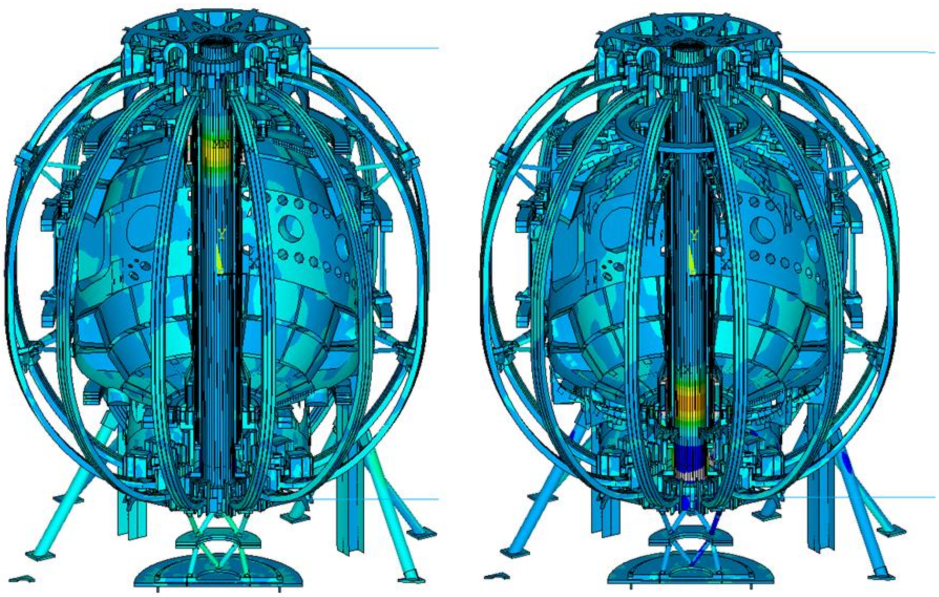
NSTX Upgrade TF Inner Leg Torsional Shear, Including Input to the DCPS

NSTXU-CALC-132-07-01 Rev 1

November 6 2015



Torsional Shear Results for PF1aU and L Unit Loads

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PPPL Calculation Form

Calculation # **NSTXU-CALC-132-07-01** Revision # 01 WP #, 0029,0037 (ENG-032)

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

Quantify and Qualify the Inner Leg Torsional Shear Stress for all the 96 scenarios, with and without plasma and provide a means of calculating the torsional shear in the Digital Coil Protection System (DCPS)

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

-See the reference list in the body of the calculation

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

Out-of-Plane (OOP) load distribution to the components of the tokamak depend on accurate modeling of the torsional stiffness of the system. The inner leg torsional shear has been investigated with different modeling and analysis techniques to try to envelope possible uncertainties in the OOP load distribution, and thus uncertainties in the torsional shear stress. All the models make some assumptions regarding connectivity and boundary conditions. The global FEA model results are considered as the most representative, but the more conservative of the values have been chosen for the DCPS.

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.)

Shear stresses are below the allowable of 25 MPa for the 96 EQ required by the GRD [8]. The largest shears typically are in the inner leg corners near the friction stir welded flags. Acceptable results from testing the CTD-425K/Cynate ester primer system have been received that support the acceptability of the calculated torsional shear. (See Appendix E, and F for "Creep" or longer dwell time results). Further tests were performed to better quantify the effect of creep, or dwell time at load. Initial tests were done at 10 hz Tests being performed in August 2011 are based on more realistic time at load. . Influence coefficients for the DCPS algorithm have been generated based on the global model [2], and using the checker's(Bob Woolley's) model.[6] The global model used in this calculation, and described in [2] has been maintained and updated as the structural elements of NSTX-U were designed and completed. The ref [6] model represents an earlier time point in the upgrade project and the global torsional stiffness is assembled from a series of sub models. DCPS coefficients have been developed using both models and the more conservative of these coefficients (Bob Woolley's) are recommended for the DCPS with the expectation that structural instrumentation being installed in the operating tokamak will help determine which set of coefficients are the most representative of actual performance, as the project approaches full performance.

Other approaches to generating influence coefficients were investigated including a single TF model with simple fixed boundary conditions, and a shell model that was used on early ITER and FIRE simulations. Of the methods investigated in this calculation, the global model derived coefficients are recommended for the DCPS. In Jan 2012 C. Neumeyer developed post disruption coil currents and these were checked with the influence coefficients developed from the global model. The torsional shear in the upper corner shifts about 7MPa less negative and magnitudes are lower.

Magnitudes are below allowables of 25 MPa for the 96 EQ required by the GRD[8]. Woolleys model produced higher values (32.6 without the headroom factor, for the no plasma condition. Titus's result for the same loading is 23.76 MPa. With plasma, Woolleys max 96 EQ shear stress is 25.23 MPa and Titus's shear is 17.98 MPa. Bob Woolleys claim is that the no –plasma numbers can't be reached in an actual disruption and justifies the conclusion that we are below the allowables.

Cognizant Engineer's printed name, signature, and date

Tim Stevenson Timothy N. Stevenson Digitally signed by Timothy N. Stevenson DN: cn=Timothy N. Stevenson, o=PPPL, ou=ENGR, email=tstevenson@pppl.gov, c=US Date: 2015.11.18 18:10:41 -05'00'

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

Checker's printed name, signature, and date

Robert Woolley Robert D. Woolley Digitally signed by Robert D. Woolley DN: cn=Robert D. Woolley, o=Princeton Plasma Physics Laboratory, ou, email=woolley@pppl.gov, c=US Date: 2015.11.13 12:11:13 -05'00'

2.0 Table of Contents

3.0 Revision Status Table

Rev0	Date	Original Issue
Rev 1	Nov. 1 2015	Calculation was substantially restructured to allow additions and revisions and add comments and corrections provided by Dr. R. Wooley
Rev 1	Sept 9 2011	Figure 22a Global Model Mid Plane Results - +13,-24 ka OH Equilibrium results replaced +24,-24kA results in the figure
Rev 1		Post disruption global model results added after page 30

Rev 1		Conclusion and Executive Summary Updated with post disruption results from C. Neumeyer
Rev 1	March 7 2012	Added Appendix H, March 7 2012 email from Charles Neumeyer that includes net torques from his disruption simulation
Rev1	October 2015	Added Appendix I , Bob Wooley's checkers calculation results
Rev1	Nov 10 2015	Added reference to Rev 6 of the GRD[8] in 6.1.1 which has a much lower full field pulse count than was originally specified.

4.0 Executive Summary:

This calculation is intended to qualify the inner leg torsional shear stress and provide an appropriate algorithm for calculation of these stresses in the digital coil protection system (DCPS). The DCPS algorithm based on the global model is also used to address the full 96 equilibria, with and without plasma. Other approaches to generating influence coefficients were investigated, including a single TF model with simple fixed boundary conditions, and a shell model that was used on early ITER and FIRE simulations. In a parallel analysis, Bob Woolley also calculated DCPS coefficients. Bob Wooleys analysis is documented in [6] Of the methods investigated in this calculation, the global model derived coefficients are considered more accurate, but because they are somewhat smaller than Woolley's coefficients, his are used for the DCPS. The evaluation of the design point 96 equilibria is presented based on coefficients from this (Titus) analysis. Results based on Bob Wooley's coefficients are also included in a summary table, 4.0-1 in this section. It should be pointed out that many of the sub components of the (Titus) global model have been checked individually to qualify the sub components.

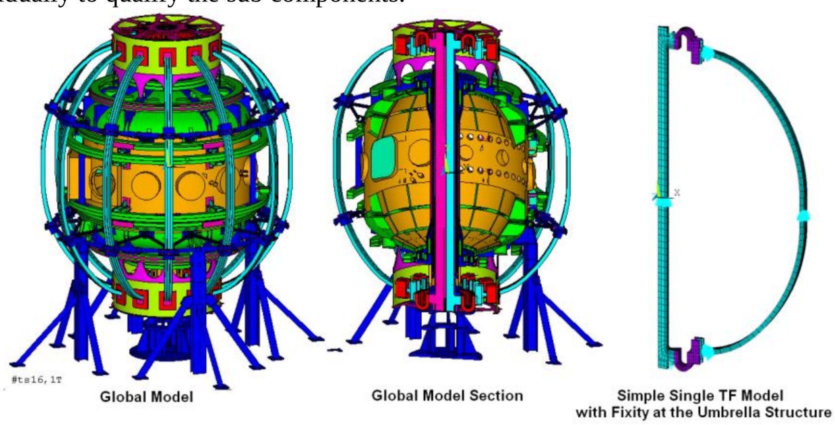


Figure 4.0-1 FEA Models Used for the Calculation if TF Inner Leg Shear Stress Influence Coefficients.

The corners of the inner leg experience some current "bunching" due to the resistive and inductive behavior of the currents turning the corner at the flag extension. This produces some higher temperatures than the Design Point Spreadsheet [13] calculates and the shear capacity of the epoxy bond degrades with higher temperature. From the global model simulations, the local peak shear stresses are below 25 MPa in the inner leg corners near the friction stir welded flags. The first global model load files were based on the earlier +/-24ka OH scenarios and the use of the influence coefficients allows computation of the TF torsional shear for the latest set of scenarios with and without plasmas. As of November 2015 the global model[2] load files were updated for the latest set of 96 equilibria. The latest version of the global model has the overlaid plate umbrella structure reinforcements and the final pedestal and knuckle clevis designs.

Out-of-Plane (OOP) loads on a toroidal field (TF) coil system result from the cross product of the poloidal field and toroidal field coil current. Support of OOP loads is statically in-determinant, or multiply redundant, requiring an understanding of the flexibility of the outboard structures and the inboard stiffness of the central column. There are a number of ways in which the torsional shear stress in the inner leg of the

TF can be calculated. The global model is the primary tool for this computation. A single TF model was investigated to see if the inner leg OOP forces alone dominate and if the outer structures could be ignored. This turned out not to be the case. This means that the global torsional stiffnesses of the umbrella structure, it's proposed upgrade reinforcement, the port region stiffness, the top and bottom spoke assembly stiffness, and the pedestal stiffness all will have some effect on the inner leg torsional shear.

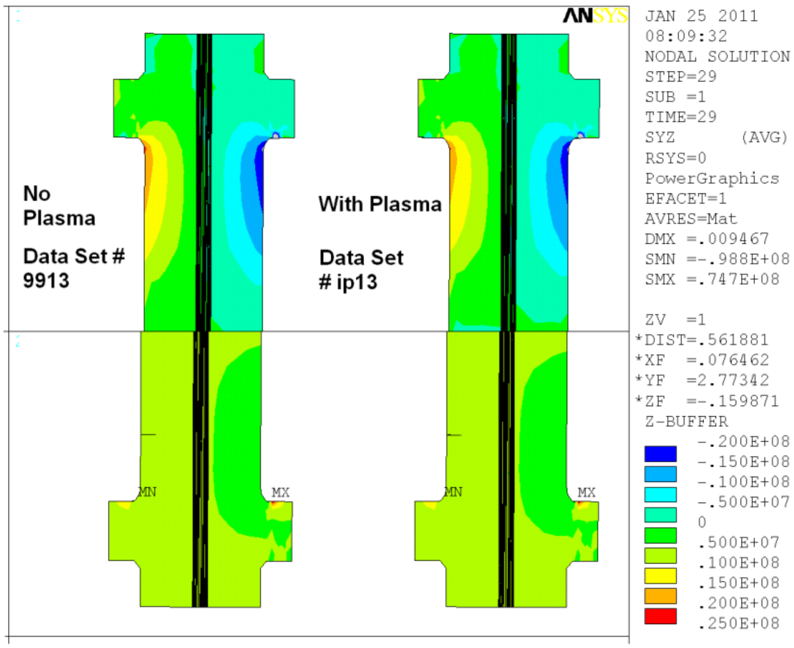
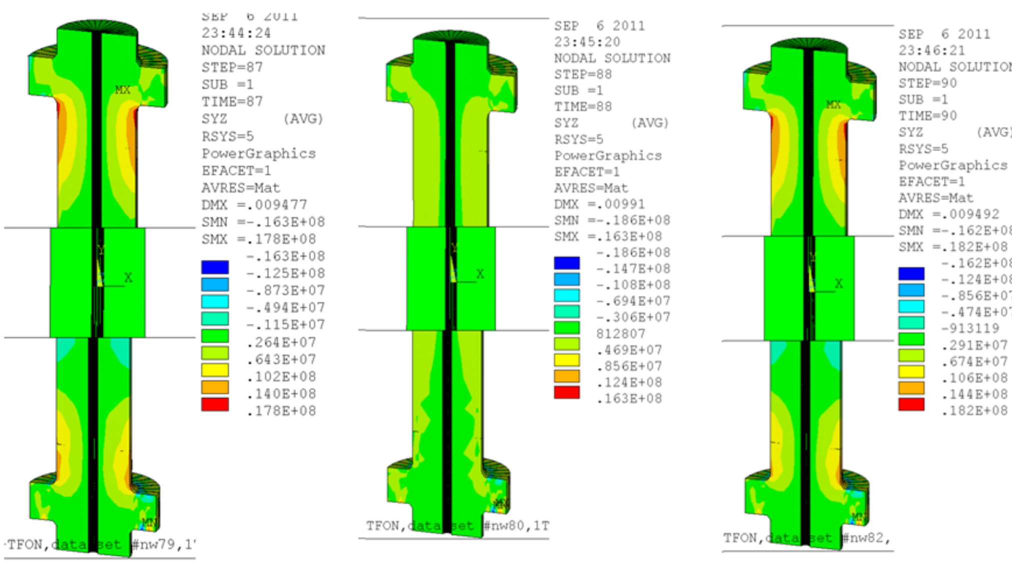


Figure 4.0-2 This shows one current set from the global model analysis, in which the plasma current effect on the torsional shear is difficult to discern. From the influence coefficient calculations it is about a 1 MPa effect (see Figure 6). The magnitude is close to 20 MPa.



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

Figure 4.0-3 Results from Run #35 with the Ten Legged Umbrella Structure

Figures 4.0-2 and 3 show the inner leg torsional stress with only the inner leg sections plotted. Figure 4.0-5 shows the TF inner leg within the global model, and the correspondence between the global model results and those obtained from the DCPS coefficients.

Torsional shear stresses in the inner leg have been found to be slightly lower with the inclusion of the plasma in the load calculations, this has been found when applying loads calculated with and without the plasma on the global model, and also in the influence coefficient calculations. In Jan 2012 C. Neumeyer developed post disruption coil currents and these were checked with the influence coefficients developed from the global model. The torsional shear in the upper corner shifts about 4MPa less. Magnitudes are still below the torsional shear allowable. Effects in the lower corner and mid height are smaller. The change in the upper corner raises the possibility of a dynamic response behaviors, but stresses are going down, and any dynamic load factor would be applied to the 4MPa difference The shielding effect of the vessel will further reduce the dynamic effect. There was no significant difference between the circular and shaped plasma torsional shear results. Influence coefficients for the DCPS algorithm have been generated based on the global model [2] and one set of these is represented below in figure 4.0-4. The rest of the coefficients are developed in section 9.0. Bob Wooley's coefficients are developed in reference [6] and are summarized in attachment H of this calculation.

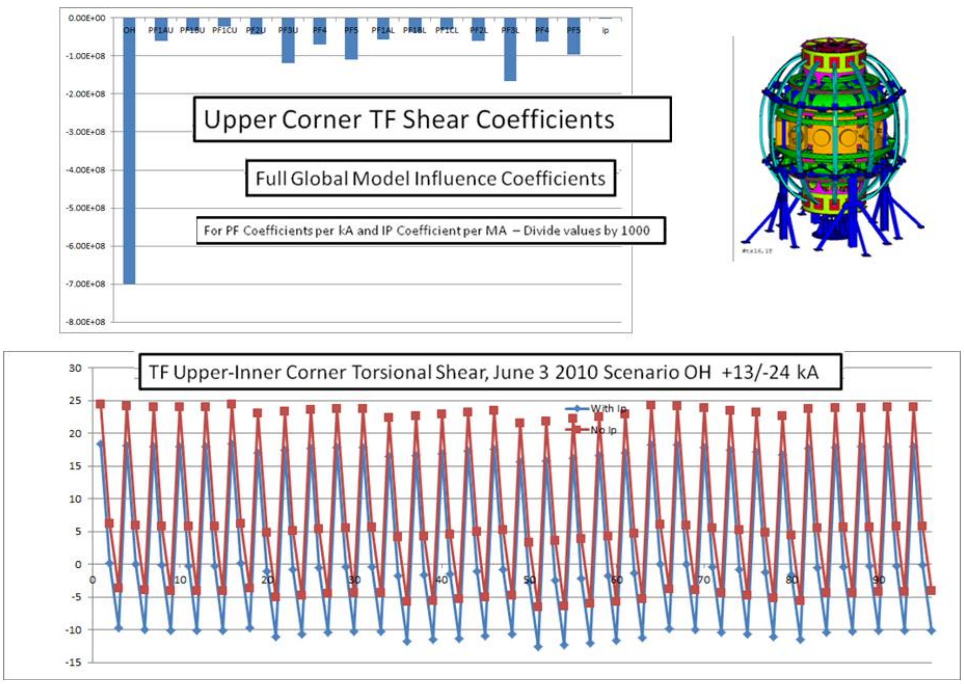


Figure 4.0-4 Torsional Shear Stresses from the Influence coefficients multiplied by the Design Point Scenarios

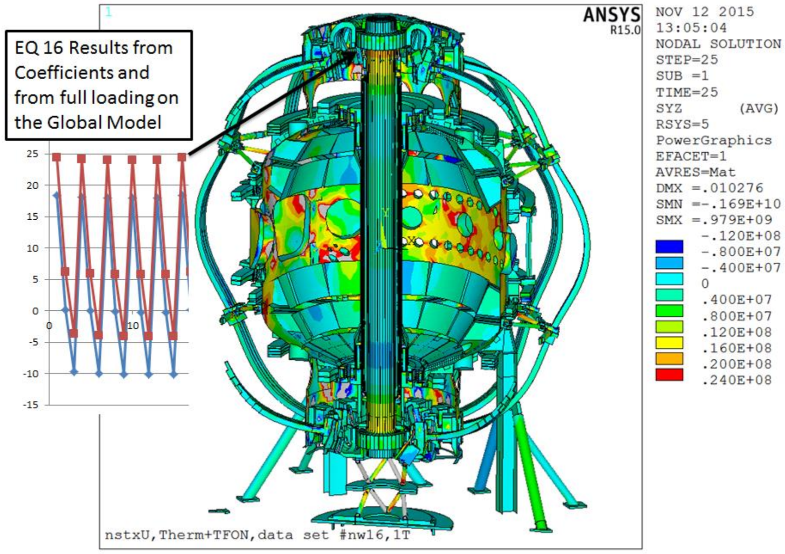


Figure 4.0-5, Torsional Shear Stress for EQ 16 Plotted in the Global Model and with a Segment of a Spreadsheet Calculation Using the DCPS Factors

Table 4.0-1

	Titus 1.0 Headroom (Mpa)	Titus 1.1 Headroom (Mpa)	Woolley 1.0 Headroom (Mpa)	Woolley 1.1 Headroom (Mpa)
96	Equilibrium	Results	Without	Plasma
Top	23.82 @EQ16	26.2	32.63 @EQ16	35.9
Middle	2.0	2.2	14.24 @EQ3	15.67
Bottom	18.835	20.7		
96	Equilibrium	Results	With	Plasma
Top	17.86 @EQ16	19.65	25.23 @EQ16	27.75
Middle	2.97	3.27	9.95 @EQ3	10.9
Bottom	17.377	19.1	25.19 @EQ64	27.7
	Post	Disruption	Results	
Top	20.55@EQ64	22.6	27.65@EQ64	30.4
Middle	1.769	1.94	11.4 @ EQ 66	12.54
Bottom	16.31@EQ1	17.941	27.65@EQ 64	30.415

Based on the DCPS influence coefficients, the TF inner leg upper corner torsional shears, for all 96 June 3 2010 scenarios are all below 25 MPa with and without plasma. Rigorously these should have the 10% headroom applied (the coefficients do not include this) - So the torsional shear stress to compare with the allowable is 26.2MPa. In the beginning of the design process, 25MPa was chosen as the allowable for 30,000 pulses and 100C. Final qualifications of the insulation system address more complex elements of the testing program, and include an estimate of the conservatism introduced by the short beam shear test sample, and creep. Final estimates of the number of design full Lorentz load shots are significantly lower than the original design criteria (See section 6.1.1). Acceptable results from testing the CTD-425K/Cynate ester primer system have been received that support the acceptability of the calculated torsional shear. See Figures 6.1.1-4 through 6. Further tests have been performed to better quantify the effect of creep, or dwell time at load. Initial tests were done at 10 hz. Tests performed in August 2011 are based on more realistic time at load - see Appendix F Some of these tests were intended to be displacement controlled. There are problems with the displacement measurements in these tests, but the important observation is that there is no failure of the epoxy for either the 19 or 30 MPa shear loading. These tests had much longer dwell times than the previous 10 hz tests, and were based on 6000 full 5sec Max TF max OH cycles - with a factor of 5 on testing life or 30, 000 test cycles to qualify the 6000 full power/full pulse length cycles.. This is consistent with rev 6 of the GRD [8]. The shear allowable of 25 MPa is a fatigue based allowable and was originally developed for 30,000 full power shots. The GRD was revised to specify 20,000 significant shots of which 4000 are at full TF and PF that would test the torsional shear capability of the inner leg..

For the majority of the shots, the “With Plasma 1.1 Headroom” shots are most representative of operation that develops significant torsion. These are all below 26.2 MPa which can be accepted based on the conservatism in the short beam shear results and the lower number of full load shots.. These results utilize the global model described in ref [2]. Higher shears than allowable are reported for Bob Woolley’s coefficients that are implemented in the DCPS and this adds some conservatism to the DCPS operation. There have been some changes in the PF scenario as well between the CDR and FDR. The influence coefficient approach not only has utility for the DCPS, but also allows 16 load files, - 15 from the PF's and 1 from the plasma to be used in spreadsheet evaluations of the 96 scenarios with and without plasma. This replaces 192 load cases with 16 load cases and spreadsheet calculations of the torsional shear. Post disruption currents, and test currents from the ISTP can also be run.

5.0 DCPS Algorithm Summary

In the table below, The Woolley coefficients are recommended for initial operation of the DCPS:

Table 5.0-1

		Woolley:															
	OH	Pf1a	pf1b	pf1cu	pf2u	pf3u	pf4u	pf5u	PF1a	PF1bl	PF1cl	pf2l	pf3l	pf4u	pf5l	Ip	TF
Top (Woolley)	-0.7115	-0.053	-0.0254	-0.022	-0.0582	-0.2303	-0.14745	-0.2272	-0.0698	-0.0456	-0.0419	-0.1046	-0.2688	-0.14745	-0.2272	-0.0037	0
Middle (Wooll	0.2601	-0.0624	-0.0396	-0.0353	-0.0873	-0.2419	-0.1356	-0.20885	-0.0662	-0.0438	-0.0399	-0.1001	-0.255	-0.1356	-0.20885	-0.00215	0
Bottom (Wool	-0.7103	-0.0611	-0.0415	-0.0373	-0.0919	-0.2559	-0.1474	-0.2272	-0.0564	-0.0293	-0.0263	-0.0704	-0.2431	-0.1474	-0.2272	-0.0037	0
		Titus:															
	OH	Pf1a	pf1b	pf1cu	pf2u	pf3u	pf4u	pf5u	PF1a	PF1bl	PF1cl	pf2l	pf3l	pf4u	pf5l	Ip	TF
Top Titus	-0.7	-0.0613	-0.0345	-0.0232	-0.0434	-0.119	-0.0708	-0.109	-0.0577	-0.0372	-0.0296	-0.0615	-0.116	-0.0622	-0.0972	-2.98E-03	0
Middle Titus	8.04E-02	-1.86E-02	-1.28E-02	-1.00E-02	-1.25E-02	-3.43E-02	-1.53E-02	-2.29E-02	-1.82E-02	-1.04E-02	-8.07E-03	-1.60E-02	-2.72E-02	-1.17E-02	-1.85E-02	4.83E-13	0.00E+00
Bottom Titus	-0.60417	-0.0318	-0.0239	-0.0192	-0.0391	-0.0701	-0.0367	-0.0561	-0.138	-0.0516	-0.025	-0.0483	-0.0362	-0.0531	-0.0772	-0.00073	0
	OH	Pf1a	pf1b	pf1cu	pf2u	pf3u	pf4u	pf5u	PF1a	PF1bl	PF1cl	pf2l	pf3l	pf4u	pf5l	Ip	TF
Top Woolley	-0.7115	-0.053	-0.0254	-0.022	-0.0582	-0.2303	-0.14745	-0.2272	-0.0698	-0.0456	-0.0419	-0.1046	-0.2688	-0.14745	-0.2272	-0.0037	0
Top Titus	-0.7	-0.0613	-0.0345	-0.0232	-0.0434	-0.119	-0.0708	-0.109	-0.0577	-0.0372	-0.0296	-0.0615	-0.116	-0.0622	-0.0972	-2.98E-03	0
	OH	Pf1a	pf1b	pf1cu	pf2u	pf3u	pf4u	pf5u	PF1a	PF1bl	PF1cl	pf2l	pf3l	pf4u	pf5l	Ip	TF
Middle Woolle	0.2601	-0.0624	-0.0396	-0.0353	-0.0873	-0.2419	-0.1356	-0.20885	-0.0662	-0.0438	-0.0399	-0.1001	-0.255	-0.1356	-0.20885	-0.00215	0
Middle Titus	8.04E-02	-1.86E-02	-1.28E-02	-1.00E-02	-1.25E-02	-3.43E-02	-1.53E-02	-2.29E-02	-1.82E-02	-1.04E-02	-8.07E-03	-1.60E-02	-2.72E-02	-1.17E-02	-1.85E-02	4.83E-13	0.00E+00
	OH	Pf1a	pf1b	pf1cu	pf2u	pf3u	pf4u	pf5u	PF1a	PF1bl	PF1cl	pf2l	pf3l	pf4u	pf5l	Ip	TF
Bottom Wooll	-0.7103	-0.0611	-0.0415	-0.0373	-0.0919	-0.2559	-0.1474	-0.2272	-0.0564	-0.0293	-0.0263	-0.0704	-0.2431	-0.1474	-0.2272	-0.0037	0
Bottom Titus	-0.60417	-0.0318	-0.0239	-0.0192	-0.0391	-0.0701	-0.0367	-0.0561	-0.138	-0.0516	-0.025	-0.0483	-0.0362	-0.0531	-0.0772	-0.00073	0

Stefan requested a check of the coefficients as they appear in the spreadsheet that prepares the data tree for the DCPS. The recommended coefficients (Woolleys', as of November 2015) were re-ordered to the DCPS order then the coefficients were overlayed with the coefficients from Stefan's DCPS spreadsheet to make sure they were identical. The results re in the table below.

Table 5.0-2

					REORDERED TO THE DCPS ORDER											
	Ip	Pf1a	pf1b	pf1cu	pf2u	pf3u	pf4u	pf5u	pf5l	pf4u	pf3l	pf2l	PF1cl	PF1bl	PF1a	OH	TF
TOP	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Woolley	-0.0037021	-0.053	-0.0254	-0.022	-0.0582	-0.2303	-0.14745	-0.2272	-0.2272	-0.14745	-0.2688	-0.1046	-0.0419	-0.0456	-0.0698	-0.7115	0
Stefan DCPS	-3.70E-03	-5.30E-02	-2.54E-02	-2.20E-02	-5.82E-02	-2.30E-01	-1.47E-01	-2.27E-01	-2.27E-01	-1.47E-01	-2.69E-01	-1.05E-01	-4.19E-02	-4.56E-02	-6.98E-02	-7.12E-01	0.00E+00
MIDDLE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Woolley	-0.0021477	-0.0624	-0.0396	-0.0353	-0.0873	-0.2419	-0.1356	-0.20885	-0.20885	-0.1356	-0.255	-0.1001	-0.0399	-0.0438	-0.0662	0.2601	0
Stefan DCPS	-2.15E-03	-6.24E-02	-3.96E-02	-3.53E-02	-8.73E-02	-2.42E-01	-1.36E-01	-2.09E-01	-2.09E-01	-1.36E-01	-2.55E-01	-1.00E-01	-3.99E-02	-4.38E-02	-6.62E-02	2.60E-01	0.00E+00
BOTTOM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Woolley	-0.003701	-0.0611	-0.0415	-0.0373	-0.0919	-0.2559	-0.1474	-0.2272	-0.2272	-0.1474	-0.2431	-0.0704	-0.0263	-0.0293	-0.0564	-0.7103	0
Stefan DCPS	-3.70E-03	-6.11E-02	-4.15E-02	-3.73E-02	-9.19E-02	-2.56E-01	-1.47E-01	-2.27E-01	-2.27E-01	-1.47E-01	-2.43E-01	-7.04E-02	-2.63E-02	-2.93E-02	-5.64E-02	-7.10E-01	0.00E+00

The source of the Woolley coefficients is included in attachment H of this calculation.

The recommended coefficients are the more conservative of the sets that Bob Woolley and the author have generated, and as we gain information from the benchmark instrumentation [19], it is expected that we will be able to improve our models and it is likely that we will be able to justify less conservative coefficients.

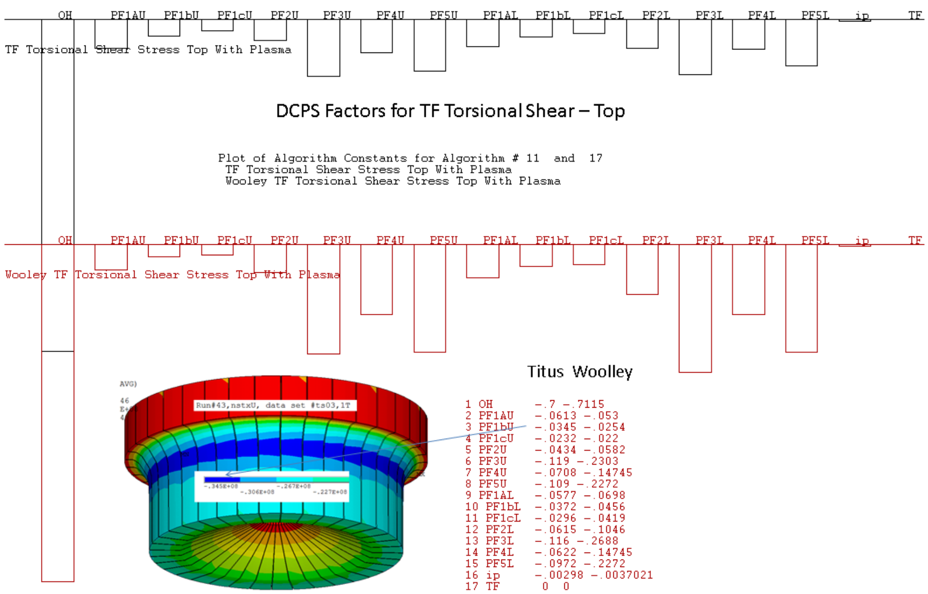


Figure 5.0-1 Comparison of Influence Coefficients (TOP)

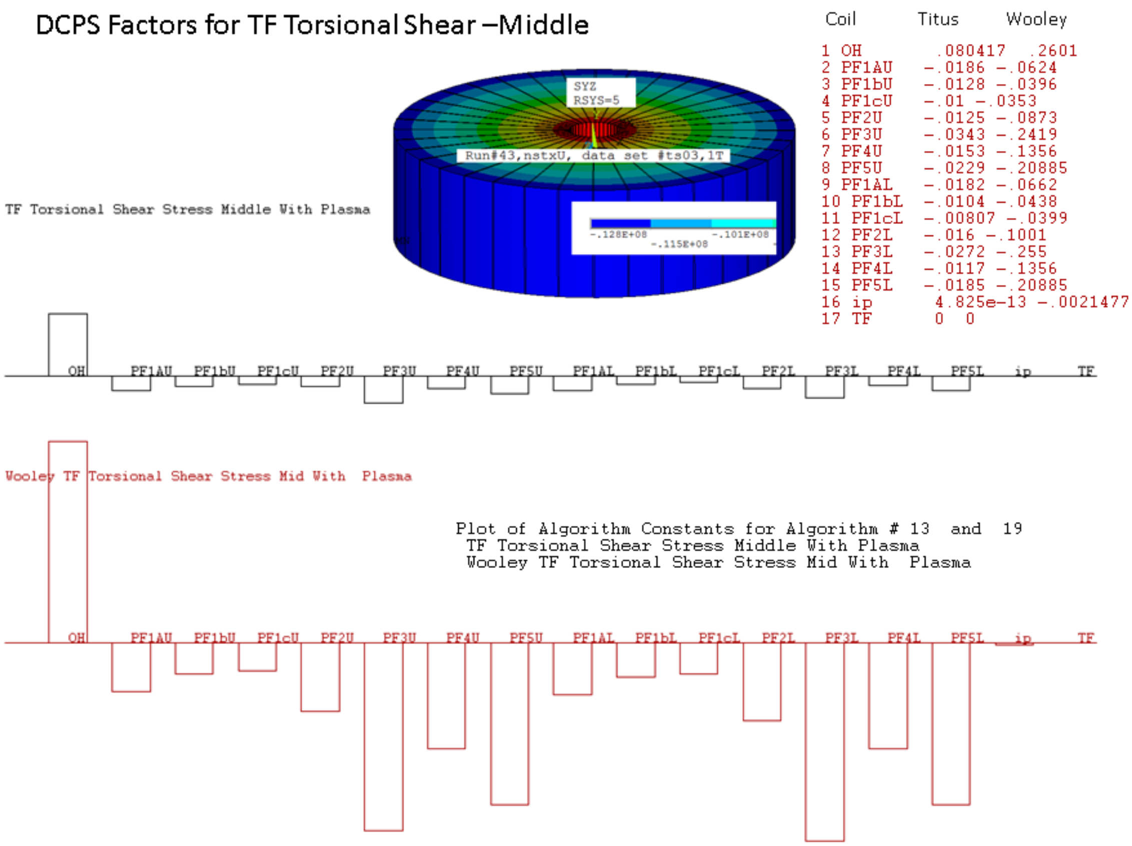


Figure 5.0-2 Comparison of Influence Coefficients (MIDDLE)

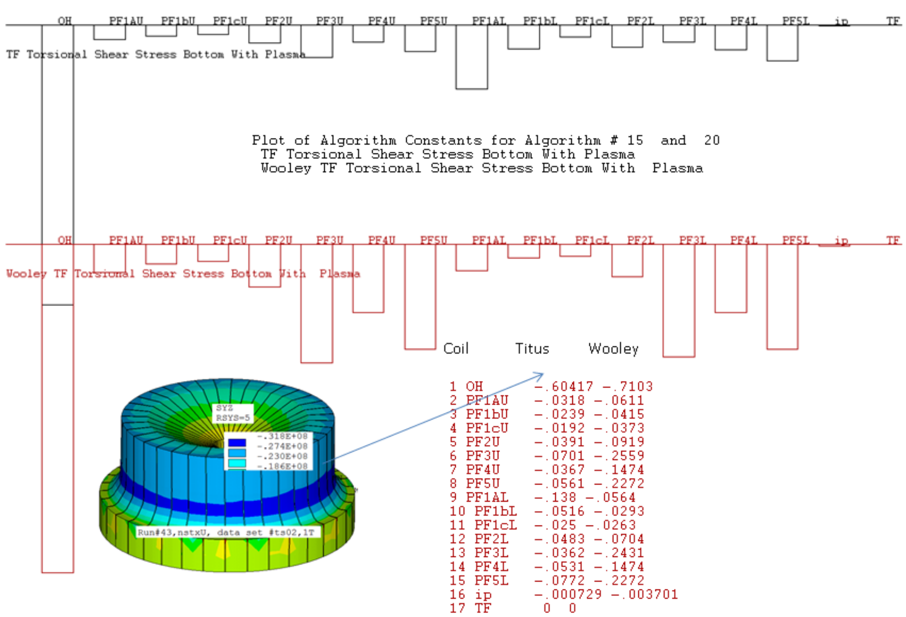


Figure 5.0-3 Comparison of Influence Coefficients (BOTTOM)

6.0 Design Input

6.1 Criteria

Stress Criteria are found in the NSTX Structural Criteria Document Ref [3]. Disruption and thermal specifications are outlined in the GRD[8] - Cyclic requirements for the TF torsional Shear mandrel shell shall be 20,000 full power operating pulses but the GRD include a shot spectrum that would allow a lower number of equivalent full power shots if a Miners Rule usage factor calculation was applied. These are assumed to develop the full 100 C temperature and thus the epoxy cyclic tests at 100 C are appropriate.

6.1.1 TF Inner Leg Epoxy Strength

The criteria document requires a static evaluation of the shear strength, but fatigue will govern.

From the Original GRD:

For engineering purposes, number of NSTX pulses, after implementing the Center Stack Upgrade, shall be assumed to consist of a total of ~ 60,000 pulses based on the GRD specified pulse spectrum.

This was interpreted as 30,000 fatigue cycles because the design OH swing was -24 kA to 13.5 kA and the second swing would produce lower fatigue damage. The final GRD specification on cyclic requirements comes from table 2-4 of rev 5 :

From the Rev 5 of the l GRD:

Table 0-1 - NSTX CSU Pulse Spectrum

Performance	60%	75%	90%	100%	
B_t	0.6	0.75	0.9	1	T
I_p	1.2	1.5	1.8	2	MA
$T_{pulse}=T_{flat\_Ip}$ (sec)					Total pulses
3	200	1800	1200	1000	4200
3.5	200	1800	1200	1000	4200
4	200	1800	1200	1000	4200
4.5	200	1800	1200	500	3700
5	200	1800	1200	500	3700
				Total	20000

This shot spectrum invites a usage factor calculation. The total number of full TF +Full Ip shots is ~4000. Not 30,000

The TF inner leg will be vacuum pressure impregnated (VPI) with the individual conductors primed with a Cyanate Ester system that improves bond strength and can survive the peak temperature in the inner leg corner - calculated by H. Zhang, ref [13] . This temp is a little over the original 100C limit. and a VPI/Primer system needed to be found that would survive the higher temperature and not creep or fail in fatigue. Gary Voss from MAST originally raised this issue of creep and this has been addressed by a CTD test program, mainly intended to address the OH preload creep .

The CTD 425 system has been tested by CTD [15]. Figures 6.1.1-1, and 2 are CDR and PDR versions of the derivation of the shear stress allowable.

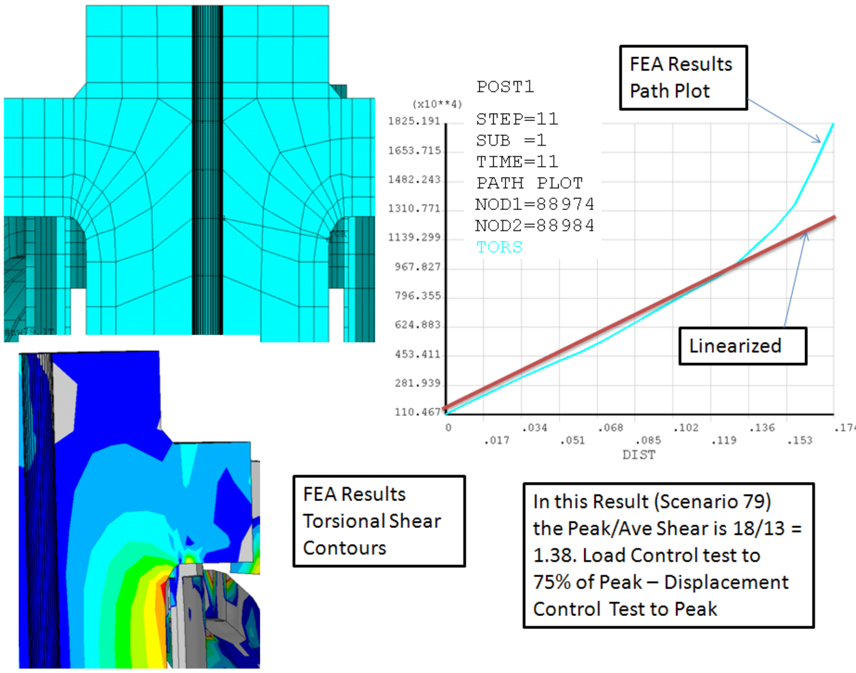


Figure 6.1.1-1 Linearized vs. Actual Shear Stress Distribution

The peak shear in the TF is similar to a stress concentration in that it peaks at the corner and is not a linear extrapolation of the shear needed to equilibrate the load controlled torsion. Results shown in Figure 6.1.1-1 indicate a significant portion of the applied shear stress is load controlled.

