NSTX Upgrade

Analysis of Existing and Upgrade PF4/5 Coils and Supports – With Alternating Columns.

NSTXU-CALC-12-05-00

Rev 0

December 2011

Prepared By:

Peter Titus Digitally signed by Peter Titus
DN: cn=Peter Titus, o, ou,
email=ptitus@pppl.gov, c=US
Date: 2012.01.06 17:19:16 -05'00'

Peter Titus, PPPL Mechanical Engineering

Reviewed By:

Irving Zatz Digitally signed by Irving Zatz
DN: cn=Irving Zatz, o=PPPL, ou,
email=zatz@pppl.gov, c=US
Date: 2012.01.06 16:27:30 -05'00'

Irving Zatz, Engineering Analysis Division

Reviewed By:

Mark Smith Digitally signed by Mark Smith
DN: cn=Mark Smith, o=PPPL, ou,
email=msmith@pppl.gov, c=US
Date: 2014.06.12 13:01:08 -04'00'

Mark Smith, Cognizant Engineer

PPPL Calculation Form

Calculation # **NSTXU-CALC-12-05** Revision # **00** ____ WP #, **1677** (ENG-032)

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

To qualify the stresses in PF4 and 5 and the stresses in their support brackets and columns.

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

Included in the body of the report - See section 6.1

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

Multiple models of PF4 and 5 are used in these calculations. Each has a different level of refinement, and is intended to address different aspects of the coils and supports. The assumptions regarding the individual models and their relationship with the other models and analyses are discussed with each model. There is a global model of the tokamak which uses smeared properties of the winding pack and there is a quarter symmetry model of just the upper half of half of the coils and associated brackets and vessel sections. The quarter symmetry model addresses local conductor and insulation stress, and the global model addresses the interactions with the full PF and TF systems.

Calculation **(Calculation is either documented here or attached)**

See the following report

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

Stress levels in both the coils and supports satisfy the NSTX CSU criteria

It is recommended that clamp plate studs be replaced with ASTM A193 B8M Class 2 bolting material. These are a work hardened 304 stainless steel. These provide assurance that if the launching loads are not equal and opposite on top vs. bottom, then 6 support points can support the net tensile loads on the studs. To mitigate the fatigue loading on the bolts, but to limit local contact pressures in the copper coils, it is recommended that the bolts be preloaded based on a 20 ksi yield and some lift-off would then occasionally cycle the bolt threads. Stud preload can be re-visited prior to assembly.

The dovetail joint in the new PF4 and 5 support clamps/columns must have a low friction coefficient (mu ~.05), and there is a geometric constraint on the slide of H/w <2, where the geometry is shown in Figure 12.6-3.

Cognizant Engineer's printed name, signature, and date

Mark Smith Mark Smith

Digitally signed by Mark Smith
DN: cn=Mark Smith, o=PPPL, ou, email=msmith@pppl.gov, c=US
Date: 2014.06.12 13:01:25 -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

Irving Zatz Irving Zatz

Digitally signed by Irving Zatz
DN: cn=Irving Zatz, o=PPPL, ou, email=zatz@pppl.gov, c=US
Date: 2012.01.06 16:28:01 -05'00'

2.0 Table of Contents
NSTX PF 4 and 5 Coils and Supports

Design Input,

Appendices

3.0 Executive Summary:

The design of the outer PF 4/5 supports has gone through a number of iterations. Initially, only 6 support points were proposed (twelve including uppers and lowers). The existing support brackets (Figure 3.0-2) were to be bypassed and an additional set of six stronger columns were to be added. This left six strong support points that could react the large attractive loads between PF4/5 upper and PF4/5 lower. If the coils could handle the spans created by the six support points, this option was thought to be attractive because the vessel shell would be off-loaded. Ultimately, 12 supports were needed.

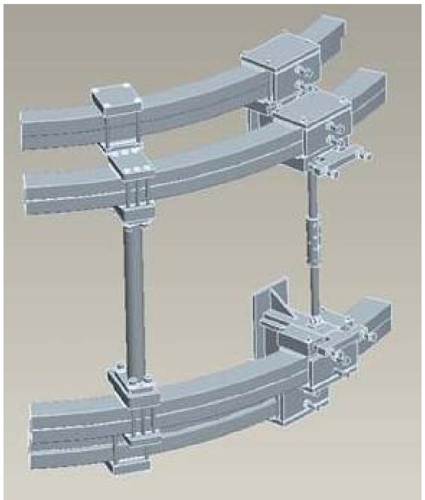


Figure 3.0-1 FDR PF4/5 Supports

The PF5 insulation system is a mylar wrapped fusifab epoxy system. Because of the poor bonding of the mylar to epoxy and to the copper conductors, twelve supports were necessary to reduce the spans and resulting bending stress. Stresses in PF4 and 5 have been calculated in a detailed model of the vessel shell, support hardware, and winding pack. In order to assess the stress in the coils, stress analysis of the winding pack is used in concert with influence coefficients to add localized stress behavior with thermal stress and for all scenarios currently postulated for NSTX - with 10% headroom in currents, with and without plasma. PF5U conductor stress is calculated to be 122 MPa with all effects included. This is below the fatigue allowable developed for the OH coil [7].

The coil support concept is as presented in the PDR, with six existing supports augmented by six new support columns. Elimination of the existing strut or column between the upper and lower existing PF4/5 supports was considered but this overstressed the cantilevered portion of the PF5 support, added loads to the pad welded to the vessel, and added stress in the port ligaments, and so, the strut/column has been retained.

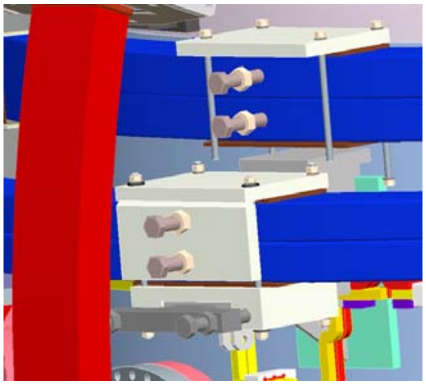


Figure 3.0-2 Existing PF4/5 Supports

PF4 and 5 have to be aligned with respect to the centerline of the plasma. The current (meaning prior to the upgrade) approach is to connect pushers and clamps around the coils to push the coils into roundness and concentricity. Currently, coil heat up is trivial. For the upgrade, the coils will be on for the 5 sec. pulse and will heat to 100C - expanding and fighting the alignment clamps. Table 6.3-2 shows the maximum temperatures expected during upgrade operation. John Menard and Masa Ono were consulted during a Wednesday project meeting. An n=2 error, i.e., an elliptical coil, is acceptable as long as it is aligned with the plasma centerline - i.e., it precludes an n=1 error, or a net lateral shift. So the coils are radially held with respect to the vessel and have them grow into an oval as they thermally expand. The degree of ovality was accepted by Jon Menard and Masa Ono.

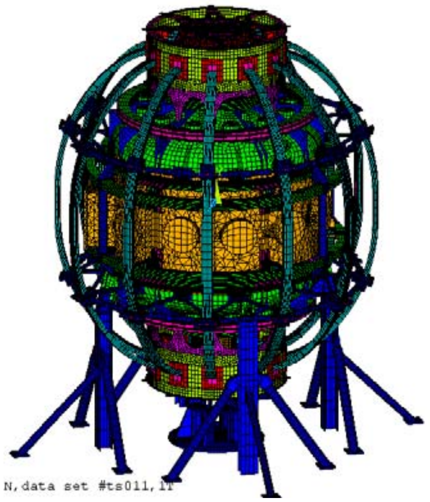


Figure 3.0-3 Linear Global Model [2] Used in Calculating DCPS Stress Multipliers

The intention is to fix the sliding blocks on two opposite, existing PF4 and 5 supports. This makes the coils and their supports symmetric about a vertical plane that cuts through both fixed supports. A 180-degree half symmetry modeling is sufficient to capture the full 360-degree behavior of the coils. Dovetail slides are proposed to allow differential thermal radial motion between PF4 and 5. Pivoting links are used to model the mechanics, but a sliding dovetail joint is actually used. Low friction materiel is required. Magna Plate is suggested. It has a friction coefficient “as low as .05”. According to the design criteria document, the friction coefficient, mu, must be assumed to be mu +.15 or .2 and this puts a geometric constraint on the slide of H/w <2. The geometry is shown in Figure 12.6-3.

In addition to the alignment issues, there are leads that require support. They currently break out of the coils and are connected to a unistrut frame that fixes them in space, providing support for Lorentz loads but allowing no thermal growth of the coil. If the fixed radial supports are chosen near the leads, then the lead supports will work - at least conceptually.

The staggered column design produces 12 supports for the attractive loads on the PF4/5 upper and lower coils. The support points alternate between support by the vessel, and support by the six columns. Most of the analysis presented in this calculation assumes that the small columns (that buckled during initial NSTX runs) are retained. They are much less stiff than the new columns, and some loading is transferred to the vessel. The new columns are modeled as 3-inches in diameter and 0.3-inch wall thickness. The welds connecting the bracket to the vessel shell concentrate at the corner of the perimeter weld. The weld is nominally 5/16-inch, but the QA report recommends an effective ¼ inch weld. Local corner stresses were high even for the existing NSTX loading, and an inspection of these corner welds was performed to determine if any fatigue failures were initiating. No indications of cracking or fatigue were found. The six (twelve included uppers and lowers) existing PF4 and 5 brackets are the only support for the assembly of PF 4 and 5 upper (U) and lower (L) coils. Most loading on the coils is attractive loading between the series connected PF4-U&L coils and PF5-U&L coils. The net loading is smaller. The attractive loads are intended to be taken by 12 columns, six original and six new columns. Without consideration of elastic effectiveness of the old columns, and considering the columns to resist all the attractive loads, then the weldments to the vessel would only take the net load with acceptable stress levels. Hand calculations of these loads show that these welds satisfy static and fatigue limits. In order for the bracket-to-vessel welds to be loaded primarily by the net assembly loads rather than the attractive loads between PF4 and 5, the existing columns must be stiffened. This was done in May, 2011 and the FDR is now based on a much stiffer set of columns all around. Buckling of the stiffer columns is addressed in section 14.0 with a large displacement solution and a load multiplier of 2.6. No indications of non-linearities were found.

Clamp plate studs are currently listed as 316SS, but no grade or condition is specified. It is recommended that they be replaced with ASTM A193 B8M Class 2 bolting material. These are a work hardened 304 stainless steel. These provide assurance that if the launching loads are not equal and opposite on top vs. bottom, then 6 support points can support the net tensile loads on the studs. To mitigate the fatigue loading on the bolts - but to limit local contact pressures in the copper coils, it is recommended that the bolts be preloaded based on a 20 ksi yield and some lift-off would then occasionally cycle the bolt threads. Stud preload can be re-visited prior to assembly.

4.0 Digital Coil Protection System Input

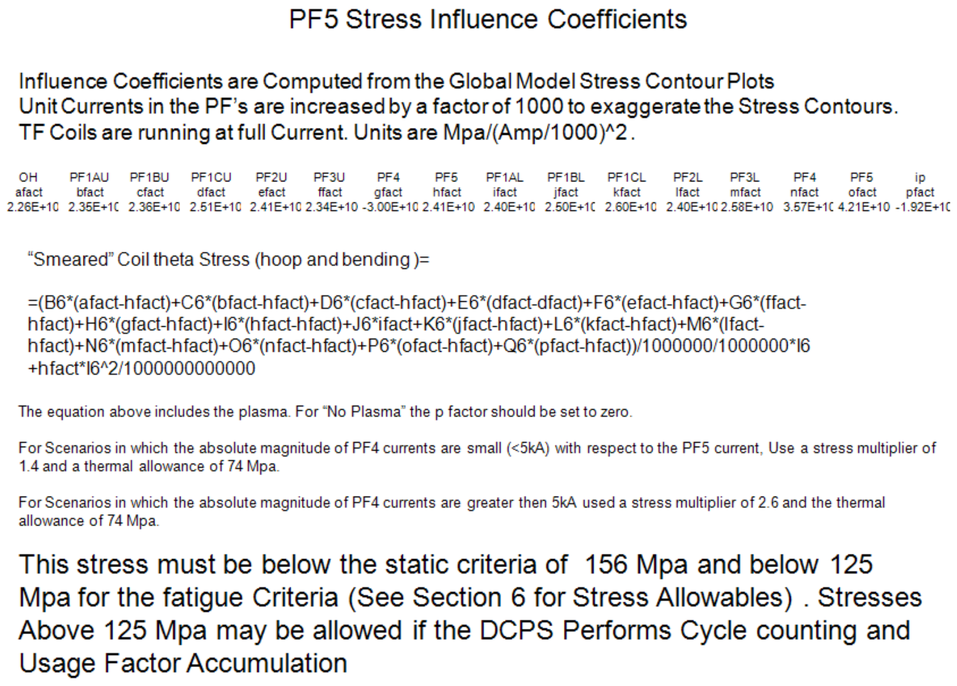
The digital coil protection system algorithms are discussed in more detail in section 9. Conceptual design of the upgrade to NSTX explored designs sized to accept the worst loads that power supplies could produce. Excessive structures resulted that would have been difficult to install and were much more costly than needed to meet the scenarios required for the upgrade mission, specified in the General Requirements Document (GRD). Instead, the project decided to rely on a digital coil protection system (DCPS). Initial sizing was then based on the 96 scenarios in the GRD design point with some headroom to accommodate operational flexibility and uncertainty. The DCPS must control currents to limit component stresses and temperatures to acceptable levels.

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. The second approach to calculating the stress multipliers/algorithms is to utilize a global model that simulates the whole structure and includes an adequately refined modeling of the component in question. Unit terminal currents are applied to each coil separately, Lorentz loads are calculated, and the response of the whole tokamak and local component stress is computed. Local component stresses may then be computed in the DCPS or in a spreadsheet for the many scenarios required by the GRD by scaling and linear superposition of the unit results. This approach has been applied to the PF4 and 5 coil stresses.

PF4/5 DCPS Multipliers

The DCPS should calculate the upward load on the upper PF4 and 5 coils individually and assume this is split over 6 of the 12 support clamp plates which each have 4 studs. Similarly, the downward load on each of the lower PF4 and PF5 coils should be split over 6 of their 12 supports. This is a conservative but needed assumption because for most loading all 12 supports will resist the tensile loads of the coils with respect to their support brackets. Up-down asymmetry in loading may effectively load the 12 supports unequally. If the existing SS316 generic studs are replaced by ASTM A-193 B8M Class 1 bolts, the stress allowable would be 2/3*95 = 63.3 ksi, which corresponds to 8000 lbs per stud. The studs should be tensioned above this or about 10000 lbs (the NSTX Structural Design Criteria Document [3] allows 0.75*yield). With proper pre-tensioning, the alternating stress affecting fatigue will be small. Coil stress algorithms are summarized in the next two figures.



PF5 Stress Influence Coefficients

Influence Coefficients are Computed from the Global Model Stress Contour Plots
Unit Currents in the PF's are increased by a factor of 1000 to exaggerate the Stress Contours.
TF Coils are running at full Current. Units are Mpa/(Amp/1000)^2 .

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
2.26E+10	2.35E+10	2.36E+10	2.51E+10	2.41E+10	2.34E+10	-3.00E+10	2.41E+10	2.40E+10	2.50E+10	2.60E+10	2.40E+10	2.58E+10	3.57E+10	4.21E+10	-1.92E+10

"Smeared" Coil theta Stress (hoop and bending)=

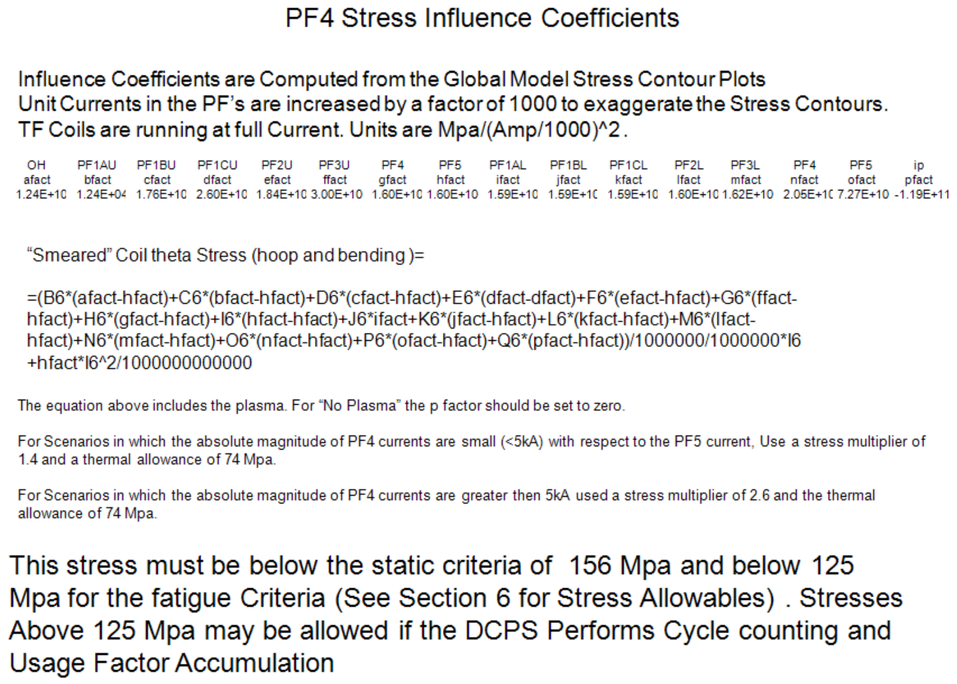
=(B6*(afact-hfact)+C6*(bfact-hfact)+D6*(cfact-hfact)+E6*(dfact-dfact)+F6*(efact-hfact)+G6*(ffact-hfact)+H6*(gfact-hfact)+I6*(hfact-hfact)+J6*ifact+K6*(jfact-hfact)+L6*(kfact-hfact)+M6*(lfact-hfact)+N6*(mfact-hfact)+O6*(nfact-hfact)+P6*(ofact-hfact)+Q6*(pfact-hfact))/1000000/1000000*I6 +hfact*I6^2/1000000000000

The equation above includes the plasma. For "No Plasma" the p factor should be set to zero.

For Scenarios in which the absolute magnitude of PF4 currents are small (<5kA) with respect to the PF5 current, Use a stress multiplier of 1.4 and a thermal allowance of 74 Mpa.

For Scenarios in which the absolute magnitude of PF4 currents are greater then 5kA used a stress multiplier of 2.6 and the thermal allowance of 74 Mpa.

This stress must be below the static criteria of 156 Mpa and below 125 Mpa for the fatigue Criteria (See Section 6 for Stress Allowables) . Stresses Above 125 Mpa may be allowed if the DCPS Performs Cycle counting and Usage Factor Accumulation



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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
1.24E+10	1.24E+04	1.76E+10	2.60E+10	1.84E+10	3.00E+10	1.60E+10	1.60E+10	1.59E+10	1.59E+10	1.59E+10	1.60E+10	1.62E+10	2.05E+10	7.27E+10	-1.19E+11

"Smeared" Coil theta Stress (hoop and bending)=

=(B6*(afact-hfact)+C6*(bfact-hfact)+D6*(cfact-hfact)+E6*(dfact-dfact)+F6*(efact-hfact)+G6*(ffact-hfact)+H6*(gfact-hfact)+I6*(hfact-hfact)+J6*ifact+K6*(jfact-hfact)+L6*(kfact-hfact)+M6*(lfact-hfact)+N6*(mfact-hfact)+O6*(nfact-hfact)+P6*(ofact-hfact)+Q6*(pfact-hfact))/1000000/1000000*I6 +hfact*I6^2/1000000000000

The equation above includes the plasma. For "No Plasma" the p factor should be set to zero.

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PF4 and 5 Support Columns

The six new columns and the replacements for the old rods in the existing supports are modeled as 3-inch OD pipes with .3 inch wall thicknesses. In table 6.3.5, the PF4U+PF5U load sum from the design point is shown to be nearly equal and opposite to the PF4-L + PF5-L load sum. This is the column compressive load. PF4 loading contributes to a bending stress in the column. The column load divided by the column cross sectional area plus the PF4 load times its offset from the column centerline divided by the column section modulus should remain below the bending allowable for the column material. In the 96 equilibrium results, this value is 200 MPa (30ksi). A material should be selected that has yield about 35 to 70 MPa (5 to 10 ksi) above 200 MPa to provide some margin for the DCPS.

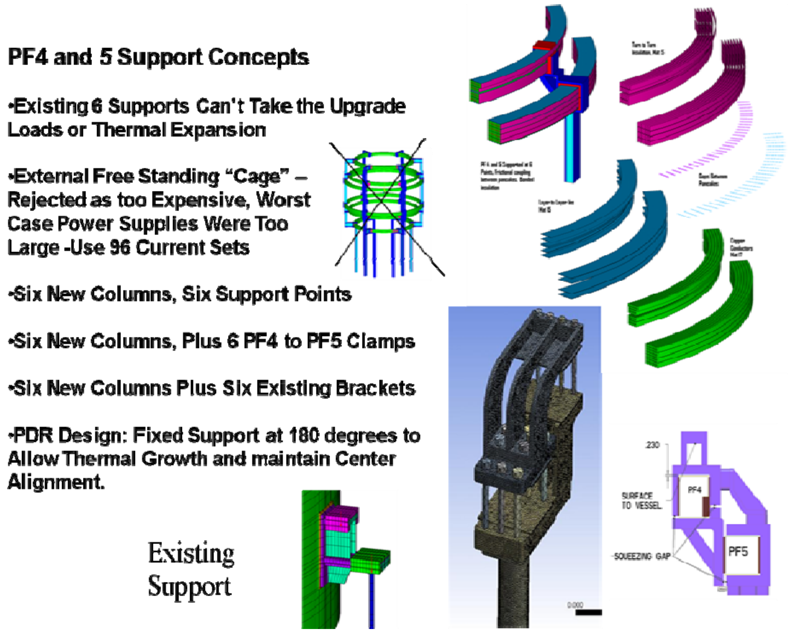
5.0 Introduction and Evolution of the Design

A number of structural concepts for the PF 4 and 5 supports have been considered and analyzed. Early in the upgrade effort "Worst Case Power Supply Loads" were used to size components. This led to a heavy support or frame intended to carry PF4 and 5 loads away from the vessel shell.

The expense of the outer PF frame – particularly the effort associated with removing diagnostics and instrumentation, power and coolant lines, to install the cage structure, led to the investigation of continuing to support the outer PF coils off the vessel. This is the original support concept used by NSTX. The re-categorization of the worst case current loads as “Extremely Unlikely”, as described in the structural design criteria document [3], has allowed consideration of less extensive modifications to the outer PF supports. In this concept, stronger columns are being added to connect the upper PF4/5 groupings and the lower PF4/5 groupings. The location for these six columns is chosen to be between the existing (small/weak) columns. These locations are judged less congested than the existing attachment points. Figure 5.0-1 shows the PF 4/5 support column upgrade mounted on the vacuum vessel.

Upgrade operations will make more extensive use of PF4 and 5, for both current levels and pulse duration. For the upgrade scenarios, the coils will warm to temperatures significantly above current operational values. The coil out-of round condition caused by the Joule heating of PF4 and 5 during normal operation is discussed in section 8.1. The structural concept chosen for the FDR and PDR uses radially restrained supports 180 degrees apart. This causes the coil to deform elliptically when energized and, more significantly, when allowed to heat to 100 degrees C during a long pulse. Table 6.3-2 shows the maximum temperatures expected during upgrade operation.

At the PDR, the columns were 5 inches in diameter and 1/2 inch thick.



PF4 and 5 Support Concepts

- Existing 6 Supports Can't Take the Upgrade Loads or Thermal Expansion
- External Free Standing “Cage” – Rejected as too Expensive, Worst Case Power Supplies Were Too Large -Use 96 Current Sets
- Six New Columns, Six Support Points
- Six New Columns, Plus 6 PF4 to PF5 Clamps
- Six New Columns Plus Six Existing Brackets
- PDR Design: Fixed Support at 180 degrees to Allow Thermal Growth and maintain Center Alignment.

Existing Support

Figure 5.0-1 Earlier Concepts for Support of PF 4 and 5

6.0 Design Input

6.1 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 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] 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] Approximate Rubber Elastic Properties from Wikipedia:

Approximate Young's modulus for various materials[3]

Material	GPa	lbf/in^2 (psi)
Rubber (small strain)	0.01-0.1	1,500-15,000

[9] Analysis of Weld Stresses for Existing PF4/5 Supports, Memo to: Ron Hatcher, Larry Dudek, Danny Mangra, NSTX Distribution, From: Peter Titus Date: Feb 11 2010
[10] NSTX General Requirements Document (GRD)
[11] email from C. Neumeyer providing explanation of temperature specs in the Design Point Spreadsheet, (included in Appendix C)
[12] April 5 2011 email from Jim Chrzanowski: PF's 2,3,4,5 are all mylar wrapped then b-stage fusifab'd (included in Appendix C)
[13] "General Electric Design and Manufacture of a Test Coil for the LCP", 8th Symposium on Engineering Problems of Fusion Research, Vol III, Nov 1979
[14] "Handbook on Materials for Superconducting Machinery" MCIC- HB-04 Metals and Ceramics Information Center, Battelle Columbus Laboratories 505 King Avenue Columbus Ohio 43201

6.2 Criteria

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

Criteria – Static Allowables for Coil Copper Stresses

The TF conductor properties are taken as representative of the PF4 and 5 copper physicals. The OH conductor is taken as representative of the fatigue performance of PF4 and 5. The TF copper ultimate is 39,000 psi or 270 MPa . The yield is 38ksi (262 MPa). Sm is 2/3 yield or 25.3ksi or 173 MPa – for adequate ductility, which is the case with this copper which has a minimum of 24% elongation. Note that the ½ ultimate is not invoked for the conductor (it is for other structural materials) . These stresses should be further reduced to consider the effects of operation at 100C. This effect is estimated to be 10%, so the Sm value is 156 MPa. and the bending allowable is 233 MPa.

- From: 2.4.1.1 Design Tresca Stress Values (Sm), NSTX_DesCrit_IZ_080103.doc [3]
- • (a) For conventional (i.e., non-superconducting) conductor materials, the design Tresca stress values (Sm) shall be 2/3 of the specified minimum yield strength at temperature, for materials where sufficient ductility is demonstrated (see Section 2.4.1.2). [3]
- It is expected that the CS would be a similar hardness to the TF so that it could be wound readily. For the stress gradient in a solenoid, the bending allowable is used. The bending allowable is 1.5*156 or 233MPa,

- (d) For bolting materials, the design Tresca stress values shall be:
  - 2/3 of the ***minimum*** specified yield strength at every point in time;

    ASME B&PV(Section III, Appendix III, Article III-2120) specifies 1/3
  - Also, the component must meet ductility requirements which are to be established for each material not specified by ASME B&PV.

  See Section 2.4.1.4.3 [3] for bolting stress limits.

I-4.1.4.3 Stress Limits for Bolting Material

For preload:

- Bolt preload stress shall not exceed the lesser of 0.75 S_y at room temperature or 0.75 S_y at operating temperature.

For operating loads:

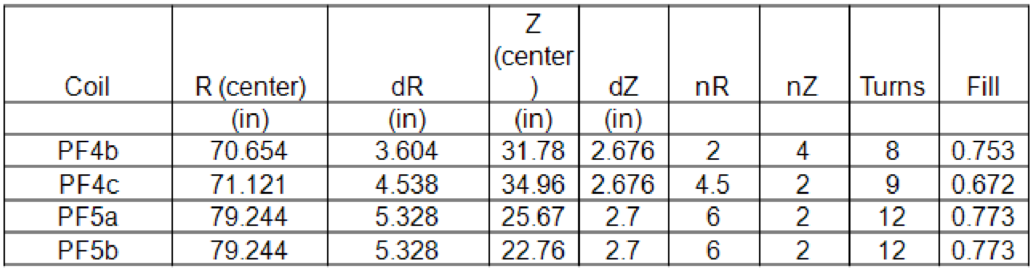
- Average tensile stress due to primary loads shall not exceed 1.0 S_m.
- Maximum direct tension plus bending stress due to primary loads shall not exceed 1.5 S_m.

For preload combined with operation:

At any point in time, combined operating loads and preload shall be evaluated for compatibility with joint design but in any case the maximum direct tension plus preload stress shall not exceed 0.9 S_y.

6.3 Coil Builds Forces and Temperatures from the Design Point

Table 6.3-1 Coil Builds from the Design Point



Coil	R (center)	dR	Z (center)	dZ	nR	nZ	Turns	Fill
	(in)	(in)	(in)	(in)				
PF4b	70.654	3.604	31.78	2.676	2	4	8	0.753
PF4c	71.121	4.538	34.96	2.676	4.5	2	9	0.672
PF5a	79.244	5.328	25.67	2.7	6	2	12	0.773
PF5b	79.244	5.328	22.76	2.7	6	2	12	0.773

Table 6.3-2 Coil Temperatures from the Design Point

Coil	Tmax_LPPI	Tmax_SPFI
	deg C	deg C
OH (half-plane)	100	100
PF4b	33	25
PF4c	33	25
PF5a	100	72
PF5b	100	72

From an email from Charlie Neumeyer [11]:

"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. “

Table 6.3-3 Fr and FzCoil Forces from the Design Point

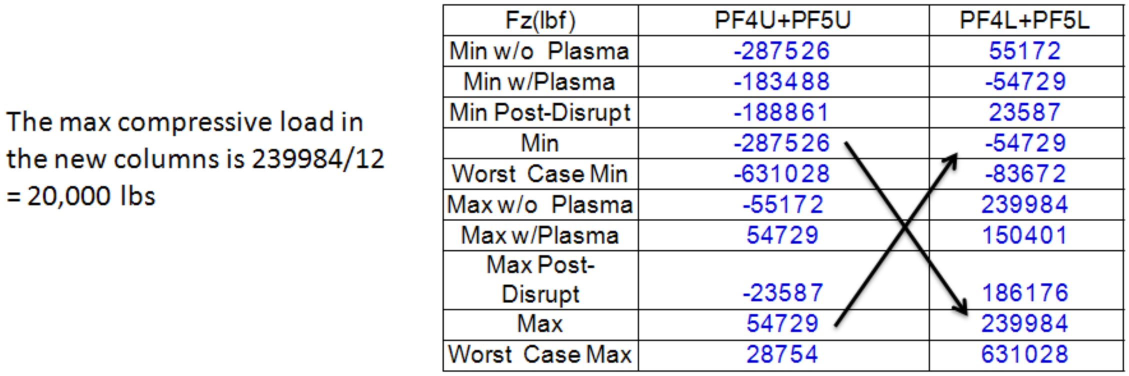
Fr(lbf)	PF4U	PF5U	PF5L	PF4L
Min w/o Plasma	-95013	82112	82136	-95015
Min w/Plasma	-103764	142324	141288	-103805
Min Post-Disrupt	-148517	37584	37596	-148573
Min	-148517	37584	37596	-148573
Worst Case Min	-147018	-20953	-20951	-147020
Max w/o Plasma	260098	507374	507445	260075
Max w/Plasma	287106	625215	625286	287213
Max Post-Disrupt	121449	363572	361490	121496
Max	287106	625215	625286	287213
Worst Case Max	468102	667642	667721	468078

Fz(lbf)	PF4U	PF5U	PF5L	PF4L
Min w/o Plasma	-203072	-239929	-49698	-78007
Min w/Plasma	-171095	-150201	-145201	-63411
Min Post-Disrupt	-89212	-203095	-20016	-133935
Min	-203072	-239929	-145201	-133935
Worst Case Min	-415803	-506937	-181134	-74506
Max w/o Plasma	78007	49698	239929	180275
Max w/Plasma	63403	145201	150218	148314
Max Post-Disrupt	133920	20017	203119	89222
Max	133920	145201	239929	180275
Worst Case Max	149049	181133	506937	415804

Table 6.3-4 Loads from Earlier (PDR) Design Point Spreadsheet

Fz(lbf)	PF4U	PF5U	PF5L	PF4L
Min	-204724	-241452	-50636	-85361
Worst Case Min	-423491	-523610	-191878	-151945
Max	85361	50636	241452	186601
Worst Case Max	151945	191878	523610	423491

Table 6.3-5 Max Column Compressive Loads from Design Point Spreadsheet



The max compressive load in the new columns is 239984/12 = 20,000 lbs

Fz(lbf)	PF4U+PF5U	PF4L+PF5L
Min w/o Plasma	-287526	55172
Min w/Plasma	-183488	-54729
Min Post-Disrupt	-188861	23587
Min	-287526	-54729
Worst Case Min	-631028	-83672
Max w/o Plasma	-55172	239984
Max w/Plasma	54729	150401
Max Post-Disrupt	-23587	186176
Max	54729	239984
Worst Case Max	28754	631028

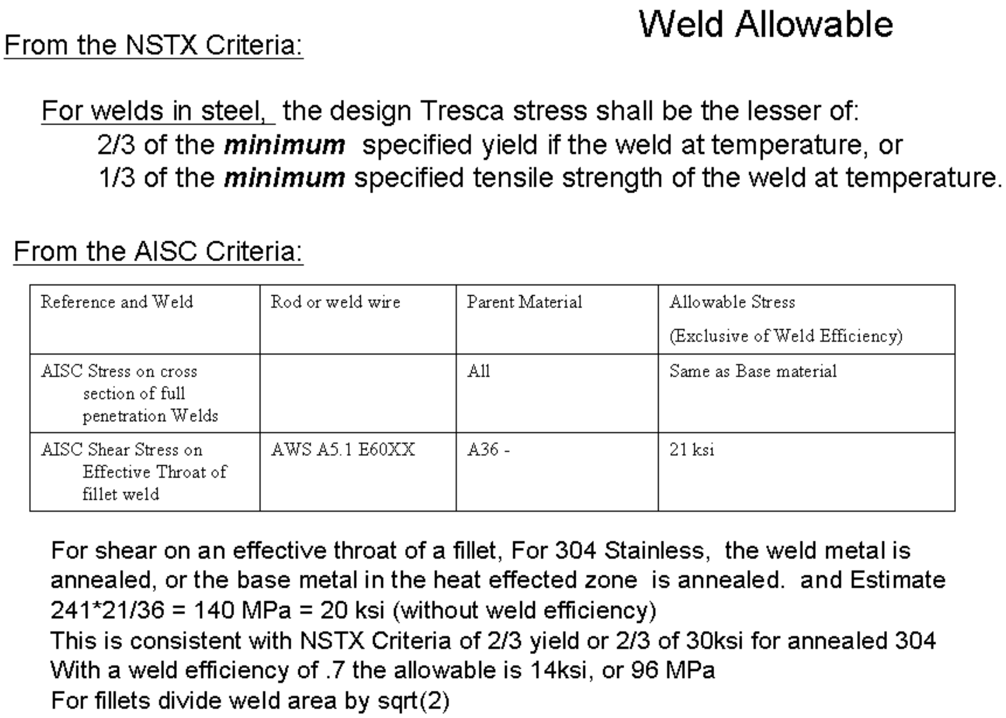
6.4 Materials Properties

Table 6.4-1Tensile Properties for Stainless Steels

Material	Yield, 292 deg K (MPa)	Ultimate, 292 deg K (MPa)
316 LN SST	275.8[13]	613[13]
316 LN SST Weld	324[13]	482[13] 553[13]
316 SST Sheet Annealed	275[14]	596[14]
316 SST Plate Annealed		579
304 Stainless Steel (Bar,annealed)	234 33.6ksi	640 93ksi
304 SST 50% CW	1089	1241 180ksi

Table 6.4-2 Coil Structure Room Temperature (292 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

Material	Sm	1.5Sm
316 Stainless Steel	184	276
316 Weld	161	241
304 Stainless Steel (Bar,annealed)	156MPa(22.6ksi)	234 MPa (33.9ksi)



Weld Allowable

From the NSTX Criteria:

For welds in steel, the design Tresca stress shall be the lesser of:

2/3 of the ***minimum*** specified yield if the weld at temperature, or
1/3 of the ***minimum*** specified tensile strength of the weld at temperature.

From the AISC Criteria:

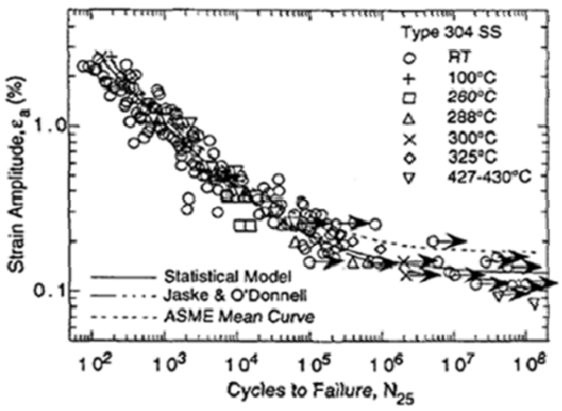
Reference and Weld	Rod or weld wire	Parent Material	Allowable Stress (Exclusive of Weld Efficiency)
AISC Stress on cross section of full penetration Welds		All	Same as Base material
AISC Shear Stress on Effective Throat of fillet weld	AWS A5.1 E60XX	A36 -	21 ksi

For shear on an effective throat of a fillet, For 304 Stainless, the weld metal is annealed, or the base metal in the heat effected zone is annealed. and Estimate 241*21/36 = 140 MPa = 20 ksi (without weld efficiency)
This is consistent with NSTX Criteria of 2/3 yield or 2/3 of 30ksi for annealed 304
With a weld efficiency of .7 the allowable is 14ksi, or 96 MPa
For fillets divide weld area by sqrt(2)

Figure 6.4-1 Weld Allowable

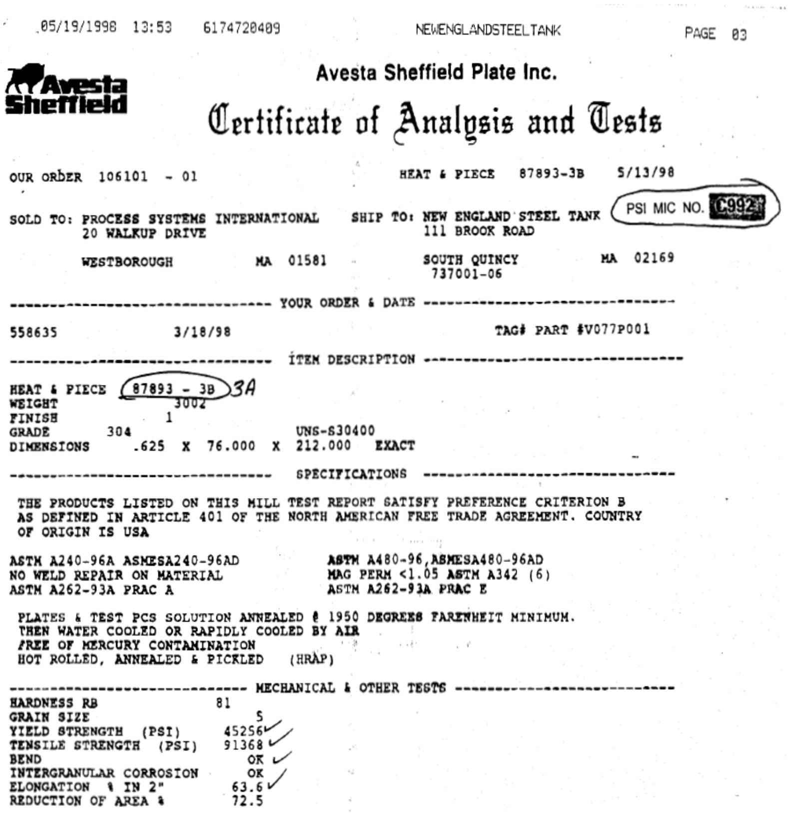
Fatigue:
for a nominal 60,000 cycles, the strain range allowable is ~.175%
For 20 on life, or 1200,000 cycles, the strain range is .15%

Strain Amplitude = 109/200000 = .05%
For 2 on stress or 20 on life the strain allowable is .00175/2 or fro a modulus of 200e9 the allowed stress is 175 Mpa. For a stress concentration of 4, the allowed nominal weld stress is 43.75 Mpa = 6345psi



From Tom Willard's Collection of SST Fatigue Data
"Estimation of Fatigue Strain-Life Curves for Austenitic in Light Water Reactor Environments Stainless Steels", Argonne Nat. Lab. 1998

Figure 6.4-2 Fatigue Allowable for 304 Stainless Steel


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

Avesta Sheffield

Avesta Sheffield Plate Inc.

