NSTX Upgrade

PF2 and PF3 Coils and Support Analysis

NSTXU-CALC-12-04-00

Rev 0

March 2011

Prepared By:

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Peter Titus, PPPL Mechanical Engineering

Reviewed By:

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Irving Zatz, PPPL Mechanical Engineer

Reviewed By:

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Mark Smith, Cognizant Engineer

PPPL Calculation Form

Calculation # **NSTXU-CALC-12-04-00** Revision # 00 ___ WP #, 1672
(ENG-032)

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

To qualify the existing PF2 and 3 coils and their supports for the upgrade loads

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

Included in the body of the calculation

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

A number of different analyses are used to qualify different attributes of the coils and their supports. The analyses are tailored to the coil or support stress of interest and are approximate with respect to others. A cyclic symmetry model is used to address the coil/support assembly including the vessel and vessel ribs. This model is only approximate with respect to the non-uniform array of supports - There are 11 PF 3 supports in what would have been a 12 fold symmetry with respect to the TF coils. Another model addresses the non-uniform array of supports but assumes the vessel dome is rigid. Another model assumes cyclic symmetry but models the PF3 bracket weld in detail. Many detailed analyses use a representative scenario for calculations and assume that the stresses may be scaled from the vertical load calculated for the latest scenarios in the design point, and through the DCPS, the operating currents.

Calculation (Calculation is either documented here or attached)

See the Body of the calculation

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

Stresses in the coils are relatively low. Hoop stress due to the radial loading is small. Stresses are predominantly driven by coil bending due to the vertical load and the spans created by the discrete supports. Coil stiffness is sufficient to transmit only a small portion of the bending moments to the supports and clamps. Coils and support hardware meet the requirements of the NSTX structural criteria with the exception that the 1/8 inch fillet welds used on the PF3 support are still judged unacceptable with respect to the AWS, AISC and ASME criteria for min weld size for given plate thicknesses. The Stainless section of the AWS code is under review and didn't offer relief. Tests are under way by the project to qualify the use of the small welds, but the stresses around the bolt holes are still too high for 1/8 fillets and the welds should be upgraded. ASTM A193 B8M class 2 bolts are recommended as a replacement for all the generic 316 bolts currently used in the supports.

Cognizant Engineer's printed name, signature, and date

Mark Smith ______________________________

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

Checker's printed name, signature, and date

Irving Zatz ______________________________

2.0 Table of Contents
NSTX PF 2 and 3 Coils and Supports

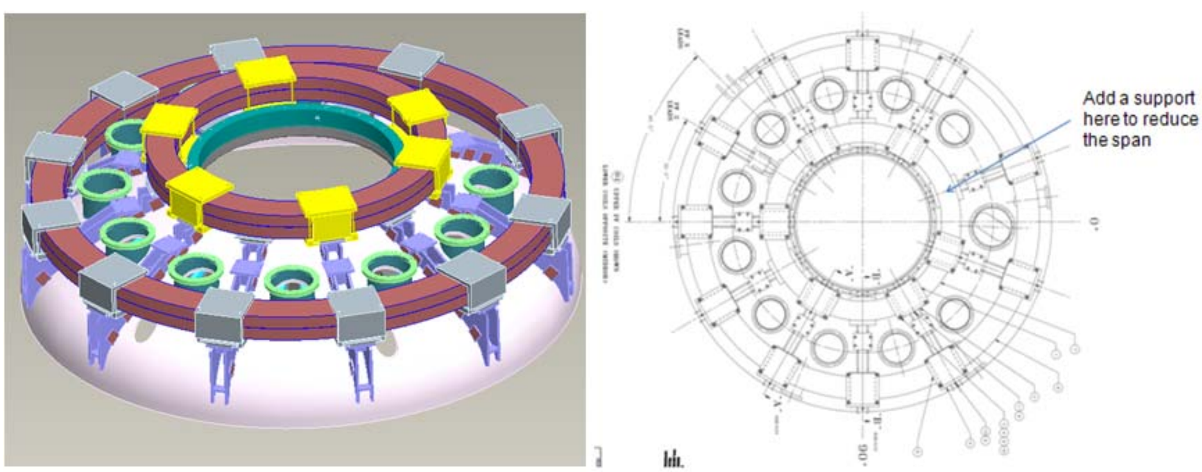
3.0 Executive Summary:

Stresses in the coils are relatively low. Hoop stress due to the radial loading is small. Stresses are predominantly driven by coil bending due to the vertical load and the spans created by the discrete supports. Coil stiffness is sufficient to transmit only a small portion of the bending moments to the supports and clamps. Coils and support hardware meet the requirements of the NSTX structural criteria with the exception that the 1/8 inch fillet welds used on the PF3 support are still judged unacceptable with respect to the AWS, AISC and ASME criteria for min weld size for given plate thicknesses. The stainless steel section of the AWS code was reviewed and the small welds are not acceptable in this section of the code. Sample 1/8 fillet welds were tested on the larger stock and found to develop the appropriate strength using the usual calculations of shear on the throat . Figure 8.1-6 shows some of the test results. Local weld stresses around the bolt holes remain high and require reinforcement.

PF 2 and 3 are supported on sliding plate supports that are lubricated with Magnaplate. The sliding surfaces are primarily intended for the bake-out differential thermal growth of the vessel. Hoop strains produce minimal radial expansion. For PF 2 and 3, bolt stresses for the net vertical loading in the coils are being checked to qualify the coil supports and coil stresses (vertical meaning upward for the upper PF2/3 and downward for the lower PF2/3). This is based on the expectation that there is a large margin in the hoop stresses in the coils, and centering loads are taken by compressive loads into the support plates and ribs,- and that the centering loads produce low stresses. Traditionally, NSTX has not checked coil hoop stresses in the existing coil protection system. Only vertical loading has been addressed. Part of the purpose of this calculation is to re-visit this assumption.

Low hoop and support stresses have been shown with a three dimensional model of the coils vessel domes and ribs. The coil pancakes and individual conductors and insulation are modeled. Other structures besides the PF2/3 supports are not included in order to isolate the effects of the PF2 and 3 loads. Representative scenarios are selected for the Lorentz load calculation Coil and vessel stresses are very low, justifying the limited stress and bolt load checks recommended for the Digital Coil Protection System (DCPS).

PF2 is currently supported at 6 places with brackets that use four 1/2-inch bolts or studs to clamp the coil. For the worst case upward vertical load, the bolt axial P/A stress is 47150/6/4/.1416=13,830 psi for the 96 scenario [4] max tensile load (see Section 5.5 for a Design Point Load Summary) This is true if the brackets are evenly distributed at 6 locations, but, in reality, the brackets are not evenly distributed. An additional support has been recommended to help with the uniformity of loading, but even with the extra support, loads vary around the perimeter of the coil.



Current (2010) locations of the PF2 supports, and the proposed location of the seventh support

Figure 3.0-1 Existing PF 2 Supports - PF2 Supports are in Yellow

Currently, there is one span that is approximately 90 degrees. This would distribute the bolt loads more like Fvert/4/4 rather than Fvert/6/4. There would be some rotation as well that might change the loads in the bolt pattern at the clamp. This has been considered in a 360 degree model of the coil and support system. This could probably be qualified to the 96 scenario loading, but would have no margin for faulted loads or any headroom for the DCPS. From table 5.5-1 the max load is 47456 lbs. 47456/4/4/.1416 = 20 ksi, which is acceptable for standard bolts. The design load went down in the later design point, Table 5.5-4. An analysis of the toroidal distribution of loading on one side of the clamp vs. the other side (i.e., the rotation effect) was carried out in section 7.6. The toroidal variation in loading was found to be 105 lbs.

If the seventh support is added, then one side looks like Fvert/6/4 and the other side looks like Fvert/8/4. The actual non-uniformity in support distribution was analyzed for one of the scenarios and the effective number of supports is 5.32 supports:

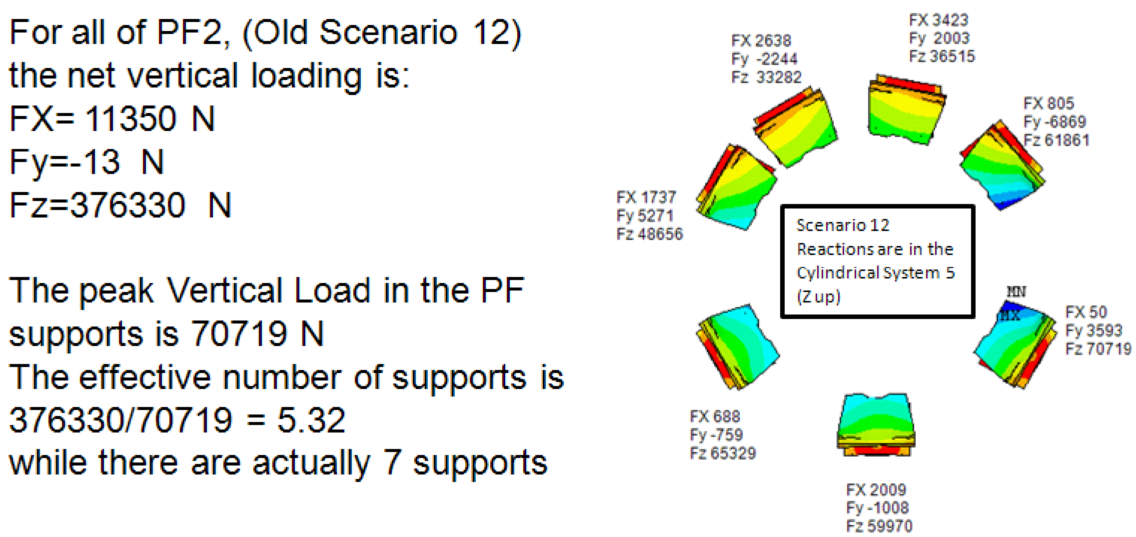


Figure 3.0-2 Effective Number of Supports

The model with the actual support arrangement is discussed in section 6.2. Bolt stress is then 47456/5.32/4/.1416 = 16ksi. This is within the capacity of many studs, but the studs are a generic 316 SS. Replacing the studs with a known material with a sufficient yield to allow 16 ksi or above is recommended. The bolts should be preloaded above this level to avoid any significant cycling.

The PF2 weld drawing shows 3/16 inch fillets as under the PF2 support plate. With a weld efficiency of .7 the allowable for a fillet is 14ksi, (96 MPa). The plate is 9 inches long. There are four 3/16 inch fillets for a total weld area of 4*9*3/16*.707 = 4.77 square inches per pad. There are effectively 5.23 pads. This would produce a capacity of 5.23 * 4.77* 14,000 = 450,000 lbs. This would even satisfy the worst case power supply loading.

PF3 support pads are also distributed non-uniformly. For the same scenario 12 used for PF2, the net vertical load is 3619 lbs or 16103N. The maximum individual support load is 1782 N and the effective number of supports is 9, while there are actually 11 supports. PF3 is supported with brackets that use 4 1/2 inch bolts or studs to clamp the coil. The bolt P/A stress is 98989/9/4/.1416=19418psi. There are actually 2 sets of bolts needing qualification, the coil clamp bolts and the welded plate to sliding block bolts. They see the same loads, and they are both the same diameter. To be sure the bolts have appropriate properties, the generic 316 bolts should be replaced with a spec that guarantees the necessary properties. ASTM A193 B8M Class2 bolts are recommended.

	Old Scenario 12	Design Point [4] Latest Max Load
PF2 Net Vertical Load lbs Old Scenario 12	84600;	-51374 Lbs (Section 5.5)

PF2 Coil Stress	31.8MPa	19.3 MPa
PF2Insulation Shear	5 MPa	3 MPa
PF3 Net Vertical Load Old Scenario 13	-133009 (Section 6.3)	-138527Lbs (Section 5.5)
PF3 Coil Stress	9 MPa	9.5 MPa
PF2 Insulation Shear	4.5 (conservatively assumed 1/2 of Tresca)	5 MPa

4.0 Digital Coil Protection System Input

Conceptual design of the upgrade to NSTX explored designs sized to accept the worst loads that power supplies could produce. Excessive structures resulted that would have been difficult to install and were much more costly than needed to meet the scenarios required for the upgrade mission, specified in the General Requirements Document (GRD). Instead the project decided to rely on a digital coil protection system (DCPS).

Two approaches are used to provide the needed multipliers/algorithms.

The first is to use the loads on PF coils computed by the DCPS software and apply these to local models of components. For PF 2 and 3, this translates into checking the bolt stresses for the launching loads. It is usual practice to utilize influence coefficient calculations to determine hoop and vertical loads from coil currents. However, the centroid of the Lorentz loads may not be at the geometric center of the coils, and a moment about a geometric center of the coil may be produced.

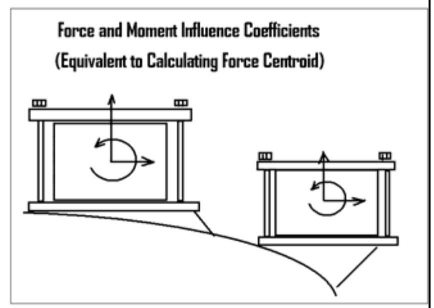


Figure 1-Force and Moments from PF Current Influence Coefficients

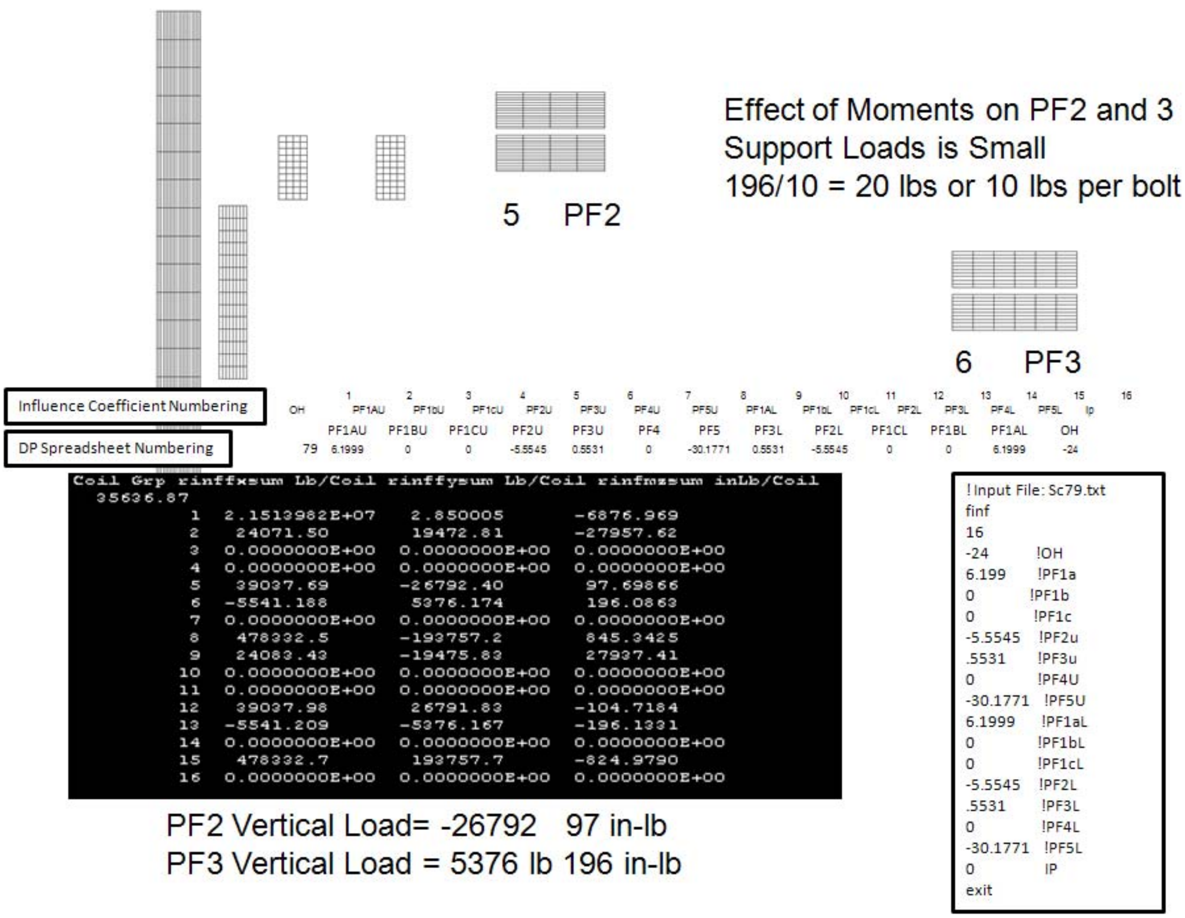


Figure 4.0-1 Results from Reference [1] NSTX Upgrad**e** Moment Influence Coefficients NSTXU-CALC-13-05-00Rev 0**,** Peter Titus, January 18 2011

Moment effects for PF2, and 3 have been found to be small and probably be neglected, but the effect is included in the DCPS multiplier table.