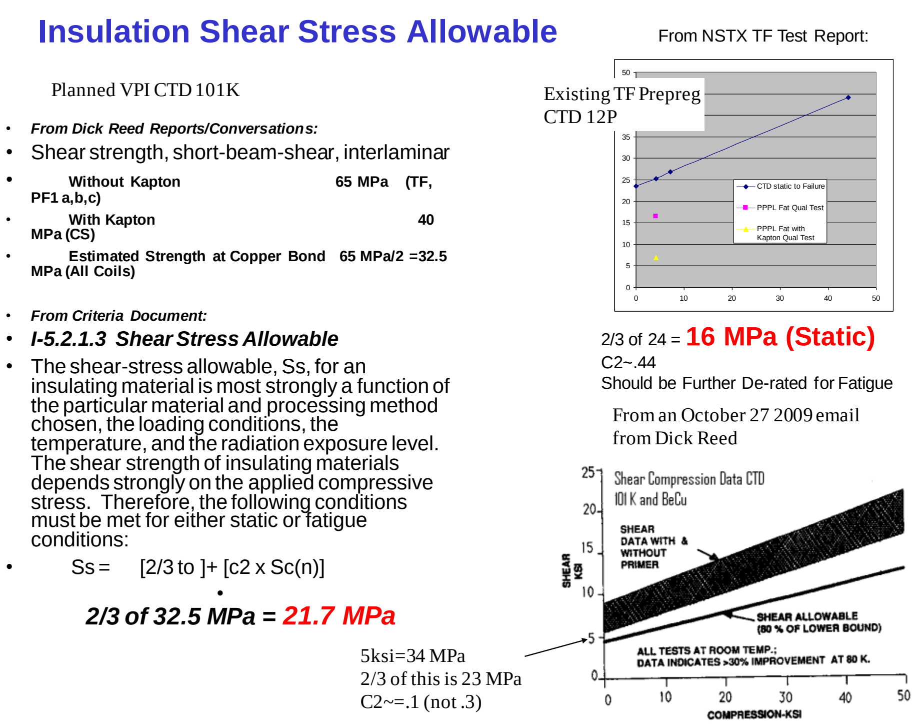


Figure 6.1.1-2 CDR Estimates of the NSTX Upgrade Shear Allowable

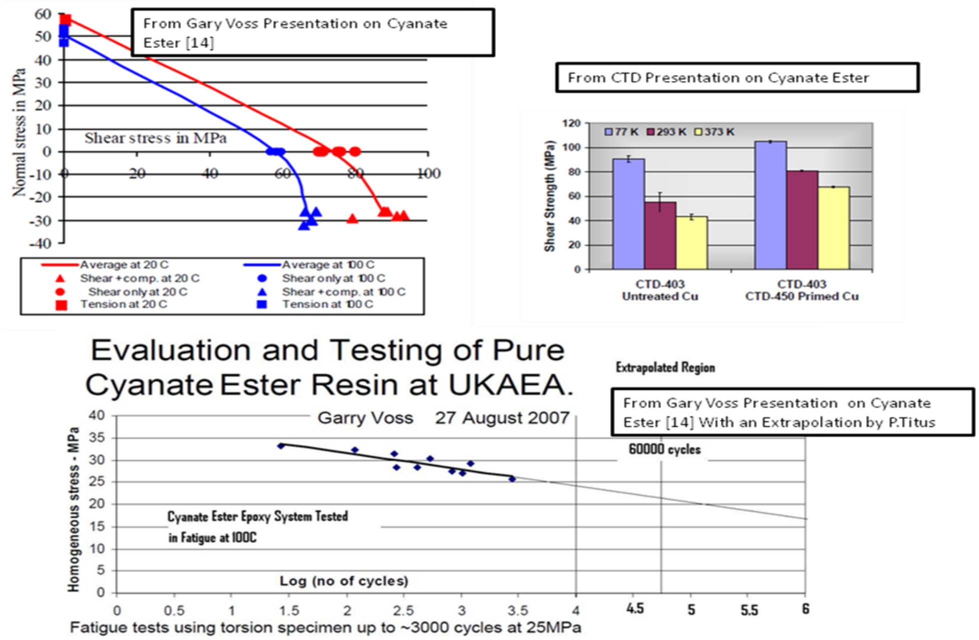
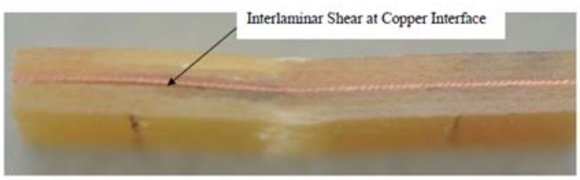
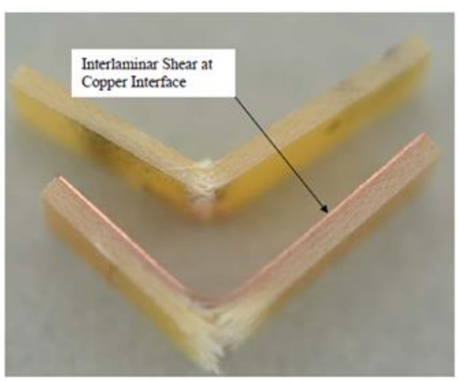


Figure 6.1.1-3 CDR Estimates of Expected

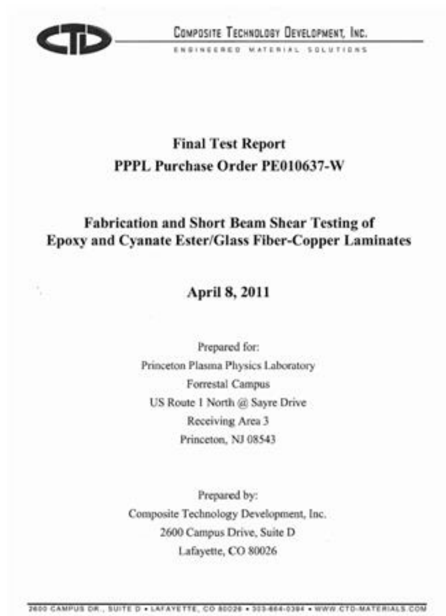
Estimates for the fatigue strength for the required 60000 cycles based on the Cyanate Ester primer at 100C were 21.5 MPa. The allowable without compression is 2/3*21.5= 14.33 MPa. Subsequent testing at Composite Technology Development, Appendix E successfully shows higher acceptable capacity.



CTD-425 Specimen #15- Fatigue at 60% of Ultimate Stress (31 MPa, 21867 cycles)



CTD-425 Specimen #14- Fatigue at 60% of Ultimate Stress (31 MPa, 26851 cycles)



Composite Technology Development, Inc.
Engineered Material Solutions

Final Test Report
PPPL Purchase Order PE010637-W

Fabrication and Short Beam Shear Testing of Epoxy and Cyanate Ester/Glass Fiber-Copper Laminates

April 8, 2011

Prepared for:
Princeton Plasma Physics Laboratory
Forrestal Campus
US Route 1 North @ Sayre Drive
Receiving Area 3
Princeton, NJ 08543

Prepared by:
Composite Technology Development, Inc.
2600 Campus Drive, Suite D
Lafayette, CO 80026

Figure 6.1.1-4 Test Results Showing "Clean" parting planes when the Insulation System Fails

A “clean” parting or failure plane is a desirable feature of an insulation system because delamination at the conductor/insulation boundary is not necessarily an electrical failure as long as the barrier formed by the insulation “shell” is not fractured, torn or cracked.

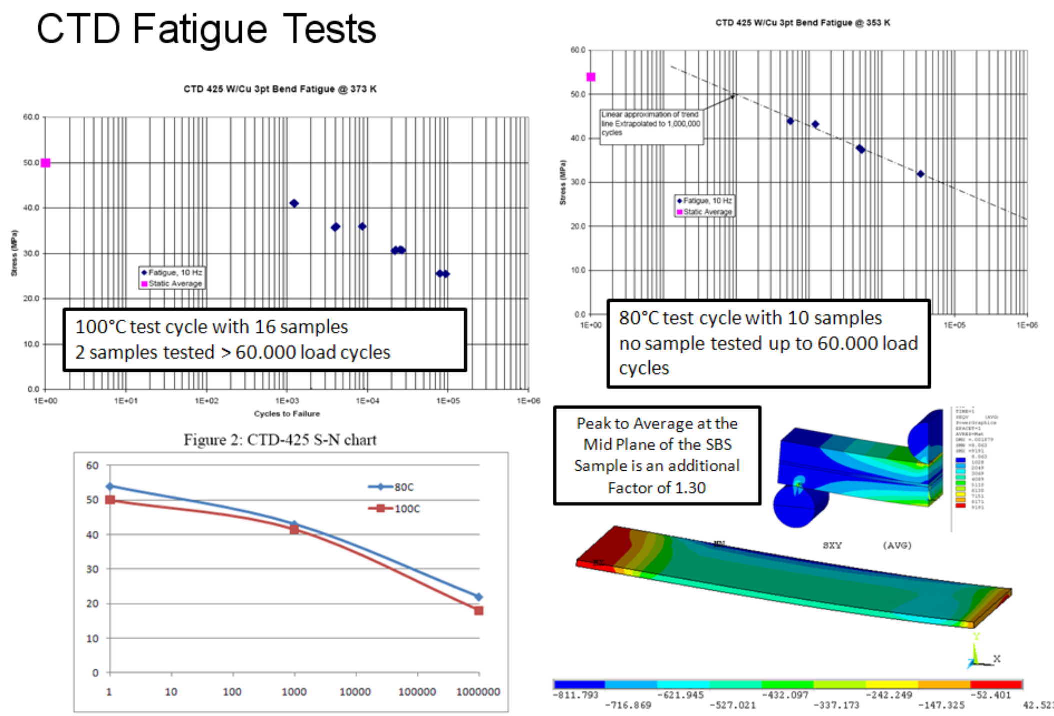


Figure 6.1.1-5 FDR Slide Showing Test Results. and Short Beam Shear Finite Element Model

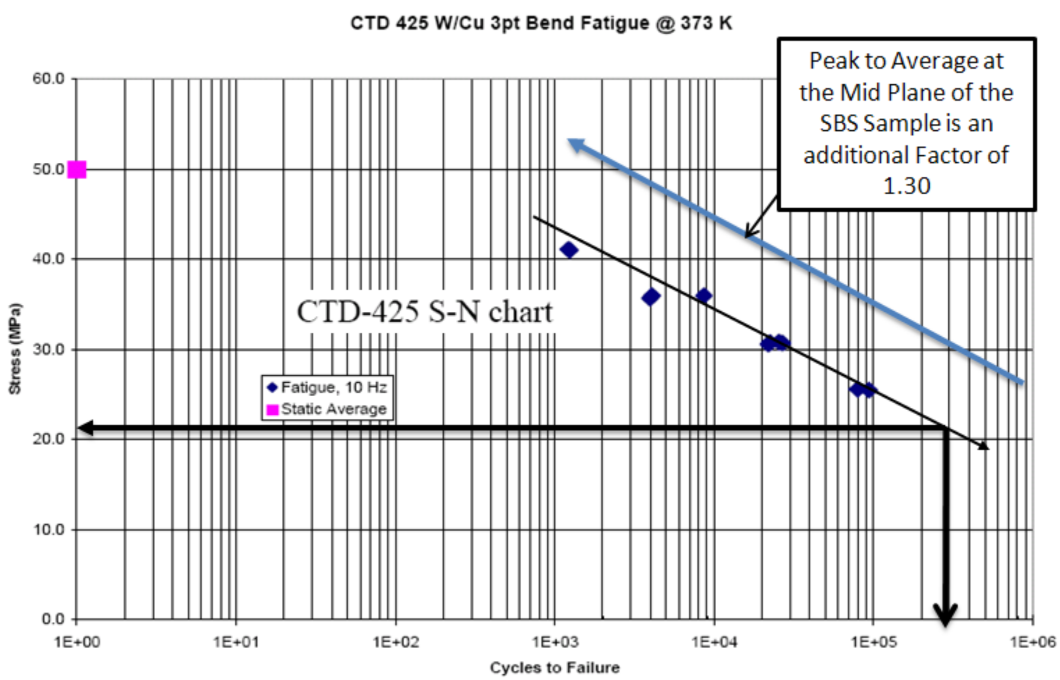


Figure 6.1.1-6 CTD Test Results With the Expected Higher Shear Capacity due to the Peaking of Stress in the Short Beam Shear Specimen

As tested, the shear capacity is just at the required shear strength ~22 MPa. The short beam shear (SBS) finite element results showed that the test specimen is pessimistic in that the shear at the edge is about 30% higher than the average or 28.6 MPa. This is cited to show some additional margin in the design. More discussion of the SBS analysis is included in appendix E

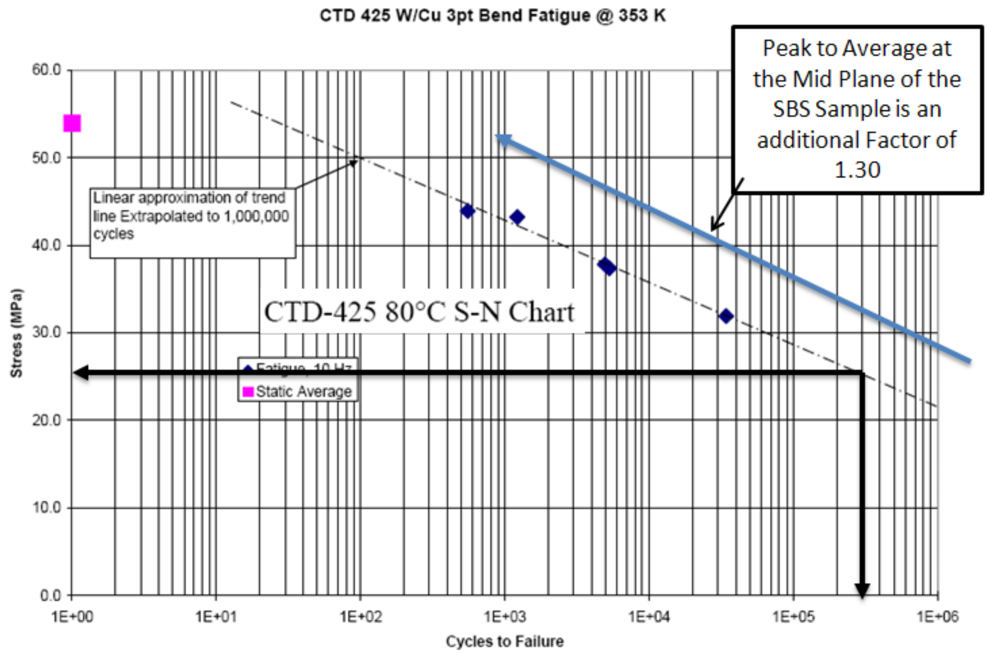


Figure 6.1.1-7 80 C Results Showing Improved Allowable Over the 100C Results

6.2 Drawing Excerpts

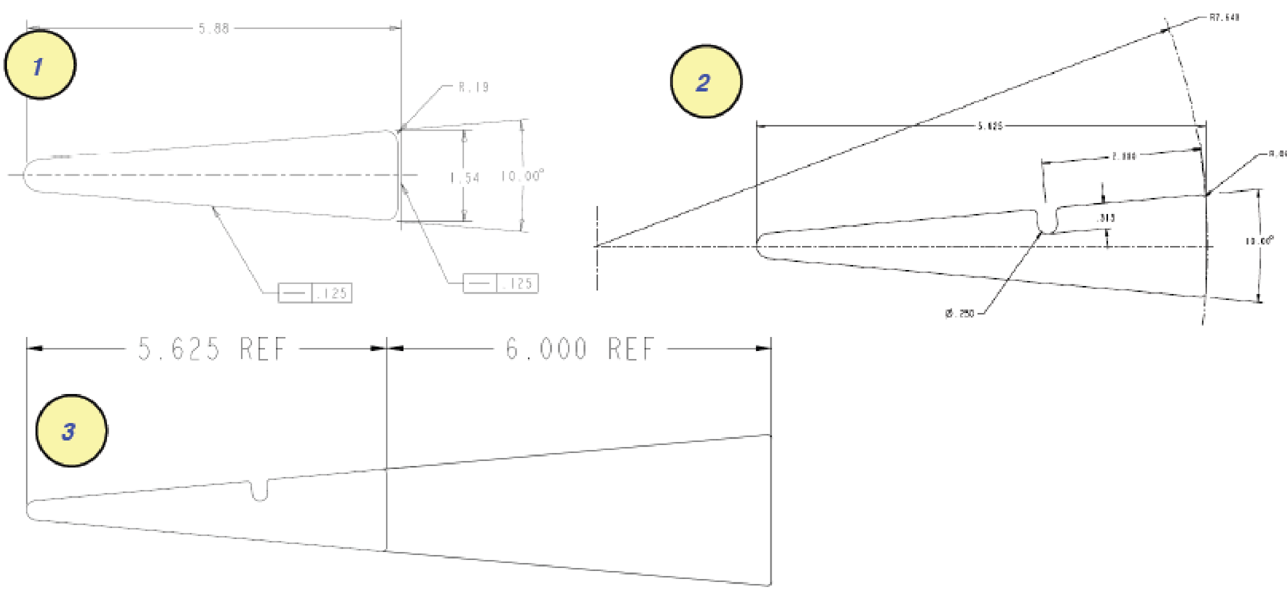
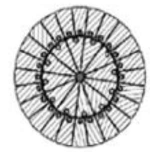


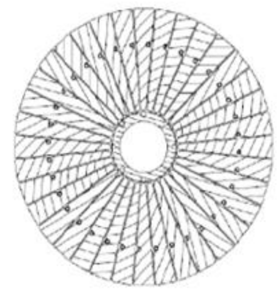
Figure 6.2-1 TF Coil Drawing Sections

	Base Design	Upgrade Design
Operating Voltage	1013 volts	1013 volts
Number of turns	36	36
Number of layers	2	1
Cooling	Water	Water
Operating current	71,168 amps	129,778 amps
Turn insulation	0.0324 in.	0.0324 in.
Dielectric strength- turn insulation		3.8 KV [3] half-lapped layer glass
Groundwall insulation	0.054 in.	0.090 in.
Copper mass	2260 lbs	10,900 lbs
Outside diameter	7.866 in.	15.752 in.
Insulation scheme	B-stage CTD-112	CTD 425 Cyanate Ester Blend
Cooling hole size ID	0.186 in.	0.305 in.

** Reference: Per half-lapped layer- 1260 volts [VPI impregnated glass]*



Current TF Bundle 7.9 inch diameter



Upgraded TF Bundle 15.7 inch diameter

Figure 6.2-2 TF Inner Leg Specifications for the Original NSTX and NSTX-U

6.3 References

[1] DIGITAL COIL PROTECTION SYSTEM (DCPS) REQUIREMENTS DOCUMENT (DRAFT), NSTX-CSU-RD-DCPS for the National Spherical Torus Experiment Center Stack Upgrade, February 5, 2010 R. Woolley

[2] NSTX-CALC-13-001-00 Rev 1 Global Model – Model Description, Mesh Generation, Results, Peter H. Titus February 2011

[3] NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc I. Zatz

[4] NSTX Design Point Sep 8 2009 http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

[5] NSTX Design Point June 3 2010 http://www.pppl.gov/~neumeyer/NSTX_CSU/Design_Point.html

[6] Torques On TF Conductors & Resulting Torsion & Shear Stress in NSTX CSU, R. Woolley, NSTXU CALC 132-03-00

[7] NSTX Influence Coefficients, calculation # NSTXU 13 03-00, Ron Hatcher DATE: July 9 2009

[8] NSTX Upgrade General Requirements Document, NSTX_CSU-RQMTS-GRD Revision 6, P. Titus, August 3 2015, Original issue by C. Neumeyer, March 30, 2009

[9] "MHD and Fusion Magnets, Field and Force Design Concepts", R.J.Thome, John Tarrh, Wiley Interscience, 1982

[10] "Provisions for Out-of-Plane Support of the TF Coils in Recent Tokamaks", P. H. Titus 1999 MT16

[11] CTD Shear Stress Testing Proposal, Appendix A

[12] NSTX MEMO**#:** 13-010515-IZ-01 DATE**:** 15 May 2001 FROM: I. J. Zatz , SUBJECT: NSTX Coil Protection Calculator, Appendix C

[13] Coupled Electromagnetic-Thermal Analysis, Han Zhang, Calc # NSTXU-CALC-132-05-00

[14] Evaluation and Testing of Pure Cyanate Ester Resin at UKAEA. Garry Voss 27 August 2007

[15]Final Test Report, PPPL Purchase Order PE010637-W Fabrication and Short Beam Shear Testing of Epoxy and Cyanate Ester/Glass Fiber-Copper Laminates April 8, 2011
Prepared for: Princeton Plasma Physics Laboratory Prepared by: Composite Technology Development, Inc.2600 Campus Drive, Suite D Lafayette, CO 80026

[16] Final Test Report, PPPL Purchase Order PE010925-W Fabrication and Testing of Cyanate Ester - Epoxy /Glass Fiber/Copper Laminates, October 7 2011, Prepared for Princeton Plasma Physics Laboratory Forrestal Campus by Composite Technology Development Inc. 2600 Campus Drive Suite D Lafayette CO 80026

[17] email from Charles L. Neumeyer neumeyer@pppl.gov Jan 13 2012 11:02 AM to me, Ronald Included in Appendix G Post Disruption Currents

[18] National Spherical Torus Experiment NSTX CENTER STACK UPGRADE, Coil Protection System Requirements Document Revision 0 February 1, 2012 Charles Neumeyer
[19] NSTX-U Structural Benchmark Instrumentation, NSTX-PLAN-12-207 DRAFT, November 2015,

7.0 Models

7.1 Global Model

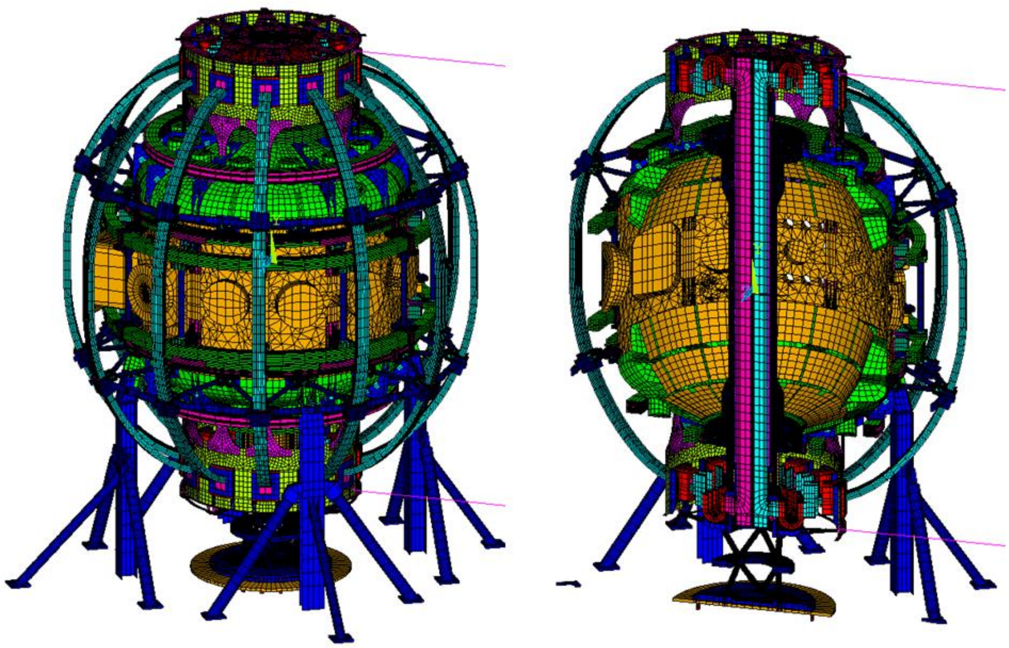


Figure 7.1-1 Global Model Used in Scenario Evaluations, and in Unit Load Analyses for the DCPS Coefficients

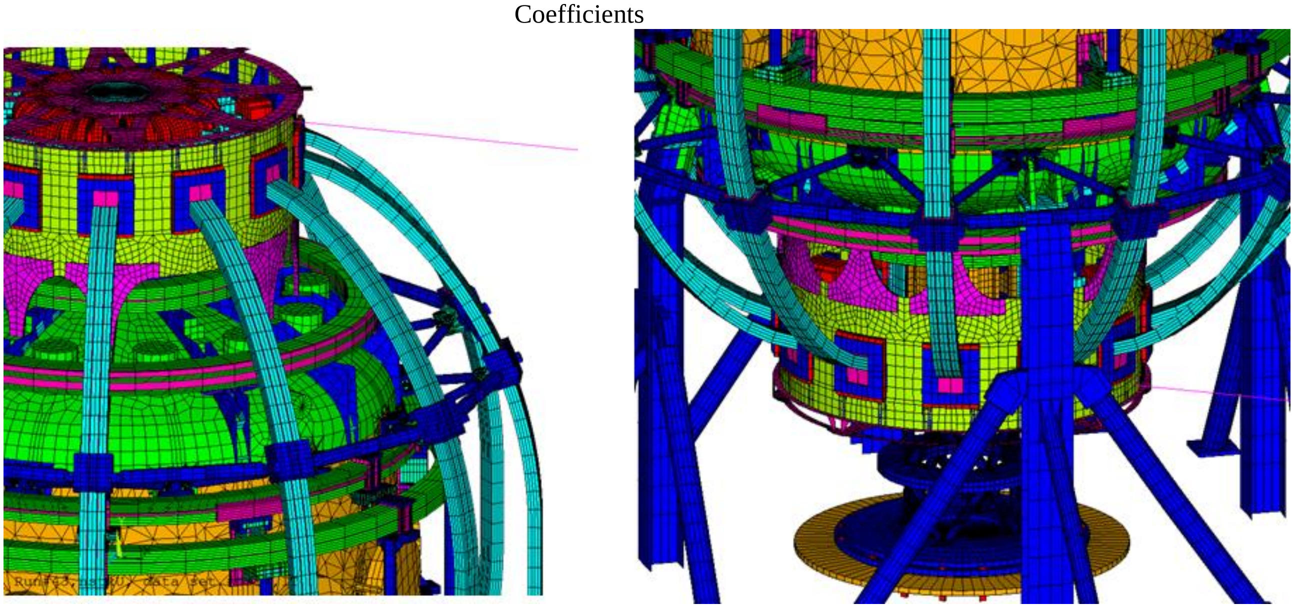


Figure 7.1-2 Global Model Used in Scenario Evaluations, and in Unit Load Analyses for the DCPS Coefficients, - Close-up views

7.2 Simple TF Model

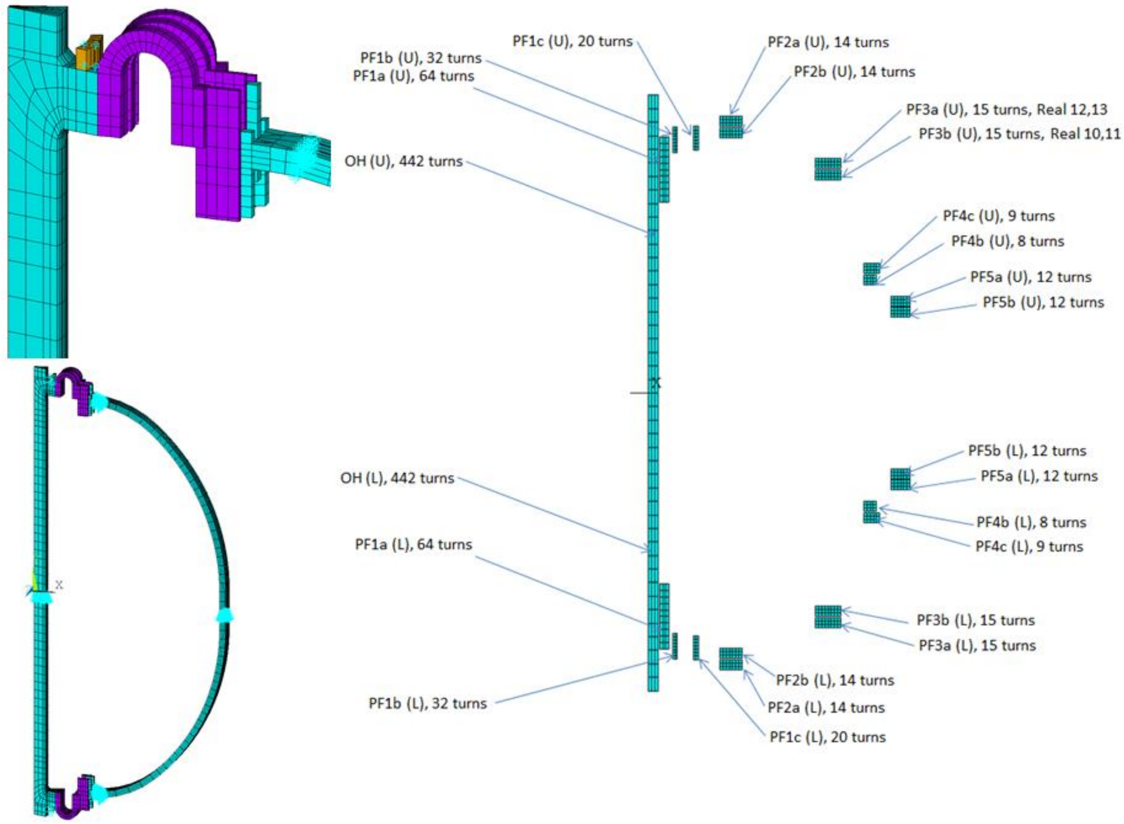


Figure 7.2-1 Simple Model PF Coils and Number of Turns in Coil Segments

7.3 Development of Unit Loads for the DCPS Influence Coefficients

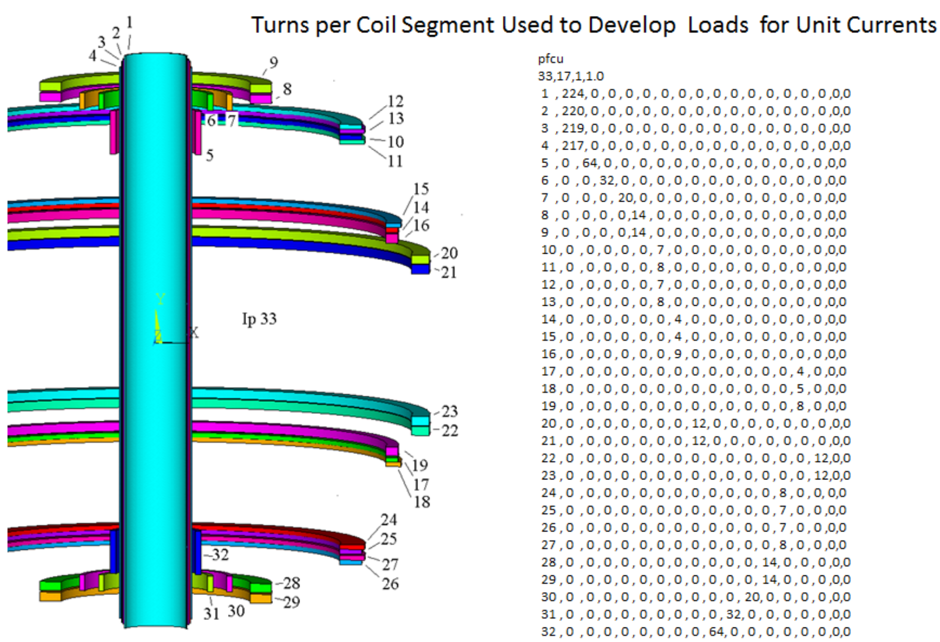


Figure 7.3-1 Global Model PF Coils and Unit Current Specification

The global model uses the original (2009) PF coil set from John Menard that has 32 coils that represent the multiple pancakes that make up the individually powered coils. The DCPS convention has separate coefficients for PF4U&L and separate coefficients for PF5U & L even though the uppers and lowers are in series. Bob Woolley uses this simplification. So the 32 coil segments must be re-grouped into the 16 coils that are tracked by the DCPS. Figure 7.3-1 shows the tabulated turn multipliers for each of the 32 coil segments, and how they are grouped into the 16 PF load cases needed for the DCPS coefficients.

7.4 Checkers Calculation Model

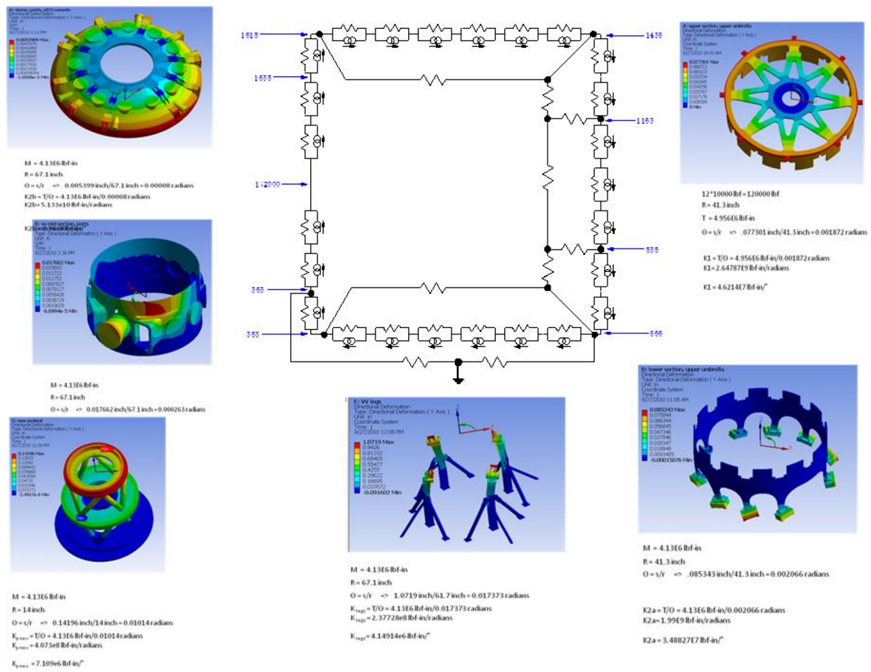


Figure 7.4-1 Excerpts from the Checkers Calculation [6]

Bob Wooley's model is described in detail in reference 6 and is an interesting variant on a global simulation of the NSTX-U structure. Torsional stiffnesses from segments of the machine are assembled into a network of resistor analogs, and then solved. As an electrical network.

8.0 Global FEA Models and Results

The global model [2] has been exercised with a number of configurations to quantify the inner leg torsional shear. The slide below, Figure 10, summarized this work for the PDR. One point made in the slide is that the compressive stresses due to TF centering load wedge pressure, are small. In other tokamaks. the compressive stress improves the shear capacity of the epoxy bond. For NSTX Upgrade there is minimal help from the compressive stress. (NSTX has more compressive stress). There are actually some tensile stresses that develop away from the corner where the currents "bunch" This is addressed in Han Zhang's coupled current diffusion calculation[13]. A number of design evolutions effected the OOP structural stiffness's and varying degrees of the 96 scenarios were analyzed for various configurations of the machine. The global model analysis is based on generation of load files outside the structural solution in ANSYS. a Biot Savart solution is used which takes about an hour per load file. Recently these have been updated to include the 10% headroom in the design point spreadsheet load calculations and load files with and without the plasma have been run. But these are still based on an older +/-24kAOH scenario set, and the results of this analysis are updated by application of the influence coefficients.

A variety of current and earlier results are shown in this section to build confidence that the shear stresses in the inner leg are adequately calculated by both individual current set calculations and applications of the influence coefficients.

TF Inner Leg Torsional Shear

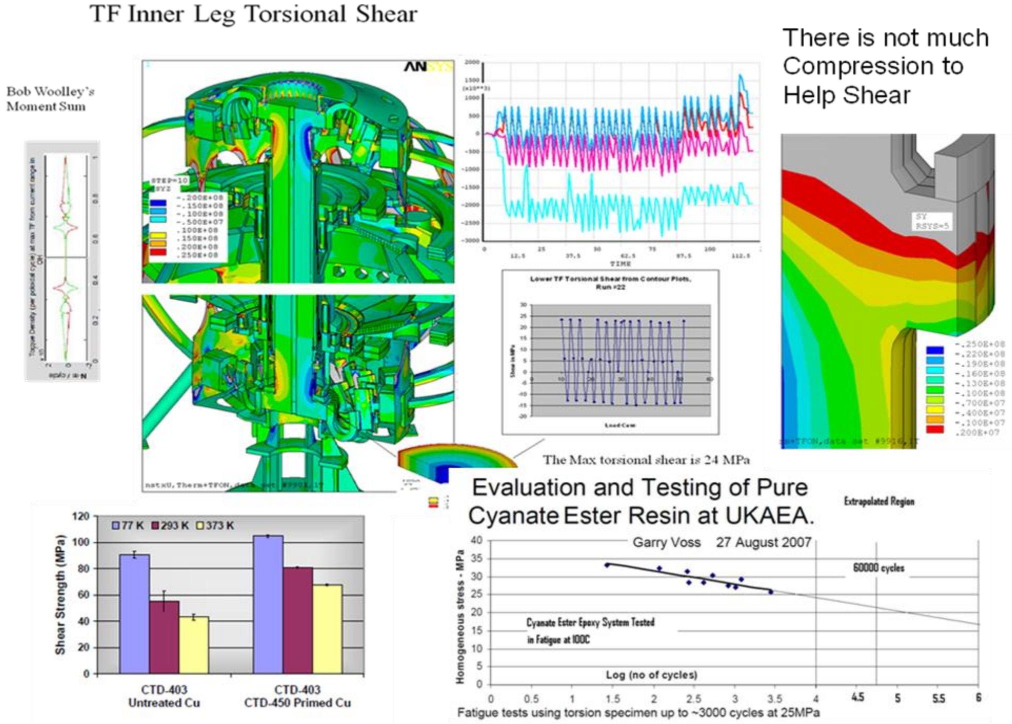


Figure 8.0-1 Initial Model Representing the Earlier (2010) configuration

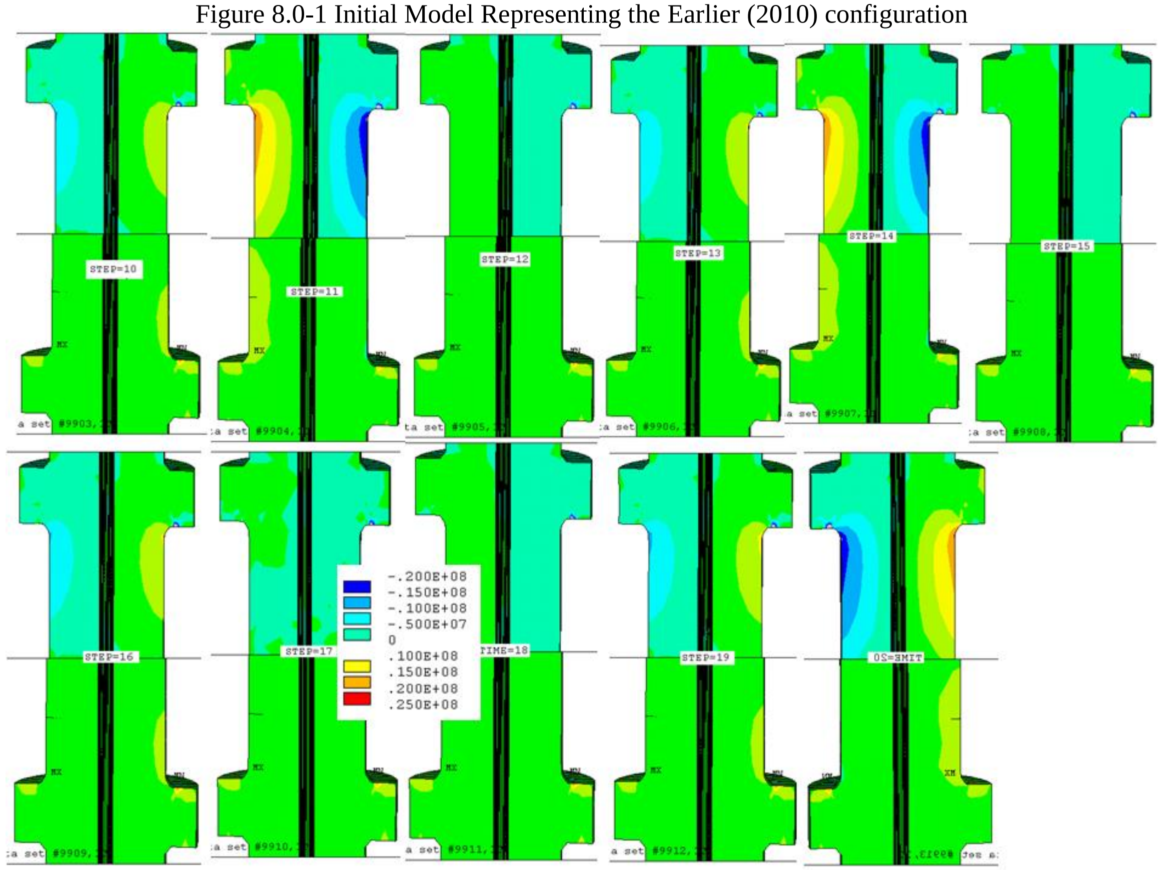


Figure 8.0-2 Torsional Shear Results from Global Run #27 [2]

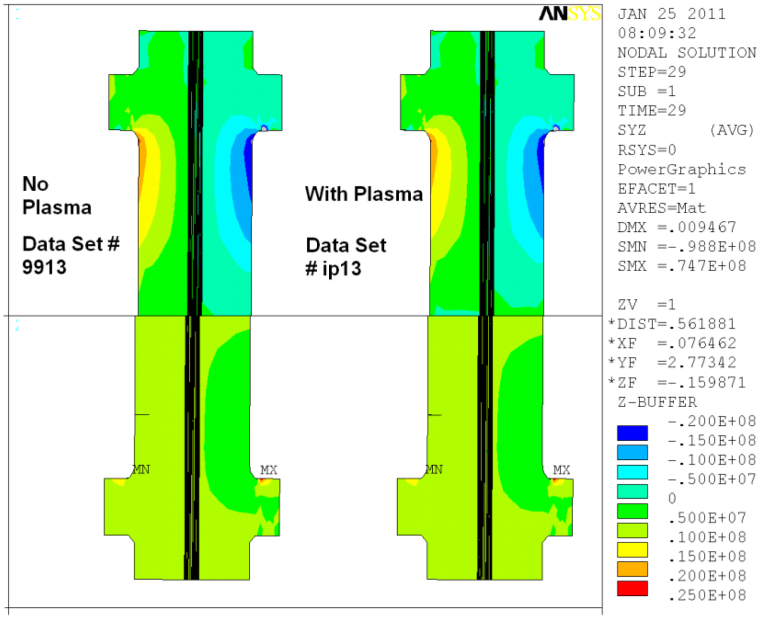


Figure 8.0-3 This shows one current set in which the plasma current effect on the torsional shear is difficult to discern.. From the influence coefficient calculations it is about a 1 MPa effect (see Figure 6). The magnitude is close to 20 MPa.