Certificate of Analysis and Tests

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

PSI MIC NO. C992

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

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

-------------------------------- YOUR ORDER & DATE --------------------------------

558635 3/18/98 TAG# PART #V077P001

-------------------------------- ITEM DESCRIPTION --------------------------------

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

-------------------------------- SPECIFICATIONS --------------------------------

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

ASTM A240-96A ASMESA240-96AD
NO WELD REPAIR ON MATERIAL
ASTM A262-93A PRAC A
ASTM A480-96,ASMESA480-96AD
MAG PERM <1.05 ASTM A342 (6)
ASTM A262-93A PRAC E

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

-------------------------------- MECHANICAL & OTHER TESTS --------------------------------

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

Figure 6.4-3 Vessel Material Mill Certifications for the 304 Vessel Show a 45 ksi Yield

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

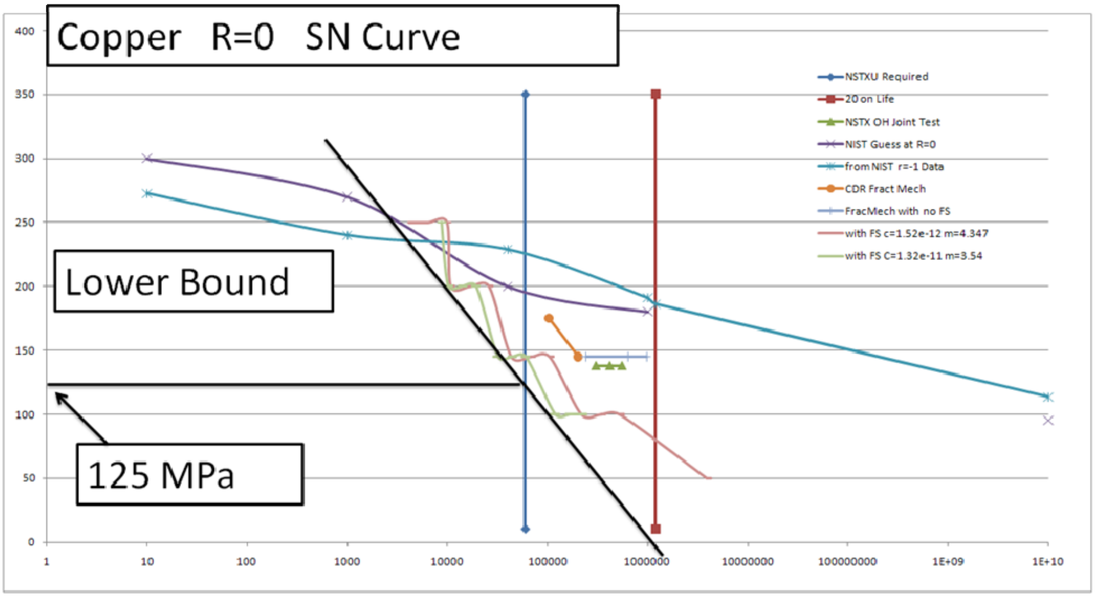


Figure 6.4-4 SN Curve developed for the OH coil in ref [7]

Insulation Shear Stress Allowable

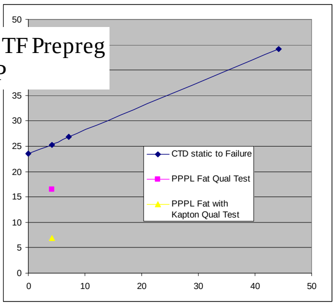
Planned VPI CTD 101K

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

- ***From Criteria Document:***
- ***I-5.2.1.3 Shear Stress Allowable***
- The shear-stress allowable, Ss, for an insulating material is most strongly a function of the particular material and processing method chosen, the loading conditions, the temperature, and the radiation exposure level. The shear strength of insulating materials depends strongly on the applied compressive stress. Therefore, the following conditions must be met for either static or fatigue conditions:
- Ss = [2/3 to]+ [c2 x Sc(n)]

2/3 of 32.5 MPa = 21.7 MPa

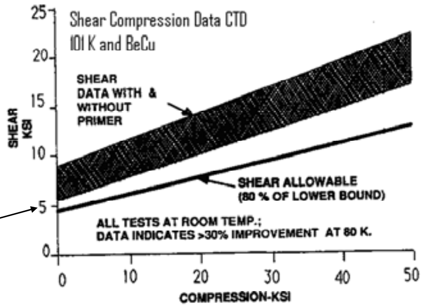
From NSTX TF Test Report:



Existing TF Prepreg
CTD 12P

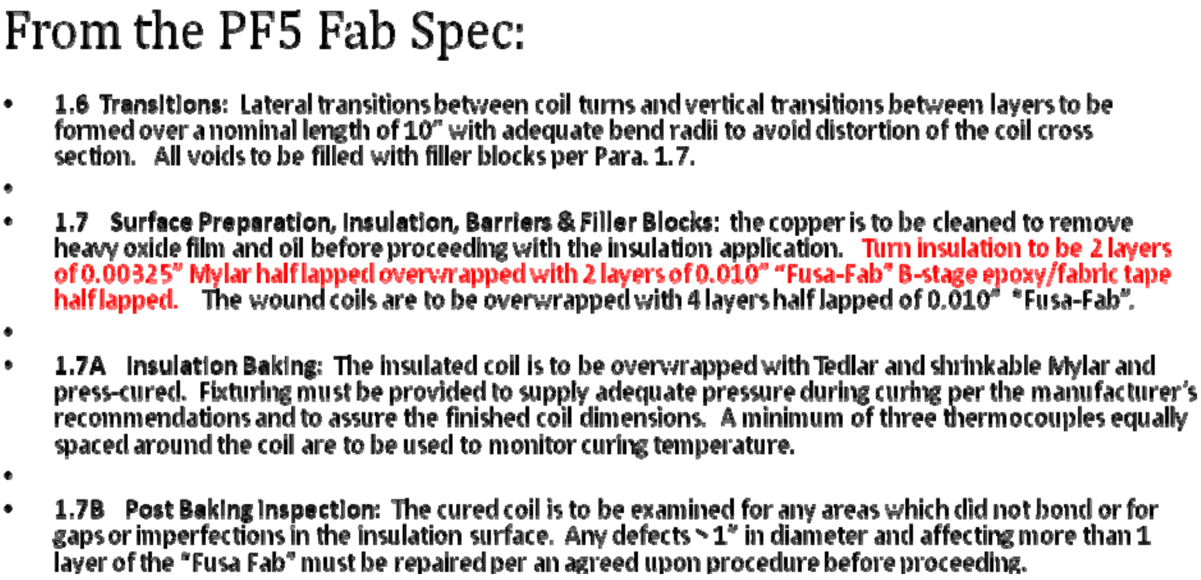
2/3 of 24 = **16 MPa (Static)**
C2~.44
Should be Further De-rated for Fatigue

From an October 27 2009 email
from Dick Reed



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

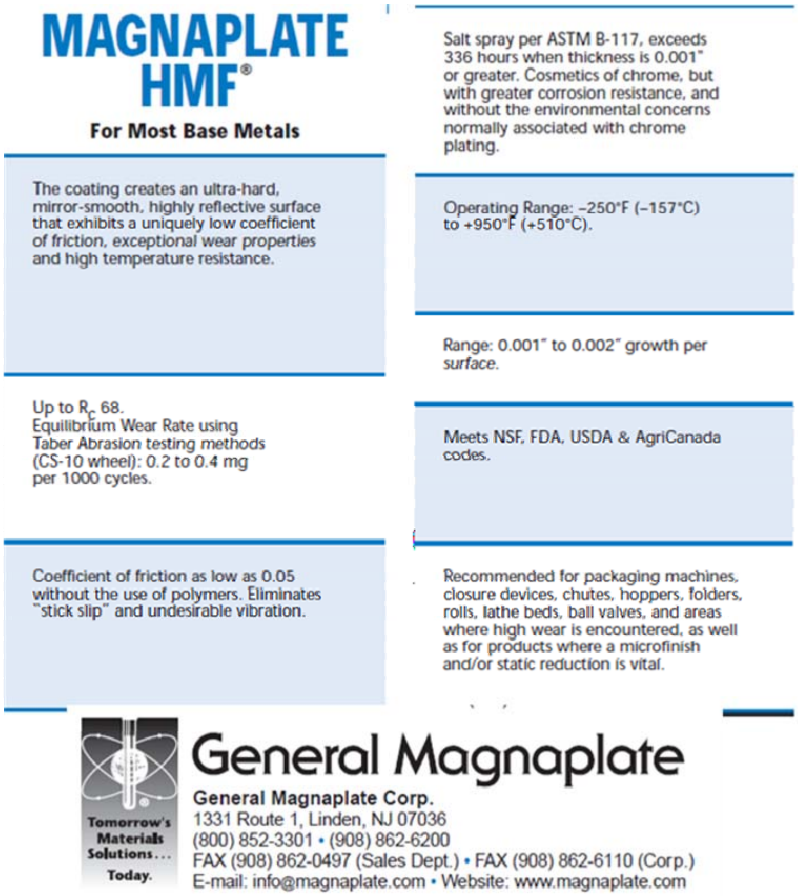
Figure 6.4-5 Insulation Shear Allowable



From the PF5 Fab Spec:

- **1.6 Transitions:** Lateral transitions between coil turns and vertical transitions between layers to be formed over a nominal length of 10" with adequate bend radii to avoid distortion of the coil cross section. All voids to be filled with filler blocks per Para. 1.7.
- **1.7 Surface Preparation, Insulation, Barriers & Filler Blocks:** the copper is to be cleaned to remove heavy oxide film and oil before proceeding with the insulation application. Turn insulation to be 2 layers of 0.00325" Mylar half lapped overwrapped with 2 layers of 0.010" "Fusa-Fab" B-stage epoxy/fabric tape half lapped. The wound coils are to be overwrapped with 4 layers half lapped of 0.010" "Fusa-Fab".
- **1.7A Insulation Baking:** The insulated coil is to be overwrapped with Tedlar and shrinkable Mylar and press-cured. Fixturing must be provided to supply adequate pressure during curing per the manufacturer's recommendations and to assure the finished coil dimensions. A minimum of three thermocouples equally spaced around the coil are to be used to monitor curing temperature.
- **1.7B Post Baking Inspection:** The cured coil is to be examined for any areas which did not bond or for gaps or imperfections in the insulation surface. Any defects ~ 1" in diameter and affecting more than 1 layer of the "Fusa Fab" must be repaired per an agreed upon procedure before proceeding.

Figure 6.4-6



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Equilibrium Wear Rate using Taber Abrasion testing methods (CS-10 wheel): 0.2 to 0.4 mg per 1000 cycles.

Coefficient of friction as low as 0.05 without the use of polymers. Eliminates "stick slip" and undesirable vibration.

Salt spray per ASTM B-117, exceeds 336 hours when thickness is 0.001" or greater. Cosmetics of chrome, but with greater corrosion resistance, and without the environmental concerns normally associated with chrome plating.

Operating Range: –250°F (–157°C) to +950°F (+510°C).

Range: 0.001" to 0.002" growth per surface.

Meets NSF, FDA, USDA & AgriCanada codes.

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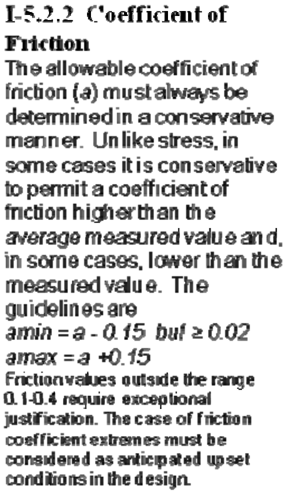
Figure 6.4-7 Magnaplate properties



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
$a_{min} = a - 0.15$ but ≥ 0.02
$a_{max} = a + 0.15$

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.

6.5 Coil Geometry and Currents

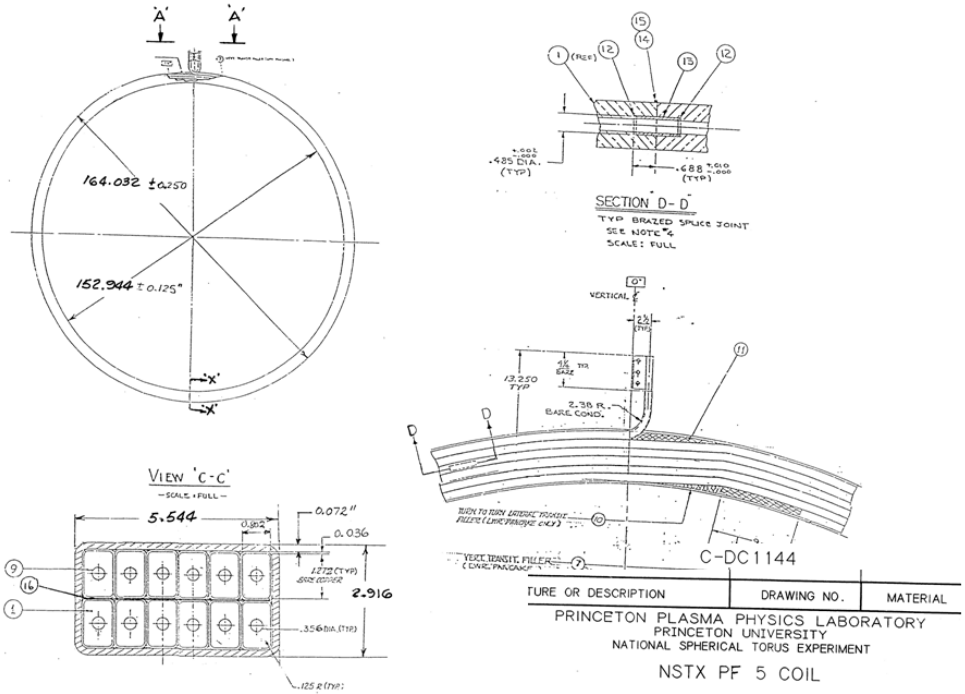


Figure 6.5-1 PF5 Coil Details

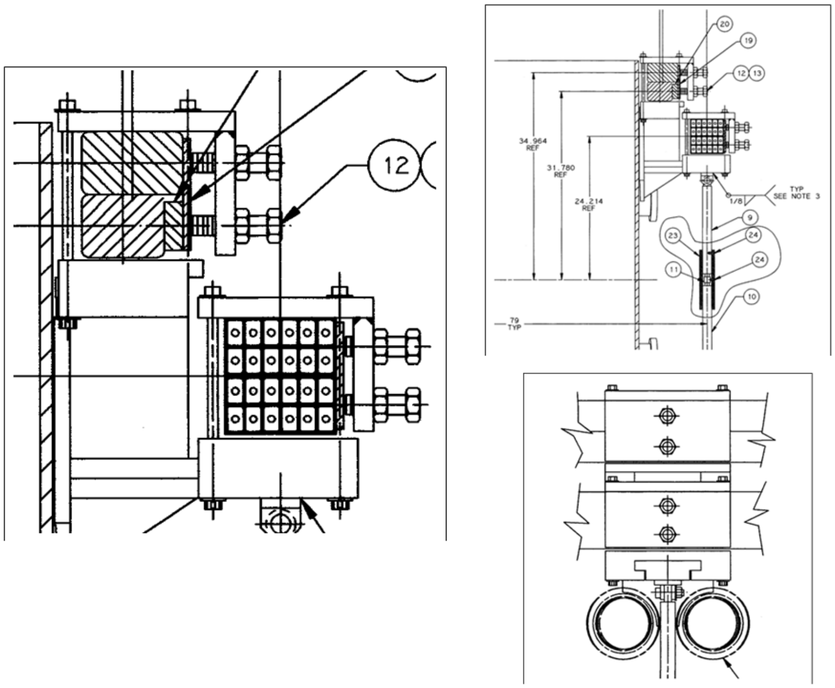


Figure 6.5-2 PF4/5 Existing Bracket Details

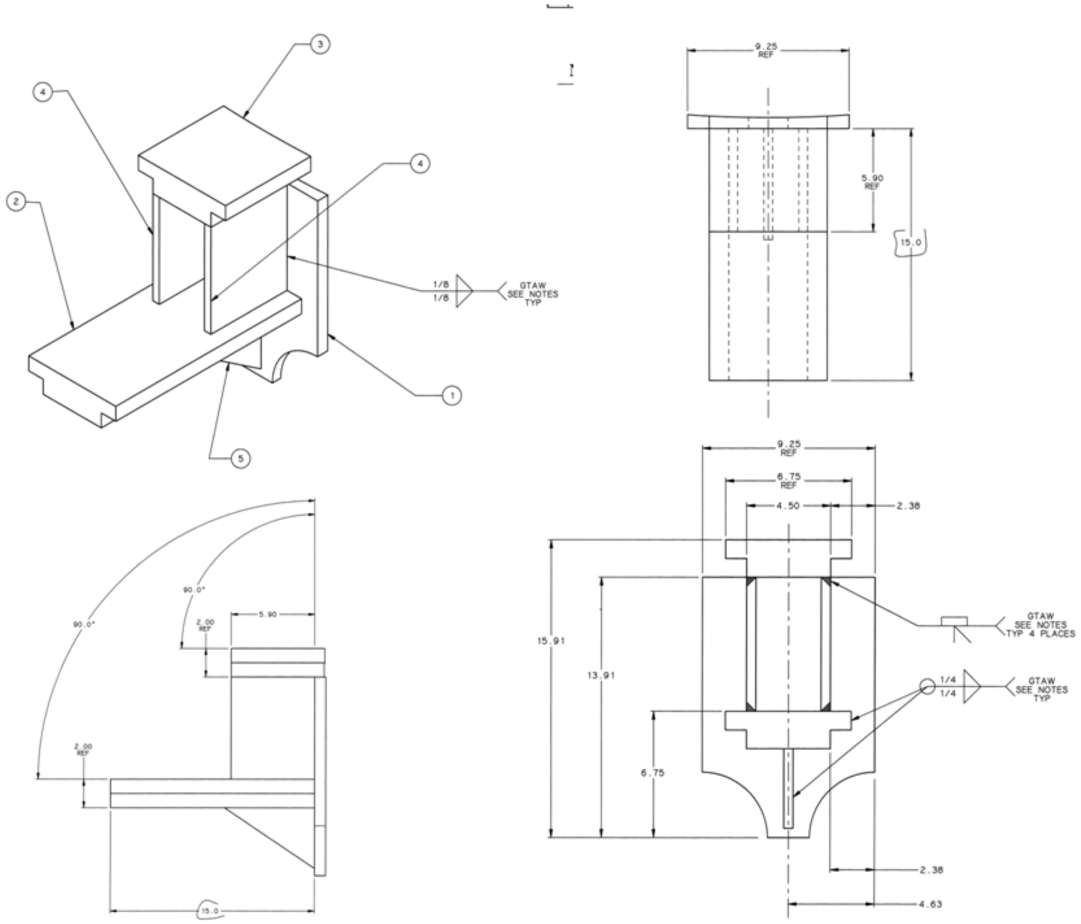


Figure 6.5-3 PF4/5 Existing Bracket Type B Bracket Details

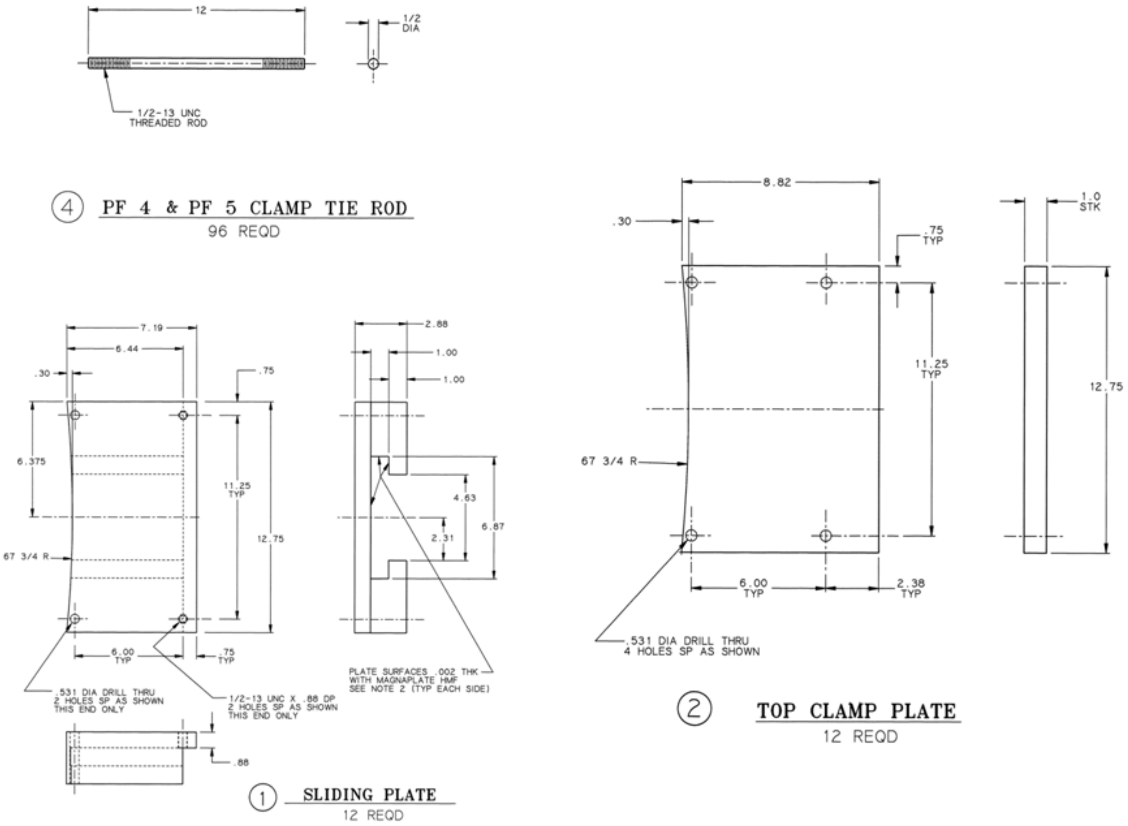


Figure 6.5-4 PF4/5 Existing Coil Clamp Details

6.6 Elastic Constants, Thermal Expansion Coefficients

There are no composite or orthotropic moduli used in these models. Isentropic moduli are listed below:

```
*do,imat,1,100
ex,imat,200e9
alpx,imat,17e-6
r,imat,10e8
*enddo
ex,90,1e9
ex,3,20e9
ex,5,20e9
ex,6,2e6
ex,7,2e6
ex,17,110e9
mu,6,.3
```

7.0 Coil and Support Model

The analysis model used for both the coils and support details is a quarter symmetry model. The vertical symmetry plane cuts through the two radially fixed supports which are two of the existing sliding block supports that have been locked. Equatorial plane symmetry is also imposed, so net vertical loading must be addressed in the global model [1]. Coil loads have been calculated from combinations of coil full current levels. Other coils are not included in the Lorentz calculations for this model. Effects of the other coil currents are addressed in other models - the global model [2] and exercising the DCPS multipliers for the latest scenarios, with and without the plasma. The model discussed in this section includes the coil cross section, pancake structures, and individual conductors and insulation layers. It was expected that the self attractive loads between pancakes would affect their ability to support bending moments due to vertical loading. The coils are supported at discrete support brackets and columns around the perimeter of the coils. In order to include the flexibility of the vessel shell, and evaluate the weld stresses of the attachments to the vessel, a portion of the vessel shell is included.

7.1 Model Elements

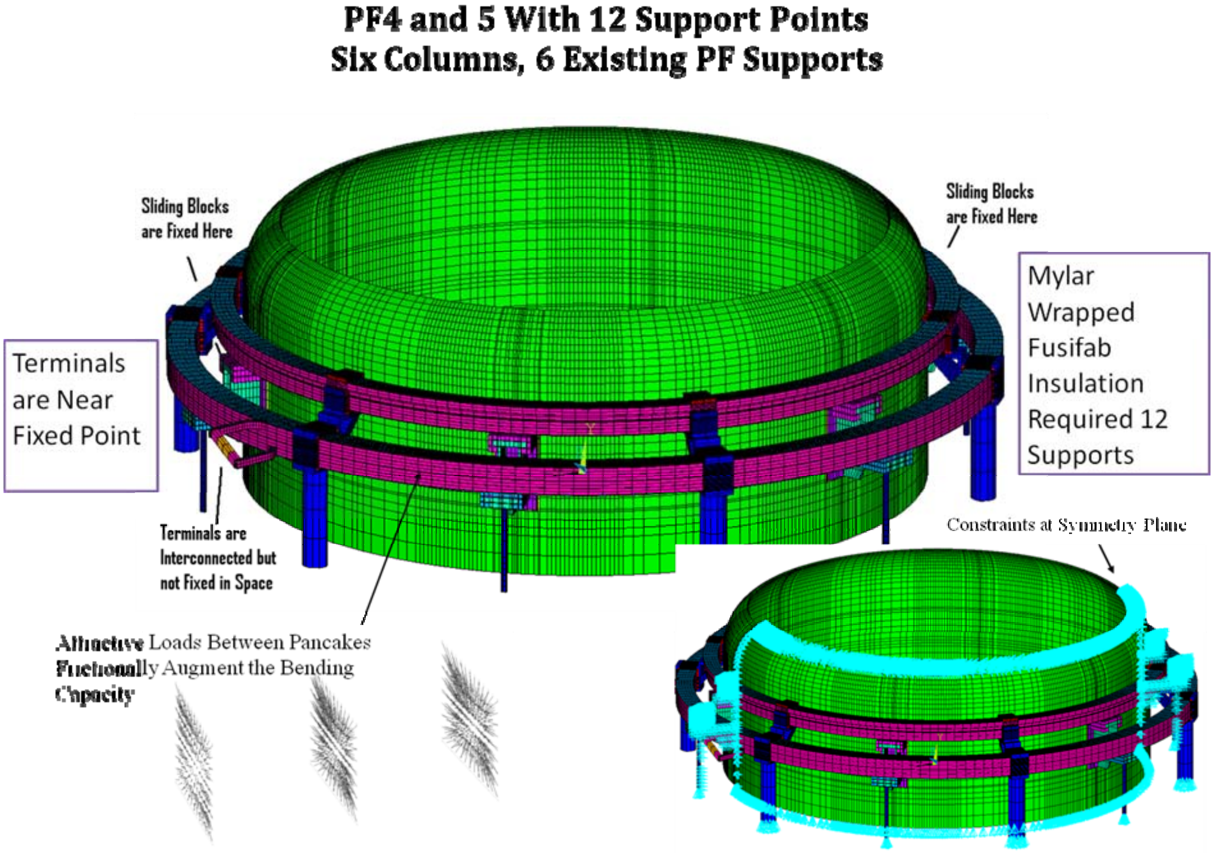


Fig. 7.1-1 180 Symmetry Model with 12 Supports

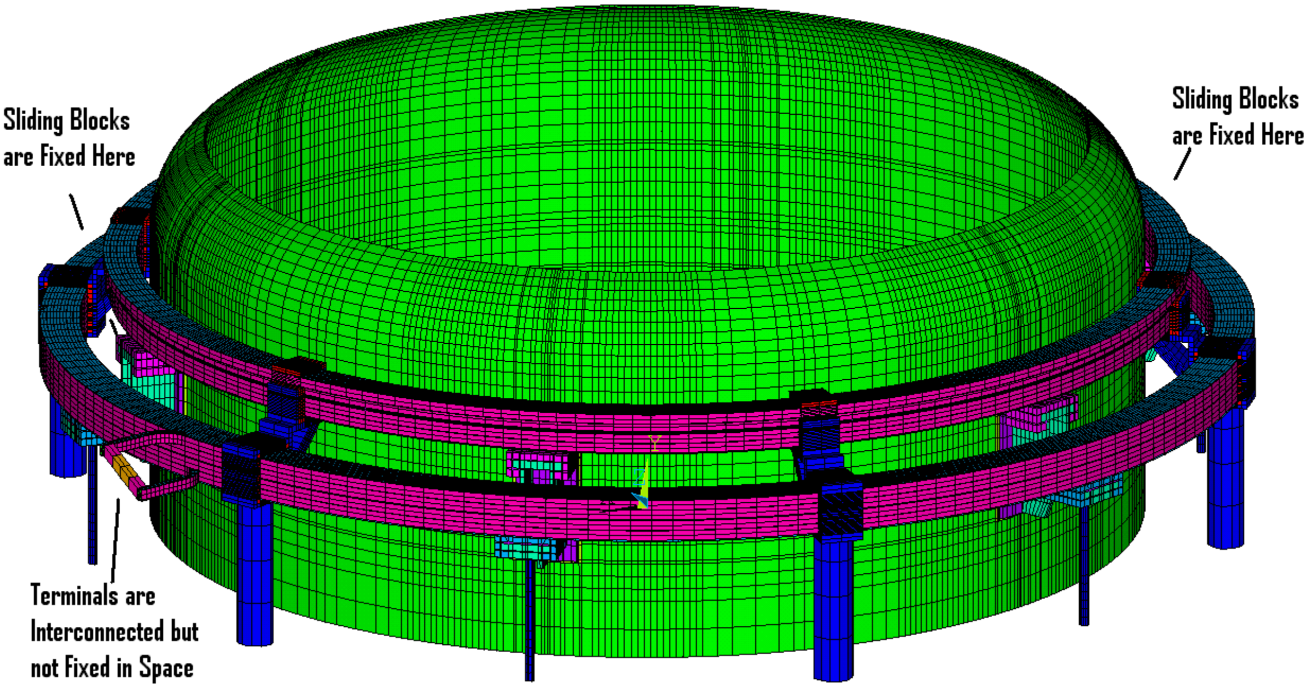


Fig. 7.1-2 Model of the PF4 and 5 supports - Support Column Upgrade Mounted on the Vacuum Vessel

The mesh generation and calculation of the Lorentz forces is done outside of ANSYS using a code written by the author of this report. The mesh generation feature of the code is checked visually and within ANSYS during the PREP7 geometry check. The author's code uses a Biot Savart solution for field calculations, based on single stick field calculations from Dick Thome's book [6] with some help from Pillsbury's FIELD3D code to catch all the coincident current vectors, and other singularities. The analysts in the first ITER EDA went through an exercise to compare loads calculated by the US, RF and by Cees Jong in ANSYS, and confirmed that the US analyses were "OK". Agreement was not good on net loads on coils that should net to zero – all the methods had some residuals, but summations on coil segments agreed very well. Some information on the code, named FTM (Win98) and NTFTM2 (NT,XP), is available at: http://198.125.178.188/ftm/manual.pdf), and on the P drive under P:\public\Snap-srv\Titus\NTFTM.

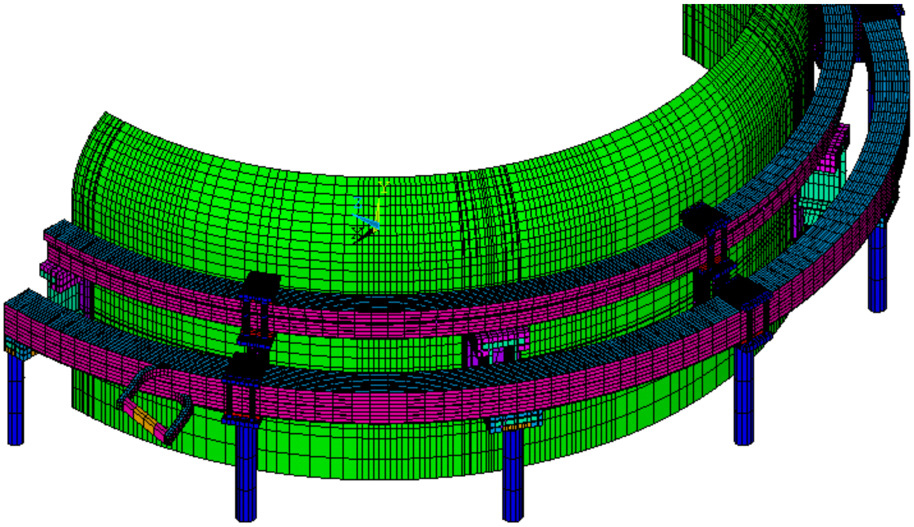


Fig. 7.1-3 June 2011 Model of the PF4/5 Support System with Heavier Columns all Around

7.2 Fields and Forces

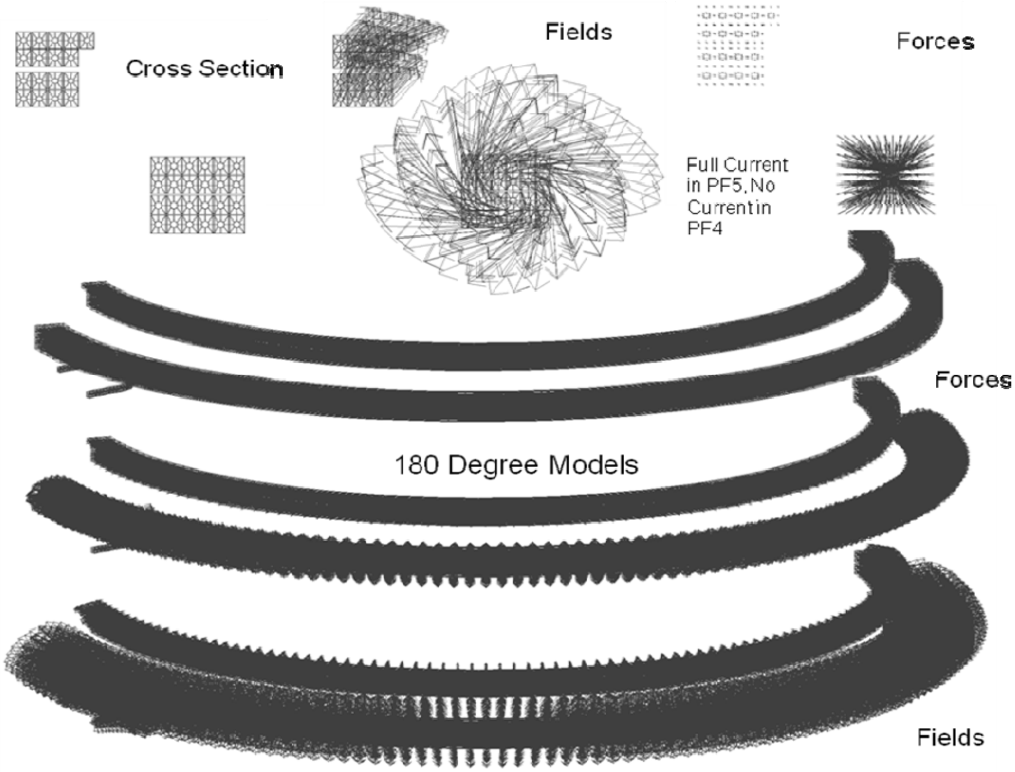


Figure 7.2-1 Fields and Forces for the 180 degree Symmetry Model with Full Current in PF5 and zero current in PF4

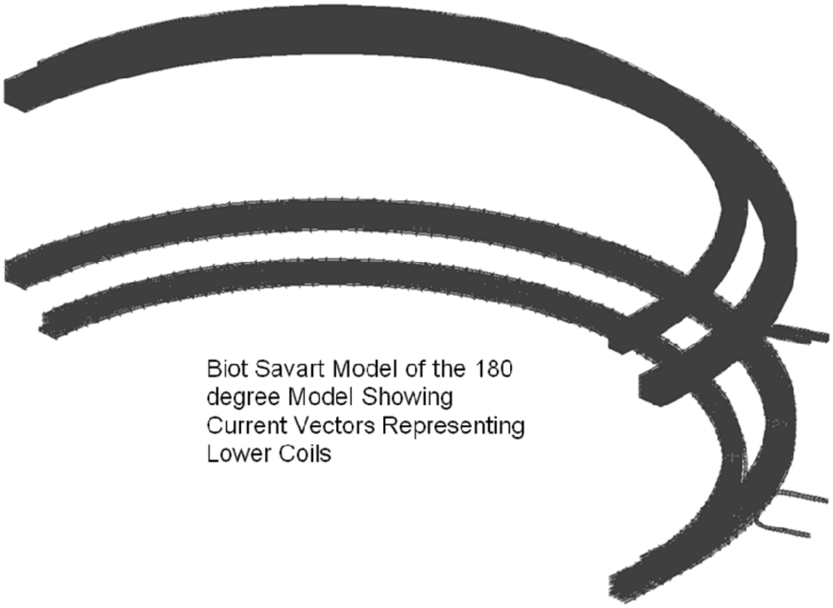


Figure 7.2-2 Biot Savart Model showing the current sticks modeling the lower coils - These are deleted in the structural model and up-down symmetry is assumed for this model. Up down asymmetries are evaluated from loads in the Design Point Spreadsheet.

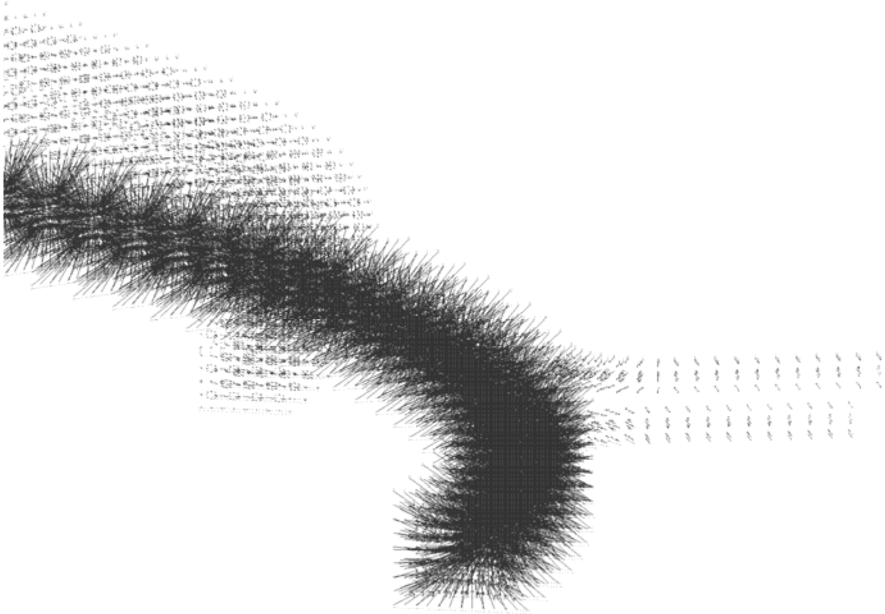


Figure 7.2-3 Local Detail of the Lorentz Forces at the Coil Leads

7.3 Provisions for Differential Thermal Growth of PF4 and 5 - Results for the Link Concept

From the NSTX Design Point Spreadsheet [4], the max temperature in PF4 is 33C degrees and PF5 is 100C degrees. The design Point Summary of these temperatures is included in Section 6.3.

