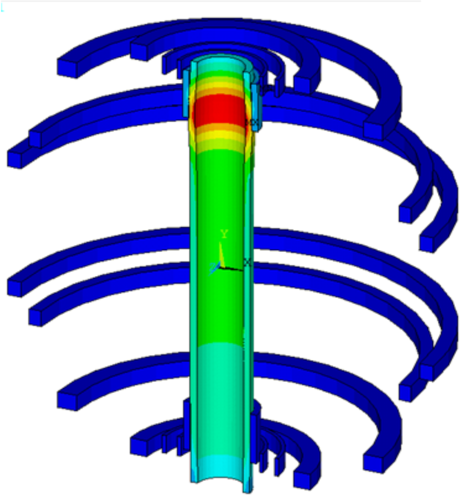
NSTX Upgrade

OH Stress and Segmented OH Influence Coefficients for the DCPS



NSTXU-CALC-133-14-00

August 3 2013

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1.1 PPPL Calculation Form

Calculation # **NSTXU-CALC-133-14-00** Revision # 00 WP #, 5200
(ENG-032)

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

Structural Algorithms are an input to the digital coil protection system (DCPS)[7]. This document is a calculation of stress influence coefficients for the mid height of the OH and those needed to address the PF1a-OH interaction. This importance of the interaction is documented in Ali Zolfaghari's calculation number, NSTXU-CALC-133-08-00. Additionally force and moment influence coefficients with the OH segmented into regions are also provided. These allow resolution of the OH radial force variation near PF1a. and in the central region of the OH. Influence coefficients for the segmented OH require handling a larger matrix than the standard and may be less attractive computationally than retaining multiplication by the 17 independent currents. Previously, influence coefficients were computed for only the OH as a whole. Addition of Moment coefficients in calculation 13-05-00 allows the effect of a shift in force centroid to be included, but if the distribution of radial loads is important – i.e for a tall thin solenoid with other short coil segments interacting with the solenoid, then further resolution of the distribution of the radial load is needed.

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

Included in the body of the calculations

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

Axisymmetry of the coils, Tresca Stress can be linearly scaled

Calculation (Calculation is either documented here or attached)

Included in the body of the calculations

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

Stress influence coefficients for the PF1a-OH interaction have been calculated and tabulated for checking other's work or inclusion in the DCPS. These factors have been used to assess the OH stress for all 96 equilibria, and for the disruption currents provided by C. Neumeyer. In all of these identified currents, the OH stresses near the PF1a coils are acceptable.

Cognizant Engineer's printed name, signature, and date

Ronald Hatcher Ronald E Hatcher

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Date: 2013.08.29 14:21:18 -04'00'

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

Checker's printed name, signature, and date

S Gerhardt	Stefan Gerhardt Digitally signed by Stefan Gerhardt DN: cn=Stefan Gerhardt, o=PPPL, ou=PPPL Physics, email=sgerhard@pppl.gov, c=US Date: 2013.09.27 14:48:42 -04'00'	Implementation in IDL
A. Zolfaghari	Ali M. Zolfaghari Digitally signed by Ali M. Zolfaghari DN: cn=Ali M. Zolfaghari, o=PPPL, ou=Engineering Analysis Division, email=azolfagh@pppl.gov, c=US Date: 2013.09.27 15:14:52 -04'00'	Consistency with OH Calculation Stresses
R. Woolley	Robert D. Woolley Digitally signed by Robert D. Woolley DN: cn=Robert D. Woolley, o=Princeton University, ou=PPPL, email=woolley@pppl.gov, c=US Date: 2013.10.01 11:15:40 -04'00'	Segmented OH

2.0 Table of Contents

3.0 Executive Summary:

Structural Algorithms are an input to the digital coil protection system (DCPS)[7]. This document is a calculation of stress influence coefficients for the middle section of the OH and those needed to address the PF1a-OH interaction. The significance of this interaction is documented in Ali Zolfaghari's calculation number, NSTXU-CALC-133-08-00[9]. Sixteen stress multipliers are computed for various stress components and for the middle and for the upper and lower regions of the OH near the PF1 a coils (the 17th TF current is not needed). These multipliers are in a form similar to that provided for the PF4 and 5 DCPS input (See section 9.0 of [11]). This is the preferred form of the DCPS algorithm for the PF1a-OH interaction because it fits a planned template for the DCPS algorithms. Additionally force and moment influence coefficients with the OH segmented into regions are also provided. These allow resolution of the OH radial force variation near PF1a. and in the central region of the OH. Influence coefficients for the segmented OH require handling a larger matrix than the standard and may be less attractive computationally than retaining multiplication by the 16 independent currents. Previously, influence coefficients were computed for only the OH as a whole. Addition of moment coefficients in calculation 13-05-00 allows the effect of a shift in force centroid to be included, but if the distribution of radial loads is important – i.e for a tall thin solenoid with other short coil segments interacting with the solenoid, then further resolution of the distribution of the radial load is needed.

Only one plasma shape has been investigated. A rectangular cross section is used. Figure 3.0-1 is a stress plot from [9] that shows the concentration of OH hoop stresses near the PF1a coil for a case where the OH has 13 kA of current at the leads and PF1a has 16.6 kA

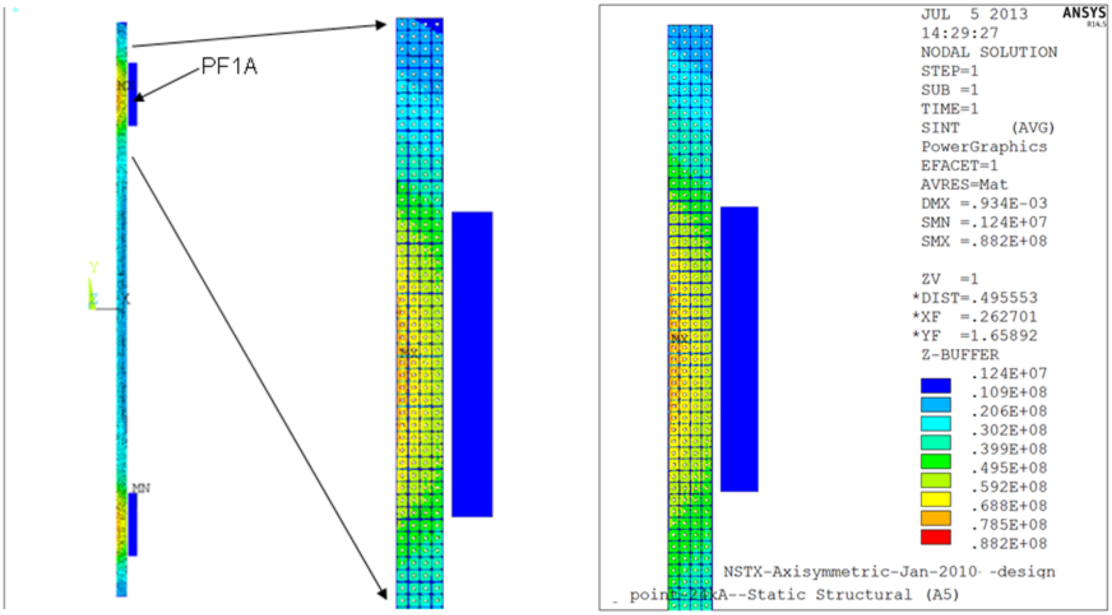


Figure 3.0-1 Figure from the OH stress analysis, ref [9]

In figure 3.0-1, only the OH and PF1a currents are considered. To evaluate the effect of all coil currents in the design equilibria, the 16 unit current contributions are computed in a simple ANSYS model that uses "smeared" coil properties. Ali Zolfaghari's results and the packing fraction computed in the design point spreadsheet are used to compute a stress correction factor to account for the insulation and coolant hole stress concentrations. The 16 factors and stress correction factor is then implemented spreadsheets. There are spreadsheets for upper, and lower regions near PF1aU and L; and there are spreadsheets for hoop stress and Tresca stress. The hoop stress is compared with the fatigue tensile stress allowable of 124 MPa. [5] The Tresca stress calculated in the spreadsheets is a peak stress in the cross section, and can be compared with 1.5*Sm or the yield stress which is 28 ksi or 193 MPa.

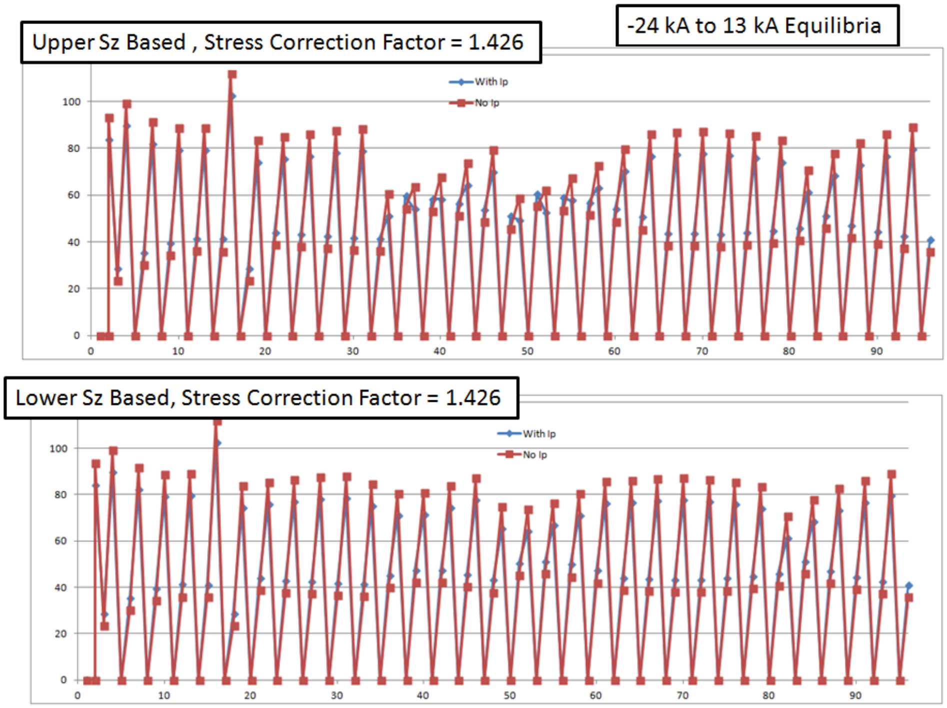
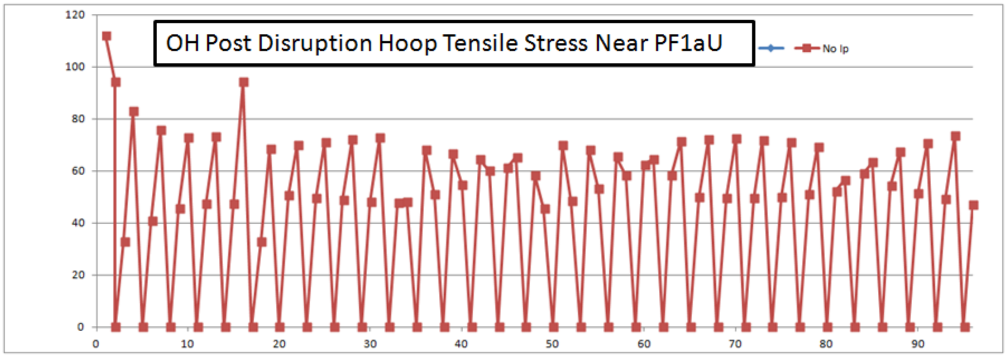
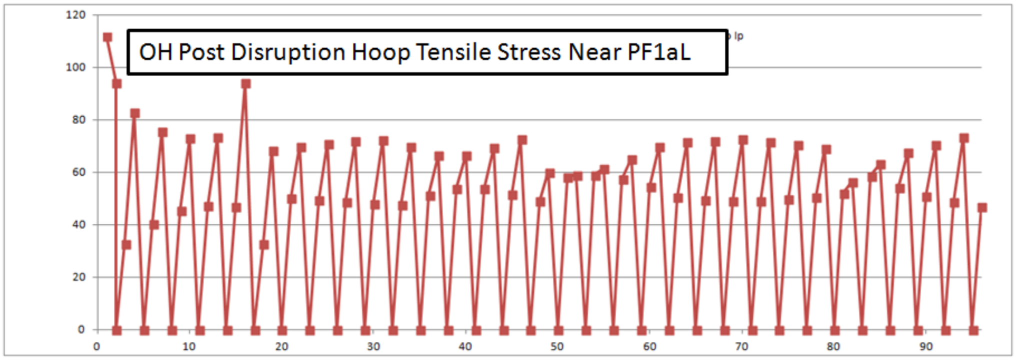


Figure 3.0-2 Hoop Stresses for the Design Equilibria Upper and Lower Coil Regions

The results of the hoop stress assessment are shown above. The allowable hoop stress based on fatigue limits is 124 MPa[5]. There is one equilibria that gets close to the allowable. This is EQ 16. It has 24 kA in the OH and large currents in PF1a,band c. It is not the maximum OH and PF1a current case. Because the limit is based on fatigue life for 20000 pulses, It might be acceptable to run a small number of shots that produce tensile stresses above the 124 MPa limit.





The multipliers were applied to the post disruption currents supplied by Charlie Neumeyer. The first equilibria gets close to the 125 MPa allowable, but all the others are well below the allowable and are in general lower than the "with plasma" results. More spreadsheet results are included in section 7.4. All of the results for the design point 96 equilibria show acceptable results. Results for the earlier -24 to 24 kA equilibria show a significant number above the 124 MPa fatigue allowable and this was the motivation for limiting the swing of the OH. Disruption currents provided by C. Neumeyer were evaluated and these were also acceptable – typically producing stresses below stresses for the nominal currents. None of the results include a 10% headroom for the power supply control system. All of thecurrently identified equilibria have margin. The DCPS is supposed to control currents adequately to keep stresses below the hoop stress fatigue limit of 124 MPa and the static Tresca stress limit of 1193 MPa

4.0 Digital Coil Protection System (DCPS) Input

4.1.1 Algorithm Based on the Stress Multipliers at OH coil mid height and near PF1a U and L

The proposed DCPS is described in detail in a draft requirements document by Robert Woolley ref [7] and later documents by R. Hatcher and S. Gerhardt [8]. The procedure recommended to address the interaction between the OH and PF1a coils is based on a procedure developed for PF4 and 5. [11]

The basic relation is:

Coil Stress= K1 * I_{oh}^2+ sum for i=1 to n (Ki* I_{oh}*I_{pfi}).

For unit currents
Coil Stress = K1 + sum for i=1 to n (Ki* I_{poh}*I_{pfi}).

For an individual ANSYS run with only OH unit currents,
The stress due to the self load is assigned the value, hfact = K1*I $_{oh}$^2. Or K1 for unit currents

For an individual ANSYS run with a pairing of OH and for example coil b, with unit currents (I_{oh}, and I_{pfb}, =1.0) the stress per unit coil currents is factb in the spreadsheet.

Coil Stress for unit OH and Pfb currents = hfact+ Kb. Where the coil stress for unit currents is assigned the bfact value

And Kb =bfact-hfact Then the total stress for all coil currents is

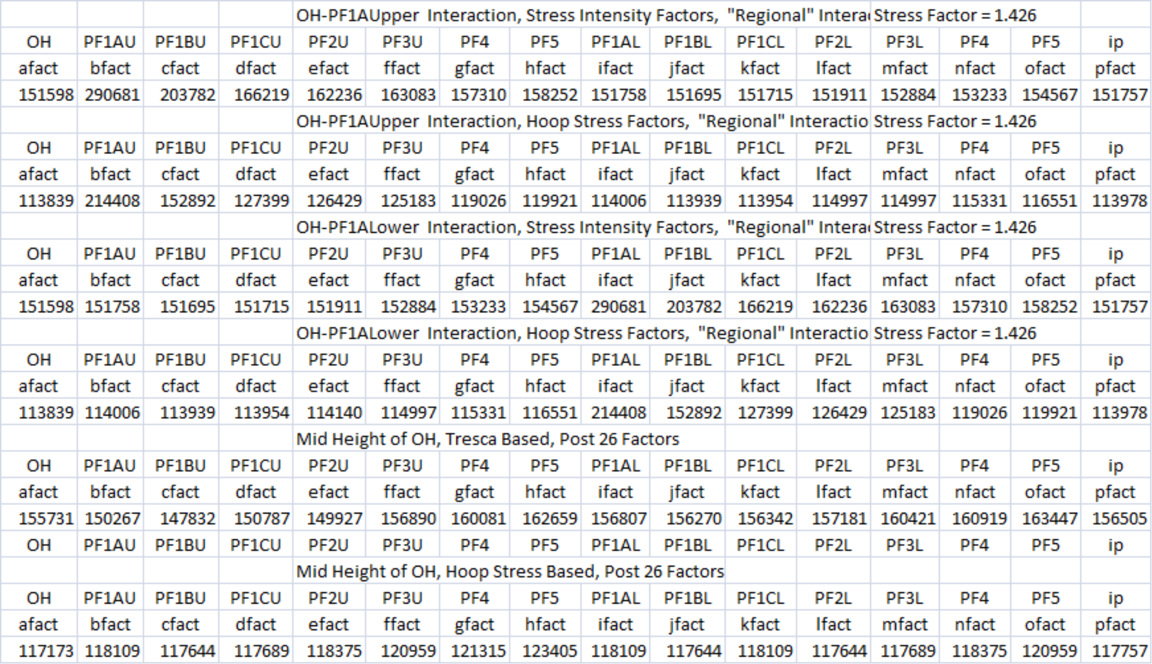
Coil Stress= hfact * I_{oh}^2+ sum for i=1 to n ((ifact-hfact)* I_{oh}*I_{pfi}).

In the spreadsheet this is implemented as:

=((B7*(afact-afact)+C7*(bfact-afact)+D7*(cfact-afact)+E7*(dfact-afact)+F7*(efact-afact)+G7*(ffact-afact)+H7*(gfact-afact)+I7*(hfact-afact)+J7*(ifact-afact)+K7*(jfact-afact)+L7*(kfact-afact)+M7*(lfact-afact)+N7*(mfact-afact)+O7*(nfact-afact)+P7*(ofact-afact)+Q7*(pfact-afact))*B7 +afact*B7^2)/1000000*PackFract

Where B7 is the OH current in the equilibrium. Notice that in the sum, the afact effect is zeroed out but then is added back in at the end multiplied by the square of the OH current.