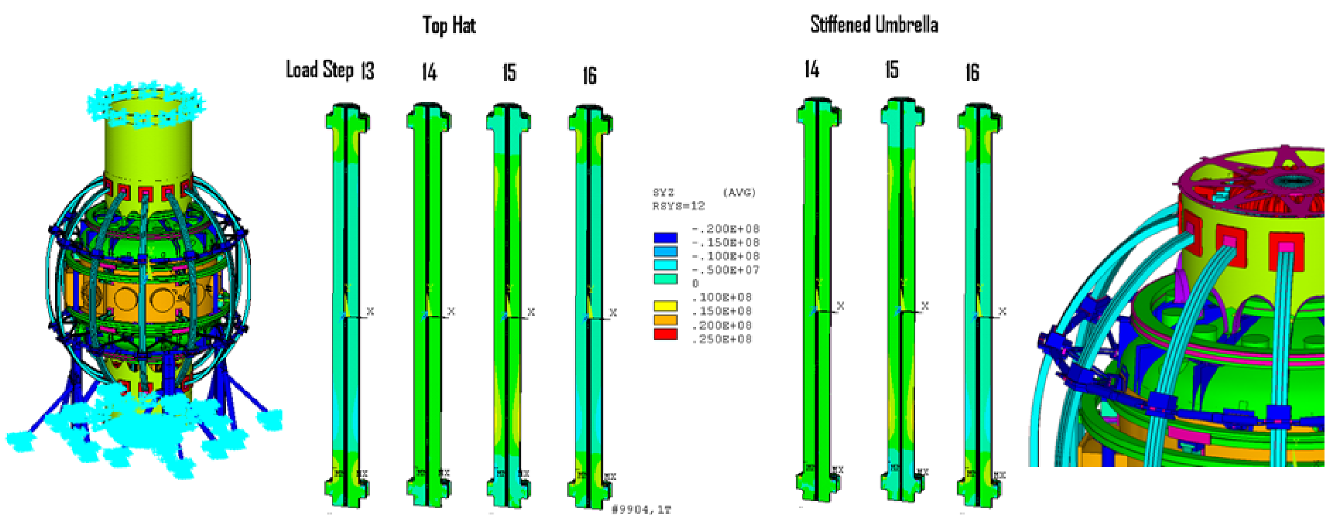


Figure 13

Torsional shear stress in the inner leg was an issue when an extension of the upper umbrella structure (Top Hat) along and struts extending to the cell walls were suggested to support the net torque of the machine and hopefully reduce the torsional loading at the vessel mid plane and other structures that were affected by the OOP loading. Competing with these reinforcements is the arch reinforcement that was proposed early in the CDR. The "top hat" did help the port region, and the umbrella legs, but did not appreciably alter the inner leg torsional shear stress. Only a few load cases were considered. It was the cost of the "top hat" installation that was unattractive.

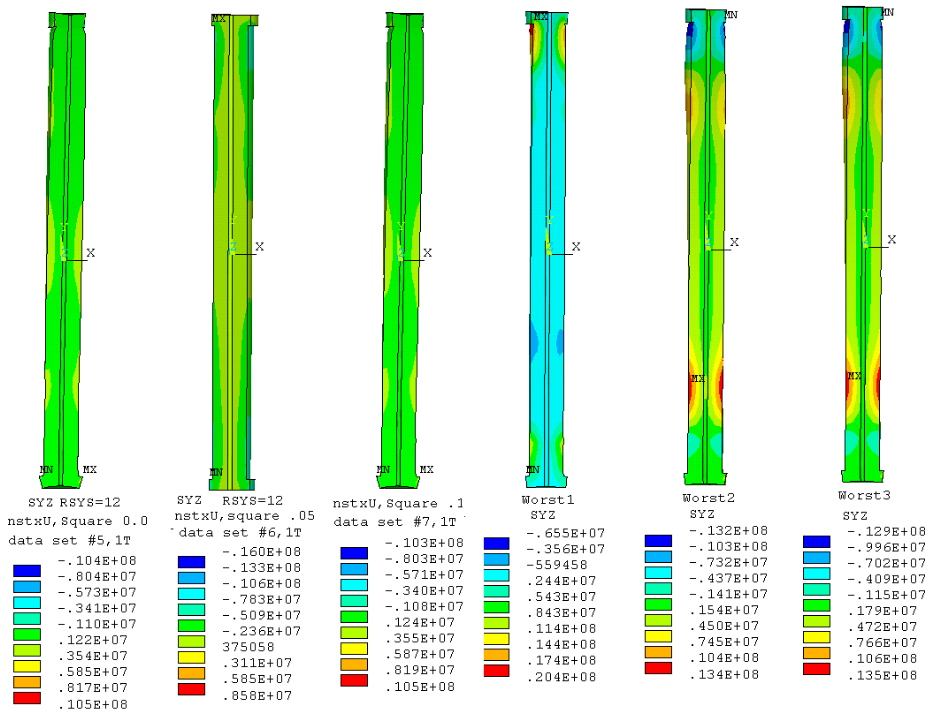


Figure 14 CDR Results

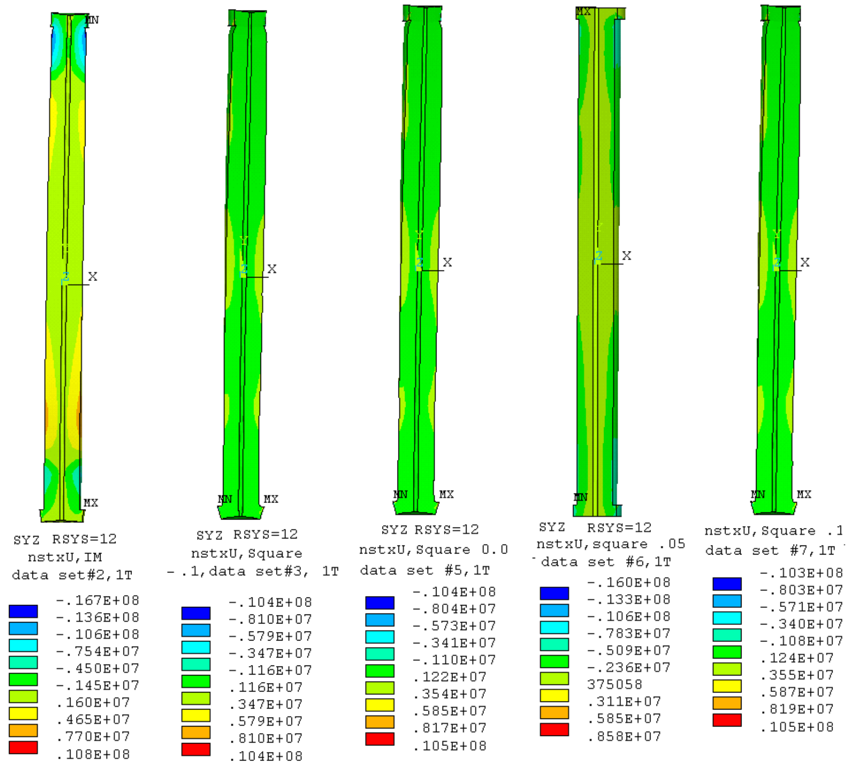


Figure 15

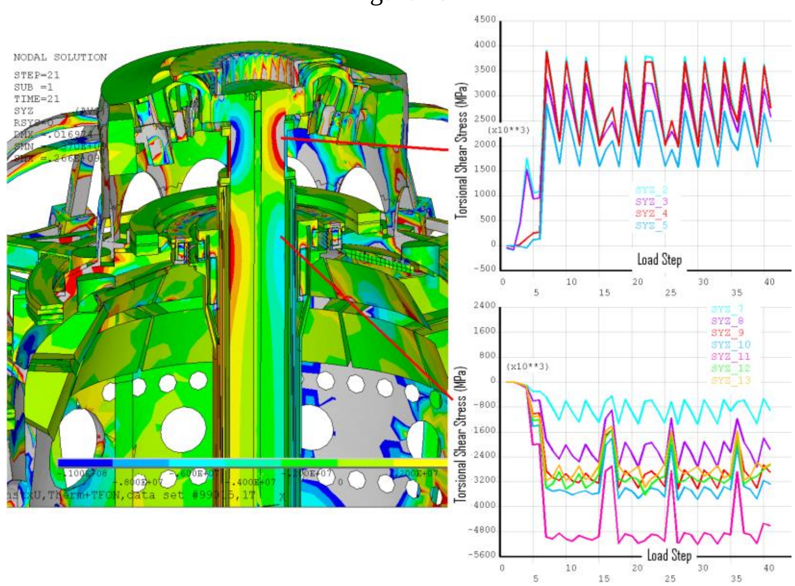


Figure 16a CDR results - Note that the time history plots are inconsistent with the contour plot results.

The inconsistency betrween the time history data and the contour data ia a consistent problem with ANSYS TimeHis6 postprocessor. The time history results are Included to show the relative values of torsional shear for a number of equilibria.

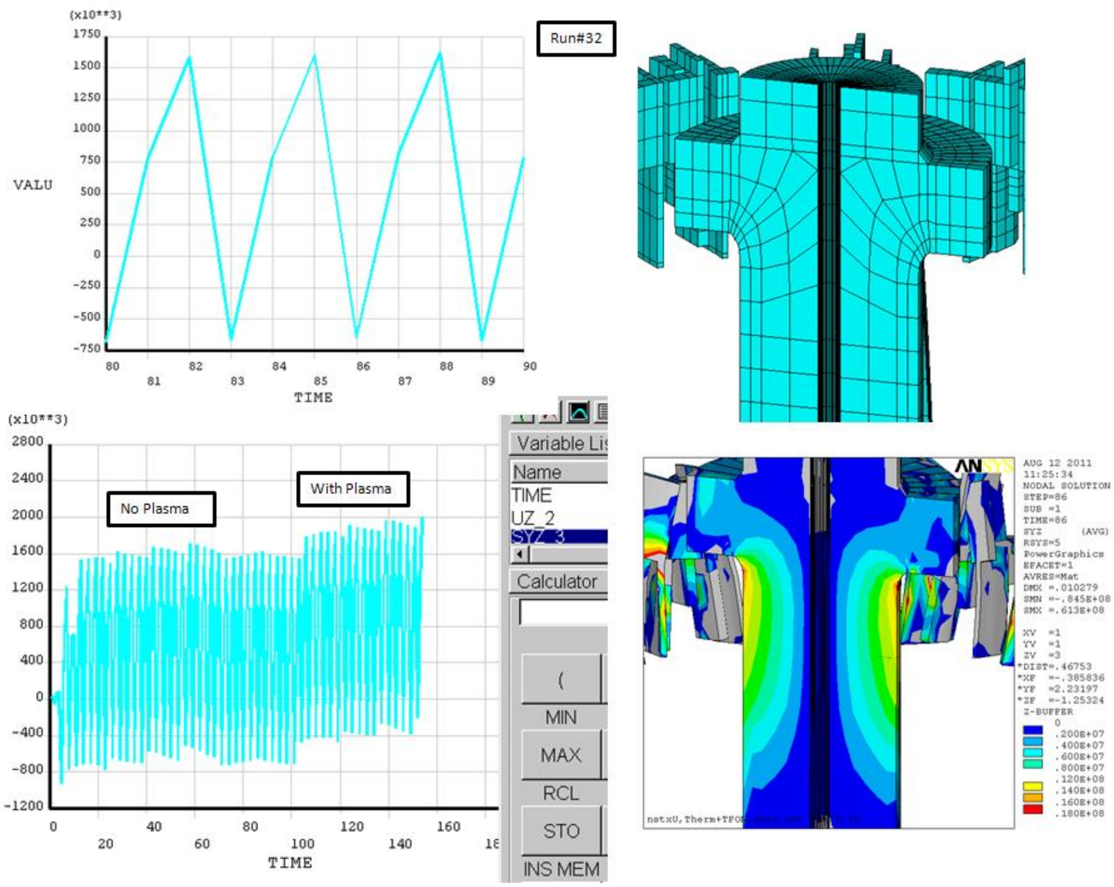


Figure 16b FDR results for Global Model Rrun #32, for the Upper Corner

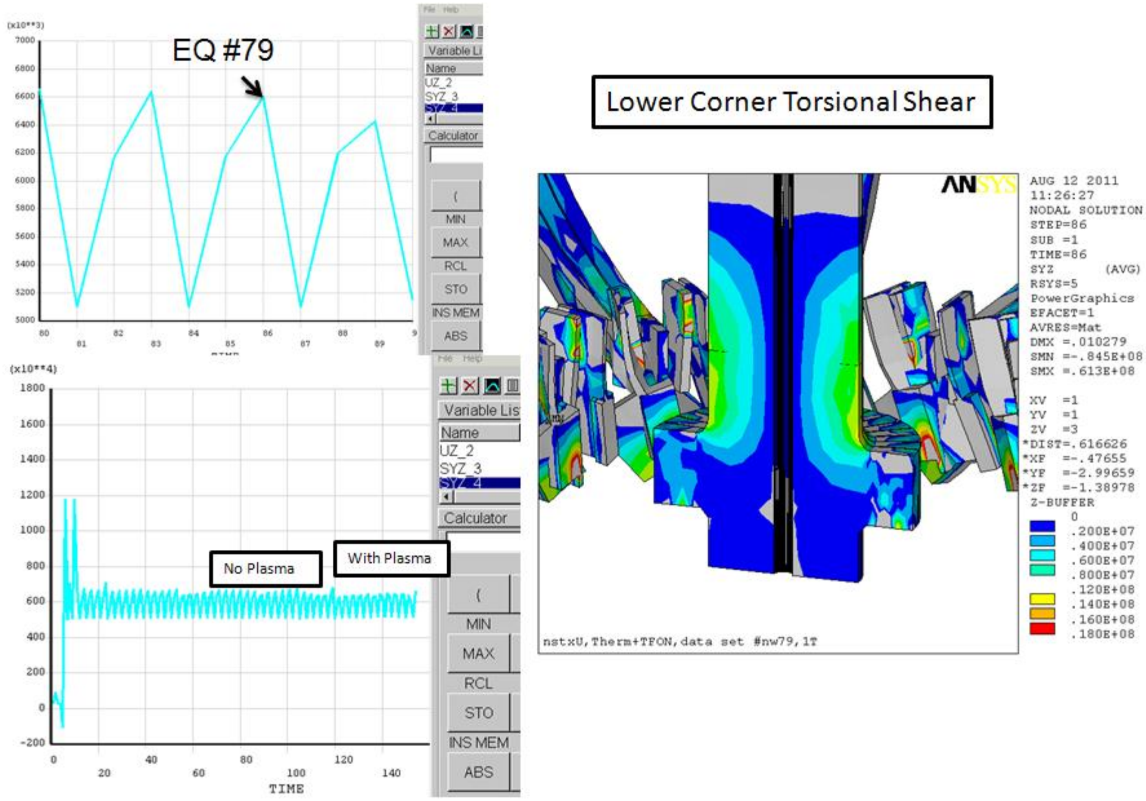
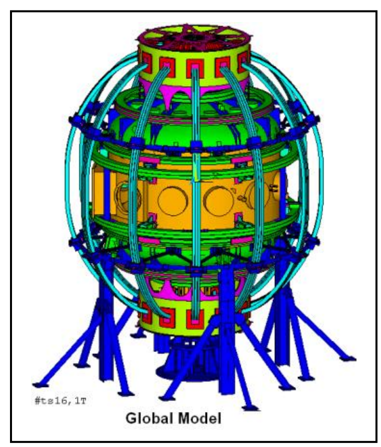


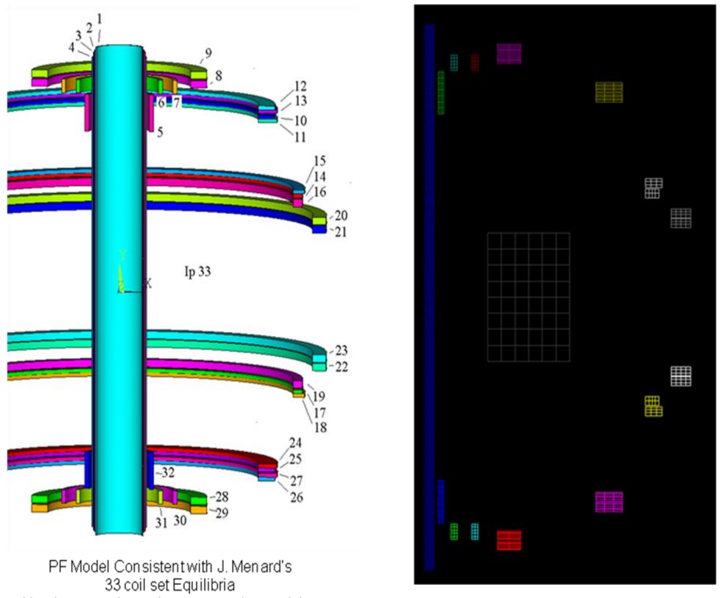
Figure 16c FDR results from the Global Model Run #32, for the Lower Corner

The difficulty with the TIM His 6 postprocessor remain in Version 13 of ANSYS. The results for the latest modeling of the global model which included the Vee truss pedestal, and the flat lower spoked lid are slightly below the 20 MPa level.

9.0 Details of the Digital Coil Protection System (DCPS) TF Inner Leg Torsional Shear Influence Coefficients from the Global Model



The methodology employed here has some history in the original NSTX. The coil protection calculator exercised a model of the TF system with unit PF currents and calculated stress multipliers. This is described in Irv Zatz's memo [12]. Much of the initial work on coil protection was done in support of TFTR operation. The theory is also described in Bob Woolley's DCPS system description document [1]. In Woolley's document he describes a system code which predicts elastic responses of the entire tokamak based on unit coil currents. The global model employed here is essentially this systems code. The inner leg torsional shear is a single stress component, and lends itself to the linear superposition methodology that Woolley describes. Other coil and structure performance evaluations will be based on equivalent stresses or combinations with thermal effects, that will make simple application of linear superposition less tractable. ,



PF Model Consistent with J. Menard's 33 coil set Equilibria Used as a starting point to create the model at right.

PF Model Consistent with R. Hatcher's 16 coil set Influence Matrix,

Figure 9.0-1 Coil Builds Used in the FEA analyses and the DCPS

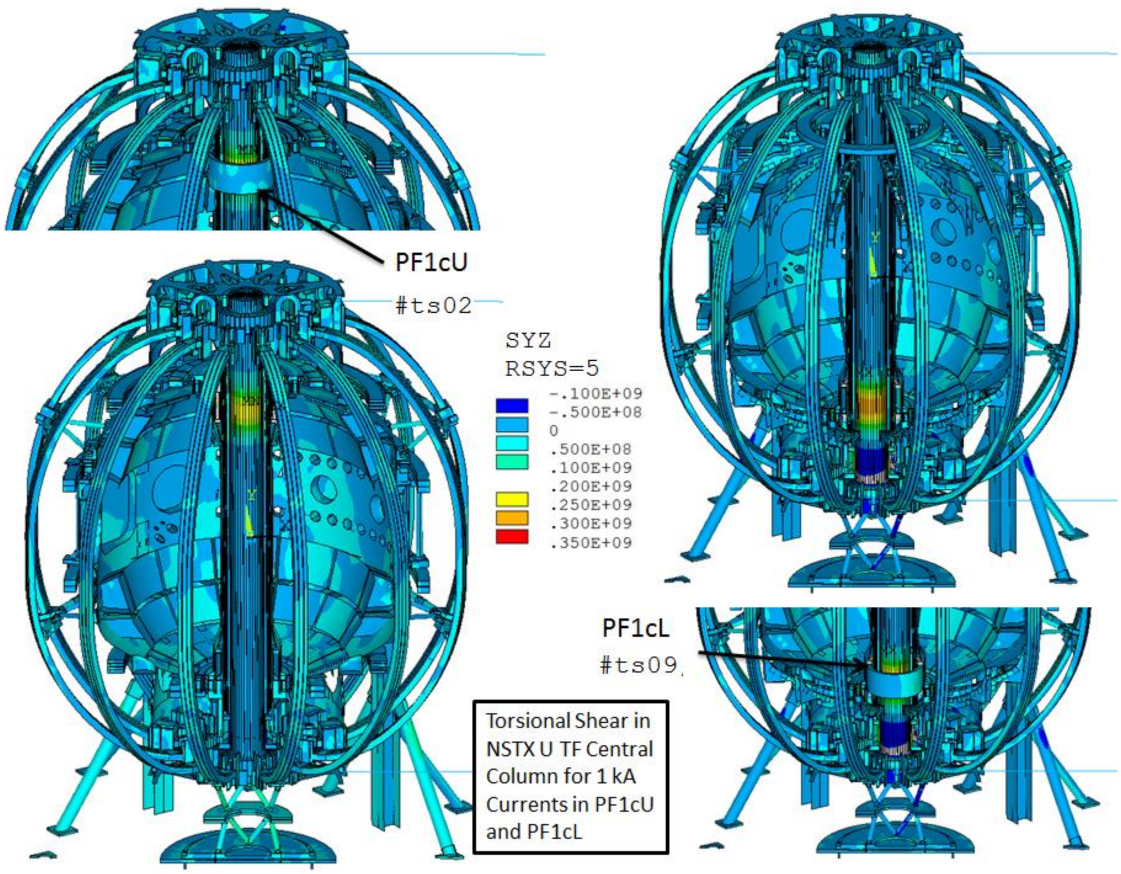


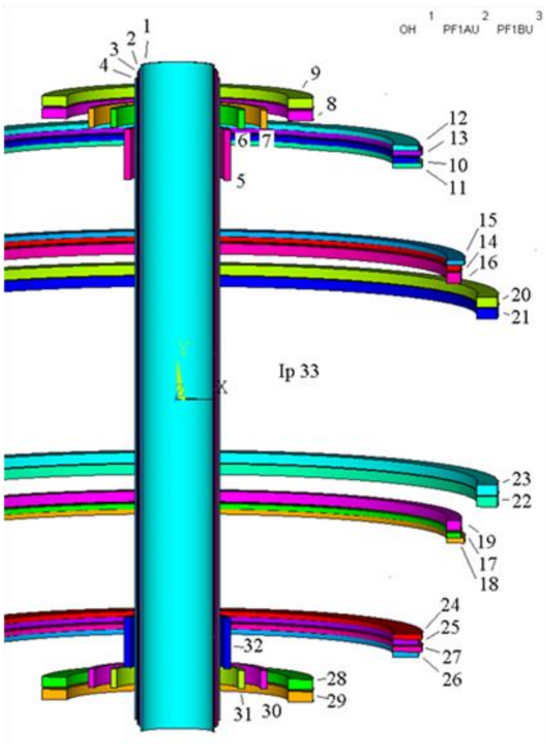
Figure 9.0-2 Global Model Response with Unit Loading from PF1cU (left) and PF1cL (Right)

The global model Lorentz Forces are computed for a coil set that includes all individual coil pancakes. To be consistent with the influence coefficients used in the DCPS, a regrouping of the coils is necessary.

If the fixity supplied by the crown connections, at the upper and lower ends of the inner leg, is sufficient, then only a model of the inner leg is needed. This would allow a simpler modeling of the inner leg shear, but calculations of the influence coefficients for the global model and a simpler TF model with fixity at the umbrella structures showed that there were large contributions from the outer PF coils that were suppressed by artificially fixing the umbrella structure.

. A detailed calculation of the inner leg shear stress relies on the elastic response of the entire tokamak and the Lorentz Loads from the poloidal field distribution crossing the inner leg currents. The global model was run with full TF current and 1000kA of current in each PF coil. The influence coefficients are based on 1 kA, but it was expected that TF loading might overwhelm the loads from individual smaller coils. The model is linear and the stress due to the PF loads should be fully scalable by current. The influence coefficients are corrected in the spreadsheet. The force calculations are computed The torsional shear in the upper and lower inner leg radii were then determined from each of the 16 load cases that resulted.