While the link concept is not being used, as a mechanism, it provides the needed degrees of freedom to allow independent thermal expansion of PF4 and 5. In the present FDR design, a sliding T slot or dovetail joint is used similar to the sliding joint used in the existing support.

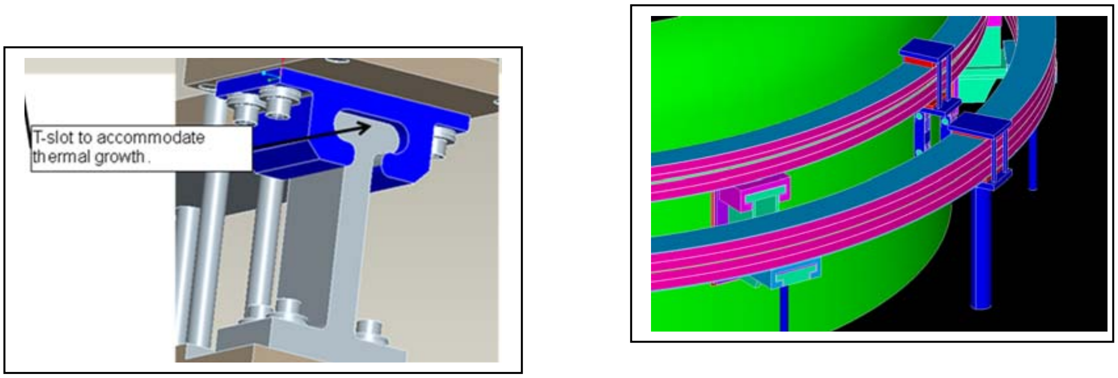


Figure 7.3-1 Left: Final Design Dovetail Slide, Right: The link Design, Mechanically Similar to the Dovetail

7.4 Run Log Files and File Locations

Run files and some results will be put on the pdrive.

P drive:
P:\public\Snap-srv\Titus\NSTX\CSU\PF45Sup

ptitus-64pc
Clam03.txt, f:\nstx\csu\PF45Sup
\nstx\csu\pf45sup\Dove01.txt April 2011
\nstx\csu\PF45Sup\Coib03\   Coib05.txt,   Link concept that allows differential thermal growth between PF4 and 5

Laptop
OuterPFs/ProE   Existing support
OuterPFs/RonHatcher   Existing support Weld Influence Coefficients
OuterPFs/Thermal   Bake-out Thermal Gradient around existing support

Titus_64 (Andrei's Computer)
e:\run27   Latest Global Model Files
e:\nstx\csu\pf45Sup   Larry's Model

8.0 PF 4 and 5 Results

8.1 Displacement Results

PF4 and 5 have to be aligned with respect to the centerline of the plasma. The present (meaning prior to the upgrade) approach is to connect pushers and clamps around the coils to push the coils into roundness and concentricity. Currently, coil heat up is trivial. For the upgrade, the coils will be on for the 5 sec. pulse and will heat to 100C - expanding and fighting the alignment clamps. John Menard and Masa Ono were consulted. An n=2 error, i.e., an elliptical coil, is acceptable as long as it is aligned with the plasma centerline - i.e., it precludes an n=1 error. So the coils are radially held with respect to the vessel and have them grow into an oval. The degree of ovality was presented, discussed and accepted by Menard and Ono.

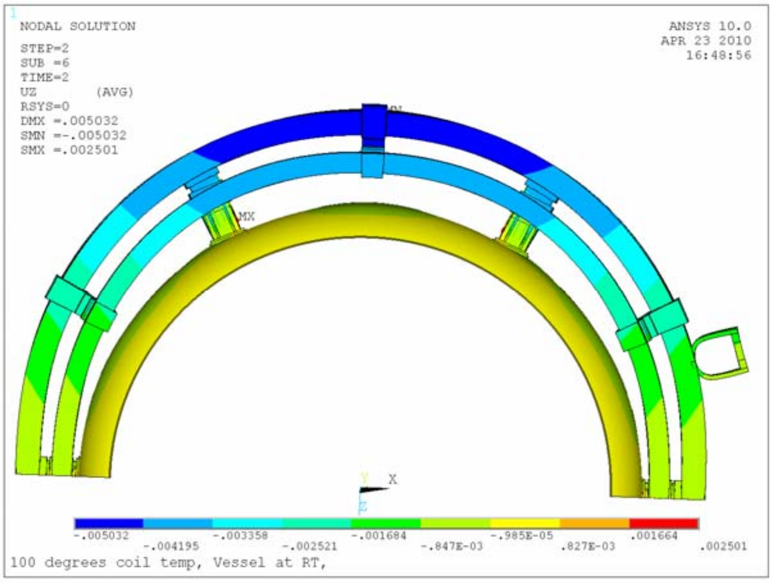


Figure 8.1-1   Coils held radially at left and right. Existing supports free to slide. Coils at 100C

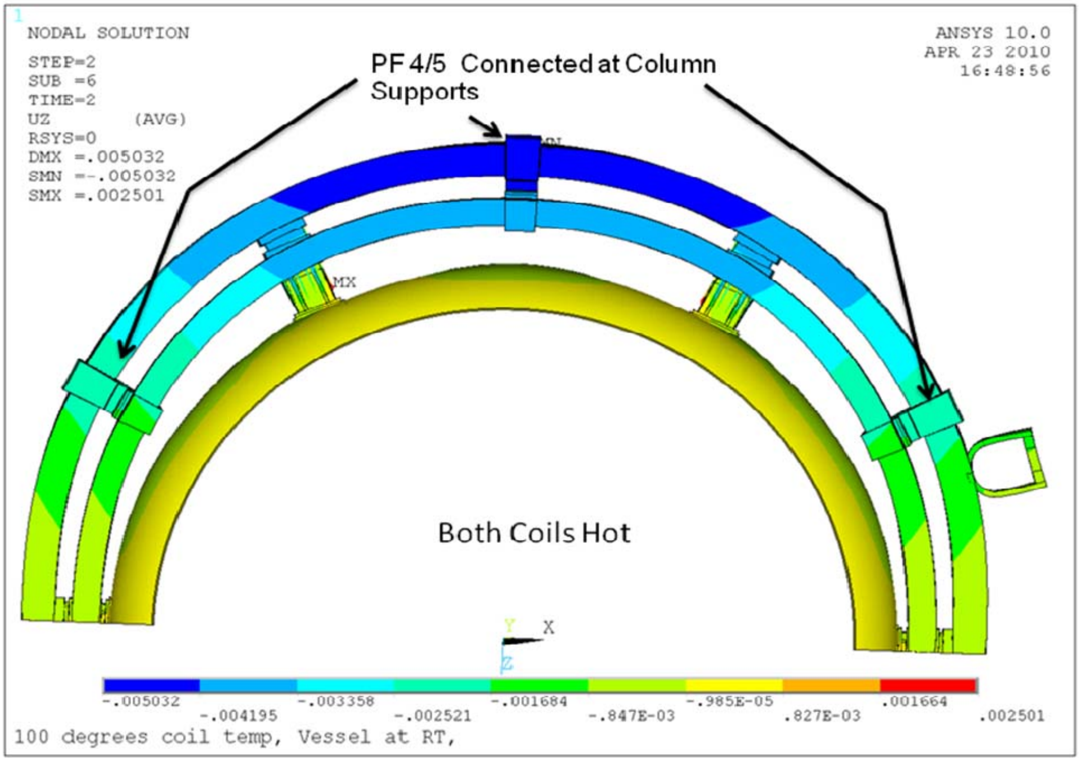


Figure 8.1-2 Coils held radially at left and right. Existing supports free to slide. Coils at 100C

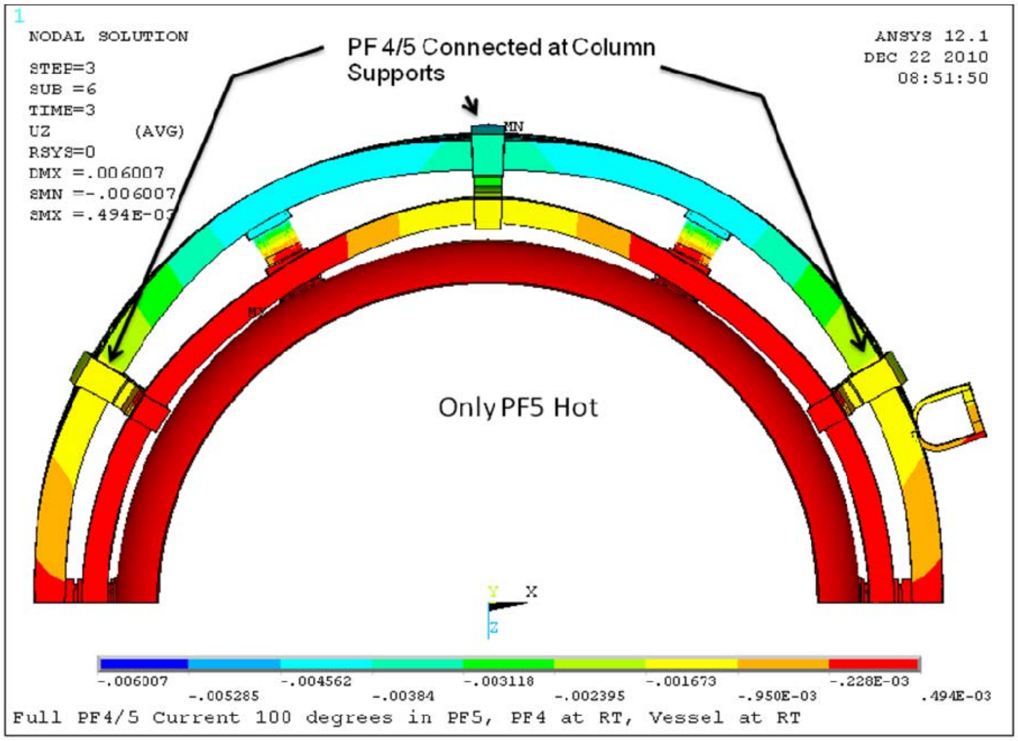


Figure 8.1-3 Coils held radially at left and right. Other supports free to slide. PF5 at 100C, PF4 and 5 clamped together at added support columns

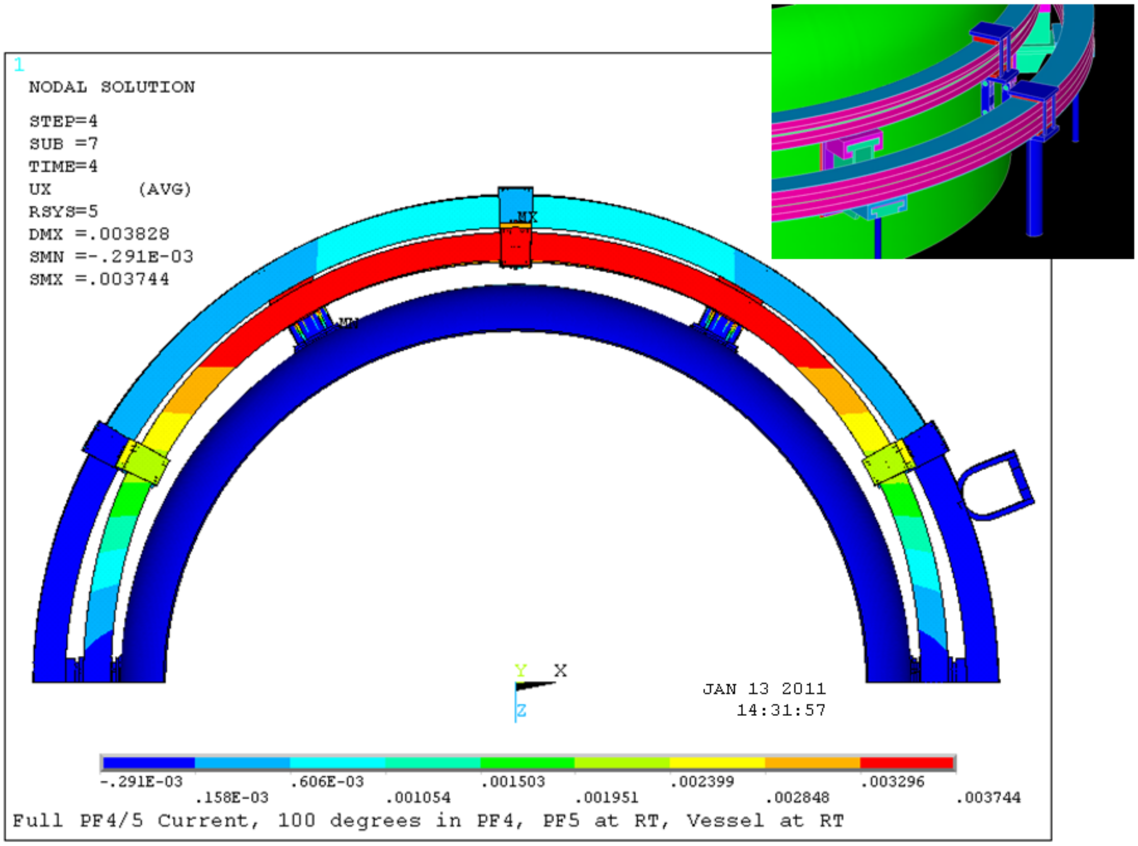


Figure 8.1-4 Coils held radially at left and right. All other supports free to slide. PF4 at 100C PF 5 at RT

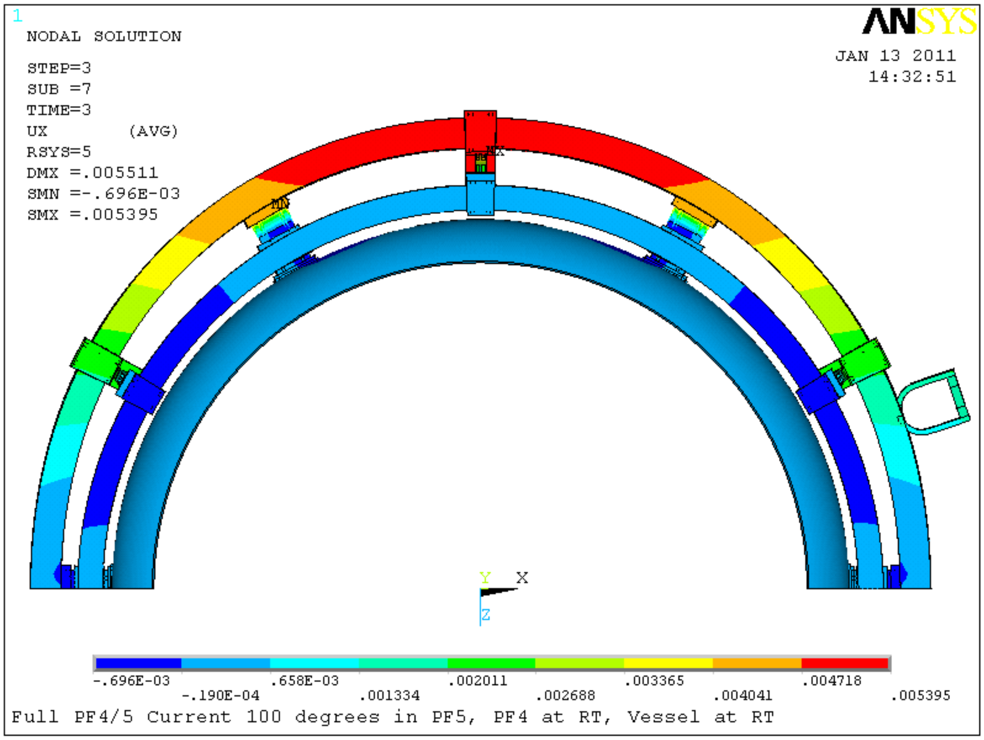


Figure 8.1-5 Coils held radially at left and right. All other supports free to slide. PF5 at 100C, PF4 at RT

8.2 PF 4 and 5 Coil Conductor Stress Results

The global model, [2] produces stress results for the 96 scenarios and for cases with and without the plasma. The coils in this model are "smeared" and do not include the effects of the details of the conductor cross section - insulation layers and coolant holes. The smeared Von Mises Stress values in the figures below are modest, 57 MPa, 63 MPa, 62 MPa and 60 MPa for scenarios 3, 13, 33, and 43, respectively. These are scenarios run without a plasma. The thermal effects of warm expanded coils are not included in the global model. These are simulated in the model, which has winding pack details and the mechanics of the sliding connections at the new column locations.

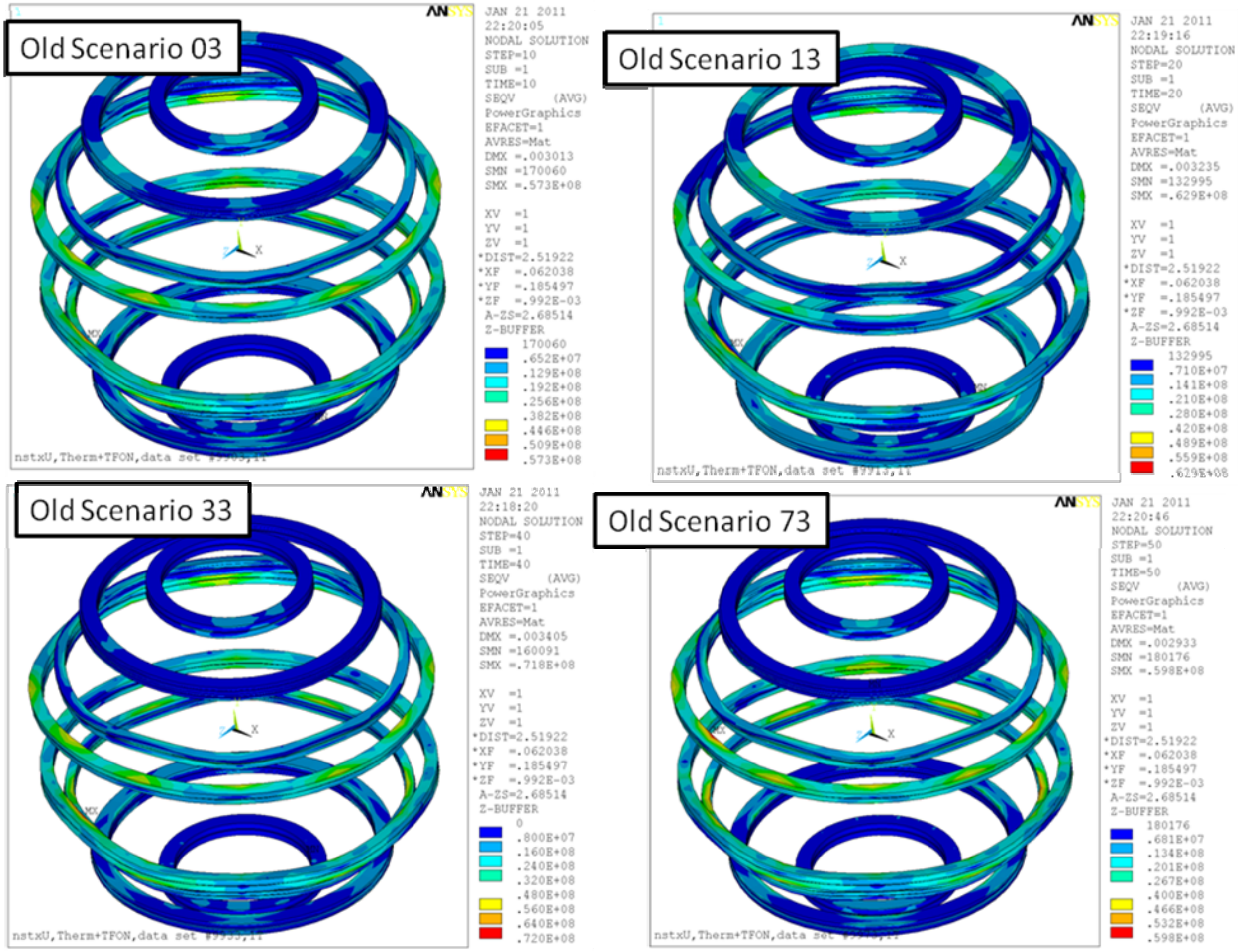


Fig 8.2-1 Global Model Results for PF4 and 5, ref [2]

In order to assess the effects of the latest scenarios, the DCPS stress multipliers offer an attractive method of keeping up with the evolution in the design point spreadsheet currents. These latest GRDS requirements include with and without plasma, and variations in plasma shape and disruption inductive coupling of the coils with the decaying plasma.

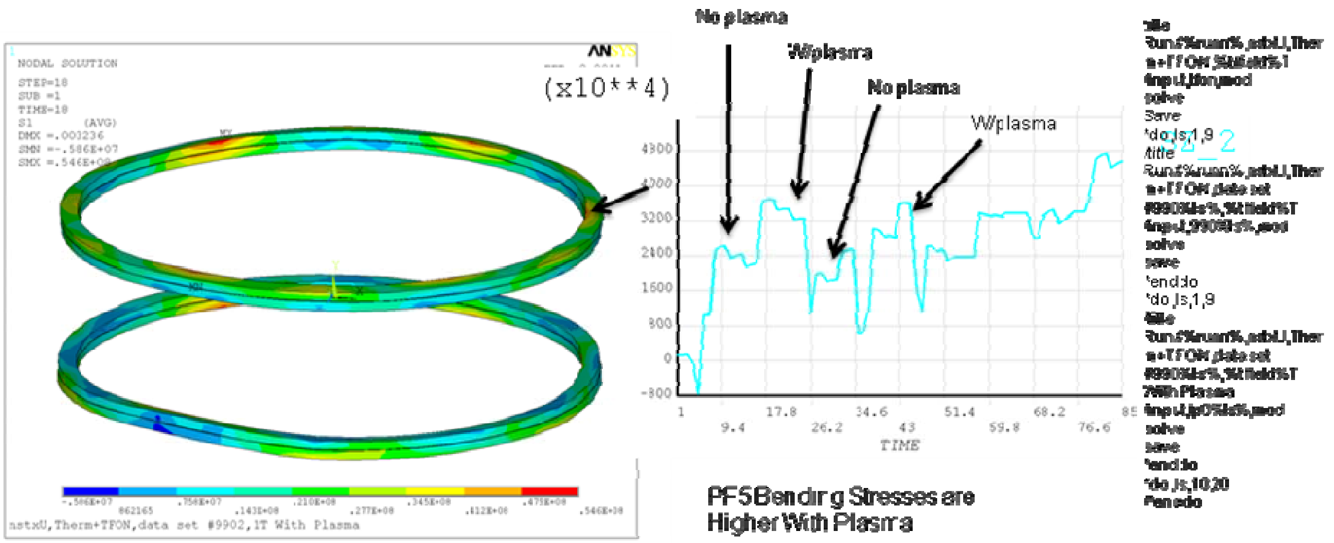
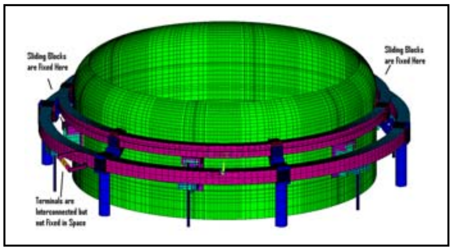


Fig 8.2-2 Global Model Results for PF5, Bending Stress ref [2]

Coil Conductor Stress

The stress in the conductor, for Lorentz loads and thermal loads, with PF4 and 5 at the same temperature, is shown below. Peak stresses are where the coils are restrained radially at the existing clamps near the lead and 180 degrees away from the lead.

The Sm value for the coil cold worked copper is expected to be similar to the TF specs or Sm is 156 MPa with the bending allowable at 233 MPa (see the criteria in section 6). Fatigue is addressed in section 11. Peak Stresses, below, are all above the 233 MPa limit.



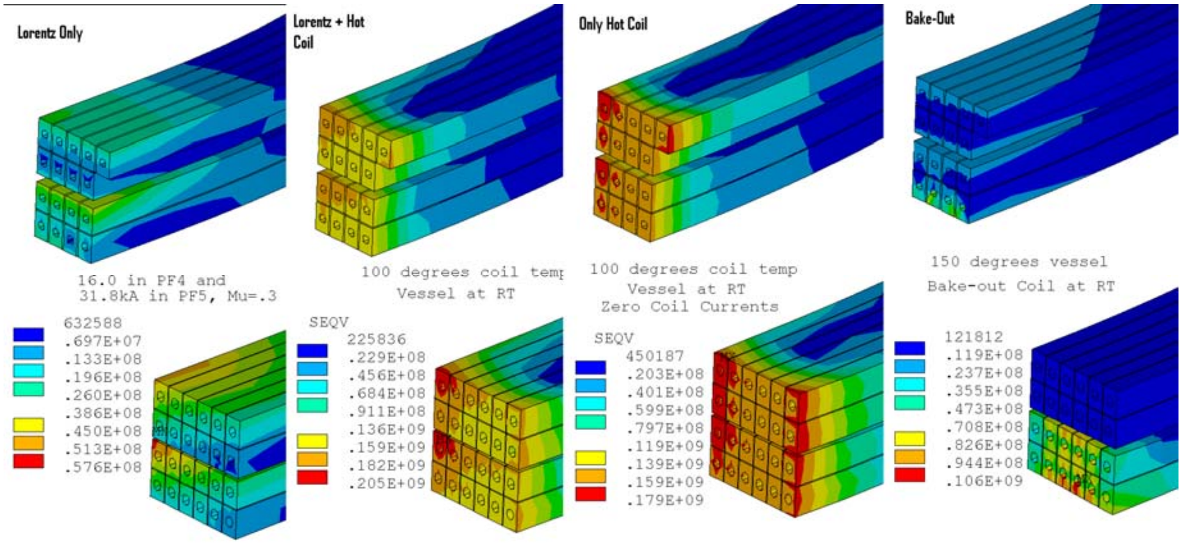


Fig 8.2-3 PF 4 and 5 Conductor Stress from the Quarter Symmetry Model

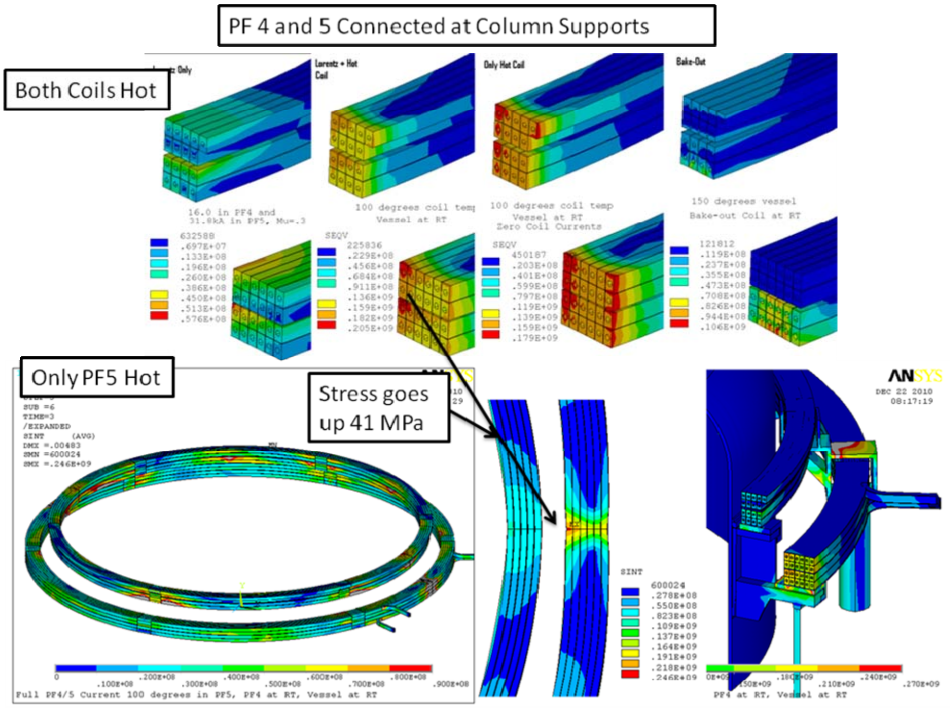


Fig 8.2-4   PF 4 and 5 Conductor Stress from the Quarter Symmetry Model with PF 4 and 5 connected at the Mid Span Supports

With PF4 and 5 rigidly connected at the added support column locations, and only PF5 hot, the stress goes up 41 MPa and is above the 233 MPa static limit.

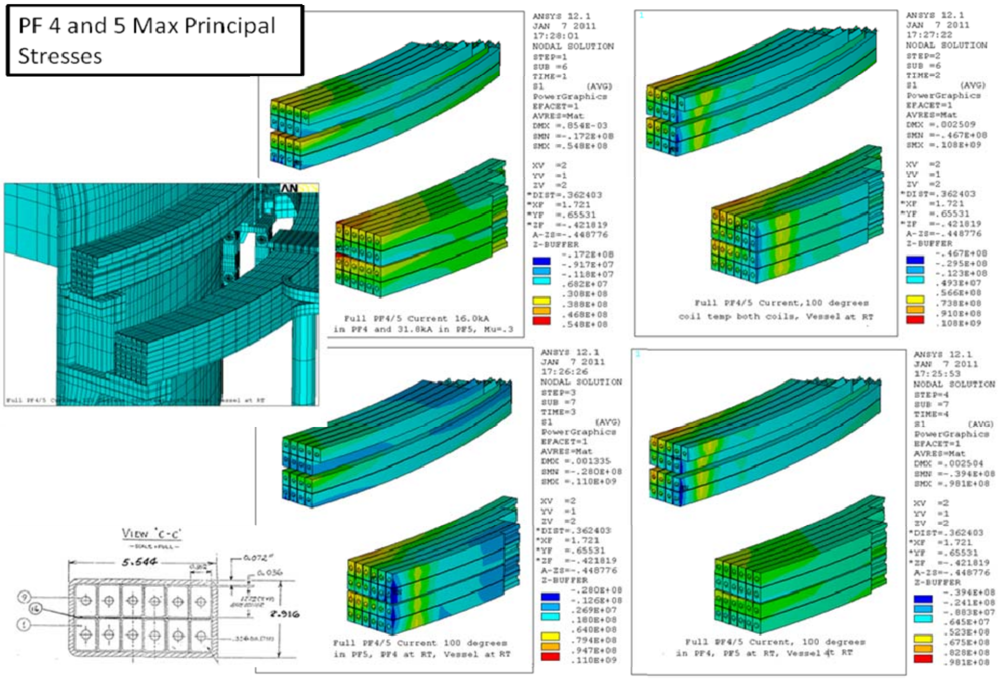


Fig 8.2-5   PF 4 and 5 Conductor Stress with a Mechanism (Pinned Links) to allow differential radial motion of PF4 and 5

8.3 PF4 and 5 Coil Insulation Stress

Insulation Stress, or more properly, insulation shear displacements, were an important concern that led to the adoption of 12 support points for the coils. The insulation system used for the PF5 coil is a mylar wrapped Fusifab Epoxy system that is expected to have minimal bond strength. Analysis of a support concept that utilized six new support columns, and did not rely on the existing support brackets, is discussed in Appendix A. This produced large copper bending stresses.

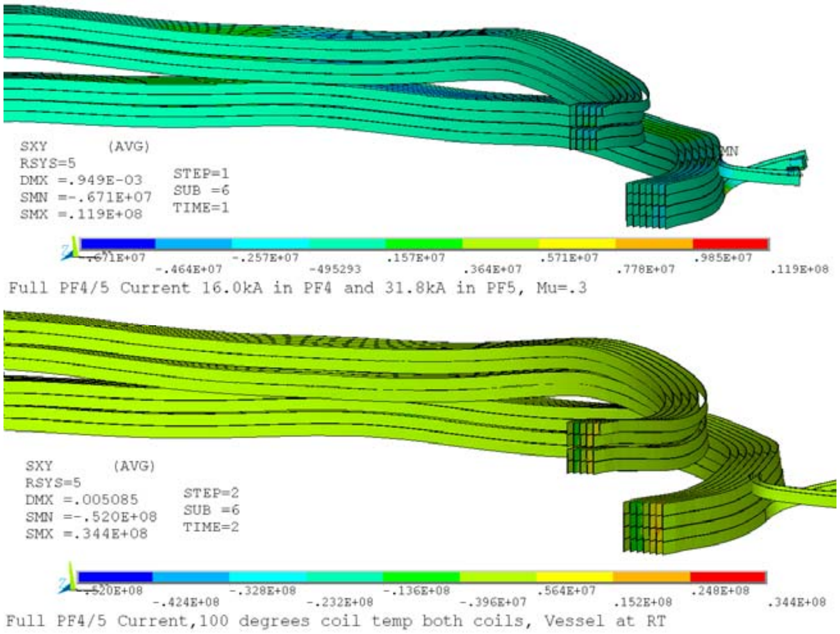


Figure 8.3-1 Radial -Theta Shear for Lorentz and Lorentz plus Both Coils Hot

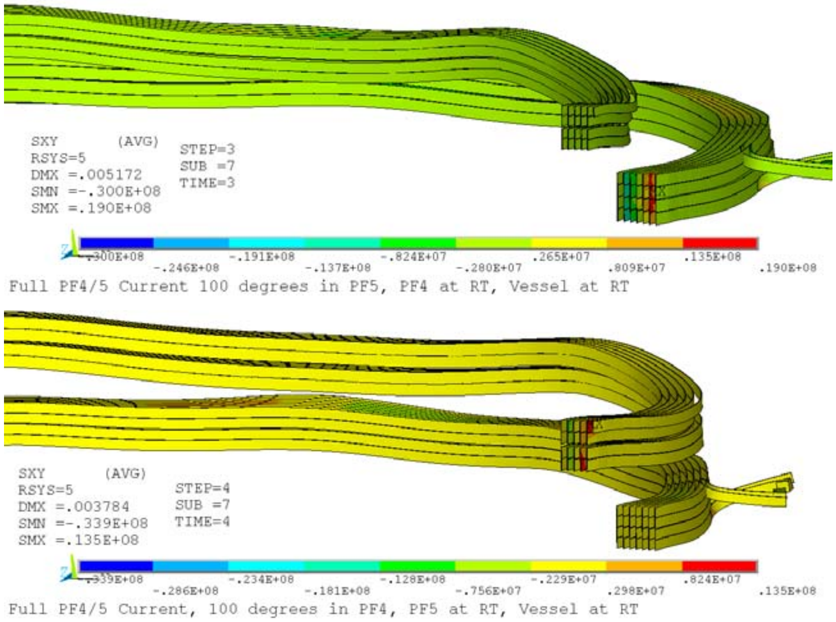


Figure 8.3-2 Radial -Theta Shear for Lorentz and Lorentz plus Hot PF5/Cold PF4

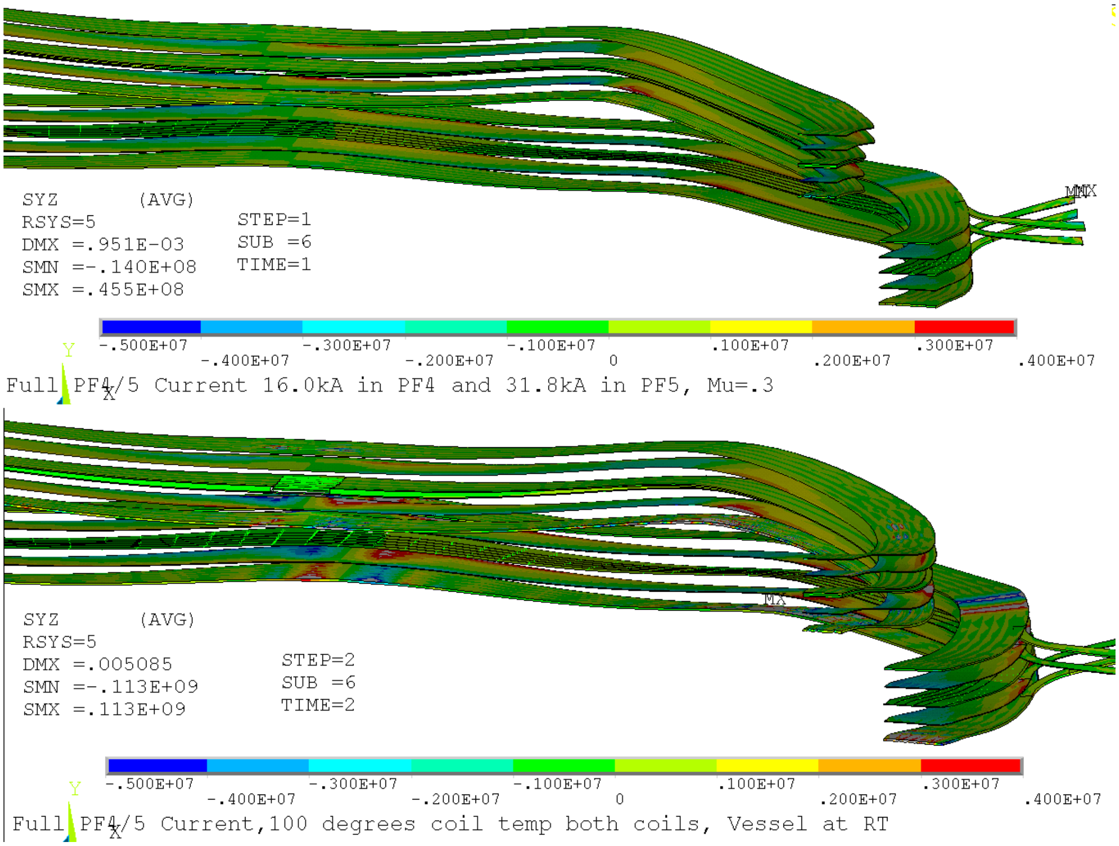
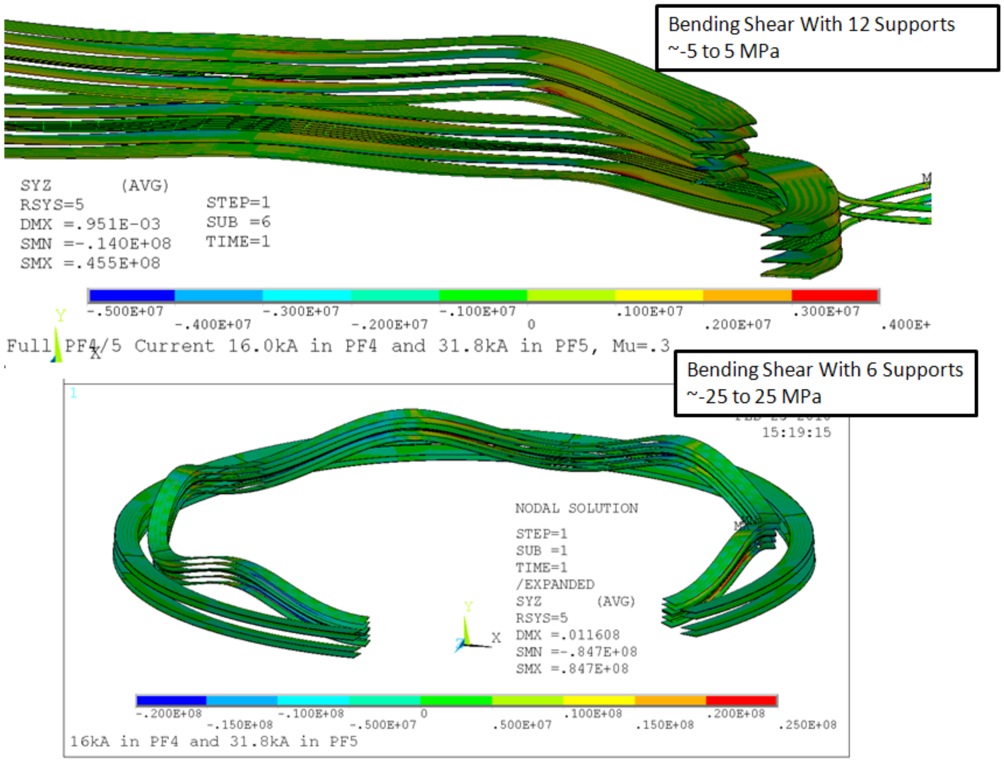


Figure 8.3-3 Radial -Vertical Shear for Lorentz and Lorentz plus Both Coils Hot


Bending Shear With 12 Supports
~-5 to 5 MPa

Bending Shear With 6 Supports
~-25 to 25 MPa

Figure 8.3-4 Radial -Vertical Shear for Lorentz Only, Full Coil Currents

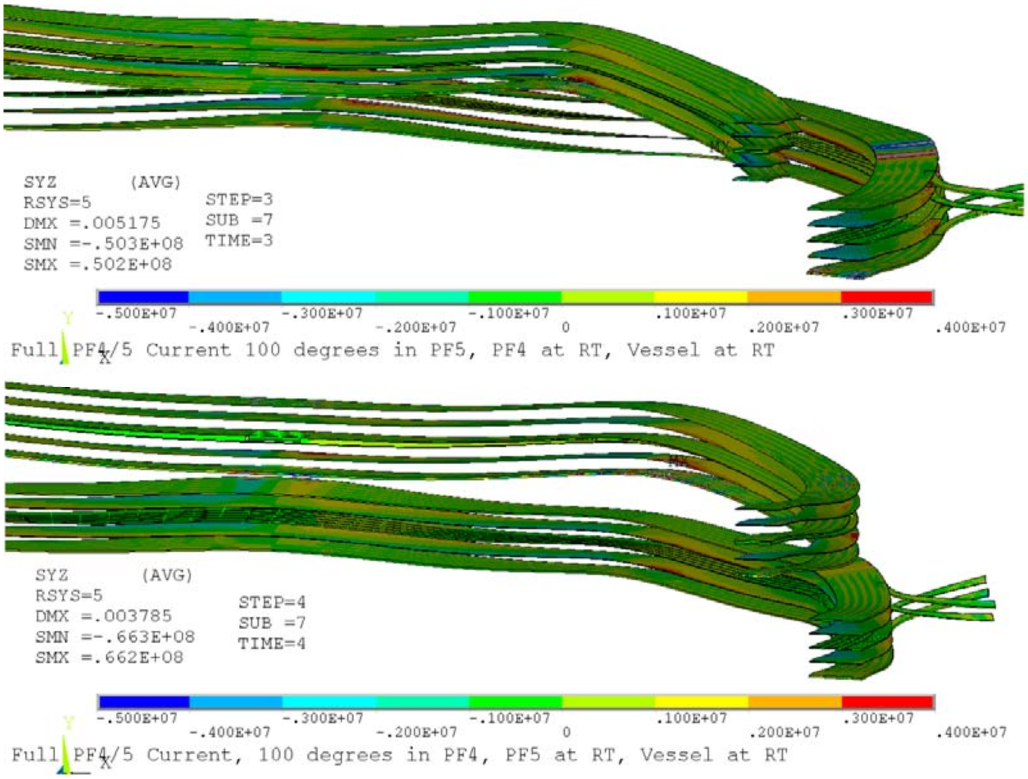


Figure 8.3-5 Radial -Vertical Shear for, Full Coil Currents, Both Coils Hot

Lowering insulation stress was a significant driver in the decision to provide 12 support points. In the figure above, the shear stress due to bending between supports is reduced from about 25 MPa to 5 MPa in PF4. PF4 is divided into two pancakes and interacts strongly with PF5. With PF4 and 5 upper and lower coils energized, PF4U is loaded downward and PF5 is attracted to both the PF4U and the PF4/5 lower pair. For this loading, the bending load in PF4 is most severe, and the bending in PF5 is moderate. PF4 pancakes partially separate and the local self load does not provide any frictional shear between pancakes to engage the full section of the coil. Both PF4 and 5 use the fusifab/mylar/epoxy system that will have minimal epoxy bond shear strength. Even the 1 or 2 MPa in the bulk of the coils for the 12 support FDR concept may be too much to eliminate sliding. Demonstration of acceptable copper stresses, small shears and displacements will have to be sufficient to qualify the coils.