PF2/3 DCPS Multipliers

Location/Component	Stress Limit	Fvert (lbs)	Mtheta (in -lbs)
PF2 1/2 inch Bolts	47,000 psi*	/5.23/4/.1416	/5.23/8in/2/.1416
PF2 Plate to Rib Weld			
PF3 Lower 1/2 inch Bolts	47,000 psi	/9/4/.1416	/9/8in/2/.1416
PF3 Plate to Rib Weld			

*Or as specified for replacement studs. If these are all ASTM A193 B8M Class 2 Bolts then the allowable would be the lesser of 125/3 or 2/3*100 =41.7 ksi

5.0 Design Input

5.1 Criteria

Coil and structural criteria are outlined in "NSTX Structural Design Criteria Document", Zatz[3]

5.2 References

[1] NSTX Upgrad**e** Moment Influence Coefficients NSTXU-CALC-13-05-00Rev 0**,** Peter Titus, January 18 2011

[2] NSTX-CALC-13-001-00 Rev 1 Global Model – Model Description, Mesh Generation, Results, Peter H. Titus March 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] OOP PF/TF Torques on TF , R. Woolley, NSTXU CALC 132-03-00

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

[7] OH Conductor Fatigue Analysis NSTXU-CALC-133-09-00 Rev 0 Jan 7 2011 Peter Titus, PPPL

[8] April 5 2011 email from Jim Chrzanowski: PF 2,3,4,5 are all mylar wrapped then bstage with fusifab

[9] email from C. Neumeyer , Mar 29, 2011 providing explanation of temperature specs in the Design Point Spreadsheet,

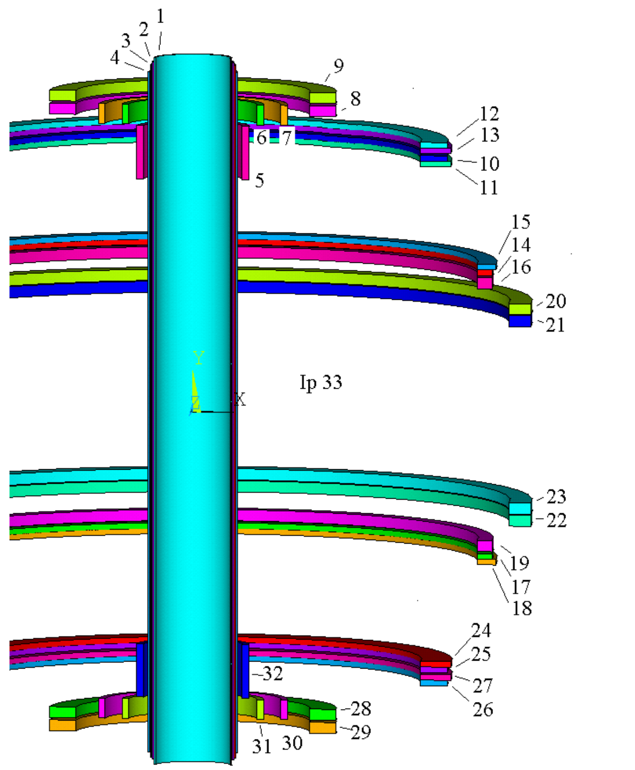


Figure 5.2-1 Real Constants from ref [2]. PF 2 is 8, and 9, PF3 is 10,11,12,13.

5.3 Coil and Support Geometry

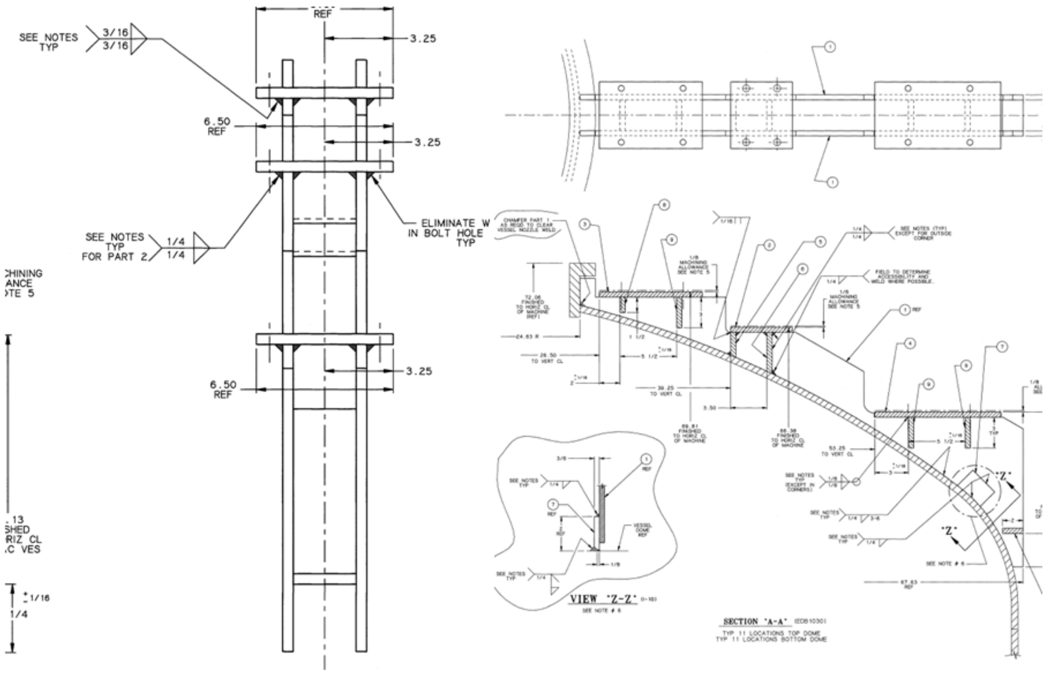
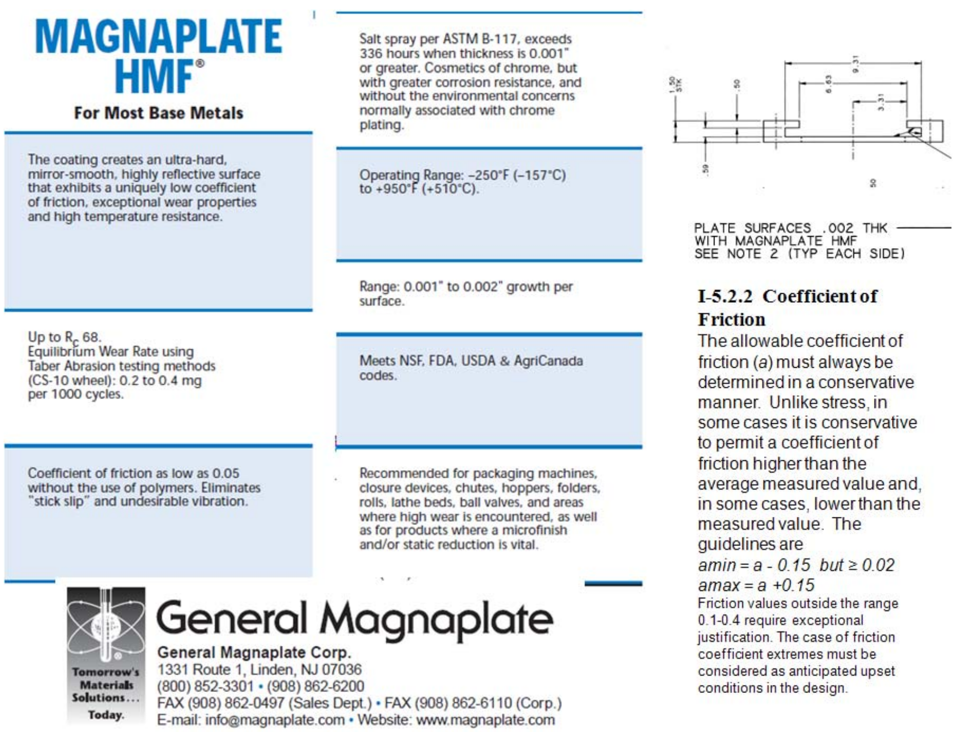


Figure 5.3-1 Vessel Rib and Coil Support Pedistal



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I-5.2.2 Coefficient of Friction

The allowable coefficient of friction (*a*) must always be determined in a conservative manner. Unlike stress, in some cases it is conservative to permit a coefficient of friction higher than the average measured value and, in some cases, lower than the measured value. The guidelines are

amin = a - 0.15 but ≥ 0.02

amax = a +0.15

Friction values outside the range 0.1-0.4 require exceptional justification. The case of friction coefficient extremes must be considered as anticipated upset conditions in the design.

Figure 5.3-2 Magnaplate Low Friction Material Data

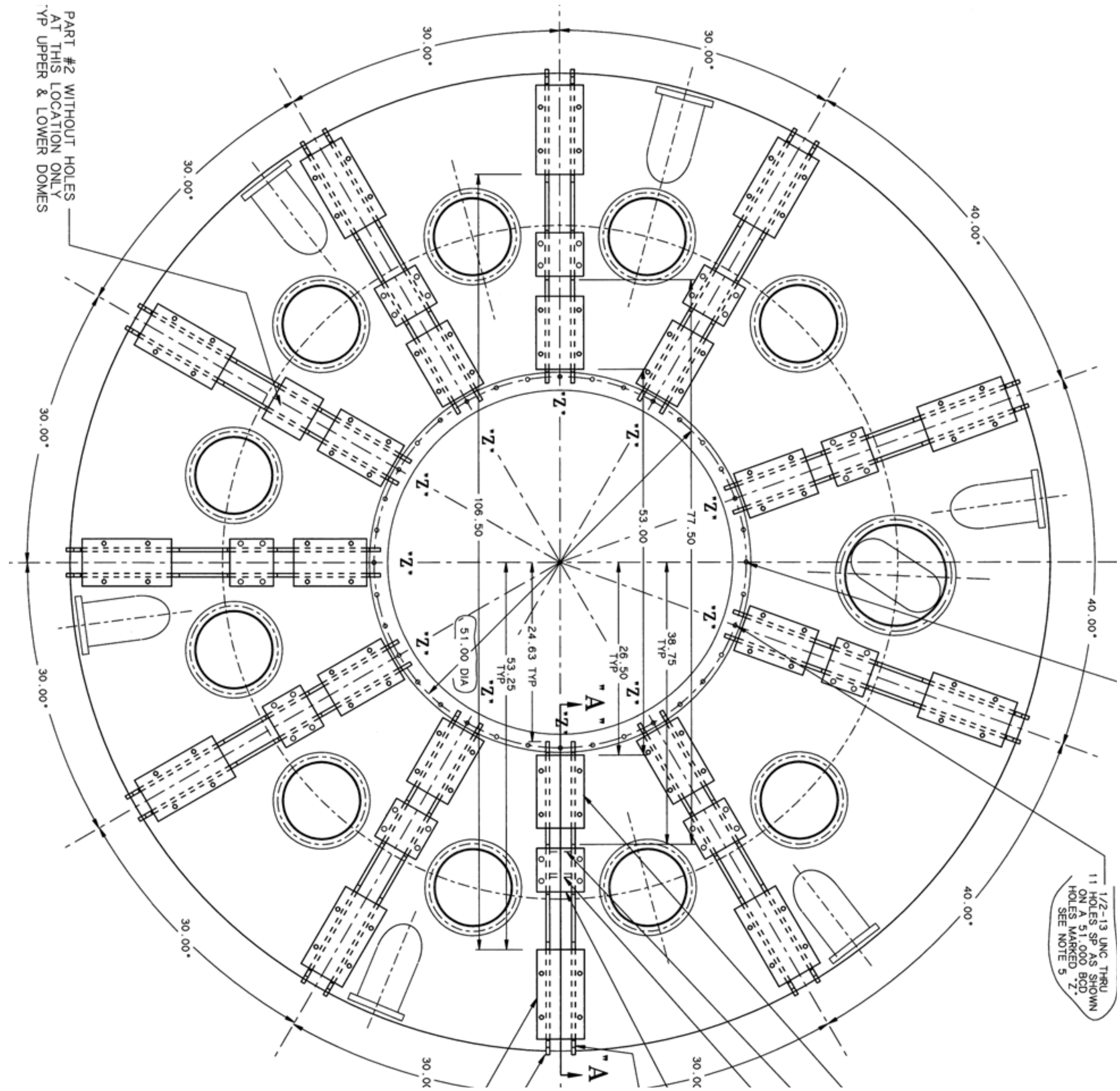


Figure 5.3-3 Vessel Head, Rib and Coil Support Layout

Figure Photo of PF3 Sliding Block

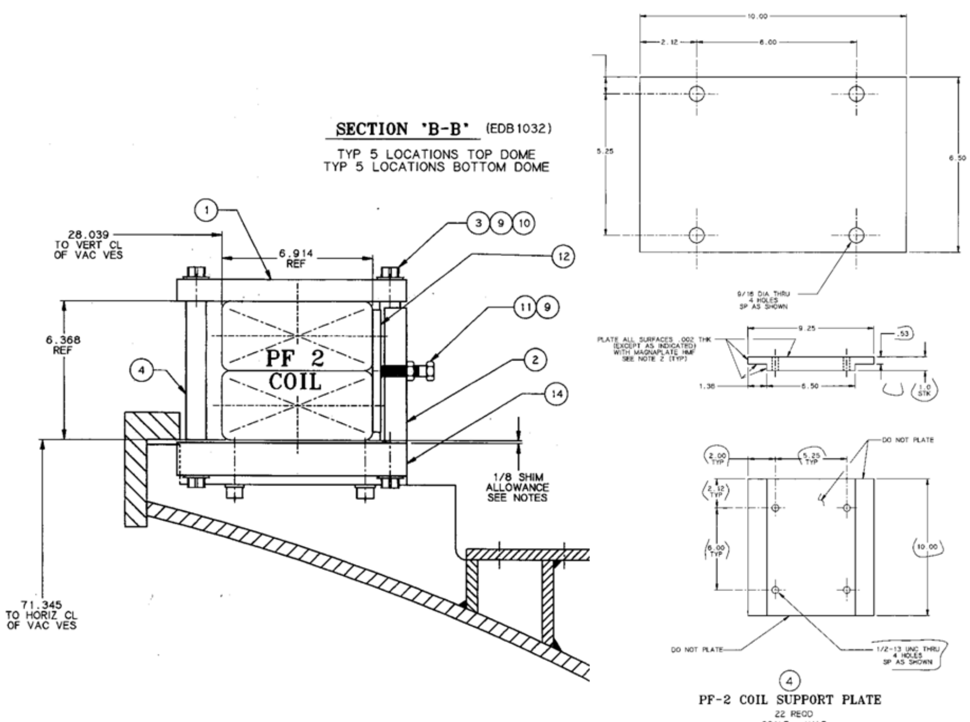


Figure 5.3-4 PF2 Support Details

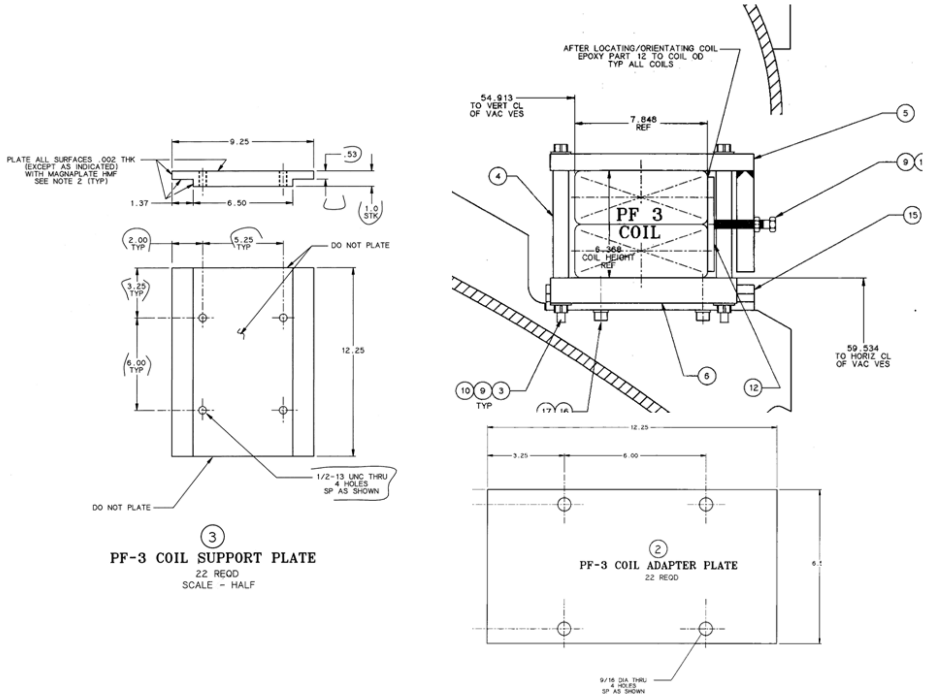


Figure 5.3-5 PF3 Support Details

5.4 Input Currents

Input currents are presented in section 6.1.2 - Fields and Forces. The currents that were used were from an earlier design point spreadsheet, and the resulting loads were compared with the latest design point loads [4]. Load calculations and discussions of the current scenarios that were analyzed are discussed in section 6.1.2