Mapping the 33 Coil set to the 16 Coil Set Used for the Influence Coefficients



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip

```
! Input to NTFTM2 in Mat, PF currents Multiplied by 1000

irdt
2
pfcu
33,16,16,1.0
1  , 245, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,0
2  , 242, 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
4  , 236, 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
6  ,0   , 0, 108, 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
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, 9, 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
21 ,0   , 0, 0, 0, 0, 0, 0, 12, 0, 0, 0, 0, 0, 0, 0,0
22 ,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, 12,0
24 ,0   , 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 8, 0, 0, 0
25 ,0   , 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 7, 0, 0,0
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, 8, 0, 0,0
28 ,0   , 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 14, 0, 0, 0,0
29 ,0   , 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 14, 0, 0, 0,0
30 ,0   , 0, 0, 0, 0, 0, 0, 0, 0, 0, 162, 0, 0, 0, 0,0
31 ,0   , 0, 0, 0, 0, 0, 0, 0, 0, 180, 0, 0, 0, 0, 0,0
32 ,0   , 0, 0, 0, 0, 0, 0, 0, 120, 0, 0, 0, 0, 0, 0,0
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Figure 9.0-3

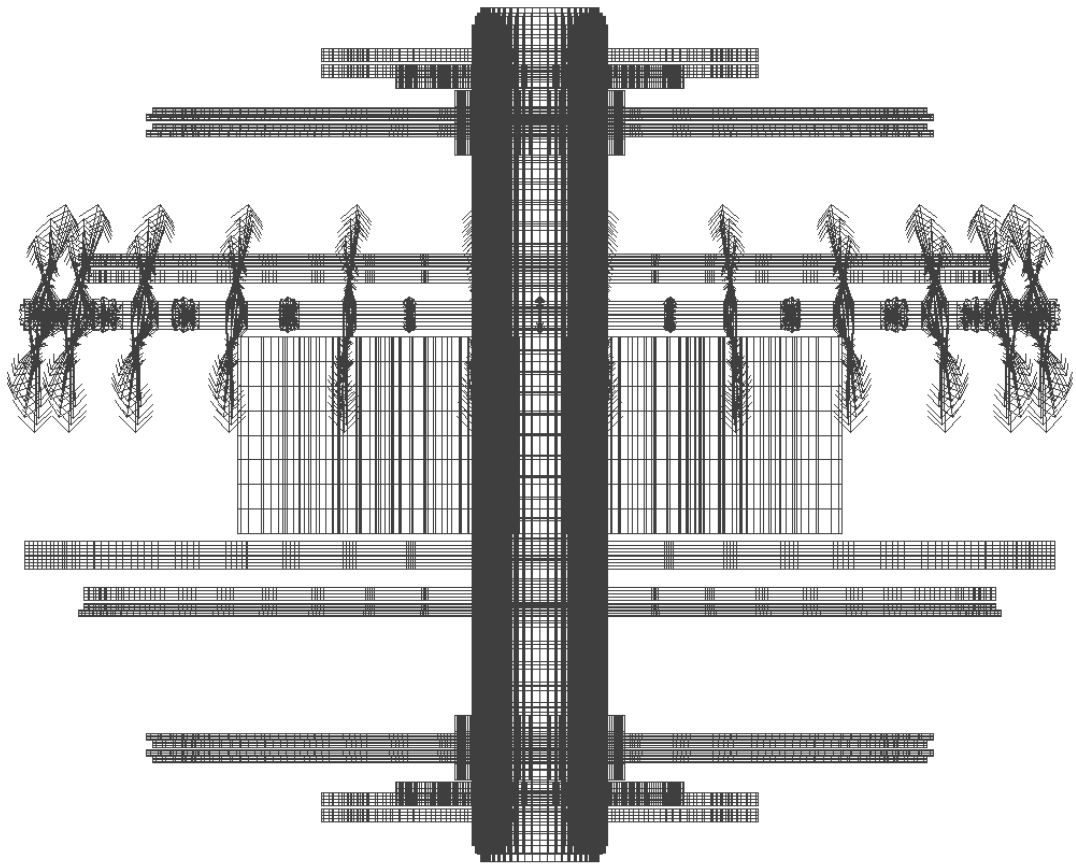
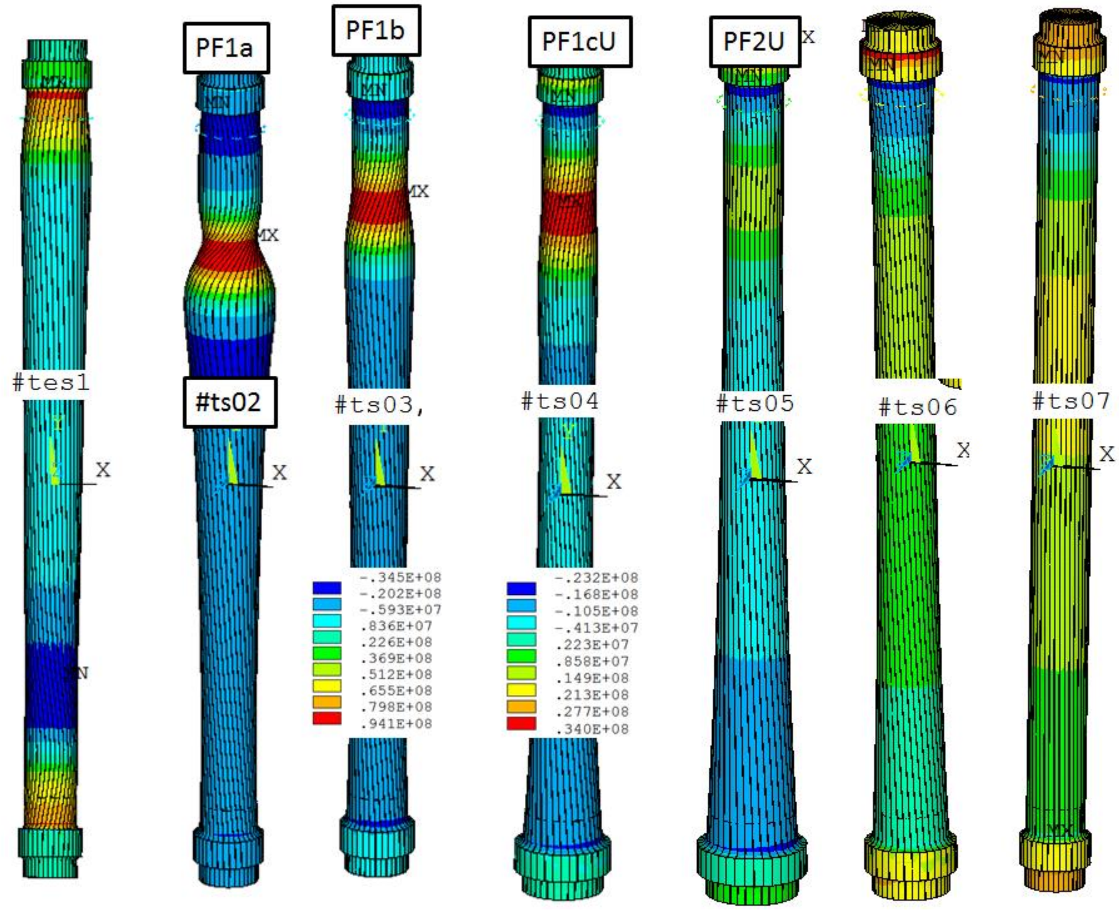
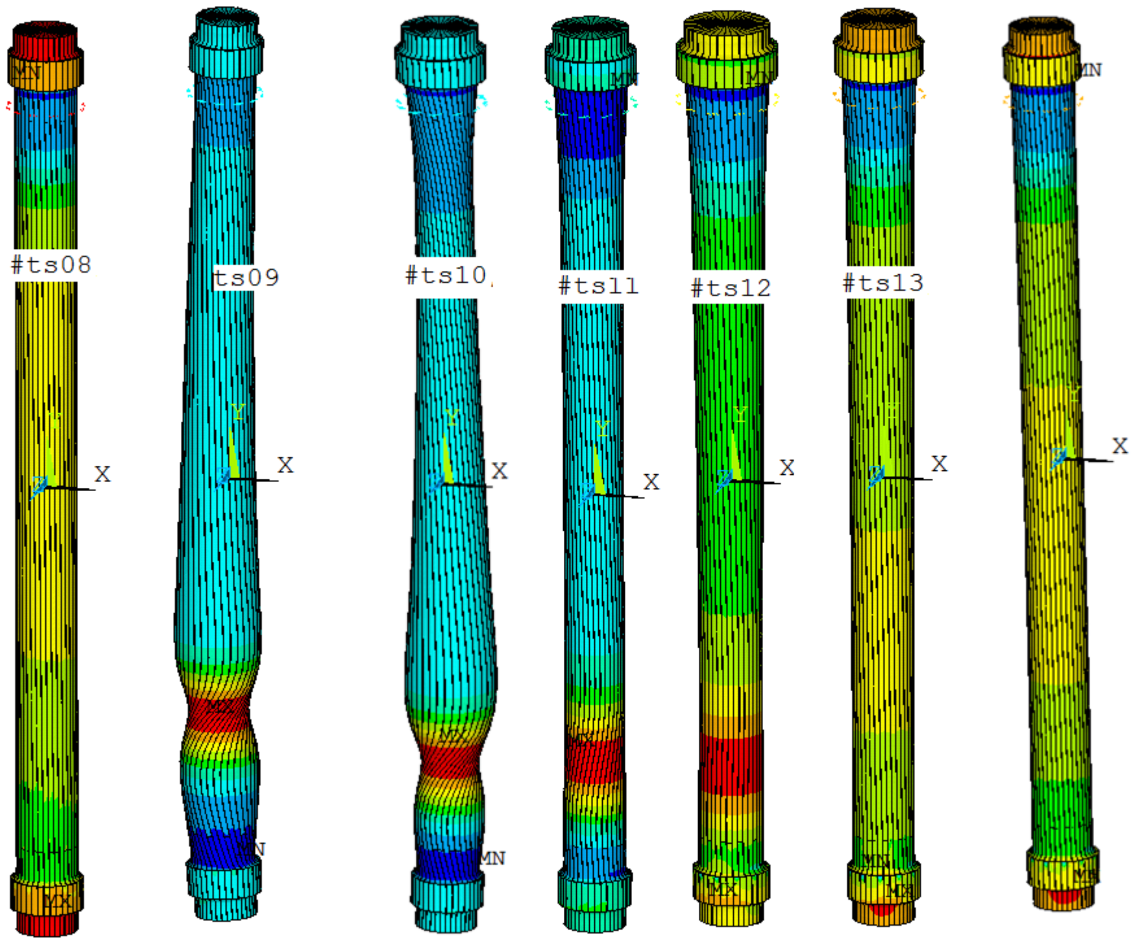


Figure 9.0-4 Forces on PF4u from a full TF current and 1 kA in PF4u. TF coils and forces have been removed to scale the much lower PF4 loads due to a kA terminal current.

Mesh generation , calculation of the Lorentz forces, and generation of the influence coefficients is done 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 elliptic integrals for 2D field calculations, and Biot Savart solution for 3D field calculations. These are based 2D formulations, and single stick field calculations from Dick Thomes book [8] with some help from Pillsbury's FIELD3D code to catch all the coincident current vectors, and other singularities.

The code in various forms has been used for 20 years and is suitable for structural calculations. It is also being used for calculation of load files in an NSTX global model[2]. Recent checks include NSTX out-of-plane load comparisons with ANSYS [10] and MAXWELL and calculations of trim coil fields for W7X compared with IPP and Neil Pomphrey's calculations. The analysts in the first ITER EDA went through an exercise to compare loads calculated by the US (using this code), RF and by Cees Jong in ANSYS, and agreements were good. Some information on the code, named FTM (Win98) and NTFTM2 (NT,XP), is available at: P:\public\Snap-srv\Titus\NTFTM


PF1a
PF1b
PF1cU
PF2U
#tes1
#ts02
#ts03,
#ts04
#ts05
#ts06
#ts07
-.345E+08
-.202E+08
-.593E+07
.836E+07
.226E+08
.369E+08
.512E+08
.655E+08
.798E+08
.941E+08
-.232E+08
-.168E+08
-.105E+08
-.413E+07
.223E+07
.858E+07
.149E+08
.213E+08
.277E+08
.340E+08



9.1 TF Upper Corner Shear Factors Based on the Global Model

9.1.1 November 2015 (Rev 1) TF Upper Inner Corner Shear Factors Based on Unit (1 kA) Loads

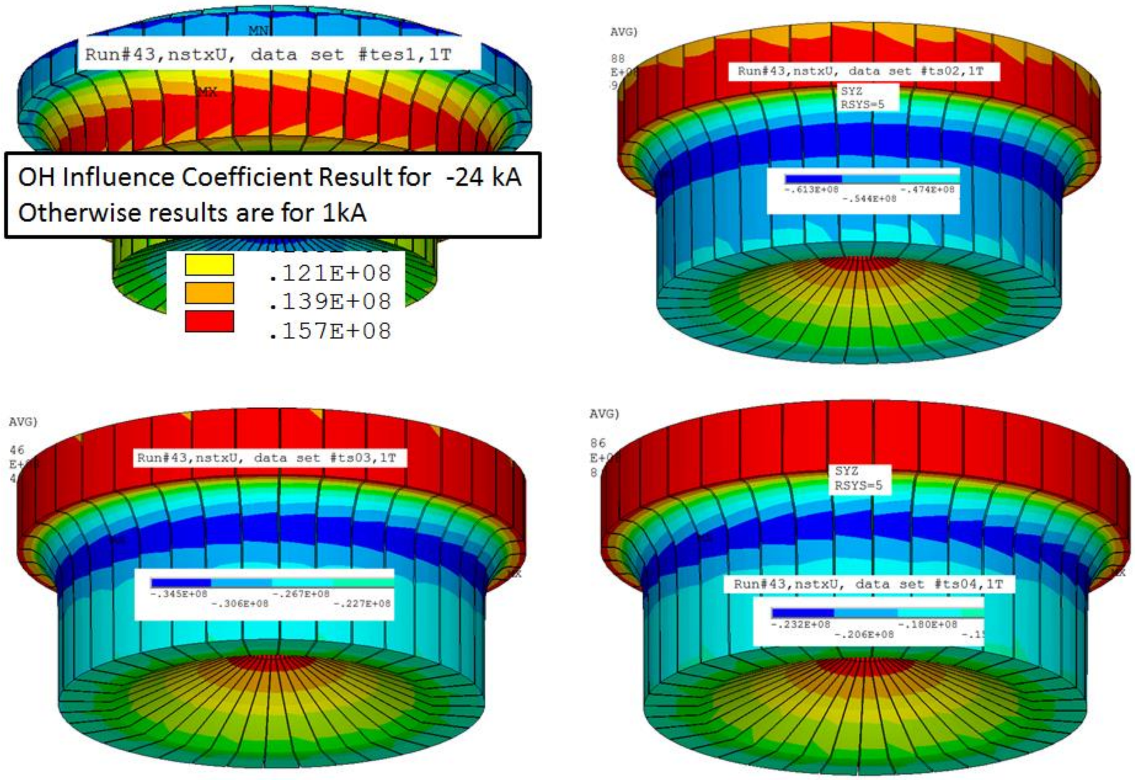


Figure 9.1.1-1Upper TF Factors 1 through 4

The OH factor is 15.7MPa/(-24kA)=-.654 MPa per kA. The remaining factor were post-processed in a manner similar to that represented in Figure 9.1.1.

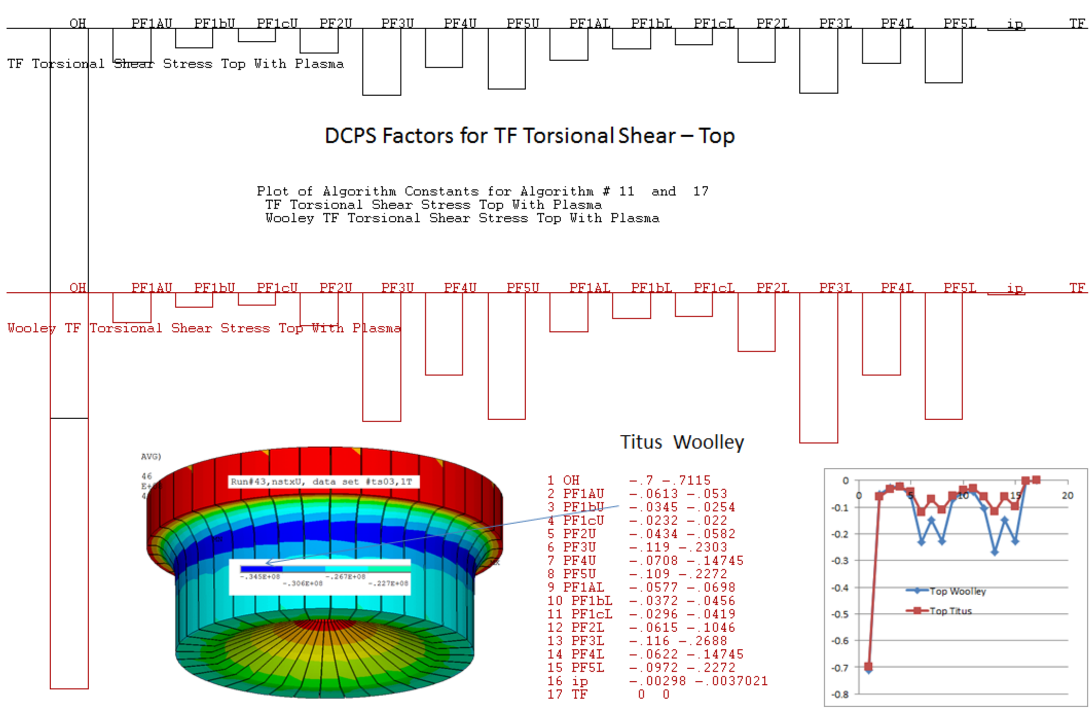
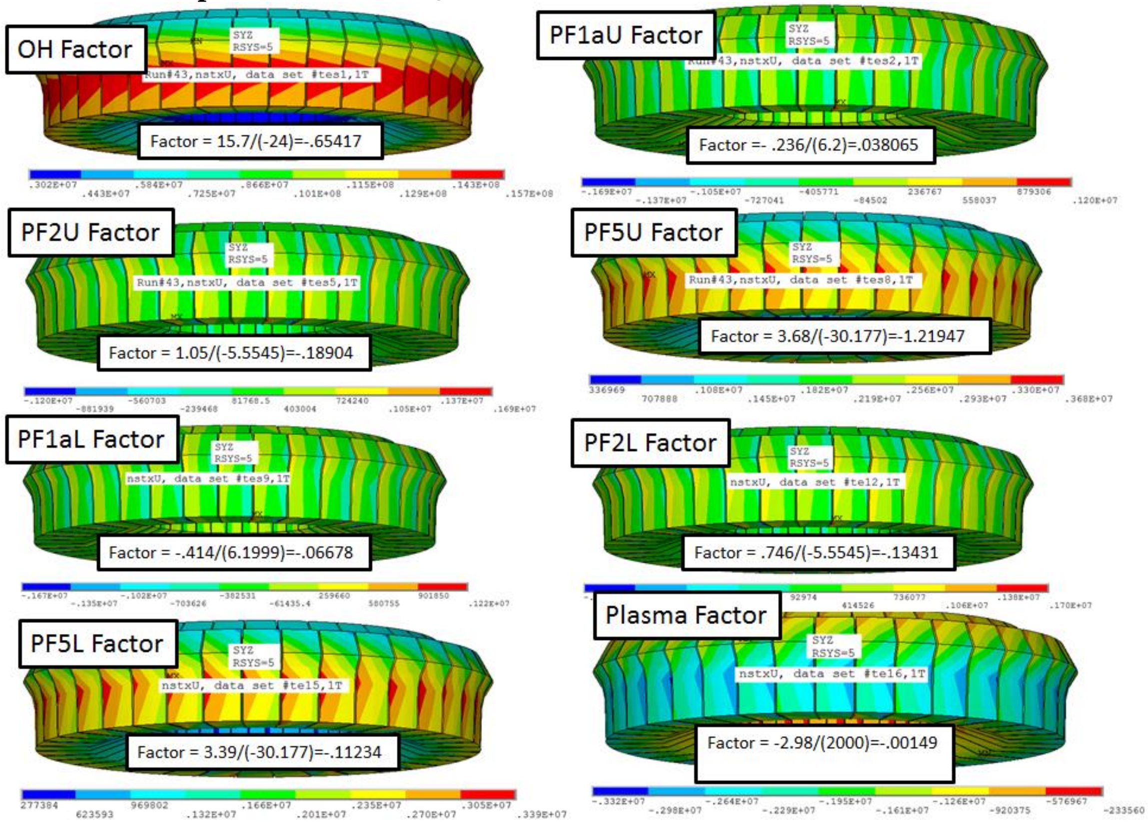
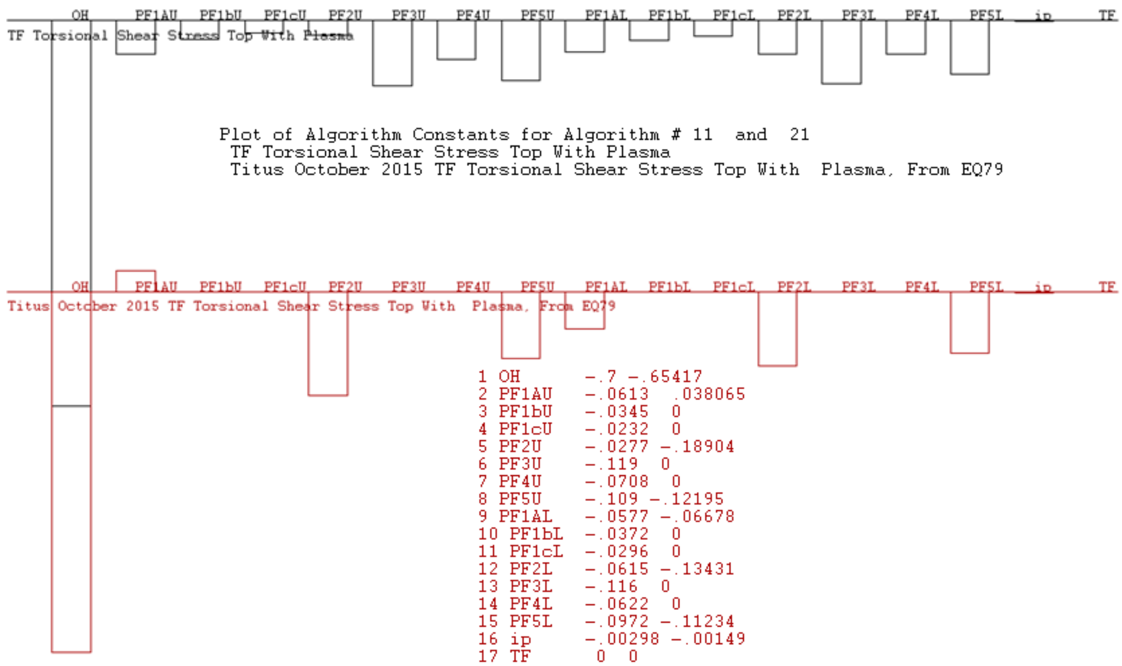


Figure 9.1.1-2 Upper TF Coefficients

Based on Components of the EQ 79 Current Set



This is a comparison of coefficients developed from unit (1kA) current loads vs. Coefficients developed from the individual EQ79 currents



9.1.2 January 2011 (Rev 0) Upper Inner Torsional Shear Factors

After checking these results they were rejected, but they are retained for comparison and to illustrate the difficulty in extracting the pertinent shear stress results from the FEA model.

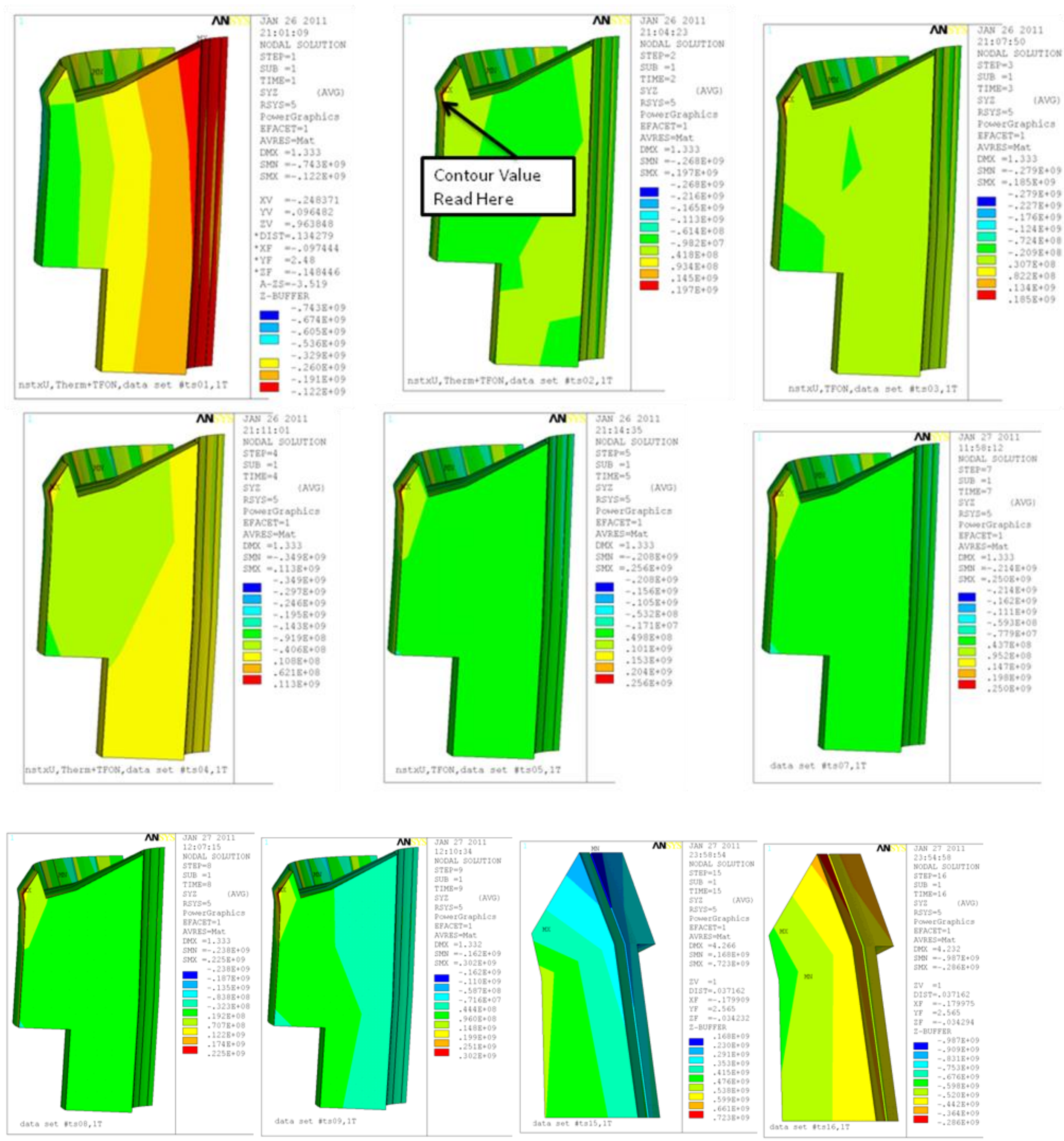


Figure 9.1.2-1 Selected Post Process Results from the upper Corner Shear Stress Influence Coefficients

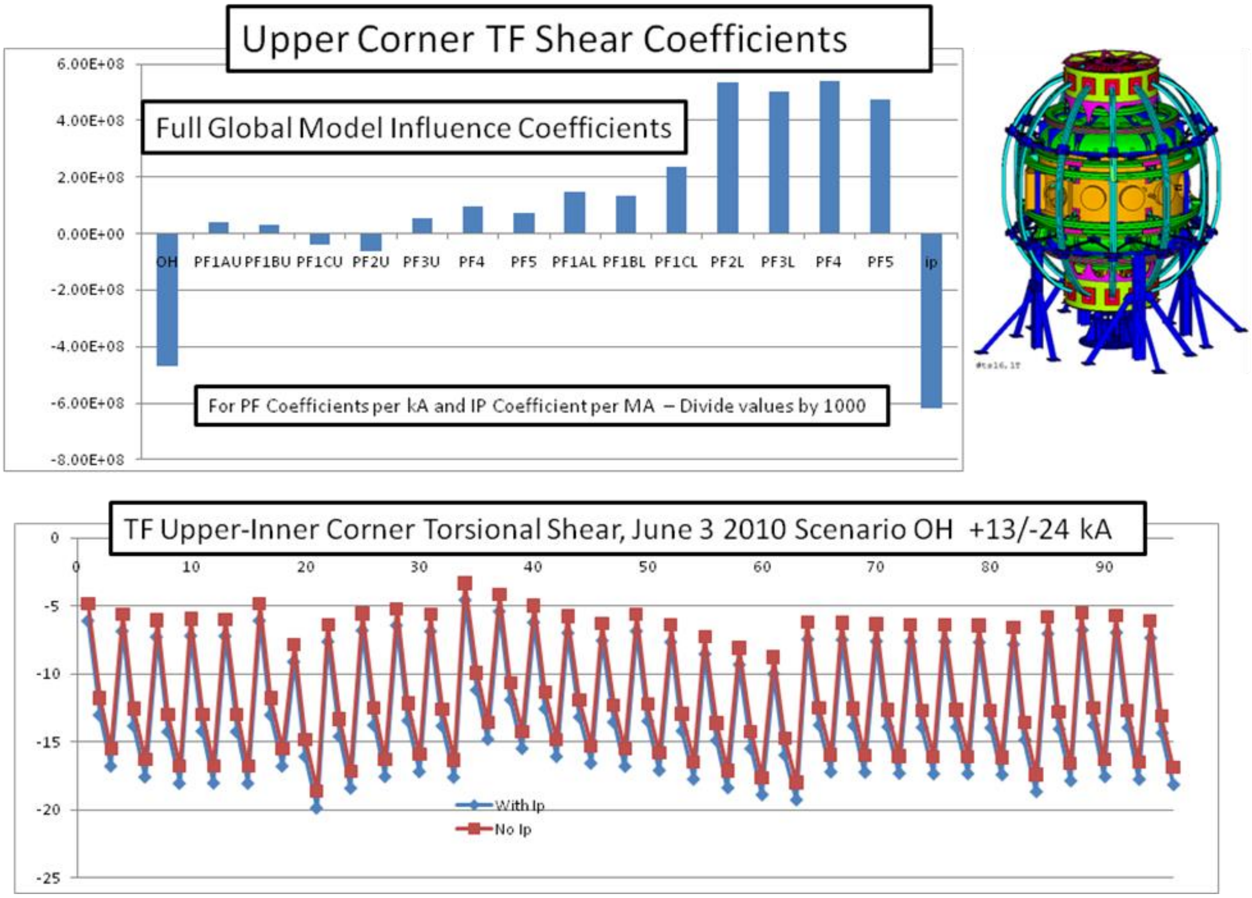


Figure 20 Global Model Upper Corner Results

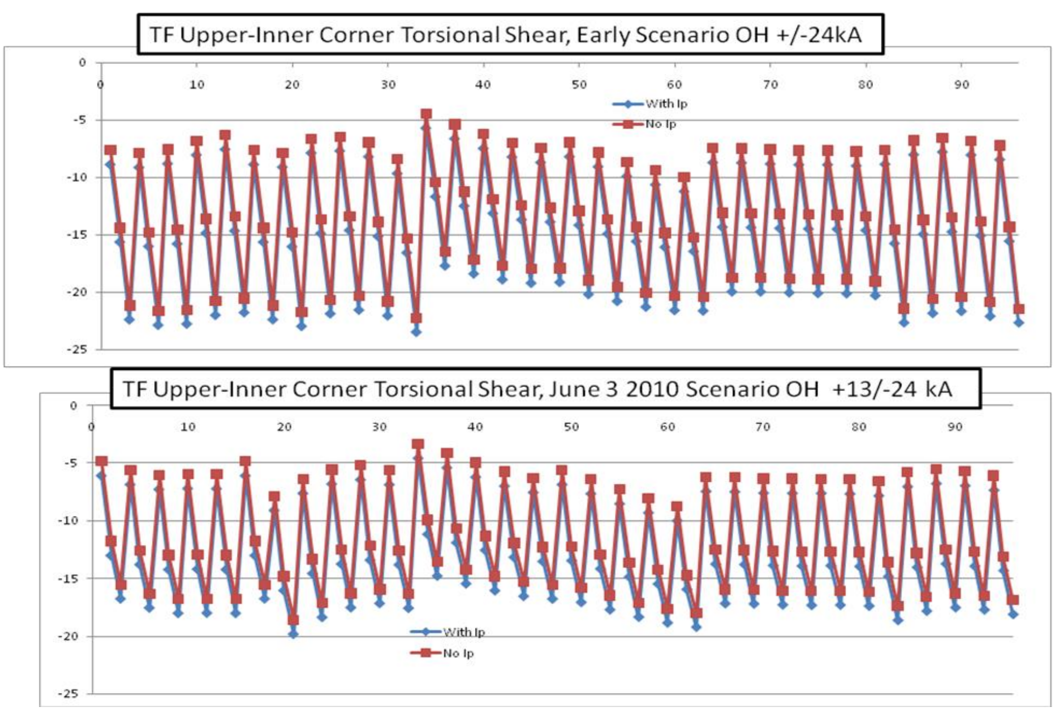


Figure 21 Global Model Upper Corner Results - Comparison of Early and Current Scenario Results.

9.2.1 Mid-Plane Torsional Shear Factors Based on the Global Model

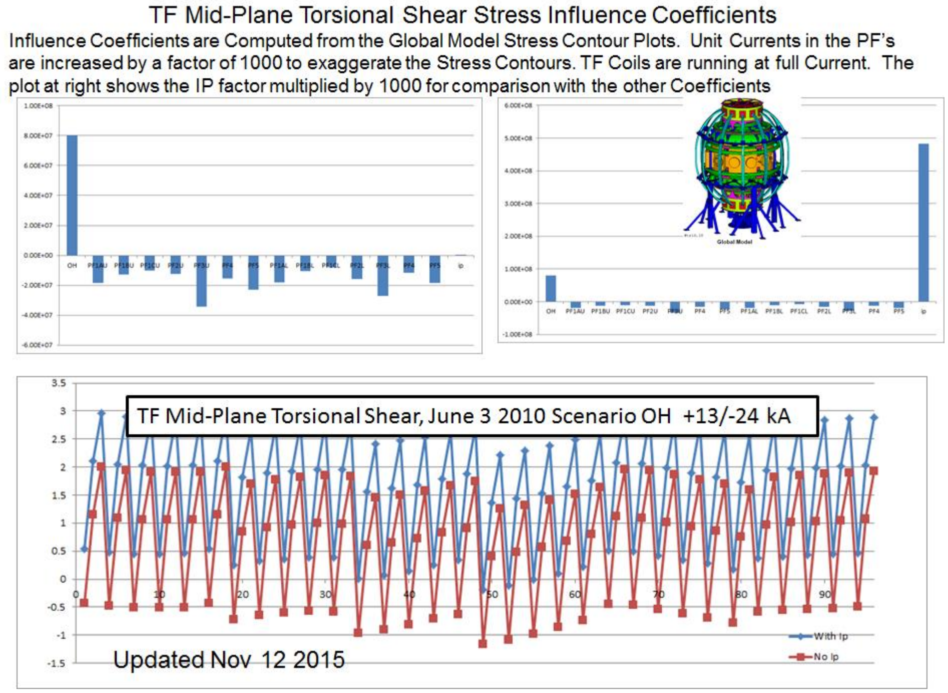


Figure 9.2.1-1 Global Model Mid Plane Results

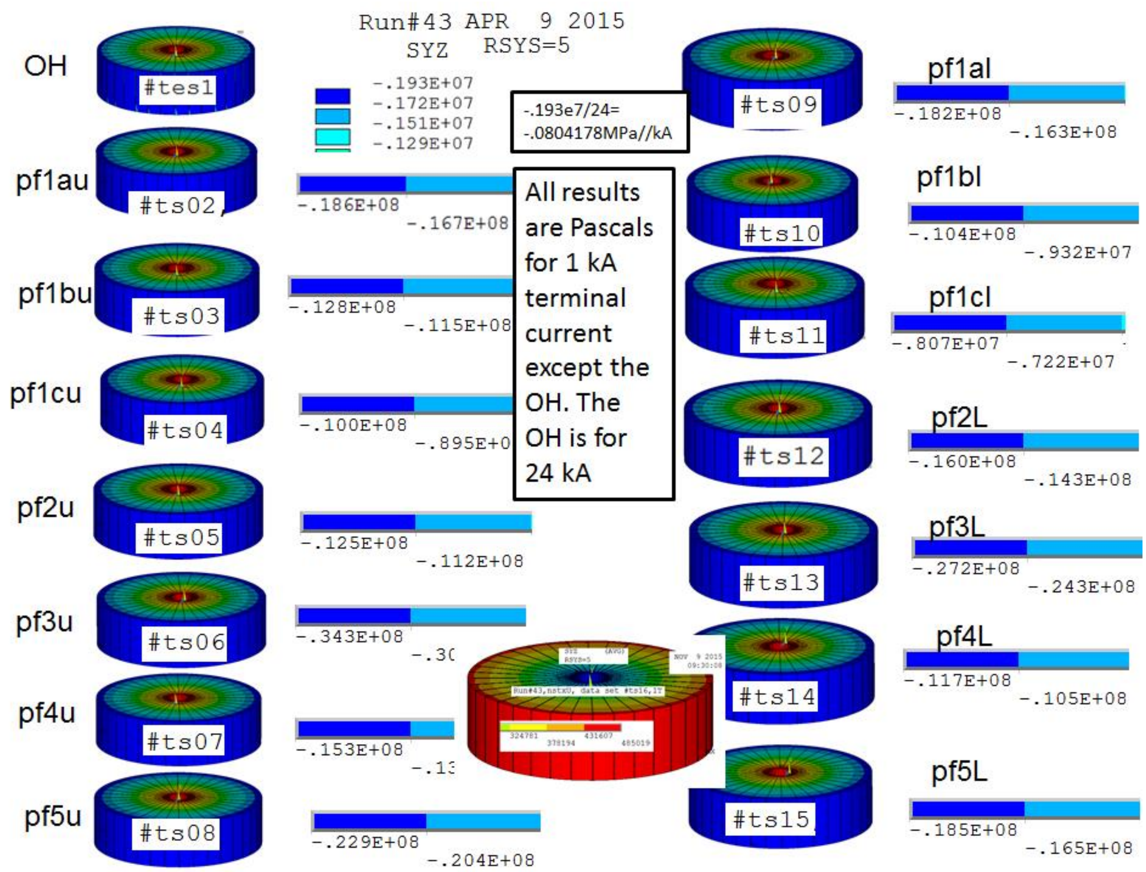
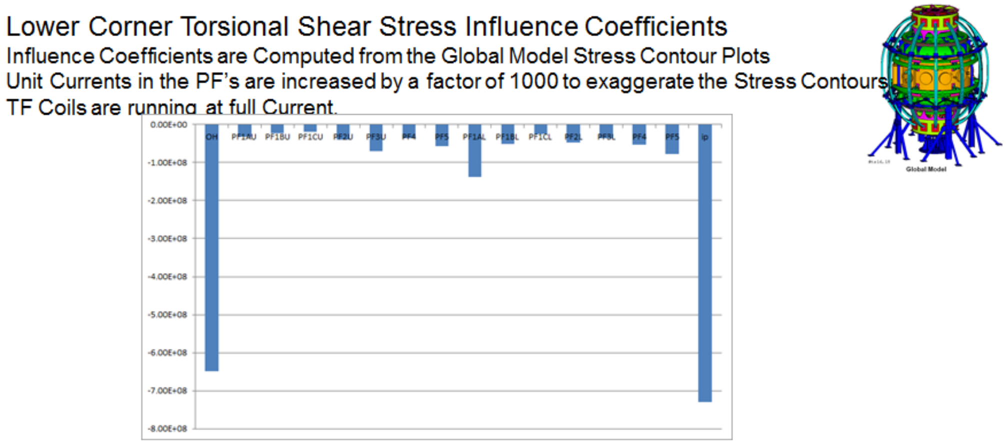


Figure 9.2-2 Global Model Mid Plane Results

The OH, and IP and values in red are derived from the nw79 EQ values.

9.3 Bottom Corner Torsional Shear Factors Based on the Global Model



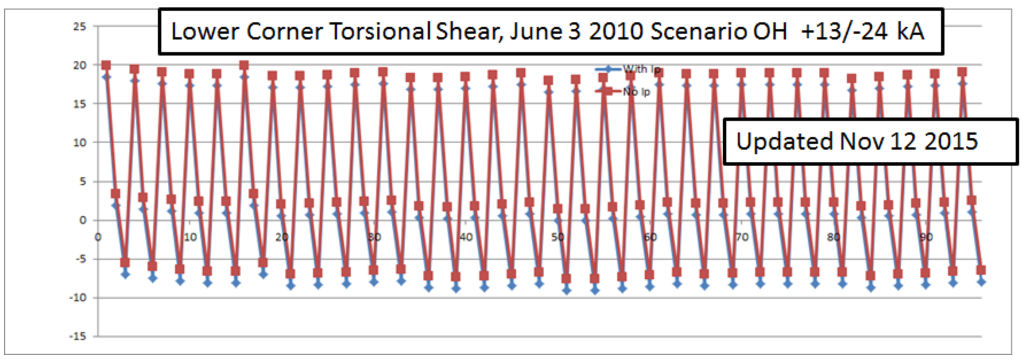


Figure 9.3.1 Global Model Bottom Corner Results

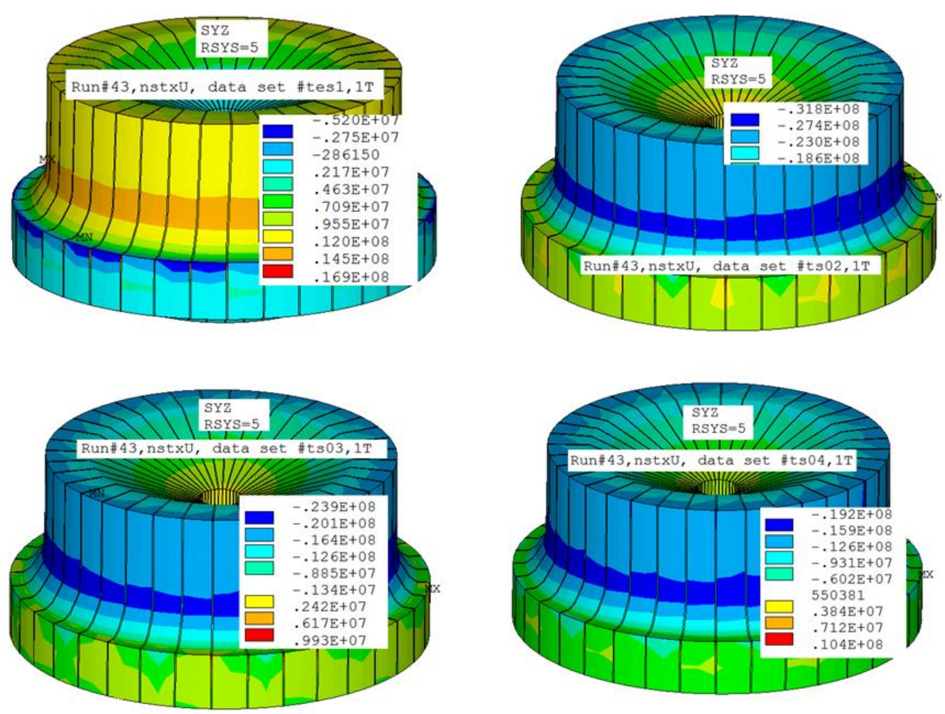


Figure 9.3.2 Global Model Bottom Corner Results, factors 1,2,3,4, OH, PF1aU, PF1bU, PF1cU

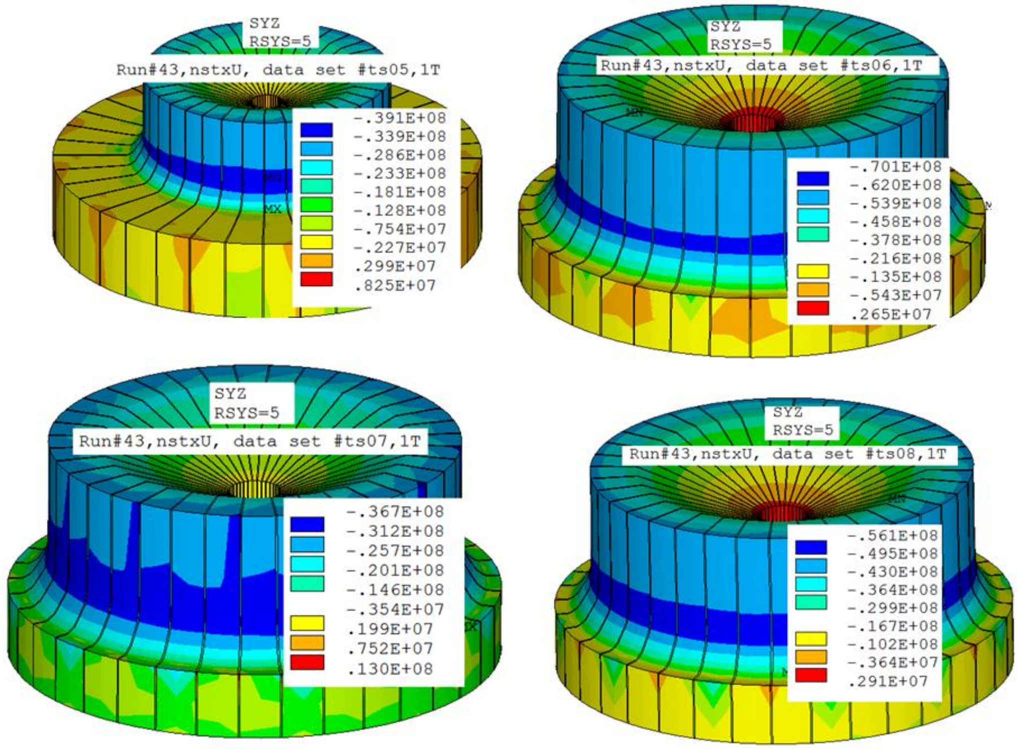


Figure 9.3-3 Global Model Bottom Corner Results for factors 5,6,7,8, PF2U,PF3U,PF4U and PF5U