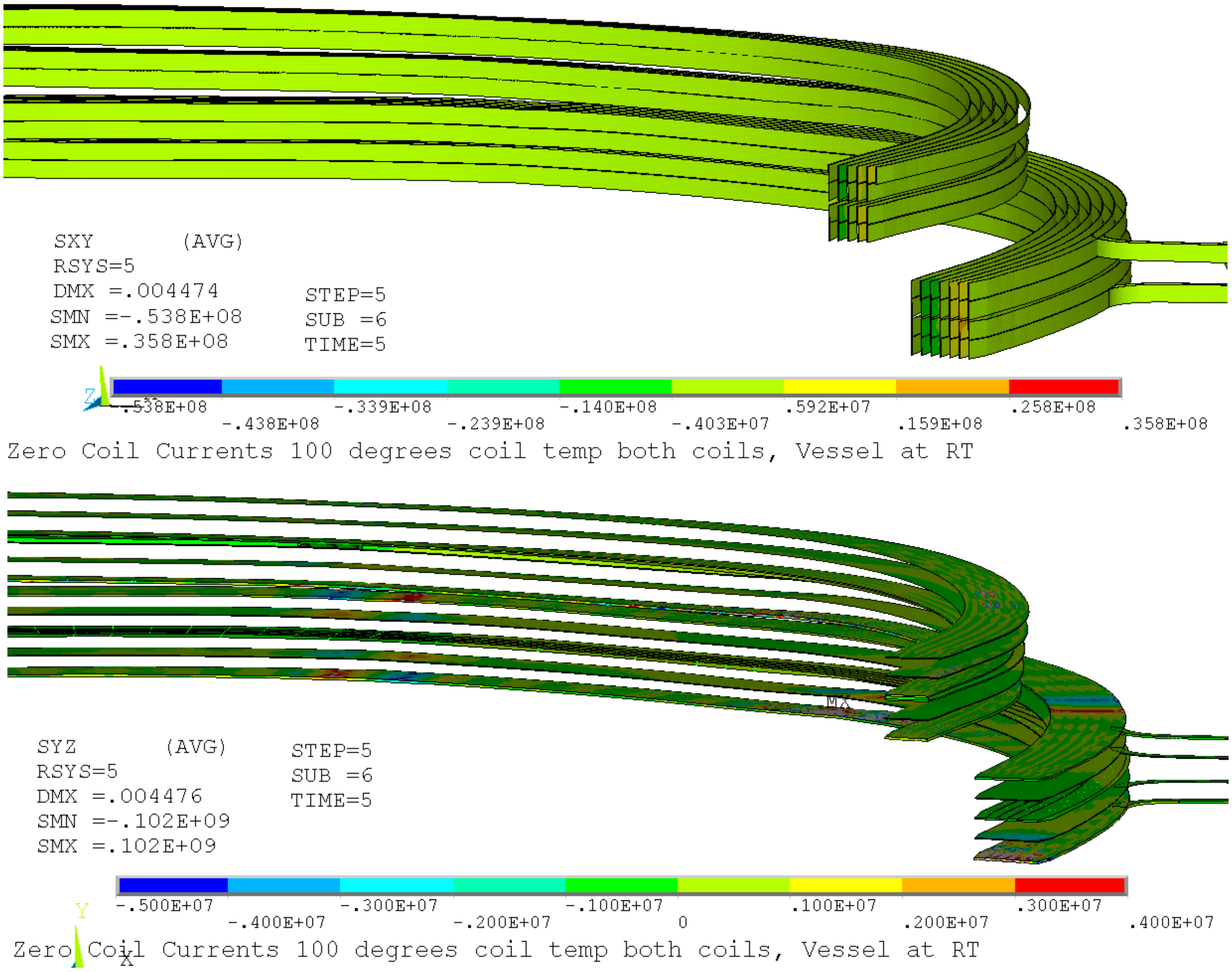


Figure 8.3-6 Radial -Vertical Shear for, No Coil Currents, Both Coils Hot

8.4 TF Ripple Loads on PF 4 and 5

PF 4 and 5 pass by the TF outer leg. The local toroidal field at the outer TF legs imposes periodic torques on the neighboring PF coils. The torques add bending stress to the existing bending stresses which result from the discrete coil support points. The ripple effect is being quantified independent of other loading. To accomplish this, the Lorentz Loads are quantified with and without the TF current and the two files are differenced to obtain loading for only the effect of the TF currents.

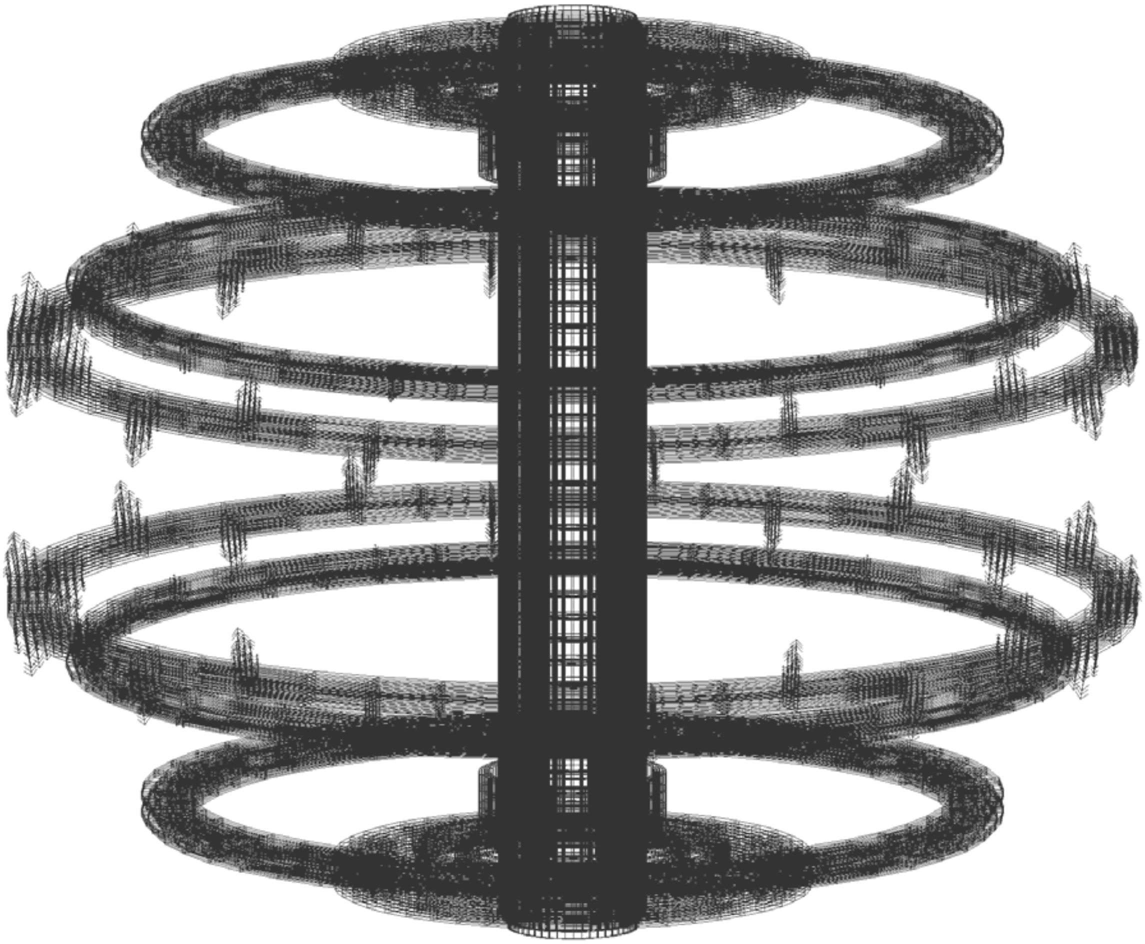
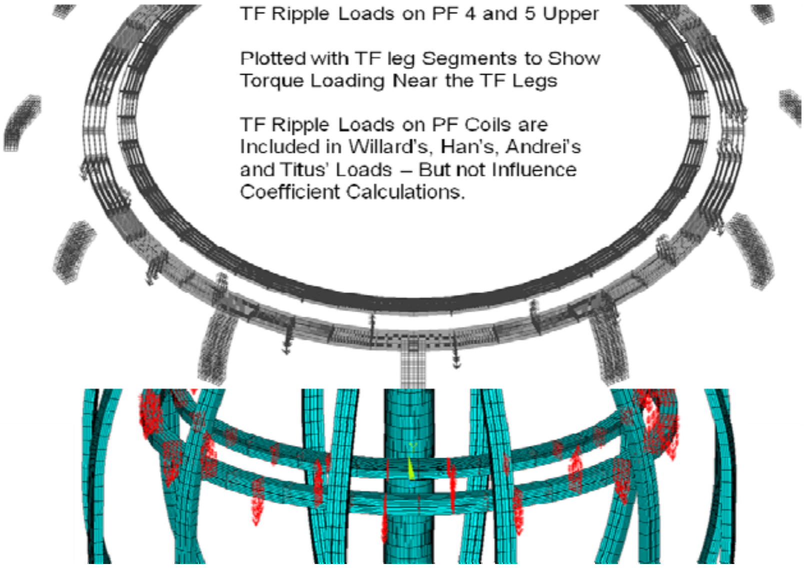


Figure 8.4-1 The Result of the Subtraction of (PF+TF) Load File and (PF Only) Load File, with only the PF coils plotted. Only the effect of the TF on the PF remains.

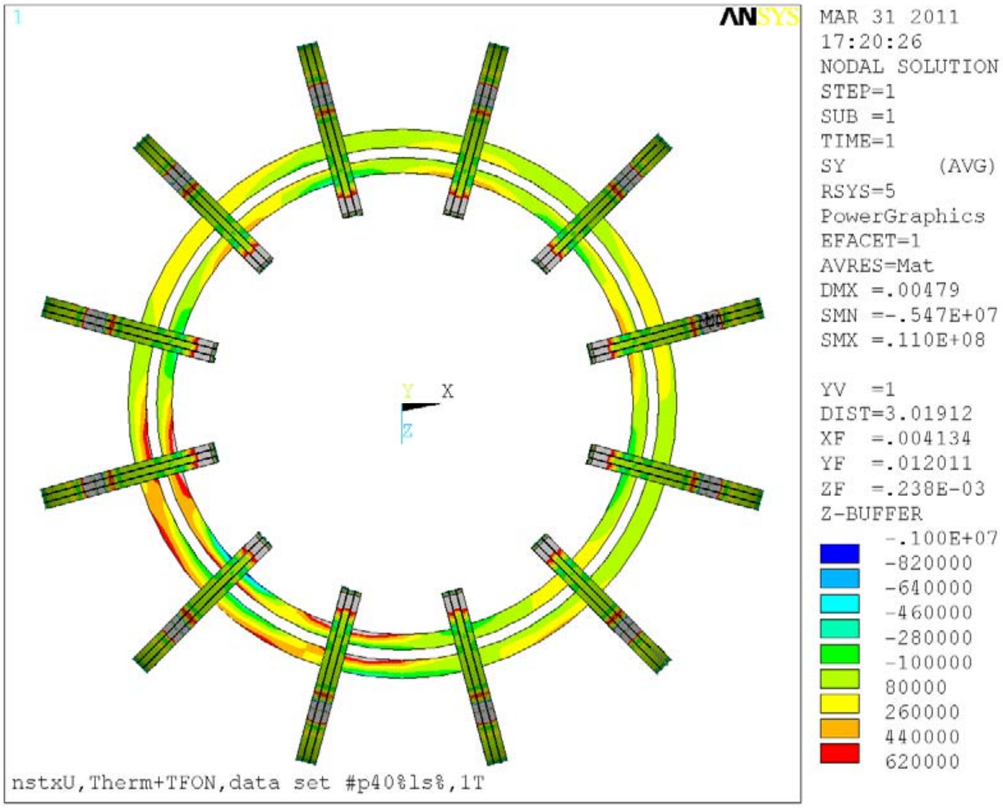


TF Ripple Loads on PF 4 and 5 Upper

Plotted with TF leg Segments to Show Torque Loading Near the TF Legs

TF Ripple Loads on PF Coils are Included in Willard's, Han's, Andrei's and Titus' Loads – But not Influence Coefficient Calculations.

Figure 8.4-2 The Result of the Subtraction of (PF+TF) Load File and (PF Only) Load File, with only the PF coils plotted. Only the effect of the TF on the PF remains.



8.4-3 Hoop Directed Stress - Bending Stress Due to TF Ripple.

The bending stress in PF4 and 5 is less than 11 MPa at most locations. The asymmetry is due to local support bracket and port modeling.

9.0 Digital Coil Protection System Input

The approach used for the PF4 and 5 coils for calculating the stress multipliers/algorithms is to utilize a global model [2] that simulates the whole structure and includes an adequately refined modeling of the component in question. Unit terminal currents are applied to each coil separately, Lorentz loads are calculated, and the response of the whole tokamak and local component stress is computed. This approach is correct for stresses that are a consequence of an individual coil load which is, in turn, a result of the superposition of contributions from all other coil currents. Local component stresses may then be computed in the DCPS or in a spreadsheet for the many scenarios required by the GRD. This approach has been applied to the PF4 and 5 coil stress. Where a component stress is a consequence of multiple coil loads, the approach must derive coefficients from unit loads which, in turn, are computed from the influence coefficients. This analysis approach has been exercised for the existing PF 4 and 5 support welds and is discussed in section 9.3 (moved to the Appendix)

At this writing, thermal stresses are assumed to be a consequence of uniform heat-up of the coils. Stresses due to temperature gradients in the coils are not considered.

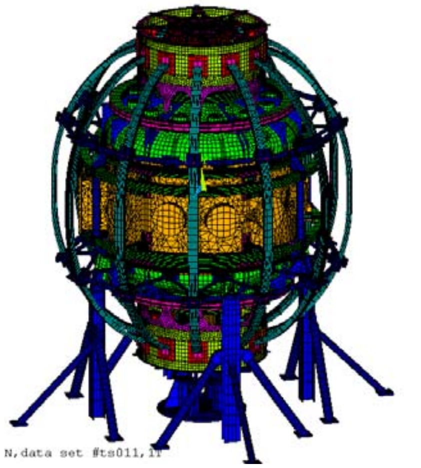


Figure 9.0-1 Linear Global Model Used in Calculating DCPS Stress Multipliers, Ref [2]

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. It is usual practice to utilize influence coefficient calculations to determine hoop and axial (vertical for tokamak's) 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. The effect of this offset in force centroid, especially on local PF supports, is discussed.

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

9.1 PF5 Coil Stress DCPS Input

9.1.1 Influence Coefficients and Stress Multipliers

First, a candidate "worst case" location is selected. The stress state that will be checked must be an individual stress component. For PF5, the peak stress in the conductor is driven by a combination of hoop stress and bending stress, in the same direction, caused by the 12 discrete points at which the large ring coil is supported.

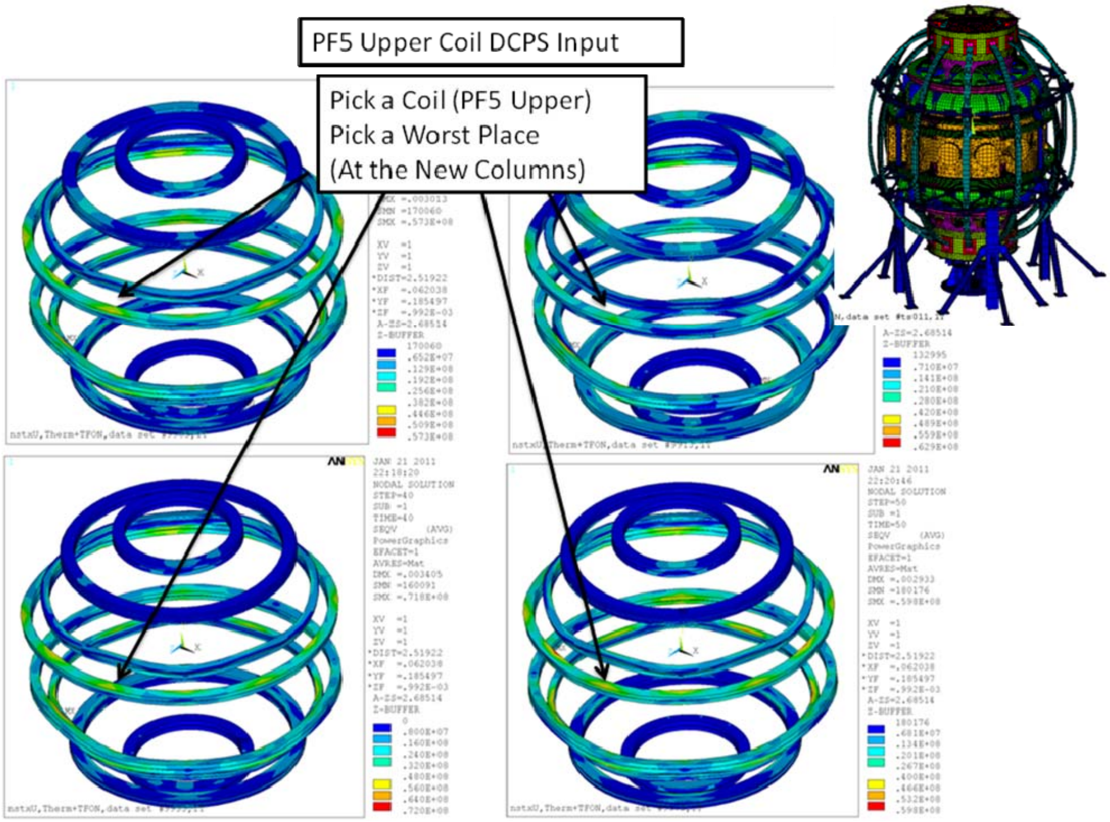


Figure 9.1.1-1 Finding a Worst Case Location to use for Calculating Coefficients

The next step is to calculate Lorentz forces. The PF 5 coil was chosen as a critical component. Lorentz Forces for each combination of PF 5 unit current and unit currents in each other coil. Stresses are determined at the critical location for each of these unit load files. In this case, the critical stress location has been chosen as the conductor on the top surface of the winding over the new column supports. The stress values form the stress influence coefficients for each PF current. These can be used in a spreadsheet to calculate the stress value for the critical location for each set of equilibrium currents or any set of coil currents.

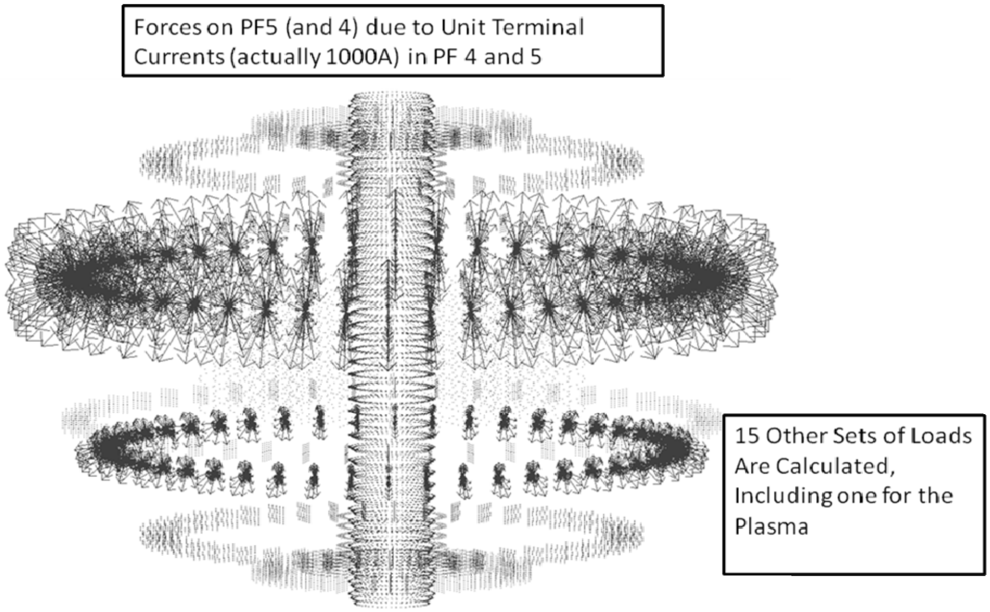
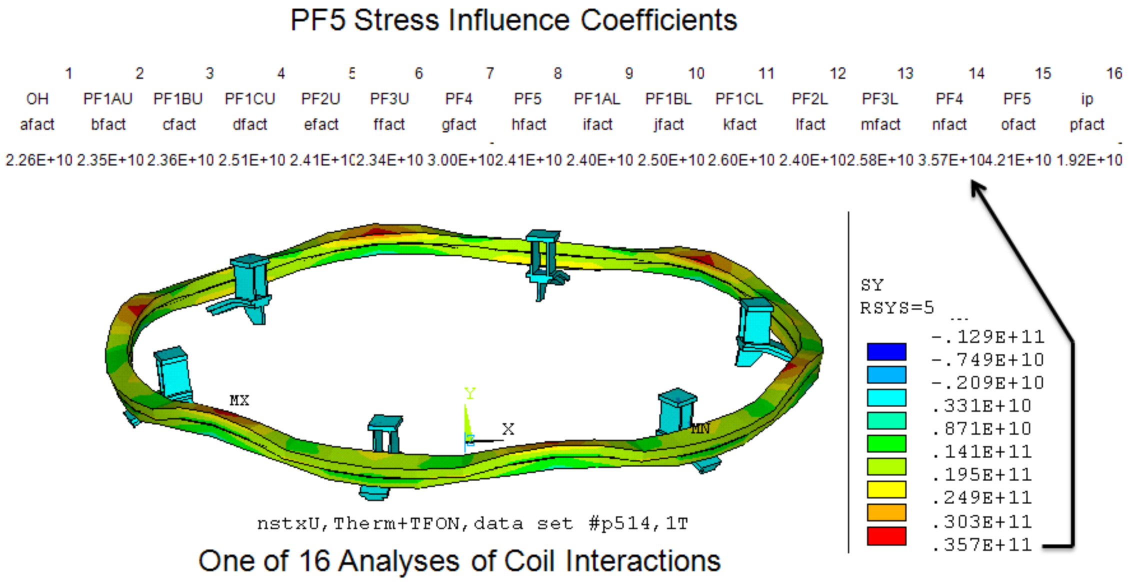


Figure 9.1.1-2 Unit Current Biot Savart Load Calculation



PF5 Stress Influence Coefficients

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
afact	bfact	cfact	dfact	efact	ffact	gfact	hfact	ifact	jfact	kfact	lfact	mfact	nfact	ofact	pfact
2.26E+10	2.35E+10	2.36E+10	2.51E+10	2.41E+10	2.34E+10	3.00E+10	- 2.41E+10	2.40E+10	2.50E+10	2.60E+10	2.40E+10	2.58E+10	3.57E+10	4.21E+10	- 1.92E+10

One of 16 Analyses of Coil Interactions

Figure 9.1.1-3 ANSYS Results for One of 16 Sets of Loads/Coefficients

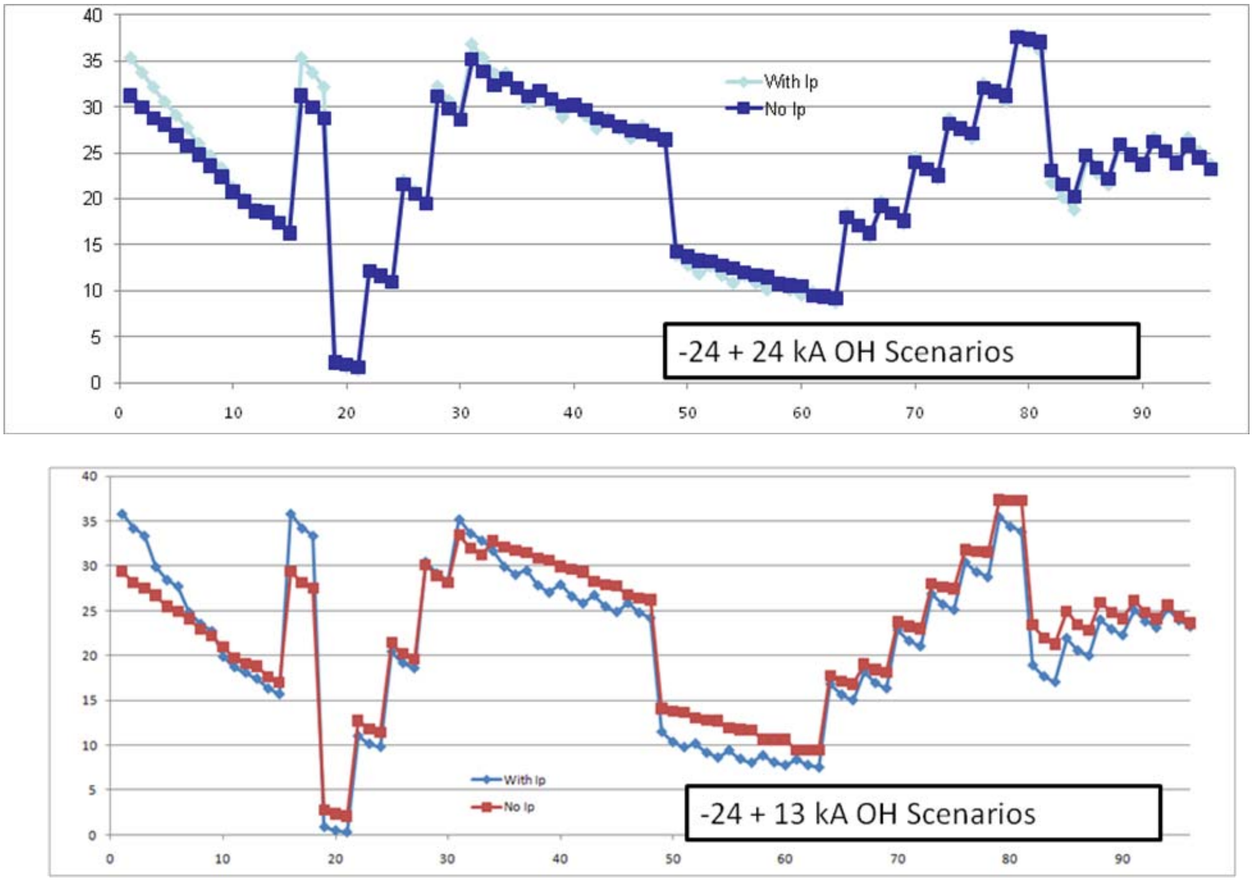
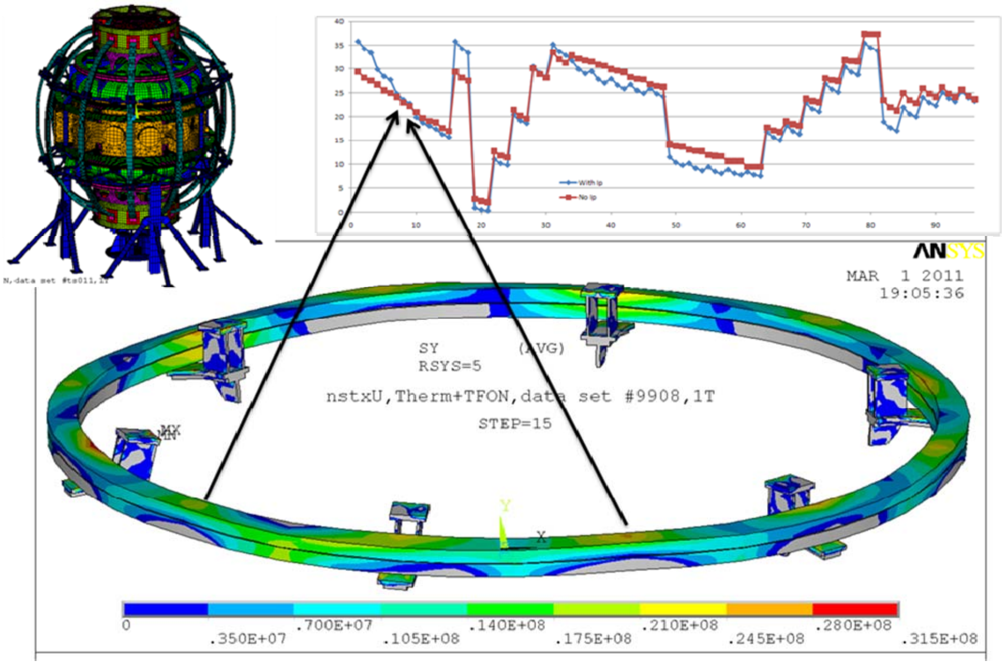
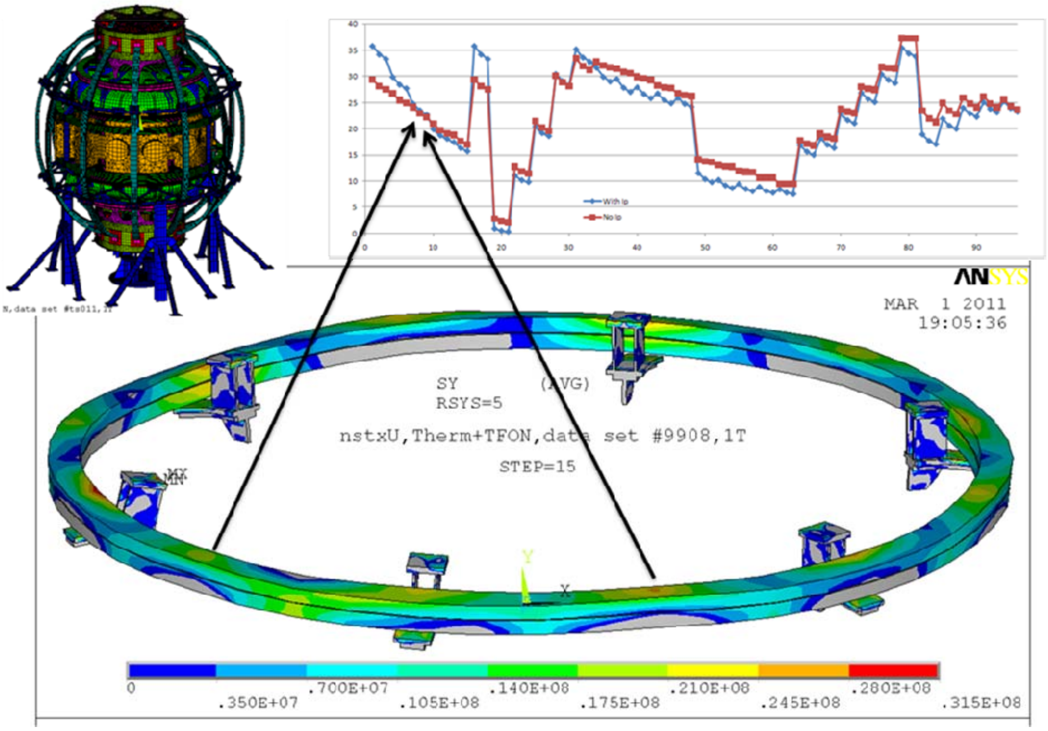


Figure 9.1.1-4 Application of Stress Coefficients to the Old Scenario



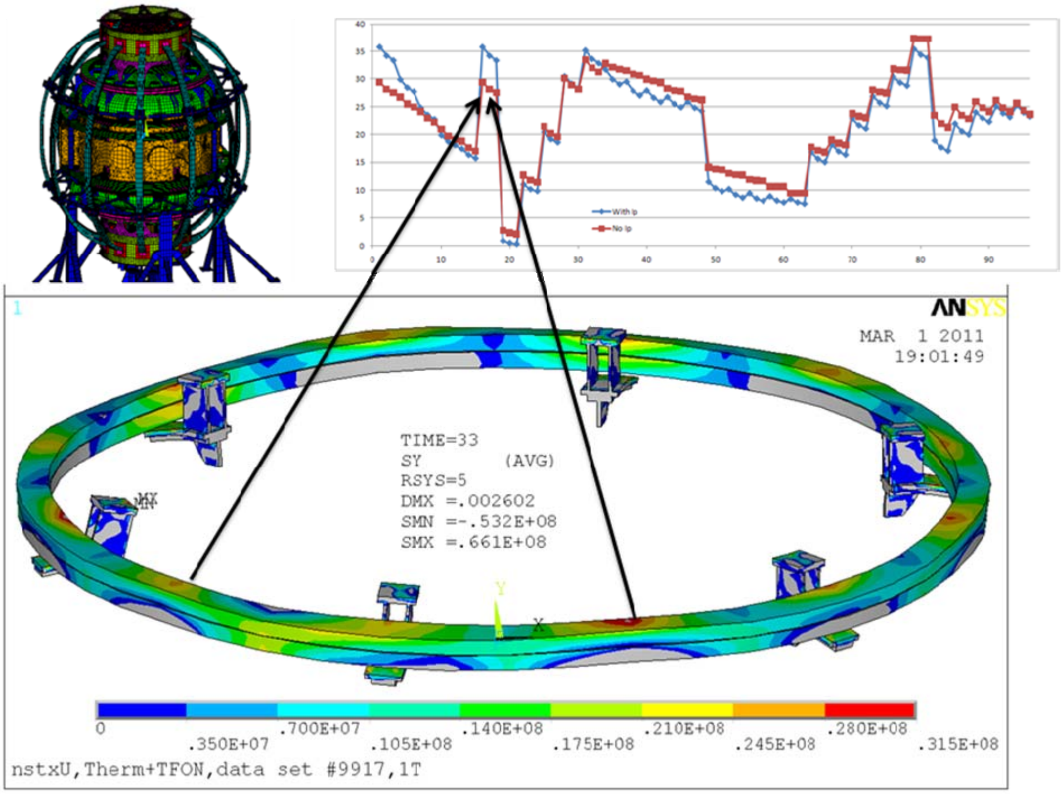
Check Influence Coefficients Against Global Model