5.5 Loads from the Design Point Spreadsheet

Table 5.5-1 Loads from the June 2010 and earlier Design Points

Fr(lbf)	PF2U	PF2L
Min	-87607	-87589
Worst Case Min	-267618	-267600
Max	104613	104618
Worst Case Max	306925	306936

Fz(lbf)	PF2U	PF2L
Min	-41256	-47456
Worst Case Min	-148494	-151752
Max	47456	40174
Worst Case Max	151752	148525

Fr(lbf)	PF3U	PF3L
Min	-87216	-42300
Worst Case Min	-197744	-197723
Max	254085	254120
Worst Case Max	494121	494159
Fz(lbf)	PF3U	PF3L
Min	-138795	-29778
Worst Case Min	-292108	-219081
Max	99045	138795
Worst Case Max	219081	292108

Table 5,5-2 Loads From the March 2011 Design Point

Fz(lbf)	PF2U	PF2L
Min w/o Plasma	-40938	-47150
Min w/Plasma	-51374	-35660
Min Post-Disrupt	-32928	-47032
Min	-51374	-47150
Worst Case Min	-149606	-152079
Max w/o Plasma	47150	40093
Max w/Plasma	35661	55892
Max Post-Disrupt	47033	37985
Max	47150	55892
Worst Case Max	152080	149636

Table 5.5-3 Loads From the March 2011 Design Point

Fz(lbf)	PF3U	PF3L
Min w/o Plasma	-138527	-29737
Min w/Plasma	-65903	-12660
Min Post-Disrupt	-94339	-43904
Min	-138527	-43904
Worst Case Min	-291685	-218764
Max w/o Plasma	98898	138527
Max w/Plasma	52893	65903
Max Post-Disrupt	92132	94339
Max	98898	138527

Worst Case Max	218764	291685

Table 5.5-4 Loads From the March 2011 Design Point

Fz(lbf)	PF2U	PF2L
Min	-51374	-47150
Max	47150	55892

Table 5.5-5 Loads From the March 2011 Design Point

Fz(lbf)	PF3U	PF3L
Min	-138527	-43904
Max	98898	138527

5.6 Materials and Allowables ASTM A193 Bolt Specs from PortlandBolt.com

B8M	Class 1 Stainless steel, AISI 316, carbide solution treated.
B8	Class 2 Stainless steel, AISI 304, carbide solution treated, strain hardened
B8M	Class 2 Stainless steel, AISI 316, carbide solution treated, strain hardened

Mechanical Properties

Grade	Size	Tensile ksi, min	Yield, ksi, min	Elong, %, min	RA % min
B8 Class 1	All	75	30	30	50
B8M Class 1	All	75	30	30	50
B8 Class 2	Up to 3/4	125	100	12	35
	7/8 - 1	115	80	15	35
	1-1/8 - 1-1/4	105	65	20	35
	1-3/8 - 1-1/2	100	50	28	45
B8M Class 2	Up to 3/4	110	95	15	45
	7/8 - 1	100	80	20	45
	1-1/8 - 1-1/4	95	65	25	45
	1-3/8 - 1-1/2	90	50	30	45

The ASTM A193 B8M Class 2 Bolts would have a Stress Allowable of the lesser of 125/2 or 2/3*100 =47 ksi

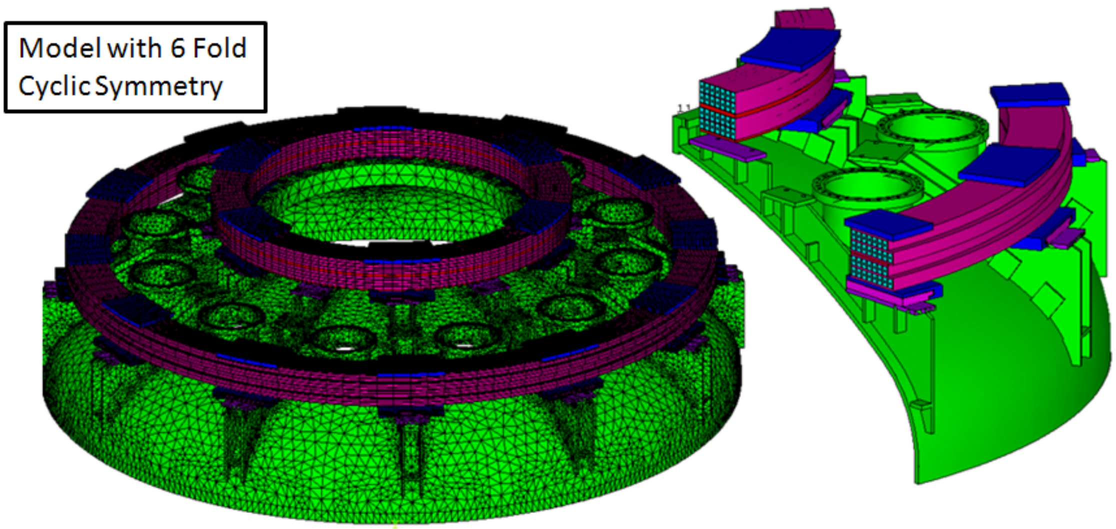
6.0 Analysis Models

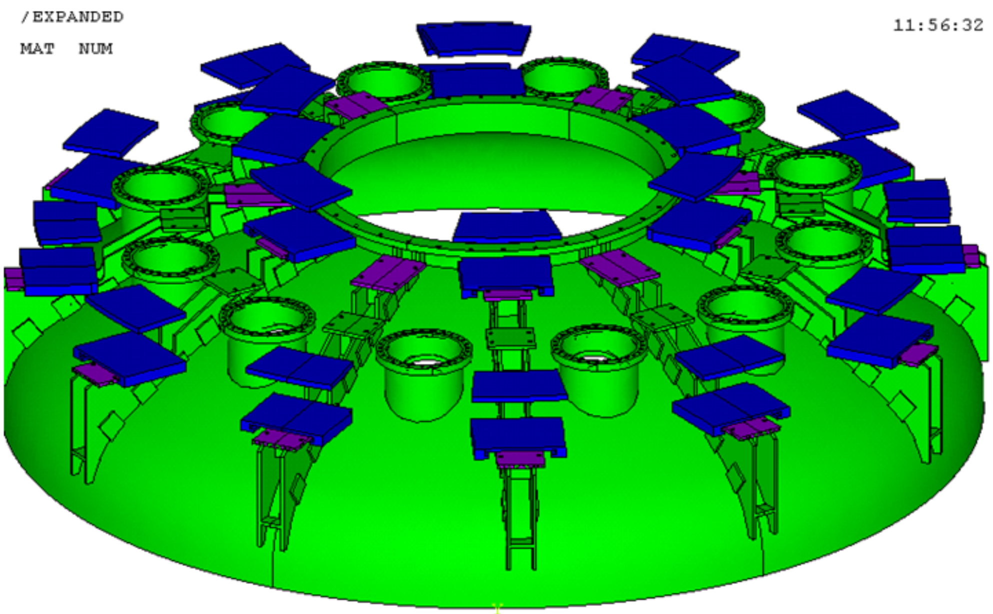
A number of different analyses are used to qualify different attributes of the coils and their supports. The analyses are tailored to the coil or support stress of interest and are approximate with respect to other attributes. A 6-fold cyclic symmetry model is used to address the coil/support assembly including the vessel and vessel ribs. A 60-degree model is needed to model the omitted PF2 supports. This model is only approximate with respect to the non-uniform array of supports. There are 11 PF3 supports in what would have been a 12 fold symmetry with respect to the TF coils. Another model addresses the non-uniform array of supports but assumes the vessel dome is rigid. Another model assumes cyclic symmetry but models the PF3 bracket weld in detail.

6.1 3D Cyclic Symmetry FEA model of PF2 and PF3, Supports and Vessel Head

6.1.1 Model Elements

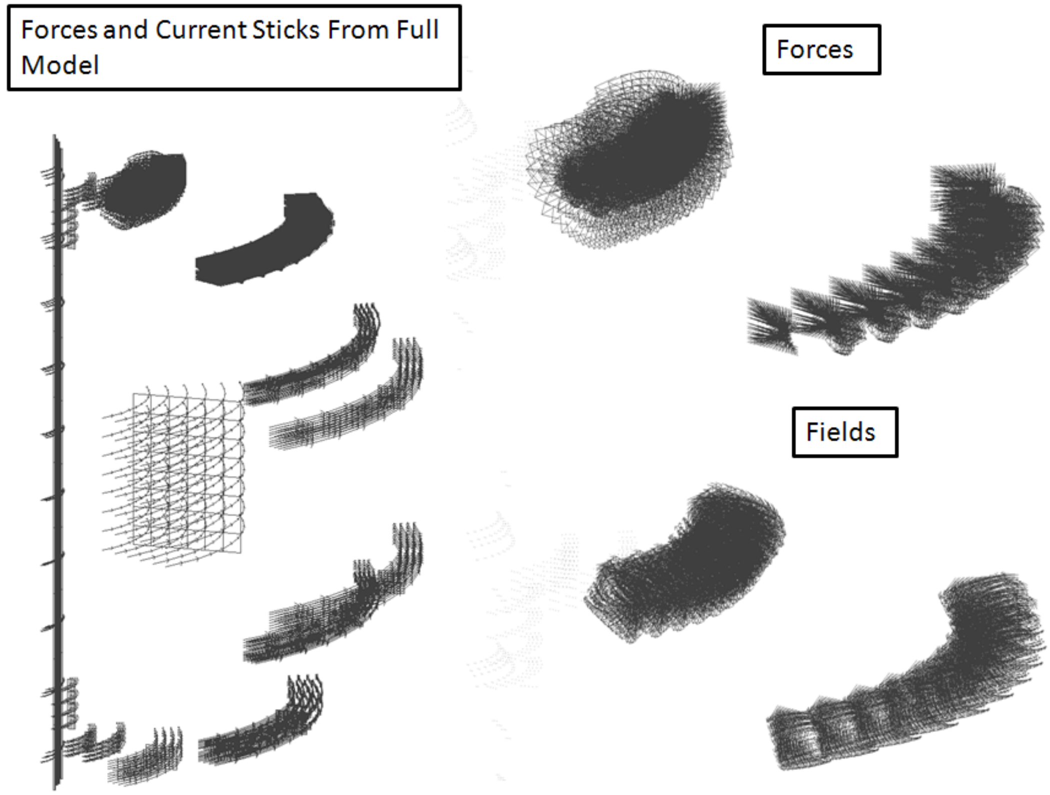
This is a cyclic symmetry model. A 60-degree model is chosen to represent the 6 PF2 supports and 12 PF3 supports in one model. This still is an approximation. The spacing is not uniform and 7 supports are recommended for PF2 to help even out the support spans. The intention of the cyclic symmetry modeling is to demonstrate that the stresses in the coils and supports are low enough that more precise modeling is not necessary.





Model shown with 6 fold symmetry expansion and coils not shown

6.1.2 Fields and Forces



Forces were computed for one of the 96 early +24 -24 kA OH current scenarios. These were used because they were readily available in a form that could be input to the PF2/3 model. In subsequent plots, the loads derived from the earlier design point are labeled "Titus's Loads". The net loads in PF2 and PF3 were then checked against the latest design point spreadsheet (March 2011) to demonstrate that the Lorentz load files were conservative.

6.1.3 Load Sums for Analyzed Scenarios.

PF 2 Scenario 12 Force Sum Vertical Load =-376331N, 84600 lbs

```
fsum
 ENTER node group for Force Summation
0
 FORCE SUMMARY FOR NODE GROUP=          0
 FXSUM=   3.1890869E-03   FXMAX=    76.03780      FXMIN=   -76.03820
 FYSUM=   -376331.1       FYMAX=    45.91640      FYMIN=   -80.05320
 FZSUM=   -1.849776       FZMAX=    76.03960      FZMIN=   -76.03930
 FTMAX=    89.29163       AT NODE        57056  FTMIN=  0.0000000E+00  AT NODE
           0
 MOMENTS ABOUT CENTER, XC=  0.0000000E+00 YC=  0.0000000E+00 ZC=  0.0000000E+00
 MXSUM=   -3.758391
 MYSUM=  -1.7970569E-04
 MZSUM=  -0.1700049
 MTOT=    3.762234
```

PF 3 Scenario 12 Force Sum Vertical Load =-15937N, 3582 lbs

```
fsum
 ENTER node group for Force Summation
1
 FORCE SUMMARY FOR NODE GROUP=          1
 FXSUM=   0.2628288       FXMAX=    55.04350      FXMIN=   -55.04380
 FYSUM=   -15937.21       FYMAX=    33.59840      FYMIN=   -35.40240
 FZSUM=   0.5031844       FZMAX=    55.04310      FZMIN=   -55.04460
 FTMAX=    55.73376       AT NODE         8806  FTMIN=  0.0000000E+00  AT NODE
           0
 MOMENTS ABOUT CENTER, XC=  0.0000000E+00 YC=  0.0000000E+00 ZC=  0.0000000E+00
 MXSUM=    1.495479
 MYSUM=   3.6953792E-03
 MZSUM=  -0.5179467
 MTOT=    1.582637
```

