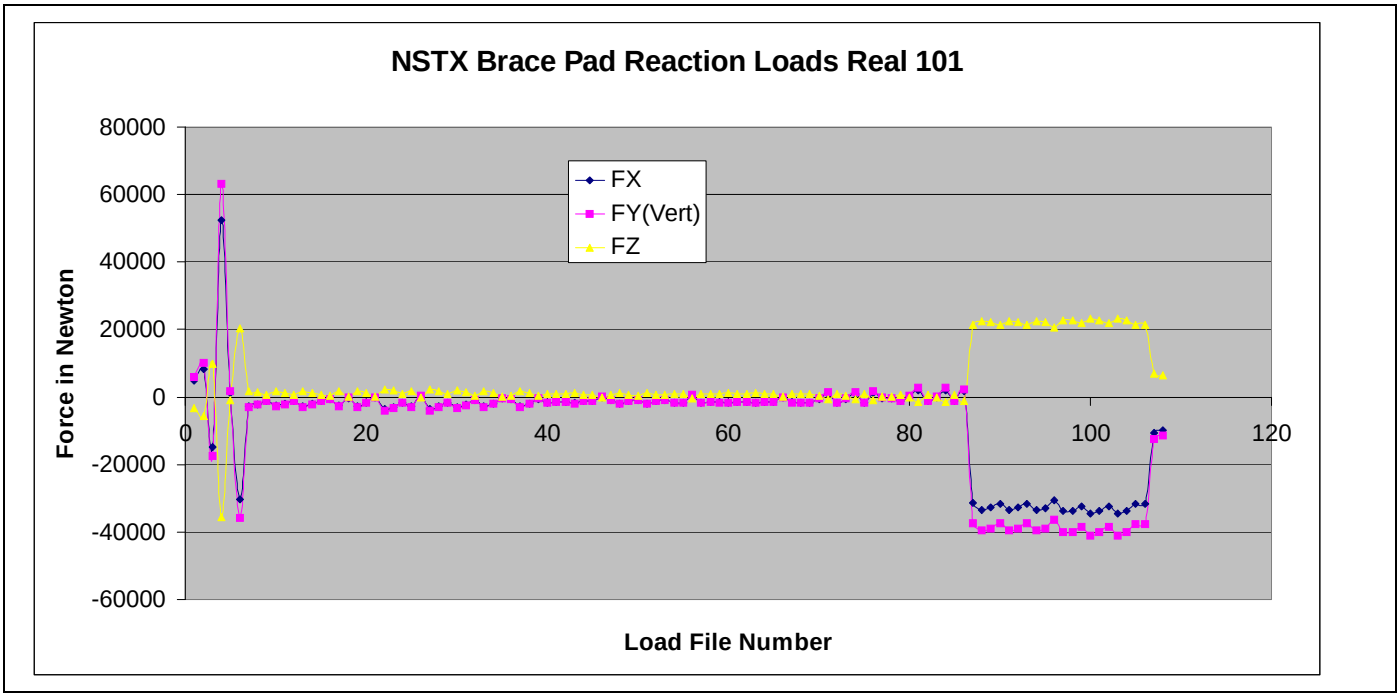


Figure 2 Braces, Pads and Real Constants used to select the individual pads



supports. It was post-processed to quantify the reaction loads at the brace pads. In order to facilitate the extraction of the reaction loads, the model of the brace structures was redone with real constants from 101 to 112 assigned to each lower pad. An ANSYS macro was used to create the reaction force files with the PRRFOR command. A true basic program was used to strip away the un-necessary text to allow reading the reaction force lists into EXCEL. Loads are in Newton. Hilti anchor loads would be the pad load divided by the number of Hilti's per pad (4?)

```
ANSYS Macro

Load1=1
load2=108

*do,ireal,101,112
/output,breaction%ireal%,txt
esel,real,ireal
nelem
nrsel,y,-5,-3.93

*do,ld,load1,load2
set,ld
prrfor
!fsum
*enddo

/output,term

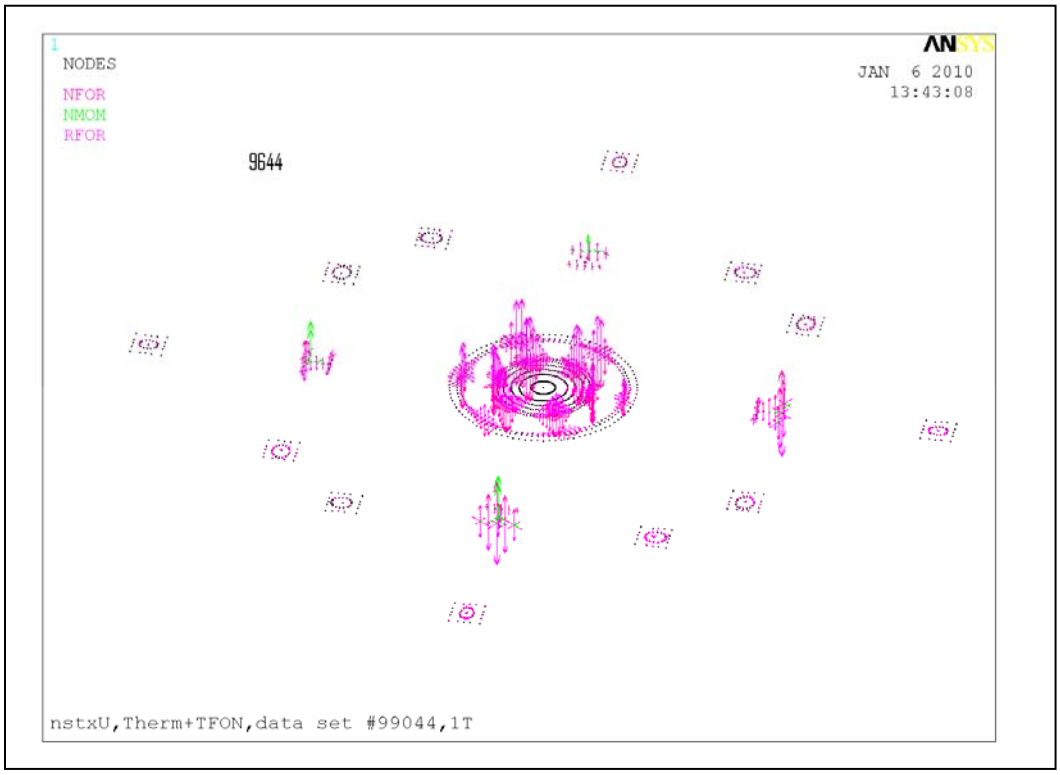
*enddo
/eof
```

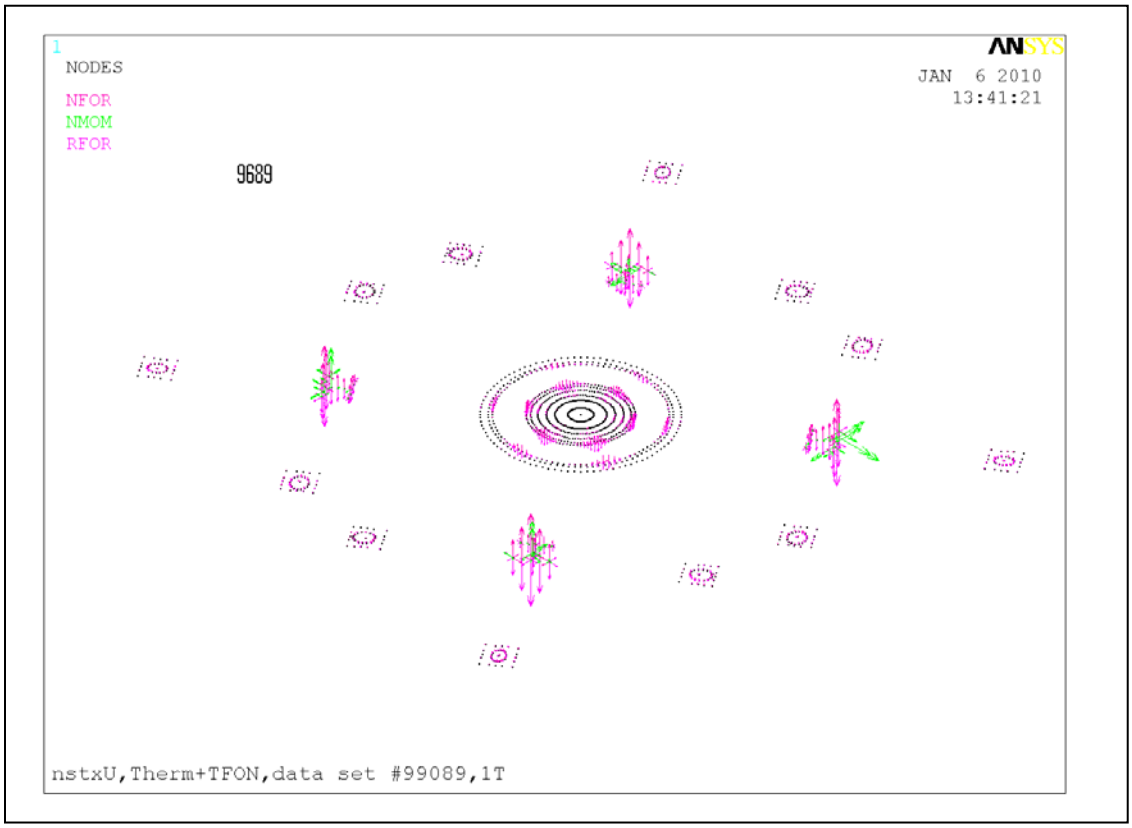
```
True Basic Program
clear
print " finding total values"
open #1: name "breaction101.txt",create newold

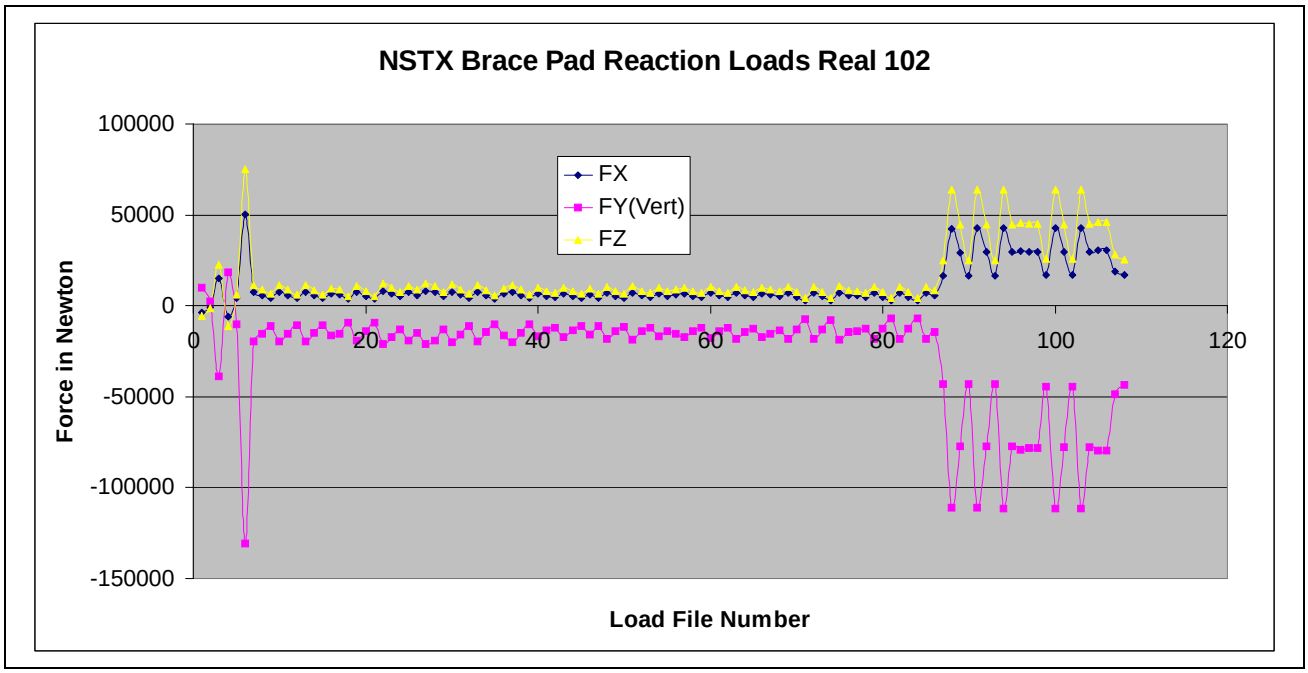
when error in
unsave "breaction.out"
use
end when

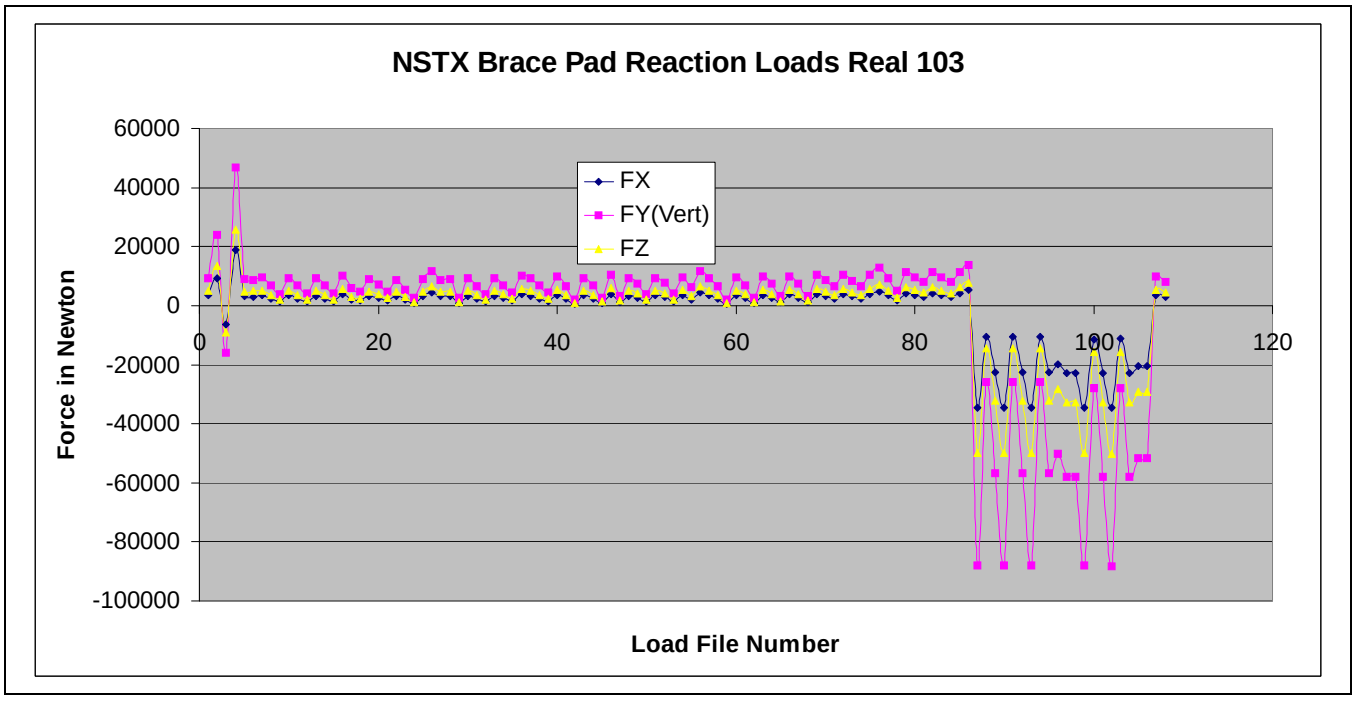
open #2:name "breaction.out", create new
do while more #1
line input#1: l$
if l$[1:13] =" TOTAL VALUES" then
line input#1: l$
print#2: l$
print l$
end if
loop
close #2
end
```

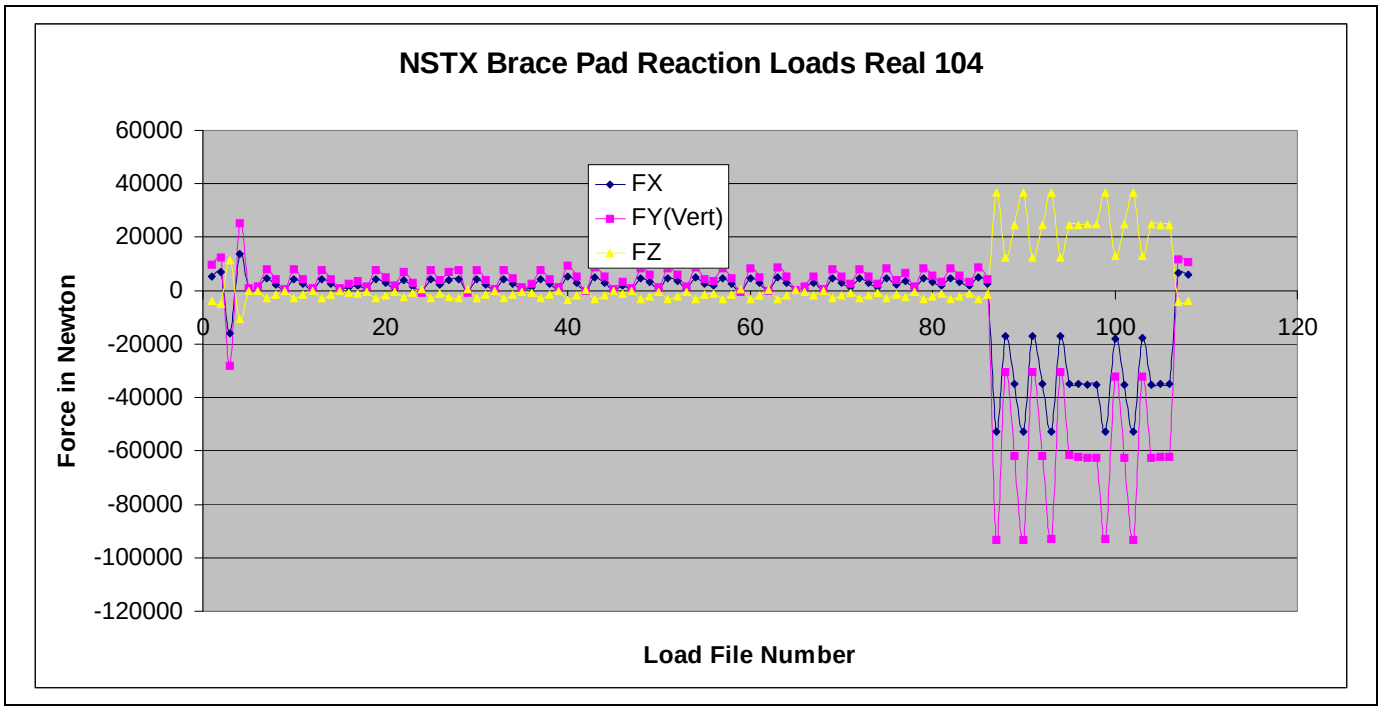
The pad reaction loads are not the only embedment loads that must be sustained. The central pedestal, and the four large columns take a larger inventory of the loads. These will be summarized in a separate memo.