Figure 9.1.1-5 Comparison with Global Model Results



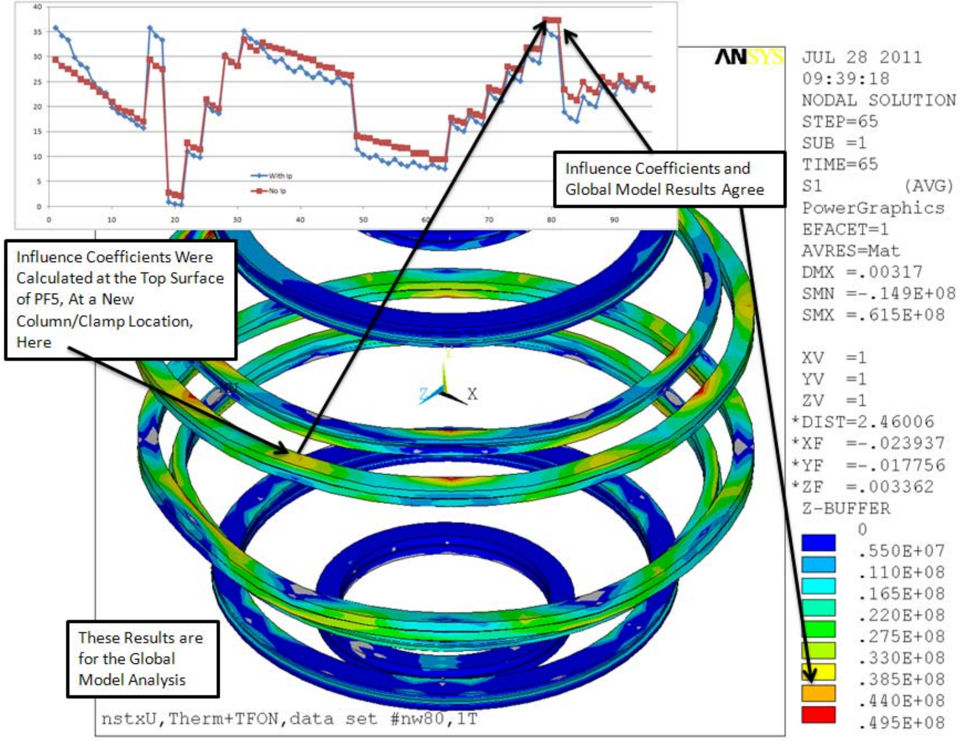
Check Influence Coefficients Against Global Model

Figure 9.1.1-6 Another Comparison with Global Model Results



Check Influence Coefficients Against Global Model

Figure 9.1.1-7 Another Comparison with Global Model Results

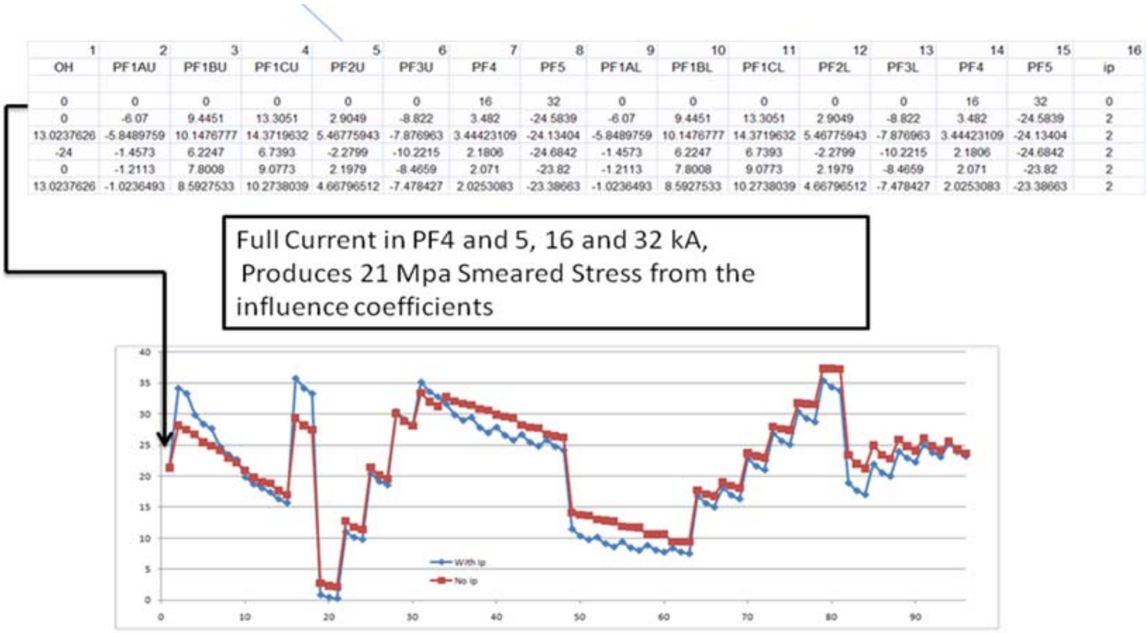


Influence Coefficients and Global Model Results Agree

Influence Coefficients Were Calculated at the Top Surface of PF5, At a New Column/Clamp Location, Here

These Results are for the Global Model Analysis

Figure 9.1.1-8 Comparison with Global Model EQ #80 Results



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
OH	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF1AL	PF1BL	PF1CL	PF2L	PF3L	PF4	PF5	ip
0	0	0	0	0	0	16	32	0	0	0	0	0	16	32	0
0	-6.07	9.4451	13.3051	2.9049	-8.822	3.482	-24.5839	-6.07	9.4451	13.3051	2.9049	-8.822	3.482	-24.5839	2
13.0237626	-5.8489759	10.1476777	14.3719632	5.46775943	-7.876963	3.44423109	-24.13404	-5.8489759	10.1476777	14.3719632	5.46775943	-7.876963	3.44423109	-24.13404	2
-24	-1.4573	6.2247	6.7393	-2.2799	-10.2215	2.1806	-24.6842	-1.4573	6.2247	6.7393	-2.2799	-10.2215	2.1806	-24.6842	2
0	-1.2113	7.8008	9.0773	2.1979	-8.4659	2.071	-23.82	-1.2113	7.8008	9.0773	2.1979	-8.4659	2.071	-23.82	2
13.0237626	-1.0236493	8.5927533	10.2738039	4.66796512	-7.478427	2.0253083	-23.38663	-1.0236493	8.5927533	10.2738039	4.66796512	-7.478427	2.0253083	-23.38663	2

Full Current in PF4 and 5, 16 and 32 kA, Produces 21 Mpa Smeared Stress from the influence coefficients

Figure 9.1.1-9 Using a Scenario/Current Set Consistent with the Local Model, Calculate a Smeared Stress for the Full Current in PF4 and 5 Model/Analysis

For computation of the stress multiplier, a consistent smeared stress must be calculated from the influence coefficients for the detailed model that had full currents in PF4 and 5 - but no other PF currents. To make the comparison with the smeared results, an "equilibrium" current set was added in the spreadsheet, that had only full currents in PF4 and 5 and the spreadsheet calculated the smeared stress that the influence coefficients would produce for this current set. This is 21 MPa.

Smeared to Local Stress Multipliers

So far, the stress computed from the influence coefficients is the "smeared" stress from the global model. The coils are more complicated than represented in the global model. There are coolant holes and a portion of the cross section is insulation and not copper. These will increase local copper stress over what is reported in the global model. Local models have better modeling of the interactions between the support pads and the coils, and include non-linearities - frictional interfaces that may increase or decrease the stress with respect to the global model results. Two detailed local models are available. The first is the upper symmetry quadrant of the PF4/5 and vessel. This is loaded with the peak currents allowed in the two coils. A second model which is a full modeling of the PF4/5 coils is loaded with the EQ#80 currents. This second model is presented in more detail in section 9.1.2. Rigorously, the stress multipliers should be consistent with the location chosen as the critical "spot".

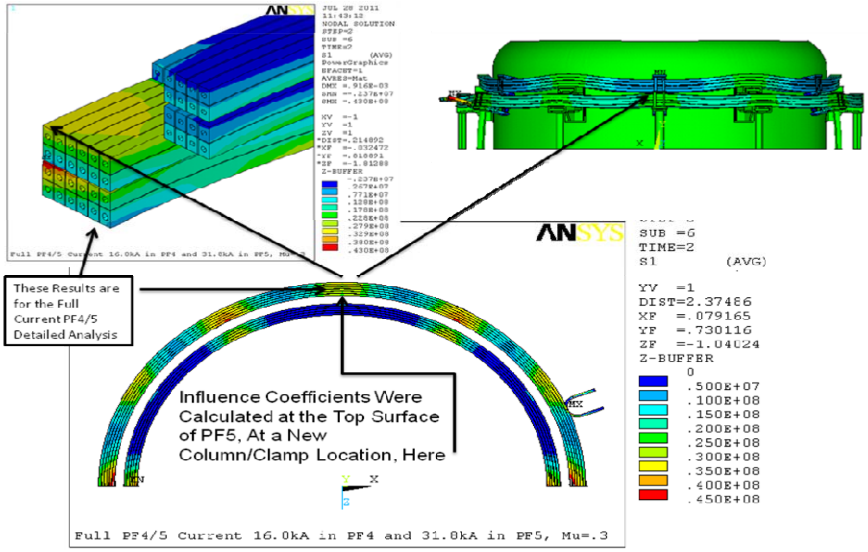


Figure 9.1.1-10 Stress Multiplier for the Full Current Loading and Model

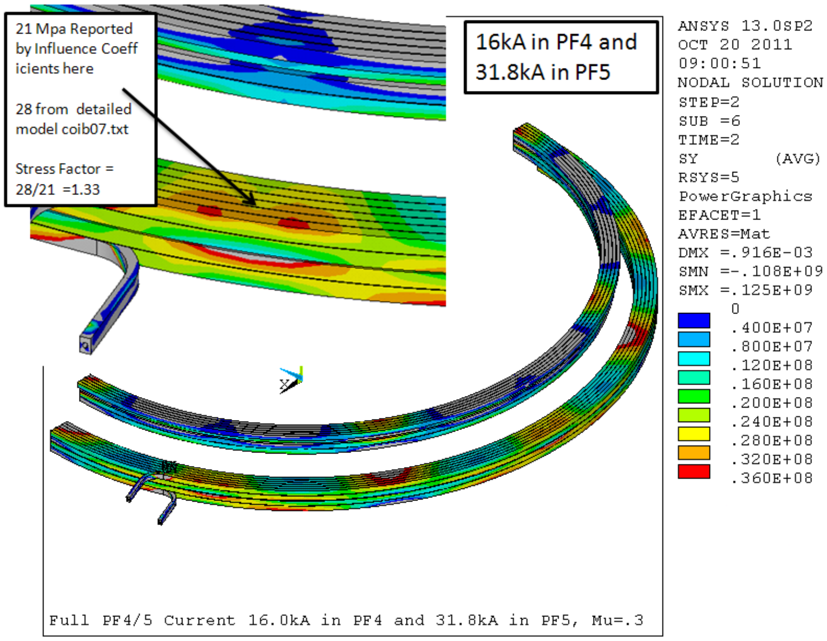
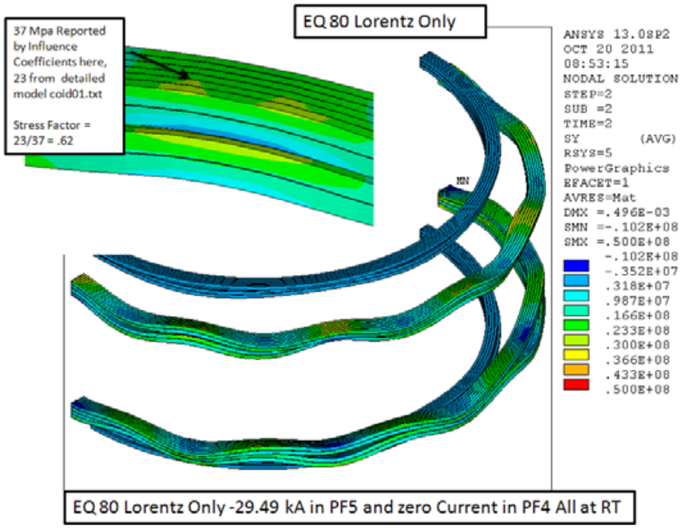


Figure 9.1.1-11 Stress Multiplier for the Full Current Loading and Model


37 Mpa Reported by Influence Coefficients here, 23 from detailed model coid01.txt

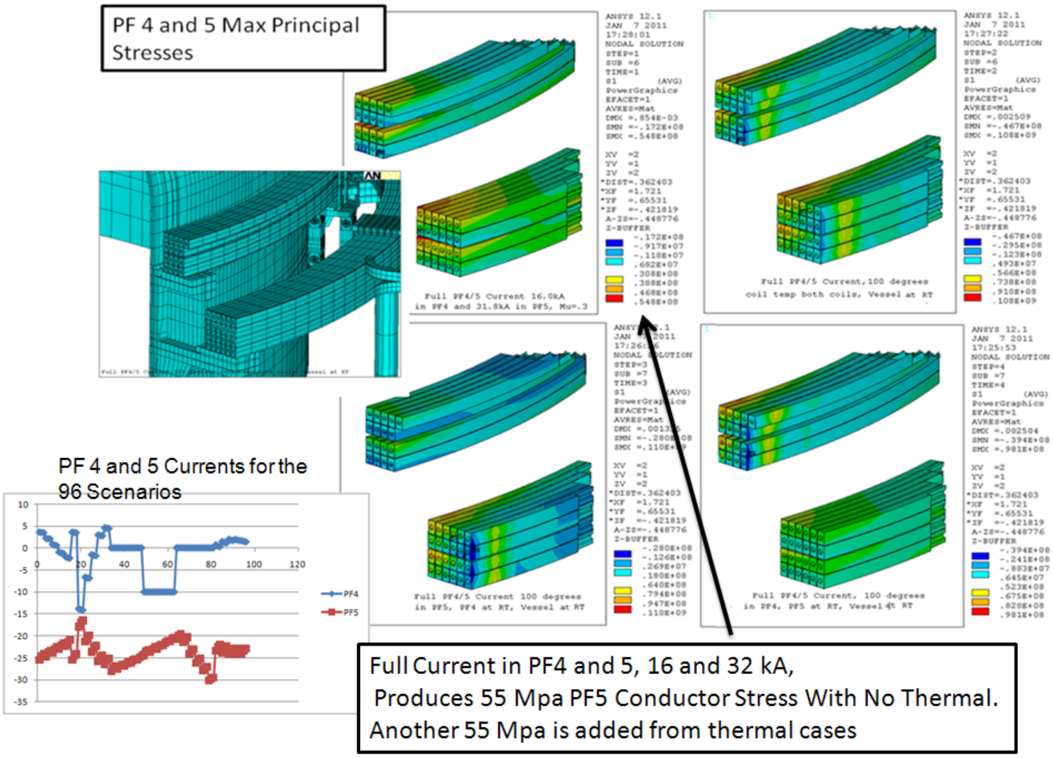
Stress Factor = 23/37 = .62

EQ 80 Lorentz Only

EQ 80 Lorentz Only -29.49 kA in PF5 and zero Current in PF4 All at RT

Figure 9.1.1-12 Stress Multiplier for the Full Model and EQ#80 Currents

There are two different stress multipliers for different loads but the same geometry. Unfortunately, the local models are non-linear. It was hoped that the behavior would be sufficiently linear to support the influence coefficient approach. Of the two examples chosen, the EQ#80 is more representative of the bulk of the design equilibria in which PF4 is not used near its capacity. This may change to even out thermal excursions of the coils. To obtain practical stress multipliers, some enveloping of both behaviors and positions is needed. The location above the fixed supports is also highly stressed, and in the local models the peak stress is not always on the top and bottom of the winding packs, but may be at the pancake interfaces at the mid-build of the coils.


PF 4 and 5 Max Principal Stresses

PF 4 and 5 Currents for the 96 Scenarios

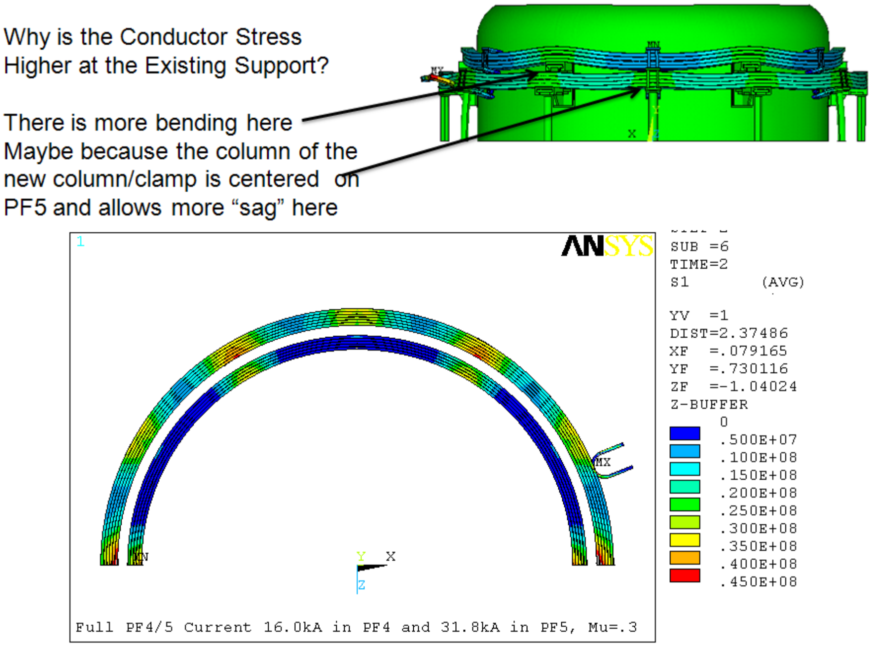
Full Current in PF4 and 5, 16 and 32 kA,
Produces 55 Mpa PF5 Conductor Stress With No Thermal.
Another 55 Mpa is added from thermal cases

Figure 9.1.1-13 Peak Stresses at other locations within the coils

Table 9.1.1-1 Stress Multipliers with the Influence Coefficient Results as a Base

Analysis Location	Critical "Spot" Over New Column	Worst over New Column	Worst over the Fixed Support	Worst Stress With Thermal	Thermal Adder
Max PF4/5 Current Model and Loading	28/21 = 1.33	40/21 = 1.9	55/21 = 2.6	110MPa	55MPa
Section 9.1.2 Benchmark Eq#80 Model	23/37=.62	40/37 = 1.08	52/37 = 1.4	126 MPa	74MPa
	88.7	51.6	53.3	53.3	

The procedure for calculating the peak hoop directed tension stress is to use the stress multipliers multiplied by the influence coefficients multiplied by the coil currents, then add the appropriate thermal contribution. Since the peak current in PF4, for all 96 scenarios, at present is 4kA, choosing the multiplier for the EQ#80 results is probably sensible.


Why is the Conductor Stress Higher at the Existing Support?

There is more bending here Maybe because the column of the new column/clamp is centered on PF5 and allows more "sag" here

SUB =6
TIME=2
S1 (AVG)

YV =1
DIST=2.37486
XF =.079165
YF =.730116
ZF =-1.04024
Z-BUFFER

Full PF4/5 Current 16.0kA in PF4 and 31.8kA in PF5, Mu=.3

Figure 9.1.1-14 Effect of New Column Position

Also, it looks like the non-uniformity in the coils stresses at the two different supports is related to compliance in the new clamp/column because the column is centered on PF5 resulting in an offset when PF4 and 5 are on. This causes a sagging of the new support which transfers load to the existing clamp location.

9.1.2 EQ 80 Benchmark

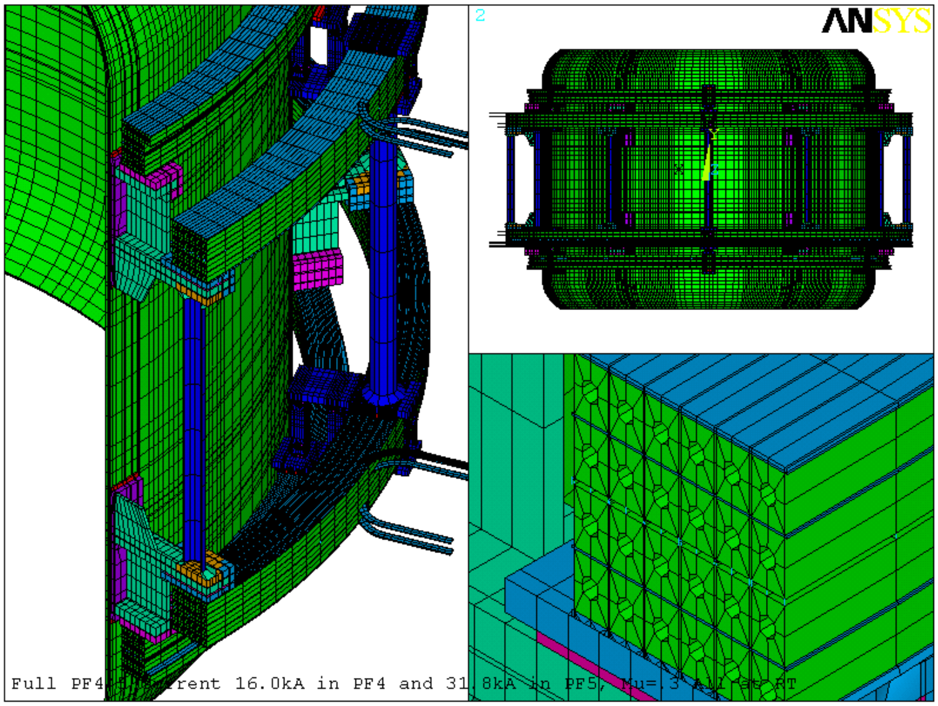
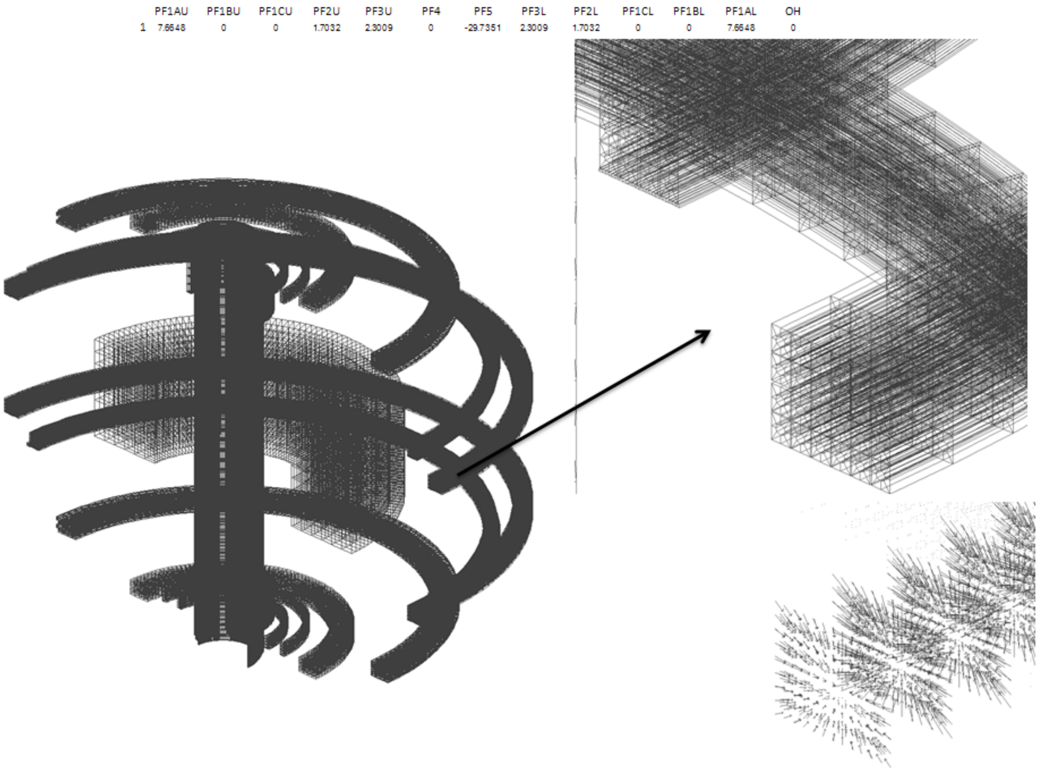


Figure 9.1.2-1 Model Without Equatorial Plane Symmetry Boundary Conditions



	PF1AU	PF1BU	PF1CU	PF2U	PF3U	PF4	PF5	PF3L	PF2L	PF1CL	PF1BL	PF1AL	OH
1	7.6648	0	0	1.7032	2.3009	0	-29.7351	2.3009	1.7032	0	0	7.6648	0

Figure 9.1.2-2 Biot Savart Model and Resulting Force Vectors

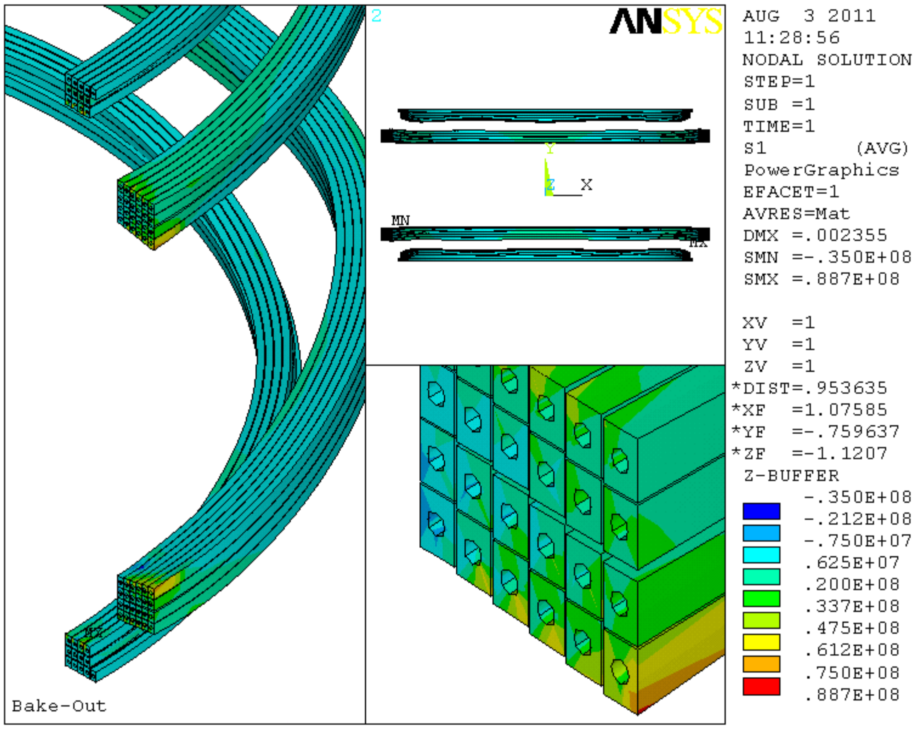


Figure 9.1.2-3 Bakeout Conductor Stress

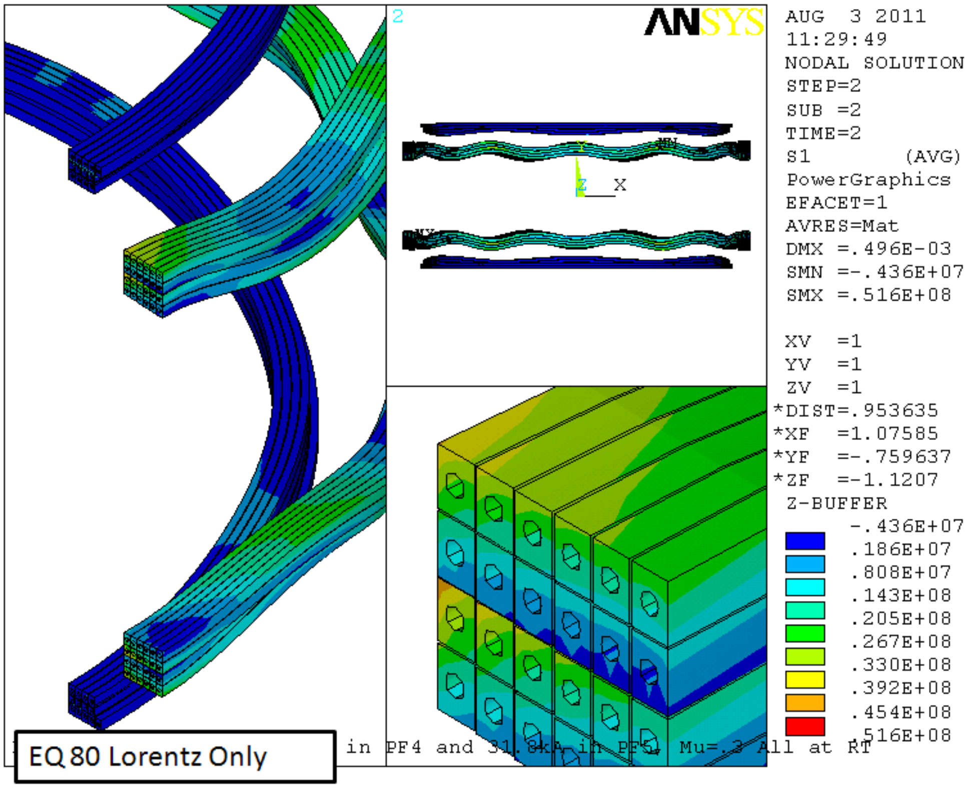


Figure 9.1.2-4 EQ80 Lorentz Only Stress

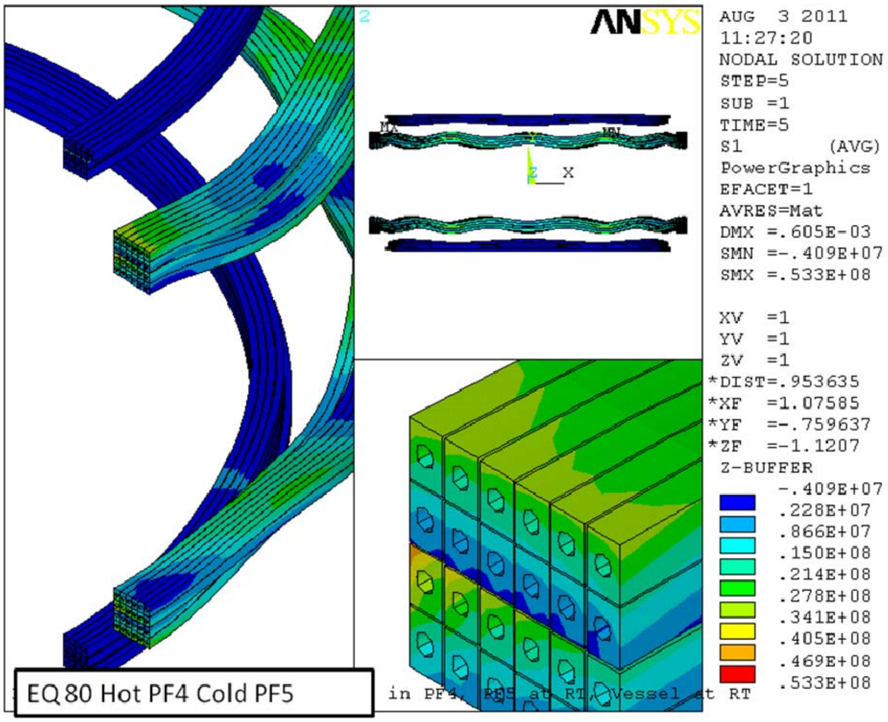


Figure 9.1.2-5 EQ80 Thermal Stress Hot PF4 Cold PF5

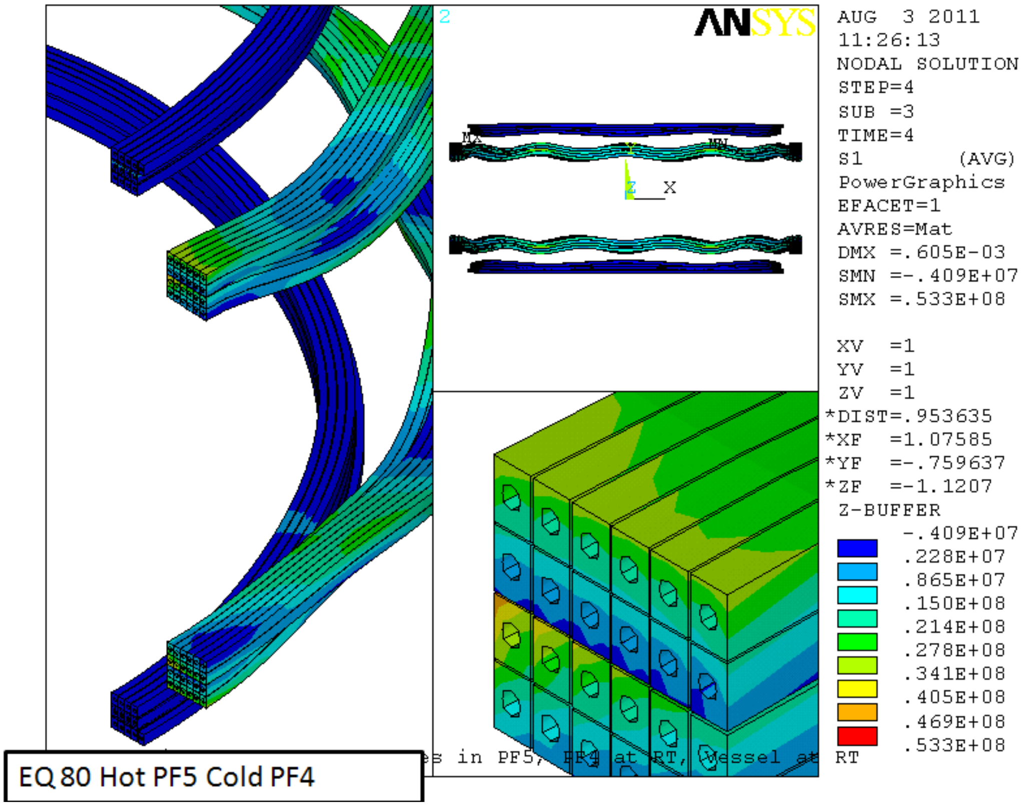


Figure 9.1.2-6 EQ 80+ Thermal Stress Hot PF5, Cold PF4

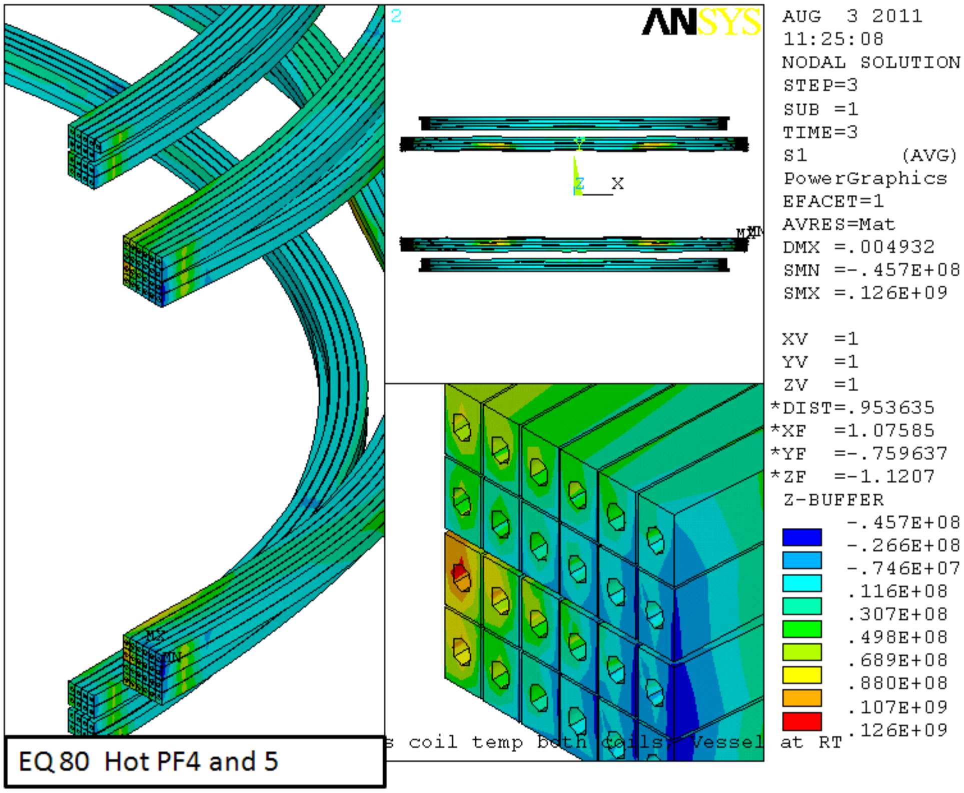


Figure 9.1.2-7 EQ 80+ Thermal Stress Hot PF4 and 5

9.2 PF4 Coil Stress DCPS Input

The procedure outlined above is applied to PF4 in this next section. The results of the ANSYS runs and multipliers are included in a spreadsheet that is available for implementation in the DCPS.

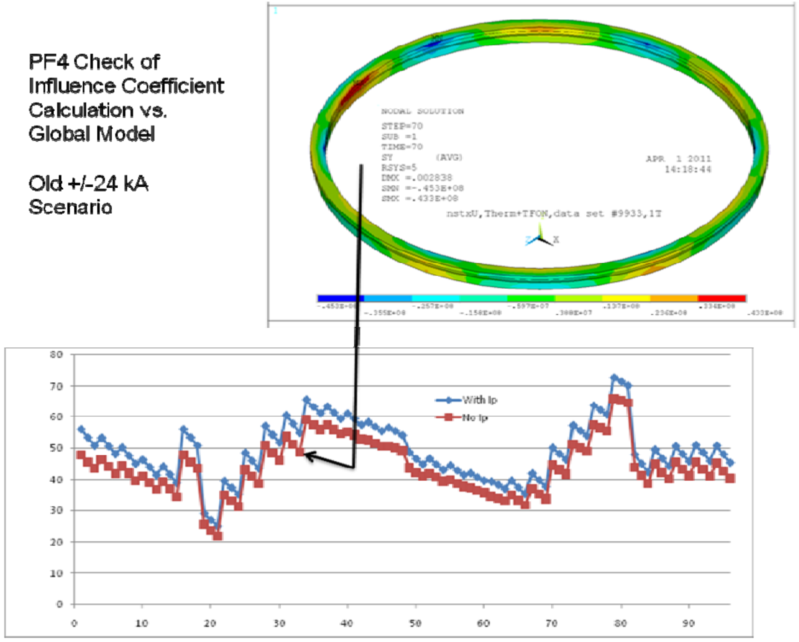


Figure 9.2-1 Comparison of Global "Smeared" Stress Results and the Results from the Influence Coefficients

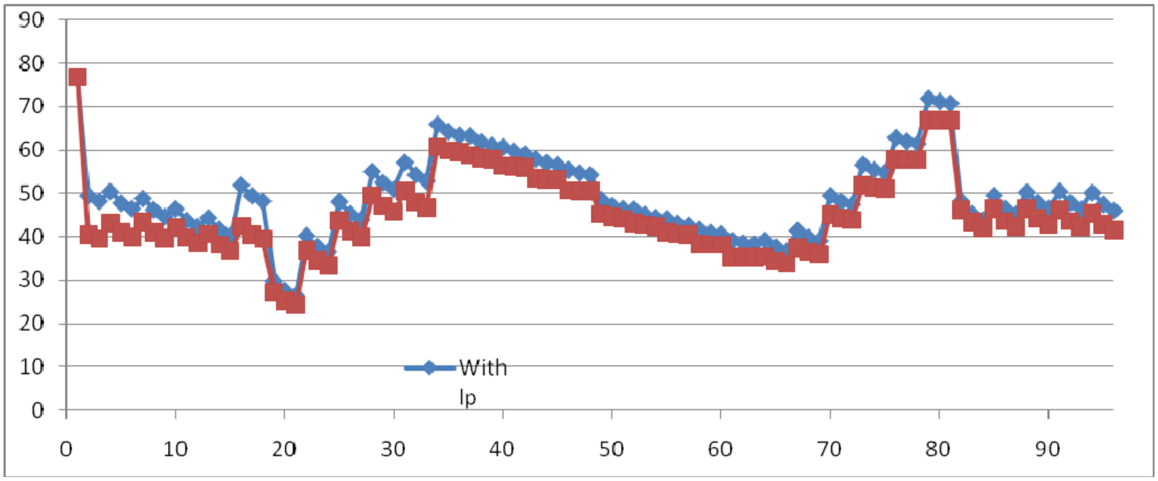


Figure 9.2-2 96 Equilibrium Results with the Full Current result replacing EQ 1

9.3 Existing Support Weld Stress Multipliers

This section derives from (Reference 9) an analysis of coefficients to relate PF4 and 5 loads to the weld stress of the bracket pad. This is pertinent to the upgrade because it was used for a protection system that was implemented in 2010 in NSTX. This same approach can be translated to the DCPS requirements. This section has been shifted to the appendices because it is not specific to the upgrade.