A listing of afact through ofact for upper and lower PF1a interactions for Tresca and for hoop stress, follows:



				OH-PF1AUpper Interaction, Stress Intensity Factors, "Regional" Intera								Stress Factor = 1.426			
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
afact	bfact	cfact	dfact	efact	ffact	gfact	hfact	ifact	jfact	kfact	lfact	mfact	nfact	ofact	pfact
151598	290681	203782	166219	162236	163083	157310	158252	151758	151695	151715	151911	152884	153233	154567	151757
				OH-PF1AUpper Interaction, Hoop Stress Factors, "Regional" Interactio								Stress Factor = 1.426			
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
afact	bfact	cfact	dfact	efact	ffact	gfact	hfact	ifact	jfact	kfact	lfact	mfact	nfact	ofact	pfact
113839	214408	152892	127399	126429	125183	119026	119921	114006	113939	113954	114997	114997	115331	116551	113978
				OH-PF1ALower Interaction, Stress Intensity Factors, "Regional" Intera								Stress Factor = 1.426			
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
afact	bfact	cfact	dfact	efact	ffact	gfact	hfact	ifact	jfact	kfact	lfact	mfact	nfact	ofact	pfact
151598	151758	151695	151715	151911	152884	153233	154567	290681	203782	166219	162236	163083	157310	158252	151757
				OH-PF1ALower Interaction, Hoop Stress Factors, "Regional" Interactio								Stress Factor = 1.426			
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
afact	bfact	cfact	dfact	efact	ffact	gfact	hfact	ifact	jfact	kfact	lfact	mfact	nfact	ofact	pfact
113839	114006	113939	113954	114140	114997	115331	116551	214408	152892	127399	126429	125183	119026	119921	113978
				Mid Height of OH, Tresca Based, Post 26 Factors											
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
afact	bfact	cfact	dfact	efact	ffact	gfact	hfact	ifact	jfact	kfact	lfact	mfact	nfact	ofact	pfact
155731	150267	147832	150787	149927	156890	160081	162659	156807	156270	156342	157181	160421	160919	163447	156505
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
				Mid Height of OH, Hoop Stress Based, Post 26 Factors											
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
afact	bfact	cfact	dfact	efact	ffact	gfact	hfact	ifact	jfact	kfact	lfact	mfact	nfact	ofact	pfact
117173	118109	117644	117689	118375	120959	121315	123405	118109	117644	118109	117644	117689	118375	120959	117757

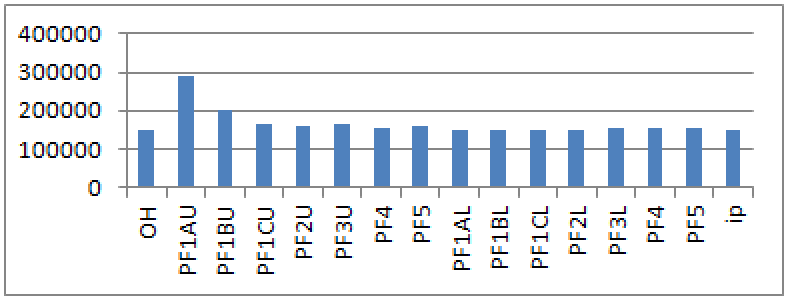


Figure 4.1.2-1 Upper OH Tresca Multipliers

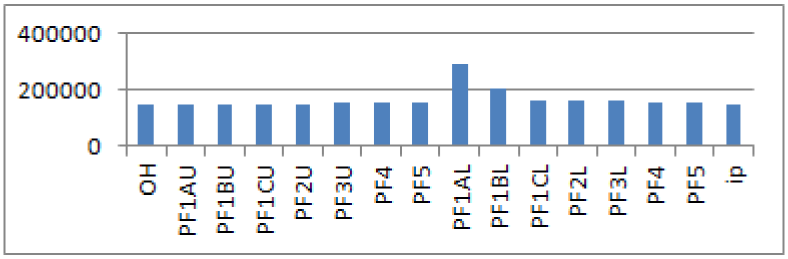
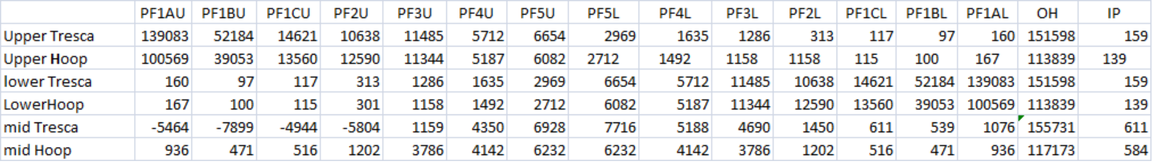


Figure 4.1.2-2 Lower OH Tresca

4.1.2 Algorithm Based on the Stress Multipliers at OH coil mid height and near PF1a U and L - Stefan Gerhardt's Form and PF Order

Stefan Gerhard's preferred form is to tabulate the summed factors (bfact-afact) through (pfact-afact) cells. These were then reordered to match Stefan's PF order. These were then plotted up to make sure they visually made sense. Mid hoop values should be symmetric in Stefan's PF order, Upper Tresca and hoop should trail off as you go around the PFs. These factors do not have the stress correction factor applied. Stefan preferred to have a separate scale factor. These results are in MultipliersJuly92013.xls

Table 4.1.2 OH Multipliers



	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4U	PF5U	PF5L	PF4L	PF3L	PF2L	PF1CL	PF1BL	PF1AL	OH	IP
Upper Tresca	139083	52184	14621	10638	11485	5712	6654	2969	1635	1286	313	117	97	160	151598	159
Upper Hoop	100569	39053	13560	12590	11344	5187	6082	2712	1492	1158	1158	115	100	167	113839	139
lower Tresca	160	97	117	313	1286	1635	2969	6654	5712	11485	10638	14621	52184	139083	151598	159
LowerHoop	167	100	115	301	1158	1492	2712	6082	5187	11344	12590	13560	39053	100569	113839	139
mid Tresca	-5464	-7899	-4944	-5804	1159	4350	6928	7716	5188	4690	1450	611	539	1076	155731	611
mid Hoop	936	471	516	1202	3786	4142	6232	6232	4142	3786	1202	516	471	936	117173	584

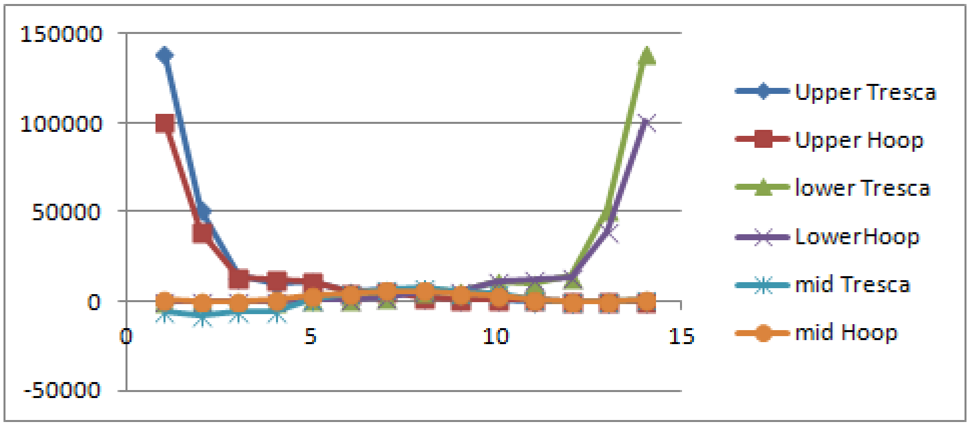


Figure 4.1.2-3 OH Stress Multipliers with OH and IP (#15 and 16) omitted

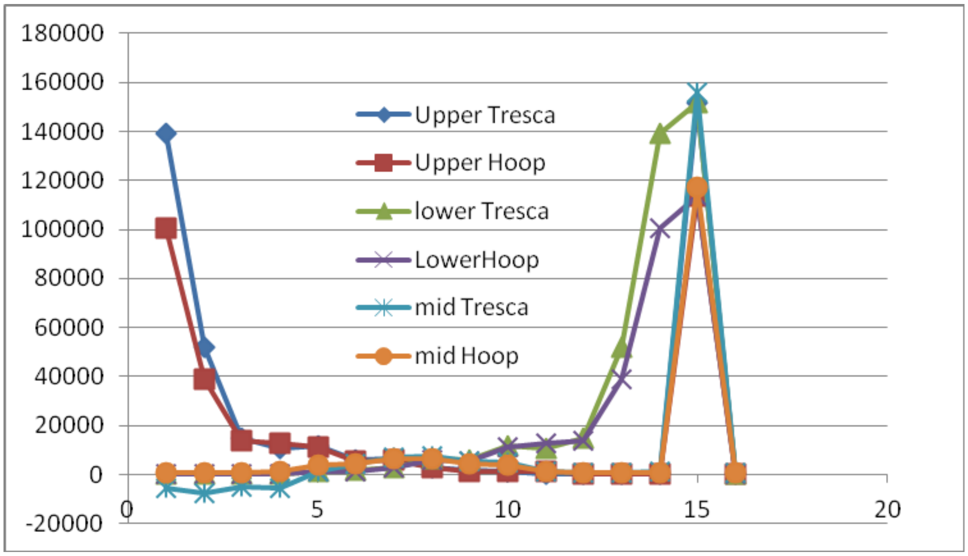


Figure 4.1.2-4 OH Stress Multipliers with OH (#15) and IP (#16) Factors

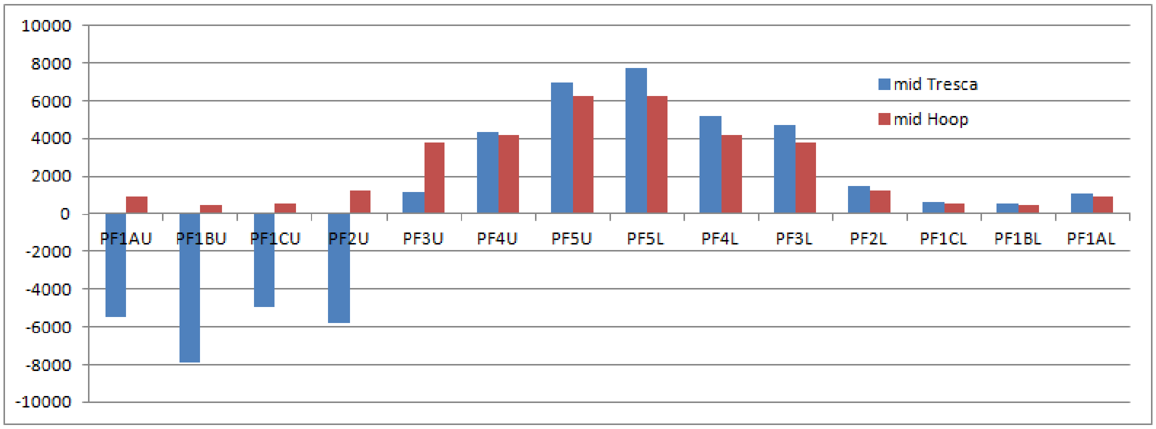


Figure 4.1.2-5 Mid Height OH Stress Multipliers

In Figure 4.1.2-5 the Tresca erroneously goes negative. The absolute value should be used, or the DCPS should be based on the hoop stress which correlates with the fatigue limit of 125 MPa.

4.2 Based on the segmented OH influence coefficients:

As of July 2013, this method of calculating the local stresses in the OH due to PF1a, is not used. It produced a 21 X 21 influence matrix which would have required a different algorithm template than planned. The results have been documented in Section 8.0 of this calculation in case the method needs to be utilized.

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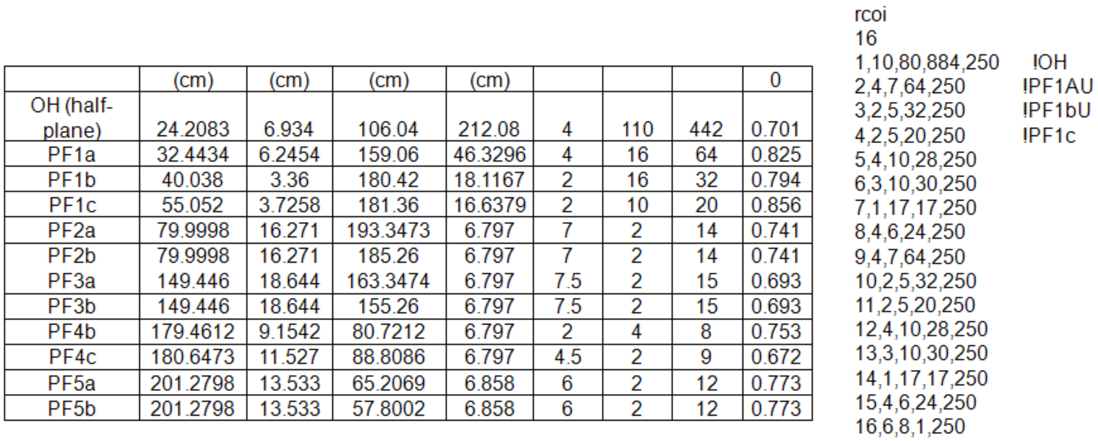
5.0 Design Input

5.1 References

[1] NSTX Influence Coefficients, calculation # NSTXU 13 03-00, Ron Hatcher DATE: July 9 2009
[2] NSTX-CALC-13-001-00 Rev 1 Global Model – Model Description, Mesh Generation, Results, Peter H. Titus December 2010
[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] OH Conductor Fatigue and Fracture Mechanics Analyses, NSTXU-CALC-133-09-00 P. Titus ,Nov 2010
[6] "MHD and Fusion Magnets, Field and Force Design Concepts", R.J.Thome, John Tarrh, Wiley Interscience, 1982
[7] 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
[8] “**DCPS** Numerical Algorithms And Coefficient Summary” S.P. Gerhardt, R. Hatcher, P. Titus
[9] NSTXU-CALC-133-08-00 CALCULATION OF OH COIL STRESSES IN THE NSTX CSU, A Zolfaghari, October 19, 2011
[10] NSTXU-CALC-13-05-00 Moment Influence Coefficients, P. Titus, January 18 2011
[11] “Analysis of Existing and Upgrade PF4/5 Coils and Support”s NSTXU-CALC-12-05-00, P. Titus

5.2 Coil Geometries



	(cm)	(cm)	(cm)	(cm)				0
OH (half-plane)	24.2083	6.934	106.04	212.08	4	110	442	0.701
PF1a	32.4434	6.2454	159.06	46.3296	4	16	64	0.825
PF1b	40.038	3.36	180.42	18.1167	2	16	32	0.794
PF1c	55.052	3.7258	181.36	16.6379	2	10	20	0.856
PF2a	79.9998	16.271	193.3473	6.797	7	2	14	0.741
PF2b	79.9998	16.271	185.26	6.797	7	2	14	0.741
PF3a	149.446	18.644	163.3474	6.797	7.5	2	15	0.693
PF3b	149.446	18.644	155.26	6.797	7.5	2	15	0.693
PF4b	179.4612	9.1542	80.7212	6.797	2	4	8	0.753
PF4c	180.6473	11.527	88.8086	6.797	4.5	2	9	0.672
PF5a	201.2798	13.533	65.2069	6.858	6	2	12	0.773
PF5b	201.2798	13.533	57.8002	6.858	6	2	12	0.773

```
rcoi
16
1,10,80,884,250    !OH
2,4,7,64,250       !PF1AU
3,2,5,32,250       !PF1bU
4,2,5,20,250       !PF1c
5,4,10,28,250
6,3,10,30,250
7,1,17,17,250
8,4,6,24,250
9,4,7,64,250
10,2,5,32,250
11,2,5,20,250
12,4,10,28,250
13,3,10,30,250
14,1,17,17,250
15,4,6,24,250
16,6,8,1,250
```

Table 5.2-1 PF Builds and Number of Turns from the Design Point Spreadsheet [4]

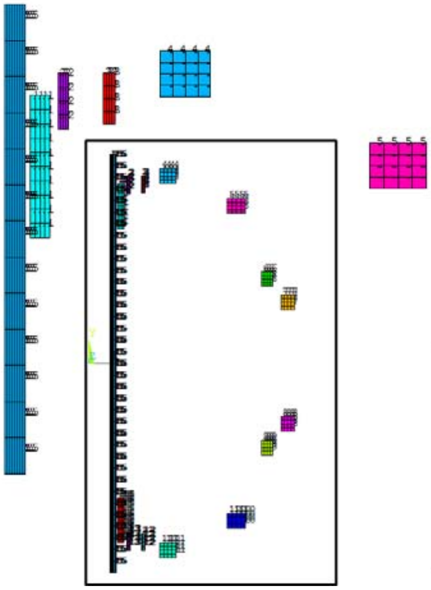
6.0 Analysis Code, NTFTM

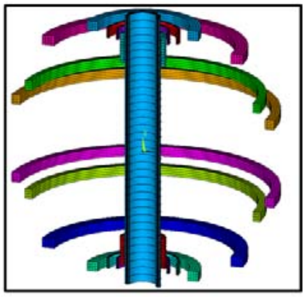
Mesh generation , calculation of the Lorentz forces, and generation of the influence coefficients is done using a code written by the author of this report. The influence coefficient subroutine is included as appendix A of ref [10] The mesh generation feature of the code is checked visually and within 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.

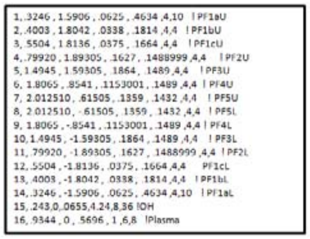
The code in various forms has been used for 20 years and is suitable for structural calculations. It is also being used for calculation of load files in an NSTX global model[8]. Recent checks include NSTX out-of-plane load comparisons with ANSYS [9] and MAXWELL, and calculations of trim coil fields and forces for W7X compared with Neil Pomphrey's and IPP'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: http://198.125.178.188/ftm/manual.pdf). or, within PPPL: at P:\public\Snap-srv\Titus\NTFTM

7.0 DCPS Algorithm Based on 16 Current Stress Multipliers

7.1 Axisymmetric Model for Local Stress Coefficients for the PF1a-OH Interaction







```
1,.3246 , 1.5906 , .0625 , .4634 ,4,10  ! PF1aU
2, .4003 , 1.8042 , .0338 , .1814 ,4,4  ! PF1bU
3, .5504 , 1.8136 , .0375 , .1664 ,4,4   ! PF1cU
4, .79920 , 1.89305 , .1627 , .1488999 ,4,4    ! PF2U
5, 1.4945 , 1.59305 , .1864 , .1489 ,4,4   ! PF3U
6, 1.8065 , .8541 , .1153001 , .1489 ,4,4 ! PF4U
7, 2.012510 , .61505 , .1359 , .1432 ,4,4   ! PF5U
8, 2.012510 , -.61505 , .1359 , .1432 ,4,4  ! PF5L
9, 1.8065 , -.8541 , .1153001 , .1489 ,4,4 ! PF4L
10, 1.4945 , -1.59305 , .1864 , .1489 ,4,4   ! PF3L
11, .79920 , -1.89305 , .1627 , .1488999 ,4,4  ! PF2L
12, .5504 , -1.8136 , .0375 , .1664 ,4,4     PF1cL
13, .4003 , -1.8042 , .0338 , .1814 ,4,4   ! PF1bL
14, .3246 , -1.5906 , .0625 , .4634 ,4,10  ! PF1aL
15, .243,0,.0655,4.24,8,36 !OH
16, .9344 , 0 , .5696 , 1 ,6,8  !Plasma
```

Figure 2 Axisymmetric Model For Local Stress in the OH

The order of the coils has been selected to coincide with the ordering that S. Gerhardt and Ron Hatcher are using [8]. This is different than the one used for the design point spreadsheet[4] so the coefficients developed for the stress in the OH have to be shuffled to fit the 96 equilibria from Charlie Neumeyer.

7.2 Unit Lorentz Force Analyses

Sixteen force computations are needed to provide input to sixteen ANSYS load steps. Force computations are done within NTFTM. Each step has to have the OH current paired with another PF coil. The toroidal field does not interact with the PF coils. To display the results, the resulting force files were subtracted from the OH – only force file to display the additional loads on the OH due to each coil current.. In the following plots, the scale factor is the same so that the effect of PF1aU (Su01.dat) can be compared with the effect of PF1bU(Su02.dat) and the other coils. The effect of PF1aU is clearly largest, but the effects of the rest of the PF coils are not trivial.