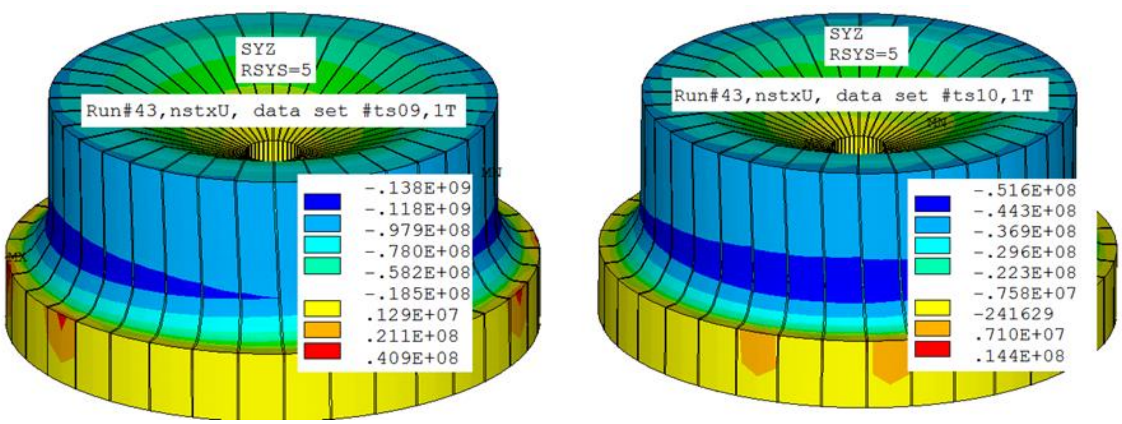


Figure 9.3-4 Global Model Bottom Corner Results, Factors 9 and 10 for PF1a l and PF1bL

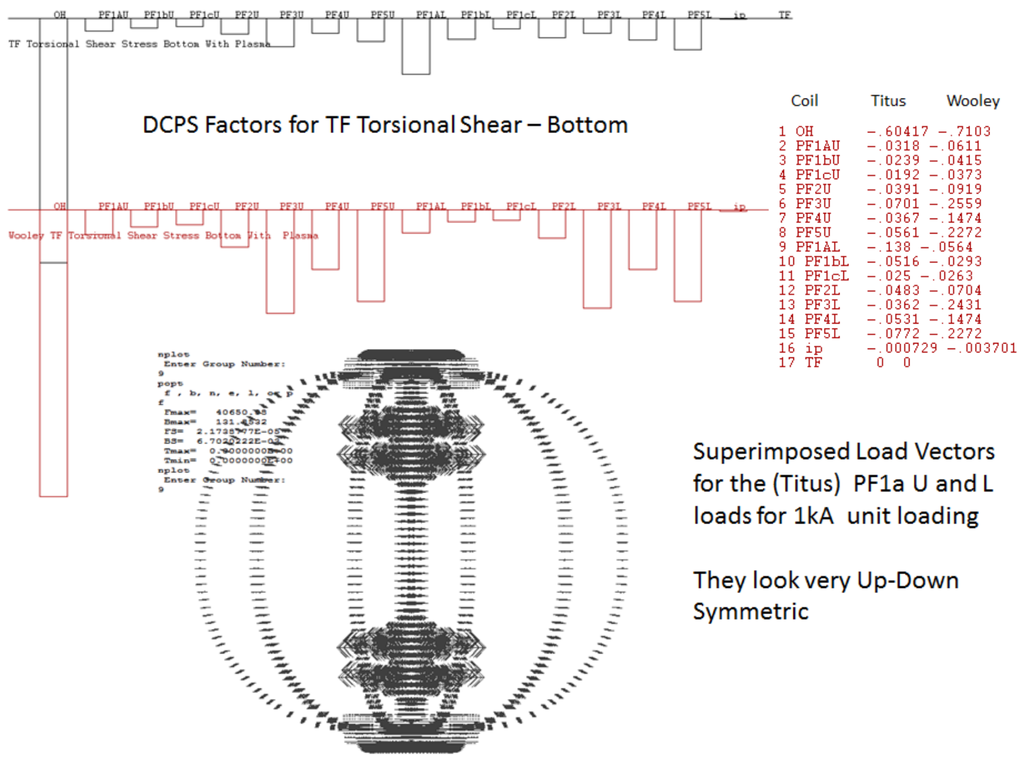


Figure 9.1.3-5 Bottom TF Factors and loading for PF1aU and L

In Figure 9.1.3-5 the loading due to PF1aU and L is up-down symmetric, but the torsional shear coefficients are different. This is a consequence of the different stiffnesses in the top and bottom of the machine. To build some confidence in the results, the load files were superimposed to check that the forces were up-down symmetric, and they were as expected.

January 2011 (Rev0) Lower Shear Stress Factors

After checking these results they were rejected, but they are retained for comparison and to illustrate the difficulty in extracting the pertinent shear stress results from the FEA model.

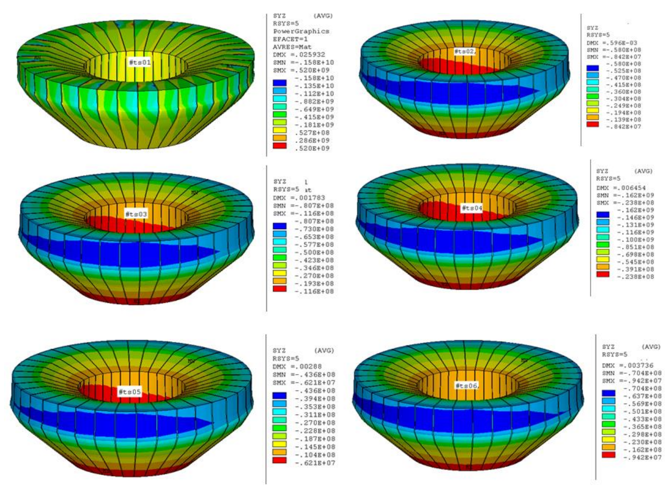


Figure 9.3-6 Rev0 Global Model Bottom Corner Influence Coefficients

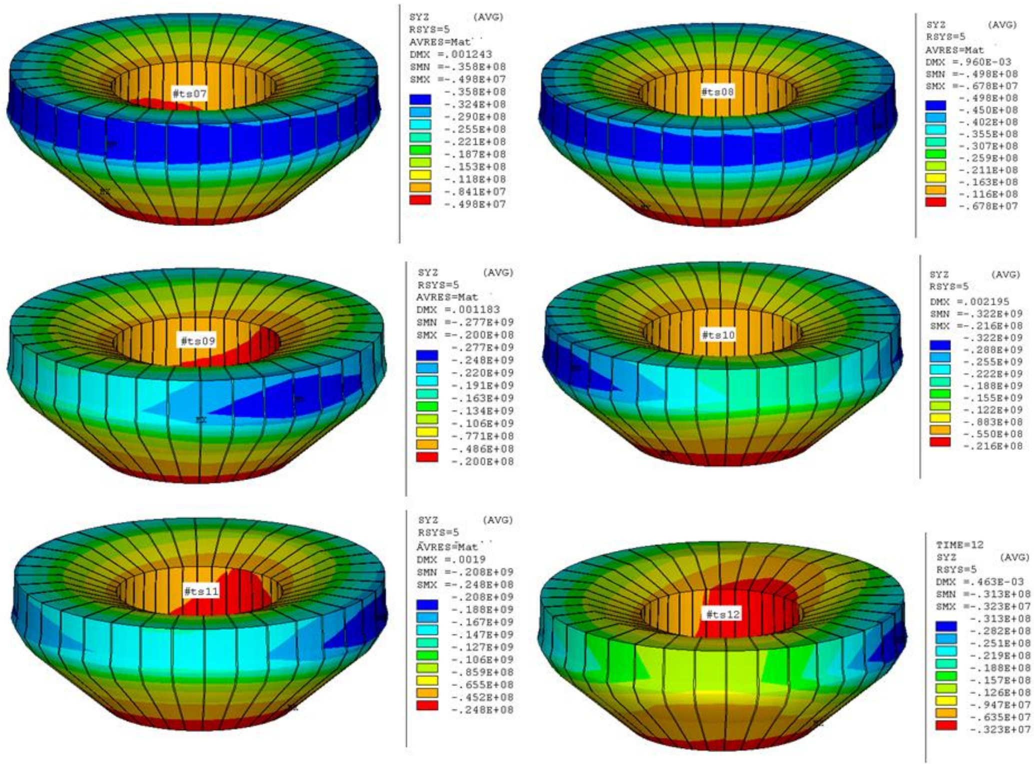


Figure 9.3-7 Global Model Bottom Corner Influence Coefficients

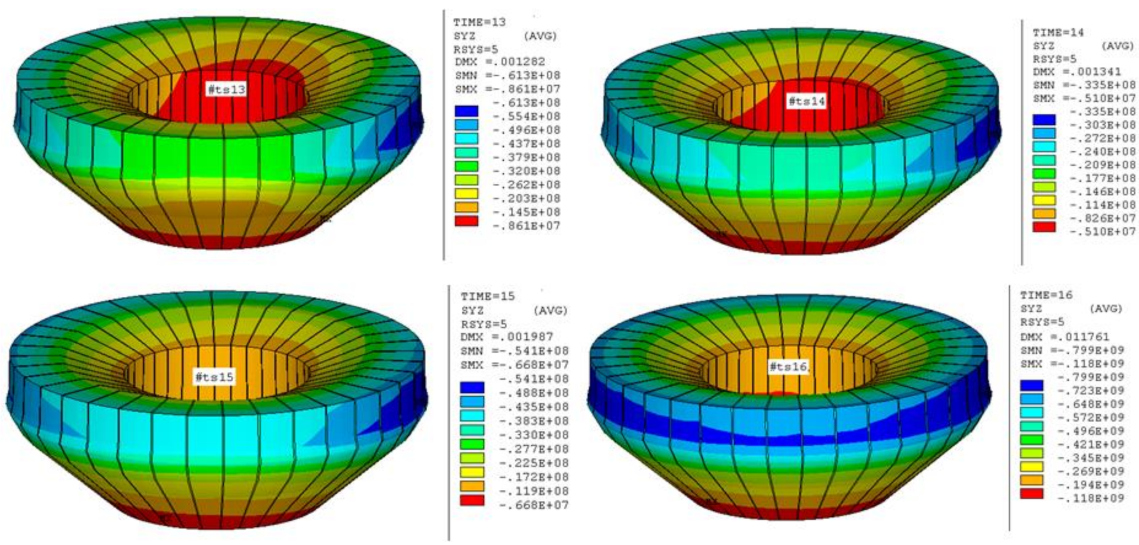
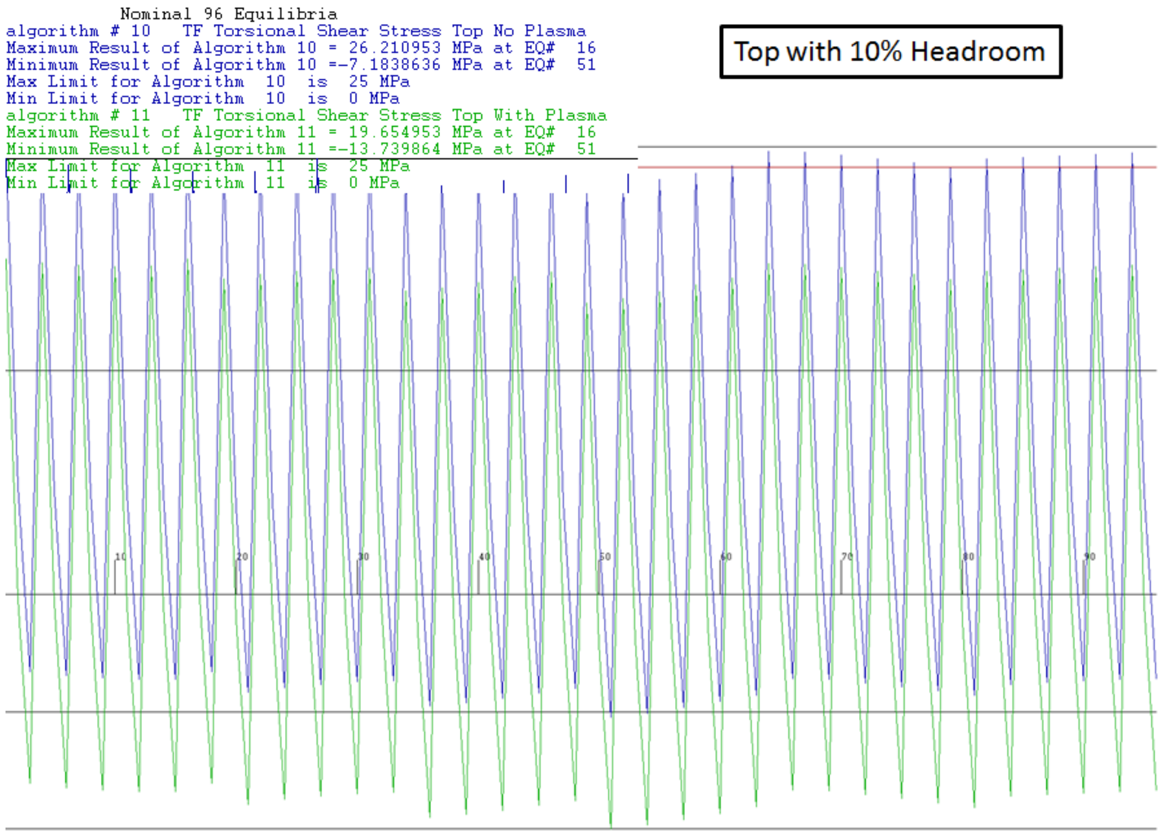
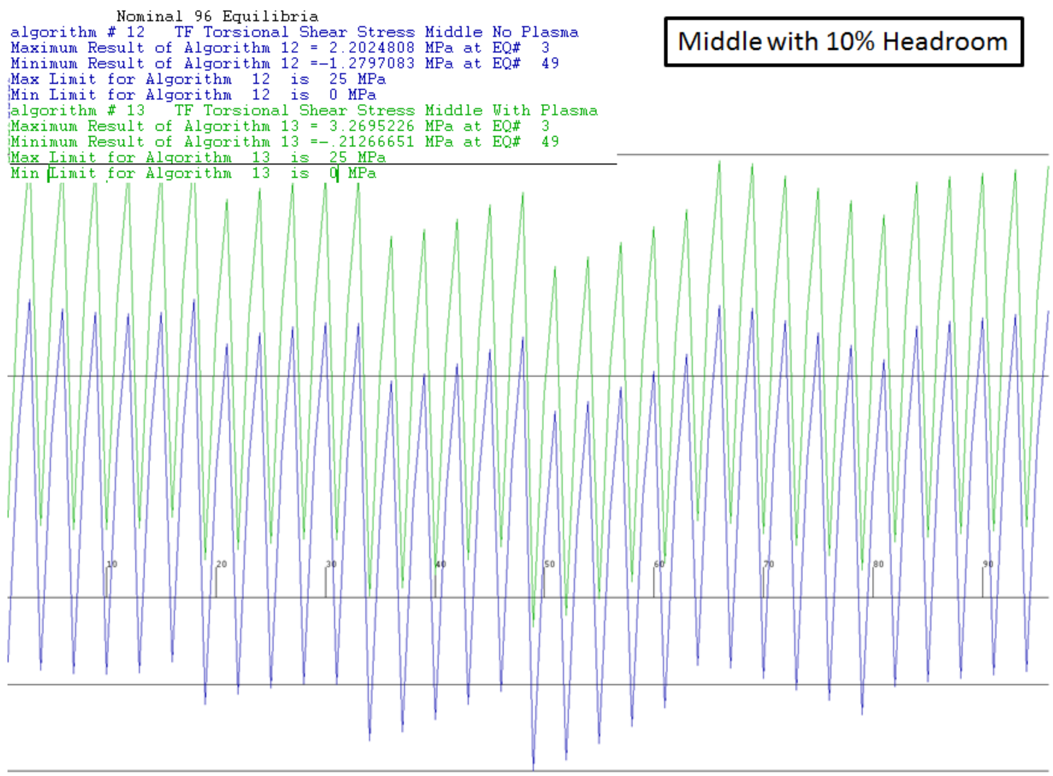


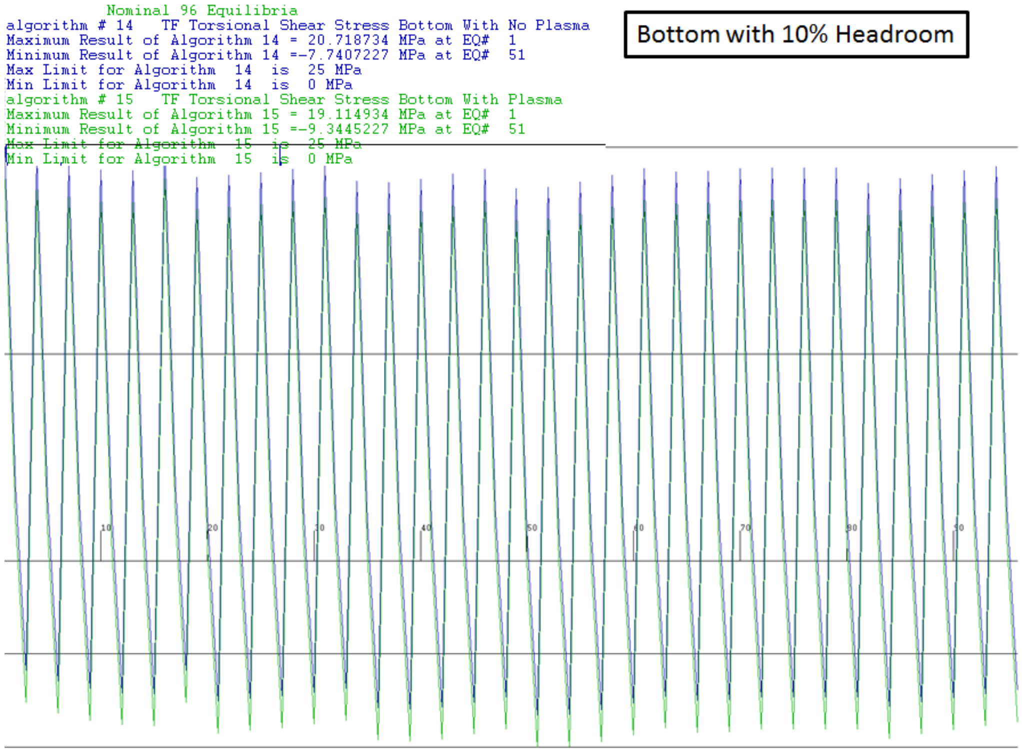
Figure 9.3-8d Global Model Bottom Corner Influence Coefficients

10.0 Scenario Results

10.1 96 Equilibrium Results


Top with 10% Headroom
Nominal 96 Equilibria
algorithm # 10 TF Torsional Shear Stress Top No Plasma
Maximum Result of Algorithm 10 = 26.210953 MPa at EQ# 16
Minimum Result of Algorithm 10 =-7.1838636 MPa at EQ# 51
Max Limit for Algorithm 10 is 25 MPa
Min Limit for Algorithm 10 is 0 MPa
algorithm # 11 TF Torsional Shear Stress Top With Plasma
Maximum Result of Algorithm 11 = 19.654953 MPa at EQ# 16
Minimum Result of Algorithm 11 =-13.739864 MPa at EQ# 51
Max Limit for Algorithm 11 is 25 MPa
Min Limit for Algorithm 11 is 0 MPa
10
20
30
40
50
60
70
80
90


Middle with 10% Headroom
Nominal 96 Equilibria
algorithm # 12 TF Torsional Shear Stress Middle No Plasma
Maximum Result of Algorithm 12 = 2.2024808 MPa at EQ# 3
Minimum Result of Algorithm 12 =-1.2797083 MPa at EQ# 49
Max Limit for Algorithm 12 is 25 MPa
Min Limit for Algorithm 12 is 0 MPa
algorithm # 13 TF Torsional Shear Stress Middle With Plasma
Maximum Result of Algorithm 13 = 3.2695226 MPa at EQ# 3
Minimum Result of Algorithm 13 =-.21266651 MPa at EQ# 49
Max Limit for Algorithm 13 is 25 MPa
Min Limit for Algorithm 13 is 0 MPa
10
20
30
40
50
60
70
80
90



10.2 Post Disruption Results

Charlie Neumeyer extracted the disruption currents from the design point spreadsheet. These are included in appendix. They were multiplied by the (Titus) coefficients and the results are shown below in figures 9.2-1 through 3. The Titus and Wooley results are also tabulated in the executive summary table at the beginning of this calculation.

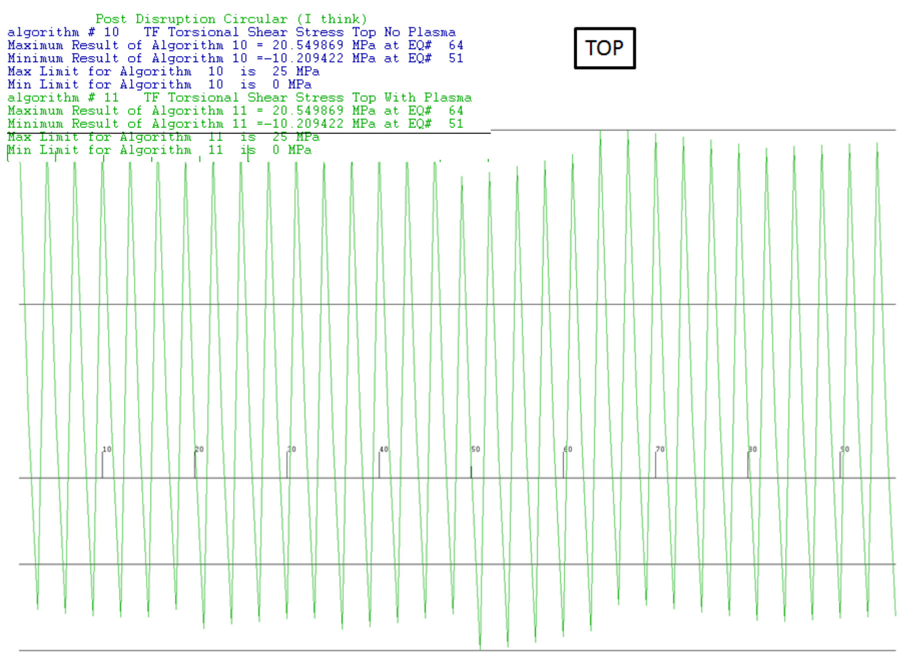


Figure 10.2-1 Post Disruption Torsional Shear Stresses at the Top of the TF Inner Leg

Note that there is no difference between the with and without plasma results because there is no plasma included in the post disruption coil currents.

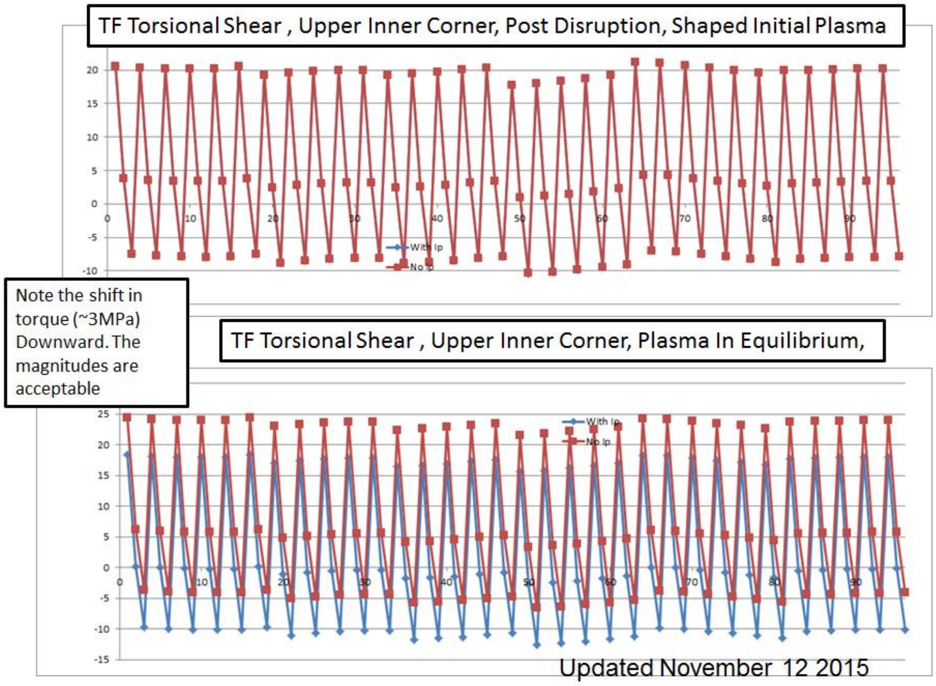


Figure 10.2-2 Comparison of Post Disruption and Nominal 96 EQ Torsional Shear Stresses at the top of the TF Inner Leg

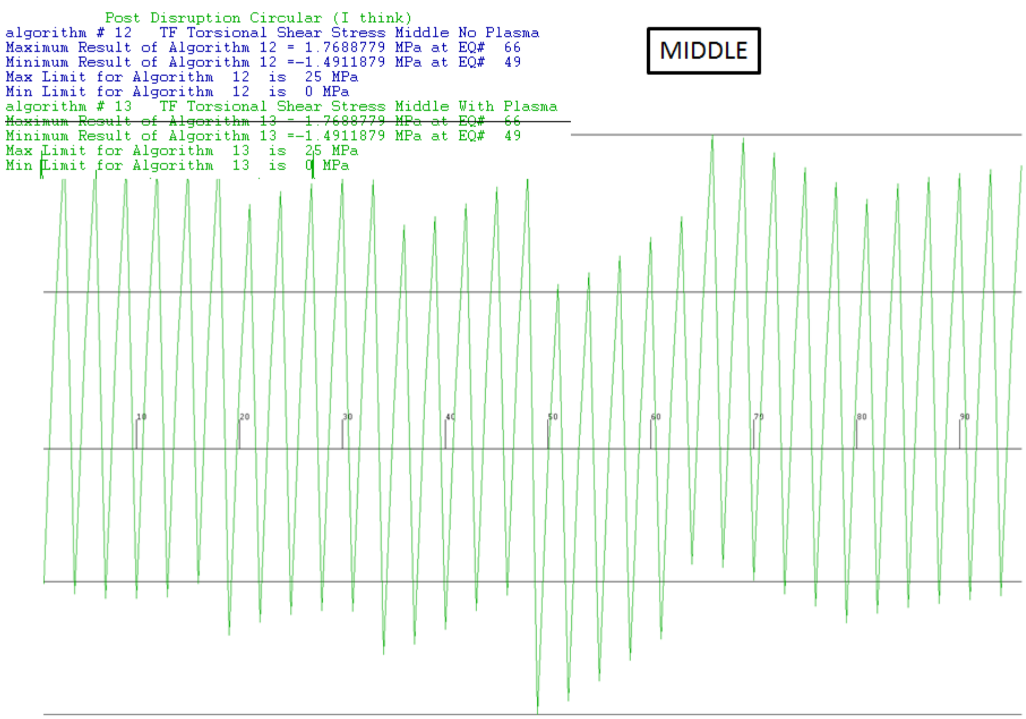


Figure 10.2-3 Post Disruption Torsional Shear Stresses at the Middle of the TF Inner Leg

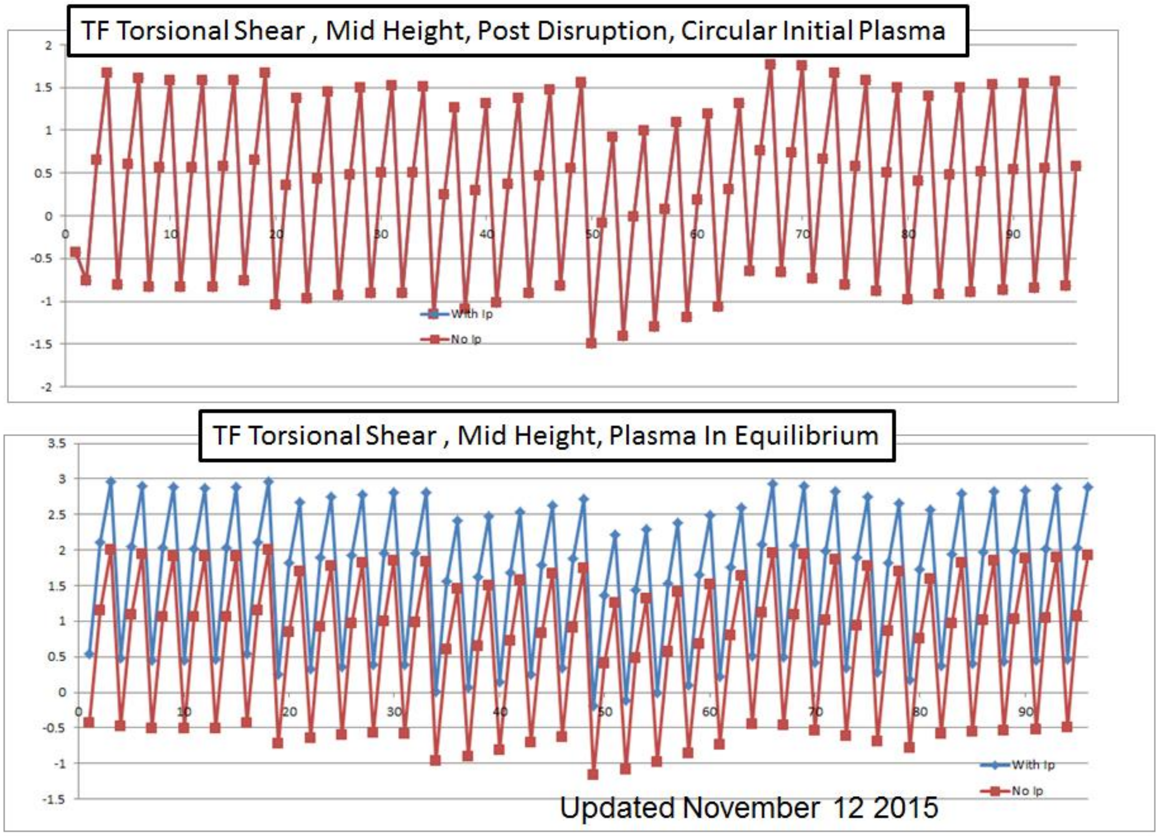


Figure 10.2-4 Comparison of Post Disruption and Nominal 96 EQ Torsional Shear Stresses at the Middle of the TF Inner Leg

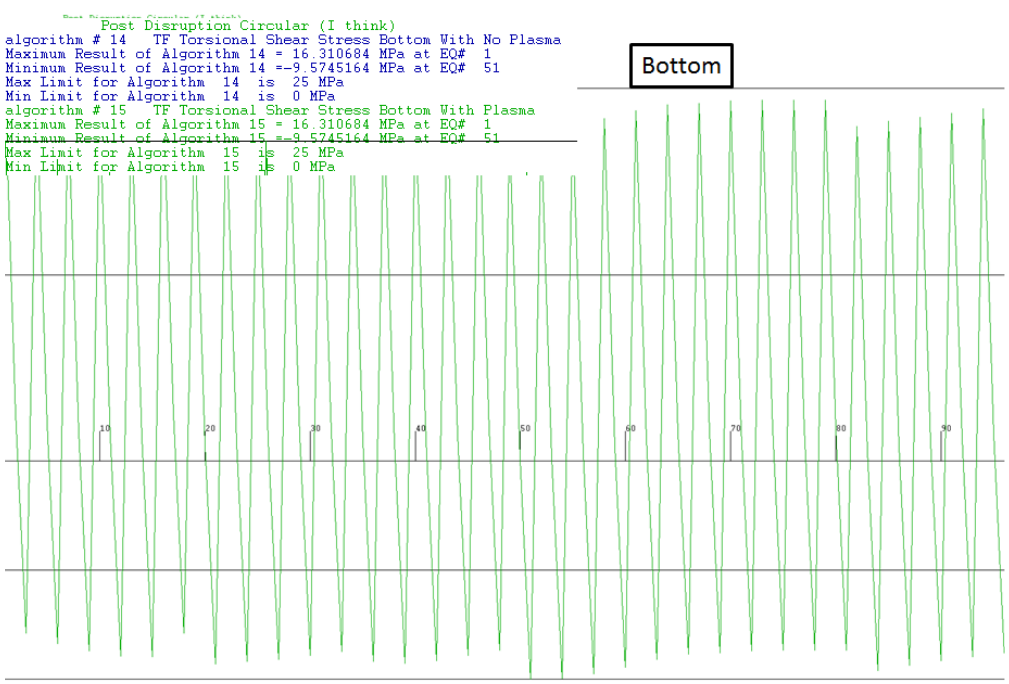


Figure 10.2-5 Post Disruption Torsional Shear Stresses at the Bottom of the TF Inner Leg

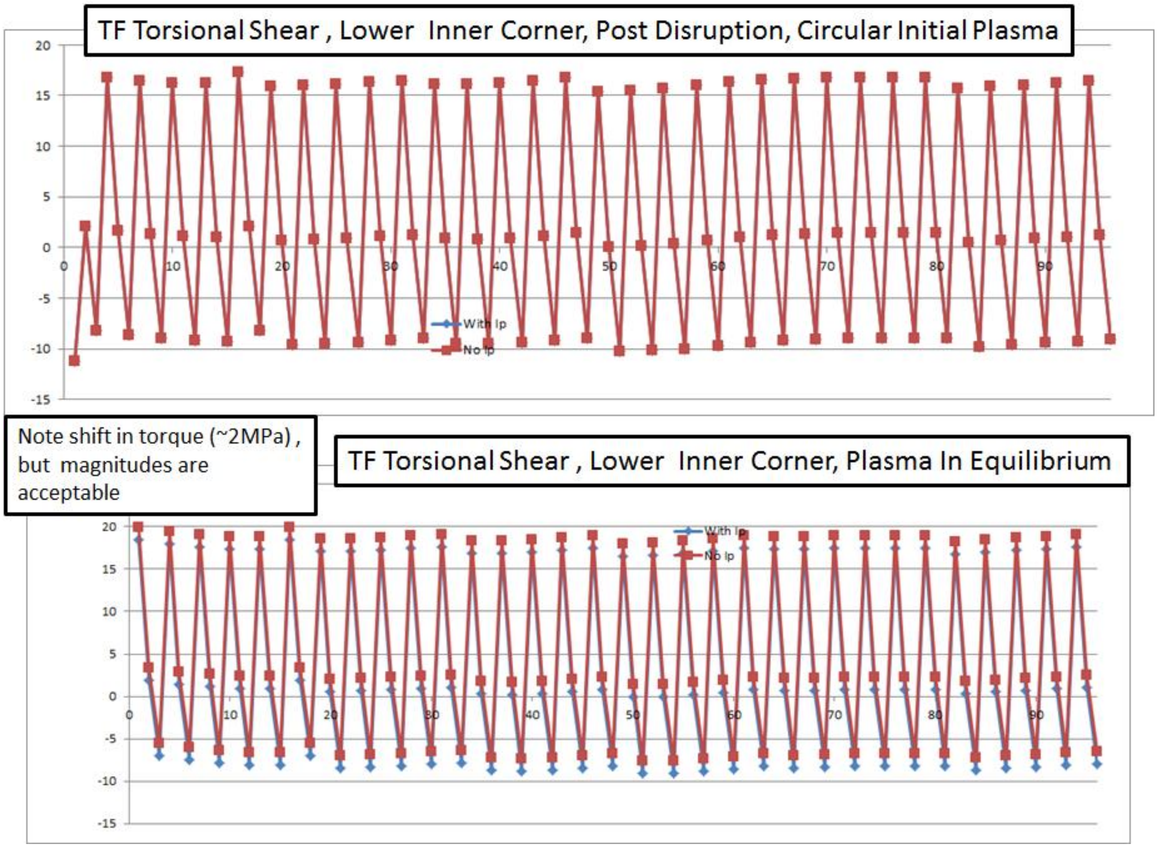
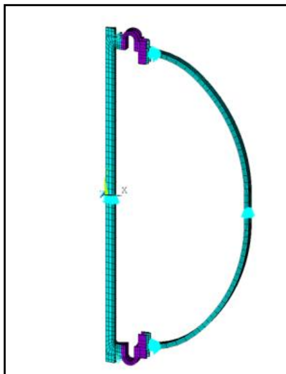


Figure 10.2-6 Comparison of Post Disruption and Nominal 96 EQ Torsional Shear Stresses at the Bottom of the TF Inner Leg

11.0 DCPS Factors from the Single TF Model With Fixity at the Crown and Umbrella Structure



Simple Single TF Model with Fixity at the Umbrella Structure

If the fixity supplied by the crown connections, at the upper and lower ends of the inner leg, is sufficient, then only a model of the inner leg is needed. This would allow a simpler modeling of the inner leg shear, but calculations of the influence coefficients for the global model and a simpler TF model with fixity at the umbrella structures showed that there were large contributions from the outer PF coils that were suppressed by artificially fixing the umbrella structure. This simpler model allows easier post processing, and with additions of stiffnesses replacing the imposed constraints, this scale of model could be useful. The results of this model are included mainly for illustration of the process (see Appendix B) and comparison with the global model results.

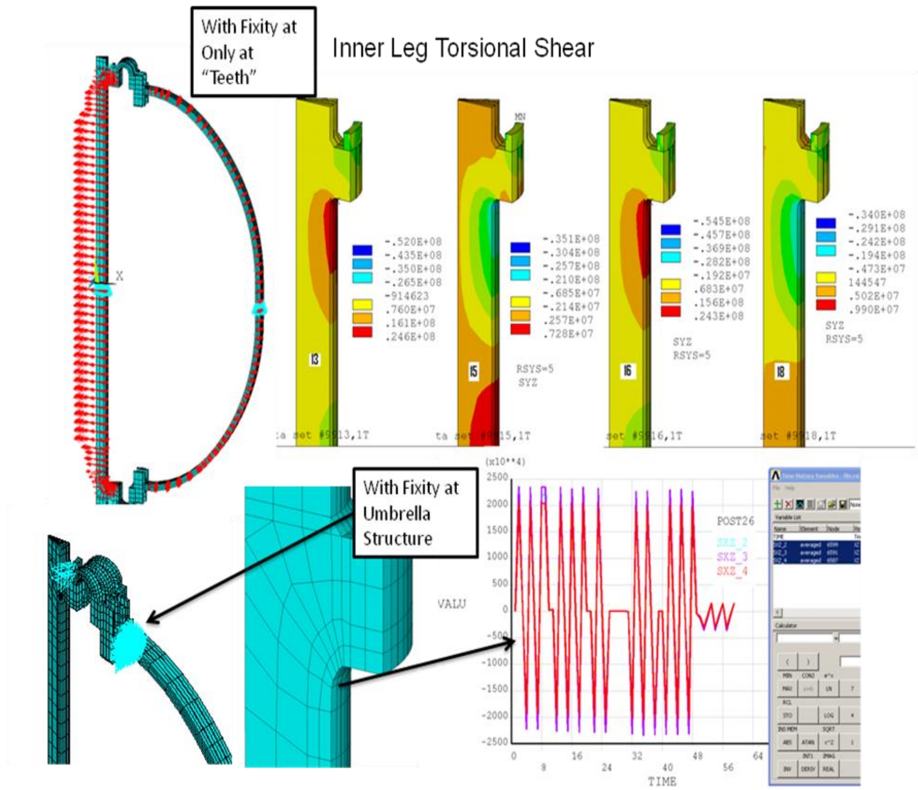


Figure 11.0 .1 Single Coil Model Results for a Few Scenario Data Points.

The single TF model is cyclically symmetric. The needed CP commands in ANSYS are created by the CPCYL command (see inset). This is not needed for the global model, which includes the full 360 degrees of the tokamak.