10.0 Leads

Analysis of the PF4 and 5 leads has been included in the analysis of the PF4/5 supports because the logic of the 180 degree "fixed" supports allows "rigid" supports of the leads if they are positioned near the fixed coil support points.

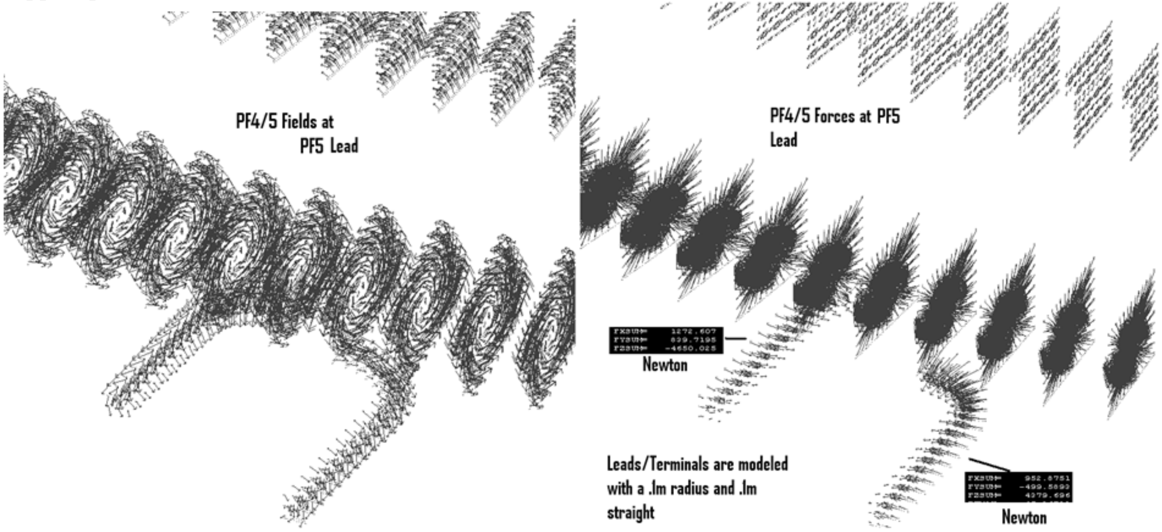


Figure 10.0-1 Fields and Forces Near the Leads

Cantilevered, un-supported leads produced excessive bending stresses due the Lorentz Loads caused by the local coil fields. The unsupported lead stresses are shown in Figure 10.0-2 (Below).

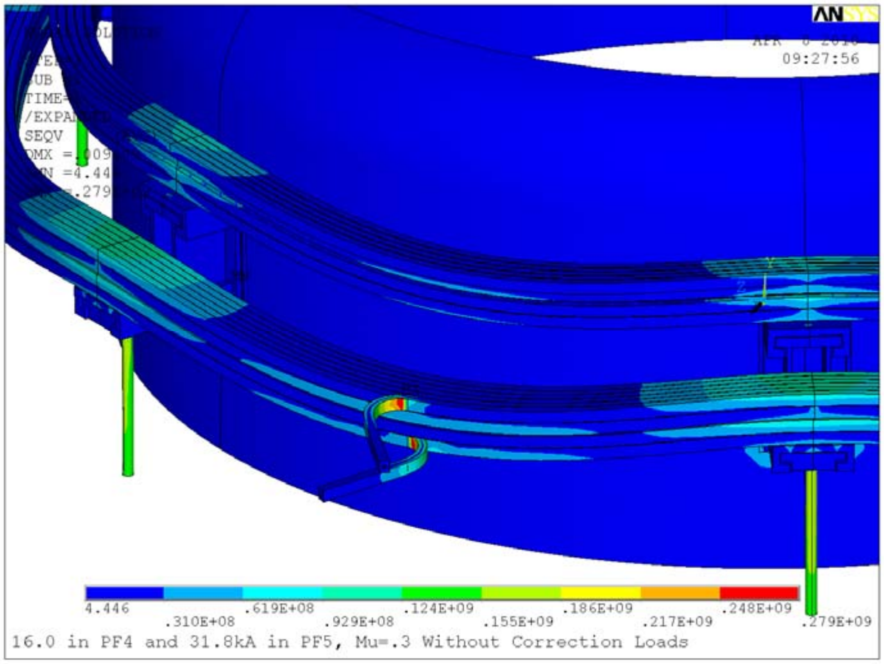


Figure 10.0-2 Local Lead Bending Stress

The bending stress would be relieved by taking credit for the connection to the bus bars on the unistrut at the support platform. This was modeled by displacement constraints. These would produce stresses if the coils move relative to the bus bar support. The PF4/5 support concept imposes fixity at two locations 180-

degrees apart. Choosing one fixed point near the lead break-out will limit the differential displacement stress in the leads.

11.0 Fatigue Analysis

Principal stresses for the PF4 and 5 coils are shown below for full currents in PF4 and 5 for various combinations of temperatures. In Section 9, the digital coil protection system stress multipliers were used to calculate the tensile stress in the hoop direction for all the available scenario currents with the 10% headroom applied with and without the plasma included.

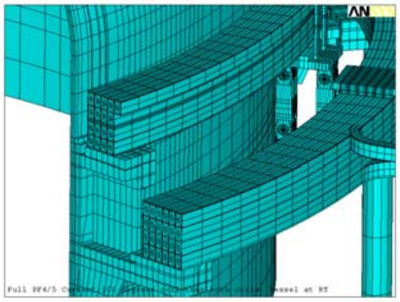


Figure 11.0-1 Link Model

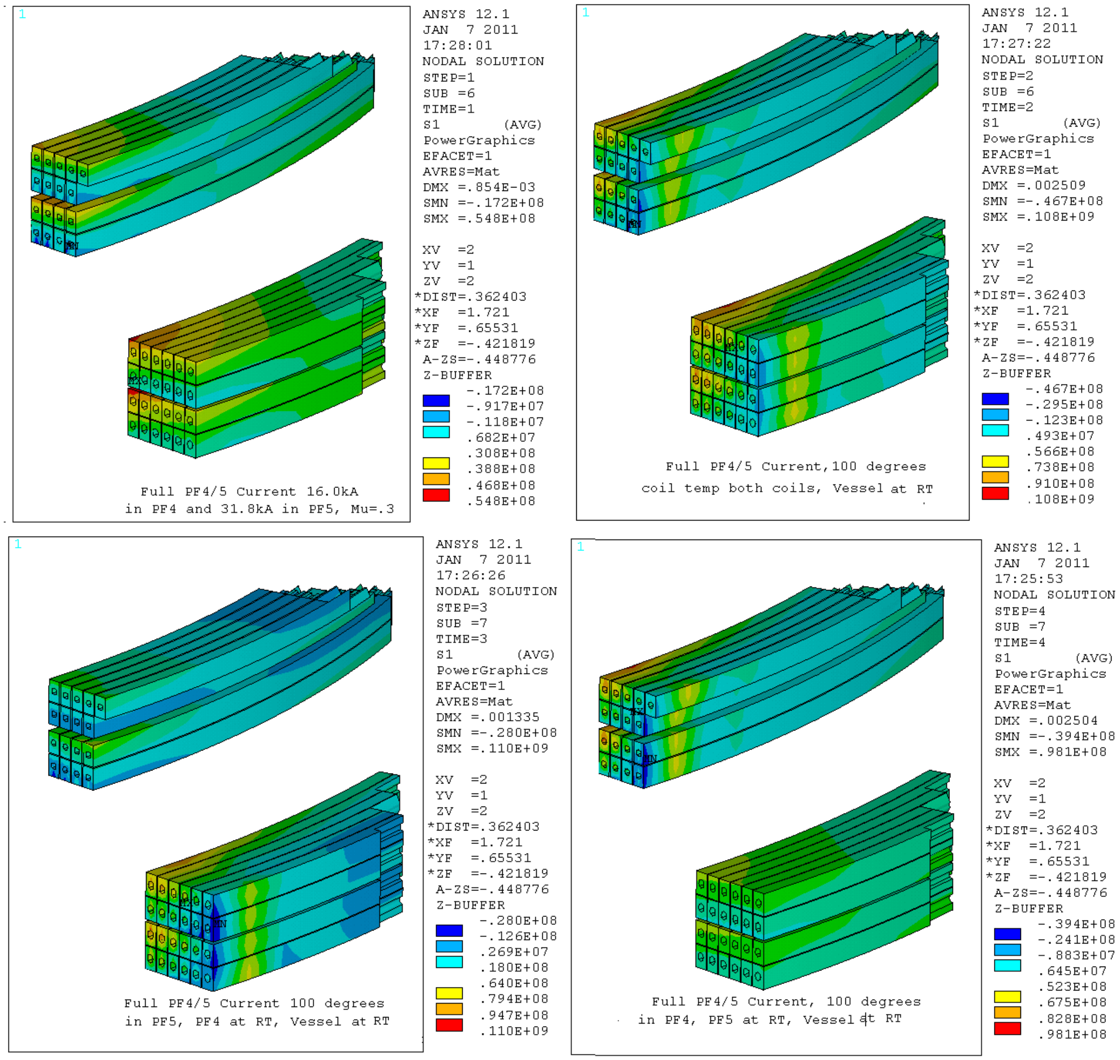


Figure 11.0-2 From Section 9, the peak Max Principal Stress in PF5 for all scenarios is=55*(37/21)+55 = 152 MPa.

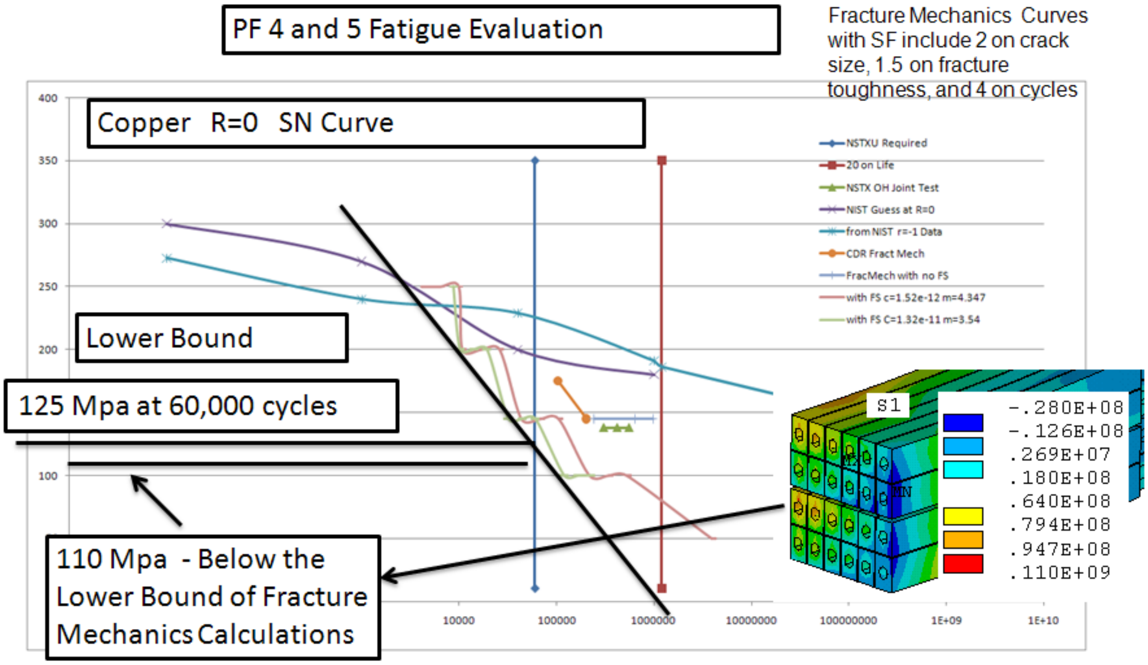


Figure 11.0-3 Fatigue Stress Evaluation for Full Currents in PF4 and 5 - No other PF currents

The PF5 Maximum Max Principal Stress for all scenarios, for all thermal conditions is 152 MPa (see Section 9). The allowable stress to meet the cyclic fatigue limit was developed for the OH coil fatigue calculation [7] and is 125 MPa.

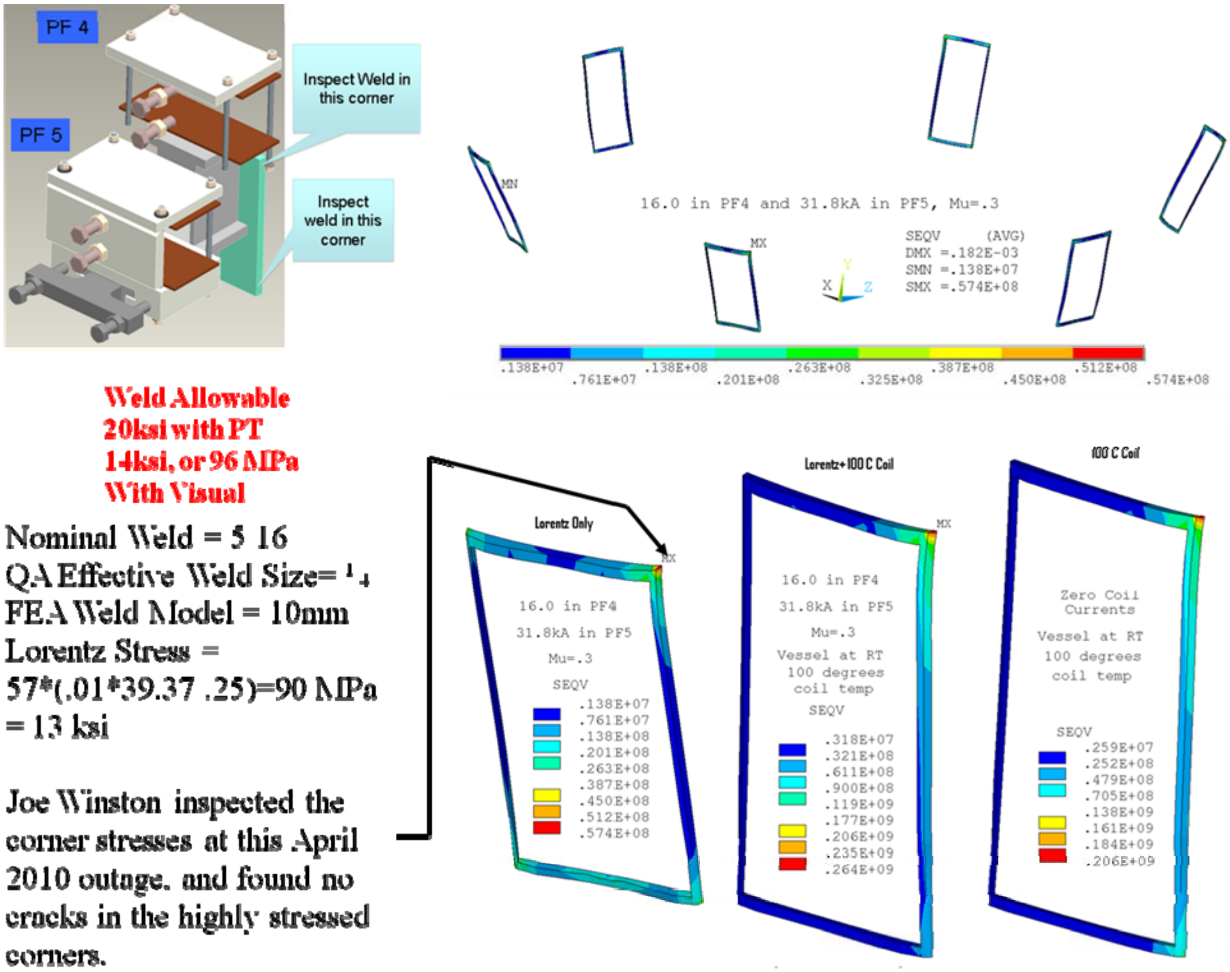
It should be emphasized that this evaluation conservatively assumed that all 60,000 pulses utilize the scenario that produces the worst case stress, and that this stress occurred when the thermal stresses are at a peak.

12.0 Brackets, Hardware and Bracket-to-Vessel Welds

12.1 Existing Bracket to Vessel Welds

This is included in the upgrade calculations because this analysis was used in an early version of the DCPS which is currently in operation. The weld stress vs. load factors calculated here were applied during operation and the coil protection system disallowed a normal test shot. The problem is that the corners of the rectangular weld pattern have significant concentrations that would be plastically relieved, but the strain range would remain to affect the fatigue life. The corners were inspected, and no fatigue indications were noted. This region will be added to an inspection regimen during outages to ensure that fatigue sensitive welds are not developing cracks.

The weld is nominally 5/16-inch, but the QA report recommends that it be treated as an effective ¼ inch weld. To facilitate meshing the weld, an arbitrary cross section is used, then the weld stress is scaled by the ratio of the weld section in the model to the actual weld section. In this case, the weld was intended as a fillet, but material has been added to accommodate the vessel curvature, and the resulting weld was derated.



Weld Allowable
20ksi with PT
14ksi, or 96 MPa
With Visual

Nominal Weld = 5 16
QA Effective Weld Size= 1 4
FEA Weld Model = 10mm
Lorentz Stress =
57*(.01*39.37 .25)=90 MPa
= 13 ksi

Joe Winston inspected the corner stresses at this April 2010 outage, and found no cracks in the highly stressed corners.

Figure 12.1-1 Weld Stresses in the Existing Bracket to Vessel Weld

The weld is assumed to have a larger cross section than a fillet, so the .707 factor was not applied. Weld allowable is a function of the level of inspection that is applied. At PPPL, only visual inspection is routine. ASME would require a weld efficiency of 0.7 or lower.

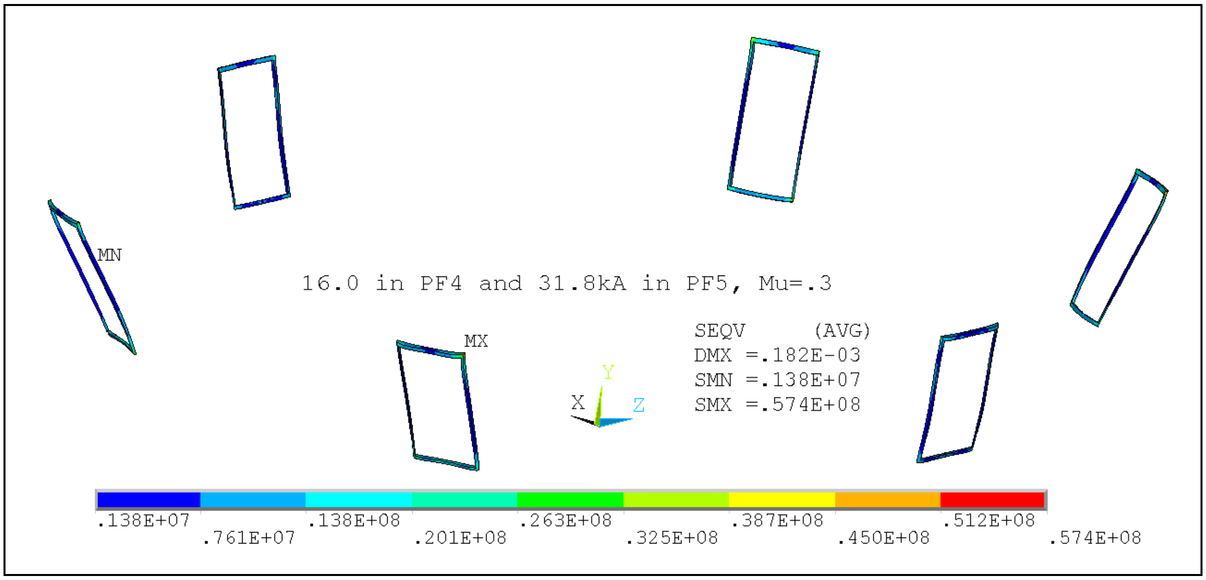


Figure 12.1-2 Weld Stresses in the Existing Bracket Weld to the Vessel - Lorentz Loads Only

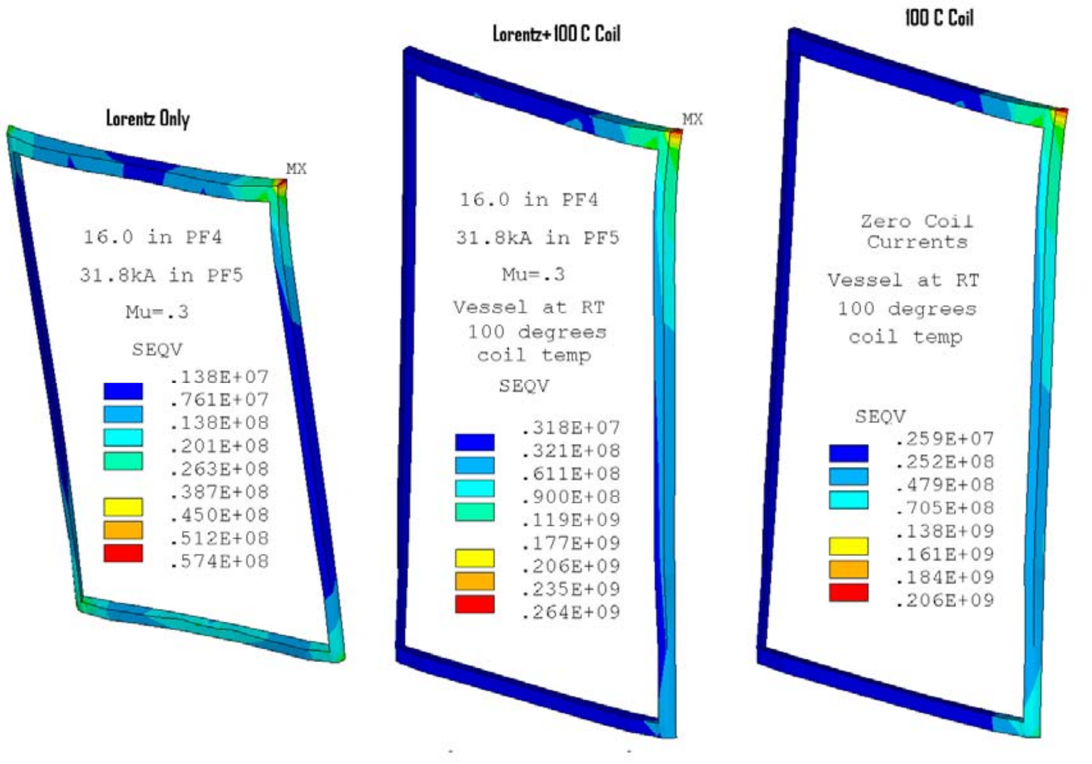


Figure 12.1-3 Weld Stresses in the Existing Bracket Weld to the Vessel

```
/title,PF4 and PF5 Upper Loads
!Remove OOP Loads
bf,all,temp,20
f,436,fz,-204000/12/.2248
f,1098,fz,-241000/12/.2248
Solve
```

PF4/5 Weldment
Nominal Weld = 5/16 in.
QA Effective Weld = 1/4
FEA Weld Model Thick =10mm
Weld Stress =90*(.01*39.37)/.25
=142 MPa = 30555 psi

Ron: Scale Weld Stress by ratio of your forces to those that I applied

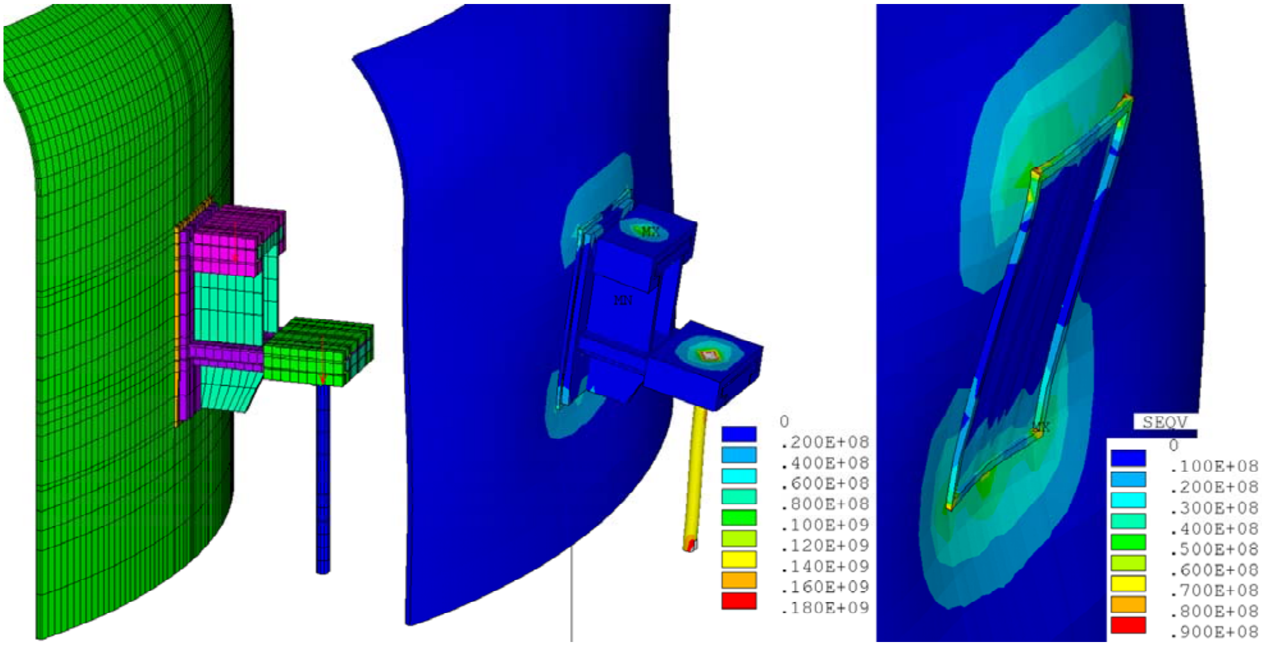


Figure 12.1-4 Weld Stresses in the Existing Bracket Weld to the Vessel
In-Plane PF4 and 5U Loads With Strut

12.2 Bracket Welds for Upgrade Loads

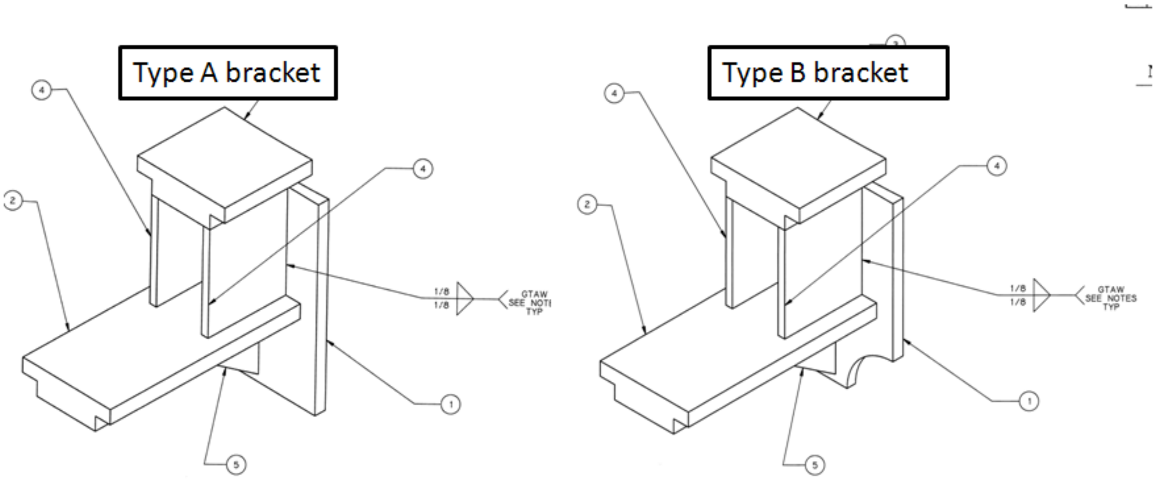
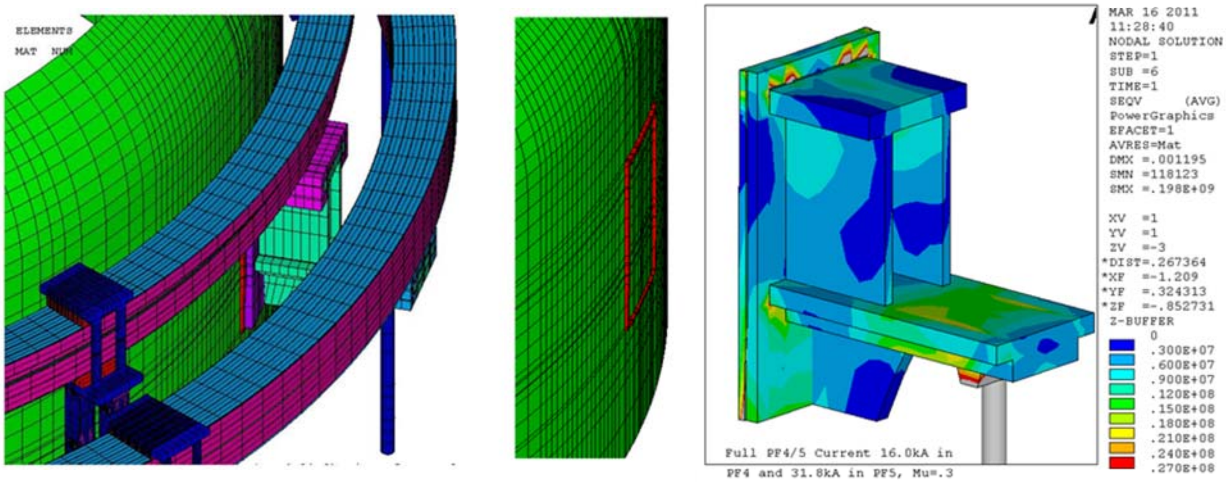


Figure 12.2-1 Bracket Types and Weld Specifications



Link Model Used as a Place-Holder for New Column plus Sliding Block

Weld

Bracket Stresses are Small – Check Only Weld, Bolting, and Support Rod

Figure 12.2-2 Analysis Model Weld Details

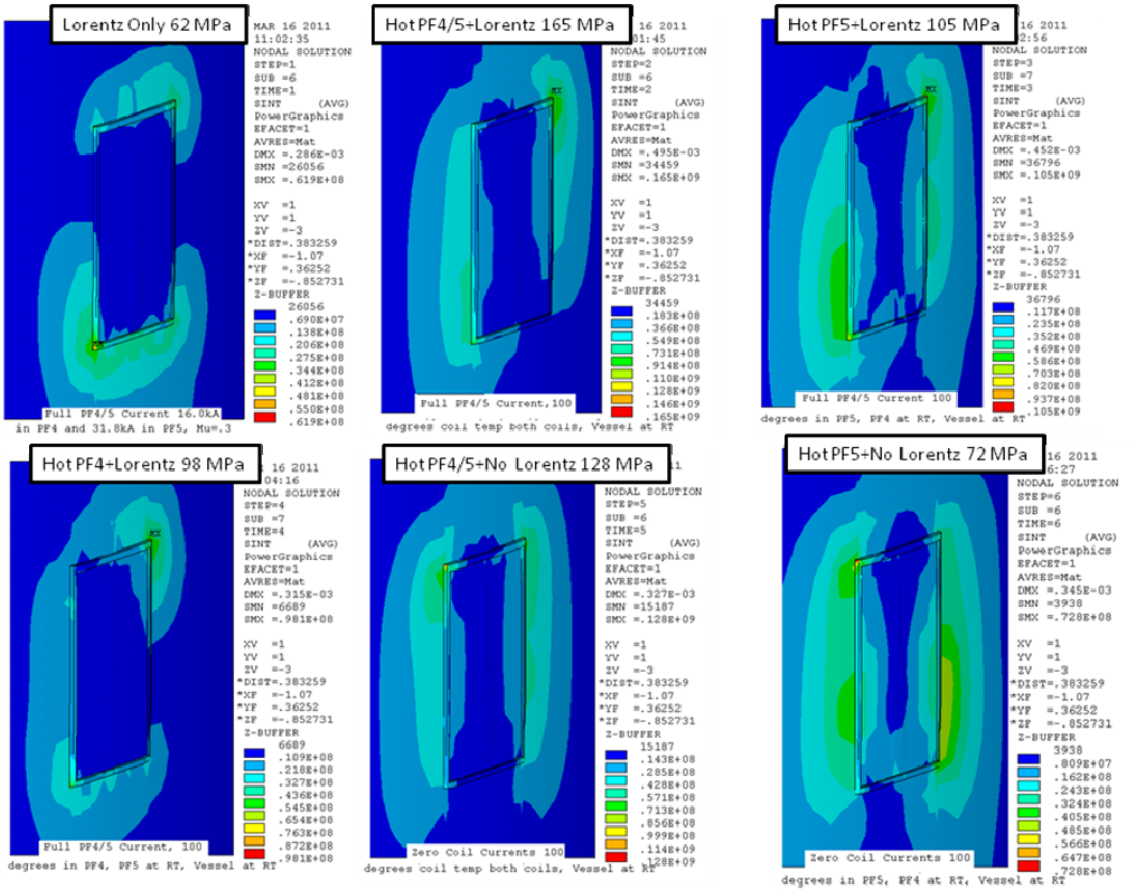
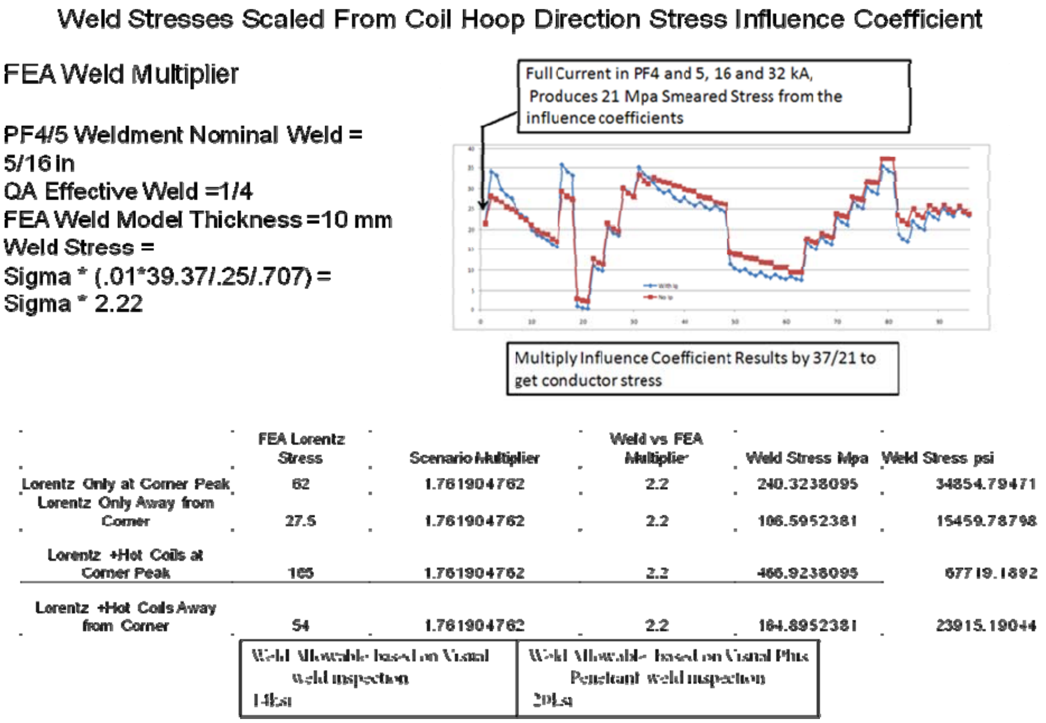


Figure 12.2-3 Weld Stresses from the Local Model of the Bracket



Weld Stresses Scaled From Coil Hoop Direction Stress Influence Coefficient

FEA Weld Multiplier

PF4/5 Weldment Nominal Weld = 5/16 in
QA Effective Weld =1/4
FEA Weld Model Thickness =10 mm
Weld Stress =
Sigma * (.01*39.37/.25/.707) =
Sigma * 2.22

Full Current in PF4 and 5, 16 and 32 kA, Produces 21 Mpa Smeared Stress from the influence coefficients

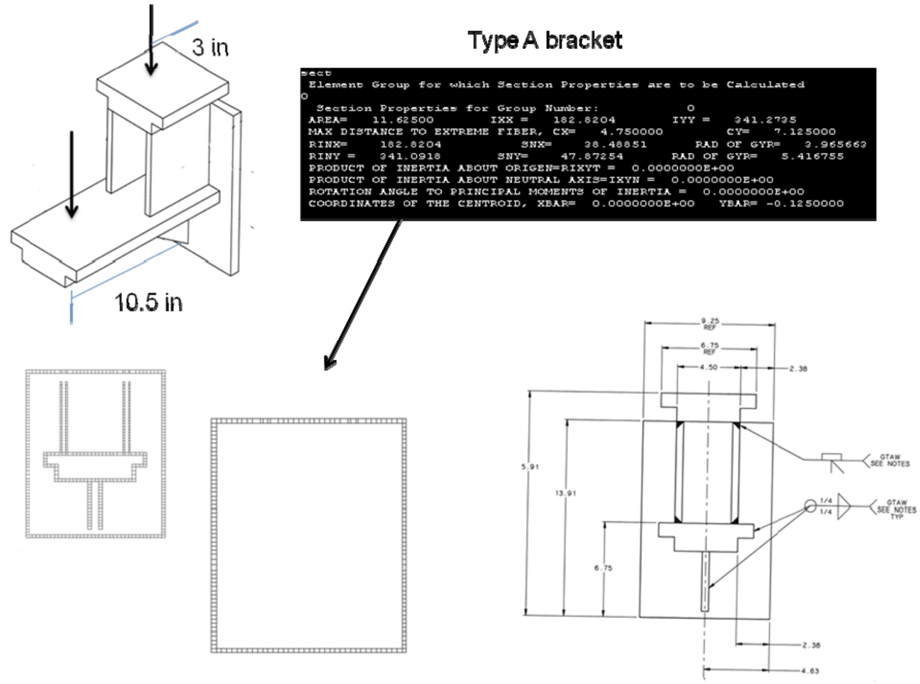
Multiply Influence Coefficient Results by 37/21 to get conductor stress