Table 7.2-1

```
pfcu
16,17,1,1.0
1,.064,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
2,0,.032,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
3,0,0,.020,0,0,0,0,0,0,0,0,0,0,0,0,0,0
4,0,0,0,.028,0,0,0,0,0,0,0,0,0,0,0,0,0
5,0,0,0,0,.030,0,0,0,0,0,0,0,0,0,0,0,0
6,0,0,0,0,0,.017,0,0,0,0,0,0,0,0,0,0,0
7,0,0,0,0,0,0,.024,0,0,0,0,0,0,0,0,0,0
8,0,0,0,0,0,0,0,.024,0,0,0,0,0,0,0,0,0
9,0,0,0,0,0,0,0,0,.017,0,0,0,0,0,0,0,0
10,0,0,0,0,0,0,0,0,0,.030,0,0,0,0,0,0,0
11,0,0,0,0,0,0,0,0,0,0,.028,0,0,0,0,0,0
12,0,0,0,0,0,0,0,0,0,0,0,.020,0,0,0,0,0
13,0,0,0,0,0,0,0,0,0,0,0,0,.032,0,0,0,0
14,0,0,0,0,0,0,0,0,0,0,0,0,0,.064,0,0,0
15,.884,.884,.884,.884,.884,.884,.884,.
884,.884,.884,.884,.884,.884,.884,.884
,.884,0,0
16,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,.001,0,
0
```

The currents in this table are the number of turns divided by one kiloAmp

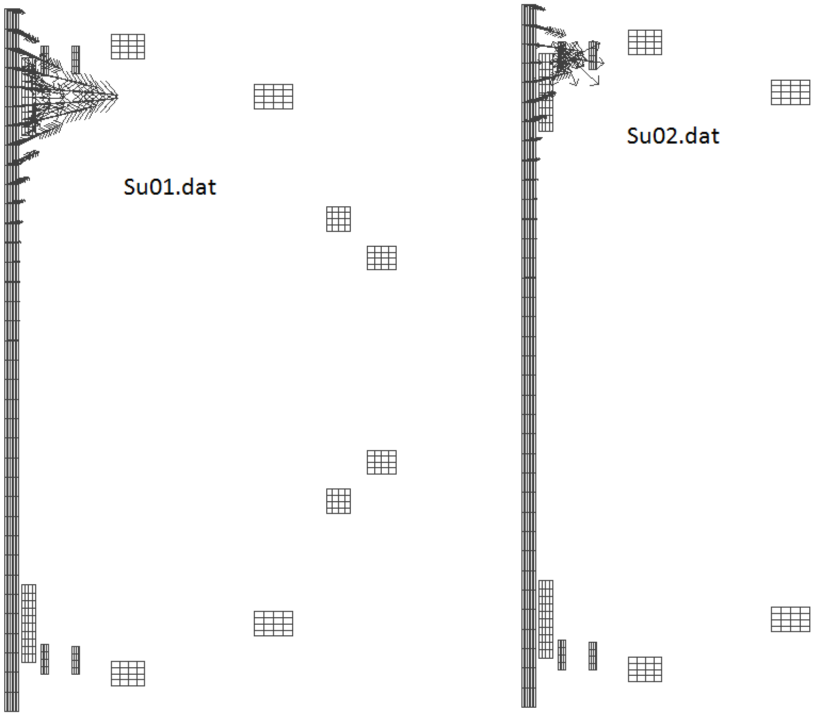


Figure 7.2-1 Load Files Differenced with the OH-Only Load File

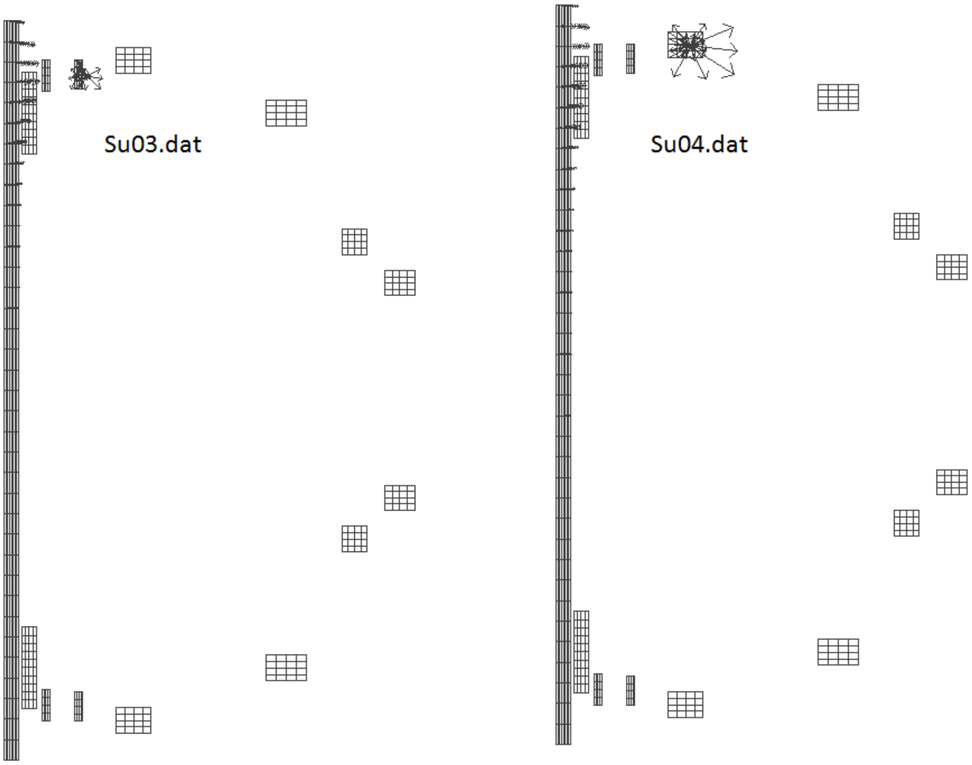


Figure 7.2-2 Load Files Differenced with the OH-Only Load File

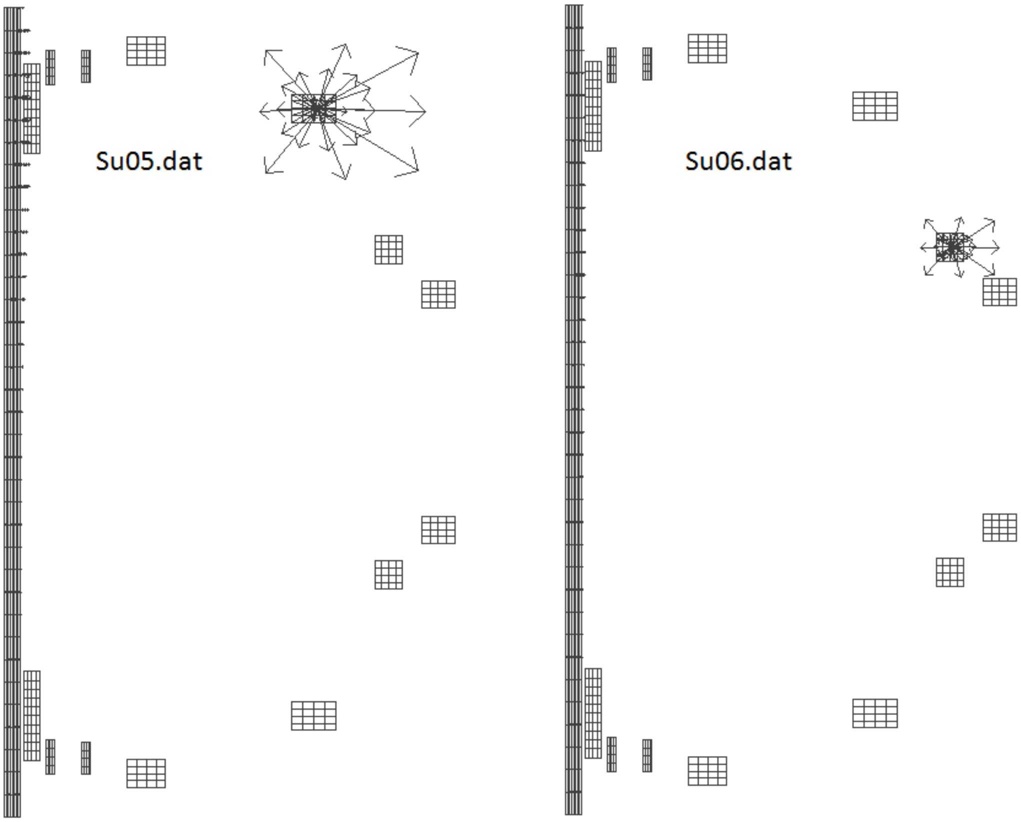


Figure 7.2-3 Load Files Differenced with the OH-Only Load File

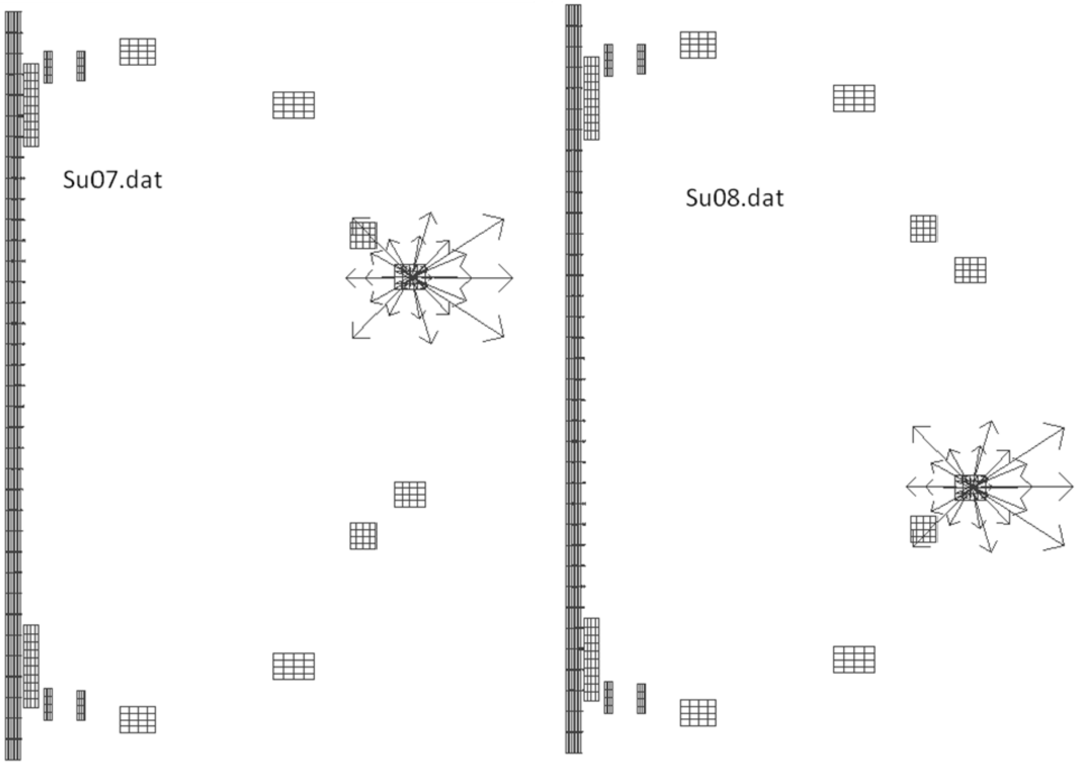


Figure 7.2-4 Load Files Differenced with the OH-Only Load File

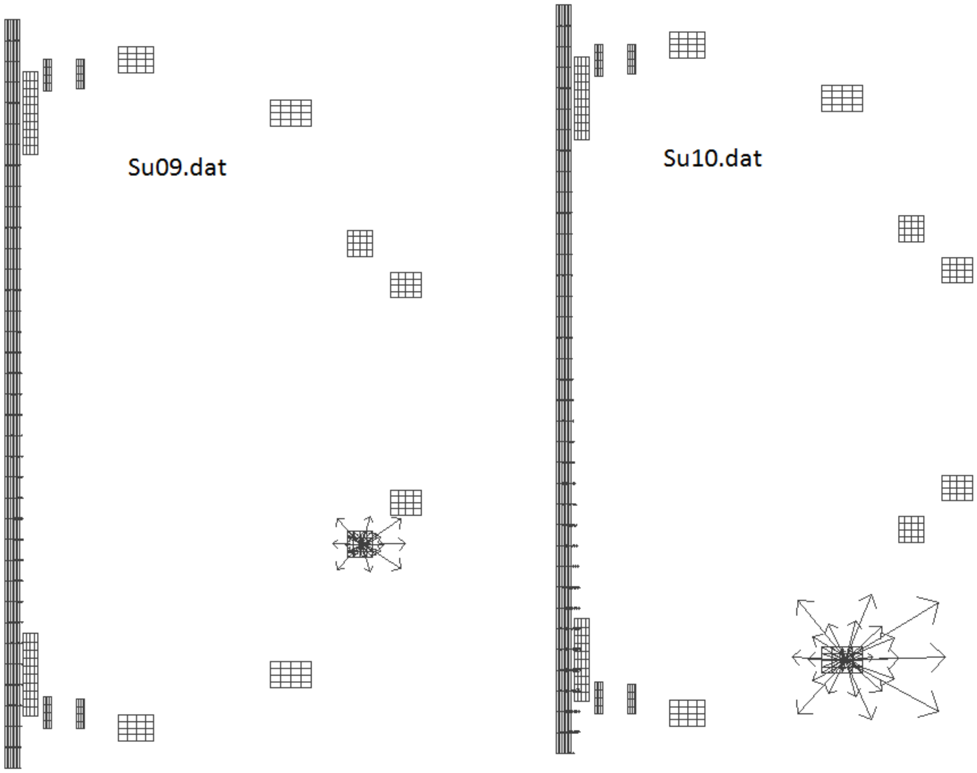


Figure 7.2-5 Load Files Differenced with the OH-Only Load File

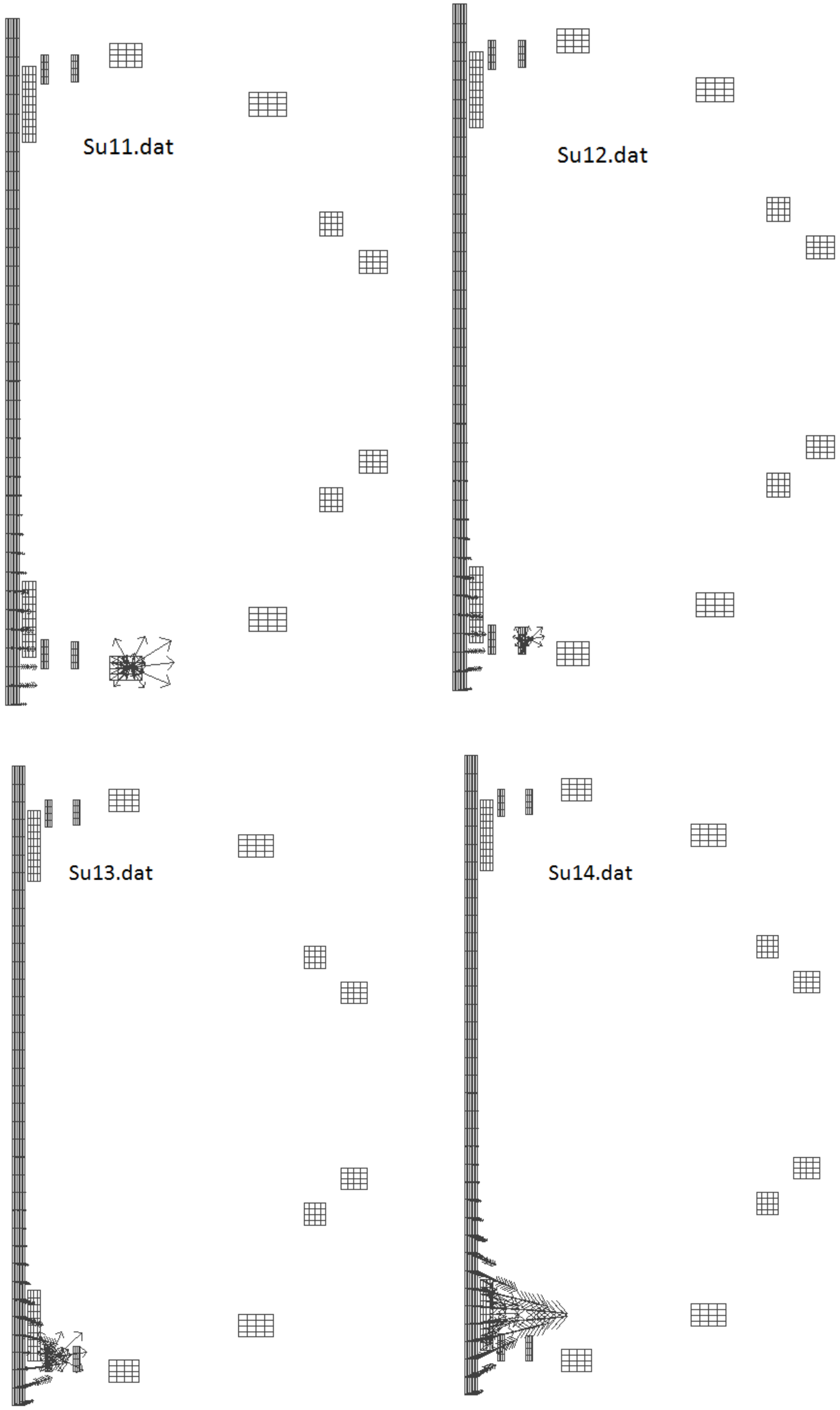
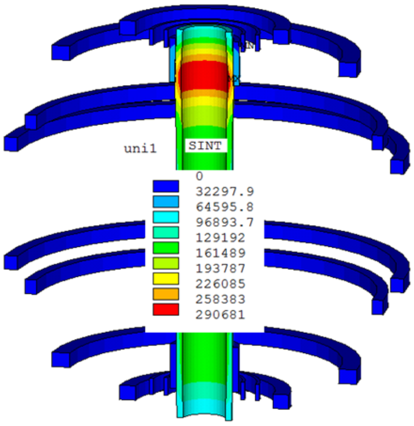
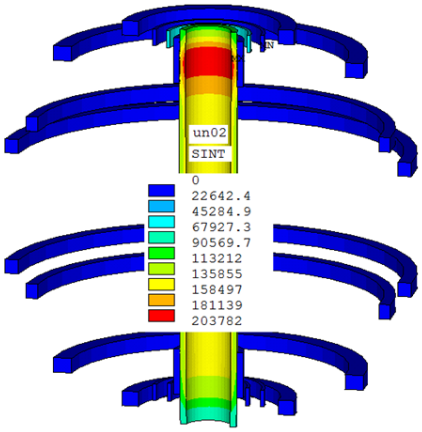


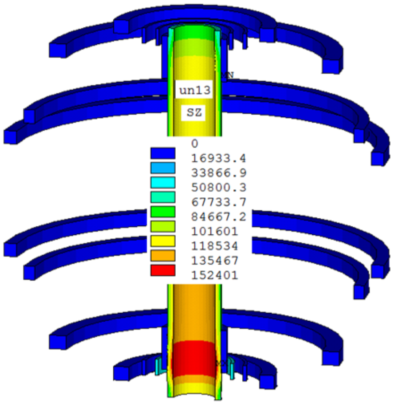
Figure 7.2-6 Load Files Differenced with the OH-Only Load File