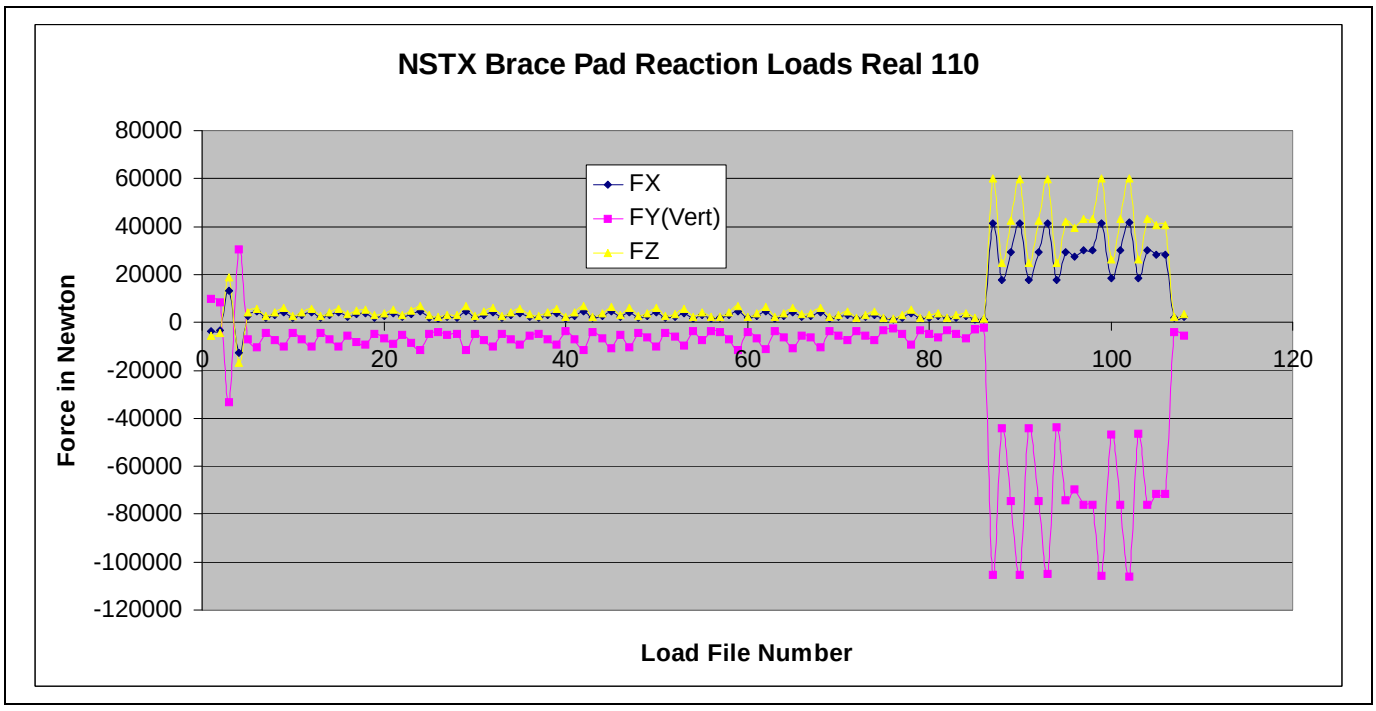





NSTX Brace Pad Reaction Loads Real 102
100000
50000
0
-50000
-100000
-150000
0
20
40
60
80
100
120
FX
FY(Vert)
FZ
Force in Newton
Load File Number


NSTX Brace Pad Reaction Loads Real 103
60000
40000
20000
0
-20000
-40000
-60000
-80000
-100000
0
20
40
60
80
100
120
FX
FY(Vert)
FZ
Force in Newton
Load File Number


NSTX Brace Pad Reaction Loads Real 104
60000
40000
20000
0
-20000
-40000
-60000
-80000
-100000
-120000
0
20
40
60
80
100
120
FX
FY(Vert)
FZ
Force in Newton
Load File Number


NSTX Brace Pad Reaction Loads Real 110
80000
60000
40000
20000
0
-20000
-40000
-60000
-80000
-100000
-120000
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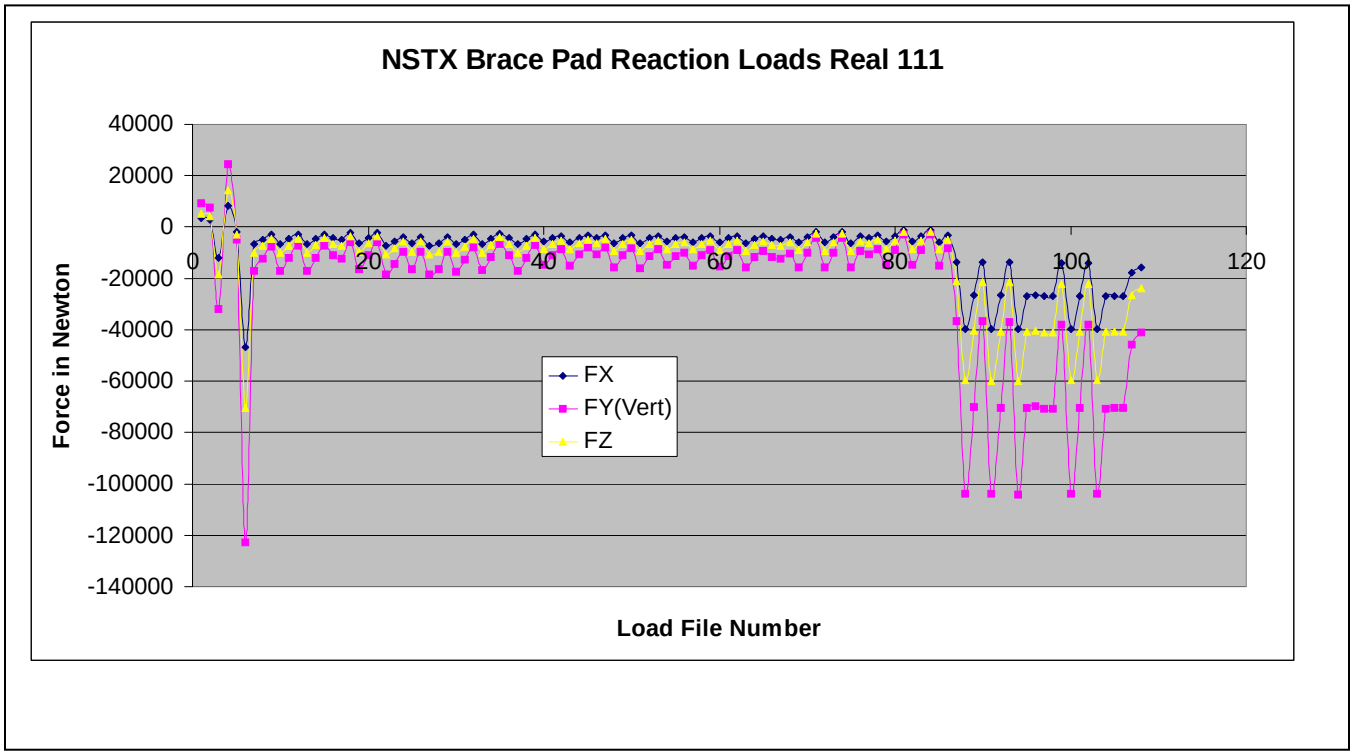
40
60
80
100
120
FX
FY(Vert)
FZ
Force in Newton
Load File Number


NSTX Brace Pad Reaction Loads Real 111
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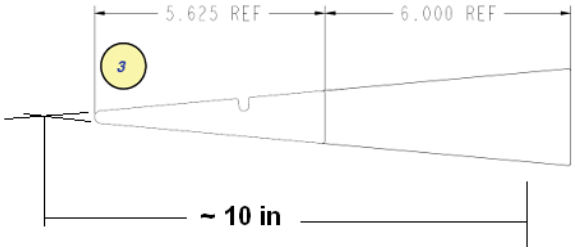
20000
0
-20000
-40000
-60000
-80000
-100000
-120000
-140000
0
20
40
60
80
100
120
Force in Newton
Load File Number
FX
FY(Vert)
FZ

12.16 Moments Transmitted Through the Lid/Flex

The torsional moment for design of the lid/flex/Diaphragm bolting and the TF steps or keys is 0.3MN-m for the lower lid (Figure 7) and 0.25 MN-m for the upper flex (Figure 8). This is the torque being transmitted from the centerstack TF to the outer rim of the umbrella structure. THese values have been used throughout the FDR to size the components at the hubs of the upper and lower spoked lids. The final design with the spoked lids has been modeled and the moment sum (using FSUM) at the mid radius of the spokes has been checked to make sure it is below the design values. With only a few scenarios checked, the worst moment on the spoked lids is .1



Radius to the Collar "Tooth"

Collar Tooth Load: = .3 MN-m/(10/39.37)*.2248/36 = 7375.3 lbs. This has been rounded up to 9000 lbs to provide some headroom for the halo current loads, and the 10% headroom on PF currents applied in the design point spreadsheet.

The prying moment at the bolt circles is 6300 N-m per meter of perimeter. The prying moment can probably be reduced by reducing the assumed thickness of the 5/8 in thick lid.

A flex plate or cover or "lid" is intended as the structure that extends from a connection to the TF central column flags to the outboard edge of the umbrella structure. These details are only concepts in the drawings currently, but a simple representation of the plate is included in the global model (Figure 1). The flex plate must allow the relative motions of the central column which is fixed vertically at the lower end by connections to the pedestal and to the lower TF flag extensions. The upper connections between the outer rim of the umbrella structure and the TF flags must allow the full vertical expansion of the central column. This is 9 mm at the elevation of the connection. The lid/flex plate is intended to bend and absorb the vertical motions elastically. Bending stresses develop at the ID and OD of the plate which produce prying moments at the bolt circles.

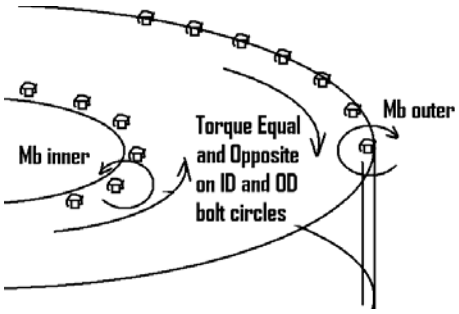


Figure 2 Torques and Moments


Figure 3 Bruce Paul's Model of the Lid/Flex Region

The prying moments or Mb inner and outer(in Figure 2) are the bending stress multiplied by the plate section modulus or on a per perimeter length basis, the moment is the stress times t^2/6
At the outboard bolt circle, the stress is about 150 MPa (Figures 4 and 5) and the moment is 150 MPa *(5/8/39.37)^2/6 = 6300 N-m/m. If there were bolts every 20cm then the prying moment would be 6300*.2 = 1260 N-m and if the distance from the bolt centerline to the edge of the plate were 10 cm, the bolt load would be 12600 N or 3000 lbs. In the global model, the inner edge is pinned, due to a plate element to solid transition. It will probably be a bolted connection, for design purposes, the inner flex can be considered as having 150 MPa bending as well as the outer diameter of the flex.

Upper Flex Plate/Diaphragm Replaces the Gear Tooth Connection

Hot Central Column, Cold Vessel

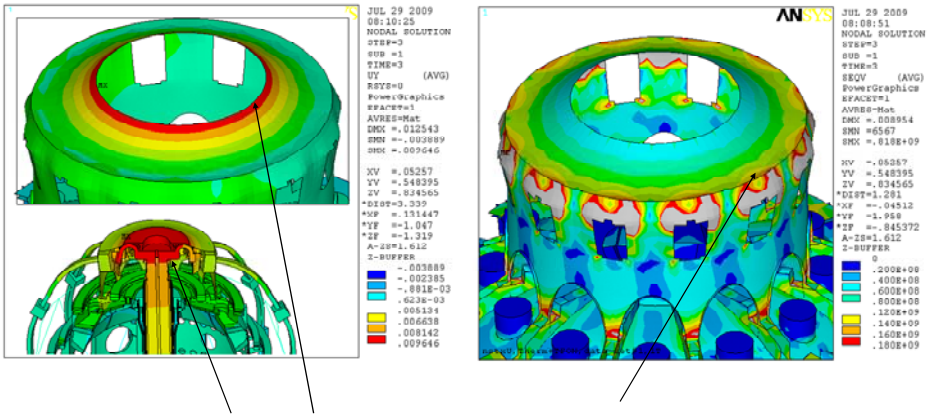


Figure 4 CDR Description of the Lid/Flex, Showing Vertical Displacement due to Centerstack Temp rise

- Vessel at 150C during Bake-Out RT Central Column
- Vessel Expands +8mm
- Flex/Diaphram Stress is 135 MPa
- Note Uniform Stress at Edge

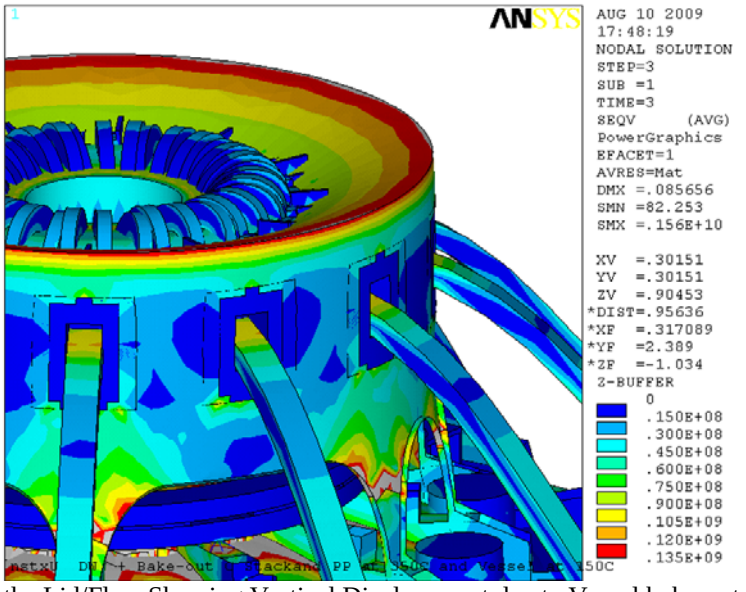
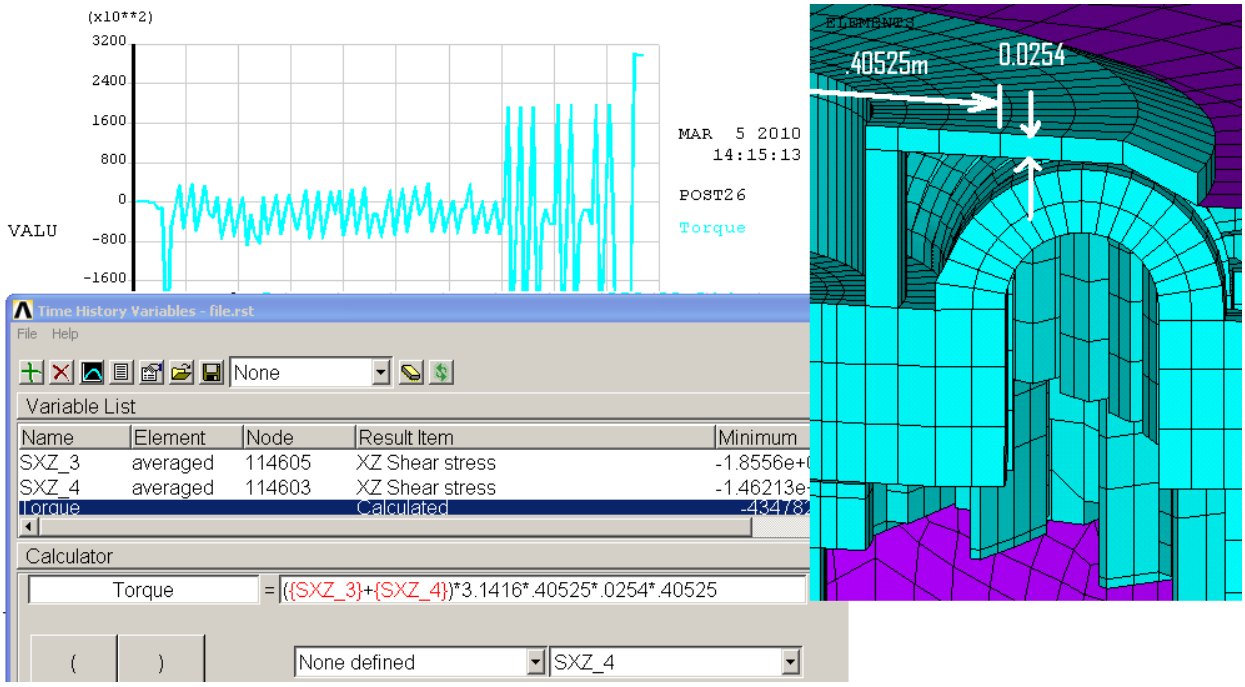
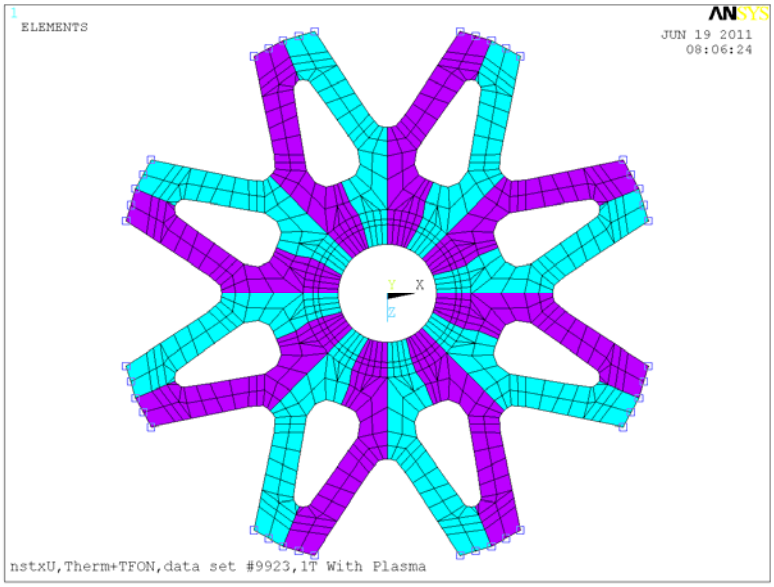