```
csys,5
nrotate,all
cpdele,all,all
cpcyc,ux,.001,5,0,30,0
cpcyc,uy,.001,5,0,30,0
cpcyc,uz,.001,5,0,30,0
nsel,z,-40,-33.5
d,all,all,0.0
```

. The loads that used in this analysis are from a calculation of a single TF coil with fixity at the umbrella structure and no support from the knuckle clevis or ring. One of the single leg analysis uses scenario #79 to compute the loads. This has been extensively checked by D. Mangra, and T.Willard, and is consistent with the net upper half-outer leg torque calculated by Bob Woolley and included in the design point spreadsheet.

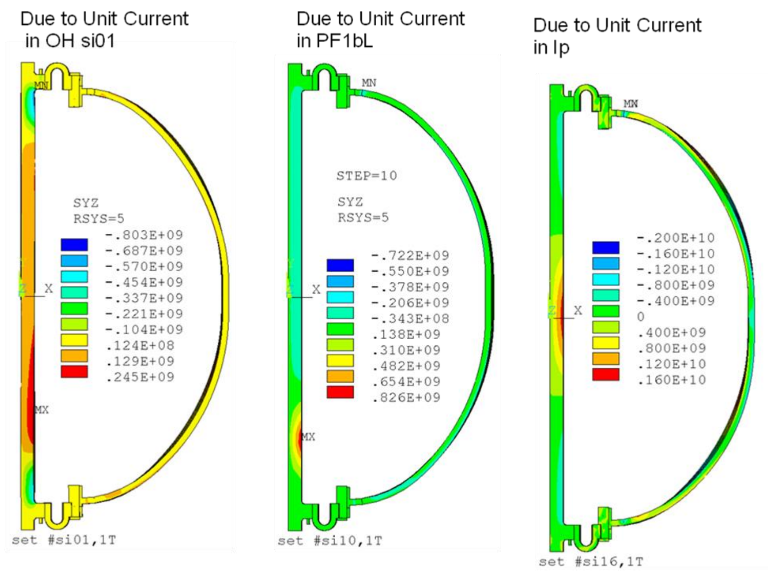
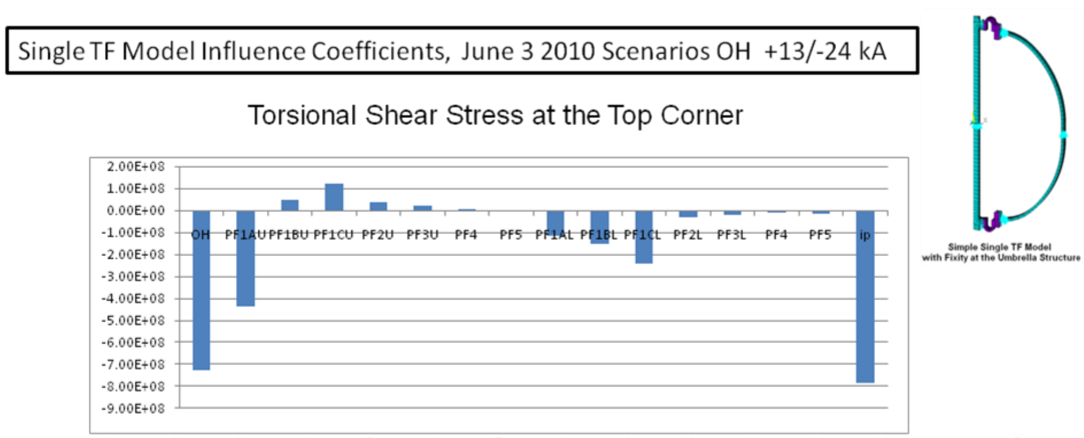


Figure 11.0-2 Single Coil Model Torsional Shear Contour Plots for 3 of the 16 Unit Loads



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
Top	-7.26E+08	-4.39E+08	4.70E+07	1.22E+08	3.60E+07	1.91E+07	7.71E+04	-5.36E+06	-1.13E+08	-1.51E+08	-2.44E+08	-2.88E+07	-2.19E+07	-1.17E+07	-1.42E+07	-7.86E+08

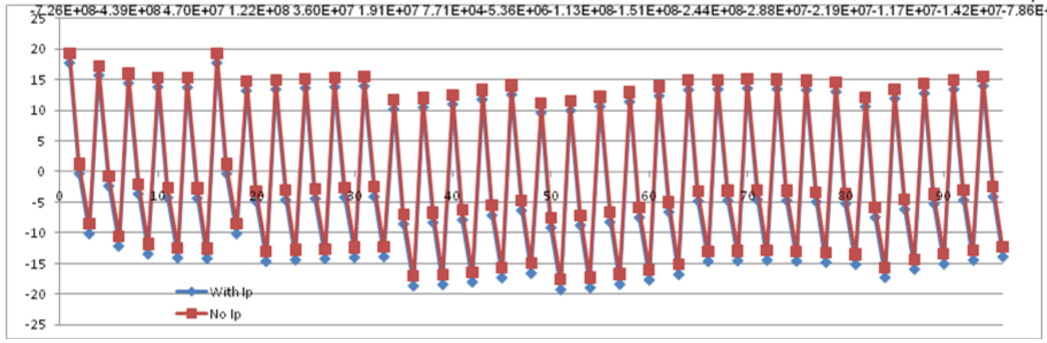


Figure 11.0-3 Single Coil Model Upper Corner Results

Mid-Plane Torsional Shear Factors Based on the Single TF Model

At the equatorial plane the torsion in the TF is more strongly affected by the presence of the plasma. The amplitude of the torsional shear is small: -8 to 4 MPa, but it shifts downward 3 to 4 MPa when there is no plasma. This magnitude might be significant with respect to the disruption effects.

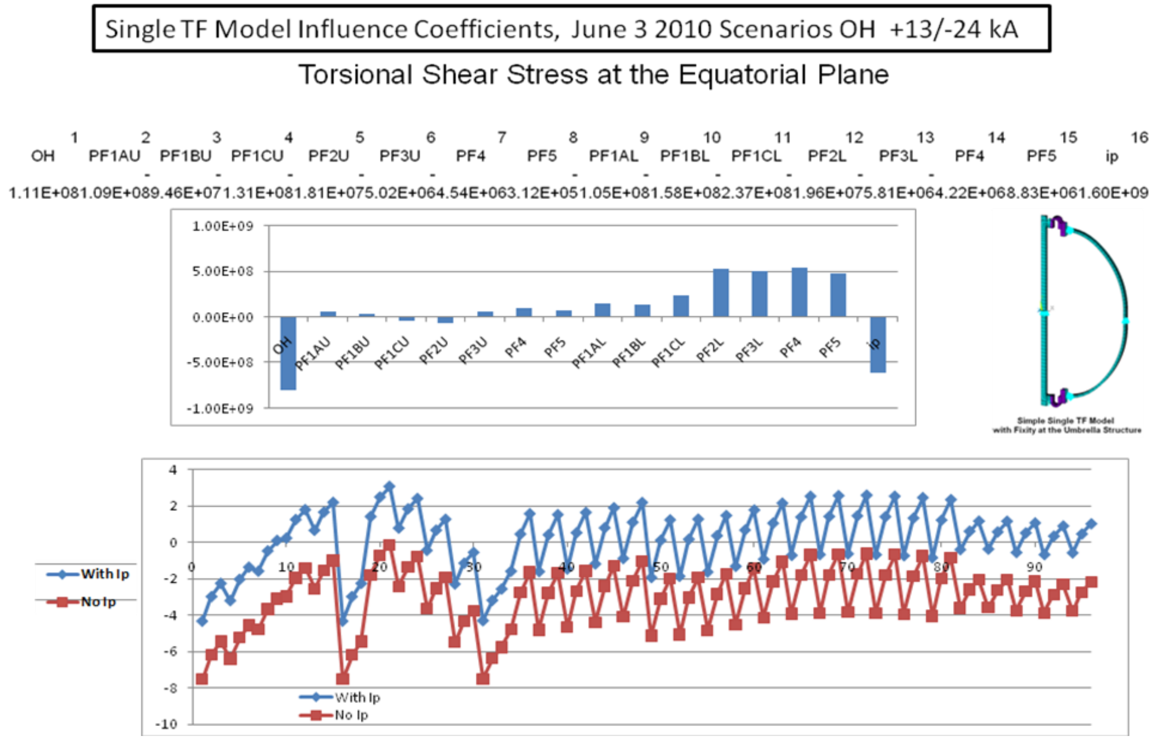


Figure 11.0-4 Single Coil Models Equatorial Plane Results

Lower Corner Shear Factors

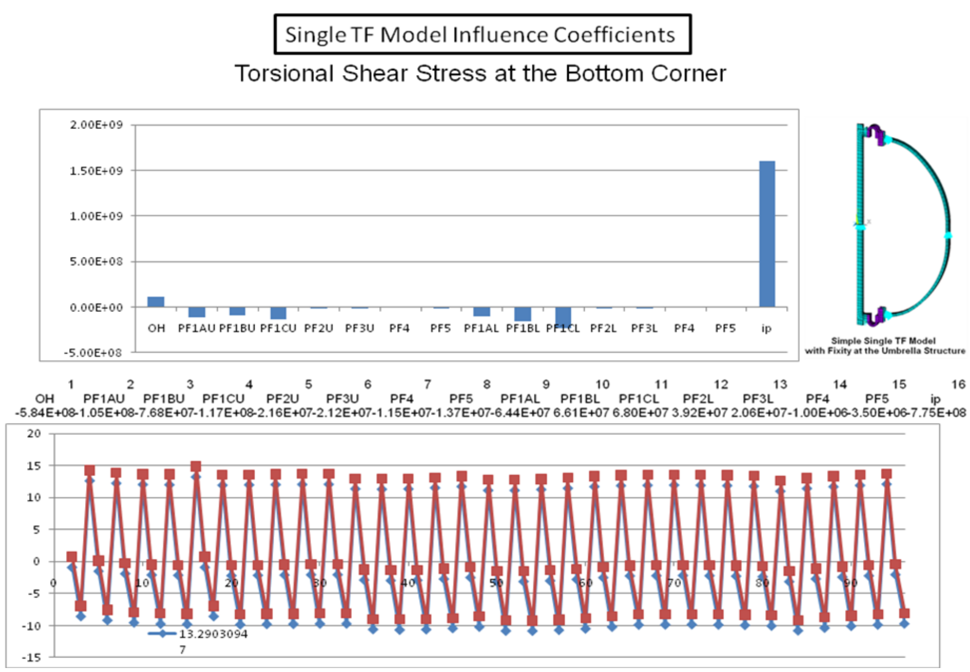


Figure 11.0-5 Single Coil Model Lower Corner Results

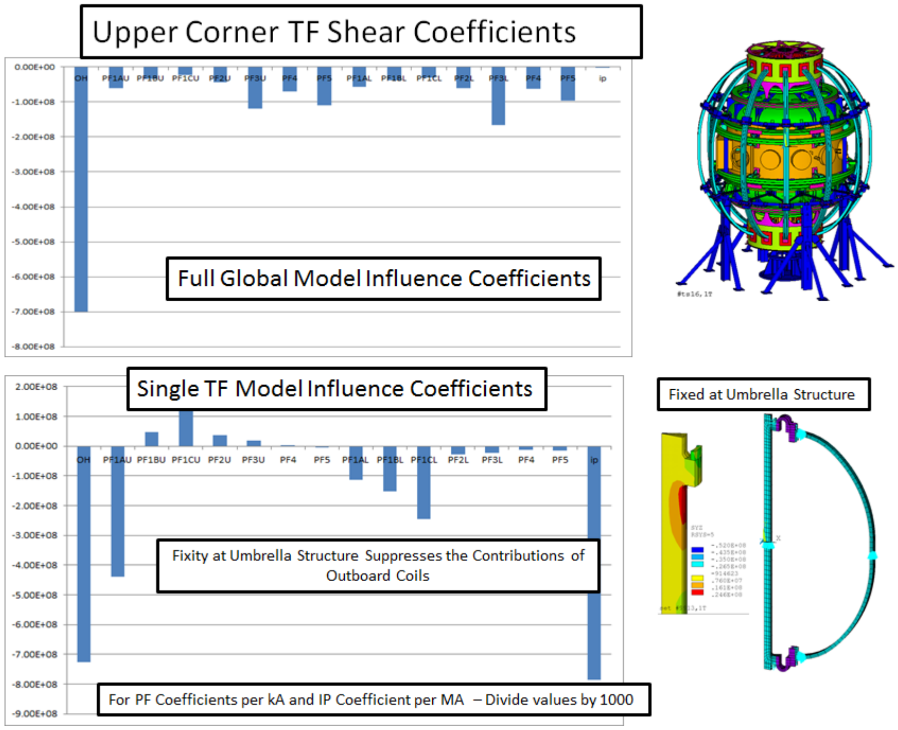


Figure 11.0 -6 Comparison of Global model and single model Upper Corner or Top Coefficients With the arbitrarily applied fixity at the outer leg, the outer PF coil effects are suppressed

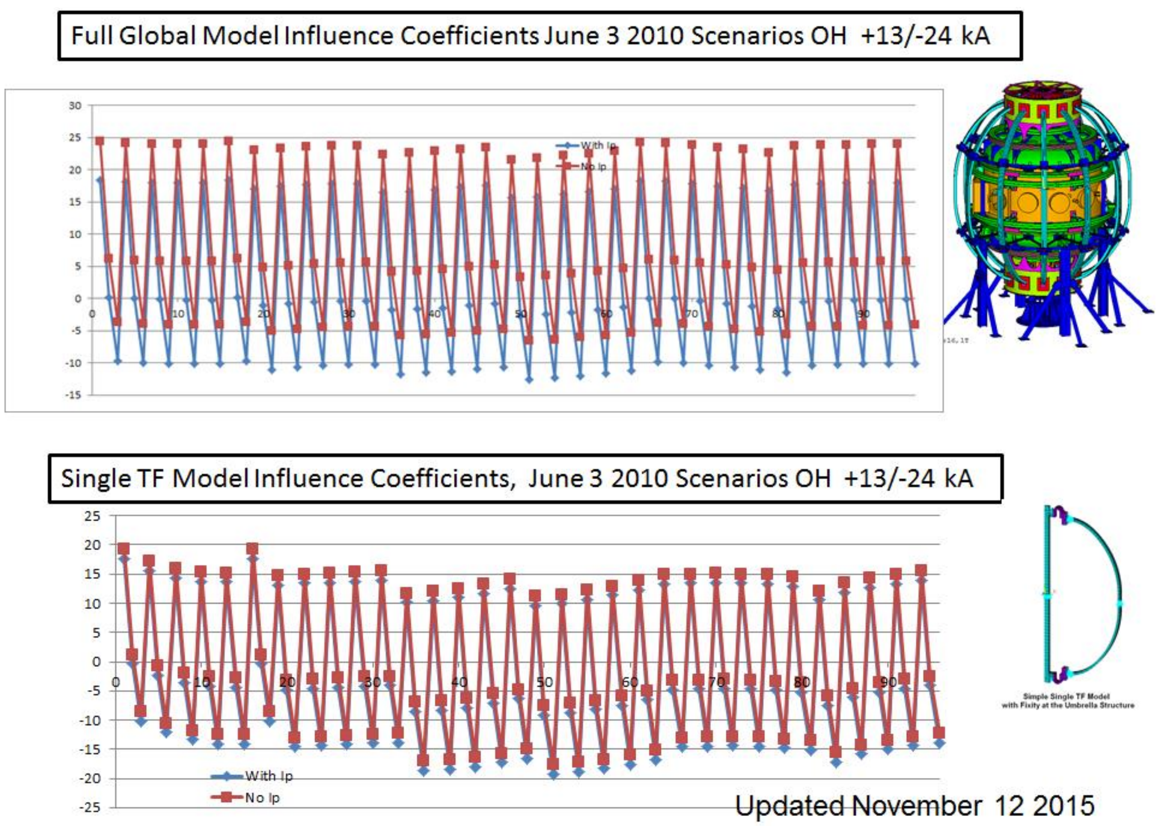


Figure 11.0-7 Comparison of Influence Coefficient Results for the Global and Single Coil Models

12.0 Suggestion for Torsional Shear Stress Estimation by Moment Summation

The distribution of torsion along the height of the TF central column is needed because there are torsional stress reversals in the central column that you won't see if you just sum the moment on the central column. These are evident in Figure 3 of this section

A useful calculation would be the build-up of torsional shear in the TF inner leg. This is calculated by summing the torsional moment from the bottom to positions along the height of the central column. This would give torque distribution and a total torque on the central column. It is assumed that the total torque is reacted equally by the top and bottom umbrella structure domes or diaphrams. Then divide by the distribution by the torsional resistance factor to get the shear stress. This could readily be implements in Charlie's system analysis program. Because the single TF FEA results are showing a dependence on the stiffness of the outer structures, torsional springs at top and bottom of the inner leg, could be added but this would not include the torque load from the outer structures.

13.0 Simple Shell Program for Determining OOP Torsionlal Shear

An early attempt at providing a simplified method for computation of the inner leg torsional shear is presented in this section. It was proposed on other reactor designs and provides some insight into the dependence of the inner leg torsional shear on external structures.

A moment summation of the upper half vs lower half of the tokamak is not useful because the stiffness of the structure will determine how much torque goes to the central column and how much goes to the outer TF and vessel structures.

Some results of the torque shell program are included. These are for the OH on only, and the "squareness" equilibria . These analyses produced a -17.7 MPa torsional shear for IM and about 4 MPa for the equilibria.

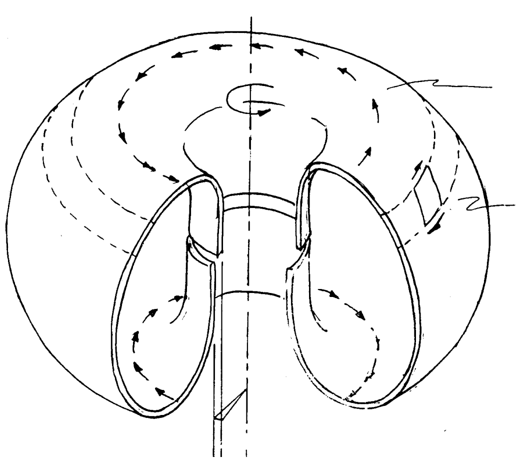


Figure 31 Simple Toroidal Shell Model. OOP loads are computed from the TF current and PF currents using an elliptical integral solution for the PF fields. TF OOP loads are assumed to be applied to a toroidal shell – with varying thickness to simulate more complex OOP structures. Shear deformations are accumulated to a split in the shell, then a moment is applied to align the split.

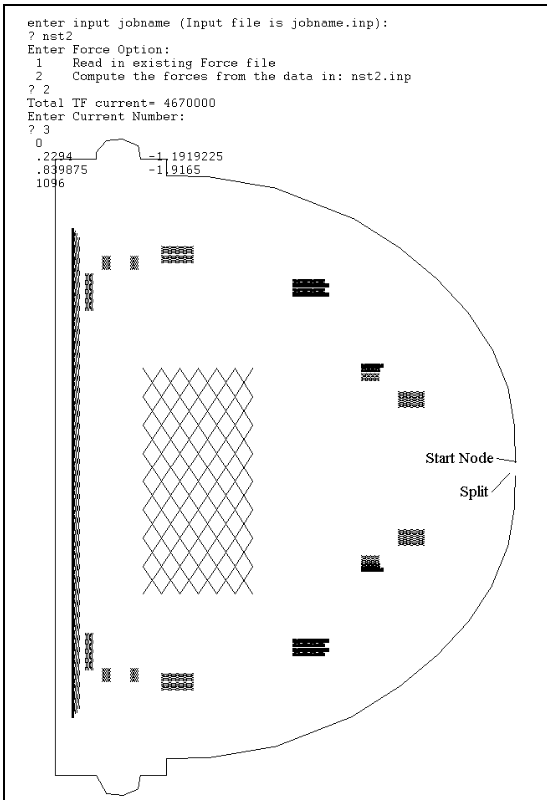


Figure 30 NSTX Shell Model

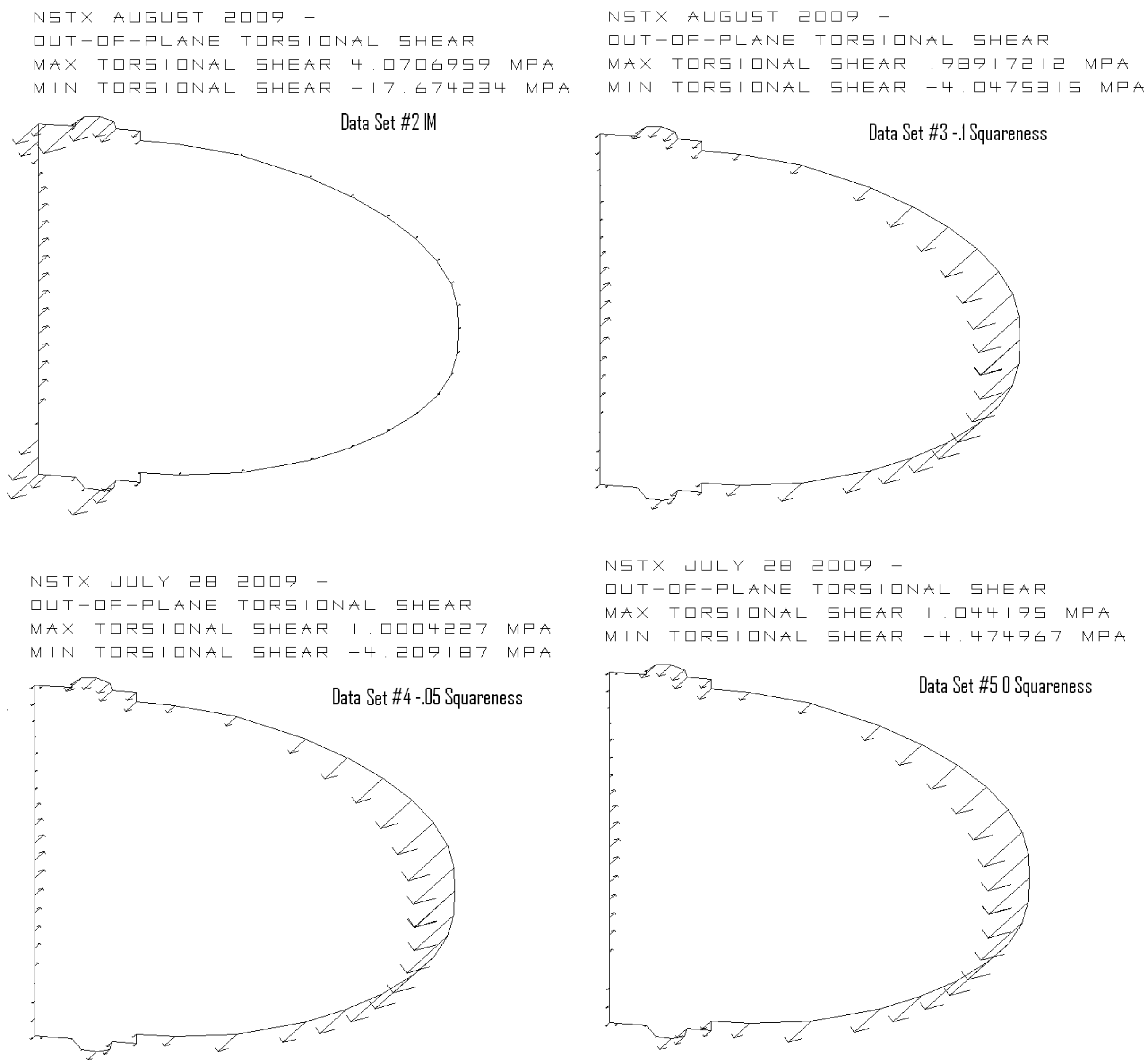


Figure 32 Torsional Shear for IM and some Equilibria

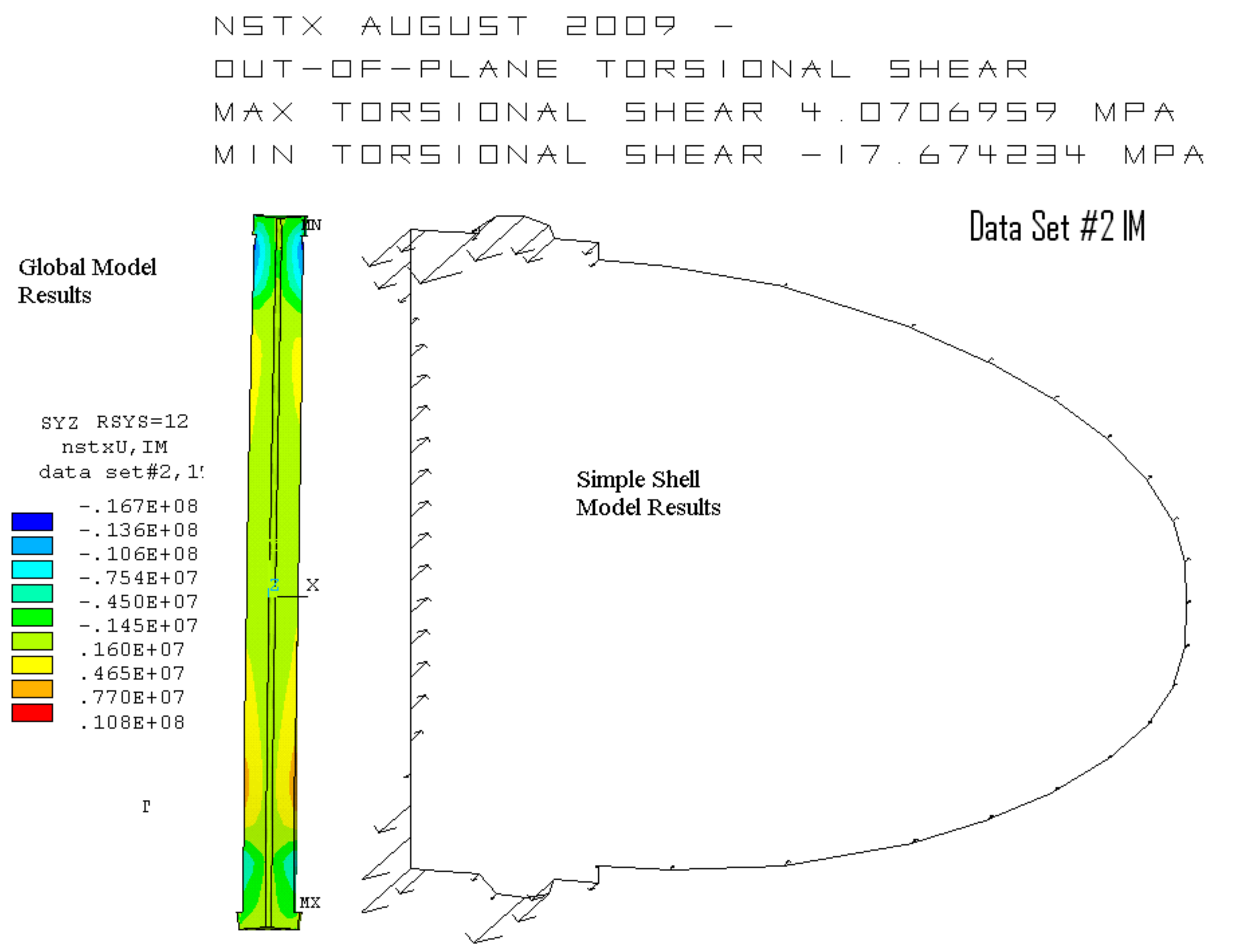


Figure 33 Comparison of Global FEA and Simple Shell Analyses

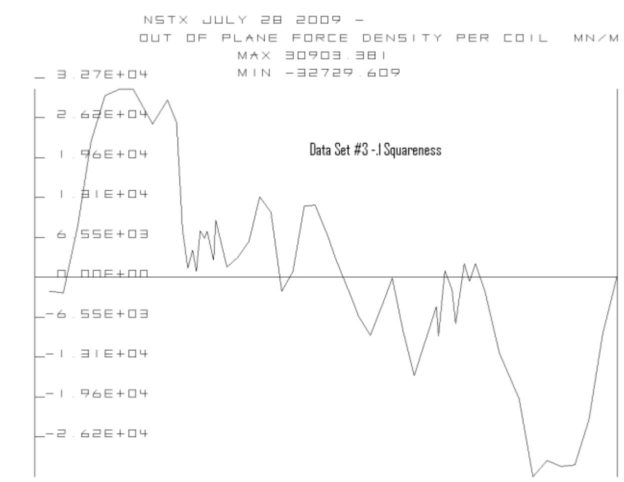


Figure 34 OOP Force Density Along TF CL starting from Outboard Equatorial Plane

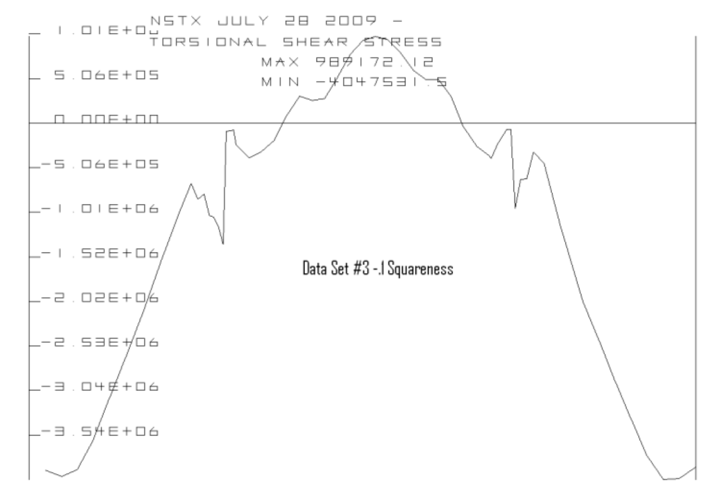


Figure 35 Torsional Shear Stress along TF CL starting from Outboard Equatorial Plane

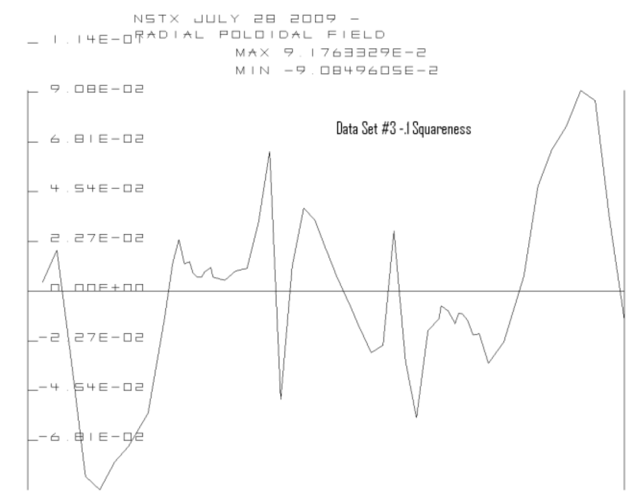


Figure 36

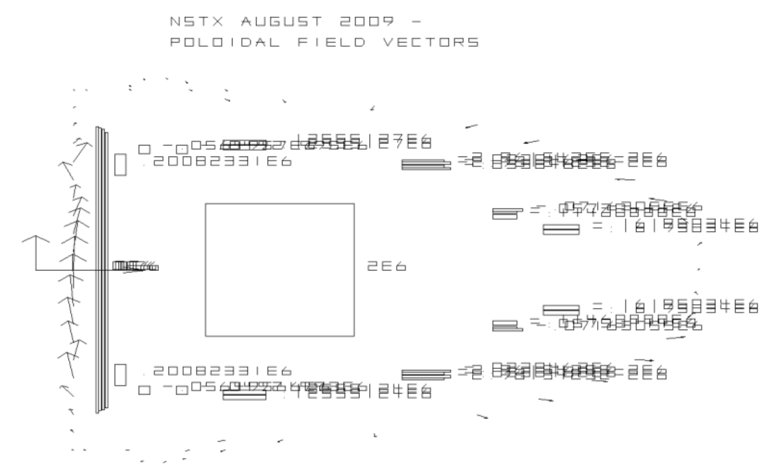


Figure 37

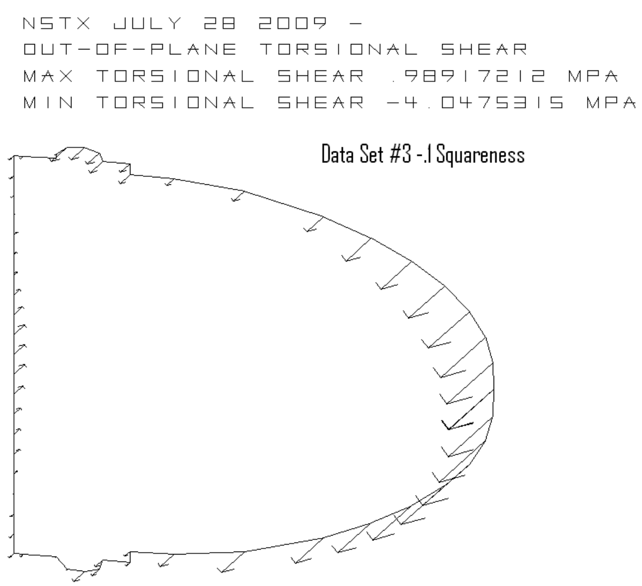


Figure 38

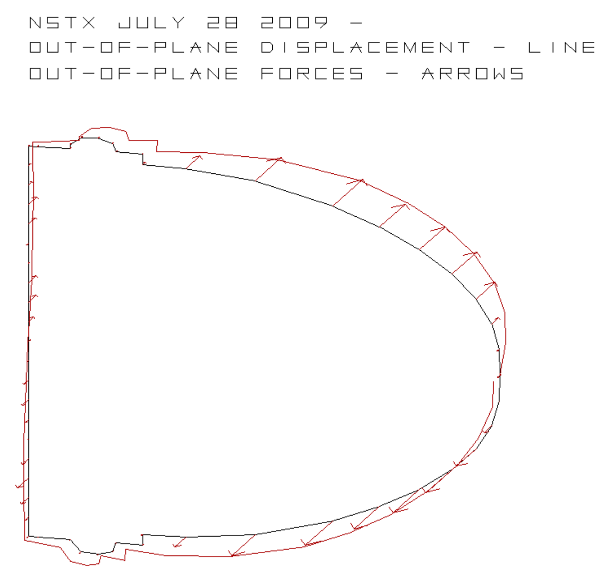


Figure 39

14.0 Torsional Stiffnesses for the Inner Leg and Outer Structure

Ref [6] also calculates torsional shear stress and to provide some comparison of the torsional stiffness coefficients used in this calculation and [6], significant global model segments were separated out and loaded with moments and rotations quantified. From the applied moment and resulting rotation, the stiffness factors were computed. The shear stress distribution in this calculation and in [6] were different. In this calculation the shear stress concentrates at the upper and lower ends of the inner leg where the connections to the crown, spoked lid, and TF strap joint are. Mid-plane torsional shear stresses are low. The location of the peak torsional stress implies that the outer global structures are stiff enough to pick up much of the OOP loads at the ends of the OH rather than react them through the middle portion of the inner leg.

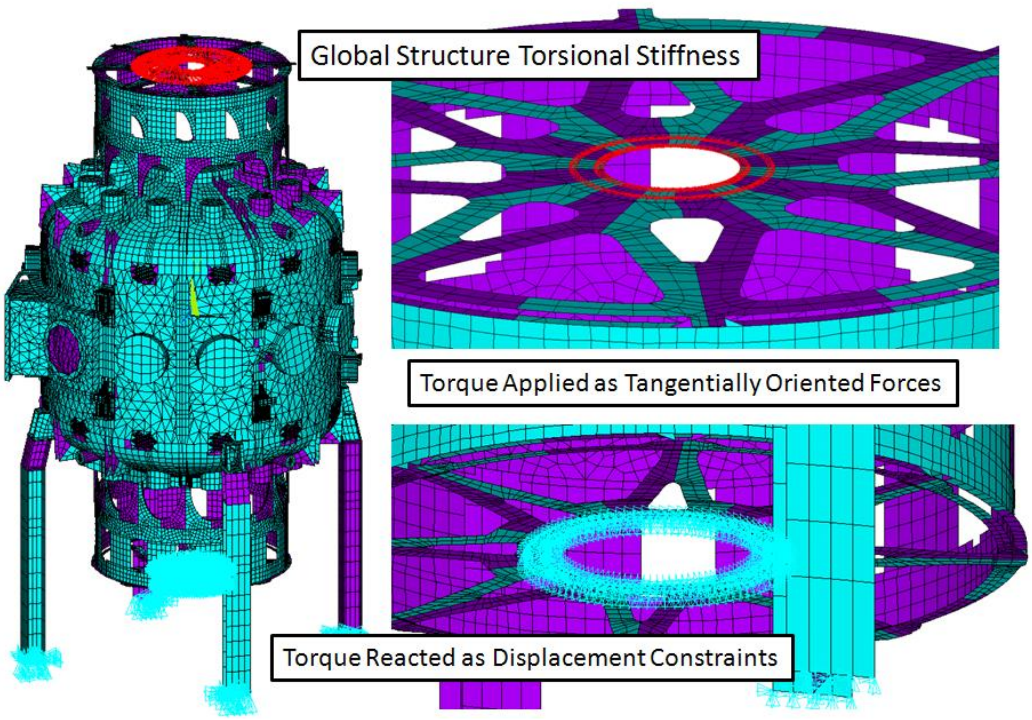
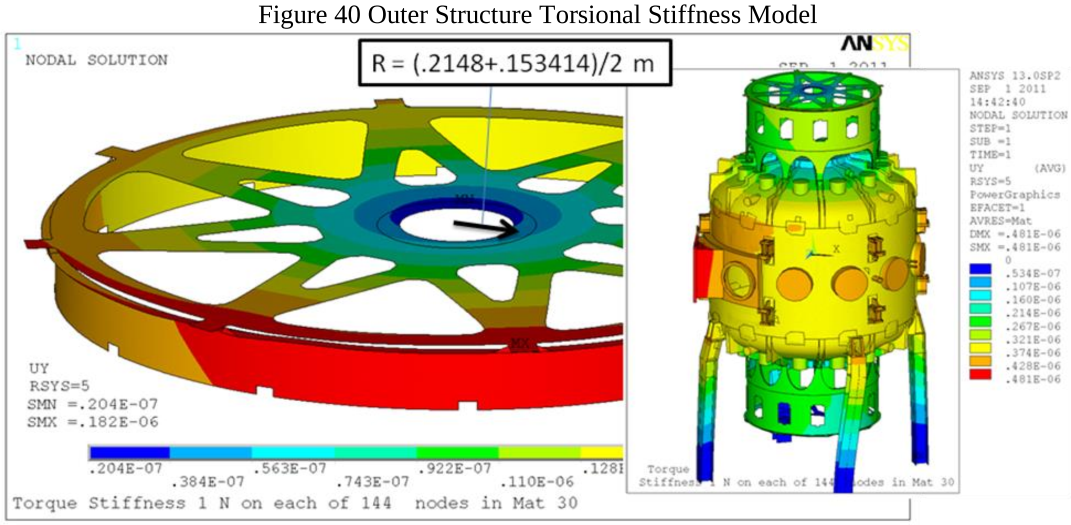
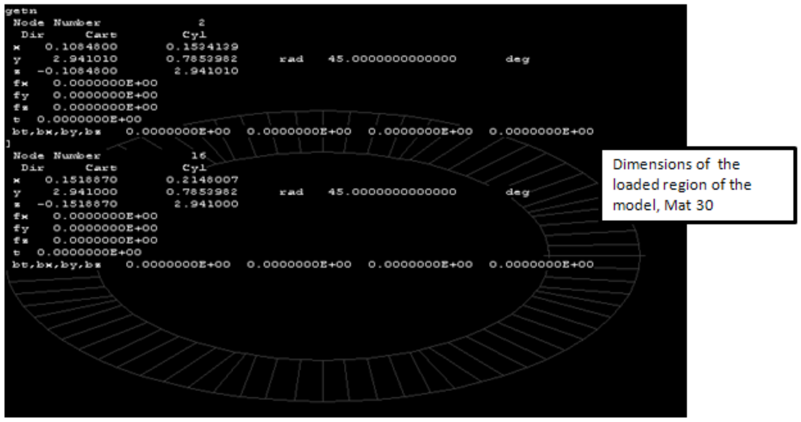


Figure 40 Outer Structure Torsional Stiffness Model



Resulting Angular Rotation = .384e-7/(.2148+.153414)*2) = 2.0857e-7Radian

Figure 41 Outer Structure Rotational Results



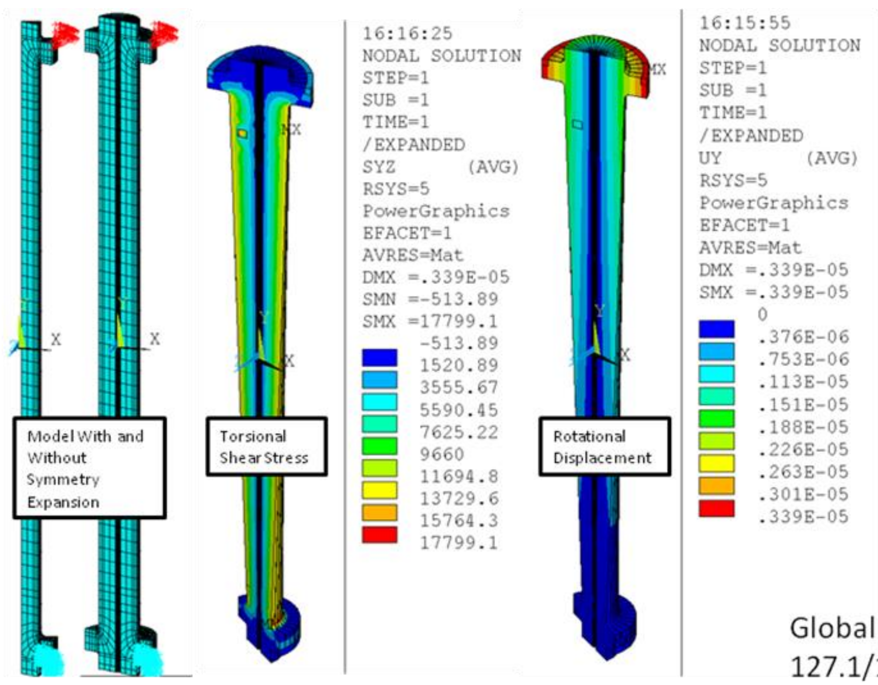
Applied Torque = 72*.1534139 + 72*.2148 = 26.51 N-m

***** SUMMATION OF TOTAL FORCES AND MOMENTS IN THE GLOBAL COORDINATE SYSTEM
FX = 0.1451167E-05
FY = 0.2826528E-12
FZ = 0.6917458E-05
MX = 0.2034429E-04
MY = -26.50754
MZ = -0.4267938E-05

Resulting Angular Rotation = .384e-7/(.2148+.153414)*2) = 2.0857e-7Radian

Torsional Stiffness = 26.51/(.384e-7/(.2148+.153414)*2) = 127.1 MN-m/radian

Figure 42 Outer Structure Stiffness Results



40 Nodes, each with 1N, at r= .31 m = 12.4 N-m per 30 degree Sector.
From ANSYS FSUM:
MZ = -12.64205 N-m or 12*12.64205 = 151.7 N-m

Angular Rotation is .339 e-5/.31 = 1.0935e-5 Radians

Rotational Stiffness = 151.7/1.0935e-5

= 13.873MN-m/Radian

Global Structure/TF Inner Leg = 127.1/13.87 = 9.16

Figure 43 Inner Leg Stiffness Results

Appendix A
CTD Shear Stress Testing Proposal

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
ENGINEERED MATERIAL SOLUTIONS

November 4, 2010

Princeton Plasma Physics Laboratory
Attn: Jim Chrzanowski
Forrestal Campus
US Route #1 North at Sayre Drive
MS41 C-Site EWA 345
PO Box 451
Princeton, NJ 08543-0451

Subject: Quotation for Specimen Fabrication and Shear Testing

Ref: (a) Electronic request for quotation received on October 28, November 2, and November 4, 2010

Encl: (1) CTD Q7277-012c Quotation dated November 4, 2010

Dear Jim:

Composite Technology Development, Inc. (CTD) is pleased to provide this Firm-Fixed-Price quotation for specimen fabrication and mechanical testing, as requested by reference (a). This quotation is based on following assumptions and understandings:

1. CTD will fabricate and test all specimens at the same time or on a mutually agreed upon schedule.
2. Any contract resulting from this proposal will be based on the incorporation of mutually agreeable terms and conditions.

This offer is valid for a period of 60 days. Please contact Paul Fabian for any technical questions and Ms. Lori Bass for any contractual questions regarding this quotation.

Sincerely,

Paul E. Fabian

Paul E. Fabian
Testing Program Manager
Composite Technology Development, Inc.

2600 CAMPUS DRIVE, SUITE D | LAFAYETTE, CO 80026 | PHONE: 303-664-0394 | FAX: 303-664-0392| WWW.CTD-MATERIALS.COM

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.

ENGINEERED MATERIAL SOLUTIONS

Q7277-012c – Fabrication and Test Quotation
11/4/10

CTD proposes to fabricate Notched Lap Shear specimens composed of a glass/epoxy composite material that is sandwiched between two layers of a copper substrate. The overall goal of the program is to determine the adhesive shear strength between the composite material and the copper substrate with and without a primer and to then determine cyclic fatigue response. Initially, two separate sandwich panels will be fabricated, one that will include a primer that is applied to the bonding surface of the copper and another which will not use any primer to determine the best surface preparation method. Following this, a third sandwich panel will be fabricated using the best surface preparation method and these specimens will be tested for fatigue response. The materials to be used are as follows:

Copper substrate:	C10100 OFC copper (due to the unavailability of C10700 copper in sheet form)
Glass reinforcement:	S2 glass fabric, 8h satin weave, style 6781, epoxy compatible silane finish
Resin system:	CTD-101K epoxy
Primer:	CTD-450

ITEM 1: Lap Shear Specimen Fabrication
Two sandwich panels will be fabricated using CTD-101K/S-2 Glass and C101 copper using a vacuum impregnation process. The copper plates will be pre-machined so as to minimize any machining stresses following the bonding of the two copper plates together. The bonding surface of each copper substrate will be solvent cleaned, grit blasted, and solvent cleaned again in preparation for proper bonding. In addition to these surface preparation steps, the surfaces of the substrates will be primed with a Cyanate Ester primer. Following surface preparation, dry glass fabric will be placed between the two copper plates, degassed, and then impregnated with CTD-101K in a vacuum impregnation process. After cure, the sandwich panels will be machined to final dimensions for notched lap shear specimens, similar to that shown in Figure 1 but with a longer lap section of 1 inch. The copper substrates will be nominally 0.20 in. thick and the composite will be nominally 0.125 in. thick and 50% fiber volume fraction. Each fabricated sandwich panel will enable the fabrication of eight (8) individual test specimens. Specimens from one panel will be used for static testing while specimens from the other panel will be utilized for fatigue testing.

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COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
ENGINEERED MATERIAL SOLUTIONS

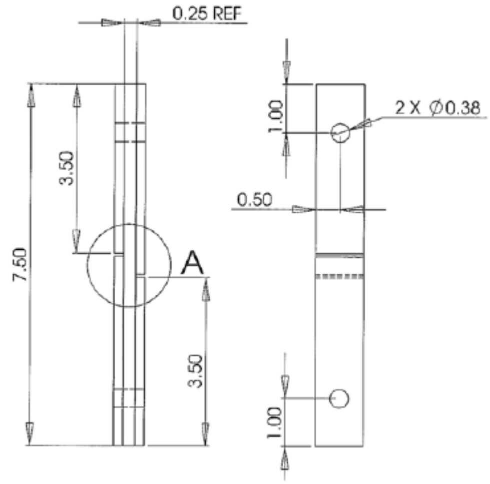

Figure 1. Typcial Notched Lap Shear specimen

ITEM 2: Lap Shear Testing
Notched Lap Shear tests on specimens fabricated in ITEM 1 will be performed at 100°C (373 K) per ASTM D3165. Specimens will be loaded in tension until failure to determine the ultimate adhesive shear strength of each set of samples. Six tests will be performed. Data deliverables will include the ultimate adhesive shear strength of each specimen and average values for each specimen group.

ITEM 3: Lap Shear Fatigue Testing
Notched Lap Shear fatigue tests on specimens fabricated in ITEM 1 will be performed at 100°C (373 K) per ASTM D3165. Specimens will be loaded in tension-tension fatigue at 10 Hz, R=0.1, and maximum stress values of 70%, 60% and 50% of their failure stress to produce an S-N curve. Two specimens will be tested in fatigue at each stress level to determine at which point the materials can withstand 60,000 loading cycles. Based on the results of the six tests performed at the three stress levels listed above, the last two specimens will be tested at other stress levels to more fully expand the S-N curve. A total of 8 fatigue tests will be performed. Data deliverables will include the fatigue results including the number of cycles to failure for each specimen and the S-N curve.

ITEM 4: Final Test Report
CTD will submit a final report providing a brief overview of the fabrication process and detailing the surface preparation steps. It will additionally include details on all test methods and test conditions and will be submitted at the completion of the program. All test data for each

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Composite Technology Development, Inc.

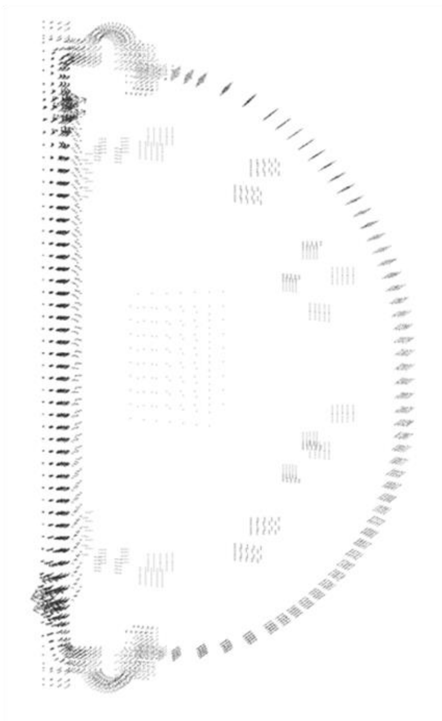
ENGINEERED MATERIAL SOLUTIONS

individual test, as well as average values, will be provided. All test specimens, included failed samples, will be returned to PPPL.

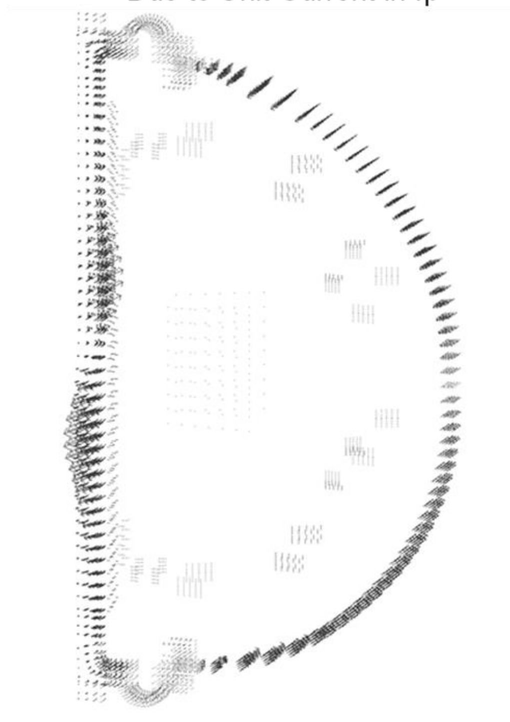
Item #	Test Type	Test Method	Test Temperature	Quantity	Unit Price	Subtotal
1	Specimen Fabrication	-	-	2 lots of 8	$4,864	$9,728
2	Notched Lap Shear Testing	D3165	373 K	6	$586	$3,516
3	Notched Lap Shear Fatigue Testing	D3165	373 K	8	$666	$5,328
4	Final Report	-		1	NSP	NSP
				Total Price		**$18,572**

Appendix B
Force Plots for Individual Influence Coeficients

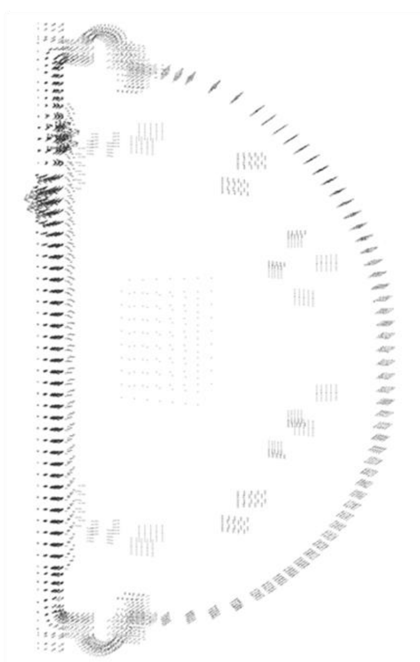
Due to Unit Current in OH si01



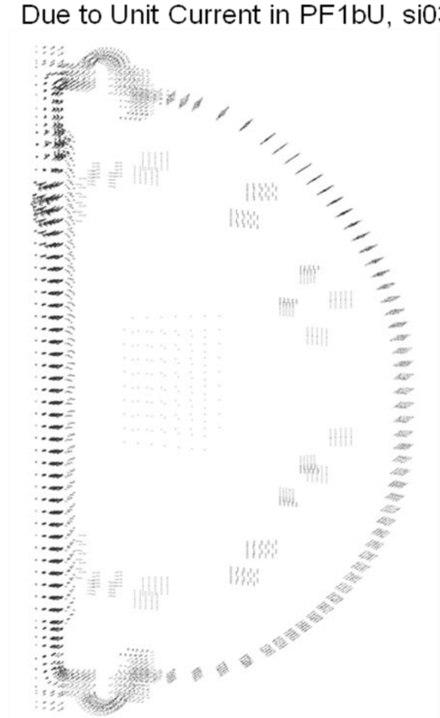
Due to Unit Current in Ip



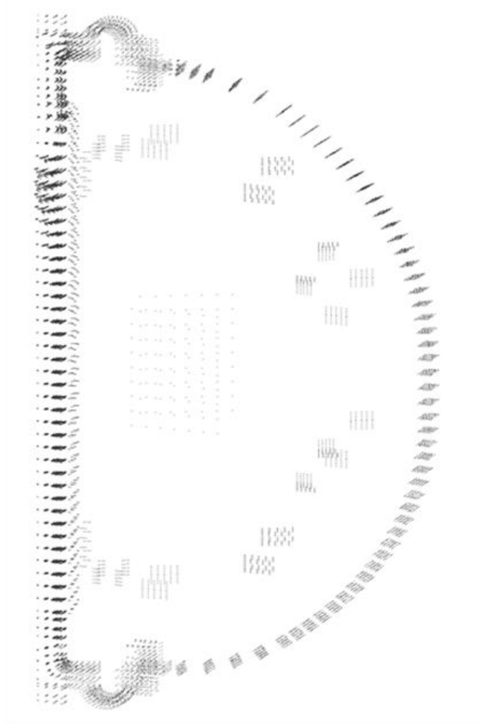
Due to Unit Current in PF1aU



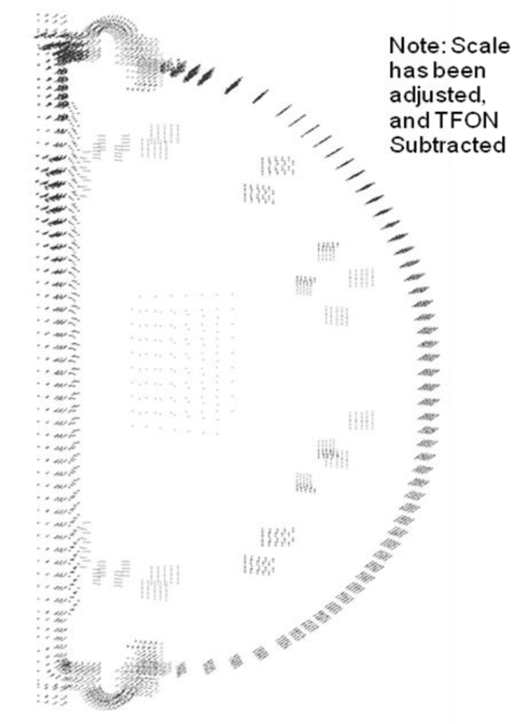
Due to Unit Current in PF1bU, si03



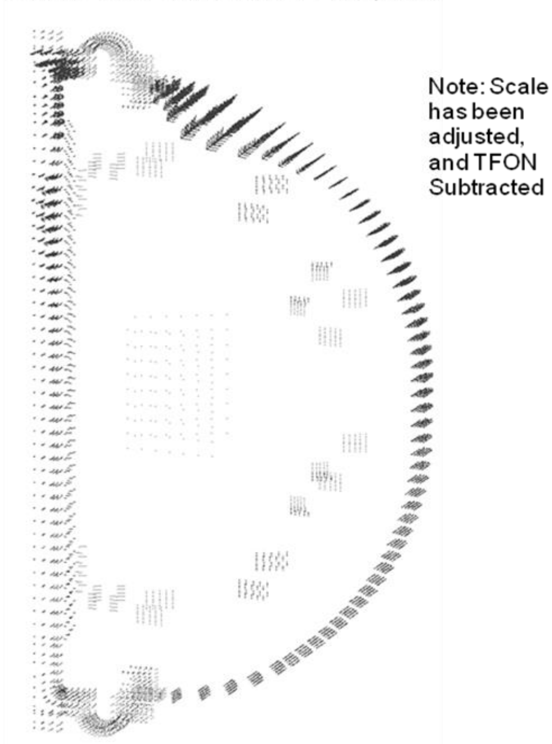
Due to Unit Current in PF1cU, si04



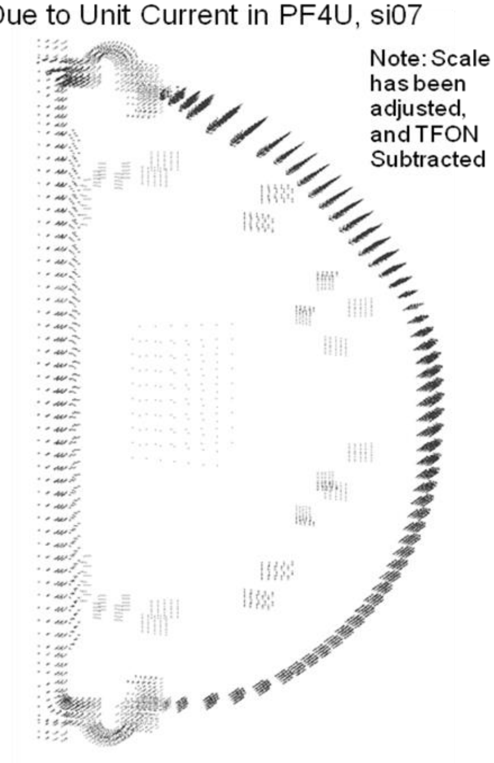
Due to Unit Current in PF2U, si05



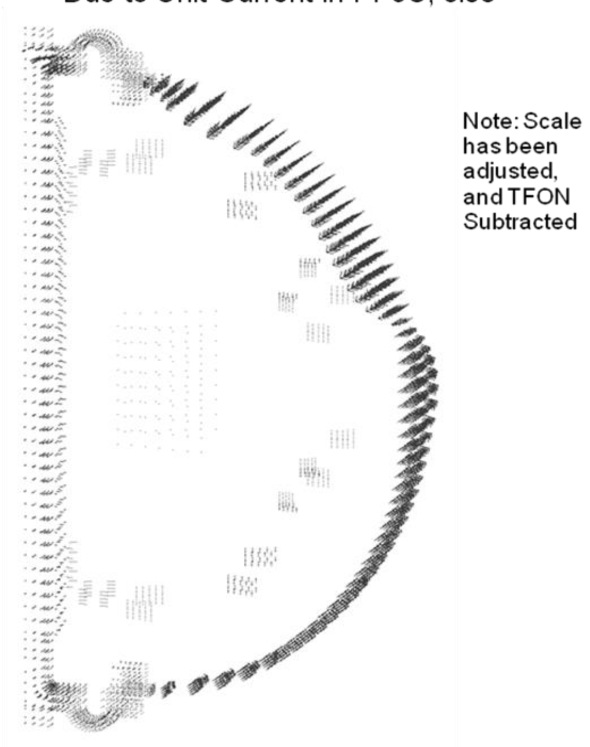
Due to Unit Current in PF3U, si06



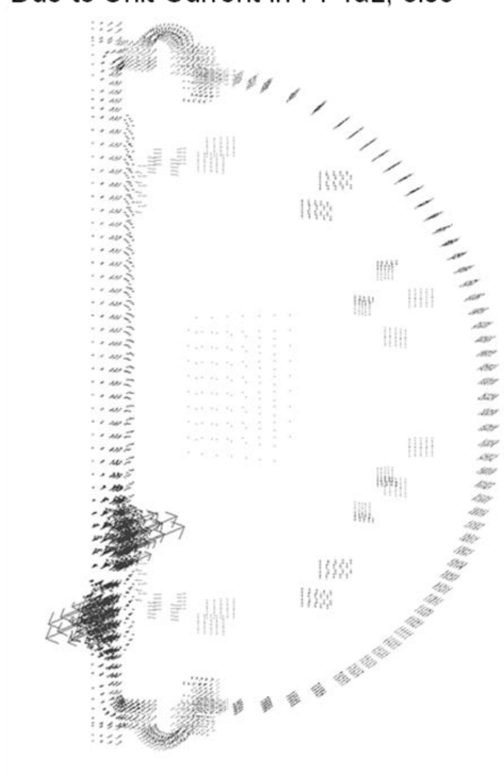
Due to Unit Current in PF4U, si07



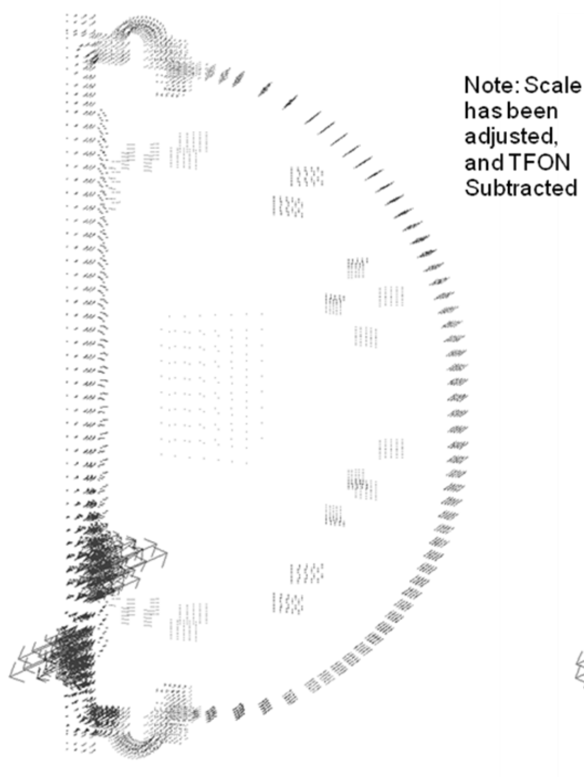
Due to Unit Current in PF5U, si08



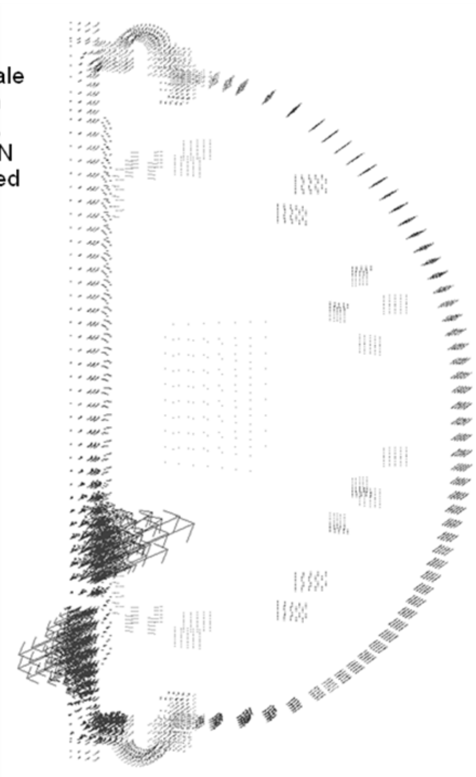
Due to Unit Current in PF1aL, si09



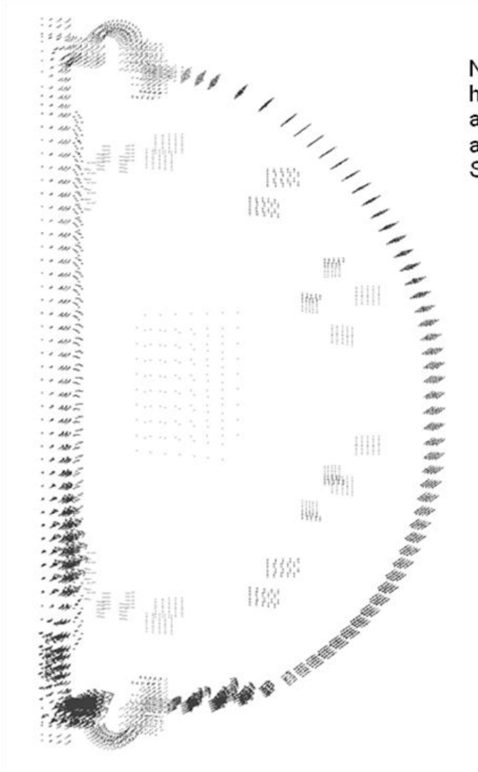
Due to Unit Current in PF1bL, si10



Due to Unit Current in PF1cL, si11

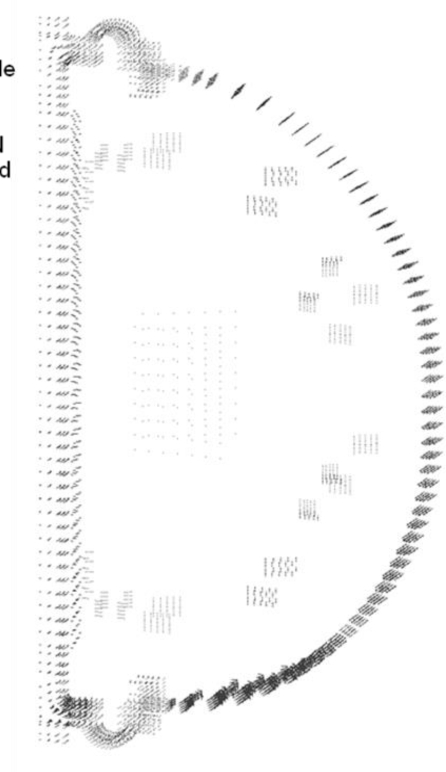


Due to Unit Current in PF2L, si12

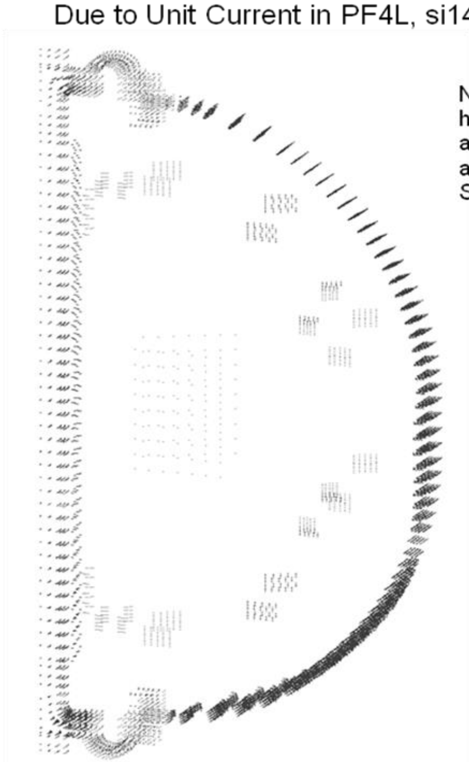


Note: Scale has been adjusted, and TFON Subtracted

Due to Unit Current in PF3L, si13

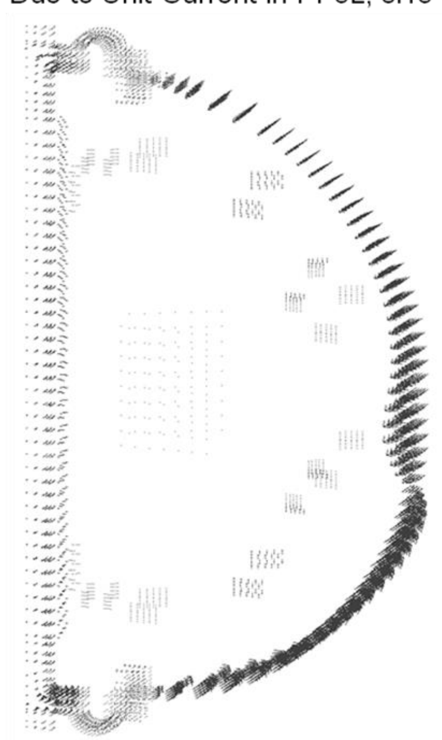


Due to Unit Current in PF4L, si14



Note: Scale has been adjusted, and TFON Subtracted

Due to Unit Current in PF5L, si15



Appendix C, Reference 12

NSTX MEMO#: 13-010515-IZ-01

TO: C Neumeyer

DATE: 15 May 2001

FROM: I. J. Zatz

SUBJECT: NSTX Coil Protection Calculator

A Coil Protection Calculator (CPC) has been developed for NSTX based on limiting the insulation shear stress in the center stack TF leg. By providing an allowable insulation shear stress, currents for the TF, OH, PF1a and PF1b can be input to the calculator, and the maximum normalized insulation shear stresses are returned. Additionally, the CPC incorporates the effects of thermal gradients in the insulation for specified operating conditions, and includes the resultant stress effects in the total. Since thermal stresses do not scale linearly, scenarios not accounted for in the initial version of the CPC will require new thermal analyses to develop and/or verify appropriate coefficients.

The CPC was benchmarked against analyses performed and documented previously by H.M. Fan in NSTX Document 13-970505-HMF-01-Rev-1.

USING THE CPC

In order to develop the coefficients necessary for this CPC, separate analyses were required for each unit current load condition. The results from these analyses were carefully scrutinized to determine which regions in the insulation needed to be monitored as candidates for high shear stresses. Fifteen discrete and varied insulation locations on NSTX were selected for the baseline CPC after studying the results of the finite element analyses. These locations were chosen based on design considerations and their tendency for high stresses. Upon more detailed examination, five of these locations were found to be consistently dominant with respect to high shear stresses. Base on the analytical results, if the insulation shear stresses are found to be acceptable at these five locations, then the insulation shear stresses are considered acceptable everywhere.

The NSTX CPC is comprised of stress coefficients representing a selection of ‘unit value’ current conditions including the following:

- 1ka in the TF
- Plus or minus 1ka in the OH in the presence of 1ka in the TF
- Plus or minus 1ka in PF1a (upper and lower) in the presence of 1ka in the TF
- 1ka in PF1b in the presence of 1ka in the TF

Once currents are provided to the CPC for each coil, the coefficients associated with these unit currents are scaled then summed via linear superposition to generate combined stresses. The effects of thermal stresses are added to these totals to create the composite stress states. The default thermal condition in the CPC is EOFT for high field currents (TF=71.16ka, OH=-22.1ka, PF1a=2ka). These coefficients can be scaled to roughly represent an EOFT low field current condition (TF=35.56ka, OH=24ka, PF1a=15ka) by using a scaling factor of 1.3 in the CPC. Any other thermal conditions would necessitate additional thermal analysis.

The CPC itself is in the form of an MS Excel spreadsheet. The highlighted cell next to each coil identifier is provided to input the current in that coil in kiloamps. The first coil identified on the spreadsheet is 'TF, ONLY'. In the cell to the right of this label, enter the TF current in kiloamps. The OH and PF coils follow below. Note that each includes 'TF' in its label. This is because the OH and PF coils will not generate forces in the center stack TF leg insulation without the presence of a TF field. Accordingly, the CPC coefficients were developed for unit currents in these coils in the presence of a unit current in the TF. Appropriate scalings and summations are performed by the CPC.

For the OH and PF1a coils, a separate set of stress coefficients were developed for both positive and negative currents in each. If a positive current is desired, enter the current, in kiloamps, in the cell to the right of the appropriate coil label. The negative current entry for that coil should either be left blank or else use a current value of zero. Do the opposite if a negative current is desired. All currents are entered into the CPC as positive numbers. For example, to apply –24ka to the OH, enter '24' (positive number) in the cell to the right of the coil ID label 'TF, -OH'. Leave blank or enter '0' in the cell to the right of the coil label 'TF, +OH'.

As previously indicated, the default thermal condition represents EOFT for high field currents. The cell next to the 'EOFT-HF' label should have an entry of '1' to include these load effects. Use '1.3' to approximate the previously descibed EOFT low field condition. Leave blank or enter '0' to exclude thermal effects. If one is interested in isolating the effect of an individual coil, specify its current in the appropriate cell and leave the other cells, including the thermal condition, blank (or enter zero). Similarly, to isolate the thermal effects, leave all of the current values blank or '0' and enter '1' (or '1.3') for the thermal scaling factor.

The CPC breaks down the shear effects into the three principle components (R-Theta, Theta-Z and R-Z) for each coil and location. A cylindrical coordinate system is used due to the geometric nature of the center stack. 'R' represents the radial direction, 'Theta' the hoop or circumferential direction, and 'Z' is the vertical or axial direction. Each shear stress component designates the value of shear stress in the plane defined by the two coordinate components. Only those shear components found to be prone to high stresses are included in the CPC, which explains why certain coefficient fields in the spreadsheet are left blank.

Beneath the stress totals on the spreadsheet, given in MPa, an entry is provided to designate the shear stress allowable in MPa. Based on the information presented in NSTX Document 13-001206-PJH-01, the recommended allowable shear stress is 20.0 MPa (2.9 ksi). The CPC divides the computed stresses by the allowable stress and lists those normalized results in the final set of cells in the CPC spreadsheet. Values less than 1.0 indicate that the computed insulation stresses are less that the designated allowable stress.

Appendix D,

-----Original Message-----
From: Matt Hooker [mailto:matt.hooker@ctd-materials.com]
Sent: Monday, November 30, 2009 6:02 PM
To: James H. Chrzanowski
Subject: RE: Discussions on 101K

Jim,

Thank you again for taking the time to talk before the Thanksgiving holidays. I did finally get a chance to locate the information you are looking for. The short-beam-shear (SBS) and flexural modulus values for CTD-101K at various temperatures are given below. Note that the flexural modulus values are estimated using load-displacement data acquired during the short-beam-shear test (which is a 3-point loading test).

CTD-101K
SBS at 77K ~ 100 MPa
SBS at 295 K ~ 65 MPa
SBS at 373 K ~ 40 MPa

Flexural Modulus at 77 K ~ 21 MPa
Flexural Modulus at 295 K ~ 18 MPa
Flexural Modulus at 373 K ~ 14 MPa

The decrease in strength and modulus as the temperature approaches Tg is consistent with other polymeric materials. We measure Tg using Dynamic Mechanical Analysis (DMA), and there are a couple of ways to define Tg using this method. Most common is to use the peak of the tan delta-versus-temperature plot, and a second method is to use the knee of the storage modulus-versus temperature plot. Both are shown on the attached for your reference. As you look at this data please note that Tg was measured on a neat resin whereas the flexural modulus was measured on glass-reinforced resins.