Figure 6.2-3 Load Summary for Analyzed Scenarios

6.1.4 Check of Lorentz Loads and Side Study of Plasma Cross Section Effects.

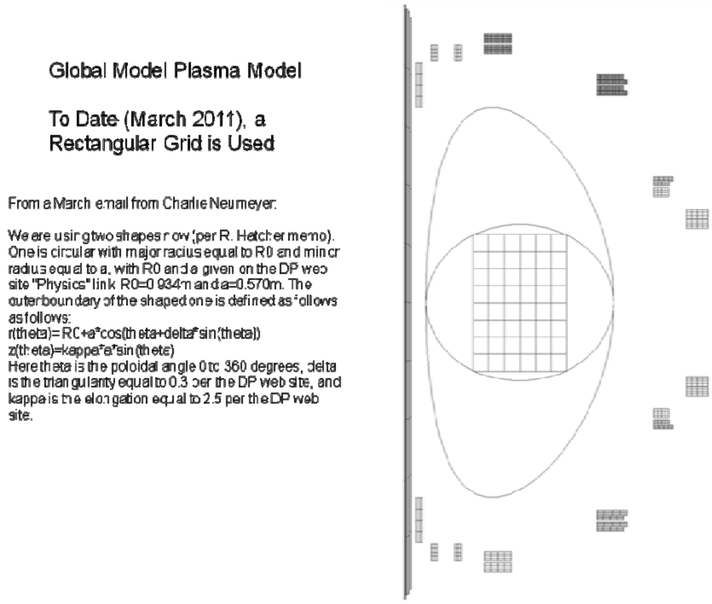


Figure 6.1.4-1 Models of the three Plasma Current Cross Sections

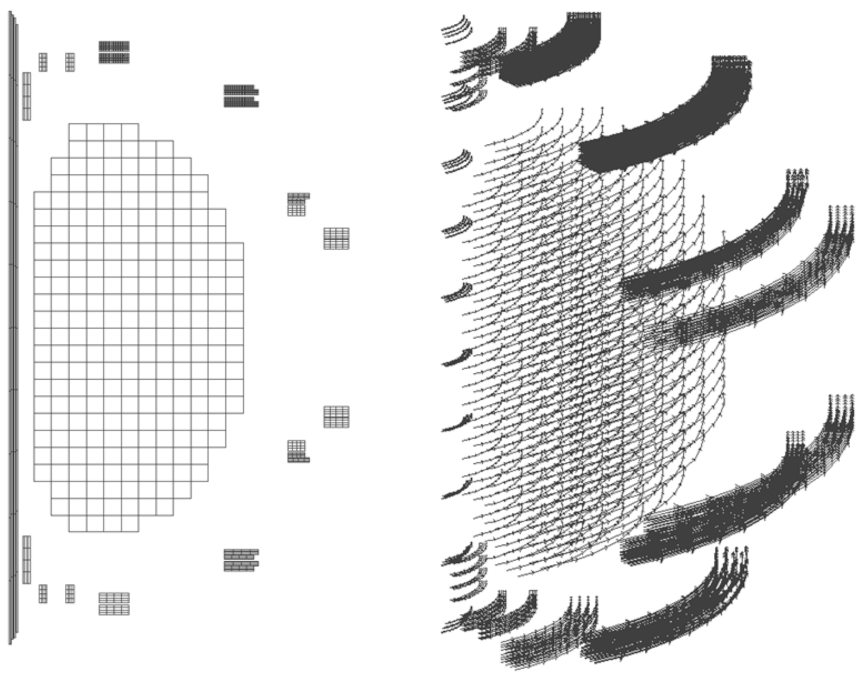
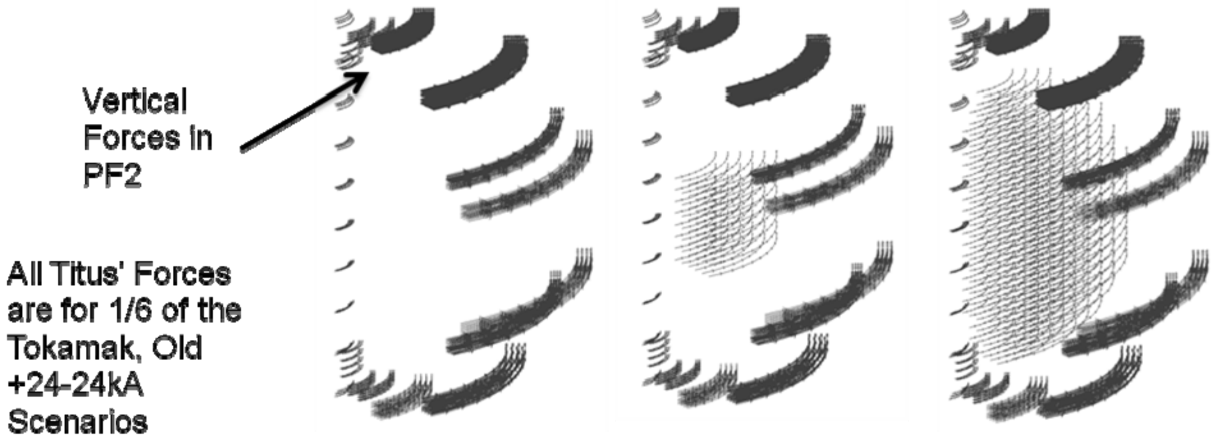
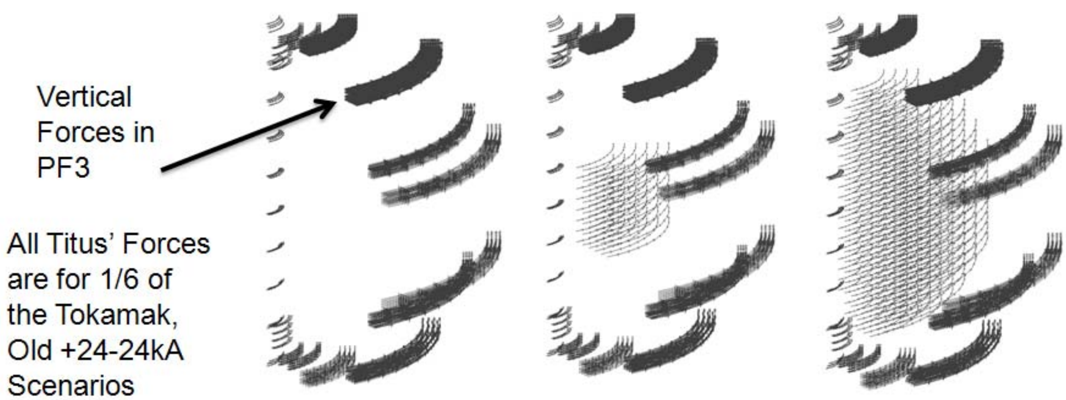


Figure 6.1.4-2 Model of the Shaped Plasma Current Cross Section. Left is the Axisymmetric Coil Cross Section that is swept and then converted to the current sticks shown at right.



	No Ip	Rectangular IP	Full IP
Charlies Min	-30557	-47385	
Data Set 12	-61631 N	-62626	-73099
Data Set 13	+27187	+21059	+17433
Data Set 14	+12949	-140	-7885
Data Set 15	-49232	-69285	

Figure 6.1.4-3 Comparisons of forces from This Biot Savart Analysis of the Three Plasma Cross Section (Labeled "Titus's" Forces) and the updated Design Point Spreadsheet Result [4] (labeled "Charlie's Min")



	No Ip	Rectangular IP	Full IP
Charlies Min	-138538/.2248/6=-102712	65913/.2248/6=-48867	
Data Set 12	-31067 N	-2691	1499
Data Set 13	-98613	-50790	-43729
Data Set 14	-61845	-23313	-17625
Data Set 15	-33870	-4277	

Figure 6.1.4-4 Comparisons of PF3 forces from this Biot Savart Analysis of the Three Plasma Cross Sections (Labeled "Titus's" Forces) and the updated Design Point Spreadsheet Result [4] (labeled "Charlie's Min")

Loads from the Design Point are lower than for "Titus's Loads" This is a consequence of the different scenario values, but the conclusion for loads on PF2 is that plasma shape does not have a strong effect on the loads, and that loads derived from the earlier scenarios are conservative.

6.2 360 degree Model of PF2 and 3 and Supports

This model distributes the support locations according to their actual position on the vacuum vessel. The larger spans are expected to distribute the net loads on the coil from the Design Point Spreadsheet non-uniformly and introduce some asymmetric bending moments that may be reacted by the supports and support bolting.

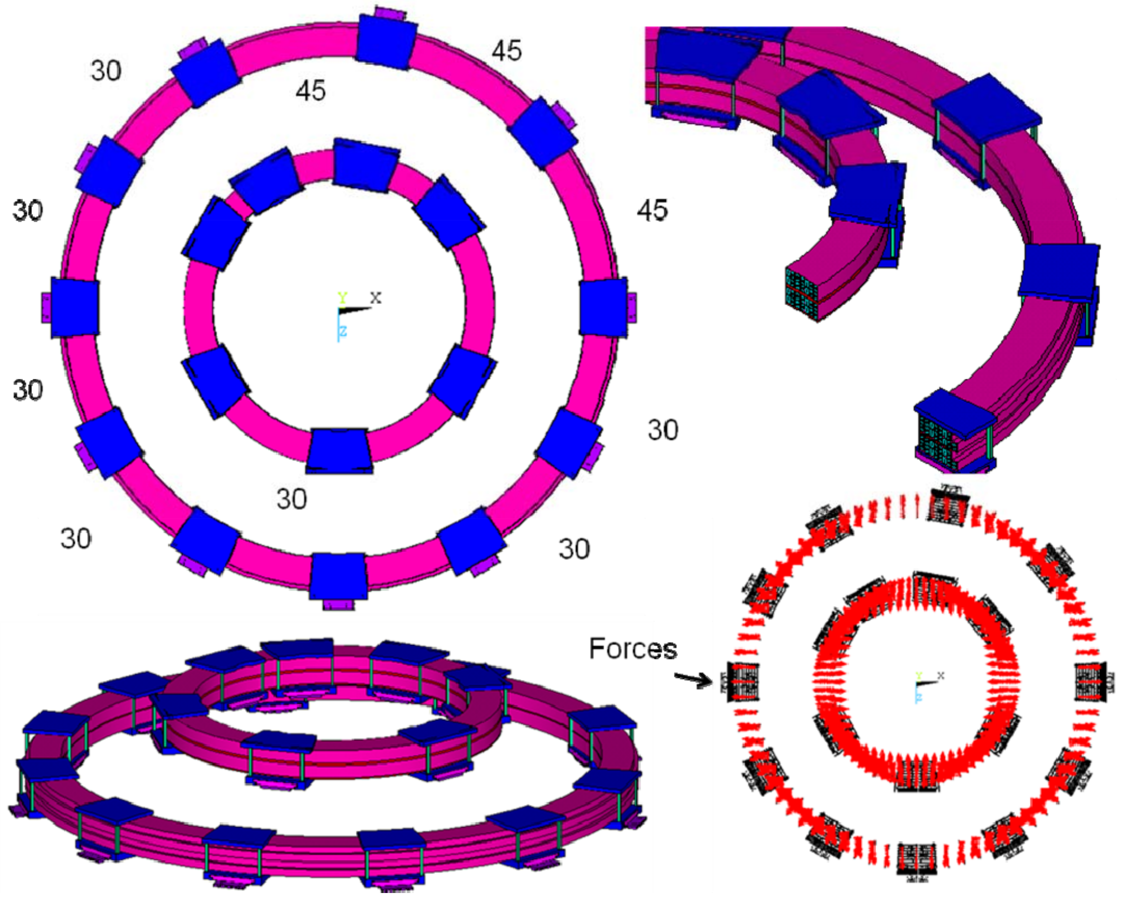


Figure 6.2-1 360 Degree Model

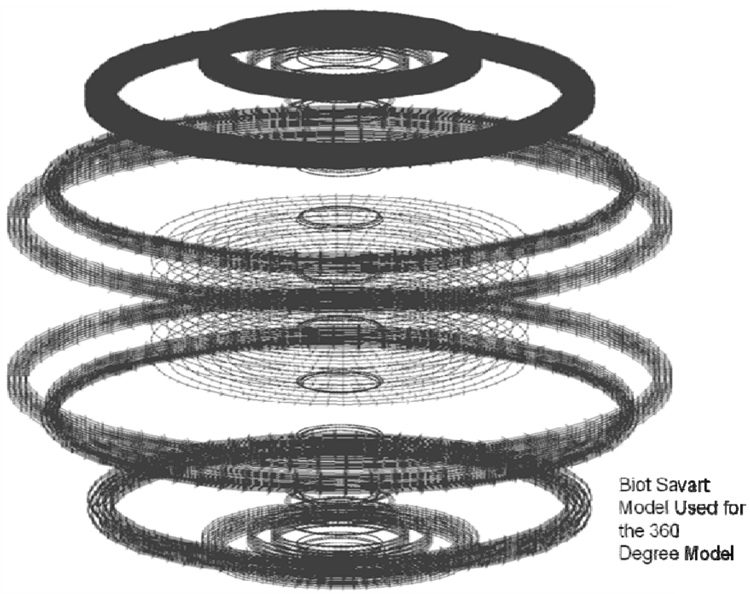
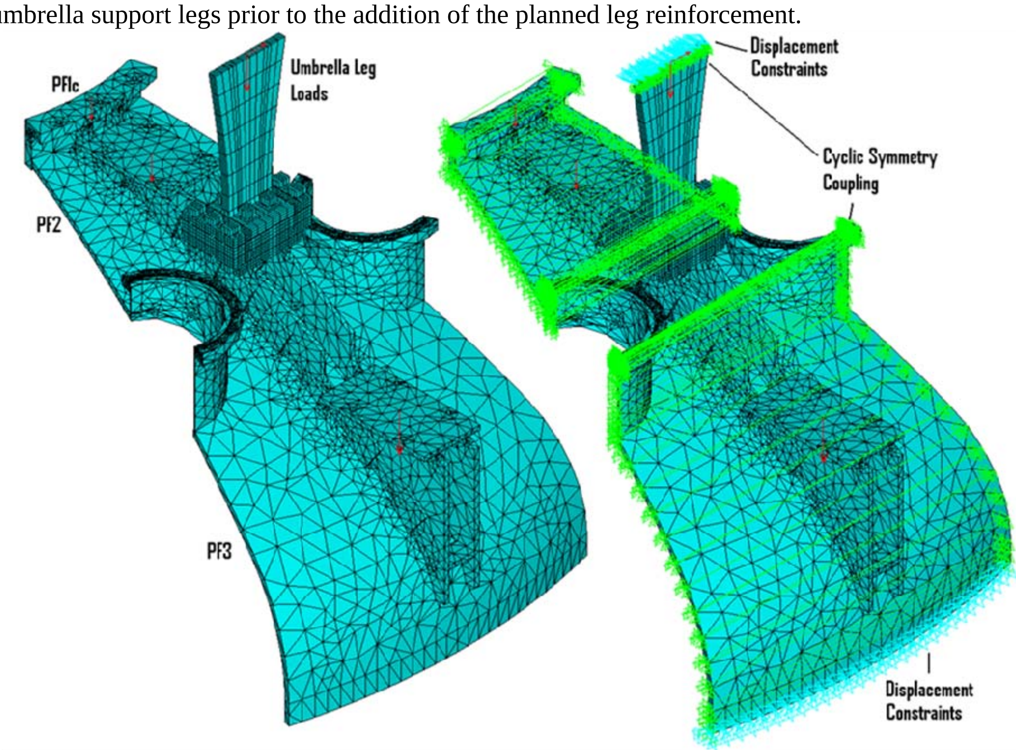


Figure 6.2-2 Biot Savart Model

6.3 Twelve Fold Cyclic Symmetry Model

This model was developed to investigate the PF3 support bracket welds. It includes a representation of the umbrella support legs prior to the addition of the planned leg reinforcement.



12 fold cyclic Symmetry Model that Includes PF coil Loads and Umbrella Sturcture Leg Loads

```
/title,PF2 and PF3 Upper 96 Scenario Vert Loads
bf,all,temp,20
f,985,fz,-30125/12/.2248      !PF1c
f,402,fz,-67757/11/.2248      !PF2
f,4588,fz,-100000     !Umb Foot
f,1237,fz,-148839/11/.2248     !PF3
solve
f,4588,fy,60000
/title,PF4 and PF5 Upper Loads Plus TF OOP Loads
solve
save
/title,OOP Loads Only
bf,all,temp,20
f,985,fz,-.001
f,402,fz,.001
f,4588,fz,.001
f,1237,fz,.001     !PF3
solve
save
/title,PF2 and PF3 Upper Worst Power Supply Loads
bf,all,temp,20
f,985,fz,-168089/12/.2248      !PF1c
f,402,fz,-194414/11/.2248      !PF2
f,4588,fz,-100000     !Umb Foot
f,4588,fy,.001
f,1237,fz,-303940/11/.2248     !PF3
solve
f,4588,fy,60000
/title,PF4 and PF5 Upper Worst Power Supply Loads Plus TF OOP Loads
solve
save
/title,OOP Loads Only
bf,all,temp,20
f,123,fz,-.001     !PF1c
f,409,fz,-.001
f,4588,,fz,.001
f,1277,fz,.001     !PF3
solve
```

6.4 Run Log

The input files and model files for each of the models used are listed below:
Analysis , Input Batch File, Model File

Analysis/Model	Batch File	Model and Load Files
Cyclic Symmetry Model	PF2301.txt	dom4.mod and pf23.mod
360 degree model	Mark01.txt	C:\nstx\CSU\PF2_3\mark2.mod
Local PF3 Weld Model	C:\nstx\csu\dome\Pf3w01.txt	C:\nstx\csu\dome\pf3w,mod