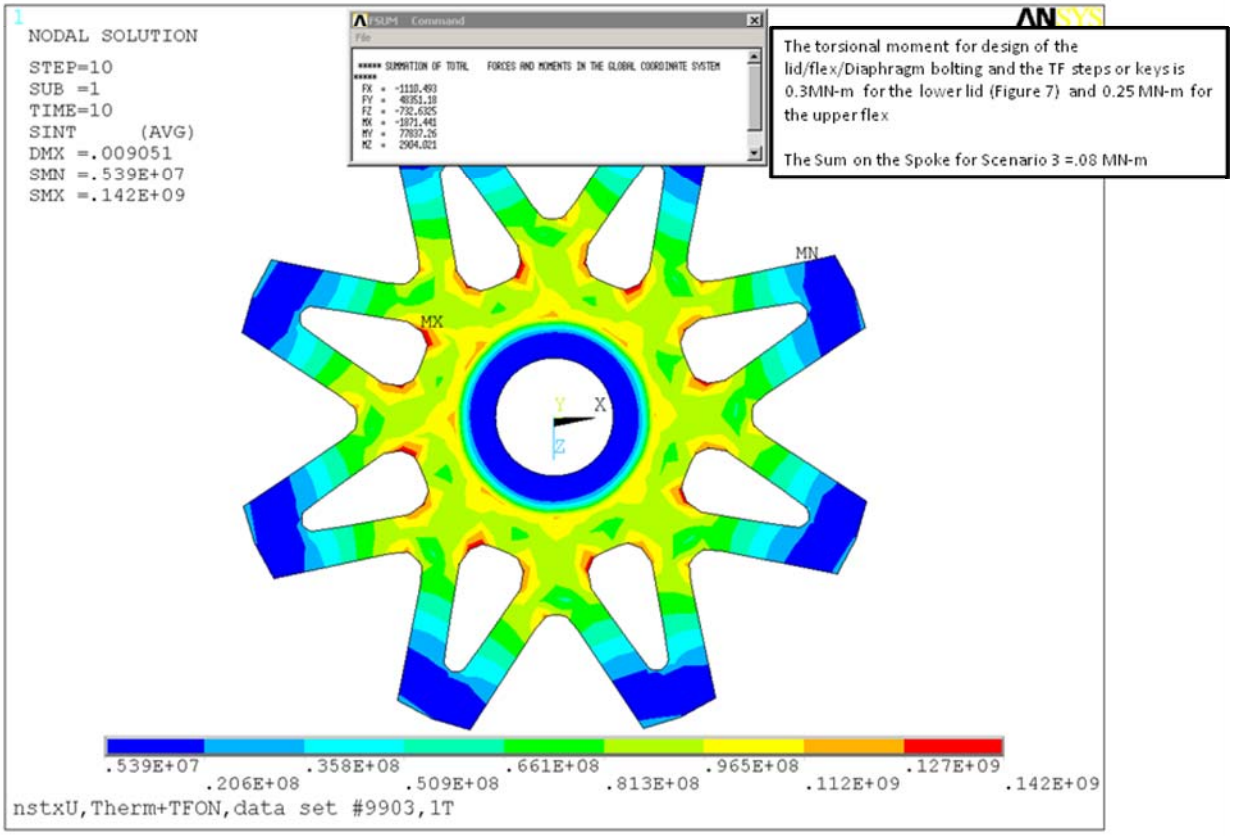
Figure 5 CDR Description of the Lid/Flex, Showing Vertical Displacement due to Vessel bake-out

As a sanity check on the torque: For Scenario 79 the total OOP load on one upper half of a TF outer leg - mid plane to aluminum block is 127000N = 28550 lbs. Subtract out 5kips for the knuckle clevis or 23550lbs This is split between the aluminum block and shear in the TF outer leg mid-plane or 11775 lbs at each end. At the aluminum block, some goes into the lid. and some goes to the umbrella legs. - assume half goes to the lid or about 5900lbs to the lid then the moment is 12*5900/.2248*1.1= .34 MN-m. The assumption of 5 kips at the knuckle was based on the soft springs at teh truss members. As of the FDR, this has been changed to a solid strut that carries about 22000 lbs at the TF coil clamp.

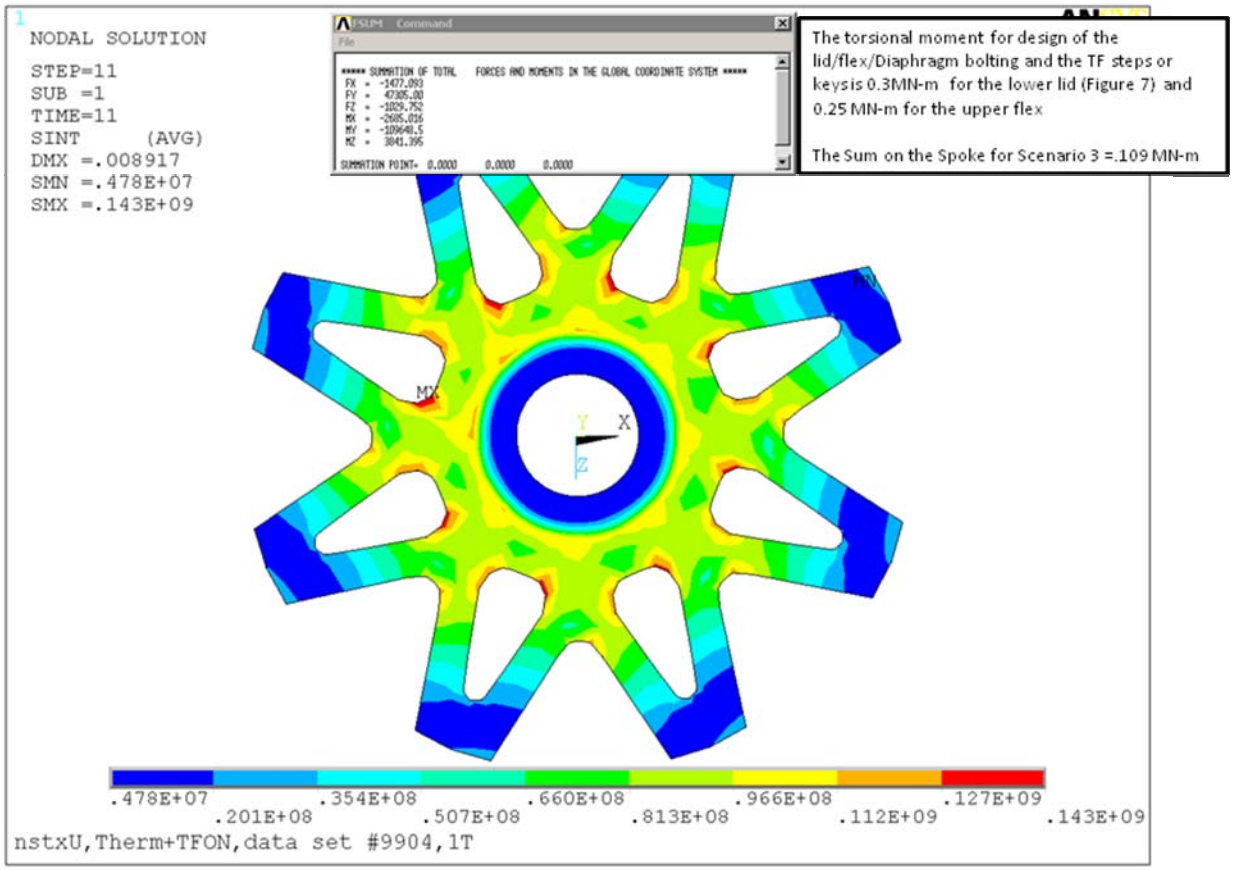




FDR Upper Spoked Lid Moment Sum - Element and Node Select for the Net Torque Using FSUM

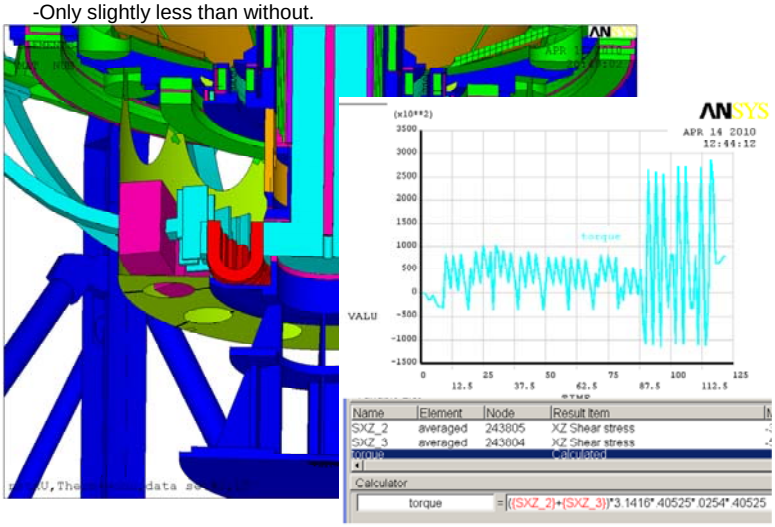


FDR Upper Spoked Lid Moment Sum



FDR Upper Spoked Lid Moment Sum

The torsional moment for design of the lid/flex/diaphragm bolting and the TF steps or keys is 0.28MN-m for the lower lid – With Holes -Only slightly less than without.



Lid/Flex/Diaphragm Moments with Access Ports

12.17 Pedestal Stresses and Torques

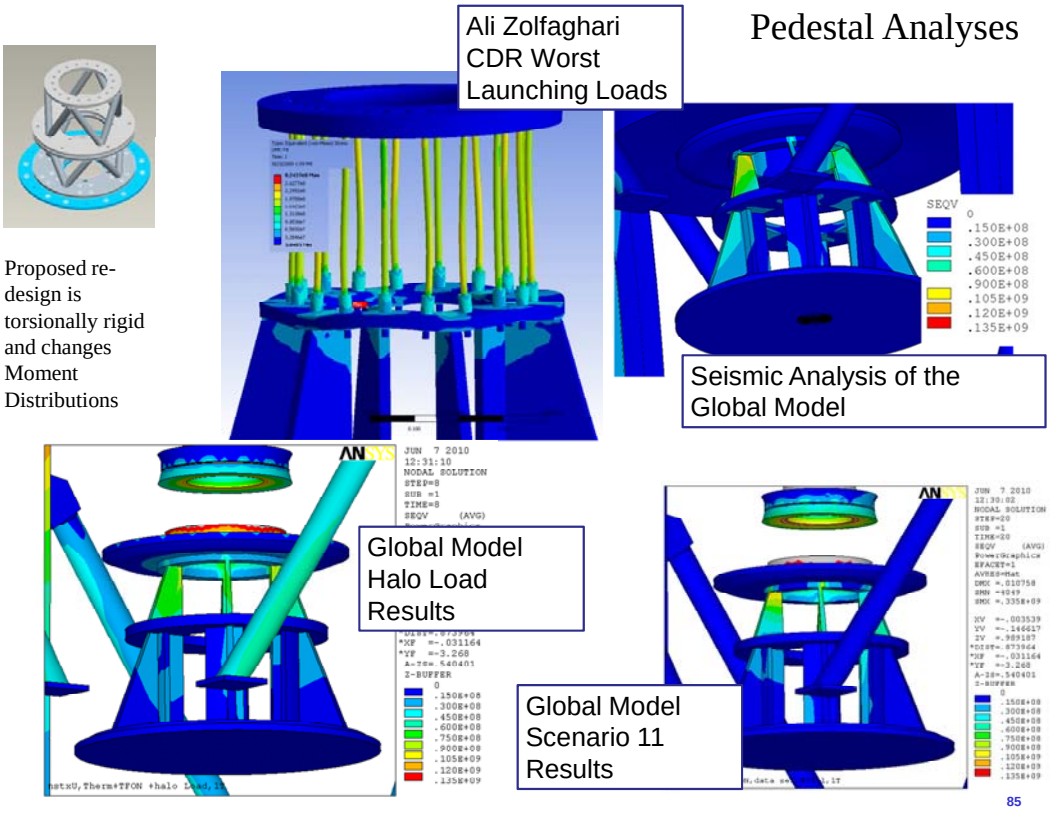


Figure 12.17-1 Present Vee Pipe (upper Left) and Earlier Pedestal Designs

The pedestal is a structure that provides gravity support for the centerstack and resists Coil Lorentz loads during operation.. Because it is connected to ground, the lower lid assembly, and the TF flags, and the skirt which supports the centerstack casing, it also is a contributor to the torsional stiffnesses that determine the distribution of the global torques in the machine.The final design of the pedestal is a torsionally stiff concpt that picks up some of the global torque and transfers it through the cell floor to the Vessel Legs. The torques that are carried through the pedistal have been determined only for a few scenarios. The maximum moment found so far is 35463 N-m or 313860 in-lbs

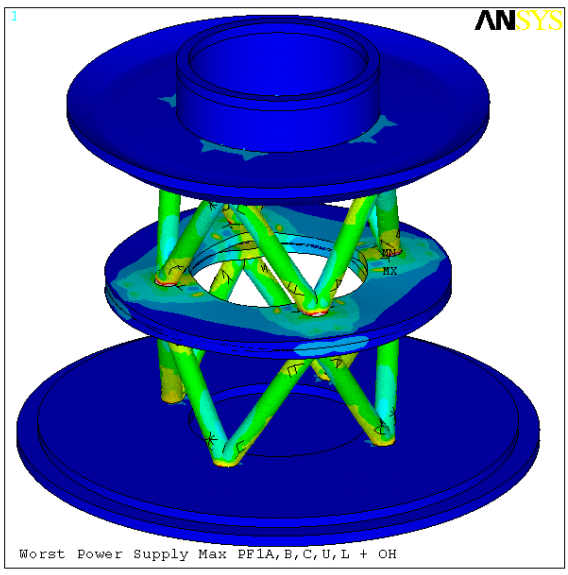


Figure 12.17-2 Representative Pedestal Stress for the Worst Case Power Supply Loads