Also, attached is a data sheet on the CTD-450 primer. This is a cyanate ester-based system originally developed for use with CE resins. It will work with 101K as well. I spoke with others here, but unfortunately we didn't know of another primer that had been tested with 101K. We have done testing on previous programs to evaluate the effectiveness of primers and other metal-surface treatments, so if you want to evaluate a candidate primer we could probably help with that if you like.

Finally, the washable mandrel material we have used here is referred to as Aquapour. There are a few versions of the product and it can be purchased from Advanced Ceramics Research (Tucson, AZ). A link to their website is below:

http://www.acrtucson.com/products/Aquapour/index.htm

I hope this will help in addressing the questions from your design review. Please let me know if you have any questions on the above, or if there is anything else I can provide.

Best Regards,
Matt

Matthew W. Hooker, Ph.D.
Senior Program Manager
Composite Technology Development
2600 Campus Drive, Suite D
Lafayette, CO 80026
Tel: (303) 664-0394, ext. 137
Fax: (303) 664-0392
E-mail: matt.hooker@ctd-materials.com

-----Original Message-----
From: James H. Chrzanowski [mailto:jchrzano@pppl.gov]
Sent: Thursday, November 12, 2009 8:40 AM
To: Matt Hooker
Cc: Thomas G. Meighan
Subject: Discussions on 101K

Matt

I would like to discuss with you some topics that came up at our recent CDR for the NSTX Upgrade activities about the properties of 101K. The new coil systems that we are designing will operate up to 100 degrees C.

Some of the topics that I would like to discuss would be:
1) Performance and properties at 100 degrees C
2) Any recommendations for conductor primer to enhance bound with conductor surface. 3) The compatibility of Corona shield C215.51 tape [von-Rolla] as a ground plane with VPI of coils.

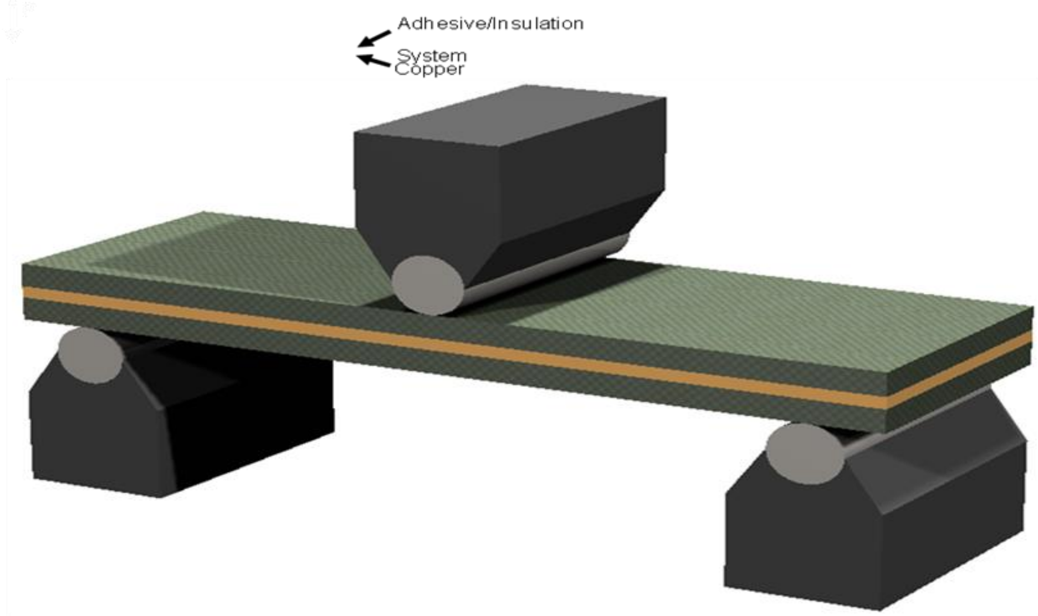
There may be other topics as well.

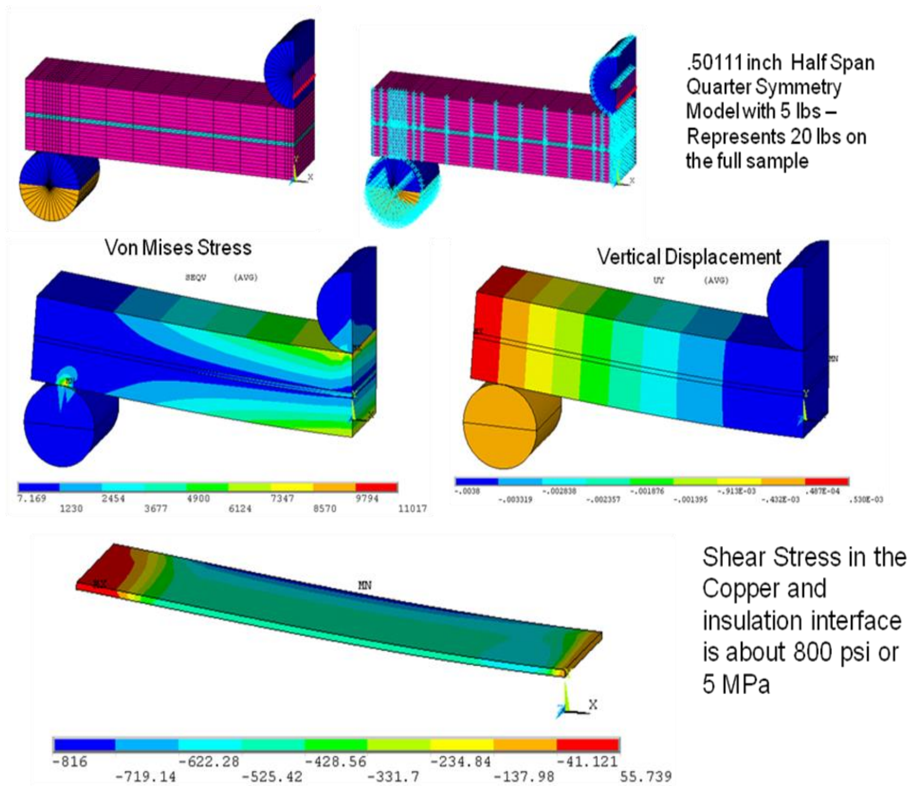
Would you be available for a phone call on perhaps Monday? Let me know when would be a convenient time for us to converse. Thanks

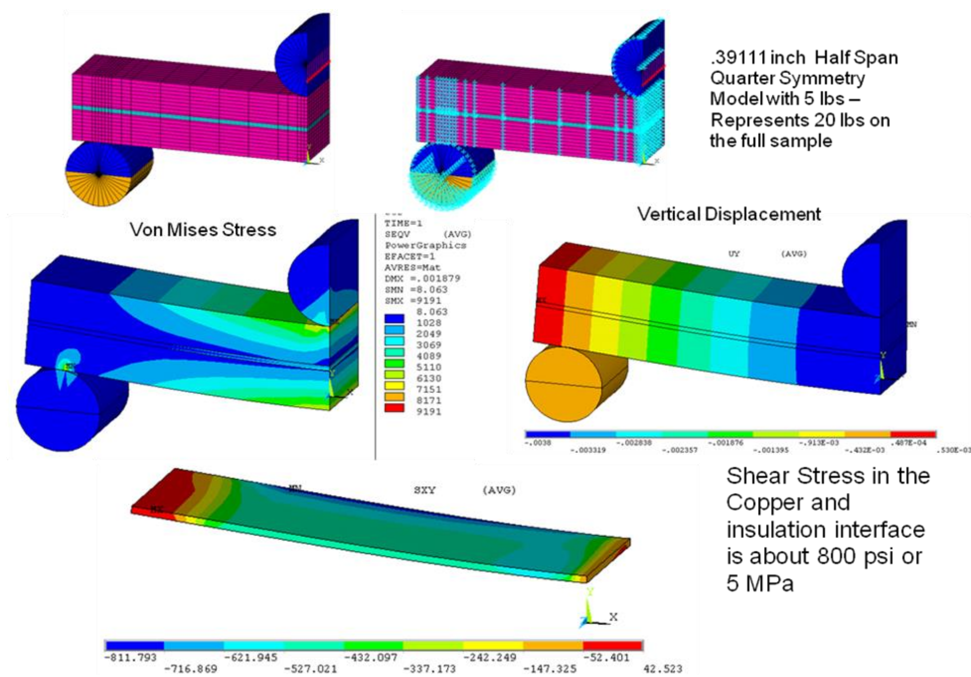
Jim

Appendix E

Nominal specimen dimensions:
Thickness: 0.125 in. (actual thickness typically varies from 0.122 to 0.125)
Width: 0.25 in.
Length: 1.1 in.
Copper thickness: 0.007 in.
Copper surface preparation: Solvent cleaned/degreased, grit blasted (both sides), CTD-450 primer applied (both sides)
Composite construction: Typically 7 plies of 6781 S2 glass fabric on either side of copper, resulting in a nominal 0.56 fiber volume fraction. If 6 plies are used per side, volume fraction is reduced to 0.48.
Span Ratio (lower support span to thickness) is typically set to 5.0. However, the span can be adjusted to reflect a ratio of 3 to 8. If a span longer than 6 is needed, the overall length of the specimen would need to increase.







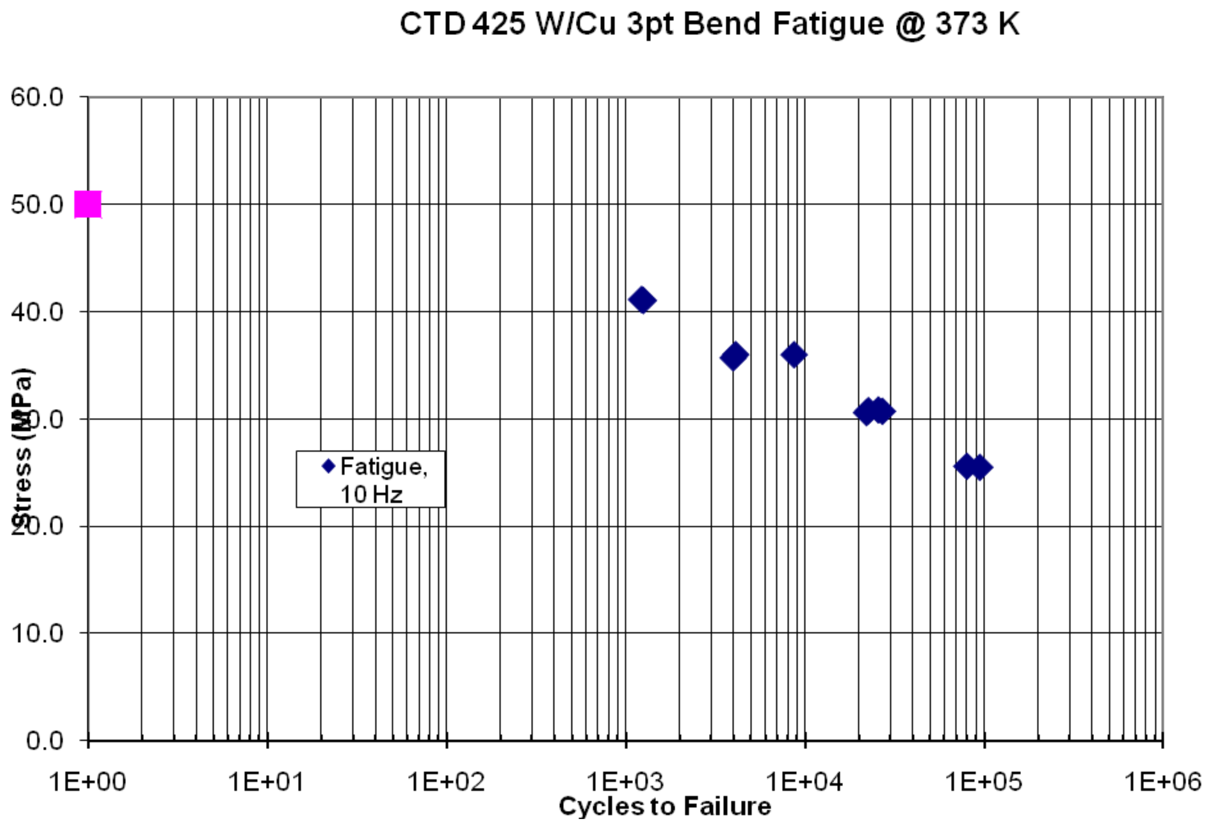
Here are the results from the CTD analysis. The 403 beats out the 425 slightly. I still want to use the 425 though. Do we need to do any additional tests? If so we need to discuss soon.

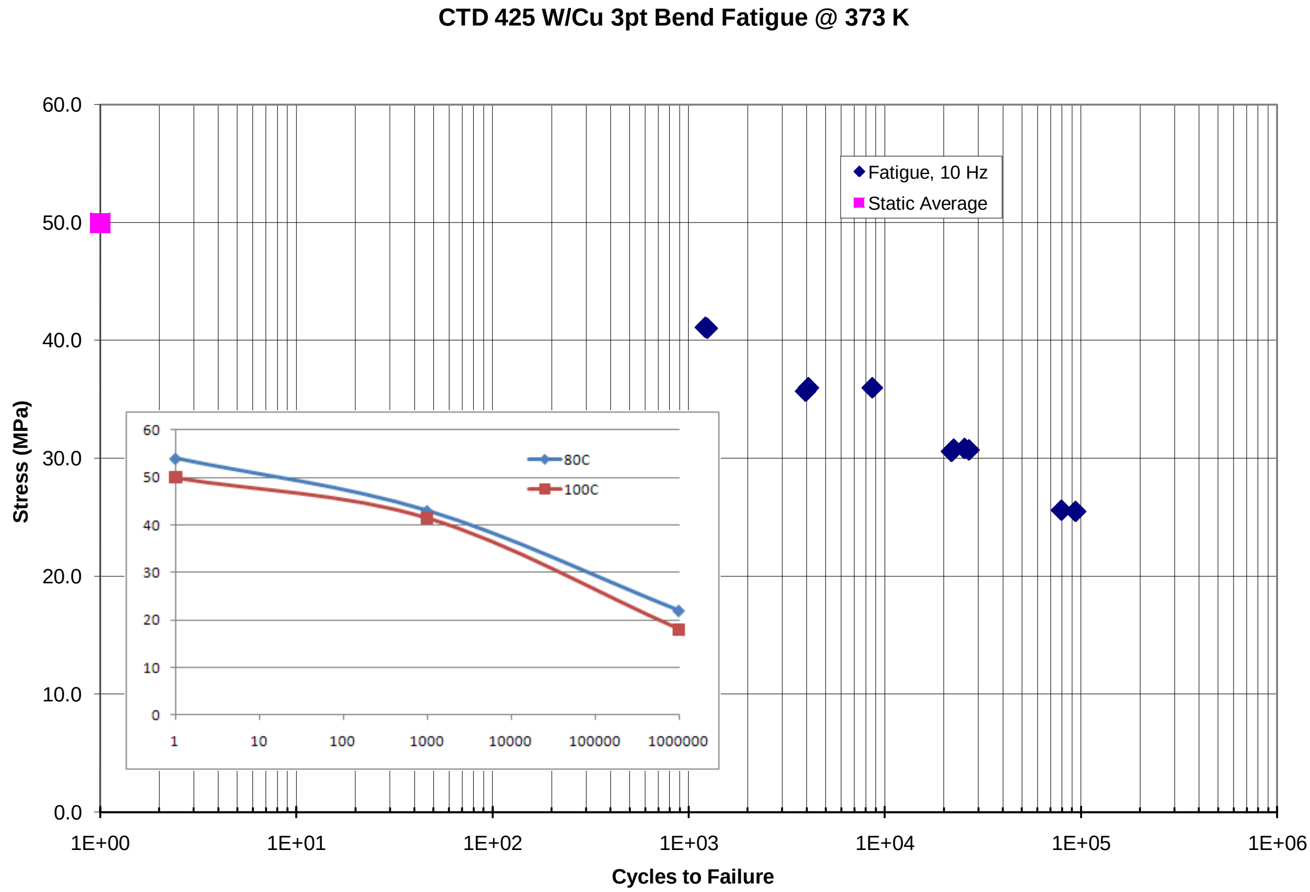
Customer:	**PPPL**	***Test Date:***	**03/10-3/17/2011**
Customer P.O.	**PE010637-W**		
CTD Program #:	**7277-032**	***Load Frame:***	**100 Kip**
		Load / Displacement Rate:	**0.05 in/min**
Material Reference:	**377005**	***Load Cell:***	**1 Kip**
Matrix System:	**CTD 403**		
Reinforcement:	**S2 Glass/ Copper**		
Standard Reference:	**ASTM D2344**		
Specimen Type:	**0.13" x 0.25" x 1.1"**	***Test Temperature:***	**100°C**
Test Fixture:	**3 point bend**	***Temperature Hold Time:***	**5 minutes**
		Specimen Conditioning:	**NA**
Fatigue Parameters			
R-ratio:	**0.1**		
Frequency:	**10 Hz**		
Static Shear Strength:	**55.3 MPa**		

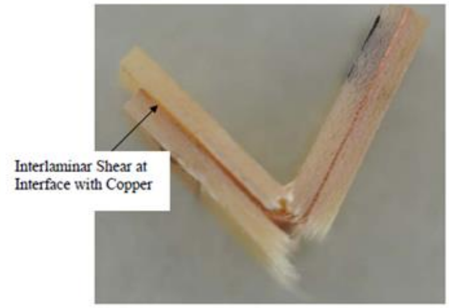
TEST RESULTS

Specimen #	Thickness (in)	Width (in)	Length (in)	Span (in)	Span Ratio	Upper Target Load (lbs)	% of Failure Load	Maximum Stress (MPa)	# Cycles to failure
377005-Average	0.1245	0.266	1.110	0.617	5.0	354.4	100.0	55.3	1.0
377005-16	0.1250	0.2490	1.117	0.6170	4.94	283.5	80.0	47.1	2973
377005-17	0.1250	0.2480	1.116	0.6170	4.94	283.5	80.0	47.3	2385
377005-11	0.1250	0.2500	1.117	0.6170	4.94	248.1	70.0	41.1	14125
377005-12	0.1240	0.2500	1.117	0.6170	4.98	248.1	70.0	41.4	18795
377005-20	0.1240	0.2470	1.120	0.6170	4.98	212.6	60.0	35.9	21939
377005-19	0.1250	0.247	1.115	0.6170	4.94	212.6	60.0	35.6	37512
377005-14	0.1240	0.249	1.121	0.6170	4.98	212.6	60.0	35.6	50543
377005-13	0.1240	0.2510	1.120	0.6170	4.98	212.6	60.0	35.3	96438
377005-15*	0.1250	0.2490	1.117	0.6170	4.94	177.2	50.0	29.4	100008
377005-18*	0.1240	0.2480	1.119	0.6170	4.98	177.2	50.0	29.8	100008

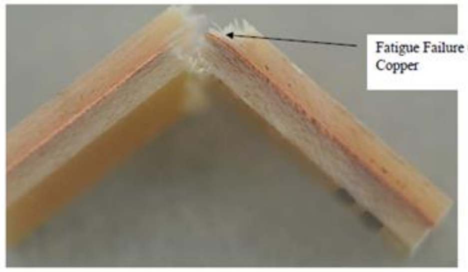
* Cyclic tests stopped prior to specimen failure.



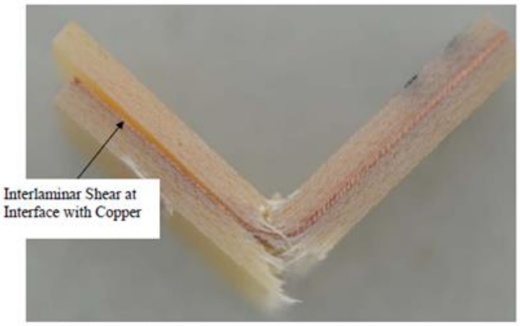

CTD 425 W/Cu 3pt Bend Fatigue @ 373 K
Stress (MPa)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
1E+00
1E+01
1E+02
1E+03
1E+04
1E+05
1E+06
Cycles to Failure
Fatigue, 10 Hz
Static Average
60
50
40
30
20
10
0
1
10
100
1000
10000
100000
1000000
80C
100C



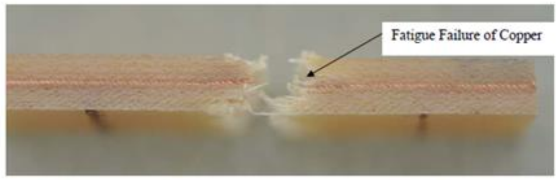
CTD-403 Specimen #16- Fatigue at 80% of Ultimate Stress (47.1 MPa, 2973 cycles)



CTD-403 Specimen #11- Fatigue at 70% of Ultimate Stress (41.1 MPa, 14125 cycles)



CTD-403 Specimen #17- Fatigue at 80% of Ultimate Stress (47.3 MPa, 2385 cycles)



CTD-403 Specimen #12- Fatigue at 70% of Ultimate Stress (41.4 MPa, 18795 cycles)

July 25 2011 Email from Gary Voss

Phil, Pete et al.
Sorry I could not join in to this meeting as I have not been at Culham much in the last few weeks.

Just to clarify our creep/fatigue results:
We tested glass reinforced cyanate ester resin (CTD 304) with the CTD 450 primer between two copper cylinders in torsion which gave a well defined shear stress distribution with no stress concentrations.
The fatigue tests were load controlled as in MAST-U we have significant shear stress (18-20 MPa) produced by the solenoid/TF field interaction i.e. a primary stress not a thermal stress.
The load was applied for 10 sec because in the early days of MAST-U some of my physics colleagues wanted a very long pulse of 7-10 sec. This long pulse option has now been dropped and the longest pulse is now expected to be 5 sec max. Hence these results are pessimistic and give some safety margin.
The tests were all done at 100 deg C which is also pessimistic for MAST-U.
The results showed failure occurred after about 3000 load cycles at a shear stress of 25-30 MPa. Clearly there will be some creep effects which will reduce the max shear stress at the outer radius of the test cylinder and spread the load out more uniformly but the degree to which this occurs is not known hence the spread in shear stress.

Hope this helps

Garry

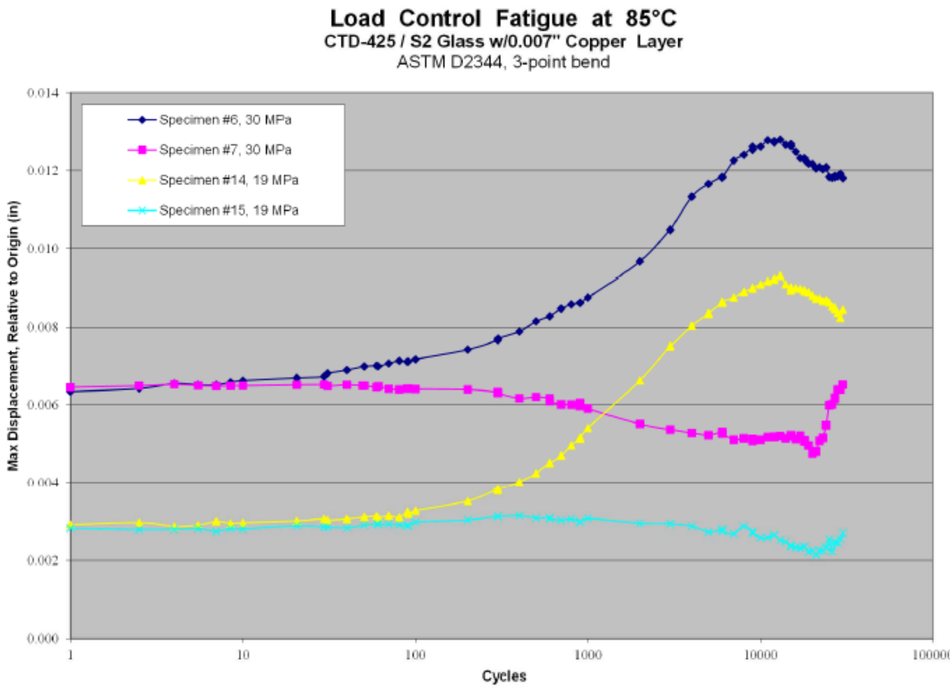
Appendix F
CTD Creep/Slower Cyclic Load Tests - Effects of Increased Dwell Times at Load

- Purpose of test: To qualify the NSTX proposed shear bond, at the highest expected temperature at peak torque, taking into account creep in the bond between the copper, primer, and laminate.
- Need 6000 x FS of 5 =30,000 cycles to meet criteria.
- Proposed test:
  - Use CTD short beam laminated specimens, grit blasted & primed.
  - Test for 6000 x 5 cycles
  - *Note: OH swing is +24 to -24 kA. The TF is cold at the first swing, so we will only consider the second, hot pulse –i.e., R=0 tests. The integrated time for the OH pulse is ~2 s. That is the rationale for 0.5 Hz. The OH swing is approximated by a 0.5 Hz sine wave programming of the tester with a short (.5 s) dwell at peak for data measurement*.
  - **Load controlled test at 85 C.** This test determines the ability of the CS to resist the torque. (test machine interlocked when tester ram went beyond 0.060")
    - Test at 19 Mpa to failure (30,000 cycles =16 hr.) 2 specimens (3rd if needed)
    - Repeat at 30 Mpa to failure, 2 specimens (3rd if needed)
  - **Displacement controlled test at peak initial strain at "hot spot" location. Perform at 100 C.**
    - Use sine wave programming 0.5 Hz with 0.5 s dwell
    - Use the displacement previously measured for the 55 MPa modulus test. Take 50% of that as representative of the peak shear of 25 MPa.
    - Test to failure. Should be >60,000 cycles, ideally. 2 specimens (3rd if needed)
    - For a second data point, use 70% of the 55 MPa displacement. 2 specimens (3rd if needed)
  - NOTE: Tensile test remains.

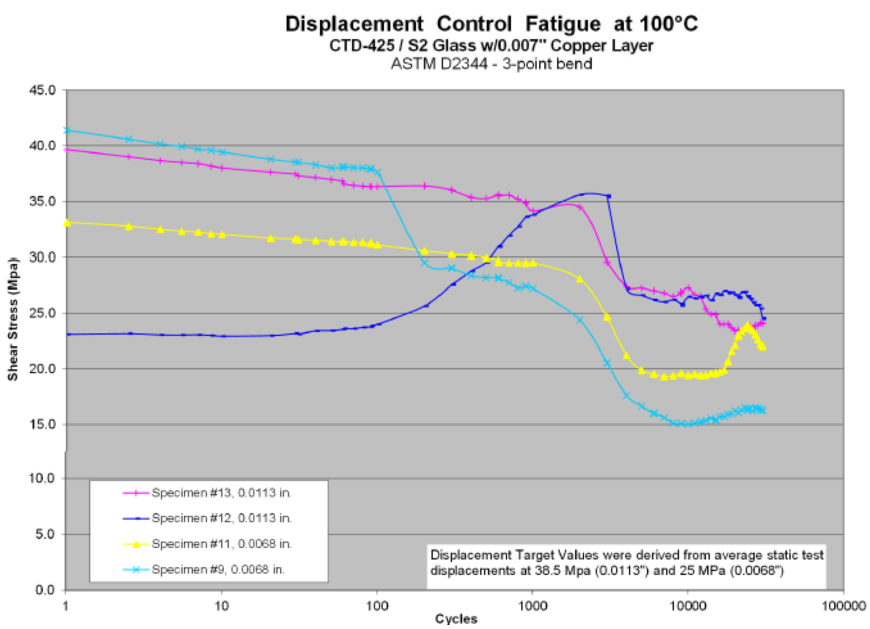
Each cycle should be 0 to peak in 3s, 0.5 s dwell, and peak to 0 in 0.5 s. Use this cycle time for both the load and the displacement controlled testing.

The next two figures show the preliminary results of the tests with longer dwell times at load. There are problems with the displacement measurements, but the important observation is that there is no failure of the epoxy for either the 19 or 30 MPa shear loading. These tests had much longer dwell times than the previous 10 hz tests, and were based on 6000 full 5sec Max TF max OH cycles - with a factor of 5 on testing life or 30, 000 test cycles to qualify the 6000 full power/full pulse length cycles.. This will have to be updated in the GRD [8].

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
ENGINEERED MATERIAL SOLUTIONS



COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
ENGINEERED MATERIAL SOLUTIONS



Appendix G Post Disruption Currents

Charles L. Neumeyer neumeyer@pppl.gov January 13 2012 email

11:02 AM (4 hours ago) to me, Ronald

Pete, per our discussion yesterday, the attached provides the coil currents for the 96 equilibria for three cases:

1) 2MA plasma
2) Post-disruption from 2MA plasma based on circular plasma model
3) Post-disruption from 2MA plasma based on shaped plasma model

These are extracted from the DP spreadsheet, and are based on the simple flux conservation approach. Ch.

Equilibria	OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5
	(kA)	(kA)	(kA)	(kA)	(kA)	(kA)	(kA)	(kA)	(kA)	(kA)	(kA)	(kA)	(kA)	(kA)	(kA)
1	-24.000	-6.509	8.178	11.378	-1.834	-10.564	3.557	-25.416	-6.509	8.178	11.378	-1.834	-10.564	3.557	-25.416
2	-21.972	-7.345	7.681	12.049	-0.443	-7.979	8.497	-20.835	-7.345	7.681	12.049	-0.443	-7.979	8.497	-20.835
3	0.000	-6.906	8.948	13.976	4.296	-6.236	8.422	-20.004	-6.906	8.948	13.976	4.296	-6.236	8.422	-20.004
4	15.052	-6.685	9.650	15.043	6.859	-5.291	8.384	-19.554	-6.685	9.650	15.043	6.859	-5.291	8.384	-19.554
5	-21.972	-2.293	5.727	7.410	-0.888	-7.636	7.121	-20.104	-2.293	5.727	7.410	-0.888	-7.636	7.121	-20.104
6	0.000	-2.047	7.303	9.748	3.589	-5.880	7.011	-19.240	-2.047	7.303	9.748	3.589	-5.880	7.011	-19.240
7	15.052	-1.859	8.095	10.945	6.060	-4.893	6.965	-18.806	-1.860	8.095	10.945	6.060	-4.893	6.965	-18.806
8	-21.972	1.686	2.435	2.776	0.760	-7.693	5.719	-19.339	1.685	2.435	2.776	0.760	-7.693	5.719	-19.339
9	0.000	1.909	4.112	5.227	5.107	-5.856	5.577	-18.493	1.909	4.112	5.227	5.107	-5.856	5.577	-18.493
10	15.052	1.987	5.101	6.623	7.408	-4.901	5.480	-17.977	1.987	5.101	6.623	7.408	-4.901	5.480	-17.977
11	-21.972	4.616	-2.907	-0.613	4.792	-8.135	3.987	-18.405	4.616	-2.907	-0.613	4.792	-8.135	3.987	-18.405
12	0.000	4.751	-0.985	2.012	8.900	-6.248	3.807	-17.543	4.751	-0.985	2.012	8.900	-6.248	3.807	-17.543
13	15.052	4.817	0.080	3.447	11.112	-5.232	3.708	-17.066	4.817	0.080	3.447	11.112	-5.232	3.708	-17.066
14	-21.972	5.259	-5.069	-0.825	6.428	-8.479	2.920	-17.768	5.259	-5.069	-0.825	6.428	-8.479	2.920	-17.768
15	0.000	5.388	-3.097	1.826	10.487	-6.564	2.717	-16.900	5.388	-3.097	1.826	10.487	-6.564	2.717	-16.900
16	15.052	5.451	-2.022	3.273	12.690	-5.549	2.603	-16.405	5.451	-2.022	3.273	12.690	-5.549	2.603	-16.405
17	-21.972	-7.345	7.681	12.049	-0.443	-7.979	8.497	-20.835	-7.345	7.681	12.049	-0.443	-7.979	8.497	-20.835
18	0.000	-6.906	8.948	13.976	4.296	-6.236	8.422	-20.004	-6.906	8.948	13.976	4.296	-6.236	8.422	-20.004
19	15.052	-6.685	9.650	15.043	6.859	-5.291	8.384	-19.554	-6.685	9.650	15.043	6.859	-5.291	8.384	-19.554
20	-21.972	7.106	-5.928	-3.842	8.018	-3.500	-8.897	-13.285	7.106	-5.928	-3.842	8.018	-3.500	-8.897	-13.285
21	0.000	7.284	-4.132	-1.333	12.301	-1.644	-9.082	-12.400	7.284	-4.132	-1.333	12.301	-1.644	-9.082	-12.400
22	15.052	7.378	-3.159	0.028	14.627	-0.637	-9.182	-11.920	7.378	-3.159	0.028	14.627	-0.637	-9.182	-11.920
23	-21.972	6.002	-4.254	-2.380	6.978	-5.436	-1.715	-16.670	6.002	-4.254	-2.380	6.978	-5.436	-1.715	-16.670
24	0.000	6.171	-2.426	0.159	11.254	-3.624	-1.880	-15.760	6.171	-2.426	0.159	11.254	-3.624	-1.880	-15.760
25	15.052	6.197	-1.396	1.569	13.541	-2.631	-1.942	-15.326	6.197	-1.396	1.569	13.541	-2.631	-1.942	-15.326
26	-21.972	4.458	-1.186	0.096	4.467	-6.590	3.407	-19.027	4.458	-1.186	0.096	4.467	-6.590	3.407	-19.027
27	0.000	4.670	0.529	2.539	8.836	-4.769	3.226	-18.118	4.670	0.529	2.539	8.836	-4.769	3.226	-18.118
28	15.052	4.763	1.473	3.875	11.186	-3.766	3.148	-17.668	4.763	1.473	3.875	11.186	-3.766	3.148	-17.668
29	-21.972	2.373	3.514	3.641	-0.153	-6.969	7.885	-21.125	2.373	3.514	3.641	-0.153	-6.969	7.885	-21.125
30	0.000	2.512	5.189	6.051	4.261	-5.160	7.754	-20.317	2.512	5.189	6.051	4.261	-5.160	7.754	-20.317
31	15.052	2.643	6.134	7.384	6.623	-4.174	7.678	-19.829	2.643	6.134	7.384	6.623	-4.174	7.678	-19.829
32	-21.972	0.284	8.635	7.348	-5.585	-6.302	9.506	-21.947	0.284	8.635	7.348	-5.585	-6.302	9.506	-21.947
33	0.000	0.477	10.355	9.775	-1.190	-4.520	9.387	-21.086	0.477	10.355	9.775	-1.190	-4.520	9.387	-21.086
34	15.052	0.597	11.252	11.065	1.227	-3.548	9.332	-20.636	0.597	11.252	11.065	1.227	-3.548	9.332	-20.636
35	-21.972	11.696	0.000	0.000	-3.162	3.207	0.000	-23.517	4.351	0.000	0.000	5.819	-3.634	0.000	-23.517
36	0.000	14.028	0.000	0.000	0.668	5.461	0.000	-22.774	5.999	0.000	0.000	11.723	-2.009	0.000	-22.774
37	15.052	15.189	0.000	0.000	2.873	6.574	0.000	-22.385	6.861	0.000	0.000	14.924	-1.122	0.000	-22.385
38	-21.972	10.829	0.000	0.000	-1.896	1.157	0.000	-22.972	5.708	0.000	0.000	3.956	-3.855	0.000	-22.972
39	0.000	13.263	0.000	0.000	1.985	3.483	0.000	-22.272	7.407	0.000	0.000	10.063	-2.213	0.000	-22.272
40	15.052	14.465	0.000	0.000	4.188	4.653	0.000	-21.911	8.287	0.000	0.000	13.372	-1.317	0.000	-21.911
41	-21.972	9.718	0.000	0.000	-1.079	-0.861	0.000	-22.315	5.840	0.000	0.000	2.384	-4.146	0.000	-22.315
42	0.000	12.363	0.000	0.000	2.804	1.711	0.000	-21.747	7.511	0.000	0.000	8.686	-2.287	0.000	-21.747
43	15.052	13.535	0.000	0.000	5.129	2.782	0.000	-21.369	8.336	0.000	0.000	12.244	-1.522	0.000	-21.369
44	-21.972	8.143	0.000	0.000	-0.596	-2.812	0.000	-21.586	5.157	0.000	0.000	1.174	-4.606	0.000	-21.586
45	0.000	10.861	0.000	0.000	3.567	-0.458	0.000	-20.969	6.671	0.000	0.000	8.082	-3.010	0.000	-20.969
46	15.052	12.195	0.000	0.000	5.871	0.772	0.000	-20.659	7.436	0.000	0.000	11.822	-2.137	0.000	-20.659
47	-21.972	6.587	0.000	0.000	-0.417	-4.223	0.000	-20.905	4.220	0.000	0.000	0.249	-4.894	0.000	-20.905
48	0.000	9.351	0.000	0.000	3.926	-1.983	0.000	-20.302	5.491	0.000	0.000	7.757	-3.450	0.000	-20.302
49	15.052	10.842	0.000	0.000	6.235	-0.763	0.000	-19.966	6.183	0.000	0.000	11.837	-2.678	0.000	-19.966
50	-21.972	12.287	0.000	0.000	-7.814	9.888	-5.060	-19.737	7.221	0.000	0.000	3.071	1.008	-5.060	-19.737
51	0.000	14.617	0.000	0.000	-4.041	12.149	-5.060	-18.989	8.854	0.000	0.000	8.973	2.629	-5.060	-18.989
52	15.052	15.771	0.000	0.000	-1.846	13.251	-5.060	-18.605	9.722	0.000	0.000	12.154	3.538	-5.060	-18.605
53	-21.972	11.407	0.000	0.000	-6.559	7.575	-5.060	-19.080	7.770	0.000	0.000	1.477	0.709	-5.060	-19.080
54	0.000	13.737	0.000	0.000	-2.650	9.823	-5.060	-18.392	9.422	0.000	0.000	7.586	2.349	-5.060	-18.392
55	15.052	15.003	0.000	0.000	-0.541	11.047	-5.060	-18.020	10.320	0.000	0.000	10.893	3.249	-5.060	-18.020
56	-21.972	10.077	0.000	0.000	-5.704	5.164	-5.060	-18.371	7.238	0.000	0.000	0.042	0.335	-5.060	-18.371
57	0.000	12.674	0.000	0.000	-1.794	7.570	-5.060	-17.706	8.902	0.000	0.000	6.472	1.992	-5.060	-17.706
58	15.052	13.907	0.000	0.000	0.414	8.786	-5.060	-17.379	9.742	0.000	0.000	9.950	2.900	-5.060	-17.379
59	-21.972	8.633	0.000	0.000	-5.576	3.061	-5.060	-17.532	6.147	0.000	0.000	-1.132	-0.202	-5.060	-17.532
60	0.000	11.312	0.000	0.000	-1.434	5.447	-5.060	-16.929	7.654	0.000	0.000	5.778	1.420	-5.060	-16.929
61	15.052	12.610	0.000	0.000	0.835	6.714	-5.060	-16.637	8.407	0.000	0.000	9.506	2.329	-5.060	-16.637
62	-21.972	6.763	0.000	0.000	-5.739	1.215	-5.060	-16.660	4.789	0.000	0.000	-1.940	-0.911	-5.060	-16.660
63	0.000	9.585	0.000	0.000	-1.380	3.521	-5.060	-16.074	6.101	0.000	0.000	5.568	0.581	-5.060	-16.074
64	15.052	10.953	0.000	0.000	0.988	4.747	-5.060	-15.783	6.745	0.000	0.000	9.630	1.388	-5.060	-15.783
65	-21.972	4.612	0.000	0.000	2.949	-11.463	0.000	-16.168	4.612	0.000	0.000	2.949	-11.463	0.000	-16.168
66	0.000	5.875	0.000	0.000	10.646	-10.392	0.000	-15.373	5.875	0.000	0.000	10.646	-10.392	0.000	-15.373
67	15.052	6.554	0.000	0.000	14.825	-9.811	0.000	-14.946	6.554	0.000	0.000	14.825	-9.811	0.000	-14.946
68	-21.972	4.424	0.000	0.000	2.495	-10.359	0.000	-16.908	4.424	0.000	0.000	2.495	-10.359	0.000	-16.908
69	0.000	5.718	0.000	0.000	10.158	-9.248	0.000	-16.136	5.717	0.000	0.000	10.158	-9.248	0.000	-16.136
70	15.052	6.390	0.000	0.000	14.313	-8.605	0.000	-15.731	6.390	0.000	0.000	14.313	-8.605	0.000	-15.731
71	-21.972	4.245	0.000	0.000	0.808	-6.584	0.000	-19.439	4.245	0.000	0.000	0.808	-6.584	0.000	-19.439
72	0.000	5.571	0.000	0.000	8.357	-5.258	0.000	-18.755	5.571	0.000	0.000	8.357	-5.258	0.000	-18.755
73	15.052	6.294	0.000	0.000	12.454	-4.527	0.000	-18.406	6.294	0.000	0.000	12.454	-4.527	0.000	-18.406
74	-21.972	4.485	0.000	0.000	-0.757	-3.341	0.000	-21.519	4.484	0.000	0.000	-0.757	-3.341	0.000	-21.519
75	0.000	5.828	0.000	0.000	6.754	-1.954	0.000	-20.911	5.828	0.000	0.000	6.754	-1.954	0.000	-20.911
76	15.052	6.585	0.000	0.000	10.781	-1.123	0.000	-20.603	6.585	0.000	0.000	10.781	-1.123	0.000	-20.603
77	-21.972	4.790	0.000	0.000	-2.165	-0.573	0.000	-23.245	4.790	0.000	0.000	-2.165	-0.573	0.000	-23.245
78	0.000	6.237	0.000	0.000	5.155	1.097	0.000	-22.749	6.237	0.000	0.000	5.155	1.097	0.000	-22.749
79	15.052	7.000	0.000	0.000	9.138	1.993	0.000	-22.479	7.000	0.000	0.000	9.138	1.993	0.000	-22.479
80	-21.972	5.364	0.000	0.000	-4.163	3.139	0.000	-25.597	5.364	0.000	0.000	-4.163	3.139	0.000	-25.597
81	0.000	6.829	0.000	0.000	3.095	4.887	0.000	-25.155	6.829	0.000	0.000	3.095	4.887	0.000	-25.155
82	15.052	7.610	0.000	0.000	7.014	5.820	0.000	-24.910	7.610	0.000	0.000	7.014	5.820	0.000	-24.910
83	-21.972	10.595	-2.926	-1.814	-0.094	-8.237	5.617	-18.760	10.595	-2.926	-1.814	-0.094	-8.237	5.617	-18.760
84	0.000	10.720	-0.808	0.692	3.991	-6.303	5.352	-17.859	10.719	-0.808	0.692	3.991	-6.303	5.352	-17.859
85	15.052	10.780	0.325	2.041	6.219	-5.234	5.207	-17.388	10.780	0.325	2.041	6.219	-5.234	5.207	-17.388
86	-21.972	7.941	-2.514	-0.837	2.055	-8.627	6.373	-19.208	7.941	-2.514	-0.837	2.055	-8.627	6.373	-19.208
87	0.000	8.007	-0.260	1.802	6.083	-6.805	6.155	-18.256	8.007	-0.260	1.802	6.083	-6.805	6.155	-18.256
88	15.052	8.050	0.791	3.132	8.384	-5.715	6.034	-17.832	8.050	0.791	3.132	8.384	-5.715	6.034	-17.832
89	-21.972	6.032	-1.471	0.039	2.396	-8.700	6.871	-19.479	6.031	-1.471	0.039	2.396	-8.700	6.871	-19.479
90	0.000	6.159	0.416	2.515	6.635	-6.719	6.706	-18.719	6.159	0.416	2.515	6.635	-6.719	6.706	-18.719
91	15.052	6.208	1.521	3.906	8.883	-5.688	6.606	-18.258	6.208	1.521	3.906	8.883	-5.688	6.606	-18.258
92	-21.972	4.547	-0.264	0.446	1.642	-8.280	6.887	-19.608	4.547	-0.264	0.446	1.642	-8.280	6.887	-19.608
93	0.000	4.652	1.707	3.053	5.802	-6.400	6.719	-18.760	4.652	1.707	3.053	5.802	-6.400	6.719	-18.760
94	15.052	4.723	2.761	4.454	8.059	-5.379	6.625	-18.295	4.723	2.761	4.454	8.059	-5.379	6.625	-18.295
95	-21.972	3.332	0.733	0.280	0.773	-7.766	6.562	-19.537	3.332	0.733	0.280	0.773	-7.766	6.562	-19.537
96	0.000	3.520	2.563	2.873	4.945	-5.885	6.396	-18.686	3.520	2.563	2.873	4.945	-5.885	6.396	-18.686
97	15.052	3.621	3.569	4.282	7.200	-4.860	6.302	-18.223	3.621	3.569	4.282	7.200	-4.860	6.302	-18.223

Appendix H
March 7 2012 email from Charles Neumeyer

Pete, As we discussed a few days ago, I'm working on a revision to the DP spreadsheet to close out the checking exercise and I added the TF torque sums for the cases with plasma. Attached is a preliminary result. New entries are all the way on the right side in blue font. It seems that the presence of the plasma decreases the torque compared to the no-plasma case (which was the only case previously reported). And then, after disruption, the OH and PF currents experience a shift (according to the flux conserving solution) but the torque remains less than the no-plasma case. So, the case previously reported holds up as a "worst case". These results will be formally issued in the next few days. Ch

Appendix I
Bob Wooleys Checkers Comments and DCPS Coefficients

Using my torsion model I decided to evaluate coefficients from coil and plasma currents to the shear stress at upper and lower corners and at center of the TF centerstack, all at the outside edge where shear is maximum over the cross sectiion. To that end, first I examined the old results to see where are the corners. I found that the peak stresses have occurred at Z=+2.60 and and Z=-2.60 meters. Other lesser peaks have occurred elsewhere for different current conditions but they have all been much less severe. I then found that the Z=+2.60 point is at node 1638, the Z=0 point is a t node 1, and the Z=-2.60 point is at node 363. In switching these over to the re-arranged 764-node shear stress matrix variable, SS, these node numbers become respectively [21 382 744].

I set up a 14 x 14 diagonal matrix with the first 13 diagonal values being 1e3 and the 14th being 1e6, in order to represent each coil or plasma being energized by itself with that number of amperes. The SS matrix, dimensioned as SS(764,14), was then calculated to hold the calculated shear stress profiles at the 764 TF centerstack Z-locations. For the three identified locations and for the 14 current sets the results are as follows. Obviously, this is for 130 kA TF current.