These are located on the P drive at P:\departments\Mech Engr\ptitus\PF2-3

7.0 Results of Coil Models
7.1 Displacement Results

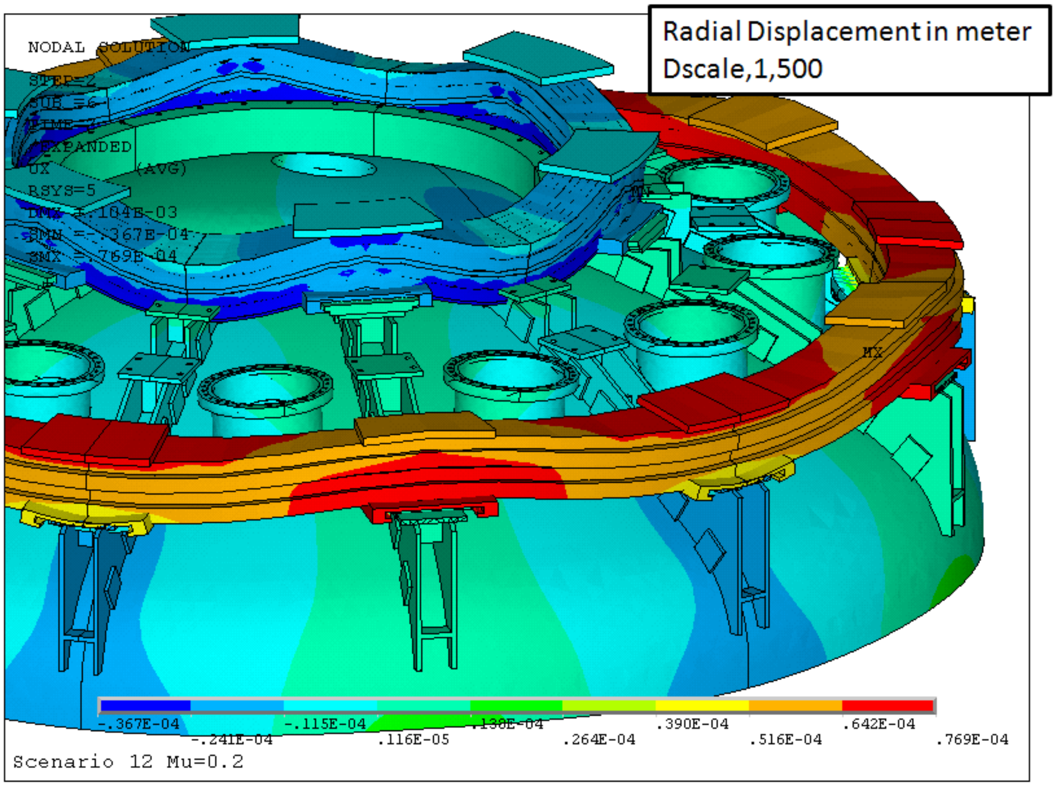


Figure 7.1-1 Radial Displacement in Meters

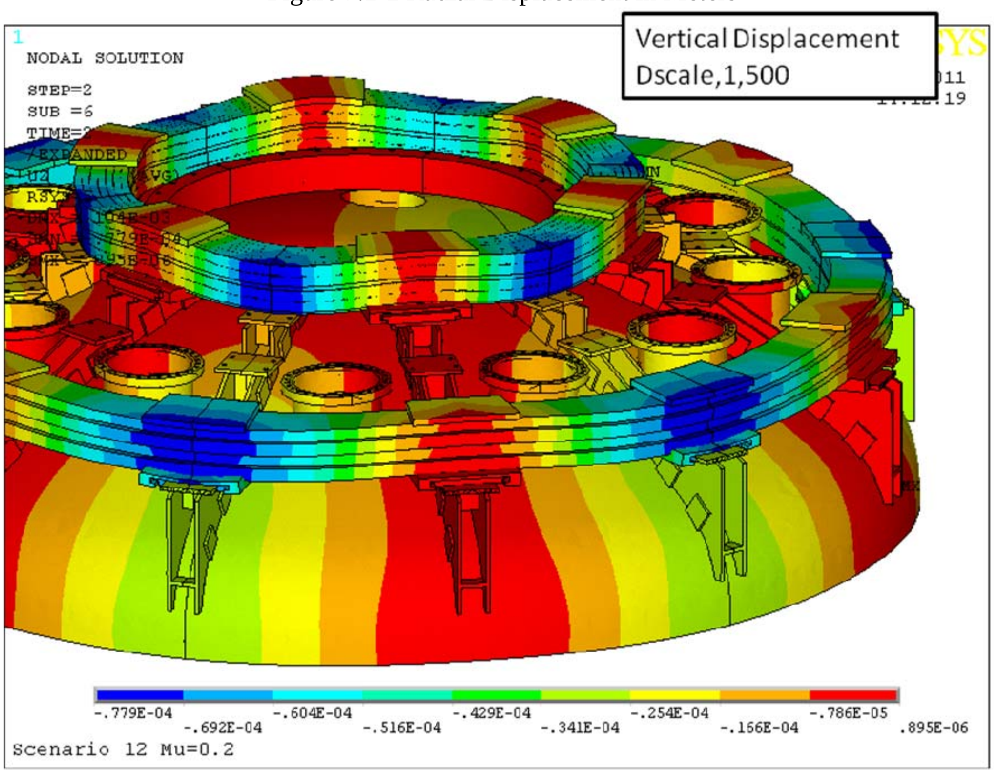


Figure 7.1-2 Vertical Displacement in Meters

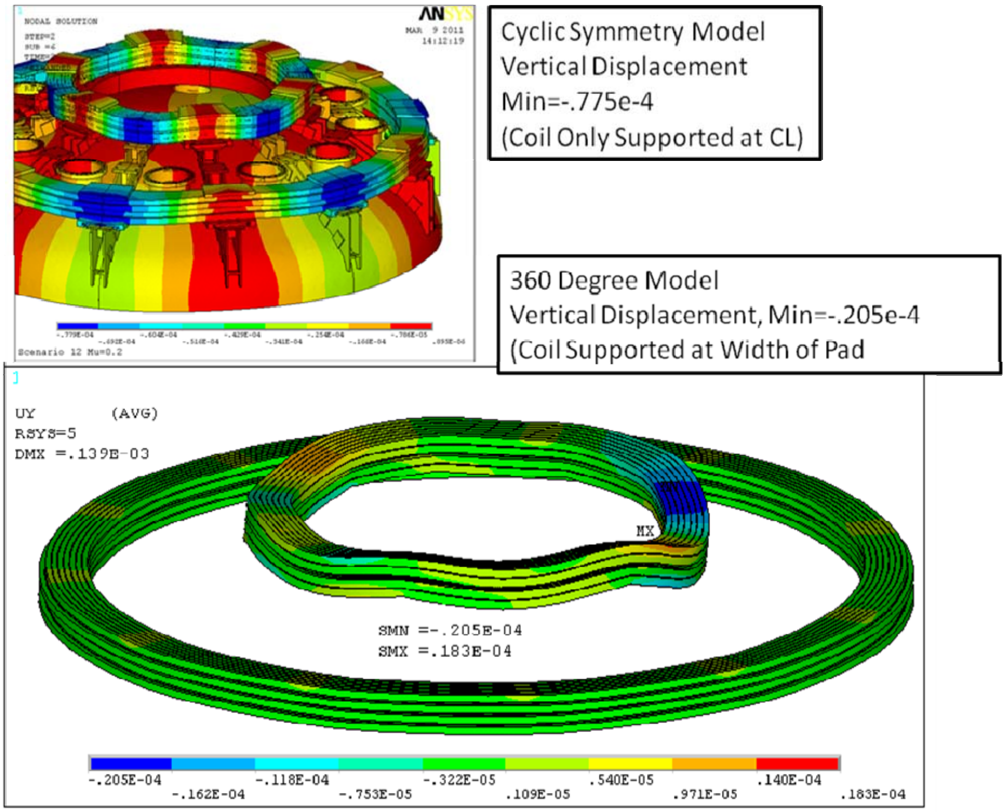


Figure 7.1-3 Comparison of Displacements in Meters for the Cyclic Symmetry And Actual Support Distribution. The distributions are different but the magnitudes are small.

7.2 Coil Stress

PF coil hoop stresses were investigated early in the upgrade project and have been reviewed before, during analyses of the original NSTX coils. Hoop stresses are small and historically were omitted from the coil protection calculator because vertical loading was more significant. Radial loads can be resisted uniformly by hoop stress in the circular coils. The PF coils are self supporting with respect to radial loads and hoop stress. Vertical loads produce bending stresses in the coils and substantial loads on the support hardware.

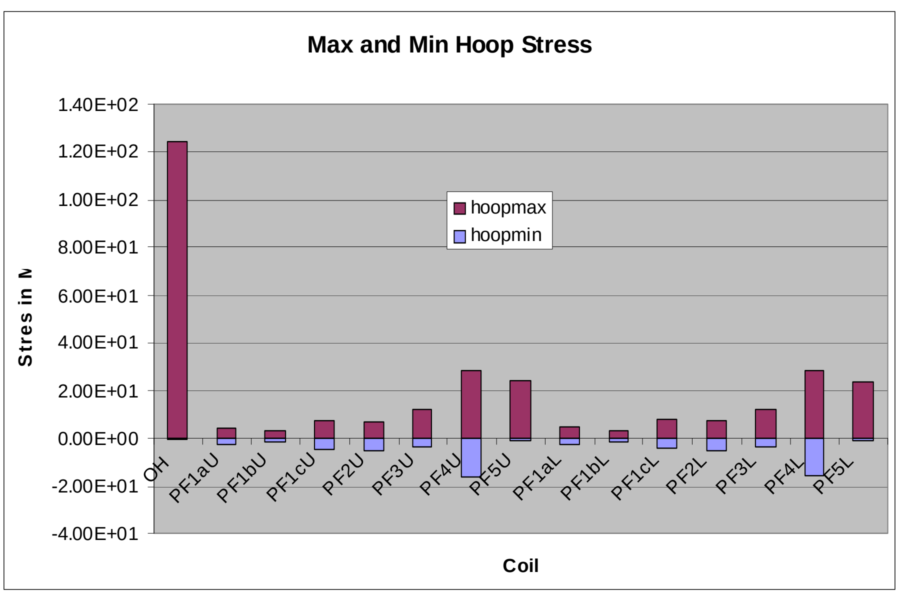


Figure 7.2-1 Early Results for Hoop Stress in the PF Cpols

Hoop Stresses from and an early Monte Carlo simulation of the original 96 scenarios. The character of hoop loading has not changed from the CDR.

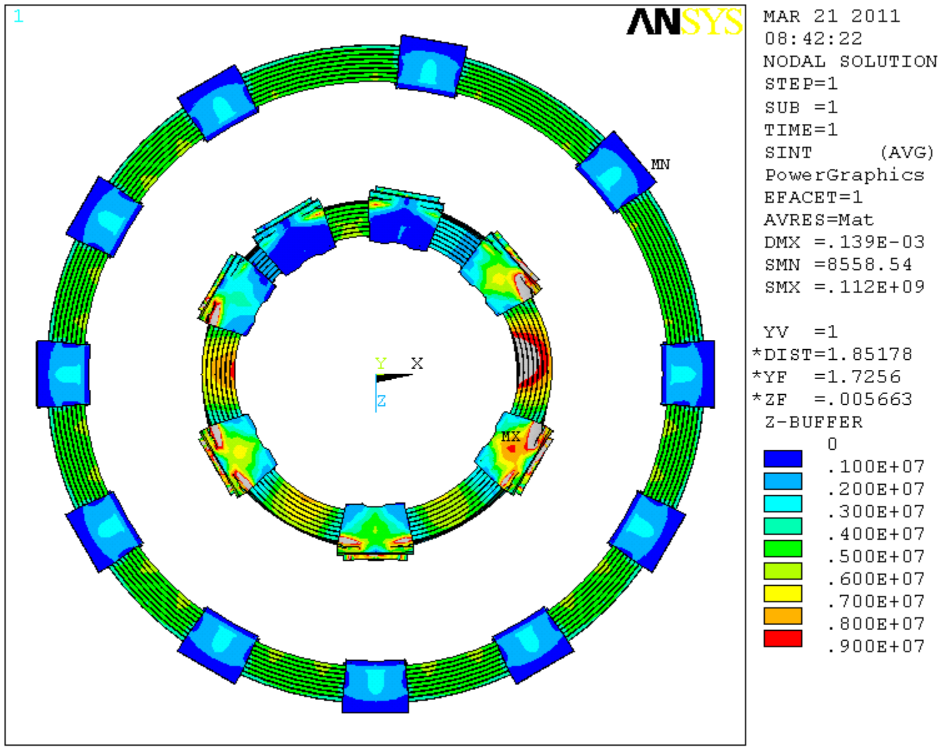


Figure 7.2-2 Stress Results for the 360 degree Model of the Upgrade Support Distribution