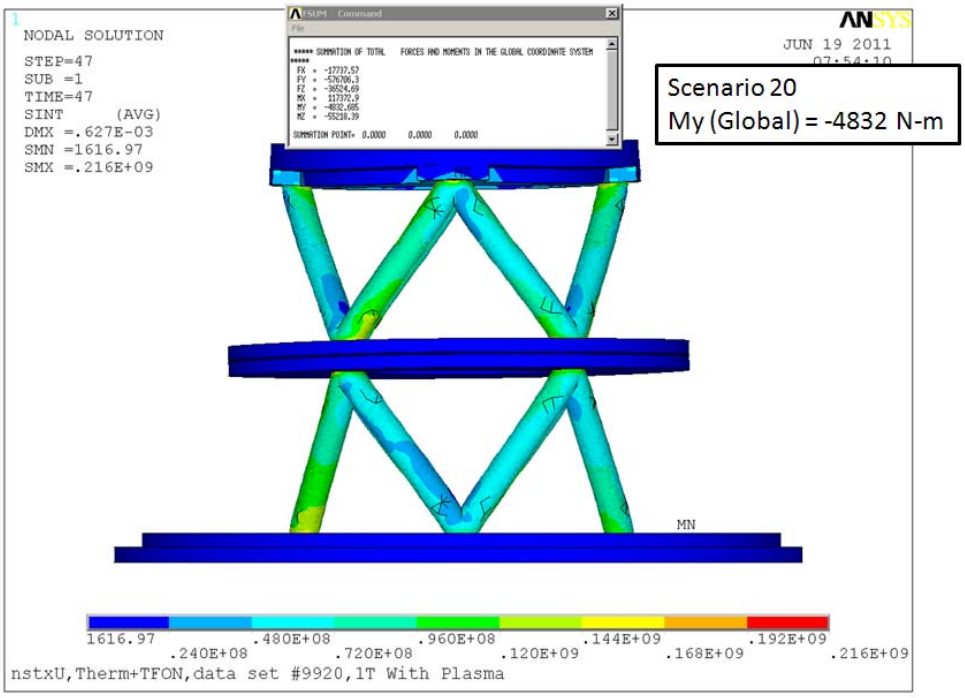


Figure 12.17-3

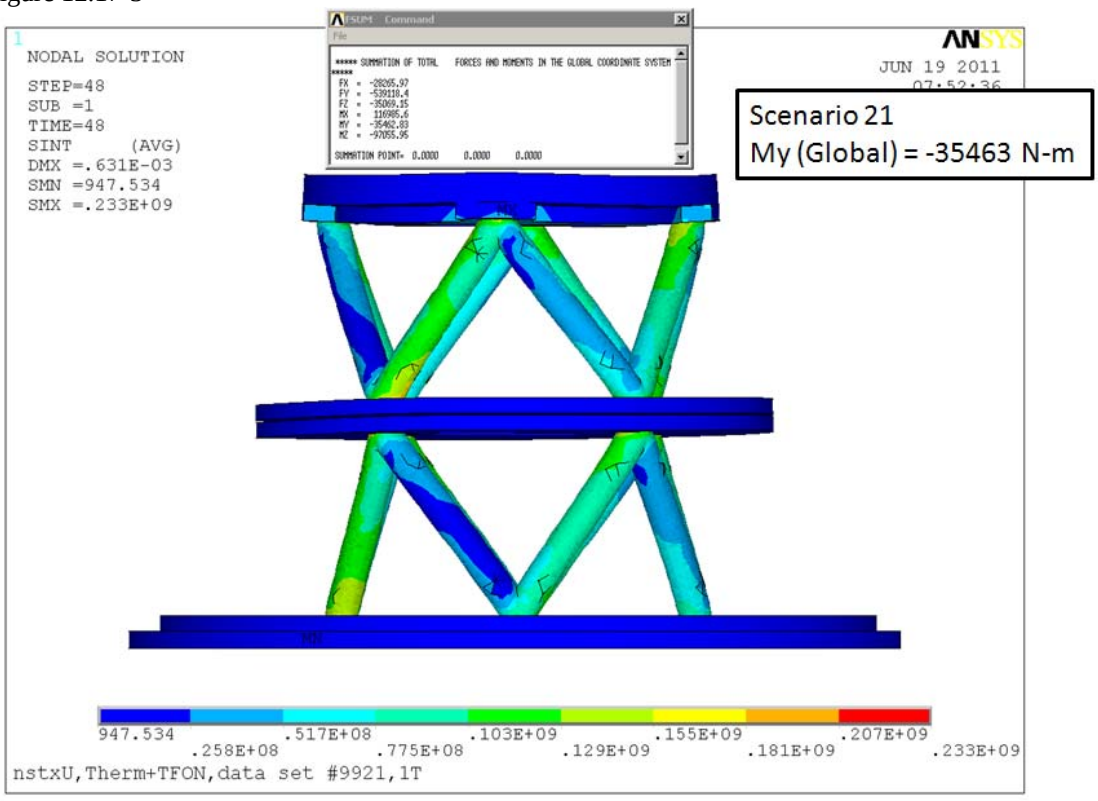
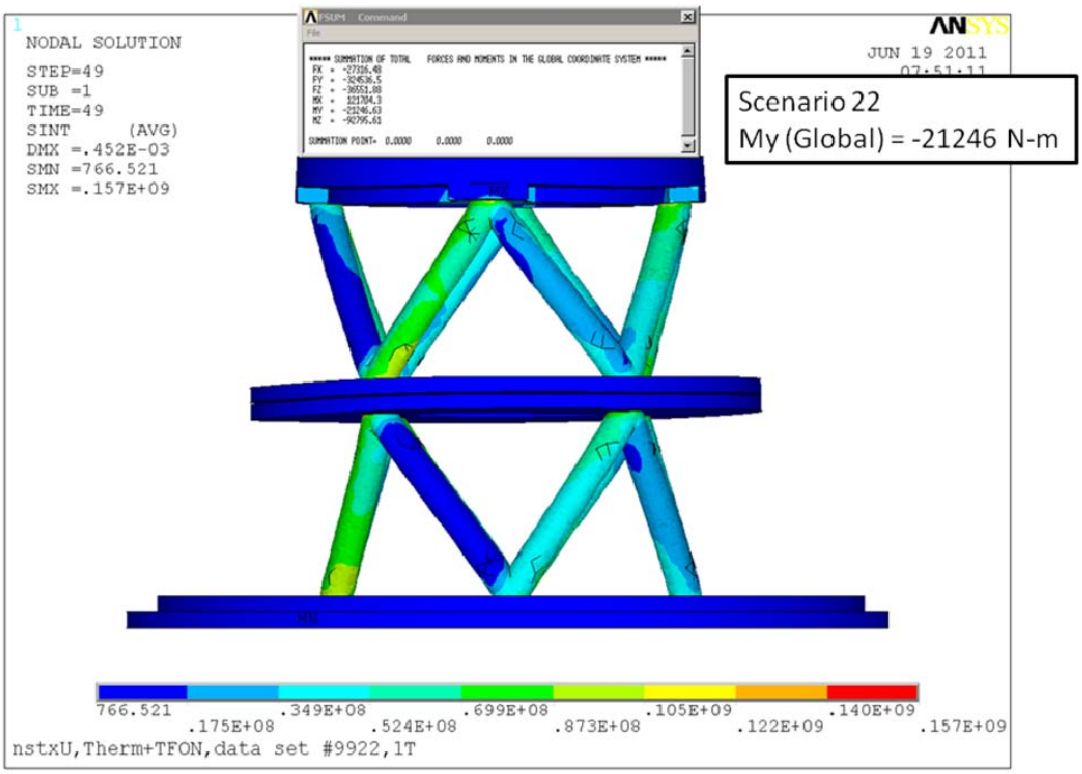


Figure 12.17-4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SUB =1
TIME=49
SINT (AVG)
DMX =.452E-03
SMN =766.521
SMX =.157E+09
JUN 19 2011
Scenario 22
My (Global) = -21246 N-m
766.521
.175E+08
.349E+08
.524E+08
.699E+08
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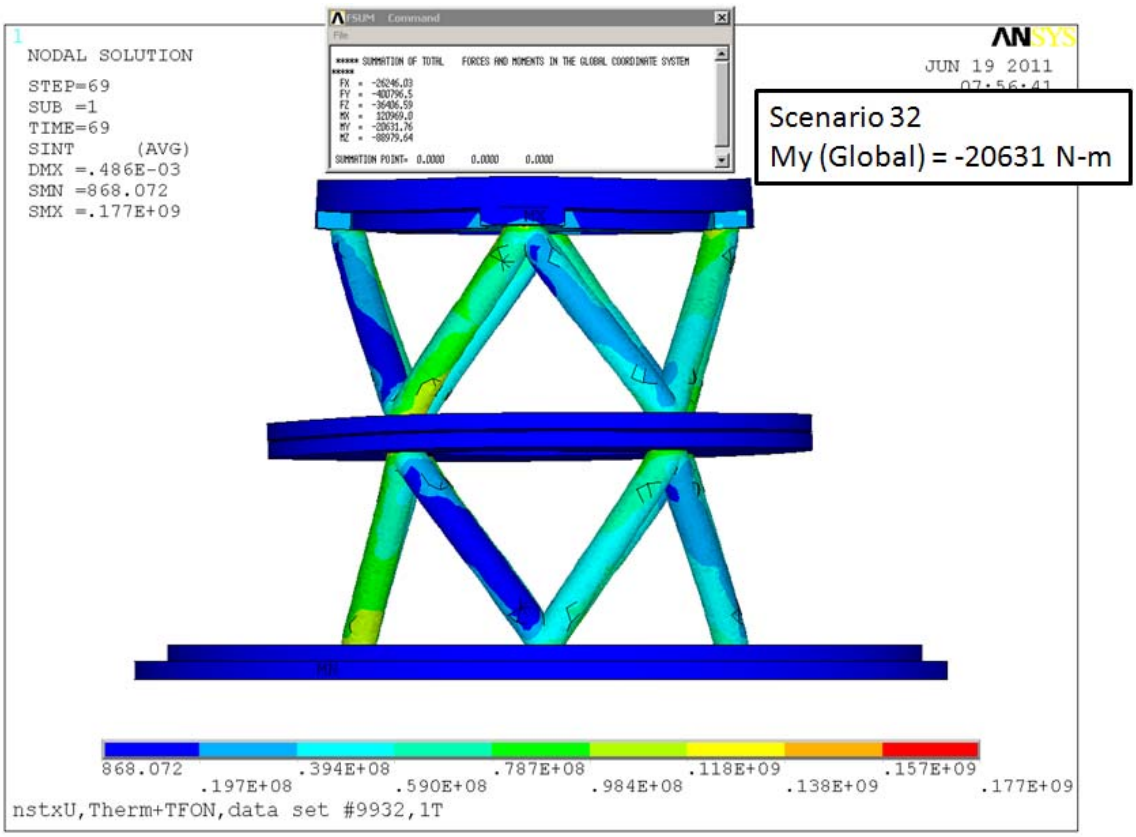
.157E+09
nstxU,Therm+TFON,data set #9922,1T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SUB =1
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DMX =.486E-03
SMN =868.072
SMX =.177E+09
JUN 19 2011
Scenario 32
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.197E+08
.394E+08
.590E+08
.787E+08
.984E+08
.118E+09
.138E+09
.157E+09
.177E+09
nstxU,Therm+TFON,data set #9932,1T