	FEA Lorentz Stress	Scenario Multiplier	Weld vs FEA Multiplier	Weld Stress Mpa	Weld Stress psi
Lorentz Only at Corner Peak	62	1.761904762	2.2	240.3238095	34854.79471
Lorentz Only Away from Corner	27.5	1.761904762	2.2	106.5952381	15459.78798
Lorentz +Hot Coils at Corner Peak	165	1.761904762	2.2	466.9238095	67719.1892
Lorentz +Hot Coils Away from Corner	54	1.761904762	2.2	184.8952381	23915.19044

Weld Allowable based on Visual weld inspection
14ksi

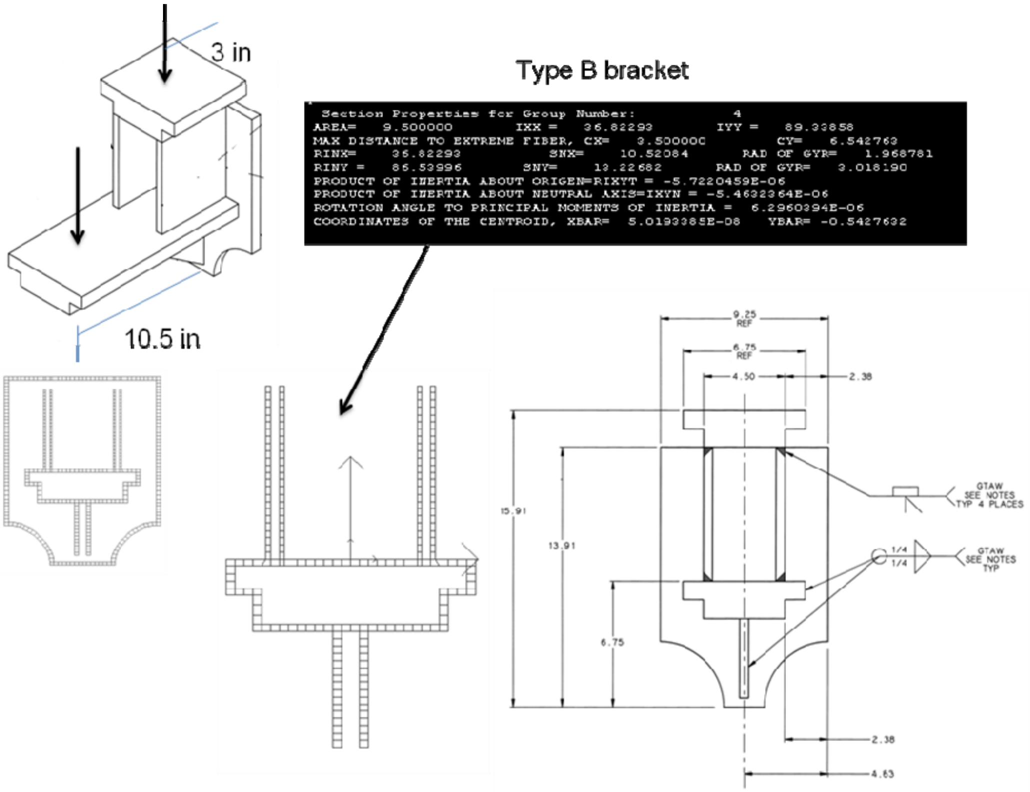
Weld Allowable based on Visual Plus Penetrant weld inspection
20ksi

Figure 12.2-4 Weld Stresses Scaled from the Local Model and Influence Coefficients



```
sect
 Element Group for which Section Properties are to be Calculated
0
  Section Properties for Group Number:           0
 AREA=    11.62500        IXX =    182.8204        IYY =    341.2735
 MAX DISTANCE TO EXTREME FIBER, CX=    4.750000        CY=    7.125000
 RINX=     182.8204          SNX=     38.48851      RAD OF GYR=    3.965663
 RINY =    341.0918        SNY=     47.87254      RAD OF GYR=    5.416755
 PRODUCT OF INERTIA ABOUT ORIGEN=RIXYT =  0.0000000E+00
 PRODUCT OF INERTIA ABOUT NEUTRAL AXIS=IXYN =  0.0000000E+00
 ROTATION ANGLE TO PRINCIPAL MOMENTS OF INERTIA =  0.0000000E+00
 COORDINATES OF THE CENTROID, XBAR=  0.0000000E+00   YBAR= -0.1250000
```

Figure 12.2-5 Weld Section Properties for the Type A Bracket



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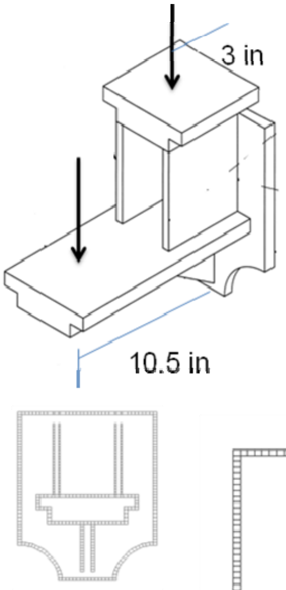
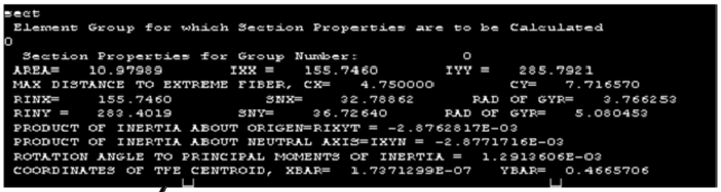
 Section Properties for Group Number:           4
 AREA=    9.500000        IXX =    36.82293        IYY =    89.33858
 MAX DISTANCE TO EXTREME FIBER, CX=    3.50000C        CY=    6.542763
 RINX=     36.82293          SNX=     10.52084      RAD OF GYR=    1.968781
 RINY =    86.53996        SNY=     13.22682      RAD OF GYR=    3.018190
 PRODUCT OF INERTIA ABOUT ORIGEN=RIXYT = -5.7220459E-06
 PRODUCT OF INERTIA ABOUT NEUTRAL AXIS=IXYN = -5.4632364E-06
 ROTATION ANGLE TO PRINCIPAL MOMENTS OF INERTIA =  6.2960394E-06
 COORDINATES OF THE CENTROID, XBAR=  5.0193385E-08   YBAR= -0.5427632
```

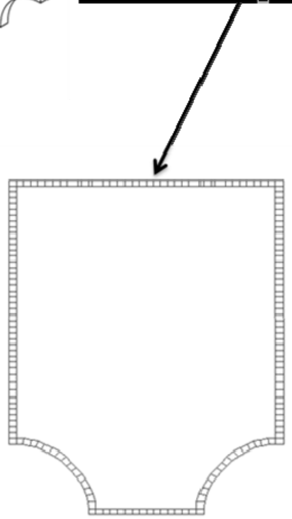
Figure 12.2-6 Weld Section Properties for the Type B Bracket



Type B bracket



```
sect
 Element Group for which Section Properties are to be Calculated
0
  Section Properties for Group Number:            0
 AREA=   10.97989       IXX =   155.7460       IYY =   285.7921
 MAX DISTANCE TO EXTREME FIBER, CX=   4.750000        CY=   7.716570
 RINX=    155.7460          SNX=    32.78862      RAD OF GYR=   3.766253
 RINY =   283.4019        SNY=    36.72640      RAD OF GYR=   5.080453
 PRODUCT OF INERTIA ABOUT ORIGEN=RIXYT = -2.8762817E-03
 PRODUCT OF INERTIA ABOUT NEUTRAL AXIS=IXYN = -2.8771716E-03
 ROTATION ANGLE TO PRINCIPAL MOMENTS OF INERTIA =  1.2913606E-03
 COORDINATES OF TFE CENTROID, XBAR=  1.7371299E-07   YBAR=  0.4665706
```



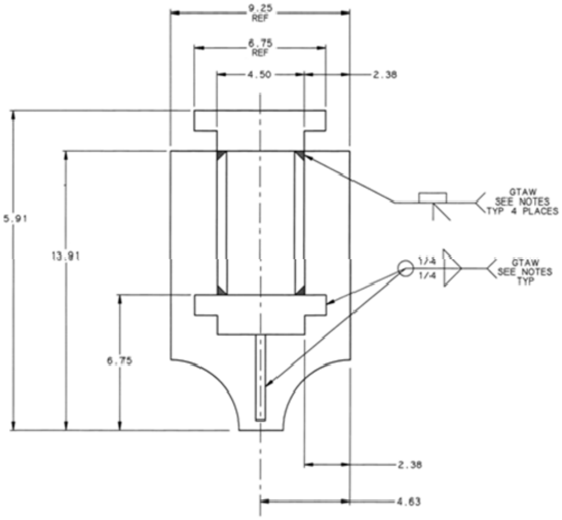


Figure 12.2-7 Weld Section Properties for the Type B Bracket

Weld Stresses Calculated From Weld Section Properties

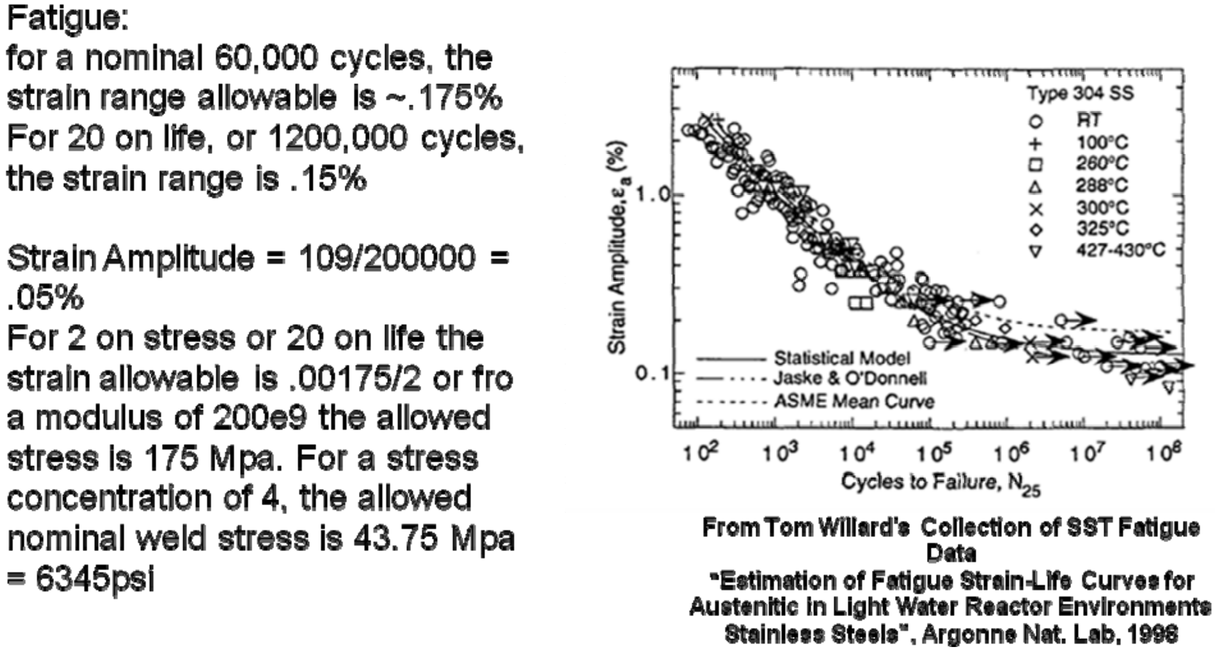
psi Type A or B Bracket	Worst Net PF4,5,U,L	Moment Sum for 6 Supports (12 U&L), 10.5" Lever	Section Modulus (in^3)	Bending Stress (psi)
psi Type A or B Bracket	-81953	-71708.875	13.22	-7672.237534
Type A Pad	-81953	-71708.875	47.87	-2118.800505
Type B Pad	-81953	-71708.875	36.7	-2763.677935

From Charlie's Design Point Spreadsheet

Fz(lbf)	(PF4U+PF5U)+(PF4L+PF5L)
Min w/o Plasma	-81947
Min w/ Plasma	-81953
Min Post-Disrupt	-58992
Min	-81953
Worst Case Min	-513255
Max w/o Plasma	0
Max w/ Plasma	17
Max Post-Disrupt	15
Max	17
Worst Case Max	513255

Conservatively uses PF5 moment arm and .707 factor on ¼ in weld

Figure 12.2-8 Net Loads on Bracket/Coil System



Fatigue:
for a nominal 60,000 cycles, the strain range allowable is ~.175%
For 20 on life, or 1200,000 cycles, the strain range is .15%

Strain Amplitude = 109/200000 = .05%
For 2 on stress or 20 on life the strain allowable is .00175/2 or fro a modulus of 200e9 the allowed stress is 175 Mpa. For a stress concentration of 4, the allowed nominal weld stress is 43.75 Mpa = 6345psi

From Tom Willard's Collection of SST Fatigue Data
"Estimation of Fatigue Strain-Life Curves for Austenitic in Light Water Reactor Environments Stainless Steels", Argonne Nat. Lab, 1998

Figure 12.2-9 Fatigue Assessment

The weld stresses in the weld of the backing plate/pad to the vessel are 2118 psi and 2763 psi for the type A and B brackets, respectively. These are well below the fatigue allowable calculated above. This is consistent with the findings of the inspection described in Appendix A. The stress in the weld between the back plate or pad and the bracket was calculated to be 7672 psi based on the 1/8-inch fillets on the vertical legs of the bracket.

12.3 PF5 Bracket Support Plate and Weld, With and without Existing Column

The existing Support bracket for PF 4 and 5 includes an extension to support PF5. During the operation of NSTX, the support column between the existing upper and lower PF5 extensions buckled, and needed reinforcement. Early upgrade PF4/5 support concepts sought to remove this column because of its weakness, and to ease clearance issues. In this section, bracket stresses are considered with and without the column. The cantilever load principally derives from attractive loads to the lower PF4 and 5 coil pair. The final design, as of November 2011, has new, heavier columns between the upper and lower support brackets. This section is an exploration of why the new column was needed.

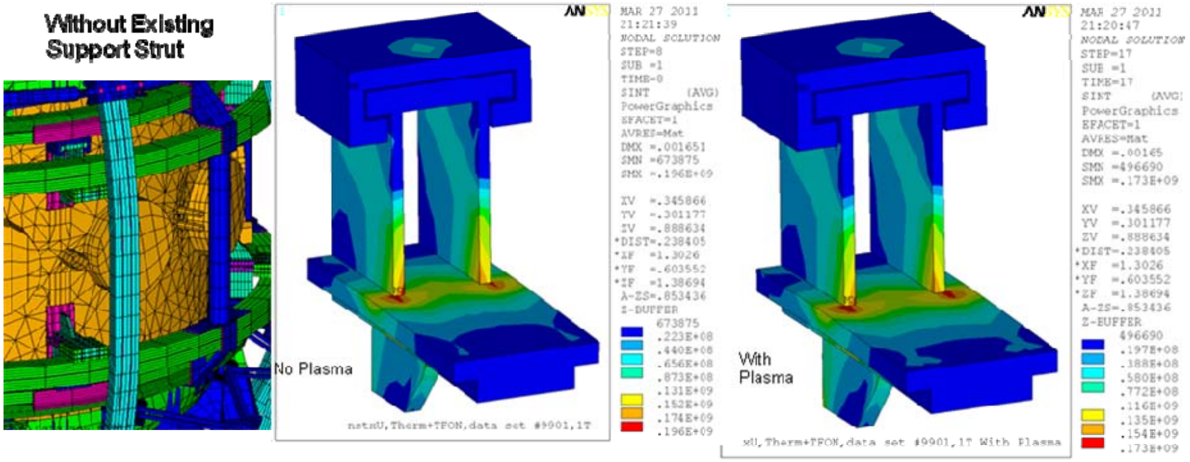


Figure 12.3-1 Existing support bracket without support strut - With and Without plasma

Without the strut, bending stress concentrates at the corners of the gusset plate weld. The global Model [2] was run with and without the support strut.

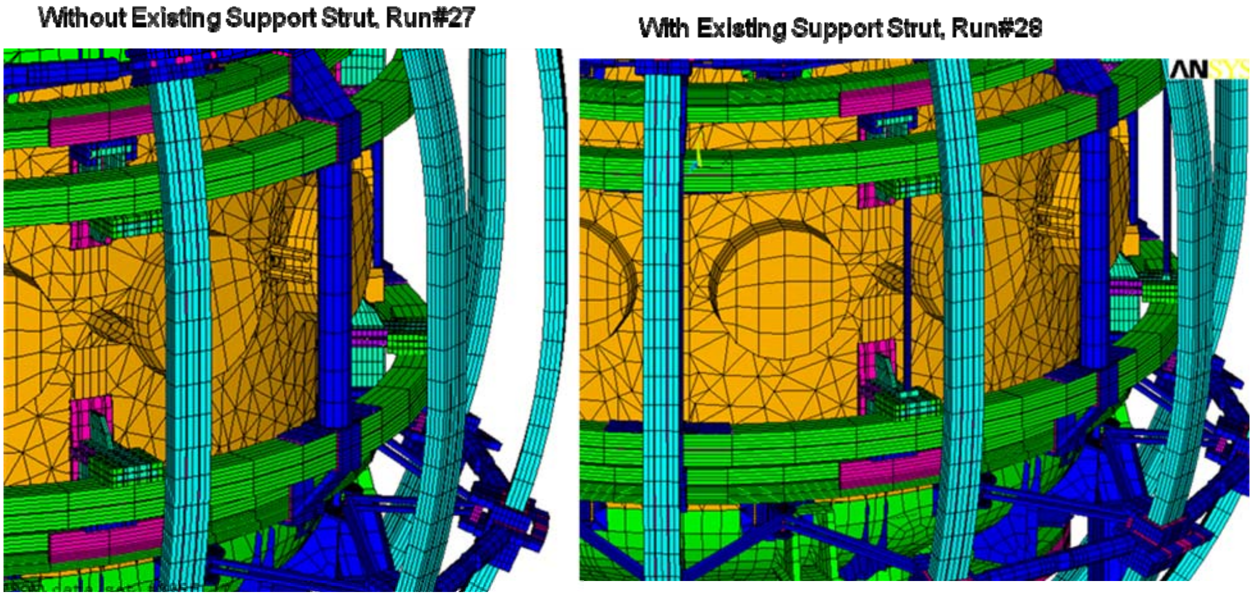


Figure 12.3-2 Models With and Without the Thin Existing Support Strut

Even though the support strut is being retained, the "no strut" case is included here because it is relatively easy to construct stress multipliers for the bending stress in the cantilevered part of the support. This allows exploration of all the identified scenarios, with and without plasmas.

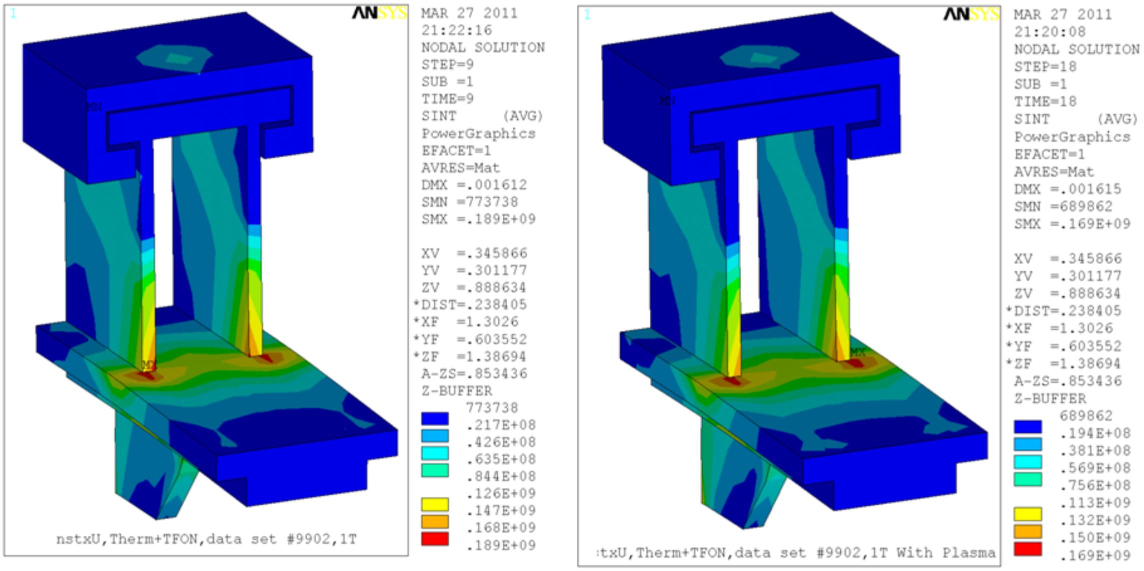


Figure 12.3-3 Existing Support Bracket - No Strut, EQ 02, With and Without Plasma

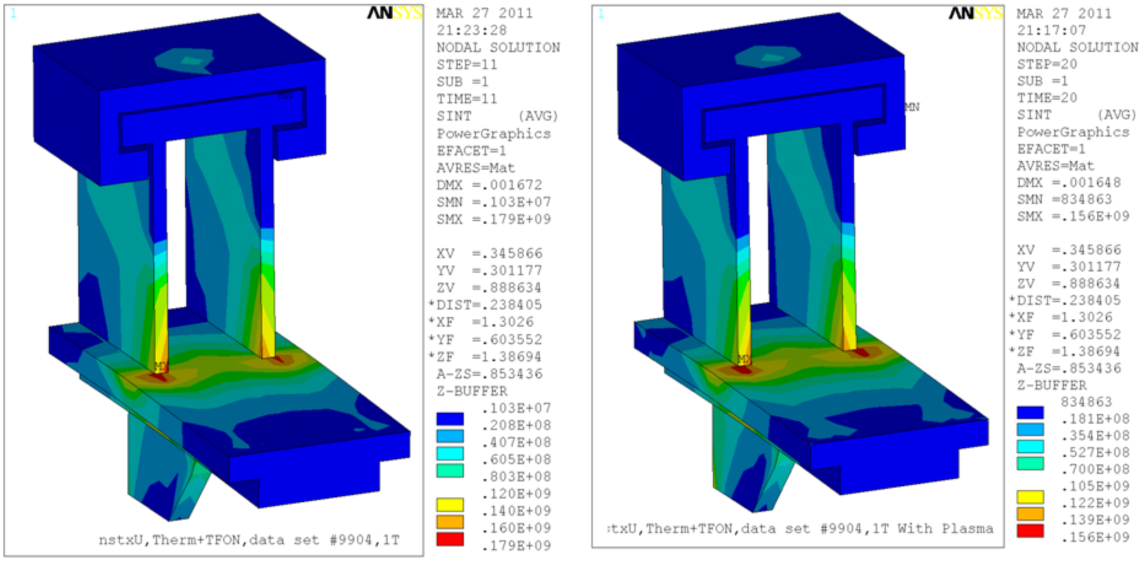


Figure 12.3-4 Existing Support Bracket - No Strut, EQ 04 With and Without Plasma

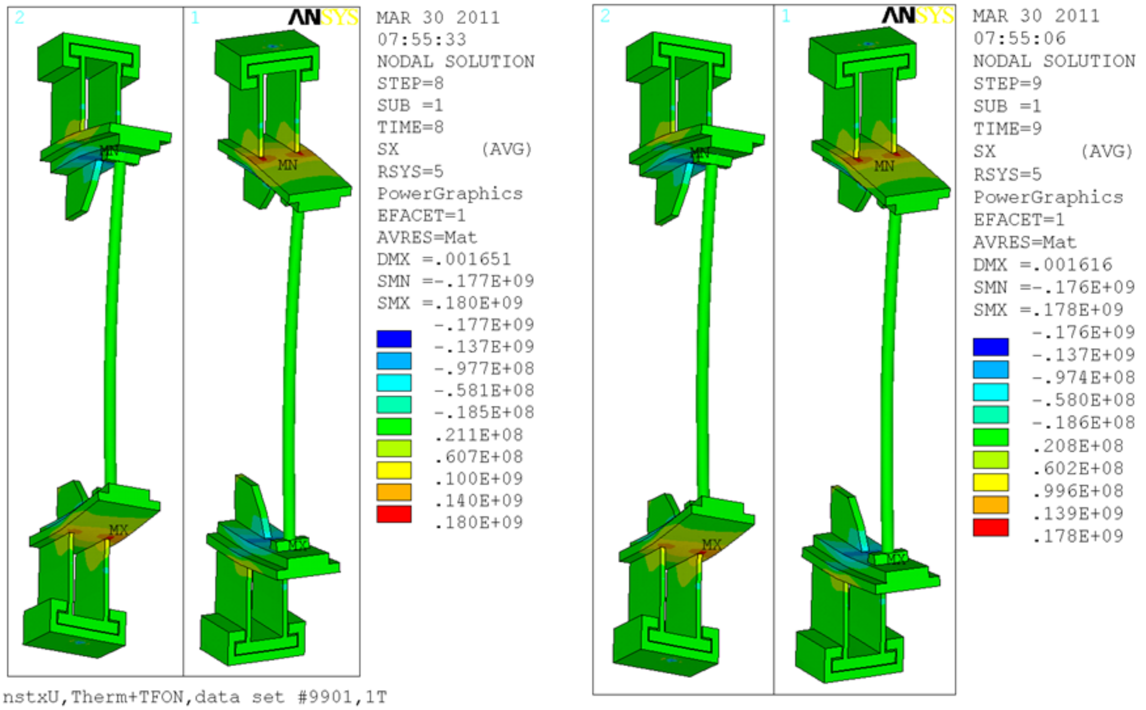


Figure 12.3-5 Existing Support Bracket - With Strut, EQ 01 and EQ 02

It is evident from this plot that the small diameter column does little to resist the cantilever bending of the PF5 support plate. A stiffer section is needed. A heavier column was added in May, 2011 and a model including this has been run and reduces the bending stress on the cantilever section substantially.

Bracket Stress by Influence Coefficients

If the bracket stress is determined primarily by the PF5 loads, the bracket stress can be related to coil current influence coefficients in a way similar to how the coil stresses can be computed. This is not rigorous technically, because the rods/columns will introduce contributions from the lower coils. This section is not included in the DCPS for this reason, but it allows consideration of all 96 scenarios, with and without a plasma.

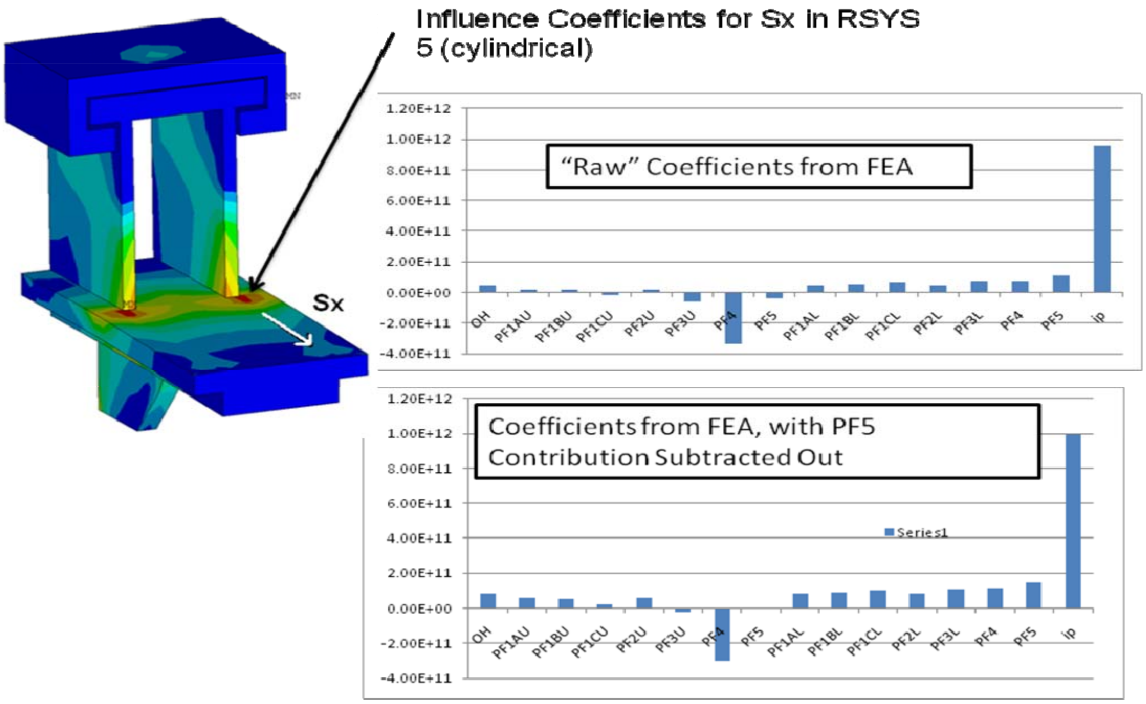


Figure 12.3-6 Influence Coefficients

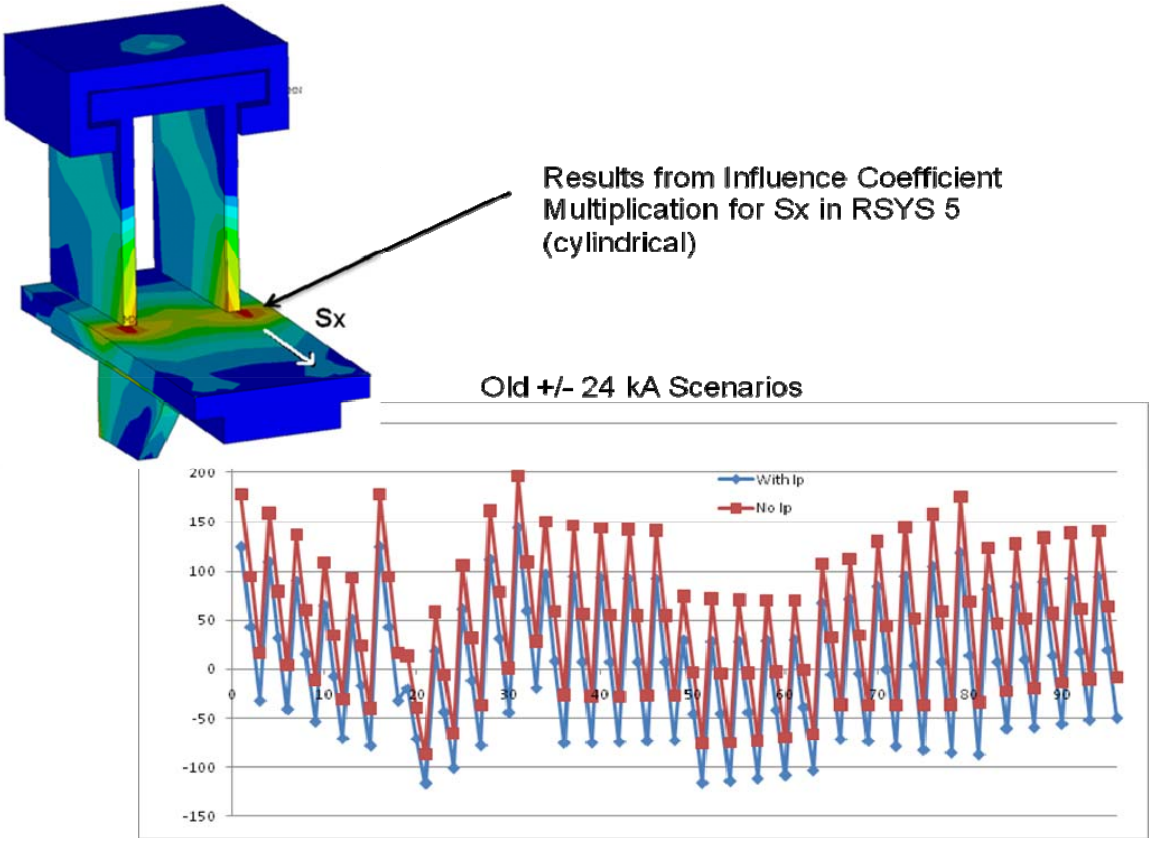
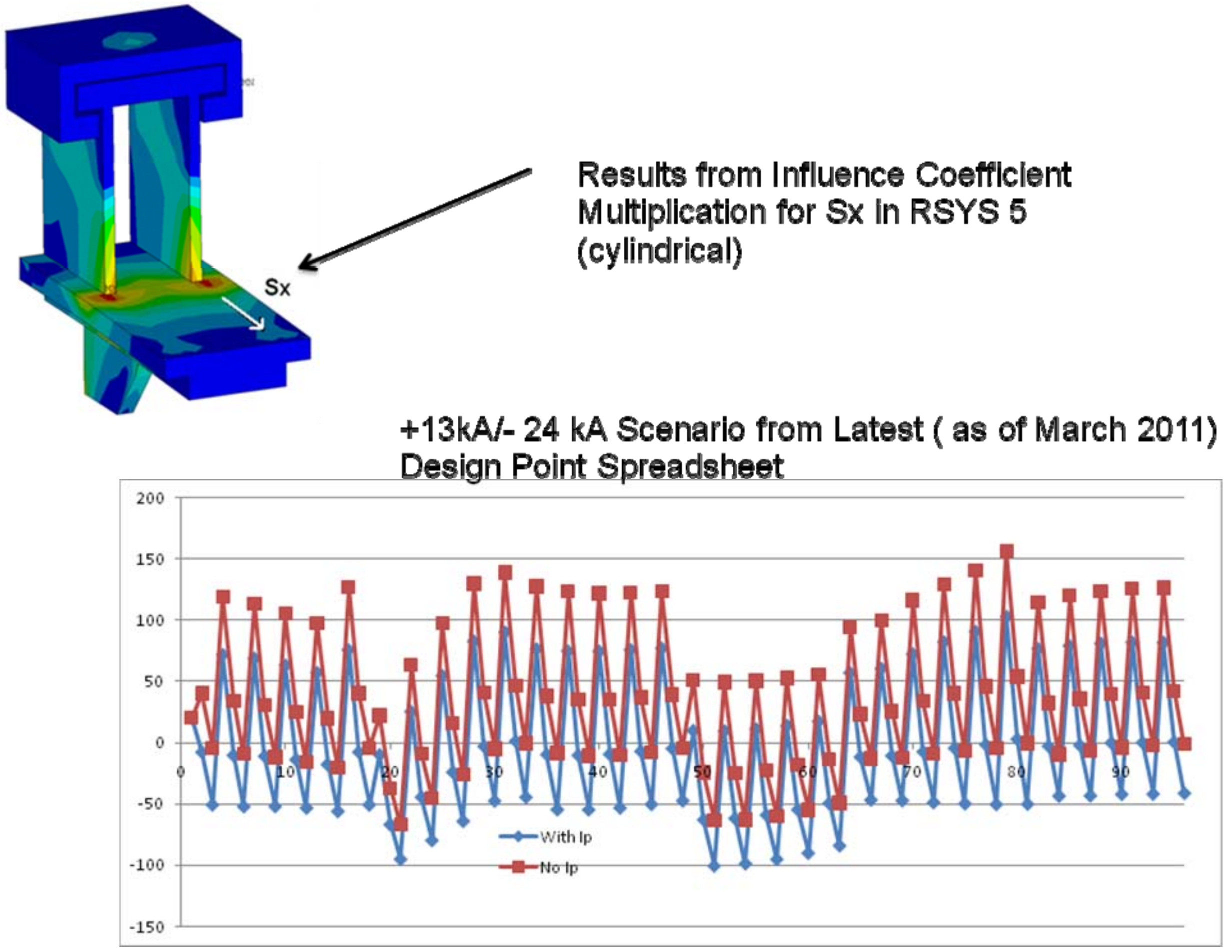


Figure 12.3-7 Influence Coefficient Results



Results from Influence Coefficient Multiplication for Sx in RSYS 5 (cylindrical)

+13kA/- 24 kA Scenario from Latest (as of March 2011) Design Point Spreadsheet

Figure 12.3-8 Influence Coefficient Results

The peak stress in the plate near the weld toe is less than 150 MPa, which is within the static allowable for the bracket material, but is probably a concern with respect to weld fatigue. This is another reason why the existing column/rod should be stiffened.

12.4 Column Stresses from the Global Model

The global model [2] is available to provide column stresses in both the added column and the existing column. Details of the columns had not been finalized at the PDR and FDR. The most recent (December 2011) results are presented in figure 12.4-1 and 2. The peak stress reported in the recent results is 200 MPa (30ksi). FDR results are presented in Figures 12.4-3 and beyond. The conclusion at the FDR was that the existing column/rod is not stiff enough to help the brackets welded to the vessel shell, the stresses in the columns and rods were small (less than 120 MPa in the rod and 30 MPa (in what was analyzed as a 5 inch pipe column at the PDR)). Subsequent to the PDR, the existing columns have been upgraded and as of Dec 2011, all the support points use 3-inch OD pipe with a 0.3 inch wall thickness.

For design of the hardware, Table 6.3-5 shows the max column compressive loads from the design point spreadsheet. The coils are relatively flexible with respect to the 12 support points, so the design point spreadsheet load combinations are adequate to estimate column loads. Find sums of PF4+5U Min (max downward load) and PF4 and 5L max, and divide by 12. This works out to 20,000 lbs on each of the 12 support points. For the PF4 support flanges, the individual coil loads are appropriate to calculate the moment on the column. Take the PF4U min load from the spreadsheet and multiply by the offset between the column CL and the PF4 coil CL, then add it to the 20,000 lbs. The column is centered on the PF5 CL.

This should be conservative because the max PF4 loading will not be at the same time that the max PF4+5 loading occurs. To address the actual combination of PF4 and 5 loading, the global model results for the 96 scenarios is needed.

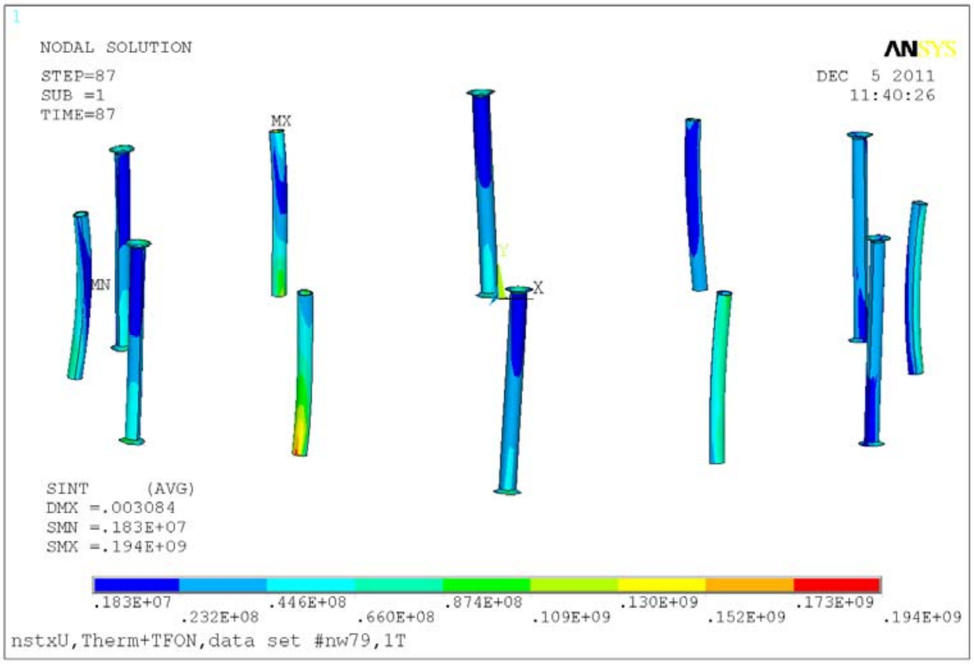


Figure 12.4-1 Column Stress From Global Model with the New Columns and the upgrade of the existing Columns modeled as 3 inch OD 0.3 inch wall thickness Pipe.

EQ 79 is plotted in figure 12.4-1 because it represents a maximum plotted in the Post26 results below.

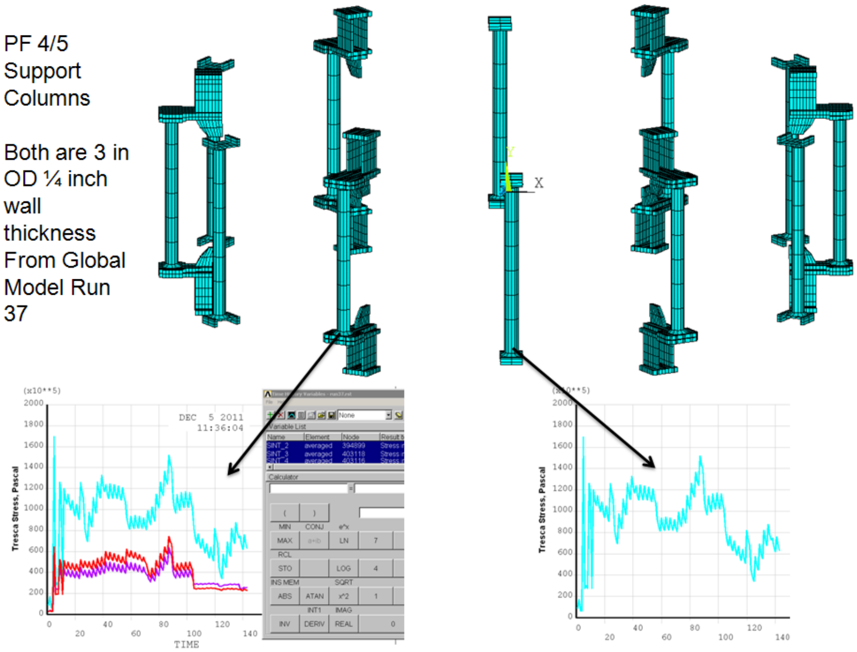


Figure 12.4-2 Column Stress From Global Model with the New Column and the upgrade of the existing column modeled as 3 inch OD 0.3 inch Wall Thickness Pipe

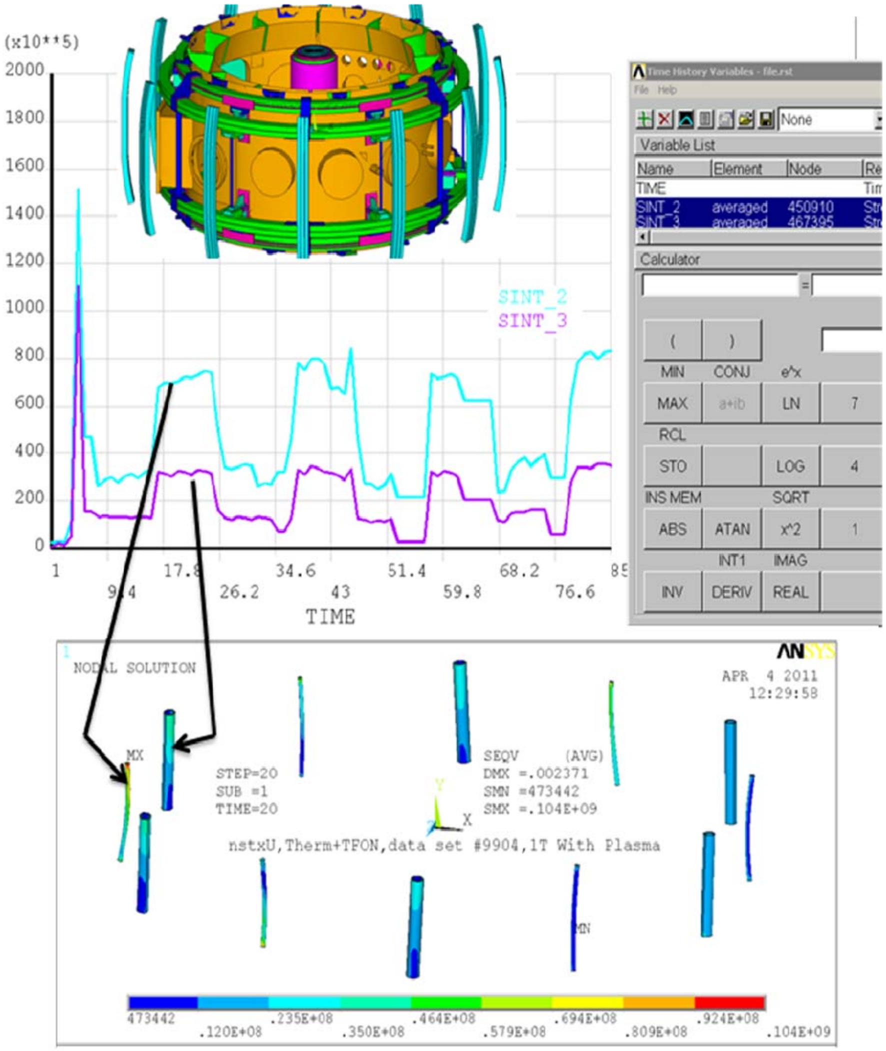
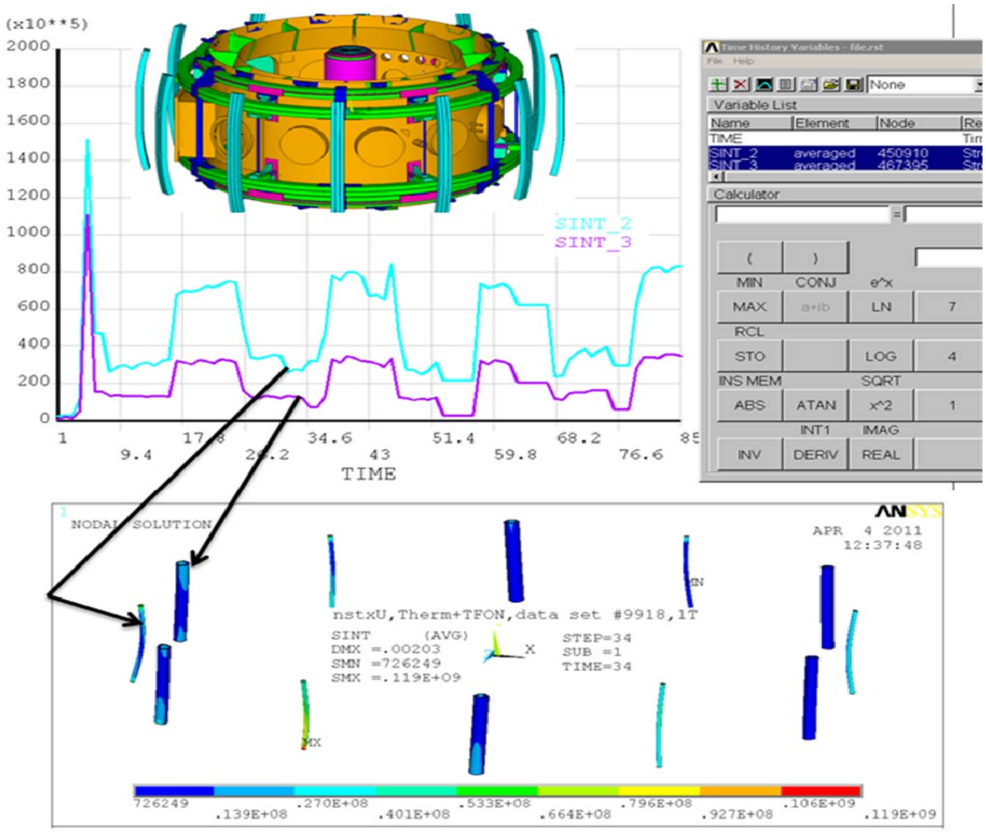


Figure 12.4-3 Column Stress From Global Model (Original Existing thin Column and 5 inch New Column)

In figure 12.4-3, the post 26 results are compared with the contour plots at load step EQ 04. The new mid-span columns are modestly stressed at about 30 MPa for the 5 inch OD column.



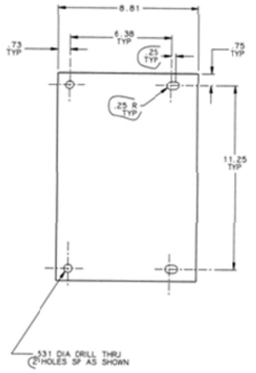
Name	Element	Node
TIME		
SINT_2	averaged	450910
SINT_3	averaged	467395

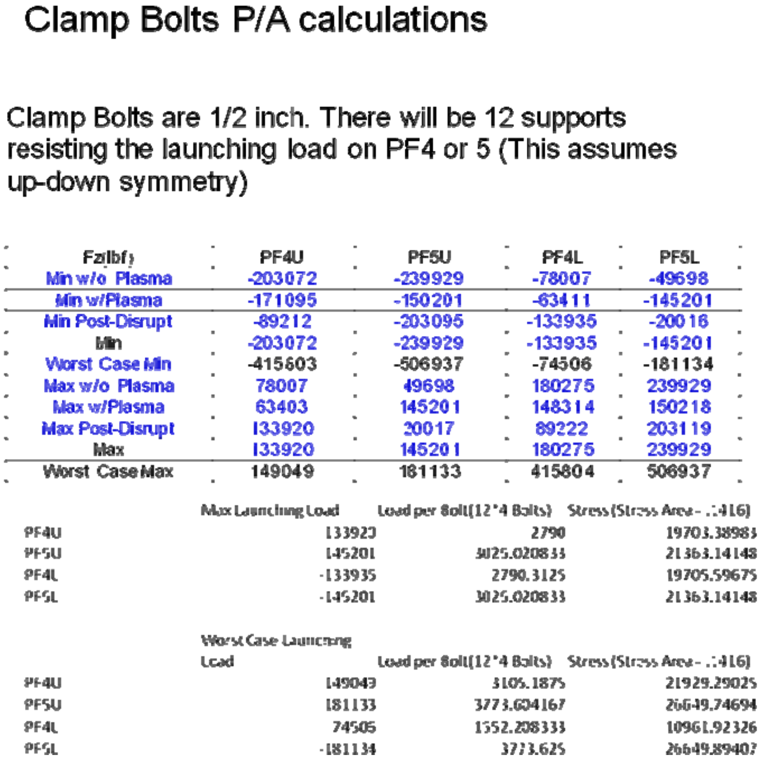
```
nstxU,Therm+TFON,data set #9918,1T
SINT      (AVG)          STEP=34
DMX =.00203              SUB =1
SMN =726249              TIME=34
SMX =.119E+09
```

Figure 12.4-4 Column Stress From Global Model (Original Existing thin Column)

In figure 12.4-2, the post 26 results are compared with the contour plots at load step EQ 18

12.5 Coil Clamp Plate Bolting





Clamp Bolts P/A calculations

Clamp Bolts are 1/2 inch. There will be 12 supports resisting the launching load on PF4 or 5 (This assumes up-down symmetry)

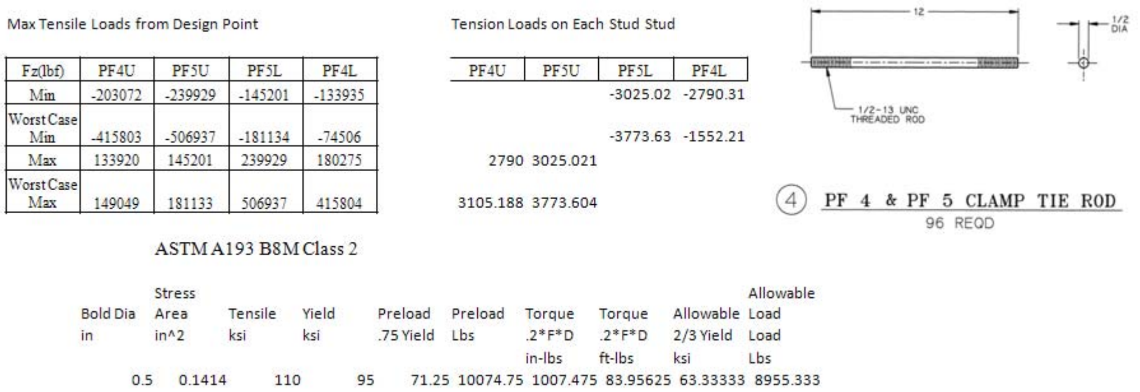
Fz(lbf)	PF4U	PF5U	PF4L	PF5L
Min w/o Plasma	-203072	-239929	-78007	-49698
Min w/Plasma	-171095	-150201	-63411	-145201
Min Post-Disrupt	-89212	-203095	-133935	-20016
Min	-203072	-239929	-133935	-145201
Worst Case Min	-415603	-506937	-74506	-181134
Max w/o Plasma	78007	49698	180275	239929
Max w/Plasma	63403	145201	148314	150218
Max Post-Disrupt	133920	20017	89222	203119
Max	133920	145201	180275	239929
Worst Case Max	149049	181133	415804	506937

	Max Launching Load	Load per Bolt(12*4 Bolts)	Stress (Stress Area - .1416)
PF4U	133920	2790	19703.38983
PF5U	145201	3025.020833	21363.14148
PF4L	-133935	2790.3125	19705.59675
PF5L	-145201	3025.020833	21363.14148

	Worst Case Launching Load	Load per Bolt(12*4 Bolts)	Stress (Stress Area - .1416)
PF4U	149049	3105.1875	21929.29025
PF5U	181133	3773.604167	26649.74694
PF4L	74505	1552.208333	10961.92326
PF5L	-181134	3773.625	26649.89407

Figure 12.5-1 PF 4 and 5 Clamp Plate Loads

For loading that is up-down symmetric, that is the upper coils are being loaded upward and the lower loads are being loaded downward, then all 12 supports will resist the loads. Then there are four studs per clamp plate and 12 sets of clamp plates. The present FDR design used ¾-inch bolts on the added column clamps, but in this analysis it is assumed that 1/2 inch bolts are used everywhere.



Max Tensile Loads from Design Point

Fz(lbf)	PF4U	PF5U	PF5L	PF4L
Min	-203072	-239929	-145201	-133935
Worst Case Min	-415803	-506937	-181134	-74506
Max	133920	145201	239929	180275
Worst Case Max	149049	181133	506937	415804

Tension Loads on Each Stud Stud

PF4U	PF5U	PF5L	PF4L
		-3025.02	-2790.31
		-3773.63	-1552.21
2790	3025.021		
3105.188	3773.604		

ASTM A193 B8M Class 2

Bold Dia in	Stress Area in^2	Tensile ksi	Yield ksi	Preload .75 Yield	Preload Lbs	Torque .2*F*D in-lbs	Torque .2*F*D ft-lbs	Allowable 2/3 Yield ksi	Allowable Load Load Lbs
0.5	0.1414	110	95	71.25	10074.75	1007.475	83.95625	63.33333	8955.333

Figure 12.5-2 PF 4 and 5 Clamp Plate Bolt Loads

If the loads are not up-down symmetric, for example, if upward loads on the upper coils are not equilibrated by the lower coils, then the clamps welded to the vessel could see larger loads. If 6 support points are assumed, then the loads on the studs for the existing brackets could double from around 4000 lbs to 8000 lbs - still within the allowable for the recommended ASTM A193 B8M Class 2 bolts.

Preloading the bolts will aid in reducing the effect of fatigue. Preloaded clamp bolts will see the preload stress up until the bolted clamp lifts off. If the preload exceeds the applied load, then the bolts only see the preload stress. If the preload is less than the applied load, then the bolts need to be sized and evaluated based on the applied load. By specifying a preload which does not exceed the bolt capacity, and ensuring that the bolt is sized appropriately for the applied loads, guarantees that the bolt stress does not exceed the allowable.

For a static allowable check, the DCPS does not need to include the effect of the preload. To mitigate the potential for fatigue, the preload in the bolts should be specified. The usual practice is to go to 70% yield - this is above the static allowable for which the bolt is qualified - so, it shouldn't unload under the applied load - but for the high strength bolts this may be overkill. The higher preload may stress the copper conductors. It is recommended that the bolts be preloaded based on a 20 ksi yield and some occasional lift-off would be allowed.

12.6 T slot Stress

All supports, except those that are locked (near the leads and 180 degrees opposite) must allow independent radial motion of PF4 and 5. At the PDR, a clamped concept was presented that didn't allow this motion, or, it was expected that the rubber pads would allow the relative motion. A rubber clamped version was run, and for the pad size assumed, the compliance was not good enough to allow the differential motion.

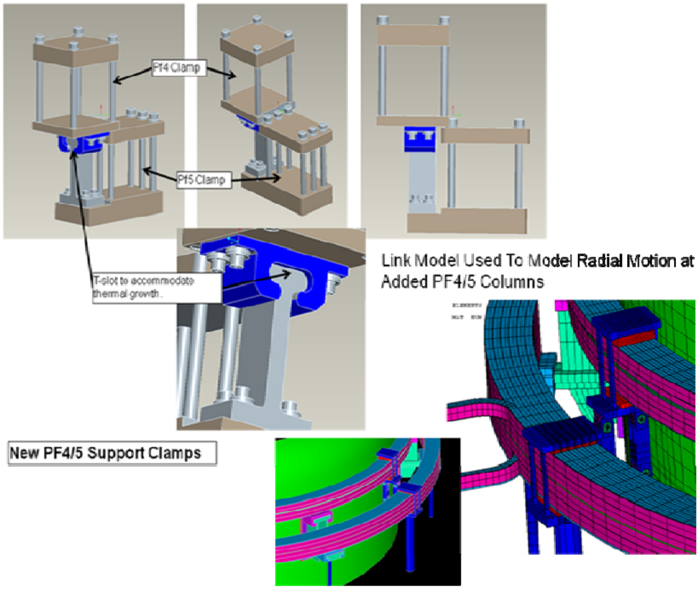


Figure 12.6-1 Dovetail or T slot sliding Block and Link Model Used to Simulate the Radial motion of the sliding block.

The FDR clamp is a design more similar to the existing sliding clamps. This latest design has only been partially analyzed but a link connected design that has the same mechanics has been used to properly model the thermal stresses in the coils. Each of the four tierods that hold PF4 down sees about 4,000 lbs (see Figure 12.5-2 Under Tension Loads on each stud). The T slot shown below (Figure 12.6-2) will see the loads from four studs or 16,000 lbs.

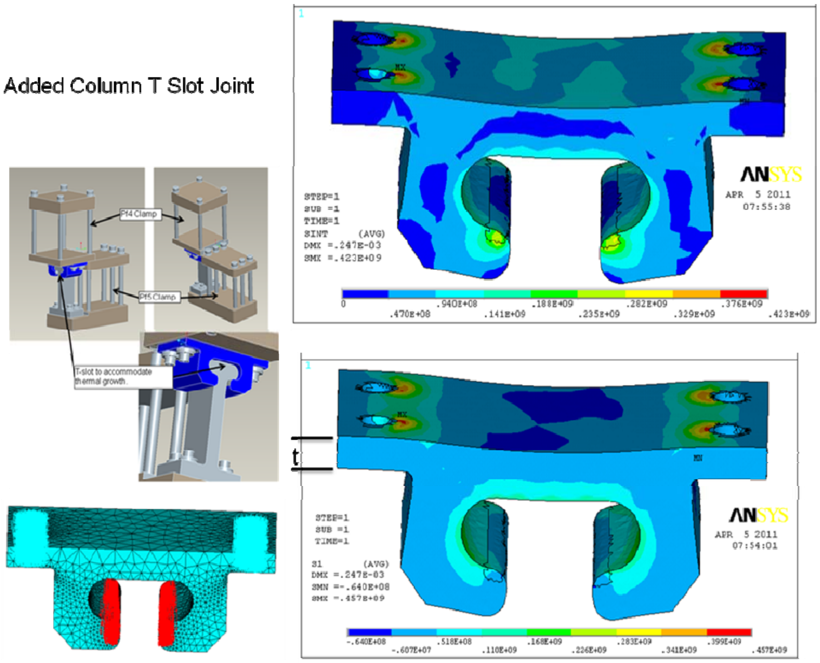
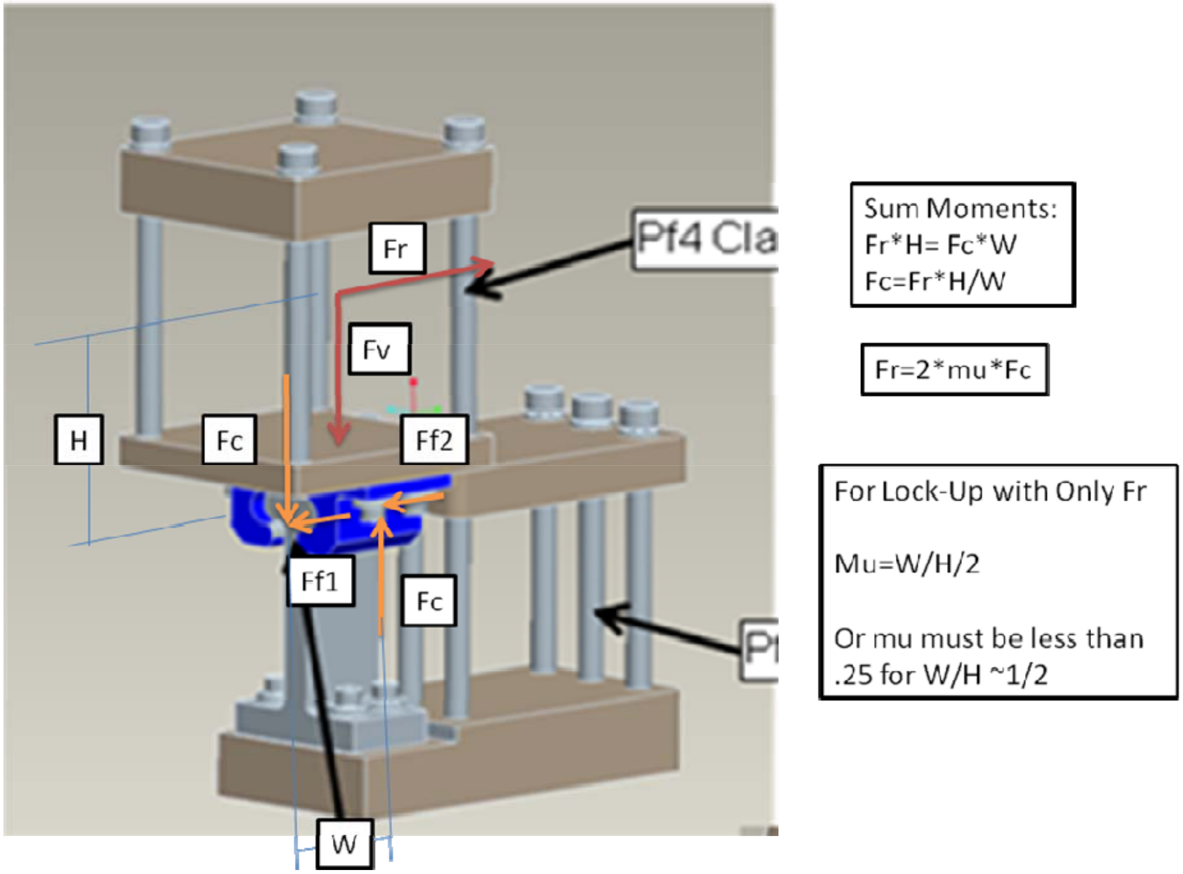


Figure 12.6-2 Dovetail Stress Analysis

Part of the T slot has been analyzed with 16,000 lbs applied. The flange thickness should be increased.



Sum Moments:
Fr*H= Fc*W
Fc=Fr*H/W

Fr=2*mu*Fc

For Lock-Up with Only Fr

Mu=W/H/2

Or mu must be less than .25 for W/H ~1/2

Figure 12.6-3 Mechanics of Self-Locking of the Sliding Support

Fr(lbf)	PF4U	PF4L
Min	-152166	-152181
Max	289472	289442

Fz(lbf)	PF4U	PF4L
Min	-203125	-134053
Max	134052	180293

Table 12.6-1 Forces on PF4 and 5 from the Design Point Spreadsheet

Restraining Force = mu* 203125 +2*mu *h/w*289472
To allow radial growth under Lorentz loads the radial load must be greater than the frictional restraining force, or: 289472 >mu*(203125+2*h/w*289472)
Or mu must be less than 289472/(203125+2*(~2)*289472) = .213
Or mu must be less than .1 for H/W~4
Magna Plate has a Friction Coefficient “as low as .05”.
We are supposed to design to mu +.15 or .2 so, H/w <2

12.7 Vessel Shell Stress

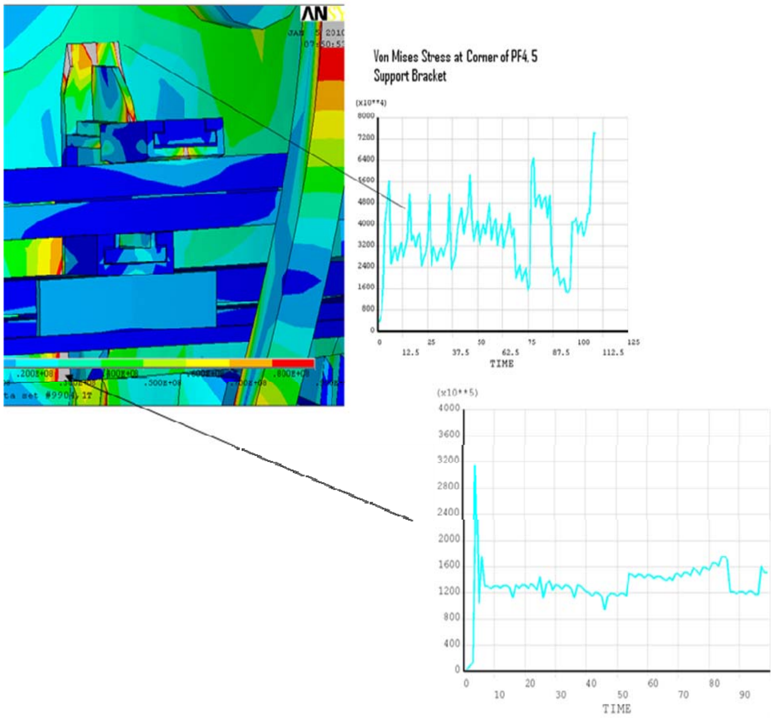
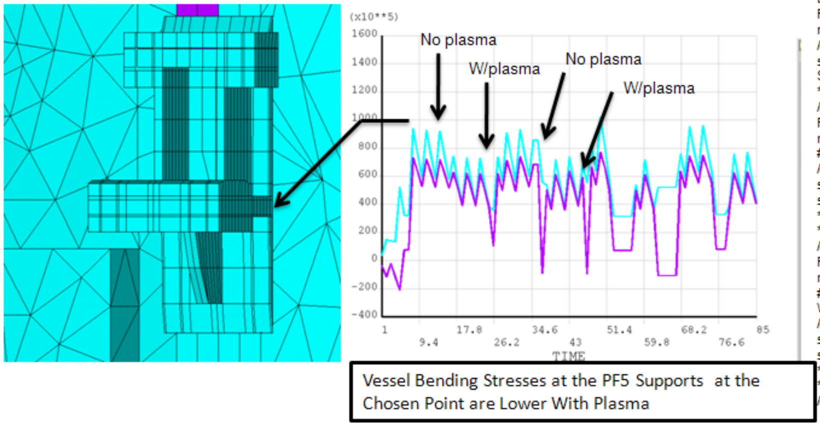


Figure 12.7-1 Vessel Shell Stress Near the Existing PF4/5 Support Brackets

Vessel stresses are 160 MPa at the bottom and 64 MPa at the top (from the Jan 6, 2011, meeting presentation).



Vessel Bending Stresses at the PF5 Supports at the Chosen Point are Lower With Plasma