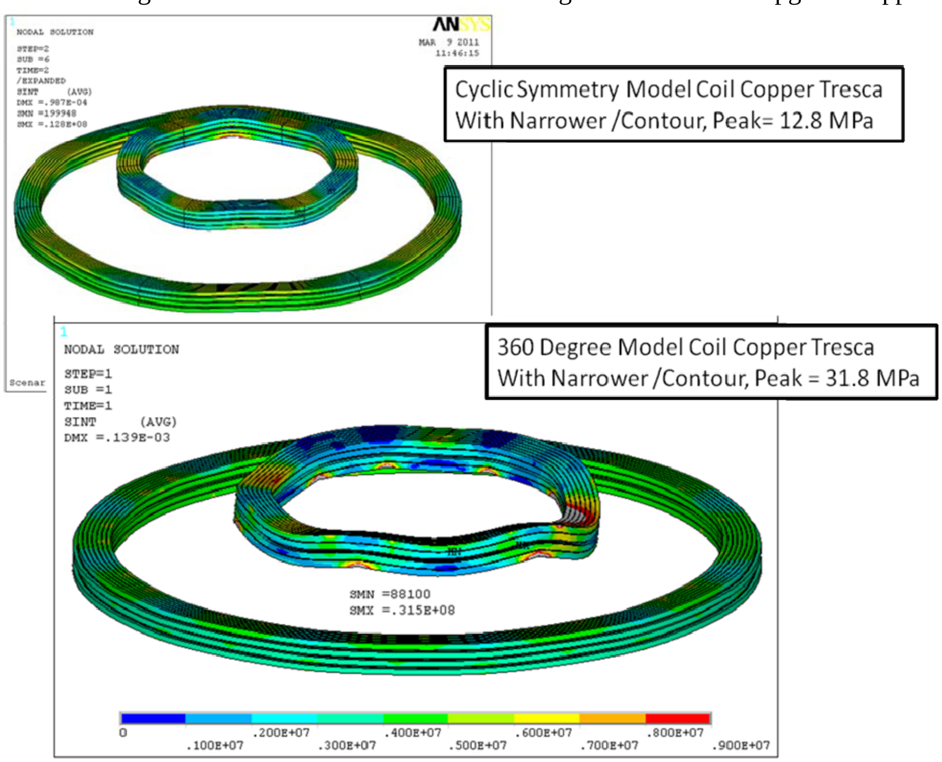


Figure 7.2-3 Comparison of 360 and cyclic Symmetry Stress Results

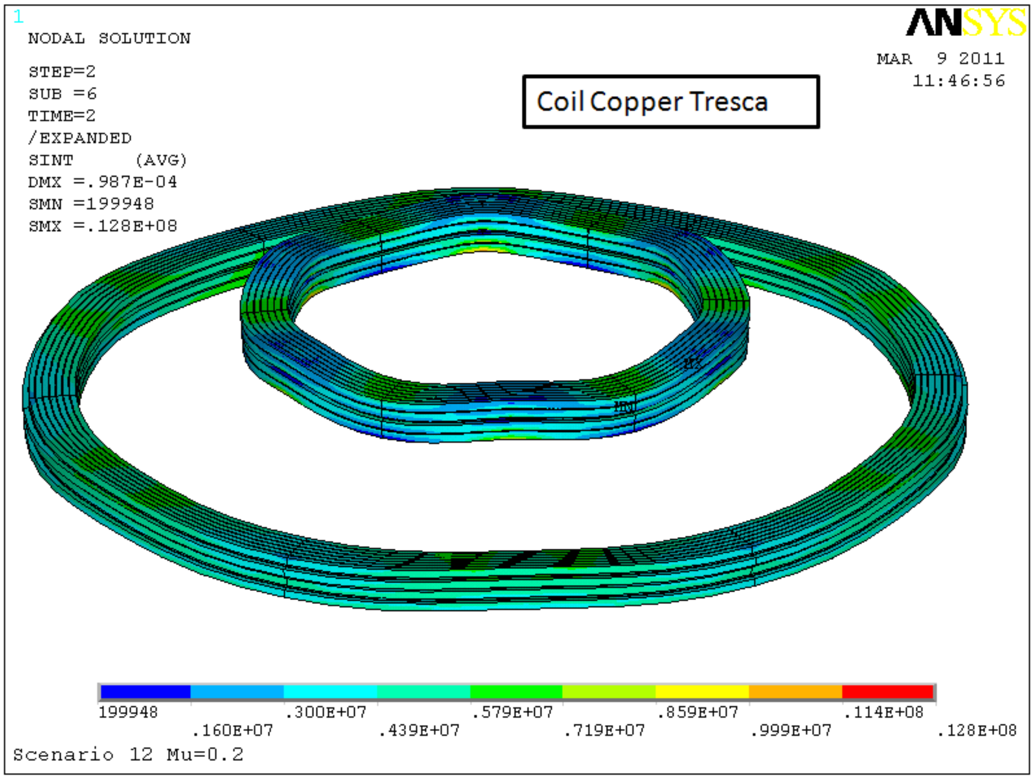


Figure 7.2-4 Cyclic Symmetry Stress Results

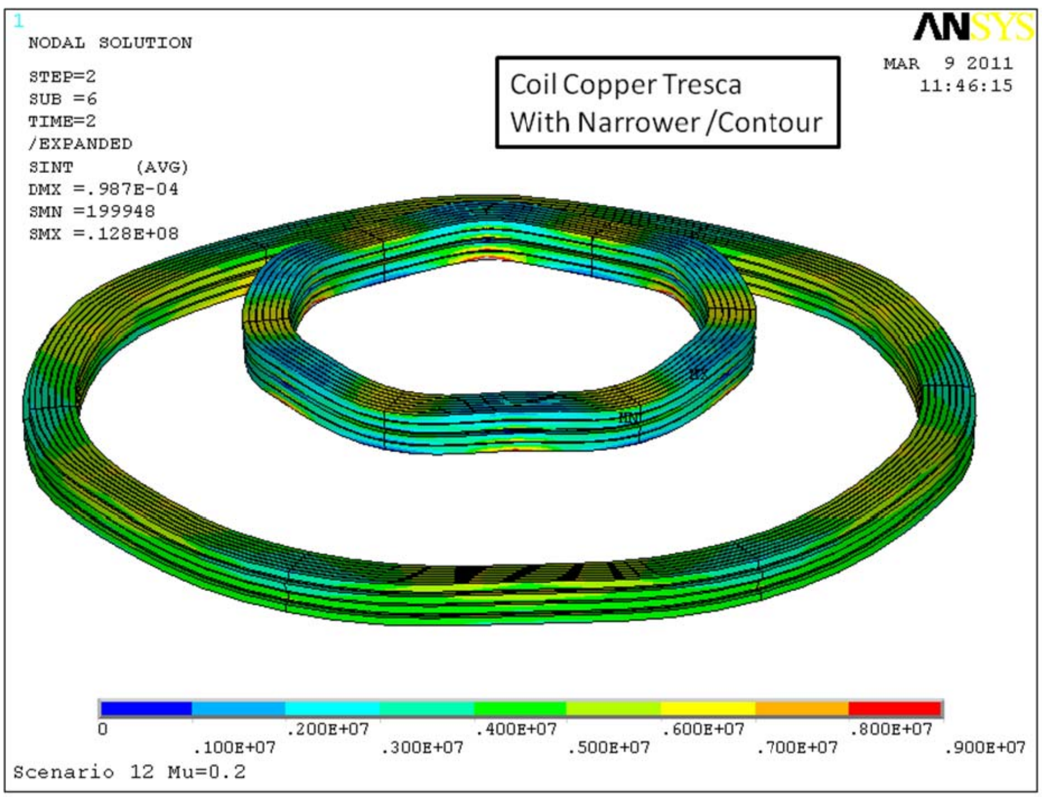


Figure 7.2-5 Cyclic Symmetry Stress Results, Scenario 12

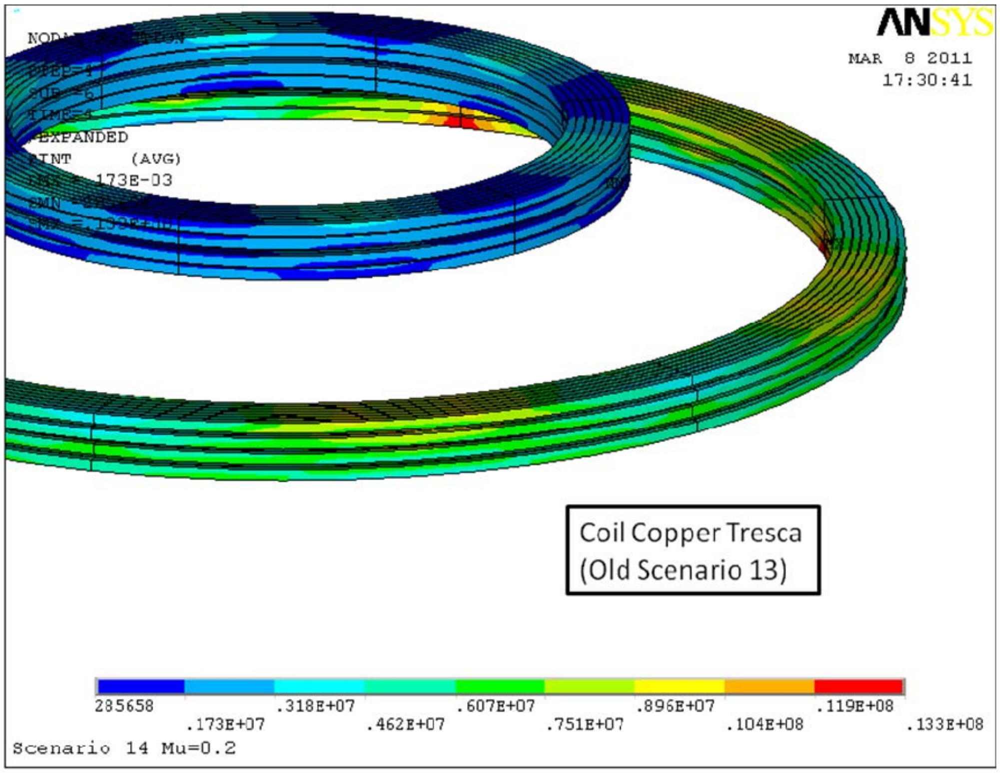
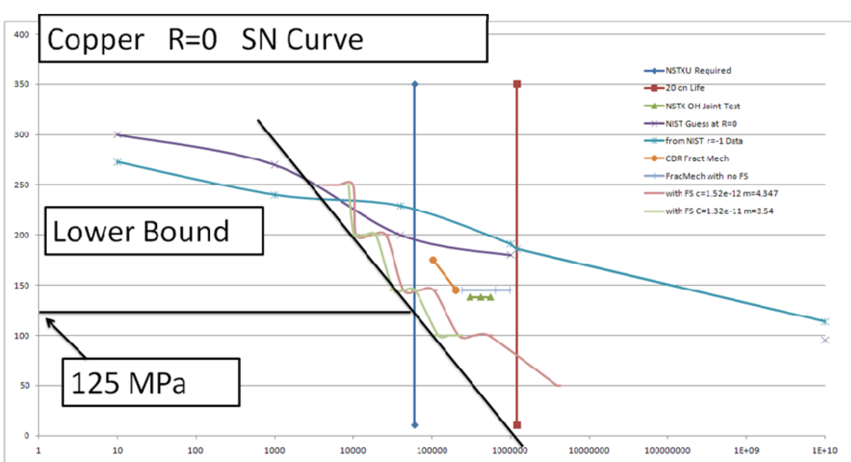


Figure 7.2-6 Cyclic Symmetry Stress Results, Scenario 13

7.3 Fatigue Analysis



SN Curve developed for the OH coil in ref [7]

The allowable tensile stress in the OH conductor was determined to be 125 MPa in ref [7]. The OH conductor is similar to the PF2 and PF3 conductors. The 31.8 MPa for the load case chosen (old scenario 12), when scaled to the latest design point [4], the conductor stress is actually lower. The peak conductor stress is a result mostly of the vertical load bending stress due to the discrete support points. The vertical loading for this load case is 84600 lbs vs. 51374 for Charlie's latest design point, ref 4 (repeated in section 5.5).

PF 3 stresses are smaller than PF2.

7.4 Insulation Stress

The PF-2, PF-3 and PF-4 were all manufactured by PPPL[8]. Their insulation scheme is four half-lapped layers of Mylar insulation, followed by (2) half-lapped layers of Fusa-Fab" B-stage insulation. The multiple layers of Mylar makes the shear bond minimal and shear stresses need to be low, and/or the copper conductor stress must be very low so that the full beam section of the coil is not needed.

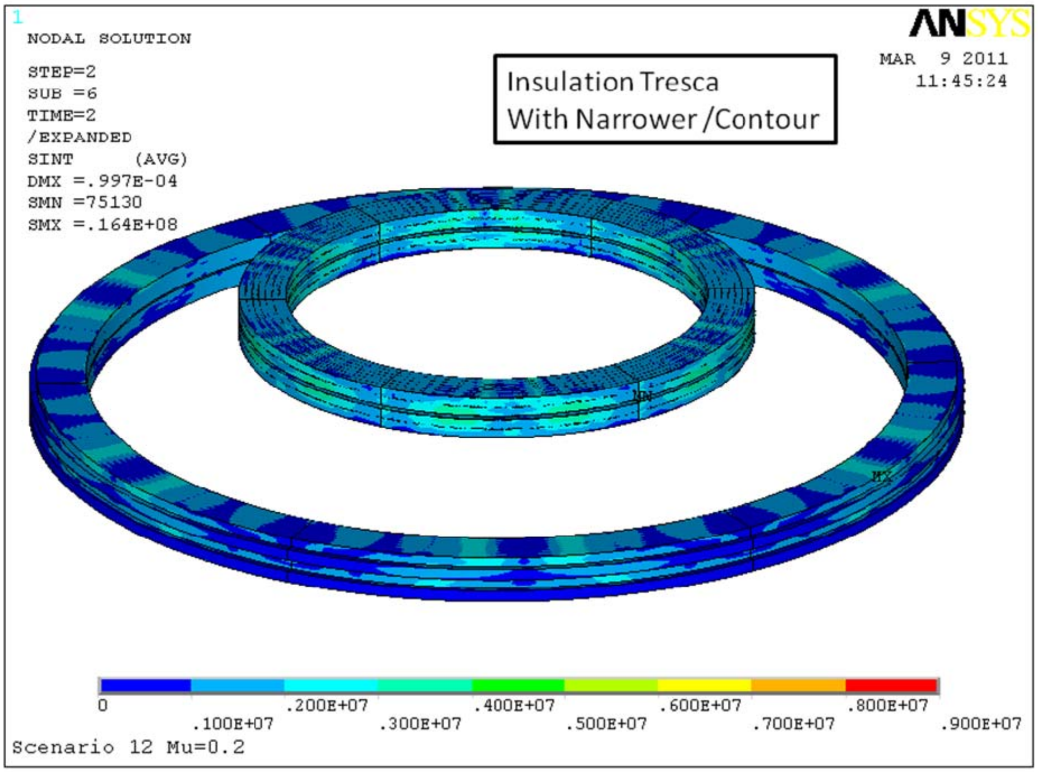


Figure 7.4-1 Cyclic Symmetry Model Insulation Tresca Stress Results Scenario 12

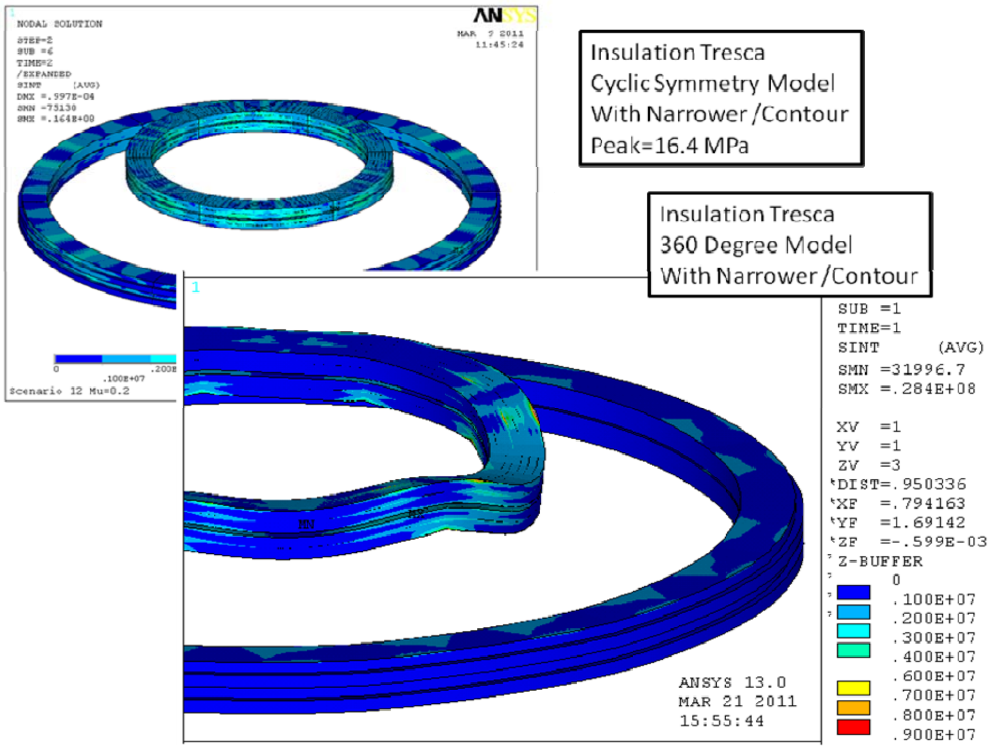


Figure 7.4-2 Comparison of 360 Degree Model and Cyclic Symmetry Model Insulation Tresca Stress Results Scenario 12

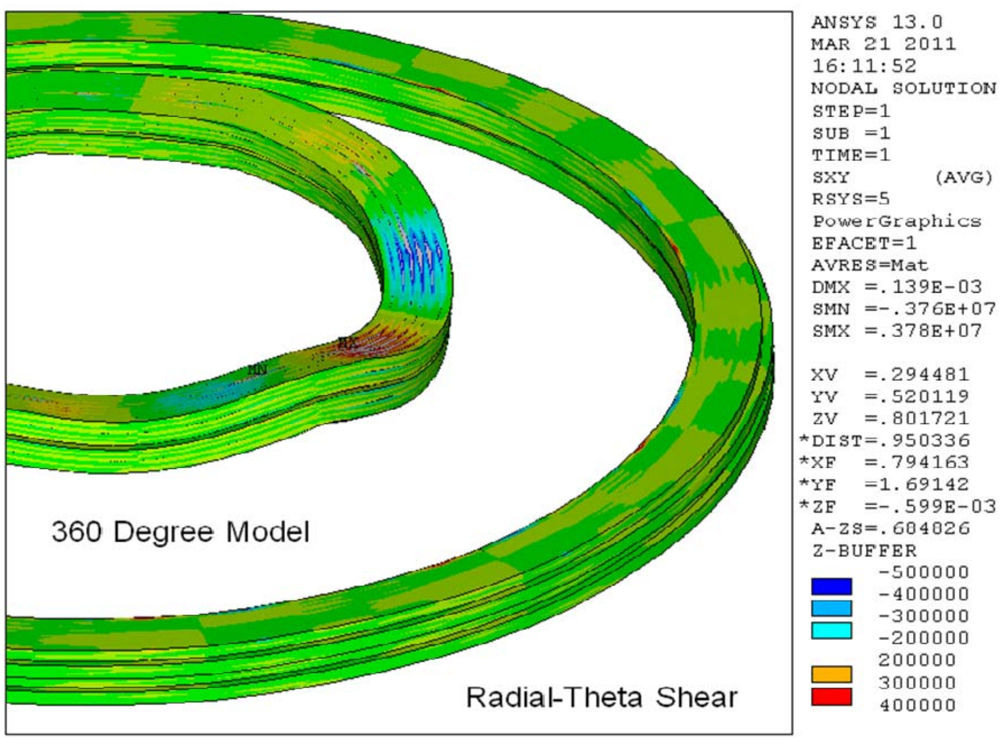


Figure 7.4-3 360 Degree Model Insulation Radial-Theta Shear Stress Results Scenario 12

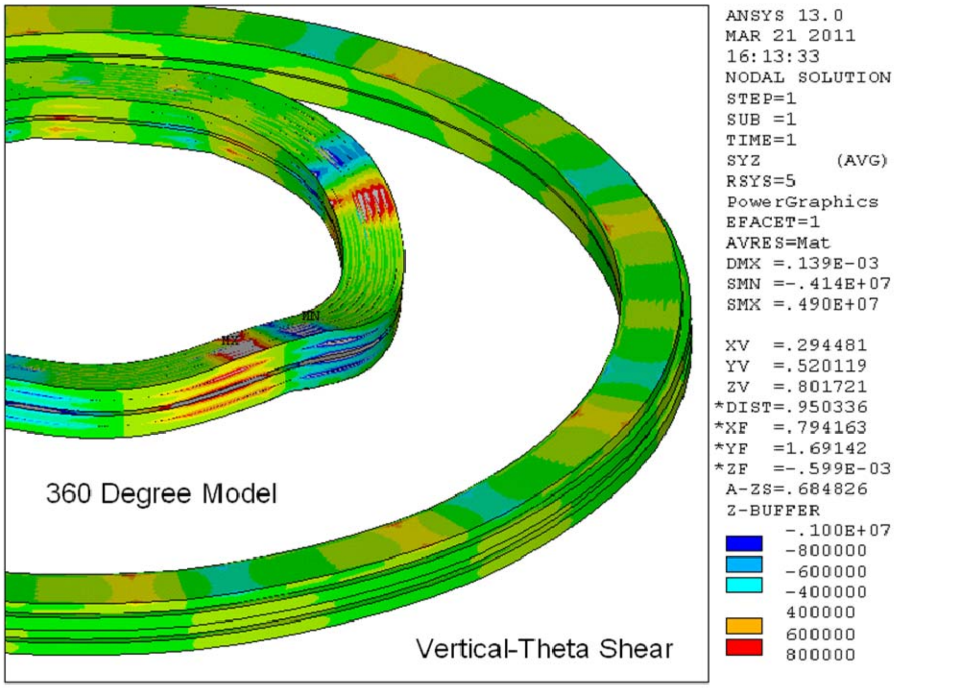


Figure 7.4-4 360 Degree Model Insulation Vertical-Theta Shear Stress Results Scenario 12