12.18 Halo Current Loading
12.18.1 Halo Loads on the Centerstack Casing

The stiffness of the pedestal and lower lid partially determine where the halo load goes. In the spoked lid calc it is claimed that the pedestal is stiff enough that it will see the halo from the centerstack casing and that the halo load from the passive plates is carried through the spoked lid[23] and reacted at the pedestal[24]. The halo loading (from Art) on the skirt and skirt to pedestal bolting is addressed in the centerstack casing calc: NSTXU-CALC-133-03-00[27], **.** The halo load is tracked more rigorously in the bellows calculation[13]. Judgmentally, if the (upper) bellows can take the centerstack load, the heavier skirt, pedestal, vessel, spoked lid structures will be able to take the load. A. Brooks'[30] and P. Rogoff [13] trade reaction forces at the bellows. The halo loads are dynamic impulsive loads and are treated in a very conservative manner in this global model calculation as static loads - P. Rogoff and A. Brooks reduced the loads by including P. Rogoff's bellows stiffness in the dynamic analysis. In this global model calculation an earlier estimate by A. Brooks of 50,000 lbs is applied on the upper and lower region of the centerstack. This is also the basis for the loads that A. Zolfaghari uses to qualify the TF crown bolting calculation.

```
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esel,mat,8
nelem
nrsel,z,.22,100
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nall
eall
solve
save
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Halo Loads are included in one of the static load cases in the global model run - Figure 12.17-1 shows the earlier pedestal model and the stresses were low, 135 MPa, and are about the same for the pipe truss design.

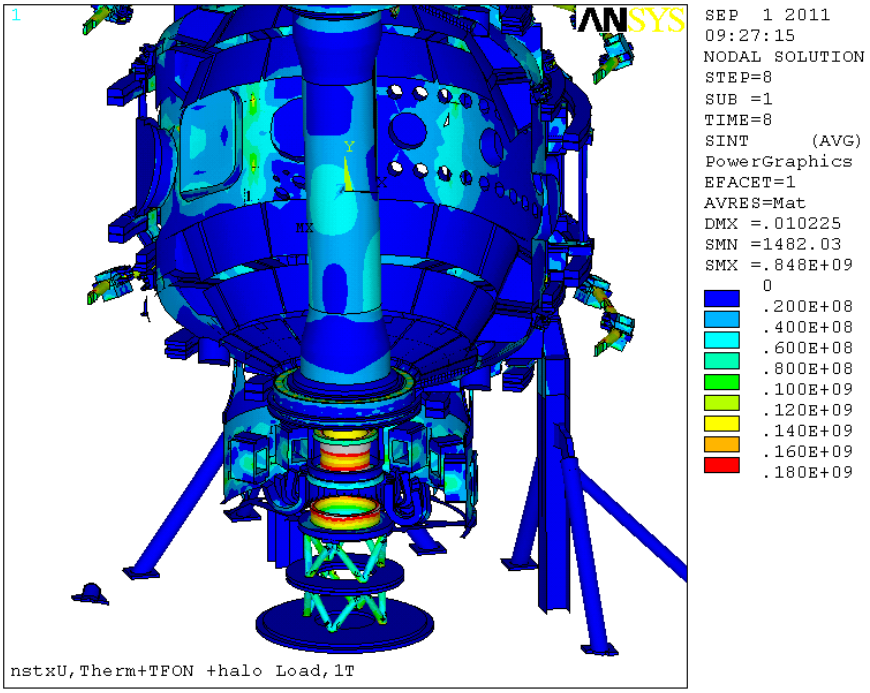


Figure 12.18.1-1 Global Model Results With 50,000lb assumed Halo Load

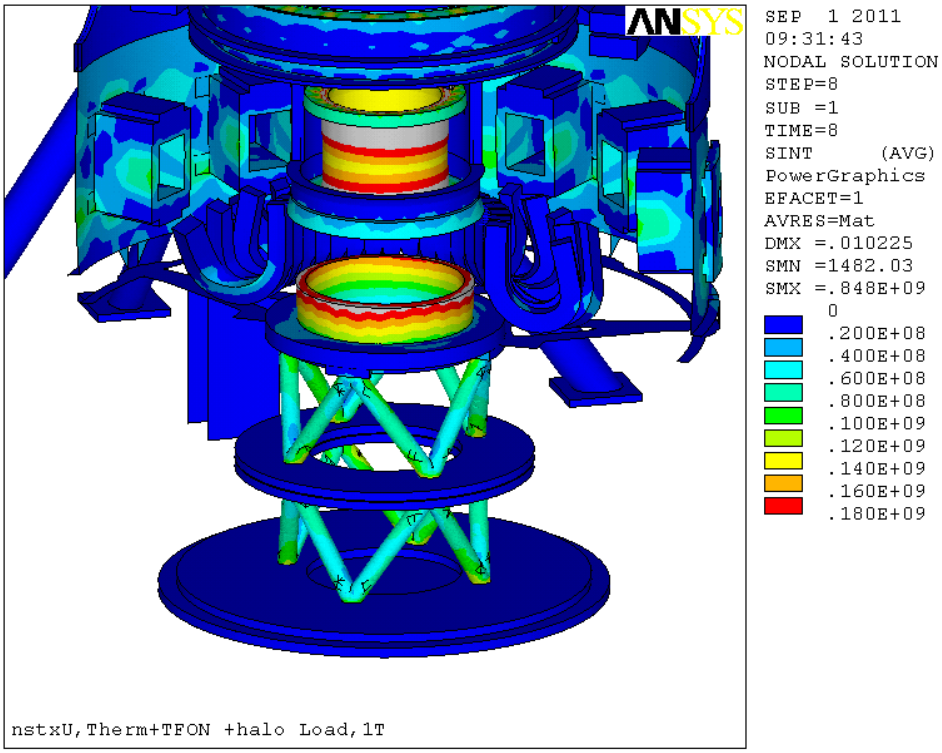


Figure 12.18.1-2 Pedestal Area Global Model Results With 50,000lb assumed Halo Load

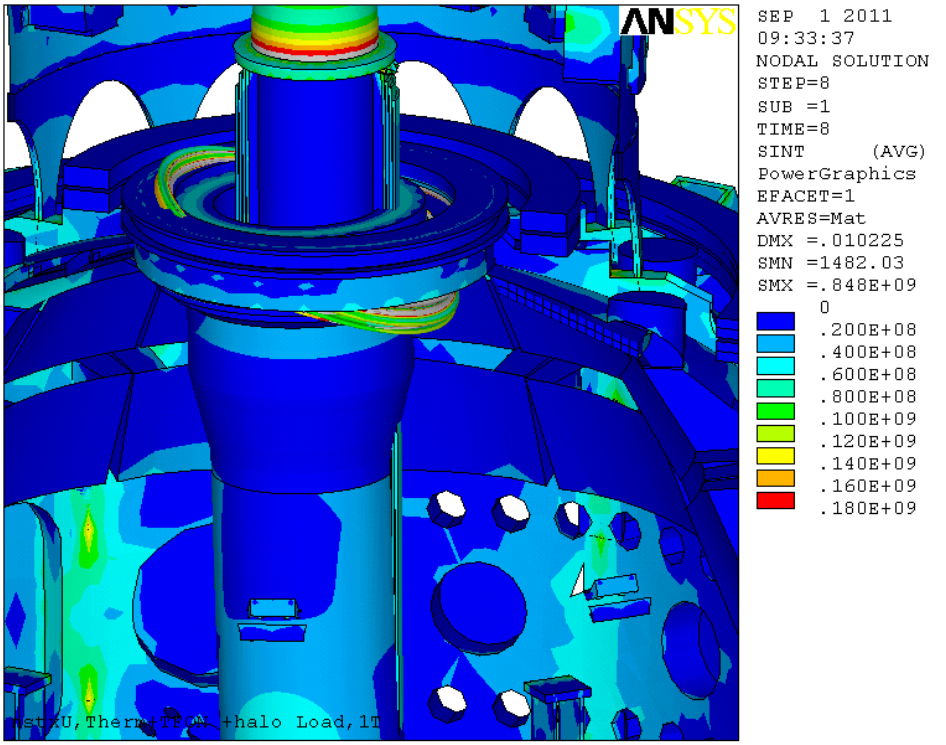


Figure 12.18.1-2 Global Model Upper Bellows Area Results With 50,000lb assumed Halo Load

Based on the stress levels above, Halo loads have the potential of severely loading the upper bellows. This structural interaction is addressed in the two calculations discussed above, [13] and [30]. With dynamic effects appropriately applied bellows loading is acceptable.

13.0 Global Buckling Large Displacement Analysis

Buckling for most of this machine is not represented by Euler or an eigenvalue buckling solution. It would be caused by a bending related collapse. For this, a large displacement solution with load multipliers is recommended. The vacuum vessel is not like a long thin column or a thin un-stiffened shell. It is multiply stiffened, and loaded by global torques and local moments and forces. It's collapse modes will be bending related collapse and not Euler collapse. Bucking is a spectrum of events - from fully elastic buckling to plastic collapse. The formal way to address buckling is to perform an eigenvalue buckling solution to identify the buckling modes. You apply loading as well. From this you get multipliers of the load vector with respect to each mode that would cause collapse. - The response however is non linear - so ANSYS recommends that you take the most critical modes and "perturb" the structure with the mode shape. -then do a large displacement solution to identify the collapse load. To properly identify the collapse load you may have to add elastic-plastic properties if the structure does not collapse elastically, and stresses go above yield. Disruption stresses are significant for the vessel, butr short lived. - so for appropriate rigor we would need to do a dynamic collapse simulation . For many structures and loading types the structure collapses plastically well before it does elastically. - Like a cantelver beam with a large bending load and a small axial load. For this type of structure/load, a static analysis demonstrating margin against yield is sufficient. In a building steel framing analysis, the columns are checked for buckling but the horizontal spans are not. (except local checks of web stiffeners). The ligments between the ports behave as beams limited by plastic collapse, and limiting stresses to well below yield will avoid collapse. But to address all these concerns, a Large displacement analysis has been performed on the global model based on equilibrium #79 loads .

Analysis Features:

- Normal Operating Centerstack Thermal Strain is Included in Steps 1 and kept on in subsequent steps.
- Eigenvalue buckling not performed. – First modes Precipitated by Lorentz Loads, Higher modes precipitated by complex displacements around port details
- NLGEO, ON Geometric non-linearities included. Stiffness matrix is recomputed each load and equilibrium step based on deformation. Loading is not re-computed from deformed shape – i.e. EM loads are based on the undeformed geometry.
- No non-linear materials (Stresses must not go above yield prior to reaching twice the load) – This may need to be corrected.

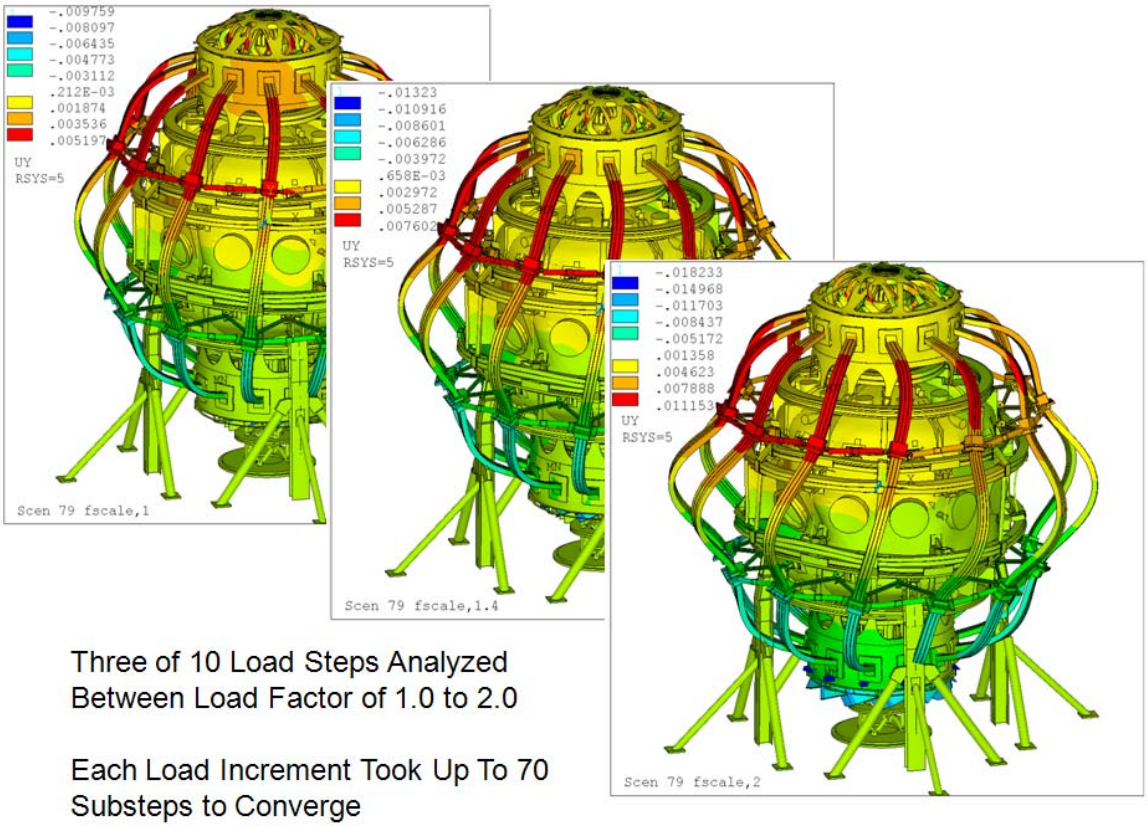


Figure 13.1

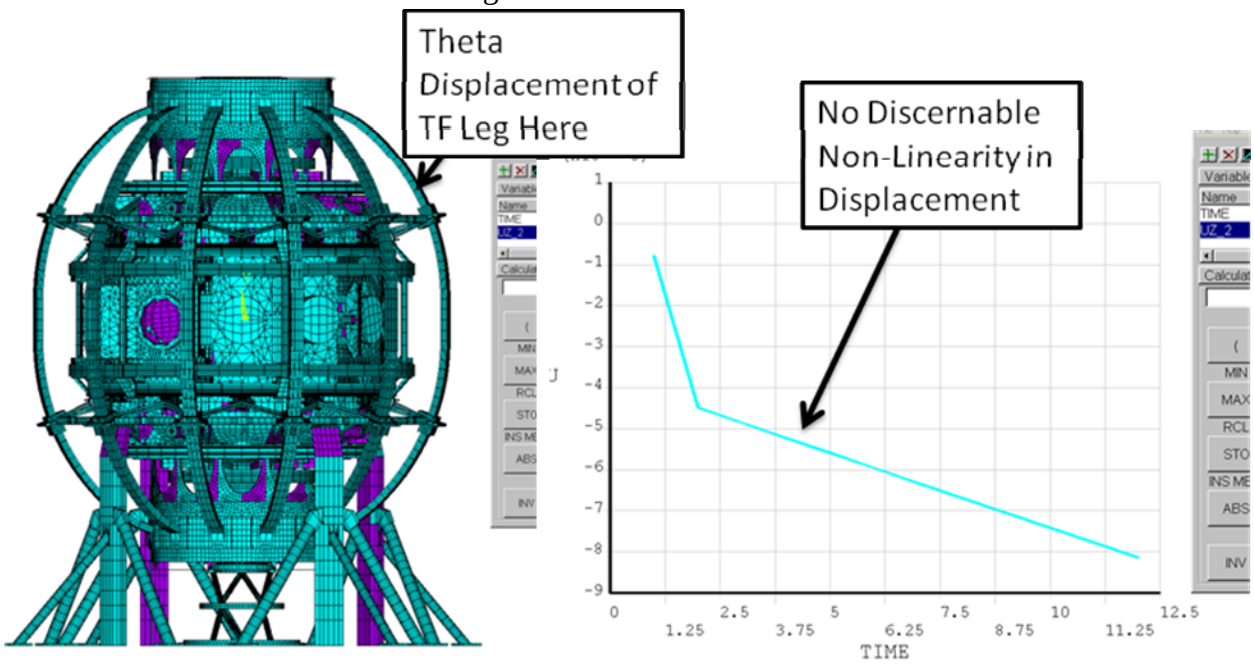


Figure 13.2