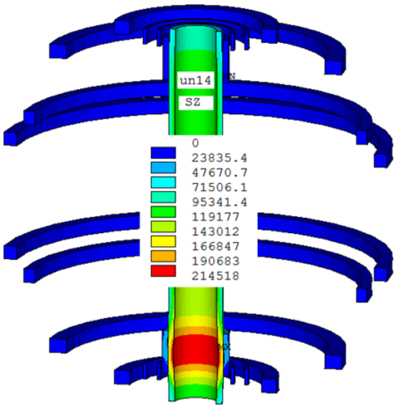
7.3 Results for the Stress Multipliers near PF1a U and L

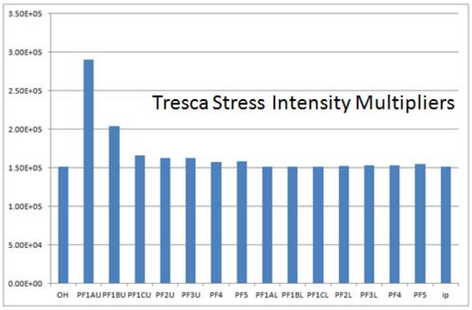
The Ansys input listing that analyzes the 16 load files is shown at riughts

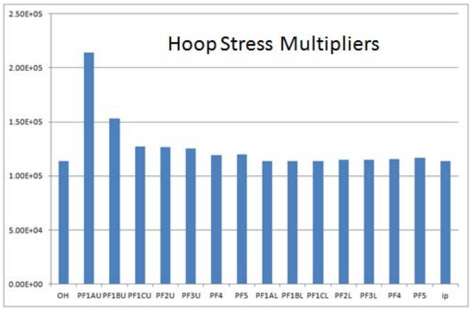


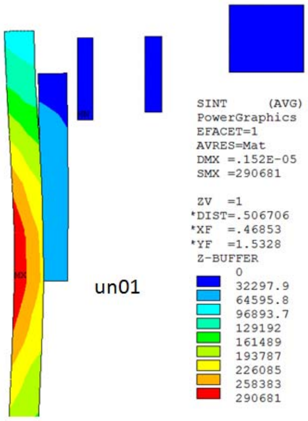












Stress Multipliers for the “region” of the OH near the PF1aU coil

These are taken from the Stress Contours

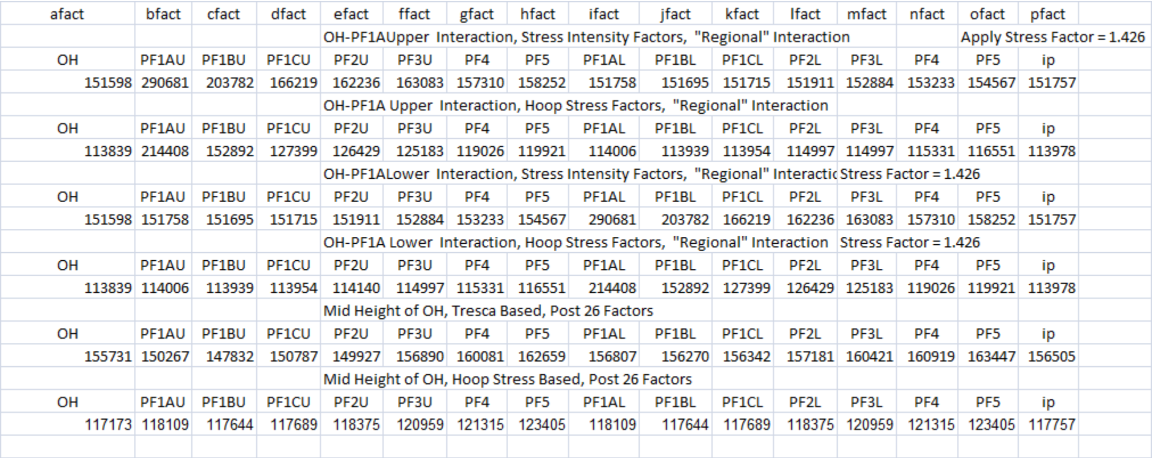
```
/batch
/nerr,1000000,1000000
/prep7
et,1,42,,,1
*do,imat,1,100
ex,imat,200e9  $dens,imat,7800
*enddo
ex,17,111e9
/input,un01,mod
nummer,node,,.003
nall $eall
esel,mat,40  $nelem
d,all,all,0.0
nall $eall
   !PF1a
nsel,y,1.35,1.36
nasel,y,-1.36,-1.35
nrsel,x,.3,.5
d,all,uy,0.0
   !PF1b
nsel,y,1.7,1.72
nasel,y,-1.72,-1.7
nrsel,x,.38,.5
d,all,uy,0.0
   !PF1c
nsel,y,1.72,1.742
nasel,y,-1.74,-1.7
nrsel,x,.53,.7
d,all,uy,0.0
   !PF2
nsel,y,1.81,1.82
nasel,y,-1.82,-1.81
nrsel,x,.7,1
d,all,uy,0.0
   !PF3
nsel,y,1.51,1.52
nasel,y,-1.52,-1.51
nrsel,x,1.4,2
d,all,uy,0.0
   !PF4
nsel,y,.77,.78
nasel,y,-.78,-.77
nrsel,x,1.7,2
d,all,uy,0.0
   !PF5
nsel,y,.54,.55
nasel,y,-.55,-.54
nrsel,x,1.9,3
d,all,uy,0.0
   !OH
nsel,y,-2.2,-2.1
nrsel,x,0,.3
d,all,uy,0.0

nall
eall
/num,1
mnum,1
save
fini
/solu
/title,uni1
fscale,6.283185307
!acel,0,9.8,0
Solve $save
lfact=6.283185307
fcum,repl,lfact
*do,ls,2,9
/title,un0%ls%
fscale,.00001
/input,un0%ls%,mod
solve   $save
*enddo
*do,ls,10,18
/title,un%ls%
fscale,.00001
/input,un%ls%,mod
solve   $save
*enddo
Fini  $ /exit
```

The results are up-down symmetric, so the coefficients for the lower interaction region can be constructed from the results for the upper region. Coefficients for both the Tresca and the hoop stress are extracted from the ANSYS run contour plots. The factors were selected from the region near PF1aU even though some of the peak stresses occurred closer to the mid-plane for coils like PF4 and 5. The stress factors for these coils were low.

The axisymmetric model used "smeared" properties for the winding pack. Local effects from the coolant hole and the insulation surrounding the conductors will increase the stress over the "smeared" results. To calculate a stress correction factor, the results for 24 kA only in the OH - no PF currents – was compared with Ali Zolfaghari's OH stress calculation [9].

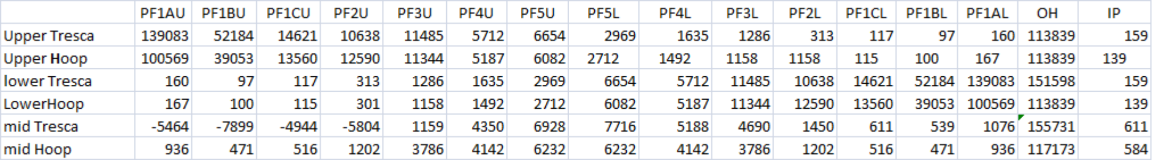
The stress multipliers were collected from the 16 load steps by plotting the region near PF1a upper and tabulating the maximum Tresca or Hoop stress. The location of the stress moved around a bit and it is a conservative approximation to superimpose the factors over the region near the inner PF's.

The stress multipliers for the mid height of the OH were extracted from the 16 load steps using the post 26 time history post processor



afact	bfact	cfact	dfact	efact	ffact	gfact	hfact	ifact	jfact	kfact	lfact	mfact	nfact	ofact	pfact
				OH-PF1AUpper Interaction, Stress Intensity Factors, "Regional" Interaction										Apply Stress Factor = 1.426	
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
151598	290681	203782	166219	162236	163083	157310	158252	151758	151695	151715	151911	152884	153233	154567	151757
				OH-PF1A Upper Interaction, Hoop Stress Factors, "Regional" Interaction											
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
113839	214408	152892	127399	126429	125183	119026	119921	114006	113939	113954	114997	114997	115331	116551	113978
				OH-PF1ALower Interaction, Stress Intensity Factors, "Regional" Interactic								Stress Factor = 1.426			
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
151598	151758	151695	151715	151911	152884	153233	154567	290681	203782	166219	162236	163083	157310	158252	151757
				OH-PF1A Lower Interaction, Hoop Stress Factors, "Regional" Interaction								Stress Factor = 1.426			
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
113839	114006	113939	113954	114140	114997	115331	116551	214408	152892	127399	126429	125183	119026	119921	113978
				Mid Height of OH, Tresca Based, Post 26 Factors											
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
155731	150267	147832	150787	149927	156890	160081	162659	156807	156270	156342	157181	160421	160919	163447	156505
				Mid Height of OH, Hoop Stress Based, Post 26 Factors											
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
117173	118109	117644	117689	118375	120959	121315	123405	118109	117644	117689	118375	120959	121315	123405	117757

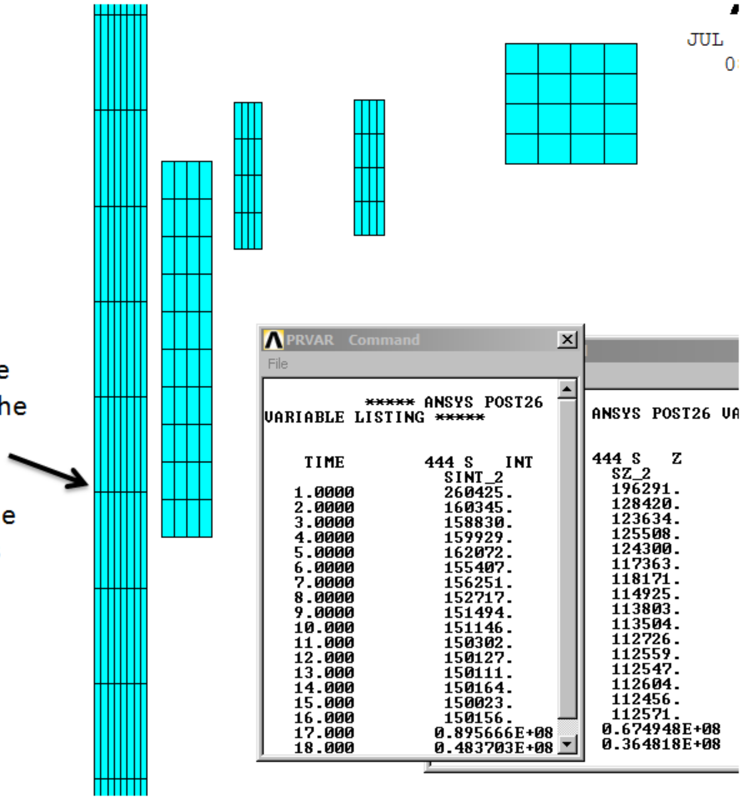
Table of (bfact-afact) through (pfact-afact) cells reordered to match S. Gerhardt's PF Order



	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4U	PF5U	PF5L	PF4L	PF3L	PF2L	PF1CL	PF1BL	PF1AL	OH	IP
Upper Tresca	139083	52184	14621	10638	11485	5712	6654	2969	1635	1286	313	117	97	160	113839	159
Upper Hoop	100569	39053	13560	12590	11344	5187	6082	2712	1492	1158	1158	115	100	167	113839	139
lower Tresca	160	97	117	313	1286	1635	2969	6654	5712	11485	10638	14621	52184	139083	151598	159
LowerHoop	167	100	115	301	1158	1492	2712	6082	5187	11344	12590	13560	39053	100569	113839	139
mid Tresca	-5464	-7899	-4944	-5804	1159	4350	6928	7716	5188	4690	1450	611	539	1076	155731	611
mid Hoop	936	471	516	1202	3786	4142	6232	6232	4142	3786	1202	516	471	936	117173	584

Stress Multipliers for the
For a Specific Point on the
OH near the PF1aU coil

These are taken from the
Post26 Listing of factors

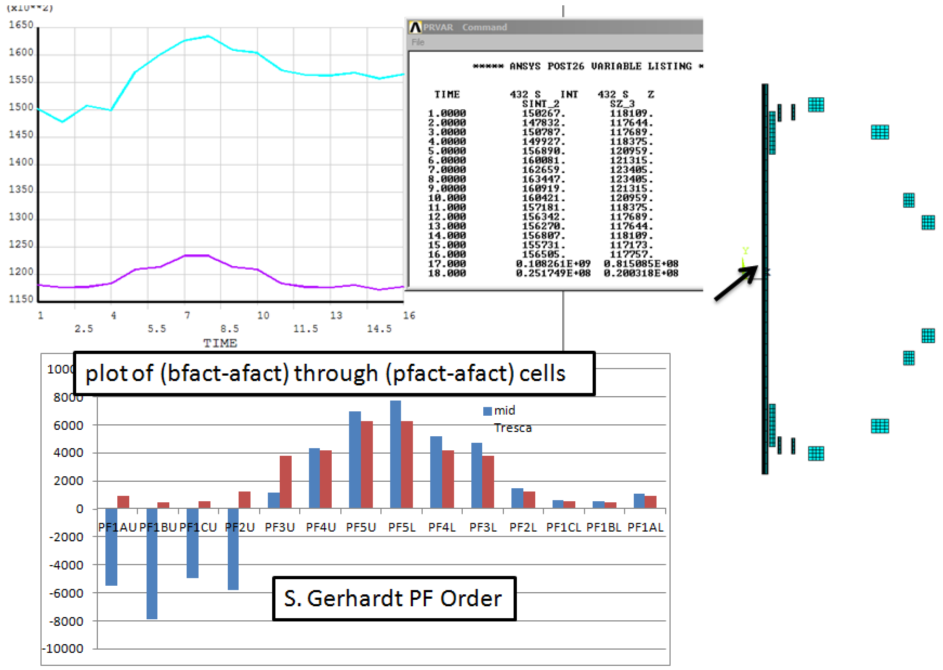


```
      ***** ANSYS POST26
VARIABLE LISTING *****

  TIME          444 S   INT
                 SINT_2
 1.0000          260425.
 2.0000          160345.
 3.0000          158830.
 4.0000          159929.
 5.0000          162072.
 6.0000          155407.
 7.0000          156251.
 8.0000          152717.
 9.0000          151494.
 10.000          151146.
 11.000          150302.
 12.000          150127.
 13.000          150111.
 14.000          150164.
 15.000          150023.
 16.000          150156.
 17.000        0.895666E+08
 18.000        0.483703E+08
```

```
ANSYS POST26 VA

444 S   Z
  SZ_2
  196291.
  128420.
  123634.
  125508.
  124300.
  117363.
  118171.
  114925.
  113803.
  113504.
  112726.
  112559.
  112547.
  112604.
  112456.
  112571.
 0.674948E+08
 0.364818E+08
```

The alternative is to pick a specific point and collect the factors for that specific point. This can be done in the Time-history post-processor in ANSYS. While more rigorous, the problem with this approach is that the worst point location for all coil currents must be identified or many points must be used. The “regional” approach yielded conservative results that were not substantially different than the tabulated points at the selected node. The Post 26 approach to tabulating the factors was applied to the mid-height region of the OH. The results are shown below:

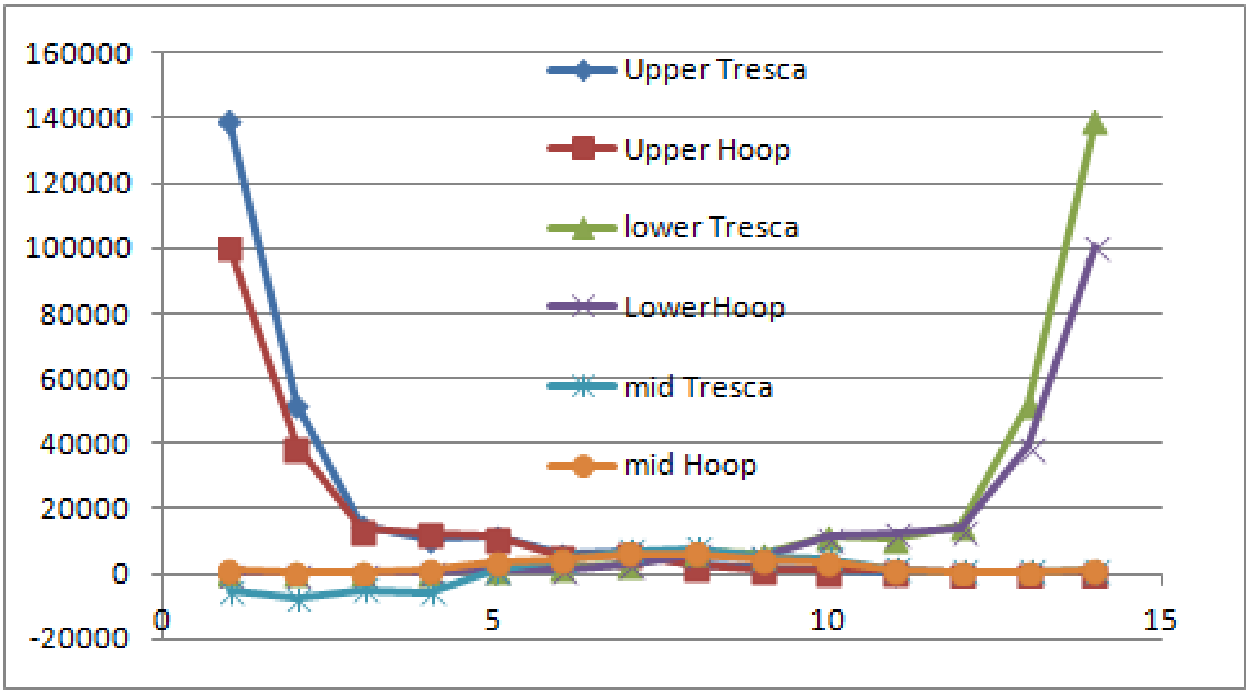
Tresca and SZ stress Factors at the ID – Mid Height of the OH