```
>> SS([21 382 744],:)'
ans =
  1.0e+06 *
  -0.0530   -0.0624   -0.0661
  -0.0254   -0.0396   -0.0415
  -0.0220   -0.0353   -0.0373
  -0.0582   -0.0873   -0.0919
  -0.2303   -0.2419   -0.2559
  -0.2949   -0.2712   -0.2948
  -0.4544   -0.4177   -0.4544
  -0.2688   -0.2550   -0.2431
  -0.1046   -0.1001   -0.0704
  -0.0419   -0.0399   -0.0263
  -0.0456   -0.0438   -0.0293
  -0.0698   -0.0662   -0.0564
  -0.7115    0.2601   -0.7103
  -3.7021   -2.1477   -3.7010
```

>>
Here, the row sequence is as follows:

PF1AU
PF1BU
PF1CU
PF2U
PF3U
PF4
PF5
PF3L
PF2L
PF1CL
PF1BL
PF1AL

OH —

PLASMA

It is interesting that all coefficients for the top and bottom corners are of the same sign. This is different from Titus' coefficients which have the OH and Plasma coefficients of one sign and most of the others of the opposite sign.

In order to be completely clear so that nothing is left to interpretation I have rewritten the algorithms using my typed-out coefficients and have also rewritten Titus' coefficients in identically the same format. Note that this format combines the upper and lower widnings of PF4 and PF5 coils which are connected in series.   Thus, the algorithms are rewritten as follows:

Upper Corner Algorithm, Woolley

$$\left[\frac{\tau_{shear}}{1\ \mathrm{MPa}}\right]_{Woolley}^{CenterstackUpperCorner} =$$

$$\left(\begin{array}{l}(-0.0530)\left[\frac{I_{PF1AU}}{1\ \mathrm{kA}}\right]+(-0.0254)\left[\frac{I_{PF1BU}}{1\ \mathrm{kA}}\right]+(-0.0220)\left[\frac{I_{PF1CU}}{1\ \mathrm{kA}}\right]\\ +(-0.0582)\left[\frac{I_{PF2U}}{1\ \mathrm{kA}}\right]+(-0.2303)\left[\frac{I_{PF3U}}{1\ \mathrm{kA}}\right]+(-0.2949)\left[\frac{I_{PF4\&LU}}{1\ \mathrm{kA}}\right]+(-0.4544)\left[\frac{I_{PF5U\&L}}{1\ \mathrm{kA}}\right]+\\ +(-0.2688)\left[\frac{I_{PF3L}}{1\ \mathrm{kA}}\right]+(-0.1046)\left[\frac{I_{PF2L}}{1\ \mathrm{kA}}\right]+(-0.0419)\left[\frac{I_{PF1CL}}{1\ \mathrm{kA}}\right]+(-0.0456)\left[\frac{I_{PF1BL}}{1\ \mathrm{kA}}\right]+\\ +(-0.0698)\left[\frac{I_{PF1AL}}{1\ \mathrm{kA}}\right]+(-0.7115)\left[\frac{I_{OH}}{1\ \mathrm{kA}}\right]+(-3.7021)\left[\frac{I_{PLASMA}}{1\ \mathrm{MA}}\right]\end{array}\right) * \left[\frac{I_{TF}}{130\ \mathrm{kA}}\right]$$

Upper Corner Algorithm, Titus

$$\left[\frac{\tau_{shear}}{1\ \mathrm{MPa}}\right]_{Titusf}^{CenterstackUpperCorner} =$$

$$\left(\begin{array}{l}(+0.0418)\left[\frac{I_{PF1AU}}{1\ \mathrm{kA}}\right]+(+0.0307)\left[\frac{I_{PF1BU}}{1\ \mathrm{kA}}\right]+(-0.0406)\left[\frac{I_{PF1CU}}{1\ \mathrm{kA}}\right]\\ +(-0.0622)\left[\frac{I_{PF2U}}{1\ \mathrm{kA}}\right]+(+0.0535)\left[\frac{I_{PF3U}}{1\ \mathrm{kA}}\right]+(+0.6322)\left[\frac{I_{PF4\&LU}}{1\ \mathrm{kA}}\right]+(+0.5467)\left[\frac{I_{PF5U\&L}}{1\ \mathrm{kA}}\right]+\\ +(+0.504)\left[\frac{I_{PF3L}}{1\ \mathrm{kA}}\right]+(+0.533)\left[\frac{I_{PF2L}}{1\ \mathrm{kA}}\right]+(+0.238)\left[\frac{I_{PF1CL}}{1\ \mathrm{kA}}\right]+(+0.133)\left[\frac{I_{PF1BL}}{1\ \mathrm{kA}}\right]+\\ +(+0.148)\left[\frac{I_{PF1AL}}{1\ \mathrm{kA}}\right]+(-0.467)\left[\frac{I_{OH}}{1\ \mathrm{kA}}\right]+(-0.620)\left[\frac{I_{PLASMA}}{1\ \mathrm{MA}}\right]\end{array}\right) * \left[\frac{I_{TF}}{130\ \mathrm{kA}}\right]$$

Midplane Algorithm, Woolley

$$\left[\frac{\tau_{shear}}{1\ \text{MPa}}\right]_{Woolley}^{CenterstackMidPlaner} =$$

$$\left(\begin{aligned}&(-0.0624)\left[\frac{I_{PF1AU}}{1\ \text{kA}}\right]+(-0.0396)\left[\frac{I_{PF1BU}}{1\ \text{kA}}\right]+(-0.0353)\left[\frac{I_{PF1CU}}{1\ \text{kA}}\right]\\&+(-0.0873)\left[\frac{I_{PF2U}}{1\ \text{kA}}\right]+(-0.2419)\left[\frac{I_{PF3U}}{1\ \text{kA}}\right]+(-0.2712)\left[\frac{I_{PF4\&LU}}{1\ \text{kA}}\right]+(-0.4177)\left[\frac{I_{PF5U\&L}}{1\ \text{kA}}\right]+\\&+(-0.2550)\left[\frac{I_{PF3L}}{1\ \text{kA}}\right]+(-0.1001)\left[\frac{I_{PF2L}}{1\ \text{kA}}\right]+(-0.0399)\left[\frac{I_{PF1CL}}{1\ \text{kA}}\right]+(-0.0438)\left[\frac{I_{PF1BL}}{1\ \text{kA}}\right]+\\&+(-0.0662)\left[\frac{I_{PF1AL}}{1\ \text{kA}}\right]+(+0.2601)\left[\frac{I_{OH}}{1\ \text{kA}}\right]+(-2.1477)\left[\frac{I_{PLASMA}}{1\ \text{MA}}\right]\end{aligned}\right)*\left[\frac{I_{TF}}{130\ \text{kA}}\right]$$

Lower Corner Algorithm, Woolley

$$\left[\frac{\tau_{shear}}{1\ \text{MPa}}\right]_{Woolley}^{CenterstackLowerCorner} =$$

$$\left(\begin{aligned}&(-0.0661)\left[\frac{I_{PF1AU}}{1\ \text{kA}}\right]+(-0.0415)\left[\frac{I_{PF1BU}}{1\ \text{kA}}\right]+(-0.0373)\left[\frac{I_{PF1CU}}{1\ \text{kA}}\right]\\&+(-0.0919)\left[\frac{I_{PF2U}}{1\ \text{kA}}\right]+(-0.2559)\left[\frac{I_{PF3U}}{1\ \text{kA}}\right]+(-0.2948)\left[\frac{I_{PF4\&LU}}{1\ \text{kA}}\right]+(-0.4544)\left[\frac{I_{PF5U\&L}}{1\ \text{kA}}\right]+\\&+(-0.2431)\left[\frac{I_{PF3L}}{1\ \text{kA}}\right]+(-0.0704)\left[\frac{I_{PF2L}}{1\ \text{kA}}\right]+(-0.0263)\left[\frac{I_{PF1CL}}{1\ \text{kA}}\right]+(-0.0293)\left[\frac{I_{PF1BL}}{1\ \text{kA}}\right]+\\&+(-0.0564)\left[\frac{I_{PF1AL}}{1\ \text{kA}}\right]+(-0.7103)\left[\frac{I_{OH}}{1\ \text{kA}}\right]+(-3.7010)\left[\frac{I_{PLASMA}}{1\ \text{MA}}\right]\end{aligned}\right)*\left[\frac{I_{TF}}{130\ \text{kA}}\right]$$