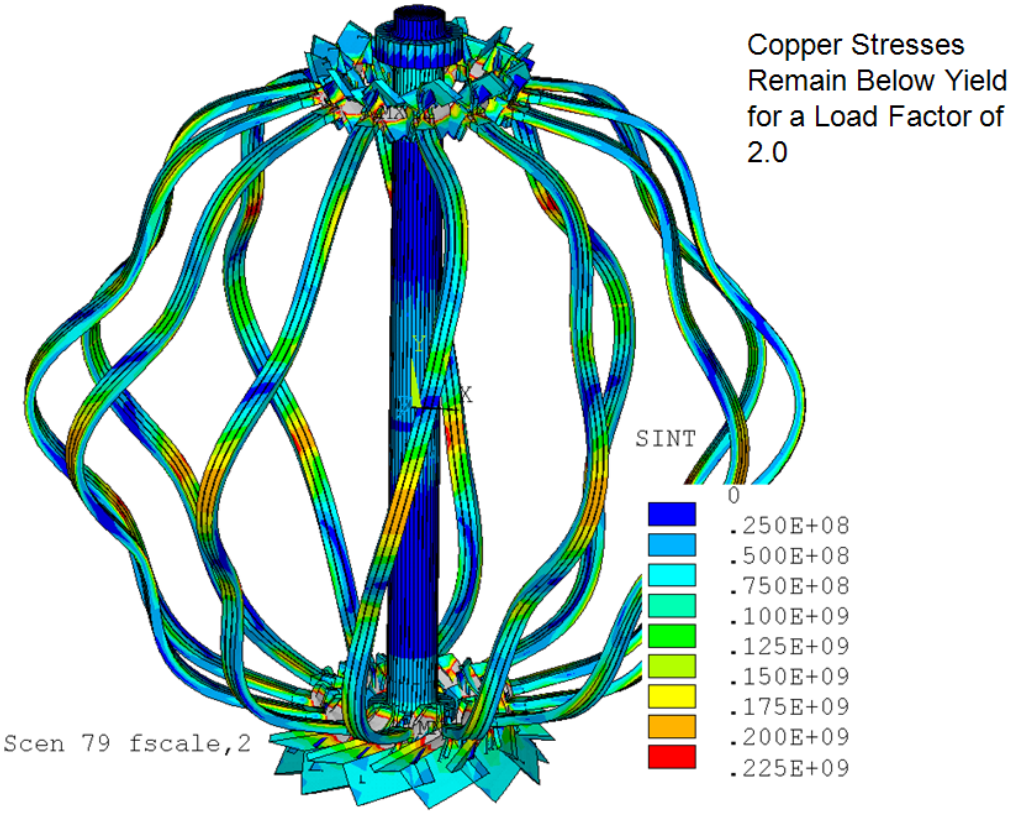
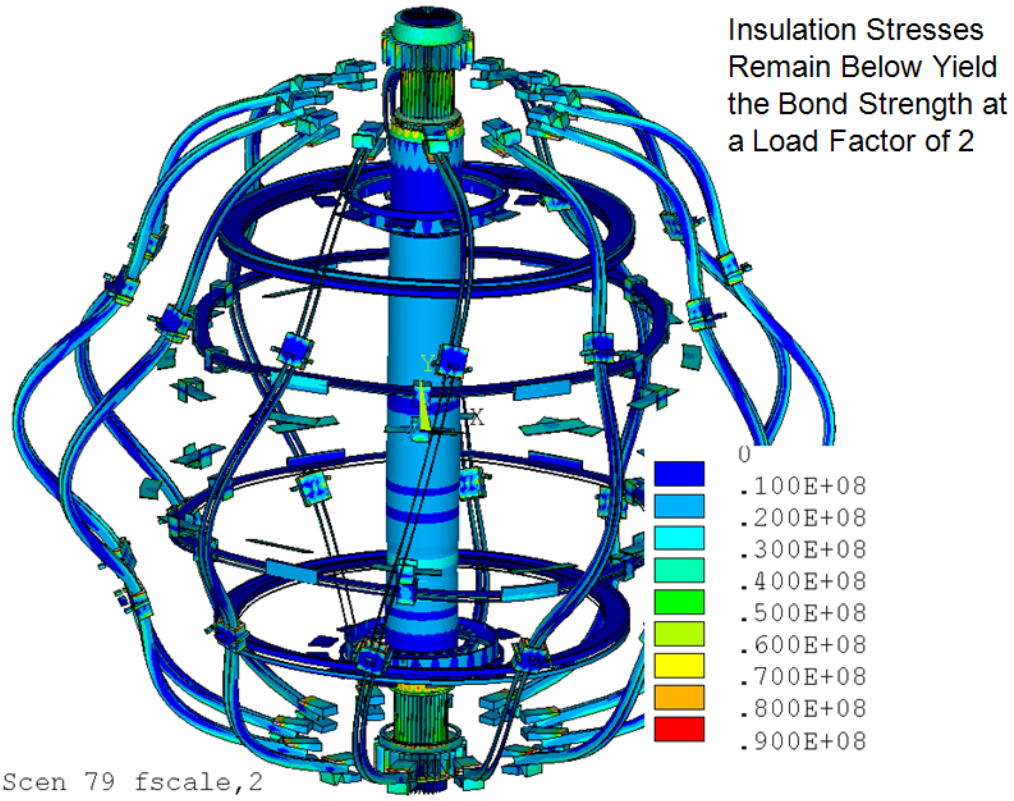

Copper Stresses
Remain Below Yield
for a Load Factor of
2.0
SINT
0
.250E+08
.500E+08
.750E+08
.100E+09
.125E+09
.150E+09
.175E+09
.200E+09
.225E+09
Scen 79 fscale,2

Figure 13.3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the Bond Strength at
a Load Factor of 2
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.900E+08
Scen 79 fscale,2

Figure 13.4

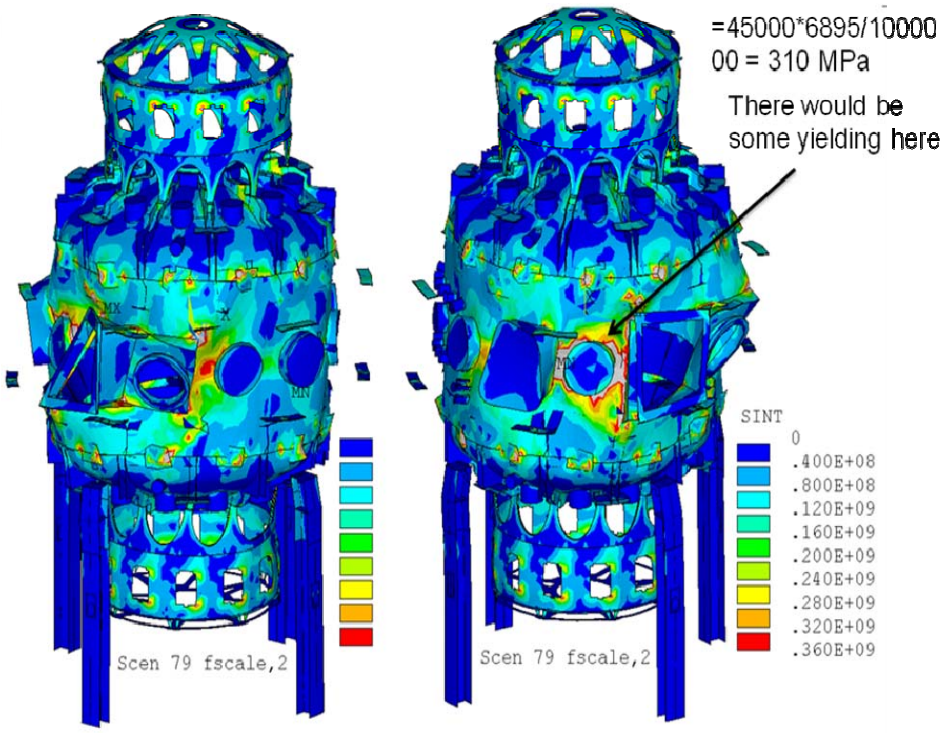
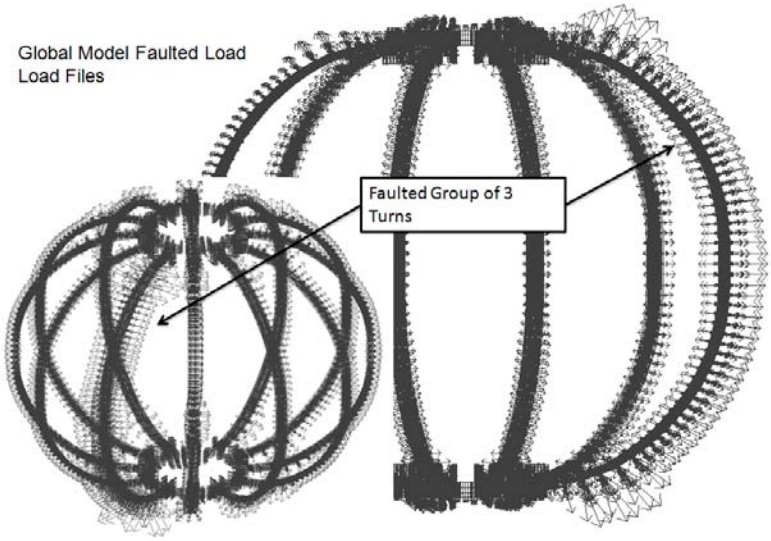
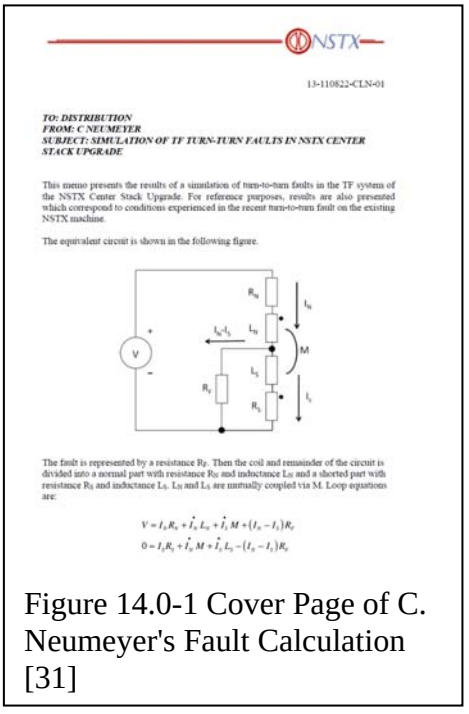


Figure 13.5

14.0 Fault Analyses

C. Neumeyer has provided the circuit simulations from which to compute the loads [31]. Only 3 turns shorted has been analyzed. 3 Turns are assumed in the same coil. 1 turn and 18 turn shorts have not been analyzed. Charging fault max load case is assumed the be the end of fault with max TF and max negative shorted coil currents. Inversion fault has been treated with two time points. All TF stresses are within normal allowables. Faults are survivable.




NSTX

13-110822-CLN-01

TO: DISTRIBUTION
FROM: C NEUMEYER
SUBJECT: SIMULATION OF TF TURN-TURN FAULTS IN NSTX CENTER STACK UPGRADE

This memo presents the results of a simulation of turn-to-turn faults in the TF system of the NSTX Center Stack Upgrade. For reference purposes, results are also presented which correspond to conditions experienced in the recent turn-to-turn fault on the existing NSTX machine.

The equivalent circuit is shown in the following figure.

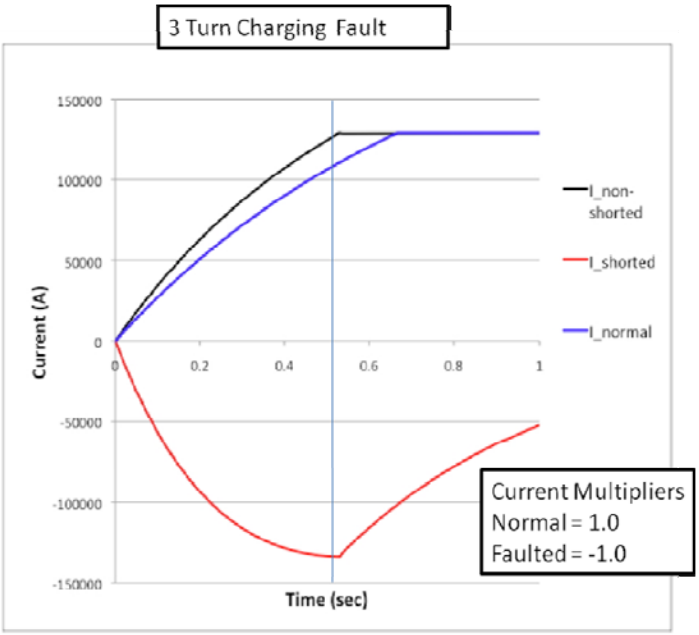
The fault is represented by a resistance R_F. Then the coil and remainder of the circuit is divided into a normal part with resistance R_N and inductance L_N and a shorted part with resistance R_S and inductance L_S. L_N and L_S are mutually coupled via M. Loop equations are:

$$V = I_N R_N + \dot{I}_N L_N + \dot{I}_S M + (I_N - I_S) R_F$$
$$0 = I_S R_S + \dot{I}_S M + \dot{I}_S L_S - (I_N - I_S) R_F$$

Figure 14.0-1 Cover Page of C. Neumeyer's Fault Calculation [31]

Figure 14.0-2 Representative Lorentz Force Calculation of coil over loads done by selecting the faulted coils or turns and scaling the real constants

14.1Charging Fault



3 Turns Shorted During Charging

Figure 14.1-1 Current Profiles for the 3 Turn Charging Fault from ref [31]

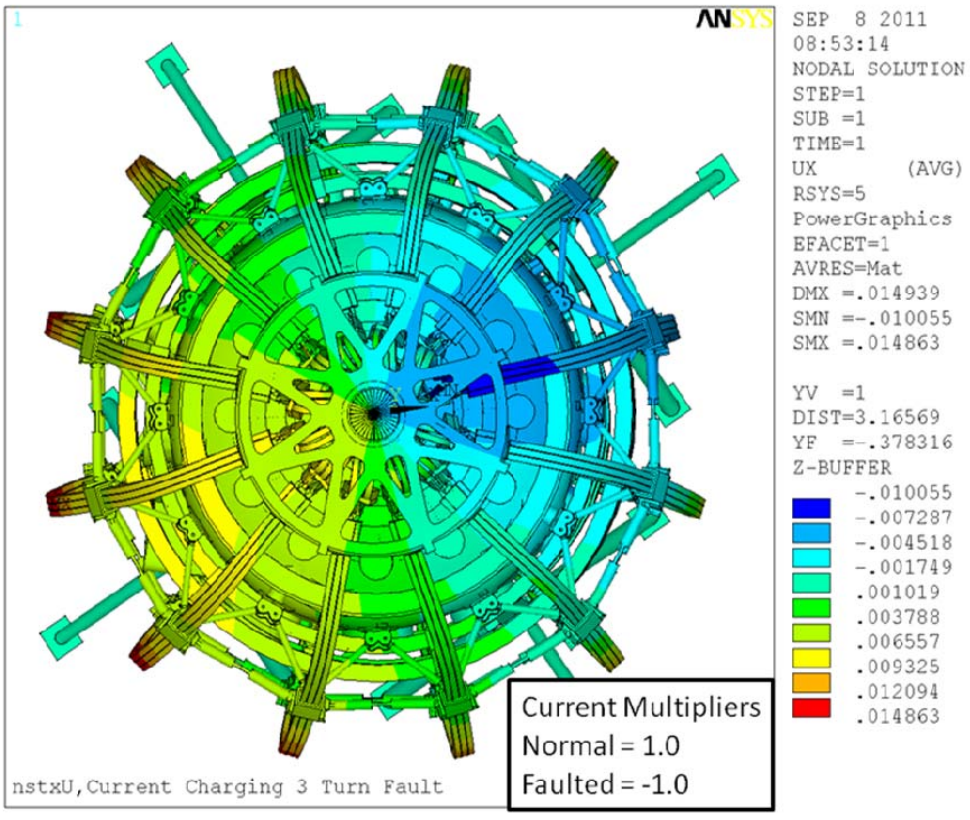


Figure 14.1-2 Radial Displacement for the 3 Turn Charging Fault from ref [31]

In this figure the "collapsed" radial displacement shape of the single outer leg is evident. During TF charge, If one coil is shorted, it develops negative currents that attempt to inductively resist the increase in currents in the other coils. In this case, the clear worst case is the end of the current charge when all the coils including the shorted TF leg are at full current and full field. Only one load case is considered for the structural analysis of this fault.

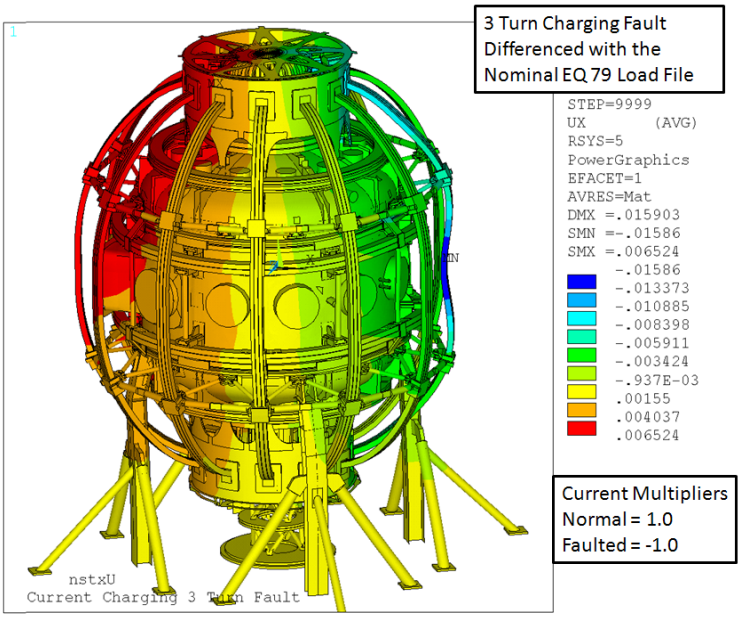


Figure 14.1-3 Radial Displacement for the 3 Turn Charging Fault Plotted as a Difference Between the Fault Load Step and the Nominal EQ79 Load Step

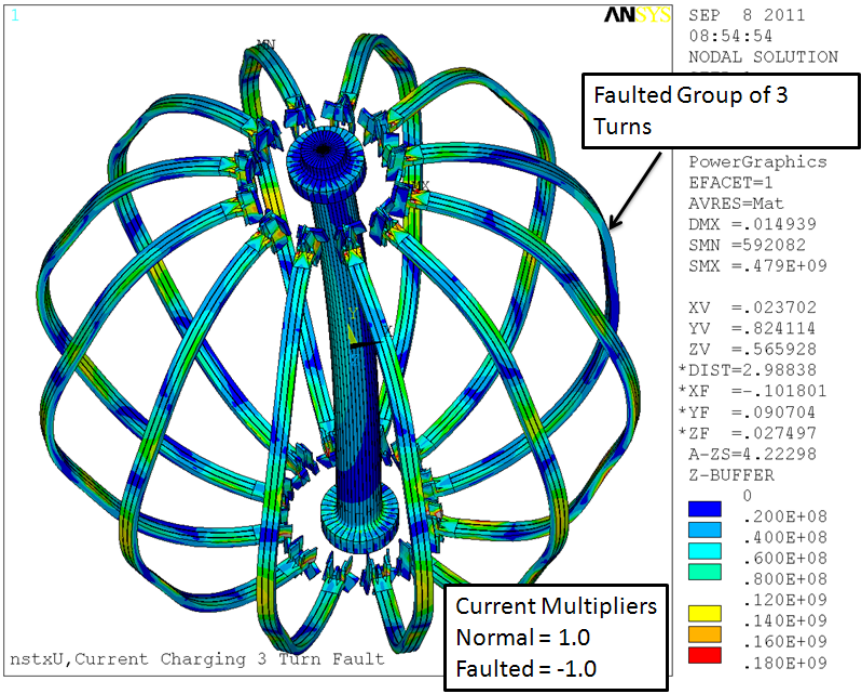


Figure 14.1-4 Coil Tresca Stress for the 3 Turn Charging Fault Plotted as a Difference Between the Fault Load Step and the Nominal EQ79 Load Step

14.2Inversion Fault

A short when the TF currents are being driven down will cause the currents in the shorted TF to increase. It is uncertain when the coil or structure stresses will be at a maximum in this case because there needs to be some significant currents in the un shorted coils along with the over-current in the shorted coil, to prorduce the largest Lorentz forces. For the structural analysis, two time points are chosen. The first is early in the fault with load multipliers of 1.356 for the faulted current and0 .62 for the un-shorted coils.

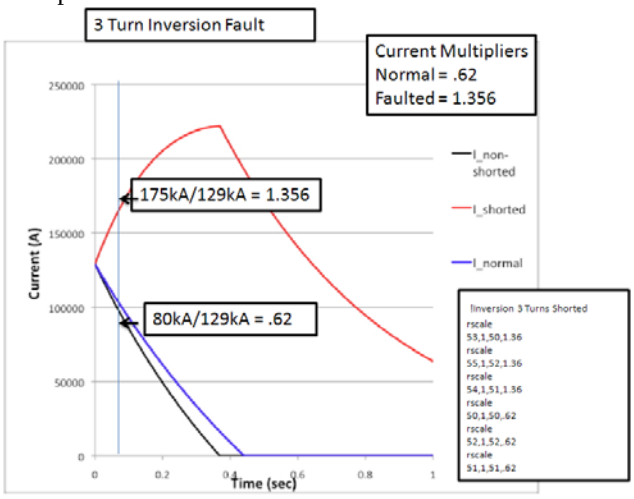


Figure 14.2-1 Current Profiles for the 3 Turn Inversion Fault from ref [31]

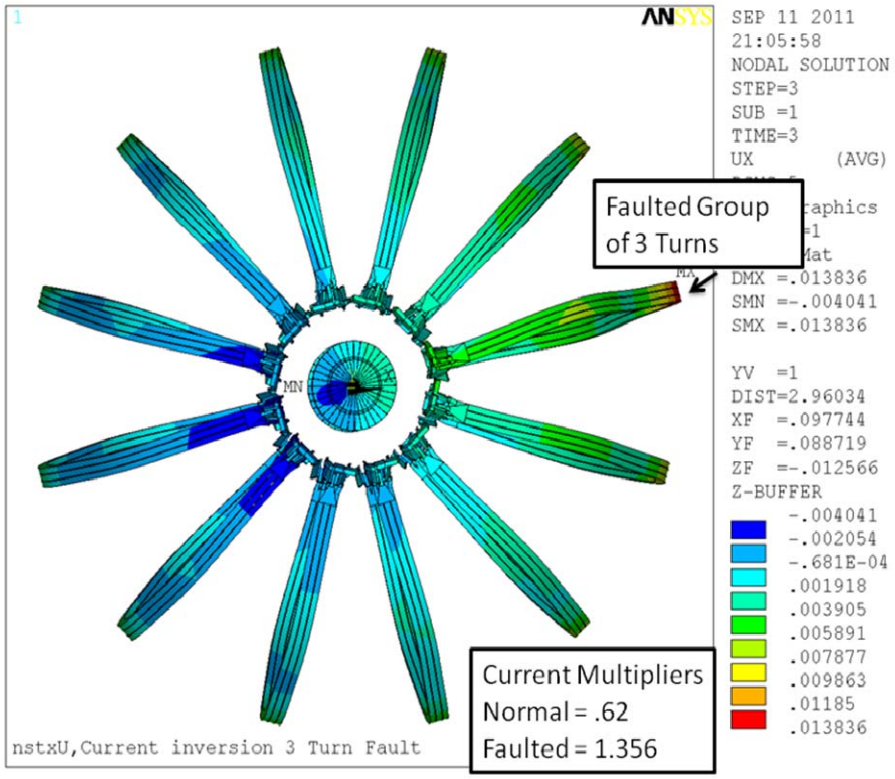


Figure 14.2-2 Radial Displacement for the 3 Turn Inversion Fault from ref [31

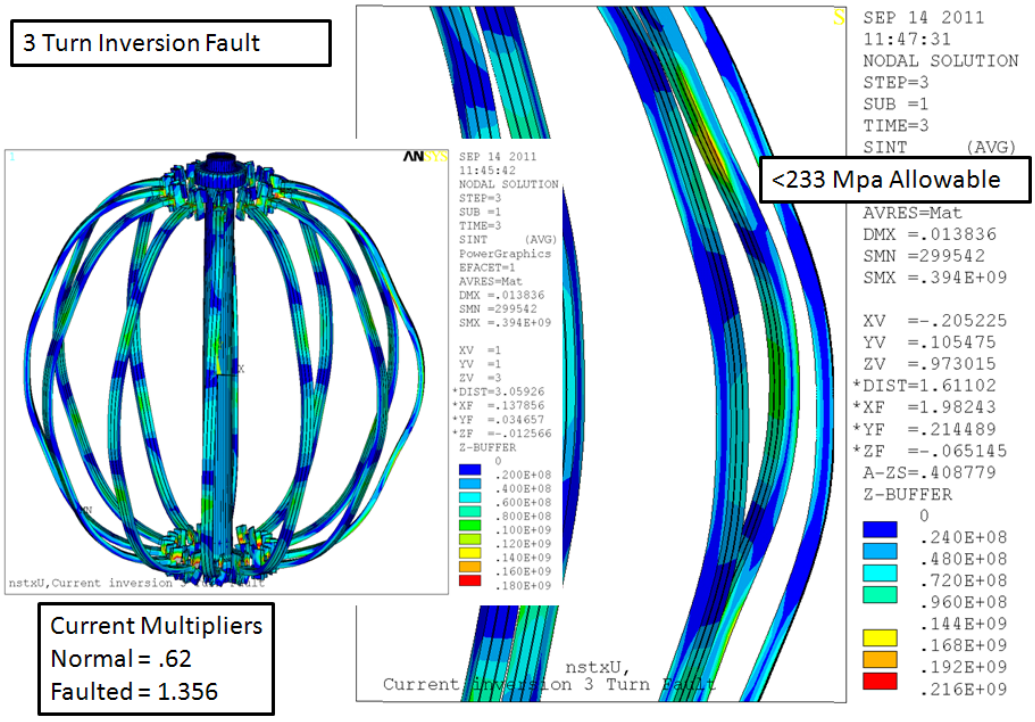


Figure 14.2-3 TF Stresses at the Beginning of the Three Turn Inversion Fault

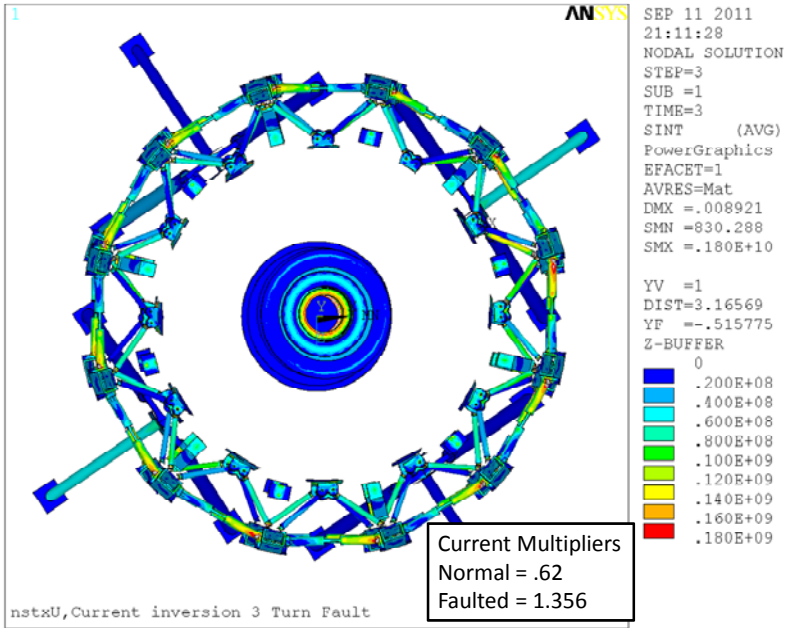


Figure 14.2-4-Outer TF Support Hardware for the 3 Turn Inversion Fault from ref [31

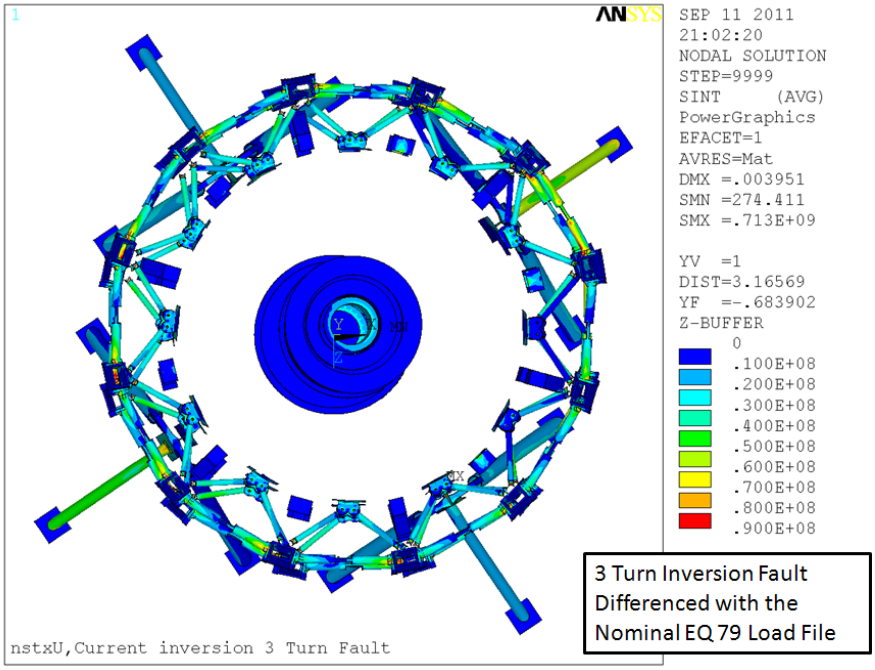


Figure 14.2-5Outer TF Support Hardware for the 3 Turn Inversion Fault from ref [31]

This plot is for load step 1 subtracted from load step 3 and shows the increase in stress for the 3Turn inversion fault for the .62 and 1.356 load multipliers shown in figure 14.2-1 and 3.

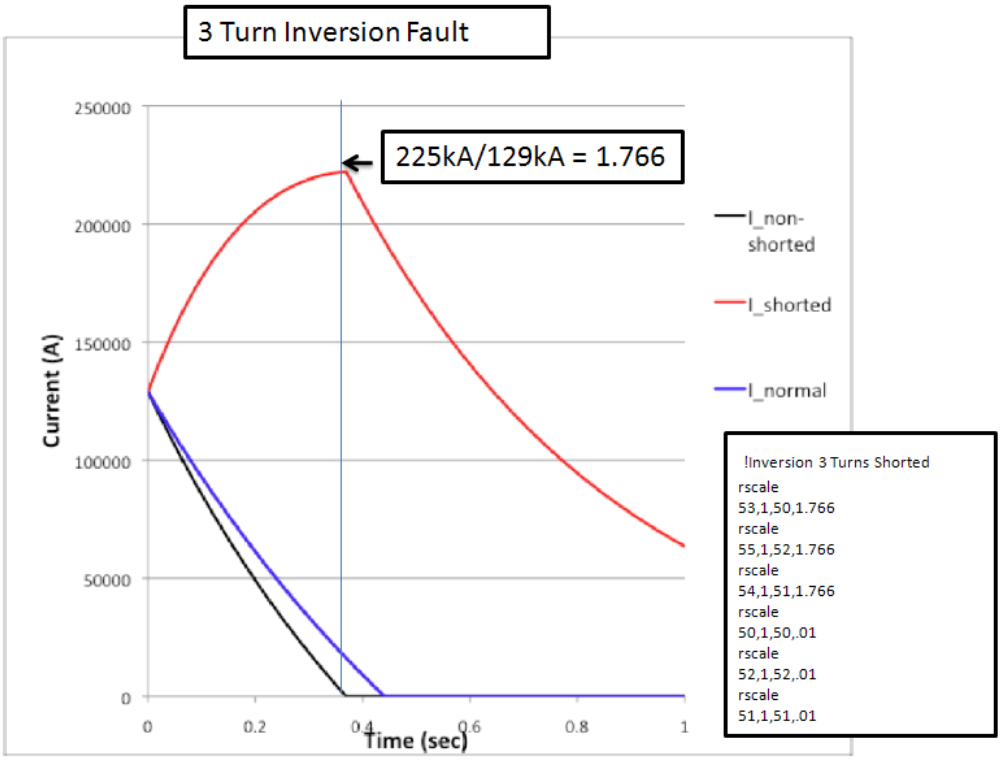


Figure 14.2-6-Currents for the 3 Turn Inversion Fault from ref [31]

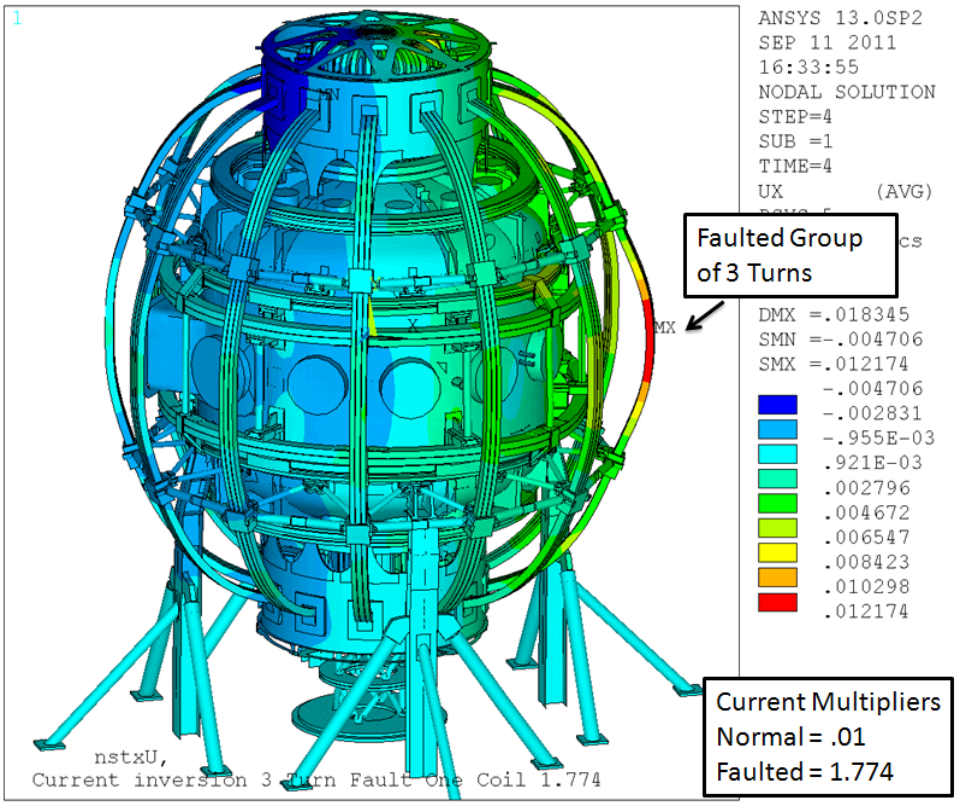


Figure 14.2-7-Faulted Coil Radial Displacements for the End of the Fault Event

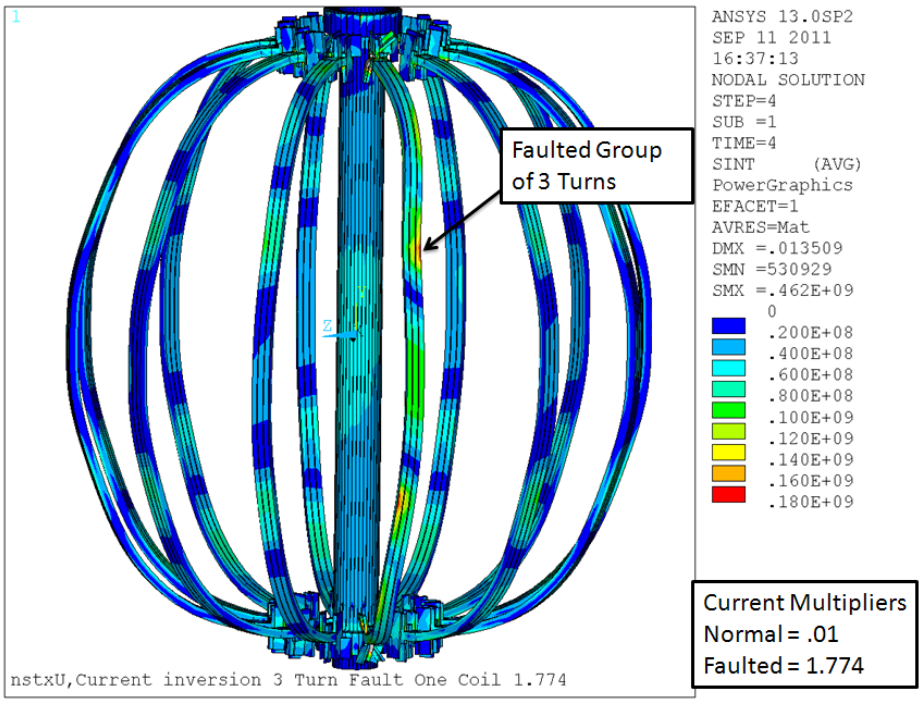


Figure 14.2-8-Faulted Coil Stress for the 3 turn Inversion - End of the Fault

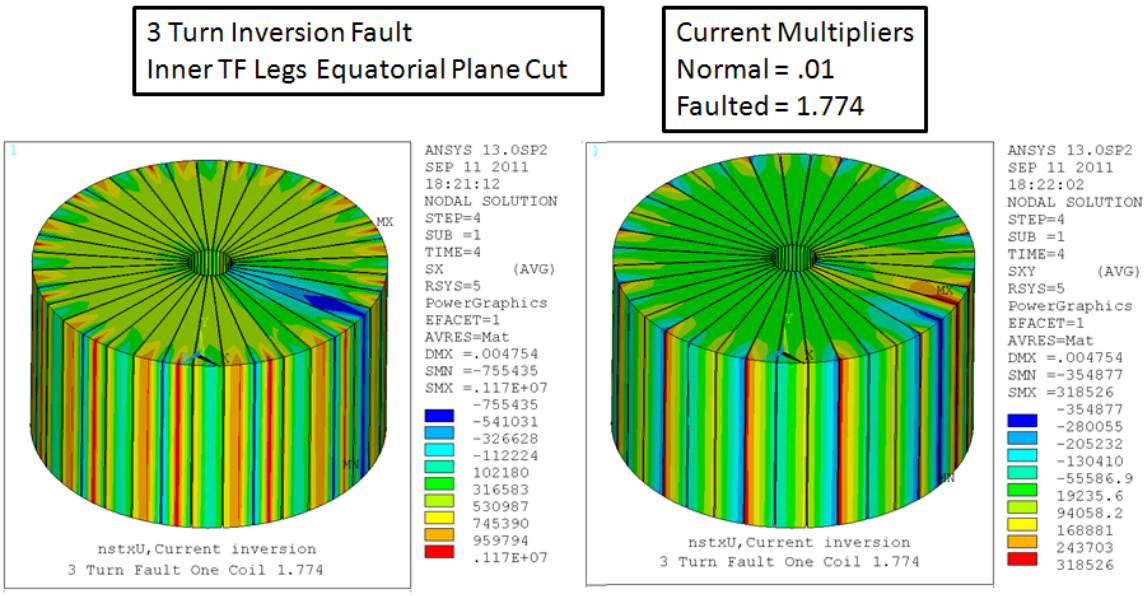


Figure 14.2-9-TF Inner Leg Column Stresses at the End of the Inversion 3 turn shorted Fault

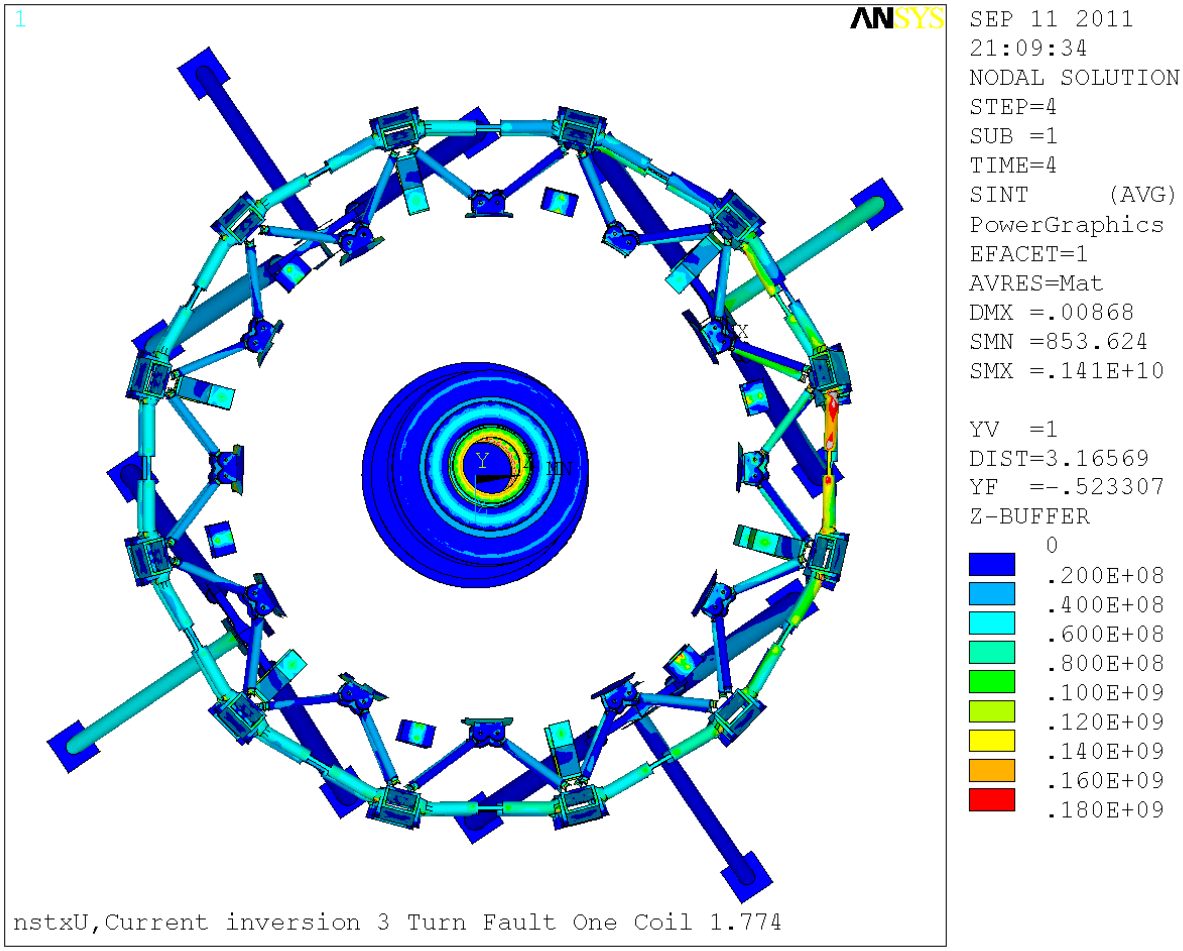
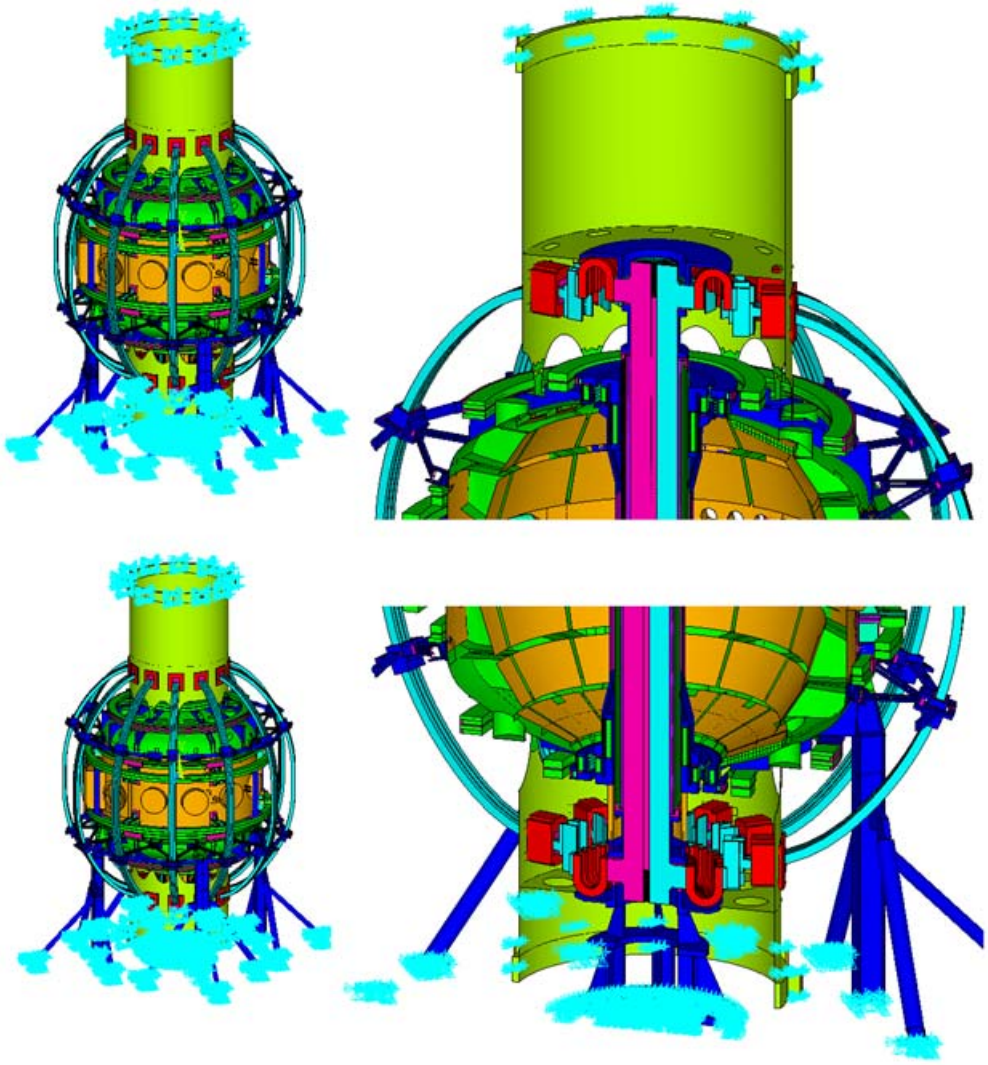
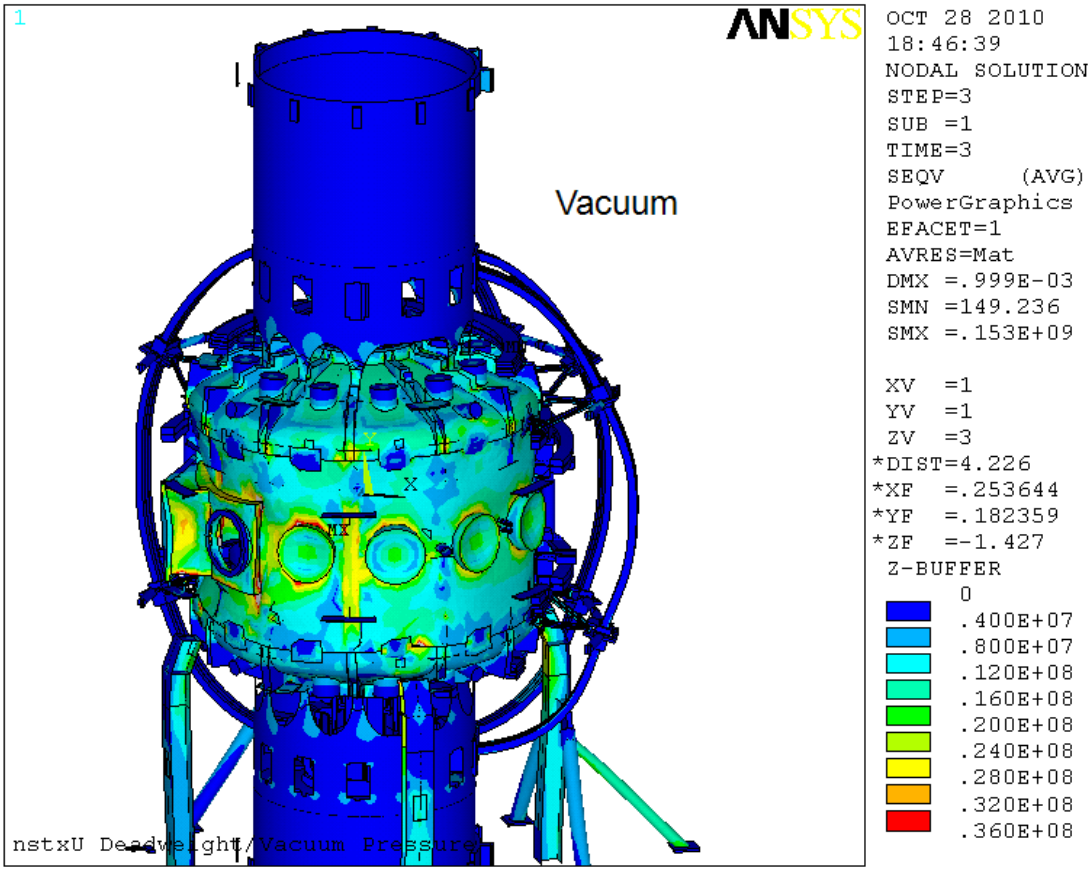