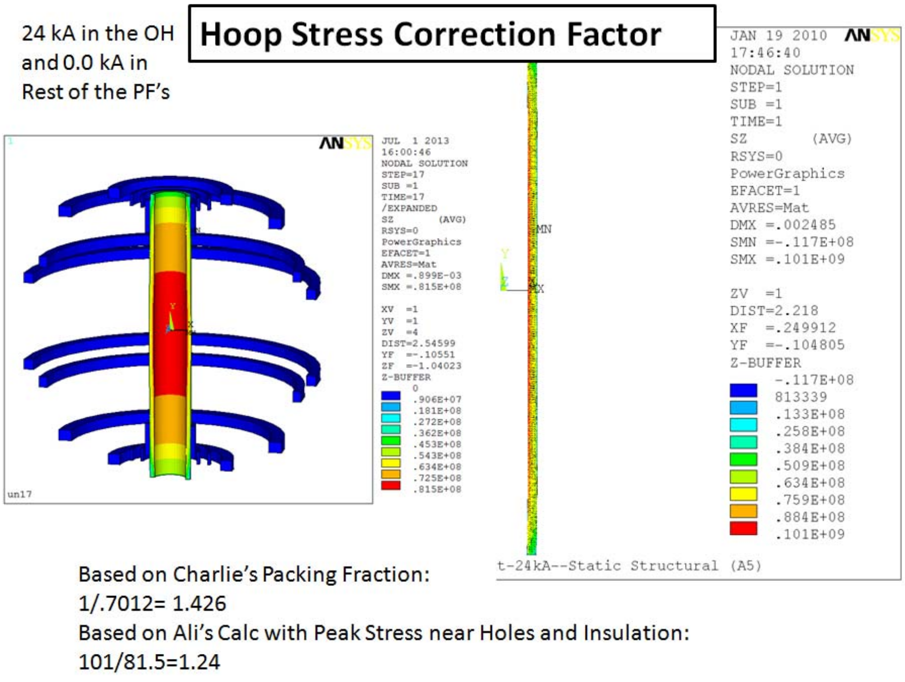
```
        ***** ANSYS POST26 VARIABLE LISTING *

  TIME        432 S   INT    432 S   Z
               SINT_2          SZ_3
 1.0000        150267.        118109.
 2.0000        147832.        117644.
 3.0000        150787.        117689.
 4.0000        149927.        118375.
 5.0000        156890.        120959.
 6.0000        160081.        121315.
 7.0000        162659.        123405.
 8.0000        163447.        123405.
 9.0000        160919.        121315.
 10.000        160421.        120959.
 11.000        157181.        118375.
 12.000        156342.        117689.
 13.000        156270.        117644.
 14.000        156807.        118109.
 15.000        155731.        117173.
 16.000        156505.        117757.
 17.000      0.108261E+09   0.815085E+08
 18.000      0.251749E+08   0.200318E+08
```

plot of (bfact-afact) through (pfact-afact) cells

S. Gerhardt PF Order



7.3.2 Stress Correction Factors to Address Coolant Holes and Insulation

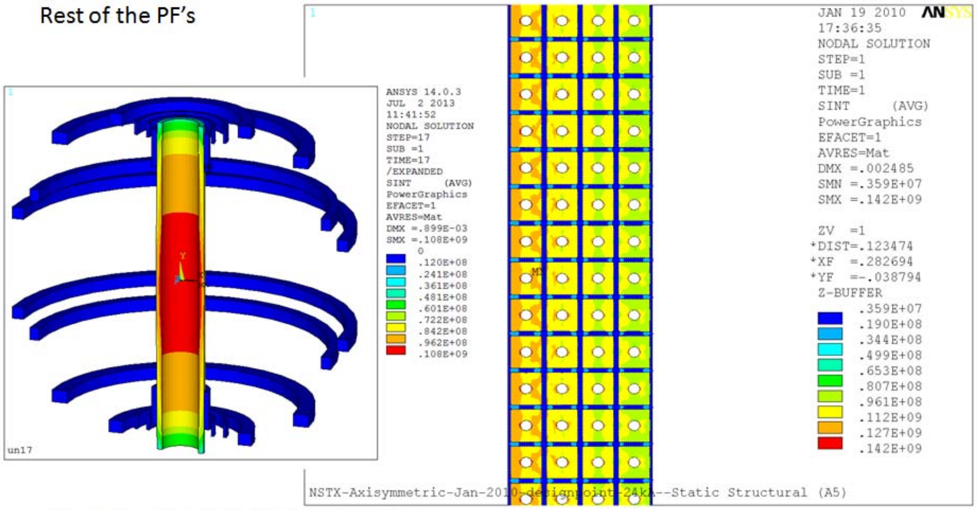


Based on Charlie's Packing Fraction:
1/.7012= 1.426
Based on Ali's Calc with Peak Stress near Holes and Insulation:
101/81.5=1.24

Based on this comparison, a hoop stress correction factor of 1.24 needs to be applied to calculate the correct local stress. This is below the value derived from the packing fraction. This implies that the insulation is contributing to the strength of the coil. The factor of 1.426 is therefore conservative. This has been used hoop stress (SZ) spreadsheet results presented.

24 kA in the OH
and 0.0 kA in
Rest of the PF's

Tresca Stress Correction Factor



Based on Charlie's Packing Fraction:
1/.7012= 1.426
Based on Ali's Calc with Peak Stress near Holes and Insulation:
142/108=1.315

The same factor is are used for the Tresca and hoop stress results. This is an approximation.. It will be different for vertical compression and hoop stress. For hoop stress alone, the packing fraction from the design point spreadsheet could be used, but this does not include the variation in hoop stress from the compressive stress poisson effects. For fatigue, the local stresses around the holes is important and the more conservative factor of 1.426 is used.

7.4 Spreadsheet Results

Eight spreadsheets are used to investigate various sets of equilibria currents. These are listed below:

```
 Directory of C:\nstx\CSU\axisym\OHPF1aInteraction
                    16 X 16 Multipliers
07/05/2013  09:55 AM          24,064 Multipliers.ls
07/02/2013  04:44 PM         153,600 Lower OH Multipliers SZ based Post Disruption.xls
07/03/2013  02:50 PM         164,864 Lower OH Multipliers SZ based.xls
07/03/2013  01:31 PM         106,496 Lower OH Multipliers Tresca Based Post Disruption.xls
07/03/2013  03:14 PM         162,304 Lower OH Multipliers Tresca Based.xls

07/03/2013  05:22 PM         162,304 Upper OH  Multipliers Tresca Based.xls
07/05/2013  08:25 AM         278,528 Upper OH  Multipliers Tresca Stefan Gerhardt scenario.xls
07/02/2013  11:54 AM         153,600 Upper OH Multipliers SZ based Post Disruption.xls
07/02/2013  04:44 PM         160,256 Upper OH Multipliers SZ based.xls
07/03/2013  02:41 PM          99,840 Upper OH Tresca Multipliers Post Disruption.xls

07/05/2013  09:54 AM         159,744 Mid Height OH  Multipliers Hoop Stress Based.xls
07/05/2013  09:39 AM         159,744 Mid Height OH  Multipliers Tresca Based.xls
                    Segmented OH
07/05/2013  10:14 AM          43,008 PF1a segmented  OH Interaction Inf.xls
```

7.4.1 Upper PF1a Region SZ, 96 Equilibria

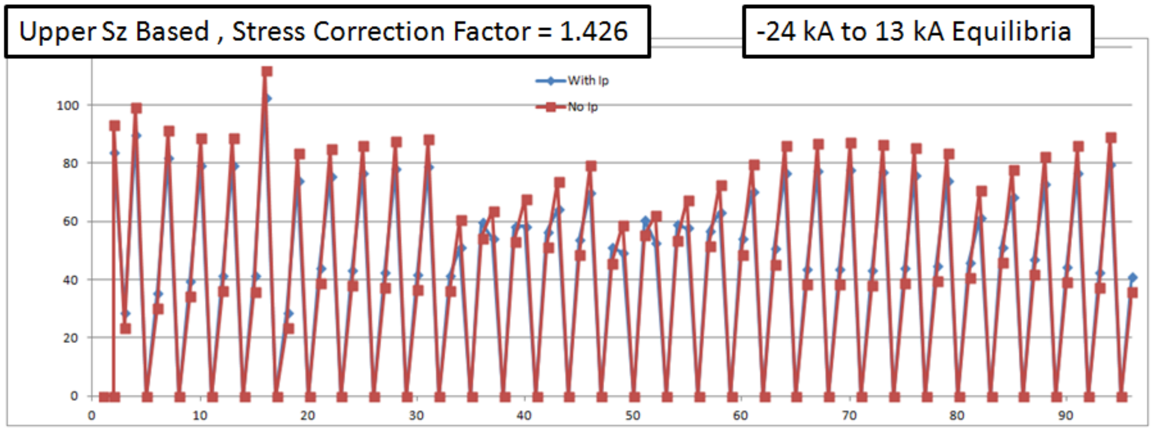


Figure 7.4.1-1

The maximum tensile stress in the conductor corresponds to the hoop stress, which according to [5] must remain below 125 MPa or else suffer a degraded fatigue life. All the later 96 equilibria satisfy this criteria.

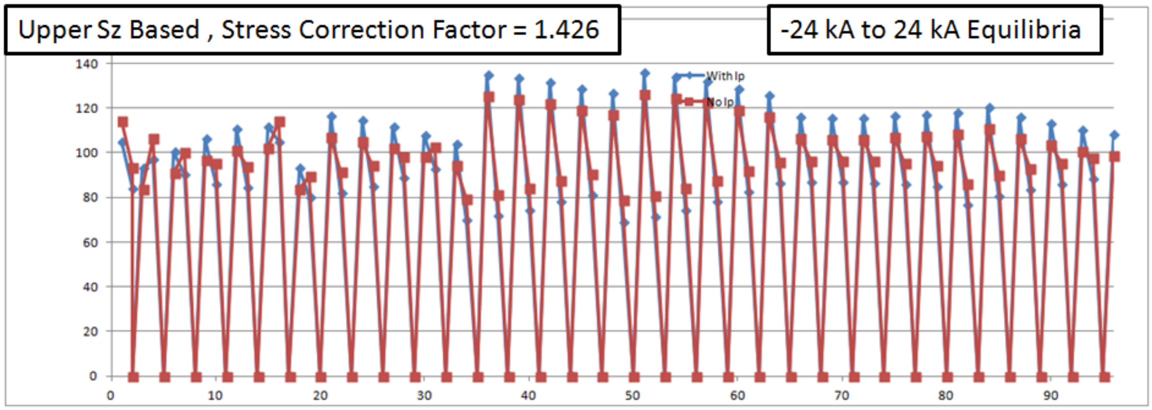


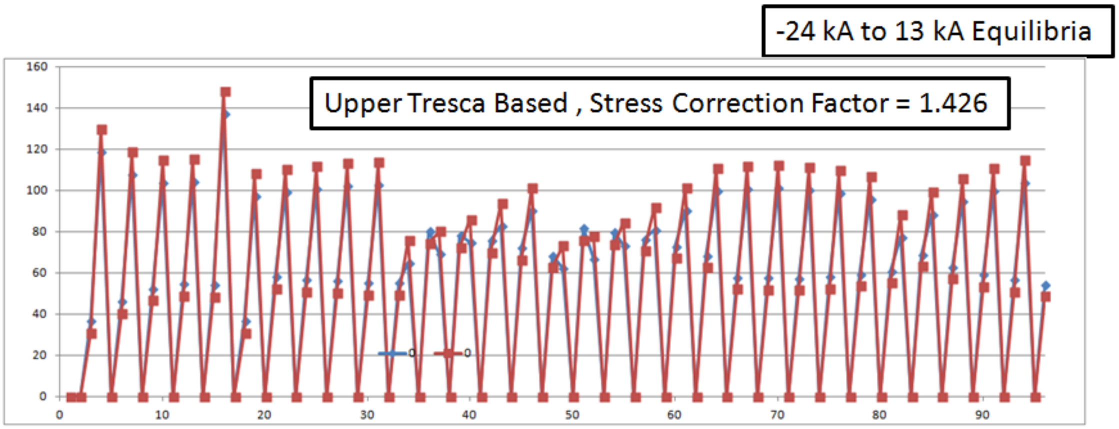
Figure 7.4.1-2

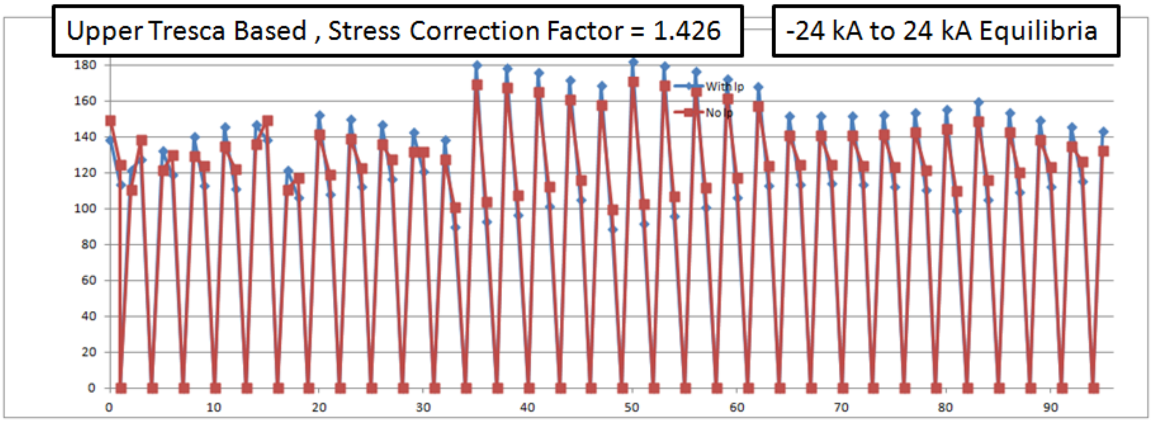
The maximum tensile stress in the conductor corresponds to the hoop stress, which according to [5] must remain below 125 MPa or else suffer a degraded fatigue life. For the earlier -24 - +24 kA OH equilibria, the stresses for EQ 36 to 60 would violate the criteria.

7.4.2 Upper PF1a Region Tresca, 96 Equilibria

From [5]:

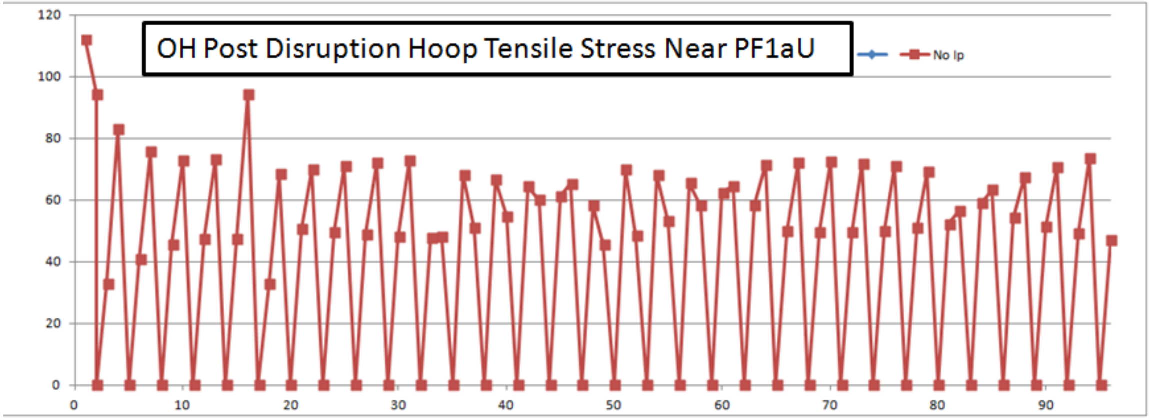
“Allowing 10% for 100 deg. C operation and 10% for DCPS this S_m is 128.4 MPa. With S_m being 2/3*S_y, the minimum S_y needs to be 193 MPa or 28 ksi. Relaxed based on actuals from Luvata to 23 ksi? 158 MPa “ For a local peak Tresca, 1.5 Sm is conservative – So maintain the Tresca stress below 193 MPa



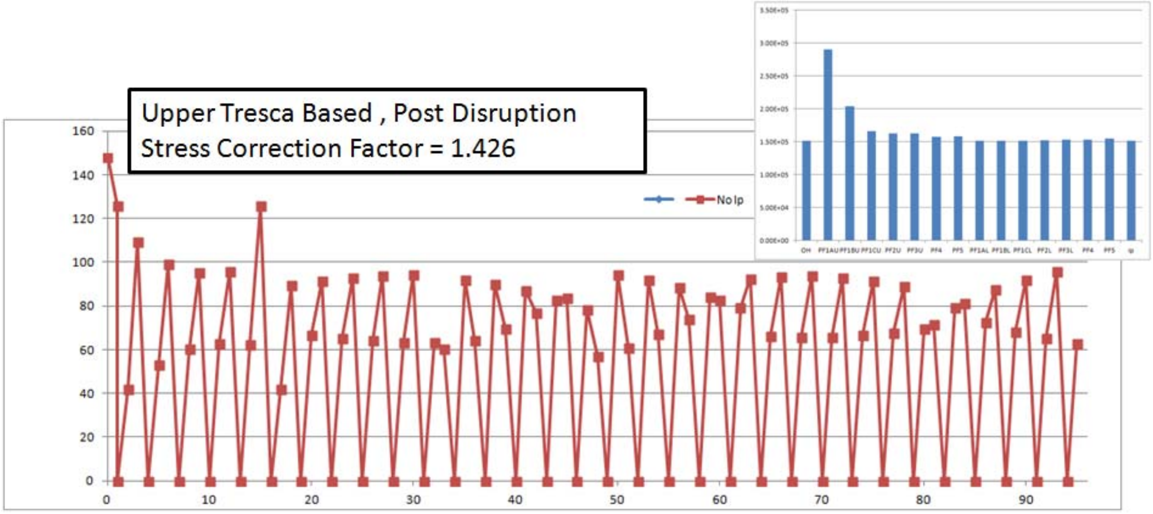


For the design equilibria – with OH currents between -245 kA and 13 kA, and for the olde3r -24 kA to 24 kA equilibria, the Tresca stress is below 193 MPa

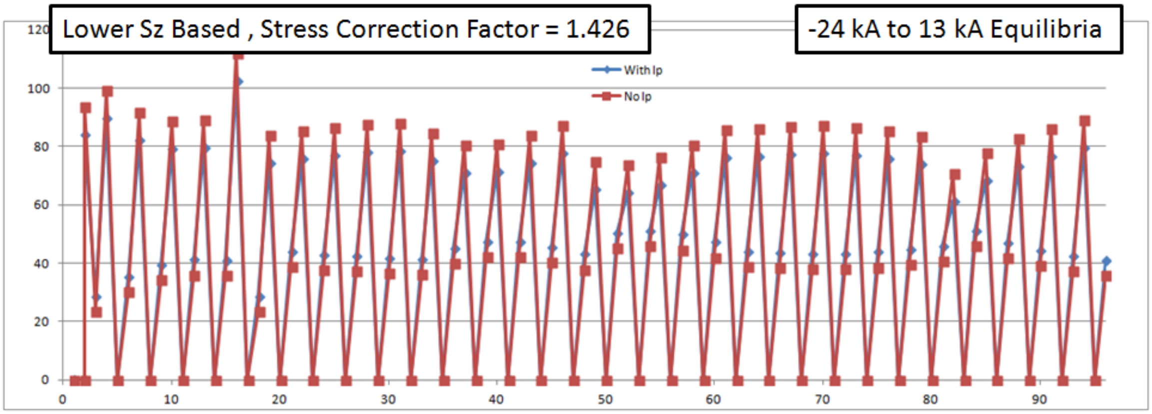
7.4.3 Upper PF1a Region SZ, 96 Post Disruption Currents