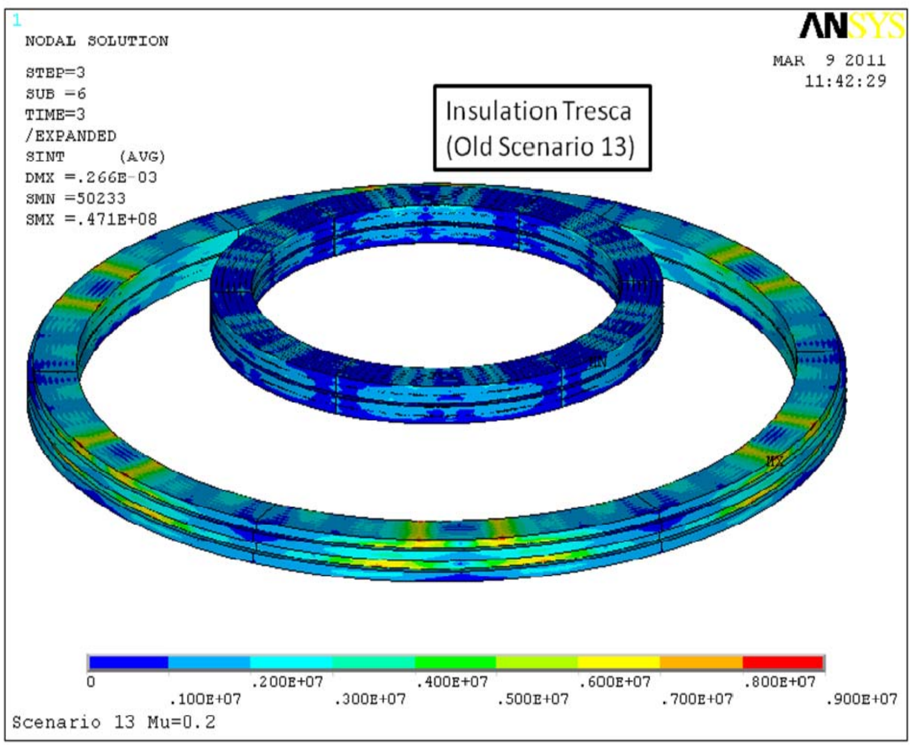
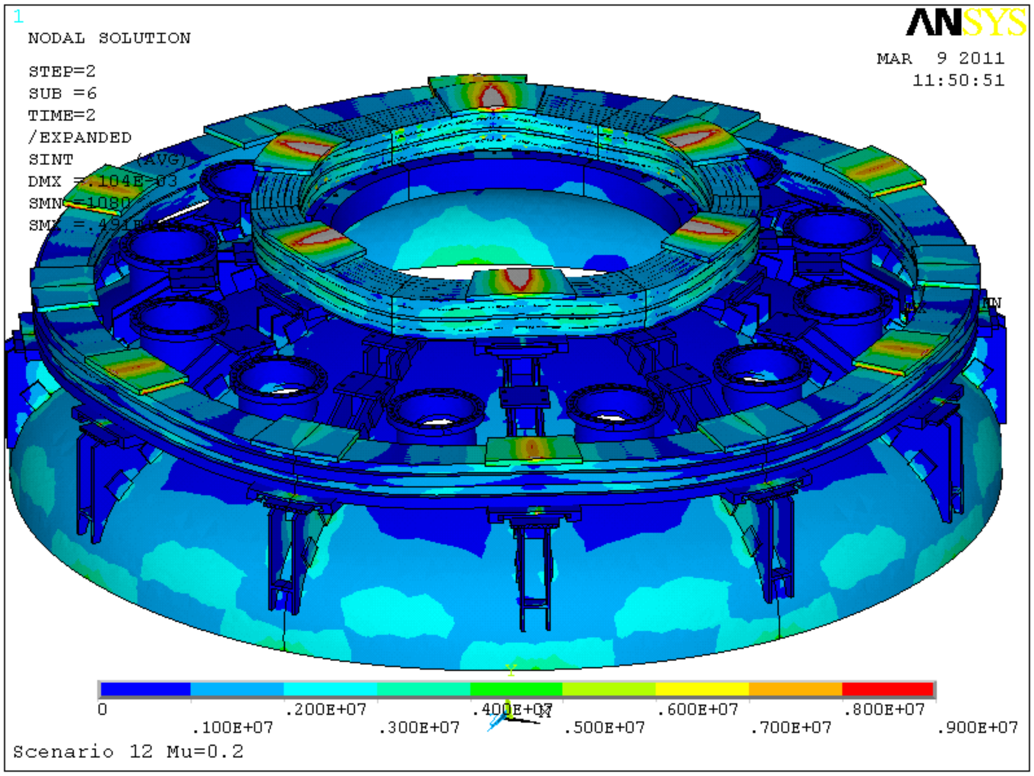
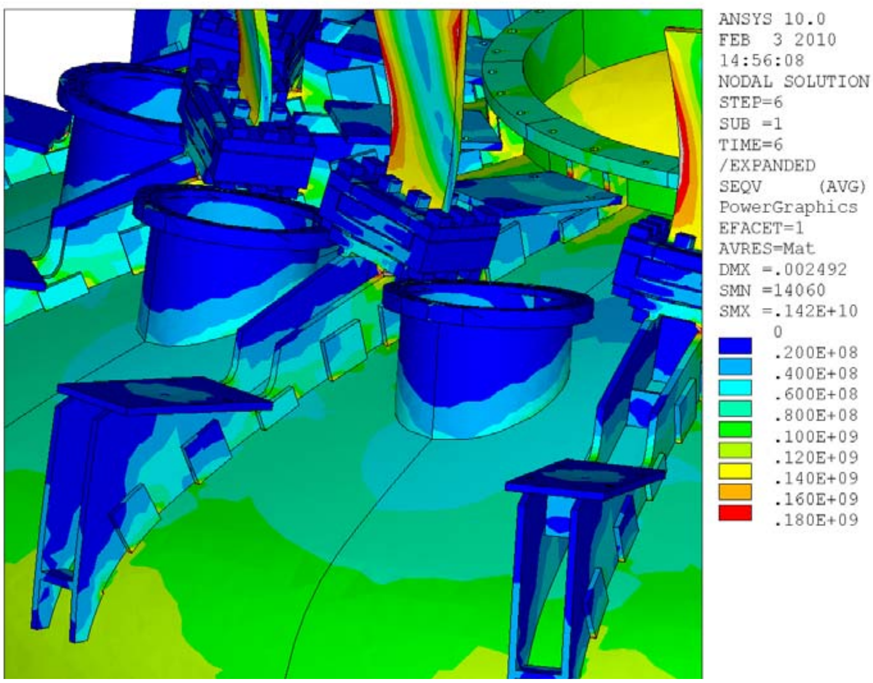


Figure 7.4-4 Cyclic Symmetry Model Insulation Tresca Stress Results Scenario 13

7.5 Vessel Dome and Rib Stress - Only Due to PF2 and 3

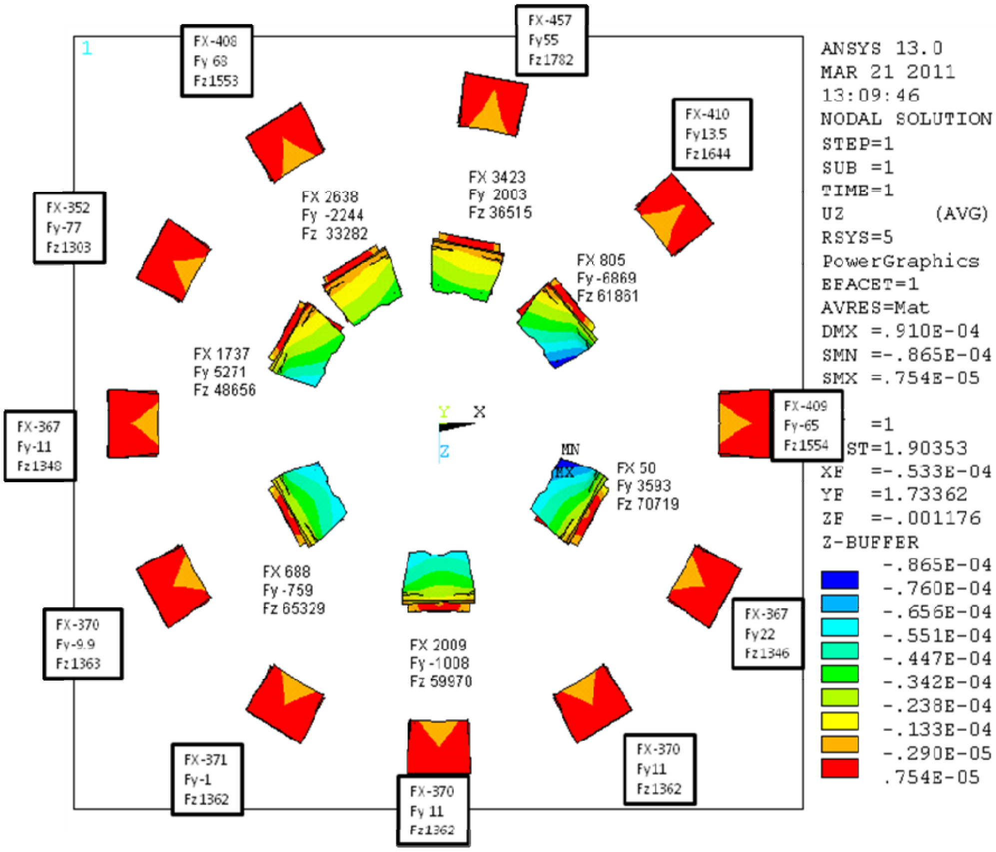
From the figure below, the vessel stresses due to the PF2 and 3 loads are small. Vessel stresses are more strongly affected by the umbrella support feet loads. An estimate of these stresses is shown in the following figures.





Stresses in the vessel and ribs from the model described in Section 6.3

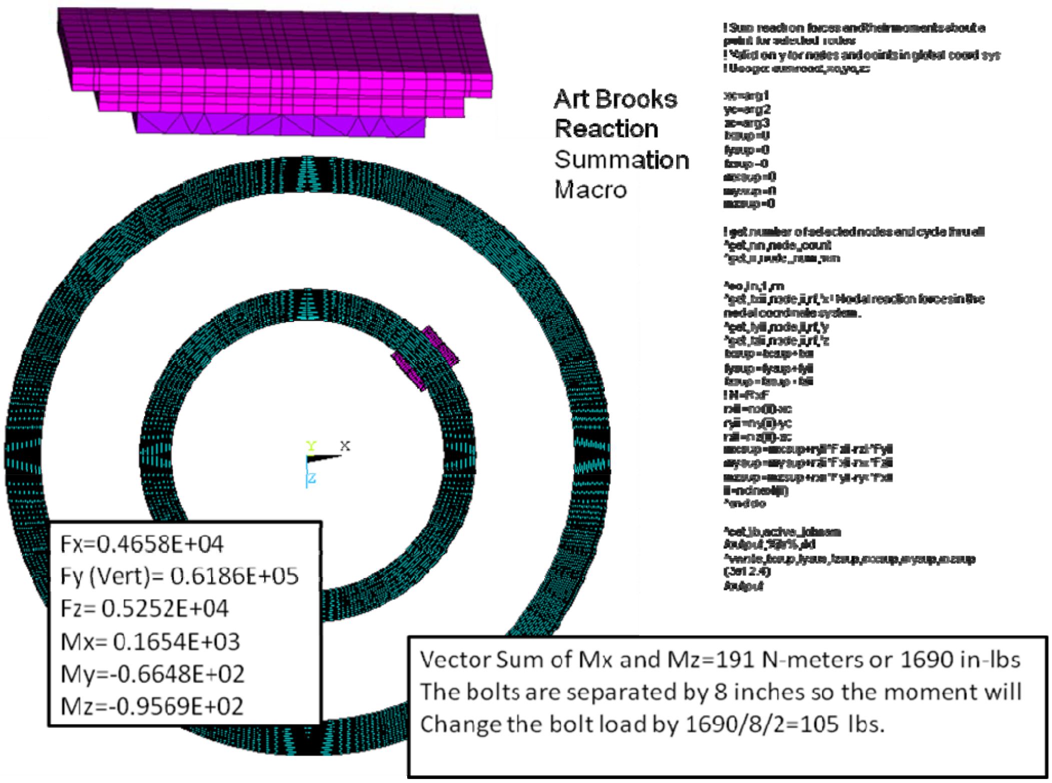
7.6 Reaction Forces and Moments



Scenario 12 Reactions are in the Cylindrical System 5 (Z up)

The non-uniformity in support distribution was analyzed for one of the scenarios and the effective number of supports is 5.32 supports.

PF3 support pads are also distributed non-uniformly. For the same scenario 12 used for PF2, the net vertical load is 16103N. The maximum individual support load is 1782 N and the effective number of supports is 9, while there are actually 11 supports.



8.0 PF3 Support Analysis Results

8.1 Welds

PF3 is supported by the ribs that are welded to the vessel dome. The connection of the support plate to the ribs is by 1/8 fillets that run around most all of the plate intersections. Average stresses on this weld could be considered acceptable, but the weld size is smaller than recommended by AWS, AISC, and ASME for plates larger than 1/4 inch. The weld concentration under the bolt holes is actually aggravated by starts and stop of the welds. The upgrade plan is to increase the size of these welds.

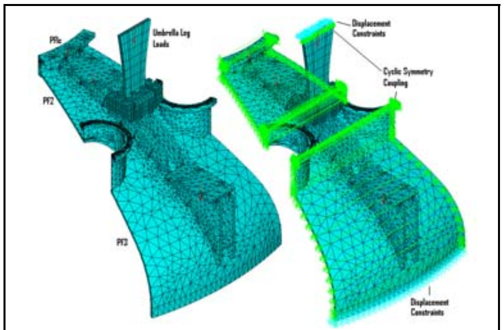


Figure 8.0-1

```
/batch
/prep7
et,1,45
*do,imat,1,100
ex,imat,295e5
*enddo
/input,pf3w,mod
!nummer,node,.0001
nsel,y,-100,47
d,all,all,0.0
nall
eall
save
fini
/solu
/title 10000lbs Vertical load
fscale,10000/570
solve
save
fini
/exit
```

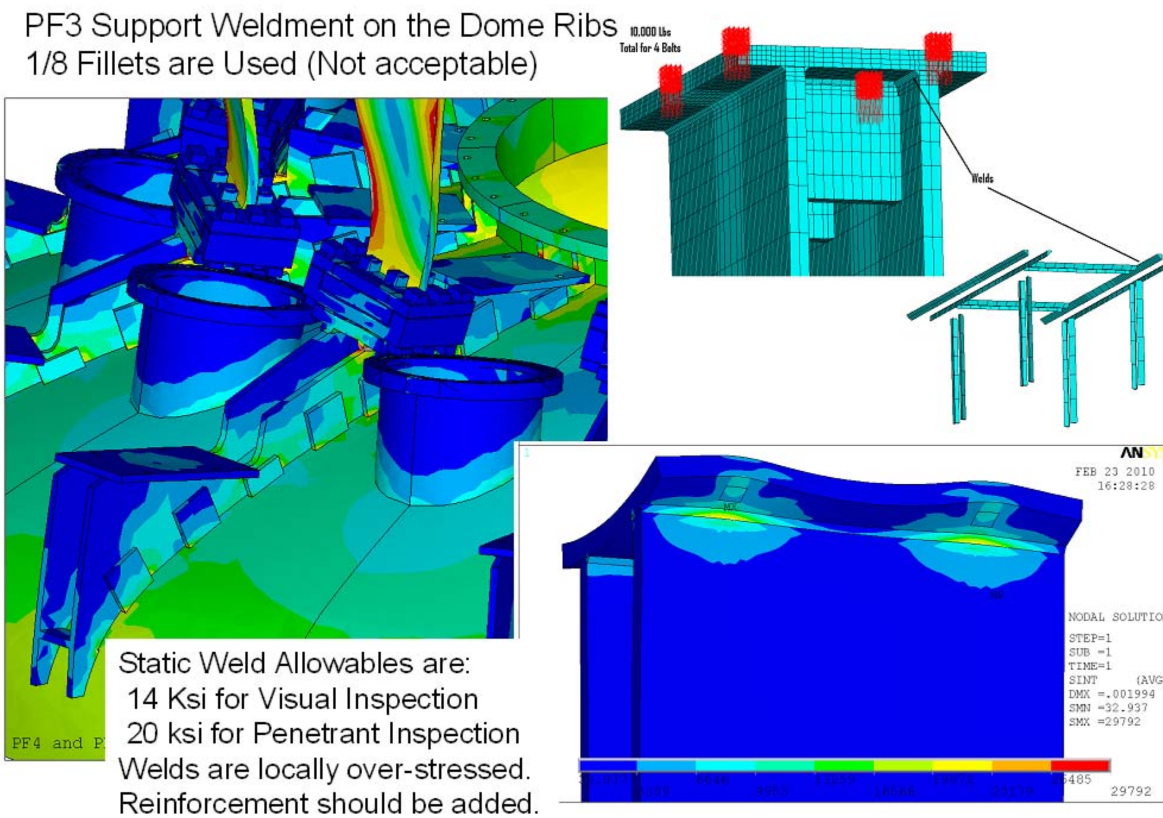
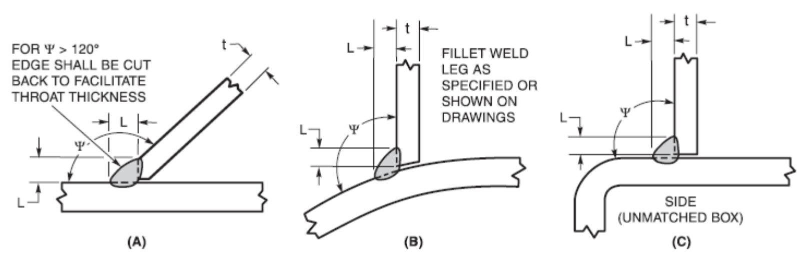
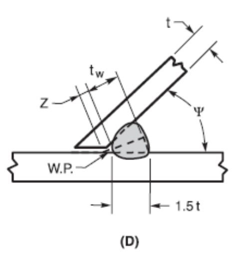


Figure 8.1-1 PF3 Welded Plate to Rib Weld Analysis





DIHEDRAL ANGLE = Ψ	MIN L FOR E = 0.7t	E = t	E = 1.07t
SIDE ≤ 100°	t	1.4t	1.5t
SIDE 100°–110°	1.1t	1.6t	1.75t
SIDE 110°–120°	1.2t	1.8t	2.0t
TOE > 120°	t BEVEL	1.4t BEVEL	FULL BEVEL 60°–90° GROOVE

Notes:
1. t = thickness of thinner part.
2. L = minimum size.
3. Root opening 0 to 3/16 in. [5 mm]—see 5.4.
4. Not prequalified for Ψ < 60°.
5. Z—see 2.16.