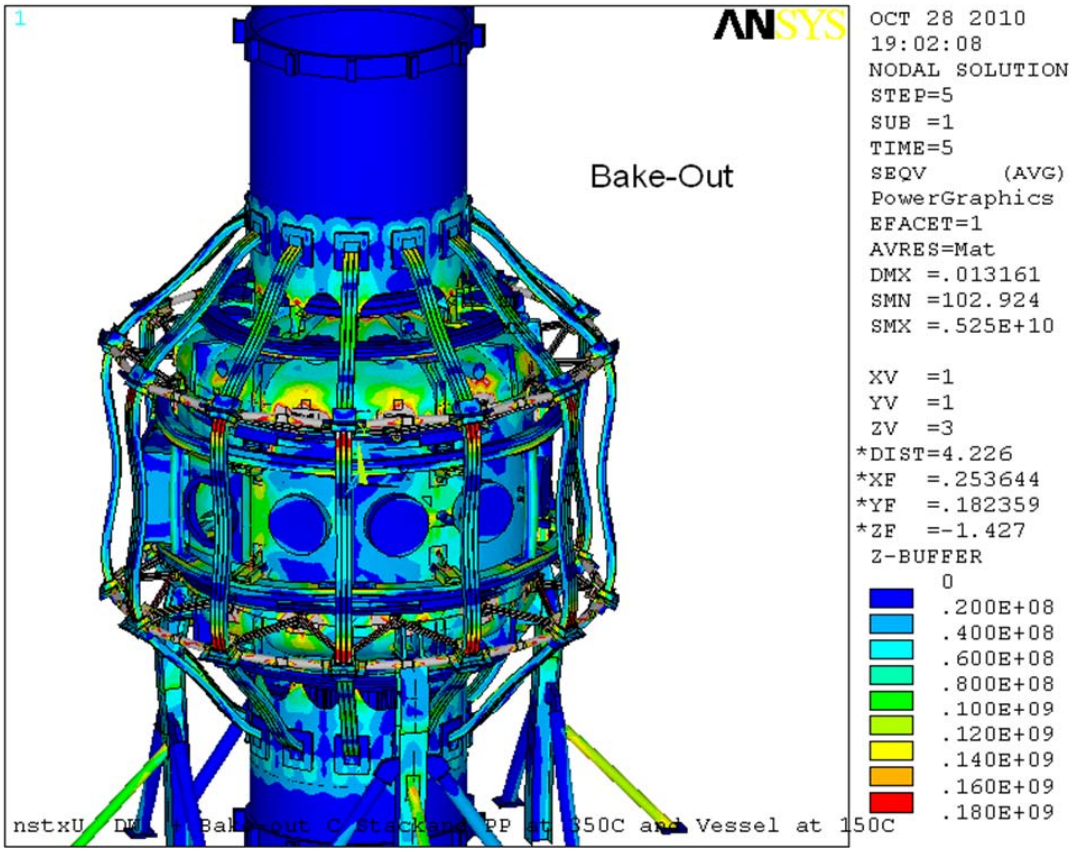


Figure 14.2-10-TF Outer TF Support Hardware Stresses at the End of the Inversion 3 turn shorted Fault

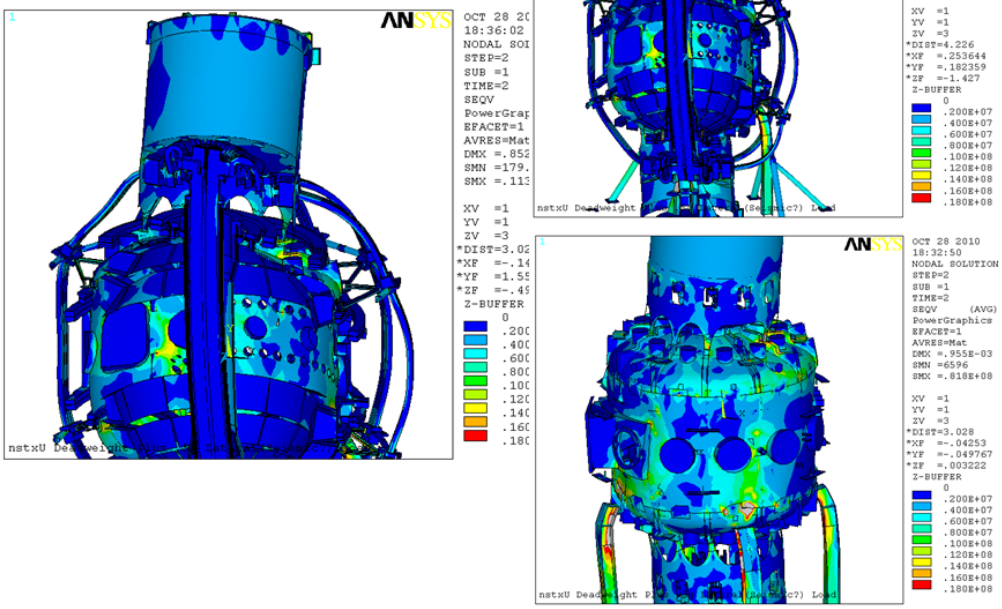
Appendix A
"Top Hat" Torque Restraint Analysis




1
ANSYS
Vacuum
nstxU Deadweight/Vacuum Pressure
OCT 28 2010
18:46:39
NODAL SOLUTION
STEP=3
SUB =1
TIME=3
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.999E-03
SMN =149.236
SMX =.153E+09
XV =1
YV =1
ZV =3
*DIST=4.226
*XF =.253644
*YF =.182359
*ZF =-1.427
Z-BUFFER
0
.400E+07
.800E+07
.120E+08
.160E+08
.200E+08
.240E+08
.280E+08
.320E+08
.360E+08

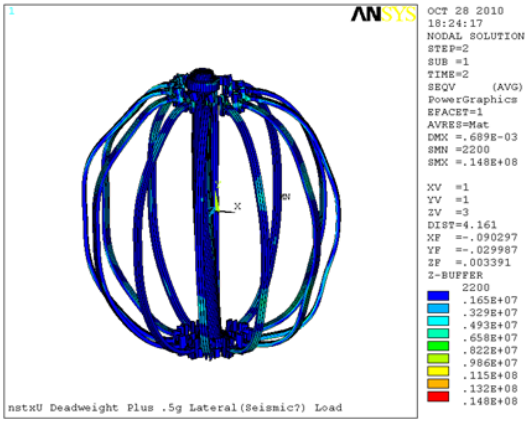


Seismic – 0.5g Lateral Inertia Load

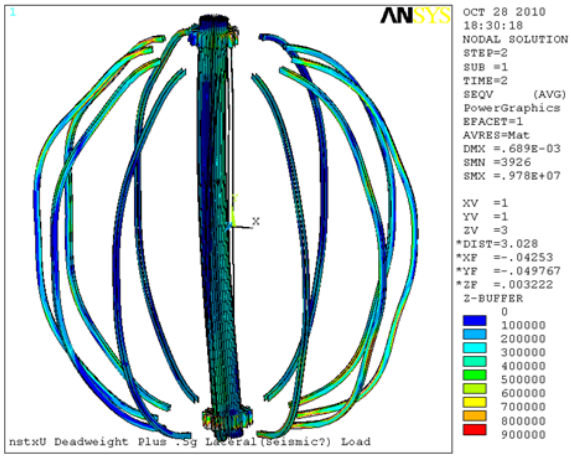


Seismic – 0.5g Lateral Inertia Load

Conductor Stress



Insulation Stress



Attachment B Emails

From: Tom Willard
Sent: Friday, August 14, 2009 1:06 PM
To: Han Zhang
Subject: RE: do you have the stiffness data for arch of TF coil from Tom's result?

Han,

The flex assembly rotates 2.57 degrees with a torque of 100 in-lbf applied.

Tom

-----Original Message-----
From: Tom Willard
Sent: Friday, August 14, 2009 1:25 PM
To: Han Zhang
Subject: RE: do you have the stiffness data for arch of TF coil from Tom's result?

Han,

The force required to deflect the 31 lamination assembly .3" vertically is 76.2 lbf.

Tom

-----Original Message-----
From: Han Zhang
Sent: Friday, August 14, 2009 11:11 AM
To: Tom Willard
Subject: RE: do you have the stiffness data for arch of TF coil from Tom's result?

Thank you for the reply.

If you can give me the OOP bending result, it will be better. I am still thinking about how to use them in my model (how to convert to the stiffness in my model).

Thanks a lot,
Han.

-----Original Message-----
From: Tom Willard
Sent: Friday, August 14, 2009 9:57 AM
To: Han Zhang
Subject: RE: do you have the stiffness data for arch of TF coil from Tom's result?

Han,

The MathCAD-calculated force required to deflect the baseline-design (38x .060" thick laminations) strap assembly vertically .3" (CS thermal displacement) is 60.85 lbf. The force required to deflect the optimized design (12x .090" thick laminations plus 19x .060" laminations) the same distance is approximately 85 lbf. If you give me a half hour, I'll give you a more exact answer. Also, if you need OOP bending or torsional stiffness let me know and I'll run a ANSYS model of the strap assembly. These results assume no interaction between the laminations (no contact).

Tom

-----Original Message-----
From: Han Zhang
Sent: Friday, August 14, 2009 9:26 AM
To: Peter Titus; Tom Willard
Subject: do you have the stiffness data for arch of TF coil from Tom's result?

Pete, do you have the stiffness data for arch of TF coil from Tom's result? I can modify the inductance model and run again over weekend to get new result?

Tom, could you give me the stiffness data for the arch of TF coil? My model now is still using 2 solid copper arches. Your model the arch with many strips and the stiffness result seems different. I can give you the current density result from my EM transient analysis but don't know which time point and which format you need. Also because in my model I use solid copper for the arch and then the pressure for the two contact areas are different and the current distribution at the contact areas will not be accurate.

Thanks,
Han.

Pete, some thoughts:

1) Plasma on/off

We are using two shapes now (per R. Hatcher memo). One is circular with major radius equal to R0 and minor radius equal to a, with R0 and a given on the DP web site "Physics" link. R0=0.934m and a=0.570m. The outer boundary of the shaped one is defined as follows as follows:

r(theta)= R0+a*cos(theta+delta*sin(theta))
z(theta)=kappa*a*sin(theta)

Here theta is the poloidal angle 0 to 360 degrees, delta is the triangularity equal to 0.3 per the DP web site, and kappa is the elongation equal to 2.5 per the DP web site.

Unfortunately as Ron discovered, neither of these plasma models seems to consistently produce a worst case condition, depending on what you are looking at. Can you run cases with each (ouch!). Or you may see a pattern which allows you to pick one or the other, depending on what you are looking at. If it helps I have attached bar graphs showing comparison of the cases for all of the coil forces and coil force combos.

2) Current shifts

What I did on the DP spreadsheet was to first determine the worst cases shifts, and then apply them to each of the 96 cases, without plasma (since we are talking post-disruption). Again, I performed this exercise for both the circular and shaped cases and then took the overall max of the force magnitudes from each. If you look at the DP spreadsheet "Disrupt_Circ" and "Disrupt_Shaped" you can see the derivation of the current shifts. I've copy/pasted them on to the the attached so you can compare. One possibility would be to take the worst from each (which I did in the third column of the attached).

3) Normal headroom

Here I simply apply a 10% factor on all currents from the 96 cases except for OH.

Sorry this is so complicated. We can meet and discuss if you like.

Have a good weekend,

Chas/

Appendix C

Subroutine that Converts Terminal Currents to 33 Coil Segment Real Constants