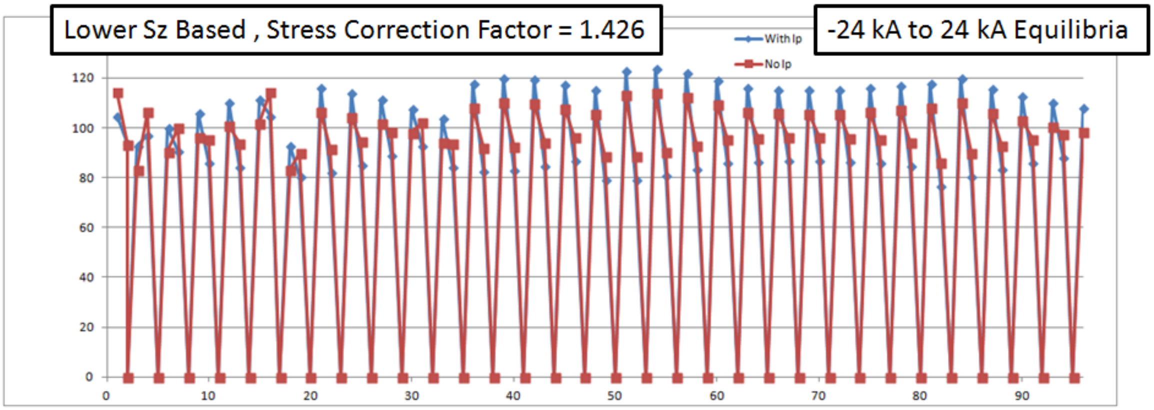


7.4.4 Upper PF1a Region Tresca, 96 Post Disruption Currents

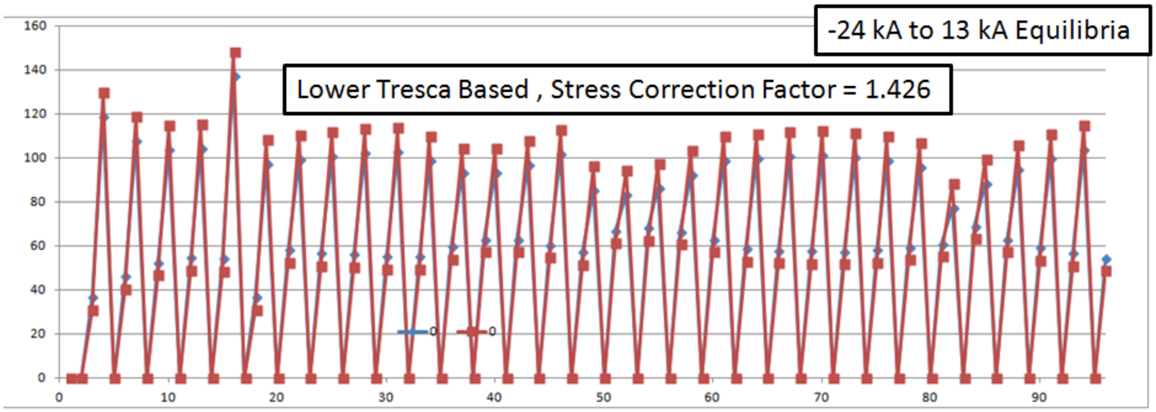


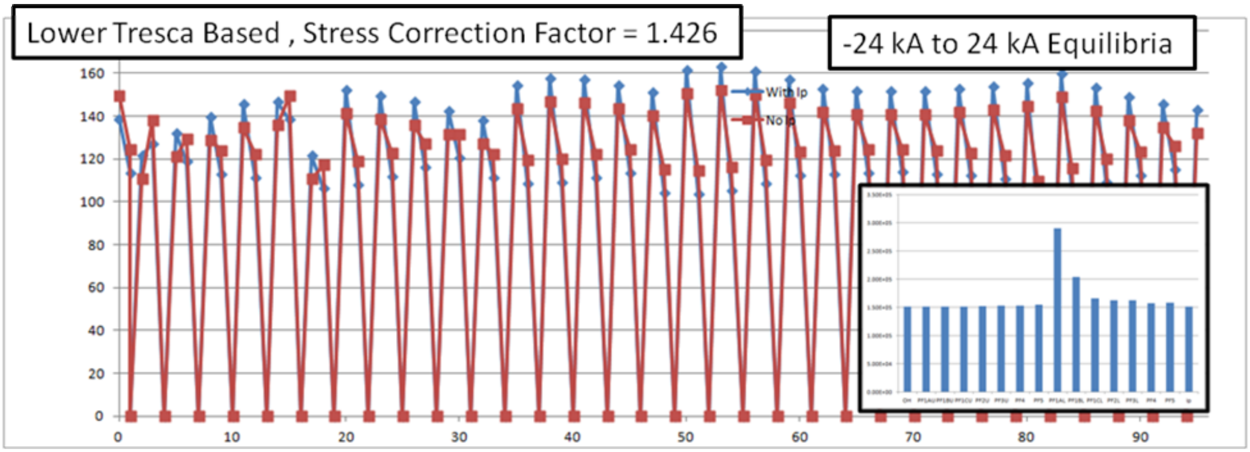
7.4.5 Lower PF1a Region SZ, 96 Equilibria



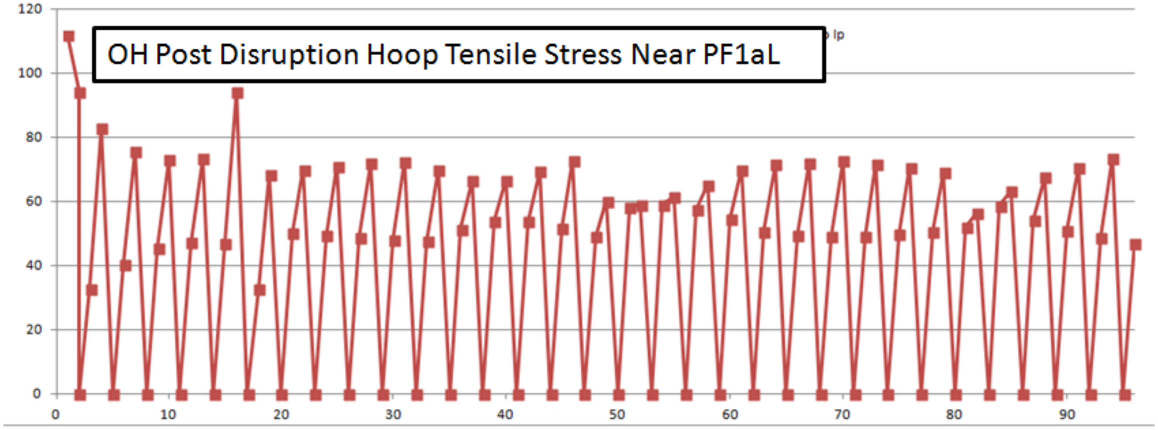


7.4.6 Lower PF1a Region Tresca, 96 Equilibria

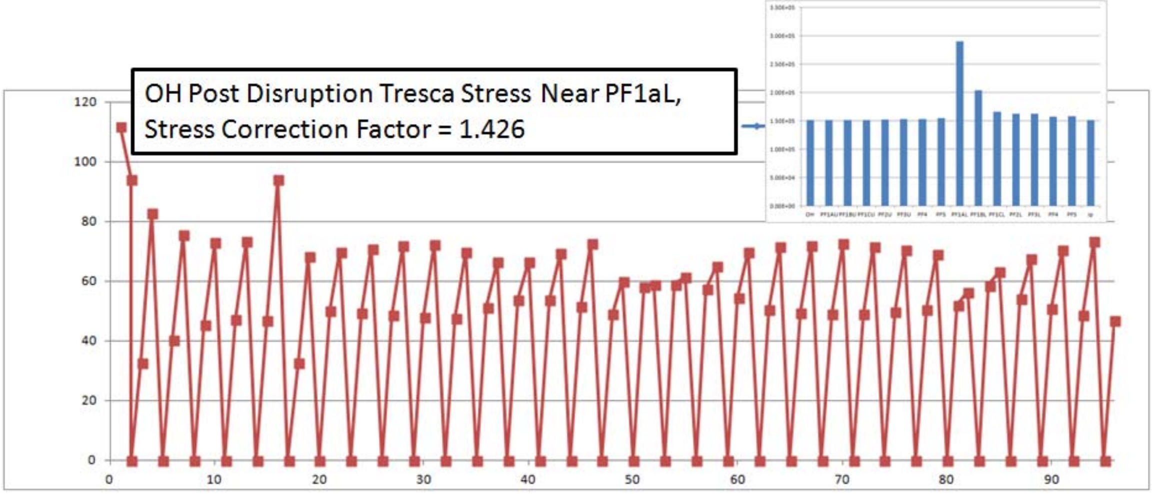


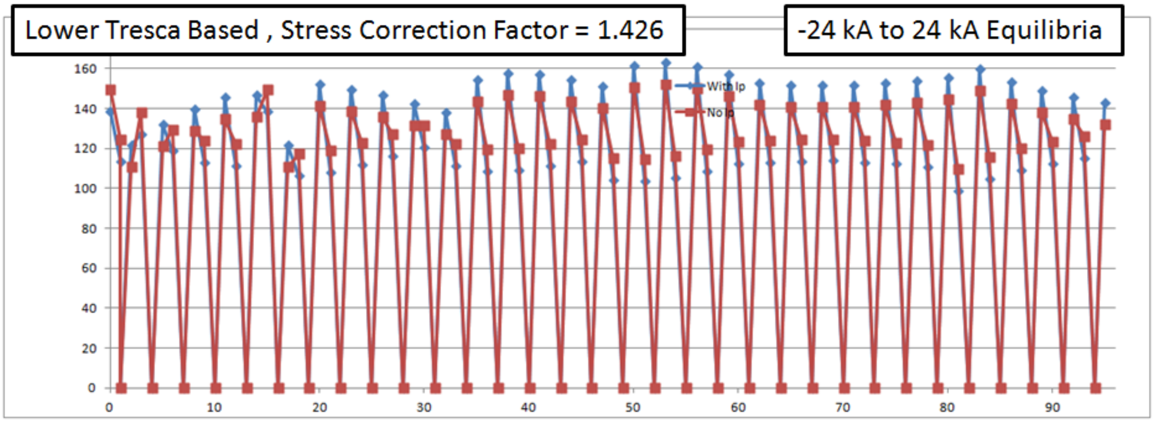


7.4.7 Lower PF1a Region SZ, 96 Post Disruption Currents

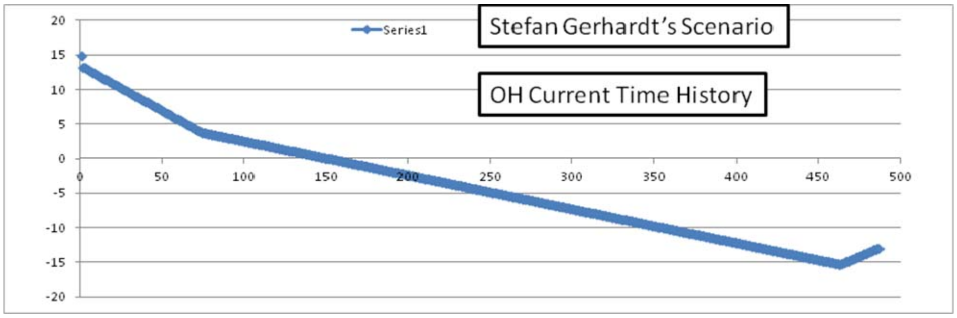


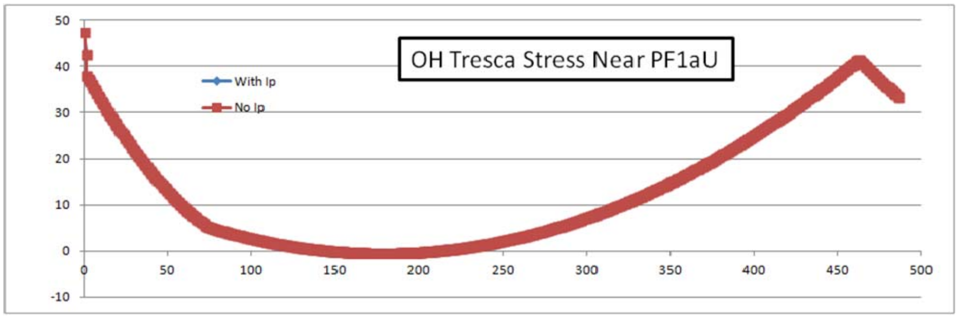
7.4.8 Lower PF1a Region Tresca, 96 Post Disruption Currents



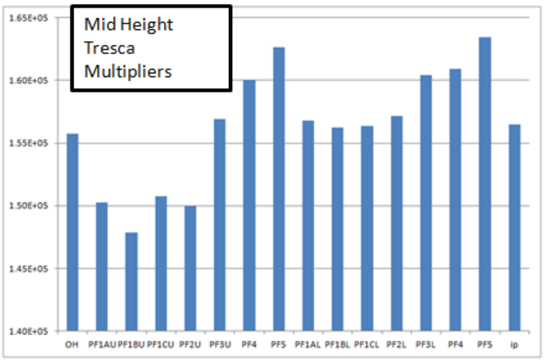


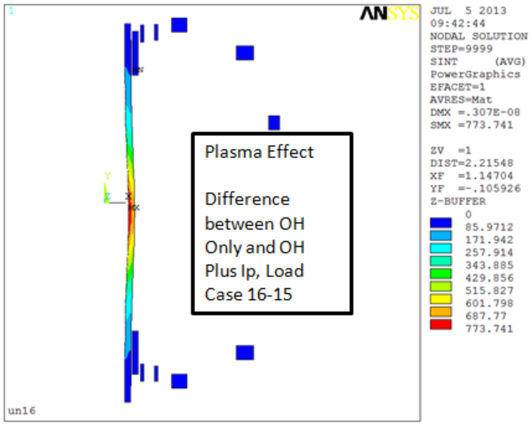
7.4.9 Stefan Gerhardt's Scenario

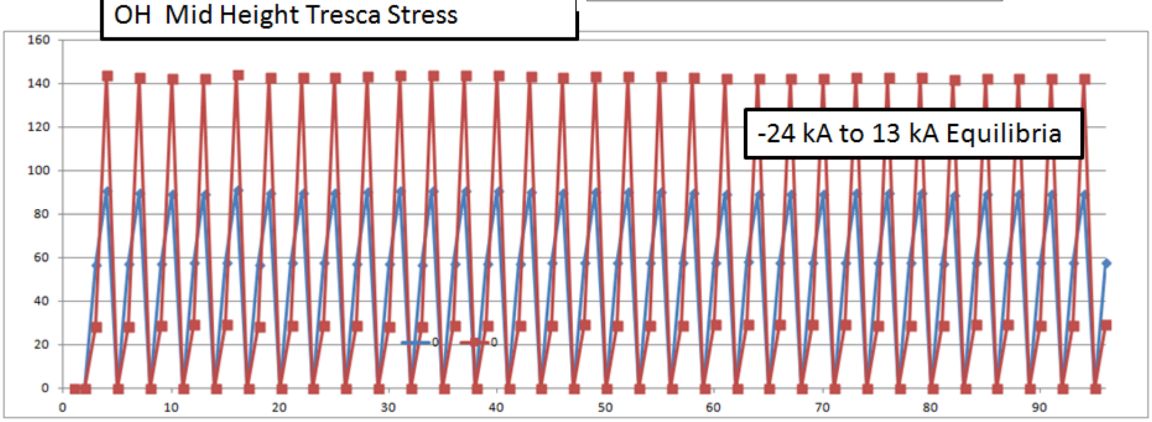




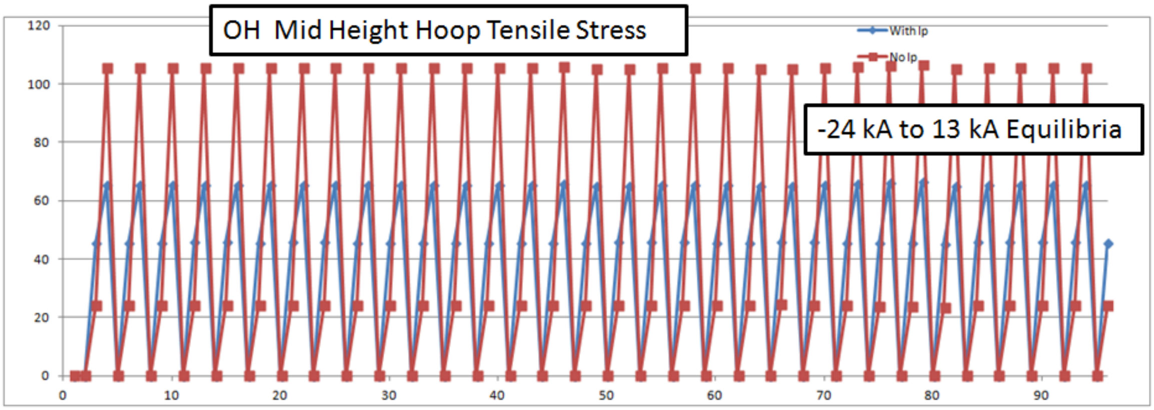
7.4.10 Mid Height OH Tresca Stress, 96 Equilibria



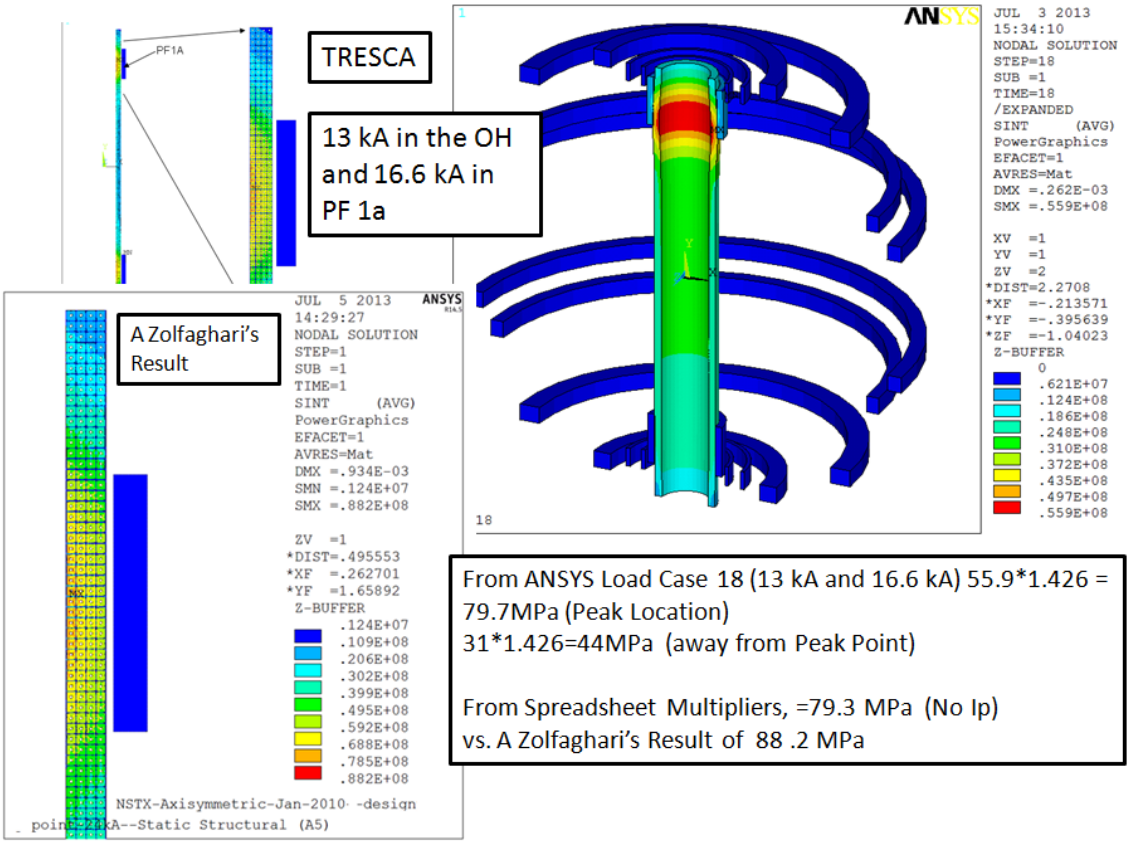




7.4.11 Mid Height OH Hoop Stress, 96 Equilibria



7.5 Comparison with Ali Zolfaghari's Results

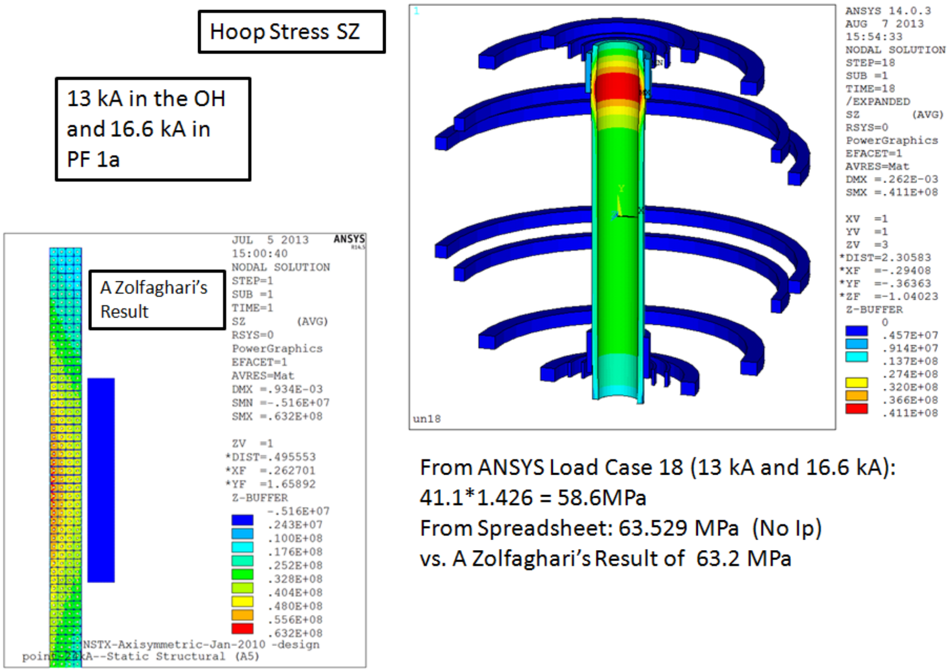


From ANSYS Load Case 18 (13 kA and 16.6 kA) 55.9*1.426 = 79.7MPa (Peak Location)
31*1.426=44MPa (away from Peak Point)