Figure 3.3—Fillet Welded Prequalified Joints (see 3.28.3)

Figure 8.1-2 From the AWS Stainless Steel Criteria

Table 8.1-1
AISC Table 1.17.5 Minimum weld sizes recommended for joined plate sizes. The same table appears in ASME and in the AWS carbon steel welding code

Material thickness of thicker part joined (inches)	Minimum size of fillet weld (inches)	Material thickness of thicker part joined (inches)	Minimum size of fillet weld (inches)
To ¼ inch inclusive	1/8	over1.5 to 2.5	3/8
Over ¼ to ½ in.	3/16	Over 2.25 to 6	1/2
Over ½ to 3/4 in.	¼	Over 6	5/8
Over ¾ to 1.5 in.	5/16		

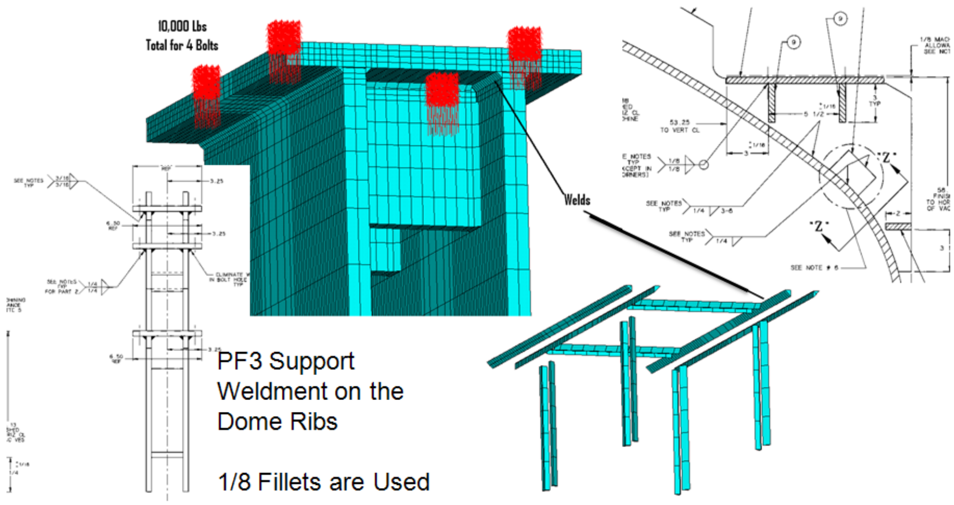


Figure 8.1-3 PF3 Welded Plate to Rib Weld Analysis Model and Drawing Excerpts

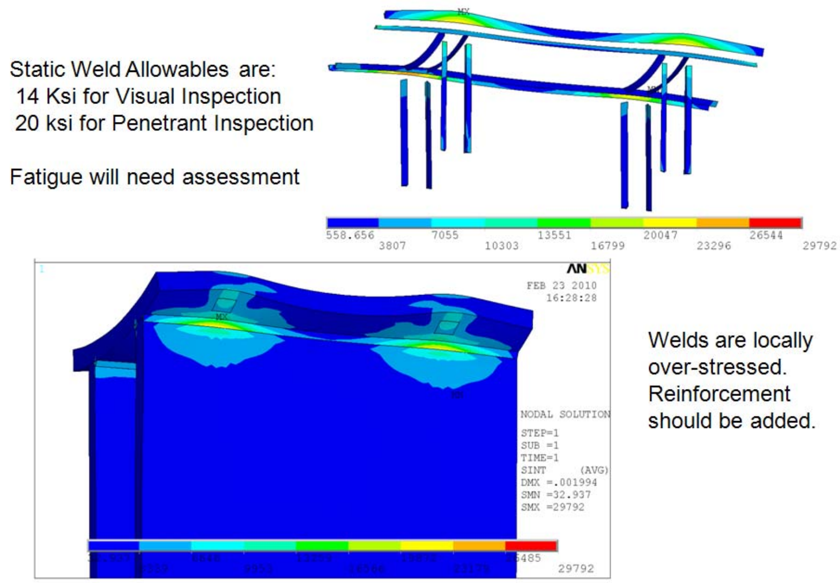


Figure 8.1-4 PF3 Welded Plate to Rib Weld Analysis - Weld Local Stress

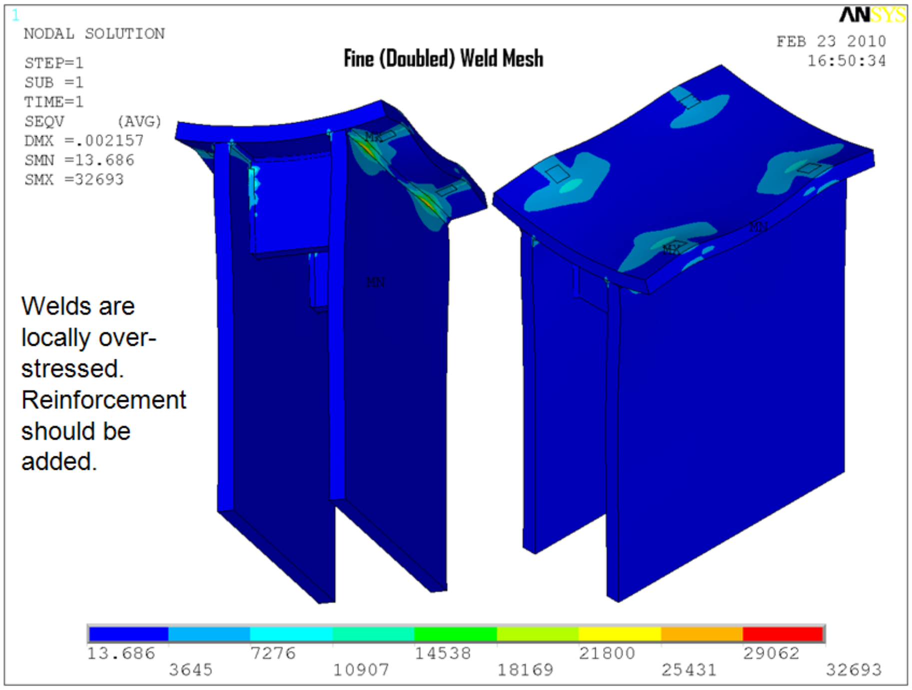


Figure 8.1-5 PF3 Welded Plate to Rib Weld Analysis - Weld Local Stress - Fine Mesh

1/8 Inch Fillets on ¼ Inch and greater stock are not accepted by AISC an AWS – But were used on NSTX. These were qualified by test.

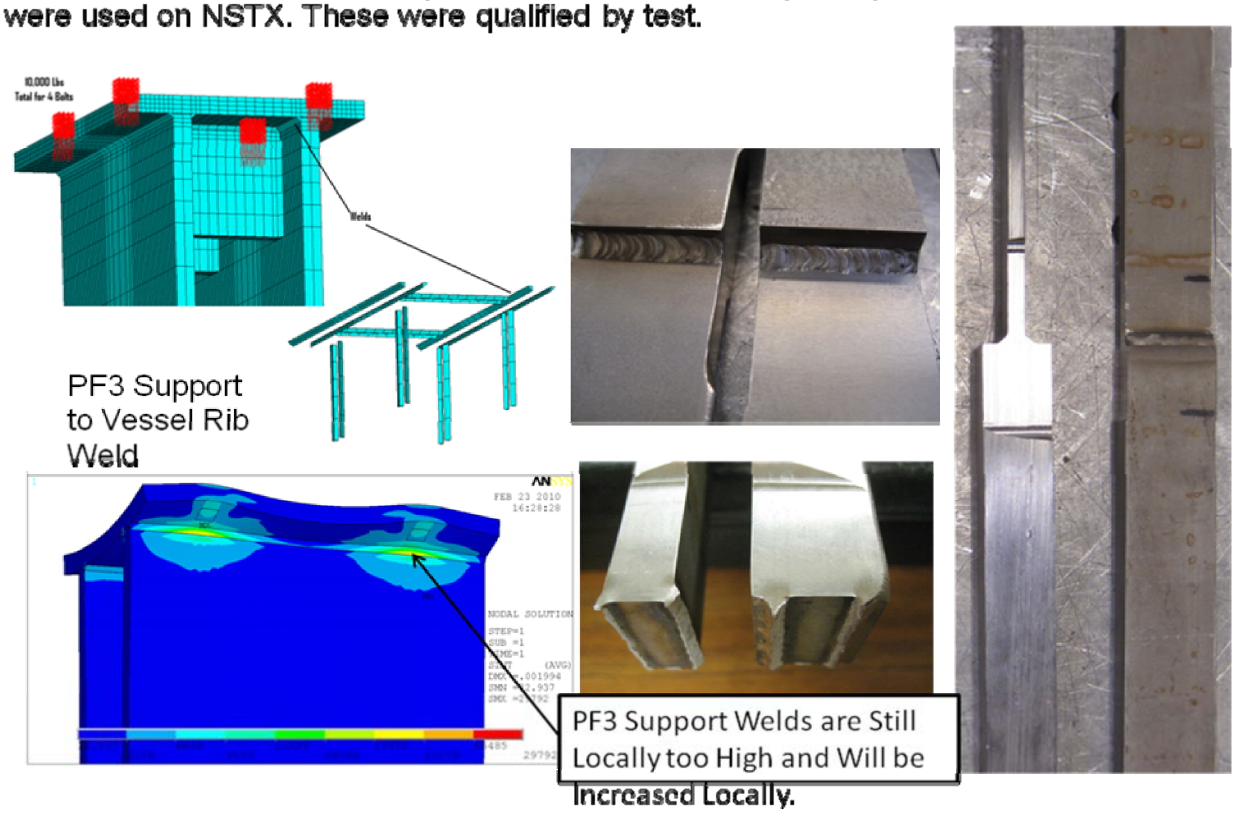


Figure 8.1-6 PF3 Welded Plate to Rib Weld Analysis - Showing Weld Test by Martin Denault

8.2 Bolts

PF3 is supported at 11 places with brackets that use 4 1/2 inch bolts to clamp the coil. The bolt P/A stress is 98989/9/4/.1416=19418psi, where the 99045 lb total vertical load is tabulated in section 5.5 and the effective number of supports was found to be 9 rather than the 11 actual number of supports. This is calculated in section 7.6. The load per bolt is than 99045/9/4 = 2751 lbs for a stress of 98989/9/4/.1416=19418 psi.

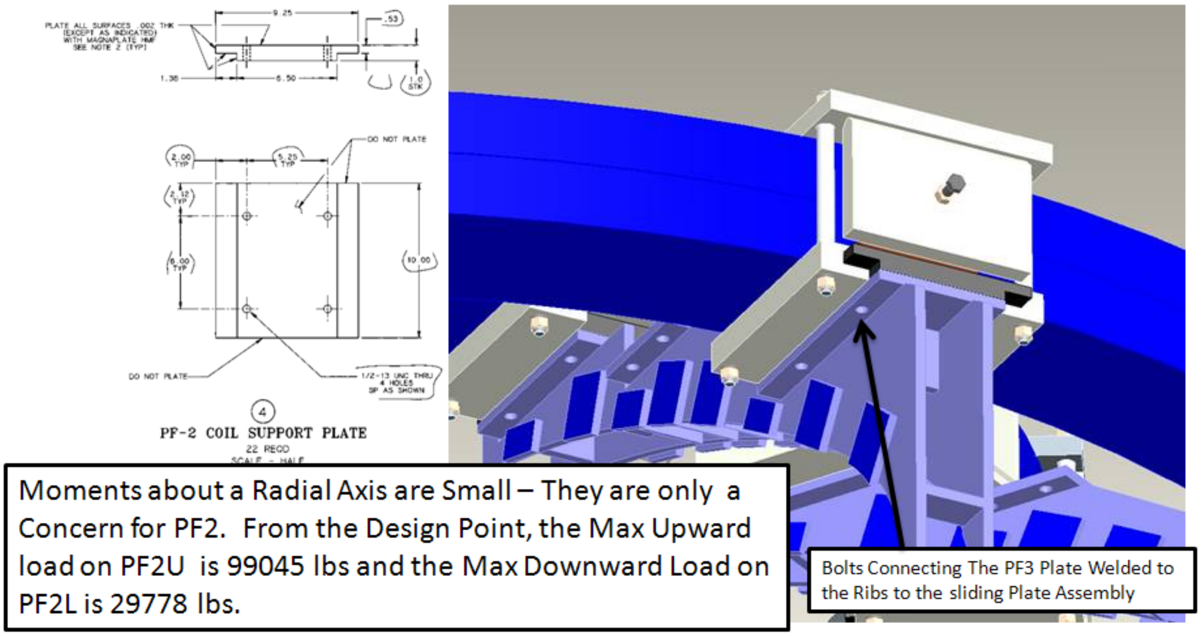
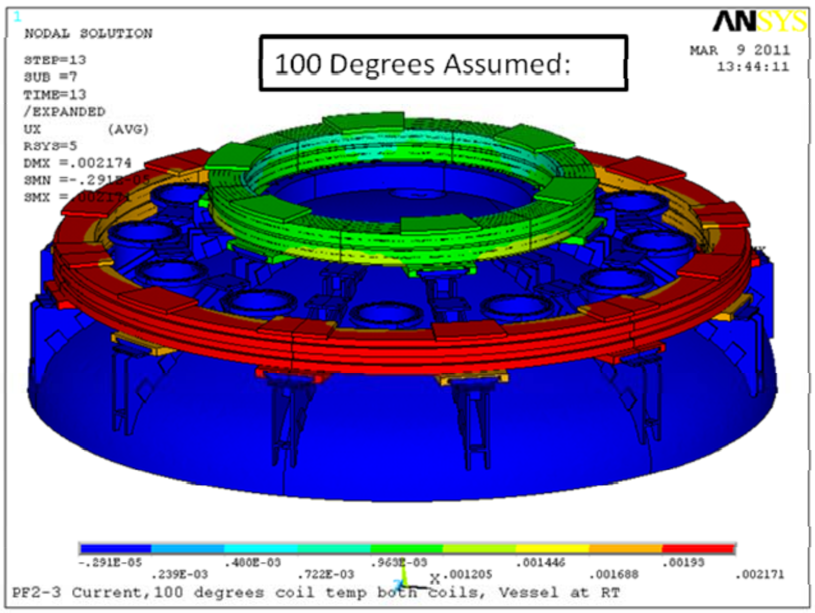


Figure 8.2-1 Sliding Block to Welded Plate Bolting

There are actually 2 sets of bolts needing qualification, the coil clamp bolts and the welded plate to sliding block bolts. They see the same loads (19418 psi), and they are both the same diameter. To be sure the bolts have appropriate properties, the generic 316 bolts should be replaced with a spec that guarantees the necessary properties. ASTM A193 B8M Class2 bolts are recommended.

9.0 Thermal Growth and Bake-Out Behavior

The sliding blocks used for both PF2 and 3 are not needed for normal operation. The normal operating temperature changes are only a few degrees warmer than RT. The main purpose of the slides is to allow thermal growth during bake-out. The sliding block bases were included in the simulations, and a "Hot" coil case was run. This illustrates that the thermal differential growth of the coils could be accommodated, or inversely the thermal growth of the vessel during bake-out could be accommodated.



From the Design Point:

	Tmax_LPPI	Tmax_SPFI
	deg C	deg C
OH (half-plane)	100	100
PF1a	[illegible]	[illegible]
PF1b	43	100
PF1c	79	79
PF2a	30	23
PF2b	30	23
PF3a	33	25
PF3b	33	25
PF4b	33	25
PF4c	33	25

Figure 9.0-1 "Hot" Coil Results

From an email from Charlie Neumeyer [9]:

"LPPI" is a term I came up to describe the nominal upgrade target, namely a 5 second (long pulse) plasma flat top where the OH current does not complete the second swing, only delivering part of its double-swing flux. The remaining flux is supplied non-inductively. Thus LPPI stands for "Long Pulse Partial Inductive".

"SPFI" is another operating mode I felt the need to describe because it forces the design to contend with the full second swing current. In this case the pulse has a flat top less than 5 seconds (short pulse) but the full OH double-swing flux is used and it is sufficient to drive the current without reliance on non-inductive means. In this case it turns out that the flat top duration is limited by the OH I2T, not the available OH flux, which is more than sufficient per my plasma model.

Appendix A Earlier Design Point Force Sums

Fr(lbf)	PF1cU	PF2U	PF3U	PF3L	PF2L	PF1cL
Min	-57346	-82994	-81153	-44102	-82995	-57334
Worst Case Min	-325149	-284922	-206499	-206499	-284922	-325125
Max	21025	108586	237091	237094	108586	21026
Worst Case Max	357267	400863	484760	484760	400863	357291

Fz(lbf)	PF1cU	PF2U	PF3U	PF3L	PF2L	PF1cL
Min	-30125	-67757	-148839	-31442	-42996	-68673
Worst Case Min	-168089	-194414	-303940	-246951	-192144	-143125
Max	68673	42996	100954	148839	54525	30125
Worst Case Max	143125	192144	246951	303940	194414	168089