```
      if (com.eq.'nstx') then
      print*, 'Reading Scenario Data'
c      read(inp,*) numcoils
      read(inp,*) nstart
       do 50,j=1,96

        read(inp,*) num,rnstx(1,j),rnstx(2,j),rnstx(3,j),rnstx(4,j),
     crnstx(5,j),rnstx(6,j),rnstx(7,j),rnstx(8,j),rnstx(9,j),
     crnstx(10,j),rnstx(11,j),rnstx(12,j),rnstx(13,j)           !,rnstx(14,j)

        print *,num, rnstx(1,j),rnstx(2,j),rnstx(3,j),rnstx(4,j),
     crnstx(5,j),rnstx(6,j),rnstx(7,j),rnstx(8,j),rnstx(9,j),
     crnstx(10,j),rnstx(11,j),rnstx(12,j),rnstx(13,j)            !,rnstx(14,j)
   50 Continue


      do 60,j=1,96
      rnstcur(1,j)=rnstx(13,j)*221/1e6                    !1 OH
      rnstcur(2,j)=rnstx(13,j)*221/1e3                    !2 OH
      rnstcur(3,j)=rnstx(13,j)*221/1e3                    !3 OH
      rnstcur(4,j)=rnstx(13,j)*221/1e3                    !4 OH
      rnstcur(5,j)=rnstx(1,j)*64/1e3                      !5 PF1aU
      rnstcur(6,j)=rnstx(2,j)*32/1e3                      !6 PF1bU
      rnstcur(7,j)=rnstx(3,j)*20/1e3                      !7 PF1cU
      rnstcur(8,j)=rnstx(4,j)*14/1e3                      !8 PF2U
      rnstcur(9,j)=rnstx(4,j)*14/1e3                      !9 PF2U
      rnstcur(10,j)=rnstx(5,j)*7/1e3                      !10 PF3U
      rnstcur(11,j)=rnstx(5,j)*8/1e3                      !11 PF3U
      rnstcur(12,j)=rnstx(5,j)*7/1e3                      !12 PF3U
      rnstcur(13,j)=rnstx(5,j)*8/1e3                      !13 PF3U

      rnstcur(14,j)=rnstx(6,j)*4/1e3                      !14 PF4U
      rnstcur(15,j)=rnstx(6,j)*4/1e3                      !15 PF4U
      rnstcur(16,j)=rnstx(6,j)*9/1e3                      !16 PF4Ur

      rnstcur(17,j)=rnstx(6,j)*4/1e3                      !17 PF4L
      rnstcur(18,j)=rnstx(6,j)*5/1e3                      !18 PF4L
      rnstcur(19,j)=rnstx(6,j)*8/1e3                      !19 PF4L

      rnstcur(20,j)=rnstx(7,j)*12/1e3                     !20 PF5U
      rnstcur(21,j)=rnstx(7,j)*12/1e3                     !21 PF5U
      rnstcur(22,j)=rnstx(7,j)*12/1e3                     !22 PF5L
      rnstcur(23,j)=rnstx(7,j)*12/1e3                     !23 PF5L

      rnstcur(24,j)=rnstx(8,j)*8/1e3                     !24 PF3L
      rnstcur(25,j)=rnstx(8,j)*7/1e3                     !25 PF3L
      rnstcur(26,j)=rnstx(8,j)*7/1e3                     !26 PF3L
      rnstcur(27,j)=rnstx(8,j)*8/1e3                     !27 PF3L
      rnstcur(28,j)=rnstx(9,j)*14/1e3                    !28 PF2L
      rnstcur(29,j)=rnstx(9,j)*14/1e3                    !29 PF2L
      rnstcur(30,j)=rnstx(10,j)*20/1e3                    !30 PF1cL
      rnstcur(31,j)=rnstx(11,j)*32/1e3                    !31 PF1bL
      rnstcur(32,j)=rnstx(12,j)*64/1e3                    !32 PF1aU
      rnstcur(33,j)=rnstx(14,j)*1/1e3                    !33 Plasma
   60 Continue

      do 70 i=1,33
      print *, i,',',rnstcur(i,nstart),',',rnstcur(i,nstart+1),',',
     crnstcur(i,nstart+2),',',rnstcur(i,nstart+3),',',
     crnstcur(i,nstart+4),',',rnstcur(i,nstart+5),',',
     crnstcur(i,nstart+6),',',rnstcur(i,nstart+7)

   70 Continue

      do 80 i=1,33
      write(7,*) i,',',rnstcur(i,nstart),',',rnstcur(i,nstart+1),',',
     crnstcur(i,nstart+2),',',rnstcur(i,nstart+3),',',
     crnstcur(i,nstart+4),',',rnstcur(i,nstart+5),',',
     crnstcur(i,nstart+6),',',rnstcur(i,nstart+7)

   80 Continue


       end if
```

Appendix D

From [14] NATIONAL SPHERICAL TORUS EXPERIMENT CENTER STACK RESEARCH AND DEVELOPMENT FINAL REPORT No. 13-970430-JHC Prepared By: James H. Chrzanowski April 30, 1997 PRINCETON UNIVERSITY PLASMA PHYSICS LABORATORY (PPPL)

Table No. 2-6
SHEAR/COMPRESSION FATIGUE TEST RESULTS
(TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness prior to cure cycle (177°C for 2 hours and 200°C for 6 hours)

Specimen ID No.	Shear Load (psi)	Compressive Load (psi)	Specimen Temp (°C)	Cycles Completed
11	2400	600	60	1,000,000
12	2400	600	60	1,000,000
13	2400	600	60	1,000,000
14	2400	600	60	1,000,000
19	2400	600	60	1,000,000
20	2400	600	60	1,000,000

=2400*6895/1000000 = 16.548MPa

Table No.2-1
DOUBLE LAP SHEAR TEST RESULTS (TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness during cure cycle. (177°C for 2 hours and 200°C for 6 hours)
Test Date: 2/12/97

Specimen ID No.	Cure Information	Specimen Test Temp. (°C)	Shear Load (Lbs)	Shear Load (psi)	Type of Failure
4	6 hrs.@ 200°C	21.7 *	1385	2770	Inter-laminar
5	2 hrs.@ 177°C	21.7 *	1800	3600	Inter-laminar
6	6 hrs.@ 200°C	21.7 *	1812	3624	Inter-laminar
7	6 hrs.@ 200°C	21.7 *	1385	3770	Inter-laminar
8	6 hrs.@ 200°C	21.7 *	1690	3380	Inter-laminar
9	6 hrs.@ 200°C	100	1630	3260	Inter-laminar

10	6 hrs.@ 200°C	100	640	1280	Inter-laminar
11	6 hrs.@ 200°C	100	2110	4220	Inter-laminar
12	6 hrs.@ 200°C	100	520	1040	Inter-laminar

* Room Temperature 21.7°C (71°F)

Table No.2-2
DOUBLE LAP SHEAR TEST RESULTS (TF Coil Insulation)

Insulation Tested: CTD-112P without Kapton (3) layers
Test Description: Samples were compressed 10% of nominal insulation thickness during cure cycle (177°C for 2 hours and 200°C for 6 hours).
Test Date: 2/22/97

Specimen ID No.	Cure Information	Specimen Temp. (°C)	Shear Load (Lbs)	Shear Load (psi)	Type of Failure
1	6 hrs.@ 200°C	23.9 *	1310	2620	Copper/DZ-80
2	6 hrs.@ 200°C	23.9 *	1340	2680	Inter-laminar
3	6 hrs.@ 200°C	23.9 *	1050	2100	Cu & Inter-laminar
4	6 hrs.@ 200°C	23.9 *	1810	3620	Copper/DZ-80
5	6 hrs.@ 200°C	23.9 *	1310	2620	Inter-laminar
6	6 hrs.@ 200°C	23.9 *	1330	2660	Cu & Inter-laminar
7	6 hrs.@ 200°C	23.9 *	1540	3080	Cu & Inter-laminar
8	6 hrs.@ 200°C	100	910	1820	Cu & Inter-laminar
9	6 hrs.@ 200°C	100	1335	2670	Inter-laminar
10	6 hrs.@ 200°C	60	1630	3260	Cu & Inter-laminar
11	6 hrs.@ 200°C	23.9 *	1680	3360	Inter-laminar
12	6 hrs.@ 200°C	60	1370	2740	Inter-laminar
13	6 hrs.@ 200°C	23.9 *	1240	2480	Cu & Inter-laminar
14	6 hrs.@ 200°C	23.9 *	1210	2420	Copper/DZ-80
15	6 hrs.@ 200°C	23.9 *	1340	2680	Inter-laminar
16	6 hrs.@ 200°C	23.9 *	1220	2440	Cu & Inter-laminar

* Room Temperature 23.9°C (75°F)