From Spreadsheet Multipliers, =79.3 MPa (No Ip)
vs. A Zolfaghari's Result of 88 .2 MPa

Figure 7.5-1 Tresca Comparison

13 kA in the OH and 16.6 kA in the PF1aU was input into the spreadsheet for the Upper PF1a region and a Tresca stress of 79 MPa was obtained. The spreadsheet uses a stress factor of 1.414 so the ANSYS result times the 1.414 = 55.9*1.426= 79.7. So the ANSYS model and the spreadsheet agree. Agreement with Ali's Results, ref [9] is not perfect. The algorithm's prediction is about 10% low.



From ANSYS Load Case 18 (13 kA and 16.6 kA):
41.1*1.426 = 58.6MPa
From Spreadsheet: 63.529 MPa (No Ip)
vs. A Zolfaghari's Result of 63.2 MPa

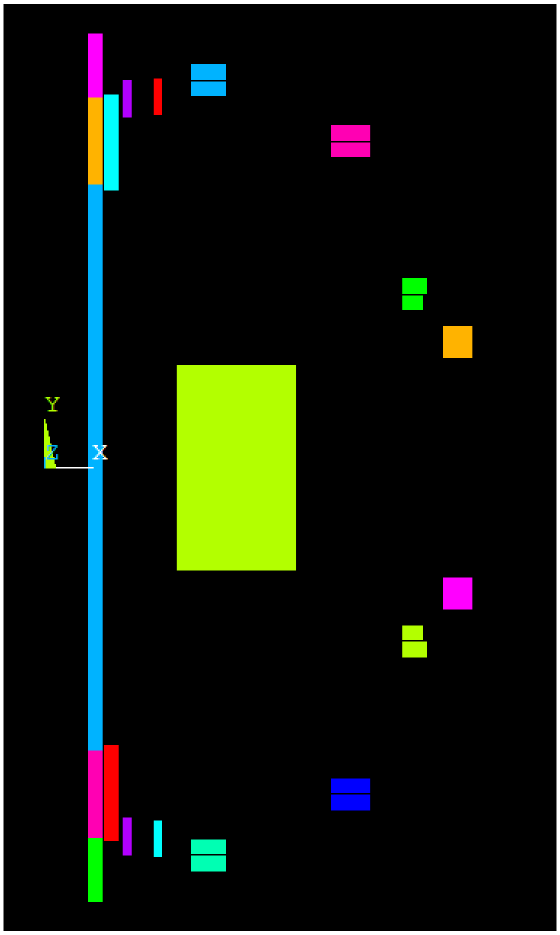
Figure 7.5-2 Hoop Stress Comparison

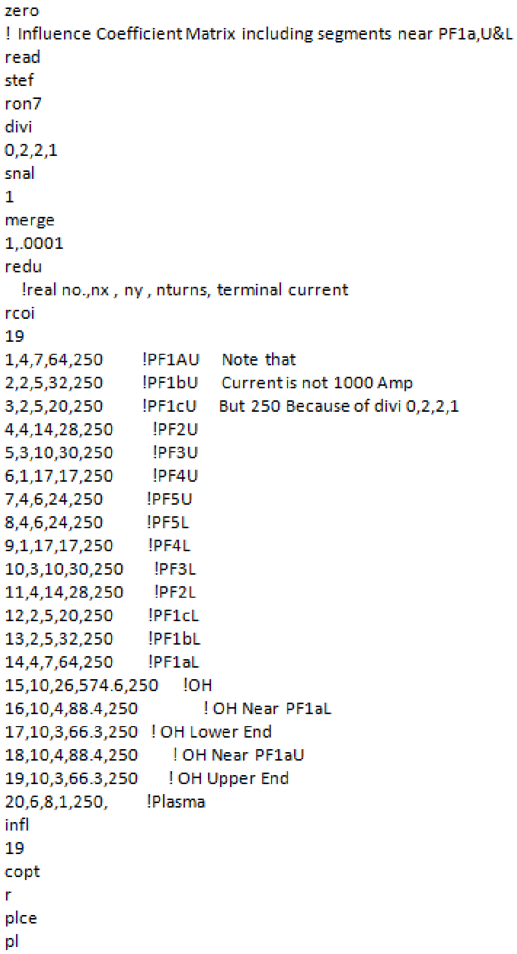
13 kA in the OH and 16.6 kA in the PF1aU was input into the spreadsheet for the Upper PF1a region and a Hoop stress of 63.5 MPa was obtained. The spreadsheet uses a stress factor of 1.414 so the ANSYS result times the 1.414 = 41.1*1.426= 58.6. Ali’s result is 63.2 MPa Agreement for the individual hoop stress component is reasonably good.

8.0 Influence Coefficients for the Segmented OH

8.1 Axisymmetric Model for Influence Coefficients for the Segmented OH

The procedure for computing the influence coefficients is the same as described in [10]. Computation of influence coefficients is done by computing contributions of fields and forces in one element group with respect to other element groups. The element groups are identified by real constant numbers for the elements in the group.





```
zero
! Influence Coefficient Matrix including segments near PF1a,U&L
read
stef
ron7
divi
0,2,2,1
snal
1
merge
1,.0001
redu
   !real no.,nx , ny , nturns, terminal current
rcoi
19
1,4,7,64,250      !PF1AU    Note that
2,2,5,32,250      !PF1bU    Current is not 1000 Amp
3,2,5,20,250      !PF1cU    But 250 Because of divi 0,2,2,1
4,4,14,28,250      !PF2U
5,3,10,30,250      !PF3U
6,1,17,17,250      !PF4U
7,4,6,24,250      !PF5U
8,4,6,24,250      !PF5L
9,1,17,17,250     !PF4L
10,3,10,30,250     !PF3L
11,4,14,28,250     !PF2L
12,2,5,20,250     !PF1cL
13,2,5,32,250     !PF1bL
14,4,7,64,250     !PF1aL
15,10,26,574.6,250    !OH
16,10,4,88.4,250           ! OH Near PF1aL
17,10,3,66.3,250  ! OH Lower End
18,10,4,88.4,250      ! OH Near PF1aU
19,10,3,66.3,250     ! OH Upper End
20,6,8,1,250,      !Plasma
infl
19
copt
r
plce
pl
```

Figure 3 Axisymmetric Model with segmented OH

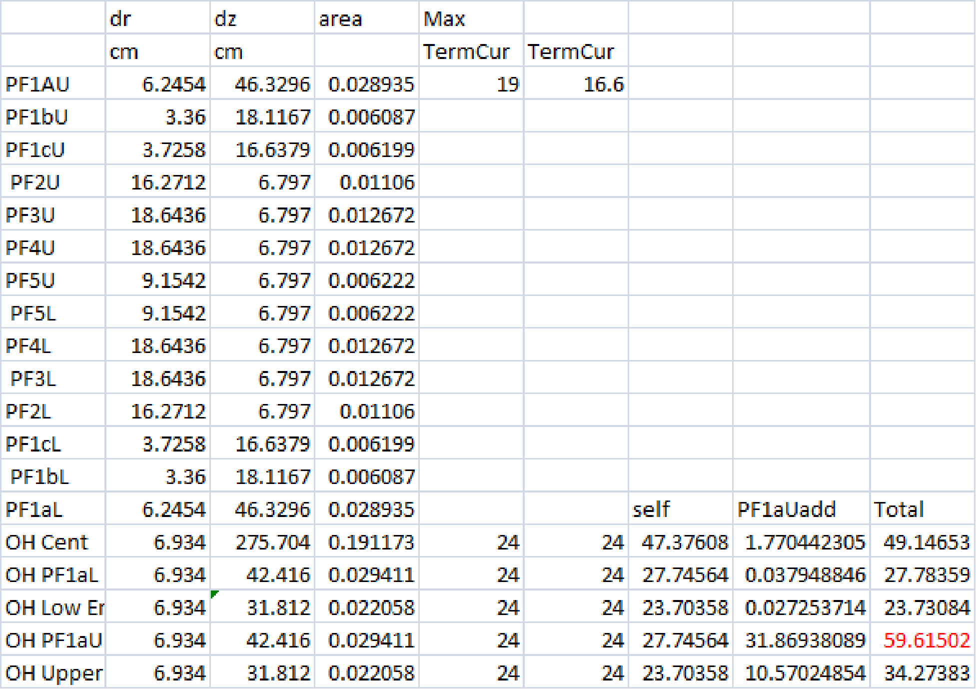
This allows coils or sections of coils to be considered in the matrix calculation. For this calculation, the element designations used by Ron Hatcher's calculation [1] have been used to allow a comparison with the force influence coefficients.

To get the average hoop stress in the coil divide the Fr/radian in N/radian results from the influence matrix multiplication by the area of the coil. This is the "smeared" stress at the center of the coil – to get the ID stress scale it by 1/r and increase by dividing by a packing fraction (~.85)

Area of 16 the lower OH region near the PF1aL is .02778 m^2
Area of 18 the Upper OH region near the PF1aU is .02778 m^2
Area of 1 PF1au is .028934 m^2
Area of 14 pf1aL is .028934 m^2

The influence coefficients are listed in the4 following spreadsheet, and in section 8.2

07/05/2013 08:34 AM 43,008 PF1a segmented OH Interaction Inf.xls

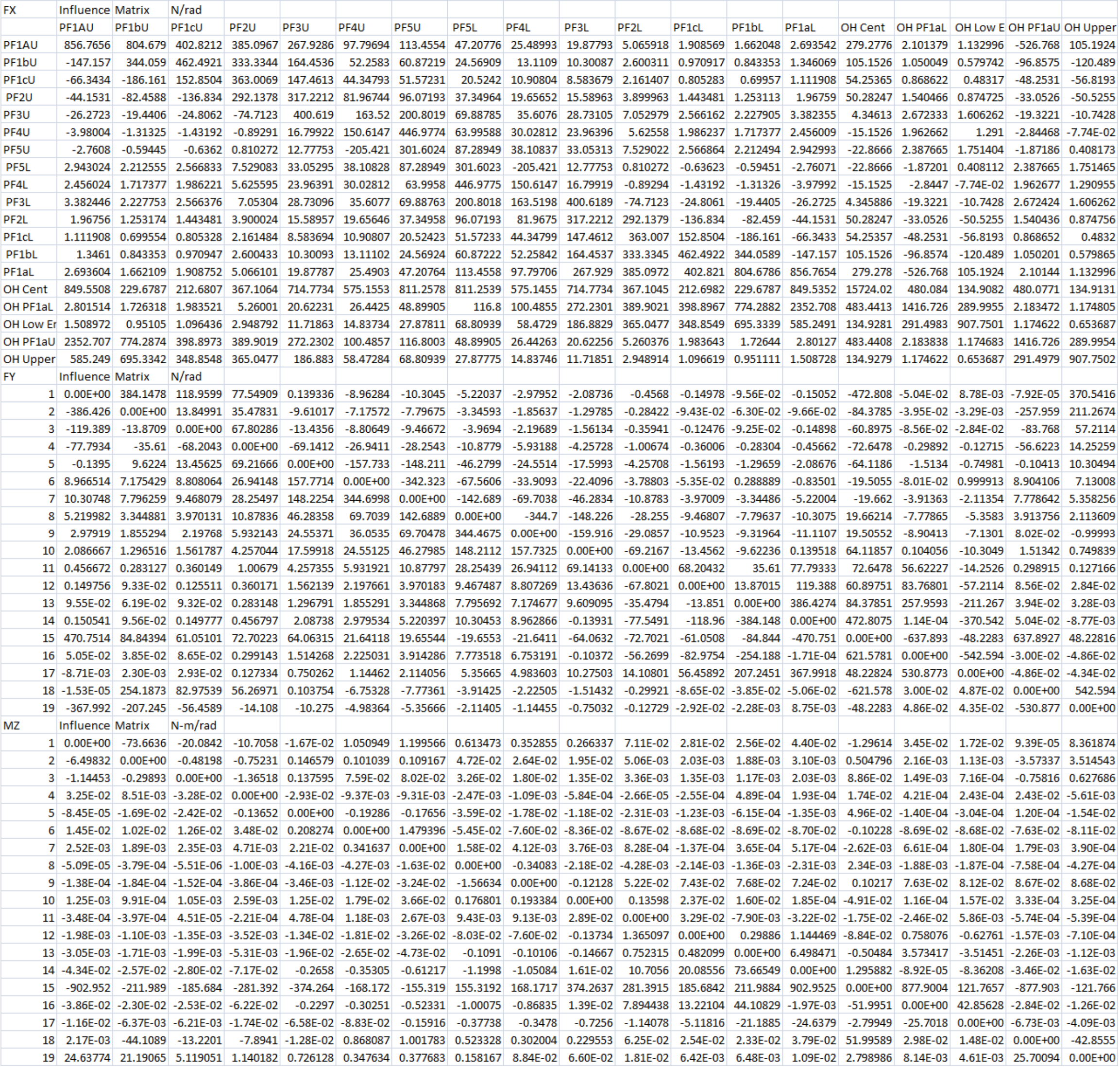


	dr	dz	area	Max				
	cm	cm		TermCur	TermCur			
PF1AU	6.2454	46.3296	0.028935	19	16.6			
PF1bU	3.36	18.1167	0.006087					
PF1cU	3.7258	16.6379	0.006199					
PF2U	16.2712	6.797	0.01106					
PF3U	18.6436	6.797	0.012672					
PF4U	18.6436	6.797	0.012672					
PF5U	9.1542	6.797	0.006222					
PF5L	9.1542	6.797	0.006222					
PF4L	18.6436	6.797	0.012672					
PF3L	18.6436	6.797	0.012672					
PF2L	16.2712	6.797	0.01106					
PF1cL	3.7258	16.6379	0.006199					
PF1bL	3.36	18.1167	0.006087					
PF1aL	6.2454	46.3296	0.028935			self	PF1aUadd	Total
OH Cent	6.934	275.704	0.191173	24	24	47.37608	1.770442305	49.14653
OH PF1aL	6.934	42.416	0.029411	24	24	27.74564	0.037948846	27.78359
OH Low Er	6.934	31.812	0.022058	24	24	23.70358	0.027253714	23.73084
OH PF1aU	6.934	42.416	0.029411	24	24	27.74564	31.86938089	59.61502
OH Upper	6.934	31.812	0.022058	24	24	23.70358	10.57024854	34.27383

For the case with 24 kA in the OH and 16.6 kA in PF1a, the OH region near PF1au had a higher hoop stress. The stresses were calculated by dividing Frad by the coil segment area. Actually the stress should include a packing fraction, 1/r correction and to calculate tTresca, the effect of vertical compression. Compare the 59.61 with the 55.9 MPa smeared results in section 7.5

With only the OH self loads in the spreadsheet, with 24 kA in the OH, the stress in the central region is 47.37MPa. This is an average hoop stress in the whole coil segment that models the central region of the OH. The 16 factor spreadsheet with only the 24 kA current produced a peak stress at the ID and mid height of the OH of 74.4 MPa. The FEA –ANSYS run also has a load step #17 that represents the 24 kA loading on the OH – not one of the 16 unit loads. This has a peak hoop stress of 67.5 MPa and a mid-build stress of 52.5. The 52 .5MPa stress can be compared with the 47.37 MPa stress result from the segmented solenoid factors. The difference is attributed to the fact that the segmented OH result is an average over the height as well as the build. To get the peak stress from the segmented result, use a factor of 108/ 47.37 to include the effects of peak vs. average in the smeared stress and local peak vs smeared result to address coolant holes and insulation.

8.2 List of Influence Coefficients for the Segmented OH



FX	Influence	Matrix	N/rad																
	PF1AU	PF1bU	PF1cU	PF2U	PF3U	PF4U	PF5U	PF5L	PF4L	PF3L	PF2L	PF1cL	PF1bL	PF1aL	OH Cent	OH PF1aL	OH Low E	OH PF1aU	OH Upper
PF1AU	856.7656	804.679	402.8212	385.0967	267.9286	97.79694	113.4554	47.20776	25.48993	19.87793	5.065918	1.908569	1.662048	2.693542	279.2776	2.101379	1.132996	-526.768	105.1924
PF1bU	-147.157	344.059	462.4921	333.3344	164.4536	52.2583	60.87219	24.56909	13.1109	10.30087	2.600311	0.970917	0.843353	1.346069	105.1526	1.050049	0.579742	-96.8575	-120.489
PF1cU	-66.3434	-186.161	152.8504	363.0069	147.4613	44.34793	51.57231	20.5242	10.90804	8.583679	2.161407	0.805283	0.69957	1.111908	54.25365	0.868622	0.48317	-48.2531	-56.8193
PF2U	-44.1531	-82.4588	-136.834	292.1378	317.2212	81.96744	96.07193	37.34964	19.65652	15.58963	3.899963	1.443481	1.253113	1.96759	50.28247	1.540466	0.874725	-33.0526	-50.5255
PF3U	-26.2723	-19.4406	-24.8062	-74.7123	400.619	163.52	200.8019	69.88785	35.6076	28.73105	7.052979	2.566162	2.227905	3.382355	4.34613	2.672333	1.606262	-19.3221	-10.7428
PF4U	-3.98004	-1.31325	-1.43192	-0.89291	16.79922	150.6147	446.9774	63.99588	30.02812	23.96396	5.62558	1.986237	1.717377	2.456009	-15.1526	1.962662	1.291	-2.84468	-7.74E-02
PF5U	-2.7608	-0.59445	-0.6362	0.810272	12.77753	-205.421	301.6024	87.28949	38.10837	33.05313	7.529022	2.566864	2.212494	2.942993	-22.8666	2.387665	1.751404	-1.87186	0.408173
PF5L	2.943024	2.212555	2.566833	7.529083	33.05295	38.10828	87.28949	301.6023	-205.421	12.77753	0.810272	-0.63623	-0.59451	-2.76071	-22.8666	-1.87201	0.408112	2.387665	1.751465
PF4L	2.456024	1.717377	1.986221	5.625595	23.96391	30.02812	63.9958	446.9775	150.6147	16.79919	-0.89294	-1.43192	-1.31326	-3.97992	-15.1525	-2.8447	-7.74E-02	1.962677	1.290955
PF3L	3.382446	2.227753	2.566376	7.05304	28.73096	35.6077	69.88763	200.8018	163.5198	400.6189	-74.7123	-24.8061	-19.4405	-26.2725	4.345886	-19.3221	-10.7428	2.672424	1.606262
PF2L	1.96756	1.253174	1.443481	3.900024	15.58957	19.65646	37.34958	96.07193	81.9675	317.2212	292.1379	-136.834	-82.459	-44.1531	50.28247	-33.0526	-50.5255	1.540436	0.874756
PF1cL	1.111908	0.699554	0.805328	2.161484	8.583694	10.90807	20.52423	51.57233	44.34799	147.4612	363.007	152.8504	-186.161	-66.3433	54.25357	-48.2531	-56.8193	0.868652	0.4832
PF1bL	1.3461	0.843353	0.970947	2.600433	10.30093	13.11102	24.56924	60.87222	52.25842	164.4537	333.3345	462.4922	344.0589	-147.157	105.1526	-96.8574	-120.489	1.050201	0.579865
PF1aL	2.693604	1.662109	1.908752	5.066101	19.87787	25.4903	47.20764	113.4558	97.79706	267.929	385.0972	402.821	804.6786	856.7654	279.278	-526.768	105.1924	2.10144	1.132996
OH Cent	849.5508	229.6787	212.6807	367.1064	714.7734	575.1553	811.2578	811.2539	575.1455	714.7734	367.1045	212.6982	229.6787	849.5352	15724.02	480.084	134.9082	480.0771	134.9131
OH PF1aL	2.801514	1.726318	1.983521	5.26001	20.62231	26.4425	48.89905	116.8	100.4855	272.2301	389.9021	398.8967	774.2882	2352.708	483.4413	1416.726	289.9955	2.183472	1.174805
OH Low Er	1.508972	0.95105	1.096436	2.948792	11.71863	14.83734	27.87811	68.80939	58.4729	186.8829	365.0477	348.8549	695.3339	585.2491	134.9281	291.4983	907.7501	1.174622	0.653687
OH PF1aU	2352.707	774.2874	398.8973	389.9019	272.2302	100.4857	116.8003	48.89905	26.44263	20.62256	5.260376	1.983643	1.72644	2.80127	483.4408	2.183838	1.174683	1416.726	289.9954
OH Upper	585.249	695.3342	348.8548	365.0477	186.883	58.47284	68.80939	27.87775	14.83746	11.71851	2.948914	1.096619	0.951111	1.508728	134.9279	1.174622	0.653687	291.4979	907.7502
FY	Influence	Matrix	N/rad																
1	0.00E+00	384.1478	118.9599	77.54909	0.139336	-8.96284	-10.3045	-5.22037	-2.97952	-2.08736	-0.4568	-0.14978	-9.56E-02	-0.15052	-472.808	-5.04E-02	8.78E-03	-7.92E-05	370.5416
2	-386.426	0.00E+00	13.84991	35.47831	-9.61017	-7.17572	-7.79675	-3.34593	-1.85637	-1.29785	-0.28422	-9.43E-02	-6.30E-02	-9.66E-02	-84.3785	-3.95E-02	-3.29E-03	-257.959	211.2674
3	-119.389	-13.8709	0.00E+00	67.80286	-13.4356	-8.80649	-9.46672	-3.9694	-2.19689	-1.56134	-0.35941	-0.12476	-9.25E-02	-0.14898	-60.8975	-8.56E-02	-2.84E-02	-83.768	57.2114
4	-77.7934	-35.61	-68.2043	0.00E+00	-69.1412	-26.9411	-28.2543	-10.8779	-5.93188	-4.25728	-1.00674	-0.36006	-0.28304	-0.45662	-72.6478	-0.29892	-0.12715	-56.6223	14.25259
5	-0.1395	9.6224	13.45625	69.21666	0.00E+00	-157.733	-148.211	-46.2799	-24.5514	-17.5993	-4.25708	-1.56193	-1.29659	-2.08676	-64.1186	-1.5134	-0.74981	-0.10413	10.30494
6	8.966514	7.175429	8.808064	26.94148	157.7714	0.00E+00	-342.323	-67.5606	-33.9093	-22.4096	-3.78803	-5.35E-02	0.288889	-0.83501	-19.5055	-8.01E-02	0.999913	8.904106	7.13008
7	10.30748	7.796259	9.468079	28.25497	148.2254	344.6998	0.00E+00	-142.689	-69.7038	-46.2834	-10.8783	-3.97009	-3.34486	-5.22004	-19.662	-3.91363	-2.11354	7.778642	5.358256
8	5.219982	3.344881	3.970131	10.87836	46.28358	69.7039	142.6889	0.00E+00	-344.7	-148.226	-28.255	-9.46807	-7.79637	-10.3075	19.66214	-7.77865	-5.3583	3.913756	2.113609
9	2.97919	1.855294	2.19768	5.932143	24.55371	36.0535	69.70478	344.4675	0.00E+00	-159.916	-29.0857	-10.9523	-9.31964	-11.1107	19.50552	-8.90413	-7.1301	8.02E-02	-0.99993
10	2.086667	1.296516	1.561787	4.257044	17.59918	24.55125	46.27985	148.2112	157.7325	0.00E+00	-69.2167	-13.4562	-9.62236	0.139518	64.11857	0.104056	-10.3049	1.51342	0.749839
11	0.456672	0.283127	0.360149	1.00679	4.257355	5.931921	10.87797	28.25439	26.94112	69.14133	0.00E+00	68.20432	35.61	77.79333	72.6478	56.62227	-14.2526	0.298915	0.127166
12	0.149756	9.33E-02	0.125511	0.360171	1.562139	2.197661	3.970183	9.467487	8.807269	13.43636	-67.8021	0.00E+00	13.87015	119.388	60.89751	83.76801	-57.2114	8.56E-02	2.84E-02
13	9.55E-02	6.19E-02	9.32E-02	0.283148	1.296791	1.855291	3.344868	7.795692	7.174677	9.609095	-35.4794	-13.851	0.00E+00	386.4274	84.37851	257.9593	-211.267	3.94E-02	3.28E-03
14	0.150541	9.56E-02	0.149777	0.456797	2.08738	2.979534	5.220397	10.30453	8.962866	-0.13931	-77.5491	-118.96	-384.148	0.00E+00	472.8075	1.14E-04	-370.542	5.04E-02	-8.77E-03
15	470.7514	84.84394	61.05101	72.70223	64.06315	21.64118	19.65544	-19.6553	-21.6411	-64.0632	-72.7021	-61.0508	-84.844	-470.751	0.00E+00	-637.893	-48.2283	637.8927	48.22816
16	5.05E-02	3.85E-02	8.65E-02	0.299143	1.514268	2.225031	3.914286	7.773518	6.753191	-0.10372	-56.2699	-82.9754	-254.188	-1.71E-04	621.5781	0.00E+00	-542.594	-3.00E-02	-4.86E-02
17	-8.71E-03	2.30E-03	2.93E-02	0.127334	0.750262	1.14462	2.114056	5.35665	4.983603	10.27503	14.10801	56.45892	207.2451	367.9918	48.22824	530.8773	0.00E+00	-4.86E-02	-4.34E-02
18	-1.53E-05	254.1873	82.97539	56.26971	0.103754	-6.75328	-7.77361	-3.91425	-2.22505	-1.51432	-0.29921	-8.65E-02	-3.85E-02	-5.06E-02	-621.578	3.00E-02	4.87E-02	0.00E+00	542.594
19	-367.992	-207.245	-56.4589	-14.108	-10.275	-4.98364	-5.35666	-2.11405	-1.14455	-0.75032	-0.12729	-2.92E-02	-2.28E-03	8.75E-03	-48.2283	4.86E-02	4.35E-02	-530.877	0.00E+00
MZ	Influence	Matrix	N-m/rad																
1	0.00E+00	-73.6636	-20.0842	-10.7058	-1.67E-02	1.050949	1.199566	0.613473	0.352855	0.266337	7.11E-02	2.81E-02	2.56E-02	4.40E-02	-1.29614	3.45E-02	1.72E-02	9.39E-05	8.361874
2	-6.49832	0.00E+00	-0.48198	-0.75231	0.146579	0.101039	0.109167	4.72E-02	2.64E-02	1.95E-02	5.06E-03	2.03E-03	1.88E-03	3.10E-03	0.504796	2.16E-03	1.13E-03	-3.57337	3.514543
3	-1.14453	-0.29893	0.00E+00	-1.36518	0.137595	7.59E-02	8.02E-02	3.26E-02	1.80E-02	1.35E-02	3.36E-03	1.35E-03	1.17E-03	2.03E-03	8.86E-02	1.49E-03	7.16E-04	-0.75816	0.627686
4	3.25E-02	8.51E-03	-3.28E-02	0.00E+00	-2.93E-02	-9.37E-03	-9.31E-03	-2.47E-03	-1.09E-03	-5.84E-04	-2.66E-05	-2.55E-04	4.89E-04	1.93E-04	1.74E-02	4.21E-04	2.43E-04	2.43E-02	-5.61E-03
5	-8.45E-05	-1.69E-02	-2.42E-02	-0.13652	0.00E+00	-0.19286	-0.17656	-3.59E-02	-1.78E-02	-1.18E-02	-2.31E-03	-1.23E-03	-6.15E-04	-1.35E-03	4.96E-02	-1.40E-04	-3.04E-04	1.20E-04	-1.54E-02
6	1.45E-02	1.02E-02	1.26E-02	3.48E-02	0.208274	0.00E+00	1.479396	-5.45E-02	-7.60E-02	-8.36E-02	-8.67E-02	-8.68E-02	-8.69E-02	-8.70E-02	-0.10228	-8.69E-02	-8.68E-02	-7.63E-02	-8.11E-02
7	2.52E-03	1.89E-03	2.35E-03	4.71E-03	2.21E-02	0.341637	0.00E+00	1.58E-02	4.12E-03	3.76E-03	8.28E-04	-1.37E-04	3.65E-04	5.17E-04	-2.62E-03	6.61E-04	1.80E-04	1.79E-03	3.90E-04
8	-5.09E-05	-3.79E-04	-5.51E-06	-1.00E-03	-4.16E-03	-4.27E-03	-1.63E-02	0.00E+00	-0.34083	-2.18E-02	-4.28E-03	-2.14E-03	-1.36E-03	-2.31E-03	2.34E-03	-1.88E-03	-1.87E-04	-7.58E-04	-4.27E-04
9	-1.38E-04	-1.84E-04	-1.52E-04	-3.86E-04	-3.46E-03	-1.12E-02	-3.24E-02	-1.56634	0.00E+00	-0.12128	5.22E-02	7.43E-02	7.68E-02	7.24E-02	0.10217	7.63E-02	8.12E-02	8.67E-02	8.68E-02
10	1.25E-03	9.91E-04	1.05E-03	2.59E-03	1.25E-02	1.79E-02	3.66E-02	0.176801	0.193384	0.00E+00	0.13598	2.37E-02	1.60E-02	1.85E-04	-4.91E-02	1.16E-04	1.57E-02	3.33E-04	3.25E-04
11	-3.48E-04	-3.97E-04	4.51E-05	-2.21E-04	4.78E-04	1.18E-03	2.67E-03	9.43E-03	9.13E-03	2.89E-02	0.00E+00	3.29E-02	-7.90E-03	-3.22E-02	-1.75E-02	-2.46E-02	5.86E-03	-5.74E-04	-5.39E-04
12	-1.98E-03	-1.10E-03	-1.35E-03	-3.52E-03	-1.34E-02	-1.81E-02	-3.26E-02	-8.03E-02	-7.60E-02	-0.13734	1.365097	0.00E+00	0.29886	1.144469	-8.84E-02	0.758076	-0.62761	-1.57E-03	-7.10E-04
13	-3.05E-03	-1.71E-03	-1.99E-03	-5.31E-03	-1.96E-02	-2.65E-02	-4.73E-02	-0.1091	-0.10106	-0.14667	0.752315	0.482099	0.00E+00	6.498471	-0.50484	3.573417	-3.51451	-2.26E-03	-1.12E-03
14	-4.34E-02	-2.57E-02	-2.80E-02	-7.17E-02	-0.2658	-0.35305	-0.61217	-1.1998	-1.05084	1.61E-02	10.7056	20.08556	73.66549	0.00E+00	1.295882	-8.92E-05	-8.36208	-3.46E-02	-1.63E-02
15	-902.952	-211.989	-185.684	-281.392	-374.264	-168.172	-155.319	155.3192	168.1717	374.2637	281.3915	185.6842	211.9884	902.9525	0.00E+00	877.9004	121.7657	-877.903	-121.766
16	-3.86E-02	-2.30E-02	-2.53E-02	-6.22E-02	-0.2297	-0.30251	-0.52331	-1.00075	-0.86835	1.39E-02	7.894438	13.22104	44.10829	-1.97E-03	-51.9951	0.00E+00	42.85628	-2.84E-02	-1.26E-02
17	-1.16E-02	-6.37E-03	-6.21E-03	-1.74E-02	-6.58E-02	-8.83E-02	-0.15916	-0.37738	-0.3478	-0.7256	-1.14078	-5.11816	-21.1885	-24.6379	-2.79949	-25.7018	0.00E+00	-6.73E-03	-4.09E-03
18	2.17E-03	-44.1089	-13.2201	-7.8941	-1.28E-02	0.868087	1.001783	0.523328	0.302004	0.229553	6.25E-02	2.54E-02	2.33E-02	3.79E-02	51.99589	2.98E-02	1.48E-02	0.00E+00	-42.8555
19	24.63774	21.19065	5.119051	1.140182	0.726128	0.347634	0.377683	0.158167	8.84E-02	6.60E-02	1.81E-02	6.42E-03	6.48E-03	1.09E-02	2.798986	8.14E-03	4.61E-03	25.70094	0.00E+00

Attachment A

Email from Jim Chrzanowski 11/7/2011

Below are the copper conductor strength values that Luvata can provide the OH conductor. Please review let me know whether I can move forward with this order.
Jim

Tensile Strength min. PPPL requested: 36-38 ksi / Luvata Proposal: 33 000 psi (min. 227 N/mm2)

Yield 0,5 % Strength: PPPL Requested: 28-30 ksi / Luvata Proposal: 29 000 - 36 000 psi (200-250 N/mm2)

Elognation A 5 min 25 %

Hardness max.: PPPL Requested: 60-70 HRF / Luvata Proposal ; 81 HRF (max. 90 HV)

Attachment B
NTFTM Input Files

```
               ! un01.txt
zero
egrp
0
ngrp
0
pfcb
16
1, .3246 , 1.5906 , .0625 , .4634 ,4,10   ! PF1aU
2, .4003 , 1.8042 , .0338 , .1814 ,4,4   ! PF1bU
3, .5504 , 1.8136 , .0375 , .1664 ,4,4    ! PF1cU
4, .79920 , 1.89305 , .1627 , .1488999 ,4,4     ! PF2U
5, 1.4945 , 1.59305 , .1864 , .1489 ,4,4    ! PF3U
6,  1.8065 , .8541 , .1153001 , .1489 ,4,4  ! PF4U
7,  2.012510 , .61505 , .1359 , .1432 ,4,4    ! PF5U
8,  2.012510 , -.61505 , .1359 , .1432 ,4,4   ! PF5L
9,  1.8065 , -.8541 , .1153001 , .1489 ,4,4 ! PF4L
10, 1.4945 , -1.59305 , .1864 , .1489 ,4,4    ! PF3L
11, .79920 , -1.89305 , .1627 , .1488999 ,4,4  ! PF2L
12, .5504 , -1.8136 , .0375 , .1664 ,4,4      PF1cL
13, .4003 , -1.8042 , .0338 , .1814 ,4,4   ! PF1bL
14, .3246 , -1.5906 , .0625 , .4634 ,4,10   ! PF1aL
15, .243,0,.0655,4.24,8,36 !OH
16, .9344 , 0 , .5696 , 1 ,6,8   !Plasma
!  NSTX coil axisymmetric analysis
!copt
!r
!plce
!pl
snal
1
seal
1
grpmat
1,17
irdt
2
pfcu
16,17,1,1.0
1,.064,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
2,0,.032,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
3,0,0,.020,0,0,0,0,0,0,0,0,0,0,0,0,0,0
4,0,0,0,.028,0,0,0,0,0,0,0,0,0,0,0,0,0
5,0,0,0,0,.030,0,0,0,0,0,0,0,0,0,0,0,0
6,0,0,0,0,0,.017,0,0,0,0,0,0,0,0,0,0,0
7,0,0,0,0,0,0,.024,0,0,0,0,0,0,0,0,0,0
8,0,0,0,0,0,0,0,.024,0,0,0,0,0,0,0,0,0
9,0,0,0,0,0,0,0,0,.017,0,0,0,0,0,0,0,0
10,0,0,0,0,0,0,0,0,0,.030,0,0,0,0,0,0,0
11,0,0,0,0,0,0,0,0,0,0,.028,0,0,0,0,0,0
12,0,0,0,0,0,0,0,0,0,0,0,.020,0,0,0,0,0
13,0,0,0,0,0,0,0,0,0,0,0,0,.032,0,0,0,0
14,0,0,0,0,0,0,0,0,0,0,0,0,0,.064,0,0,0
15,.884,.884,.884,.884,.884,.884,.884,.884,.884,.884
,.884,.884,.884,.884,.884,.884,0,0
16,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,.001,0,0
17,   ! TF
```

```
               ! un01.txt (Continued)
snal
1
merge
1,.0001
redu
seal
1
egrp
7
ngrp
7
ccur
1,1,2,3,4,0,0,0,0
smat
10,1
snel
1,1
sfield
1
stype
7,7
gerase
7
redu
fscale
1,.0001,.0001,.0001
smat
10,10
mfor
1,1,2,3,4,0,0,0,0
!1,1,2,3,4,1,2,3,4
seal
1
srel
16,16
gerase
16
redu
repla
un01
tmsa
un01,2
zecp
exit
```

```
   Muni.txt

macro
un01
macro
un02
macro
un03
macro
un04
macro
un05
macro
un06
macro
un07
macro
un08
macro
un09
macro
un10
macro
un11
macro
un12
macro
un13
macro
un14
macro
un15
macro
un16
macro
un17
macro
un18
exit
```