```
title
Run#%runn%,nstxU,Ther
m+TFON,%tffield%T
/input,tfon,mod
solve
Save
*do,ls,1,9
/title
Run#%runn%,nstxU,Ther
m+TFON,data set
#990%ls%,%tffield%T
/input,990%ls%,mod
solve
save
*enddo
*do,ls,1,9
/title
Run#%runn%,nstxU,Ther
m+TFON,data set
#990%ls%,%tffield%T
With Plasma
/input,ip0%ls%,mod
solve
save
*enddo
*do,ls,10,20
/*enddo
```

```
/title
Run#%runn%,nstxU,Ther
m+TFON,data set
#99%ls%,%tffield%T
/input,99%ls%,mod
solve
save
*enddo
*do,ls,10,20
/title
Run#%runn%,nstxU,Ther
m+TFON,data set
#99%ls%,%tffield%T With
Plasma
/input,ip%ls%,mod
solve
save
*enddo
*do,ls,21,30
/title
Run#%runn%,nstxU,Ther
m+TFON,data set
#99%ls%,%tffield%T
/input,99%ls%,mod
solve
save
*enddo
```

Figure 12.7-2 Vessel Shell Stress Near the Existing PF4/5 Support Brackets

These results show the shell stress slightly higher with no plasma. In the load sequence, first 10 load cases without plasma are analyzed then 10 load cases with plasma are analyzed. The trend in coil tensile stress is the opposite - see Section 9 - but the differences aren't great.

13.0 Bake-Out Thermal Stress

In an early analysis, the existing PF 4 and 5 support hardware was modeled as remaining at RT during bake-out. This produced a sharp gradient between the PF4/5 support bracket and the vessel shell. During a 2010 outage, the bracket was instrumented with thermocouples and the actual bake-out temperature gradient was measured. This was then imposed on the structural model and the stresses were found to be much reduced, particularly in the weld.

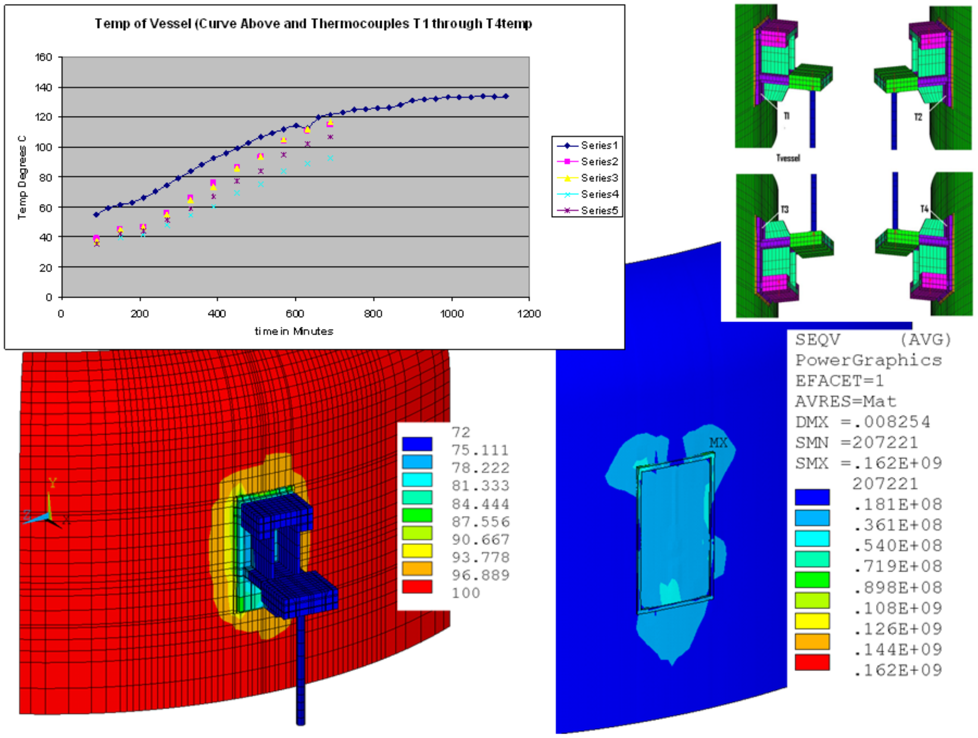


Figure 13.0-1 Vessel Shell Stress Near the Existing PF4/5 Support Brackets During Bake-Out Based on the Measured Bake-Out Temperature Transient

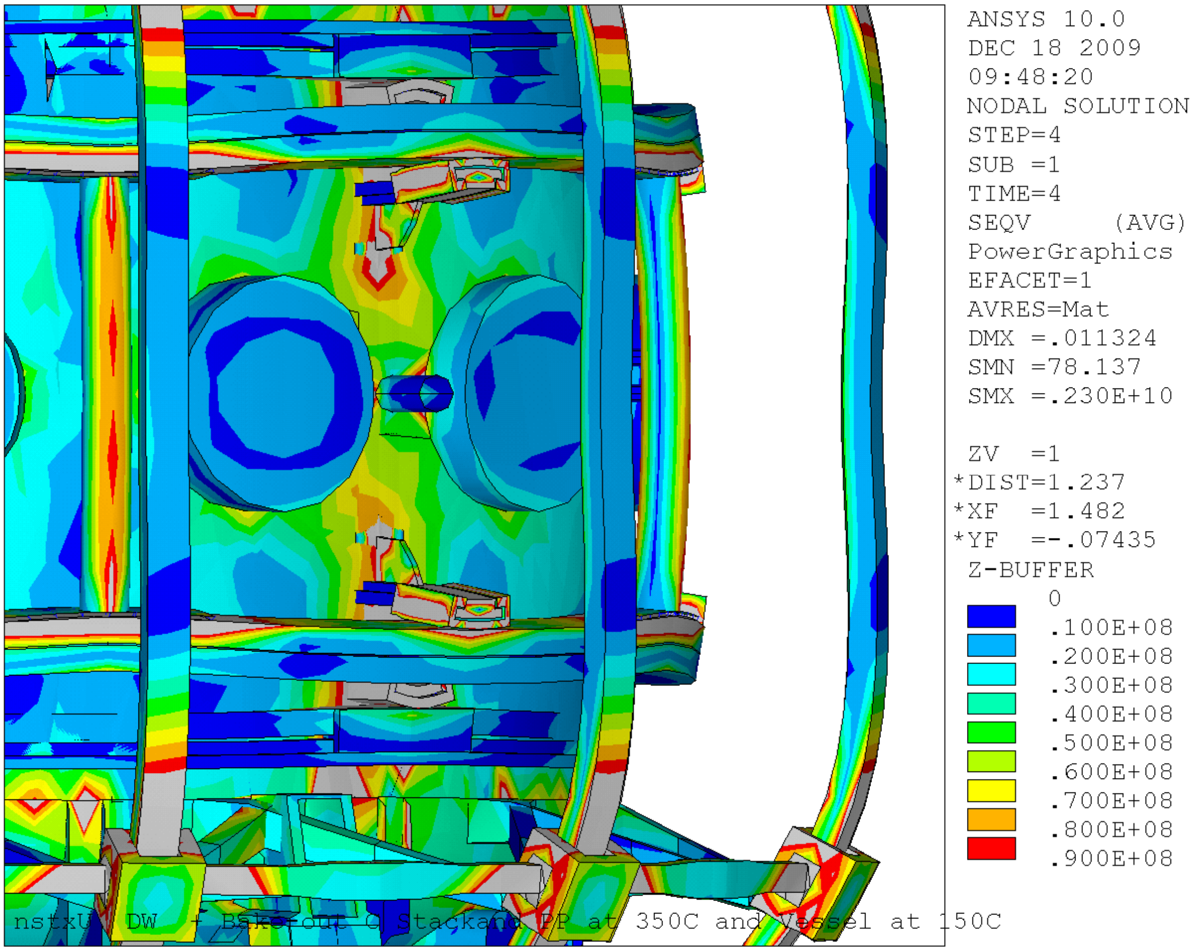


Figure 13.0-2 Vessel Shell Stress Near the Existing PF4/5 Support Brackets During Bake-Out From the Global Model [2] From the Jan 6, 2010 Meeting report.

14.0 Buckling Stability

The new columns were approximated replacing the existing columns with the same pipe section used for the new clamp/column assembly. This is a model that could be meshed quickly. Then, a large displacement solution (ANSYS nlgeo,on) with increasing loading up to 2.6 times the loads for the full current in PF4 and 5 (but no other PF coil or plasma current) was run. The results are linear and the column stresses are 20 ksi at the fully loaded condition. There is no indication of impending collapse under fully loaded conditions - either geometric non-linearity or stresses that would introduce plastic hinges. The analysis was run with increased loading but was terminated prior to the collapse loading.

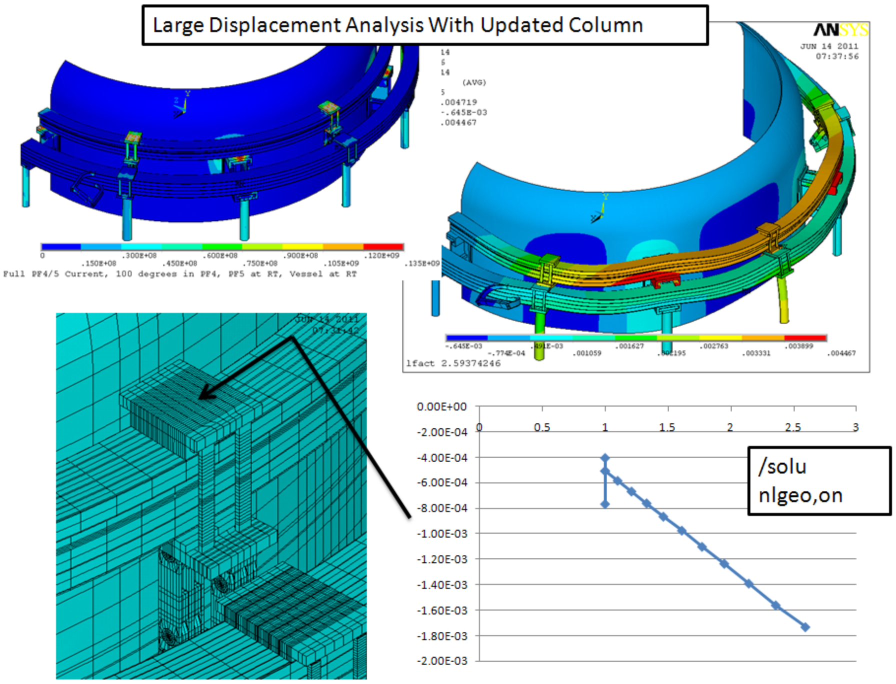
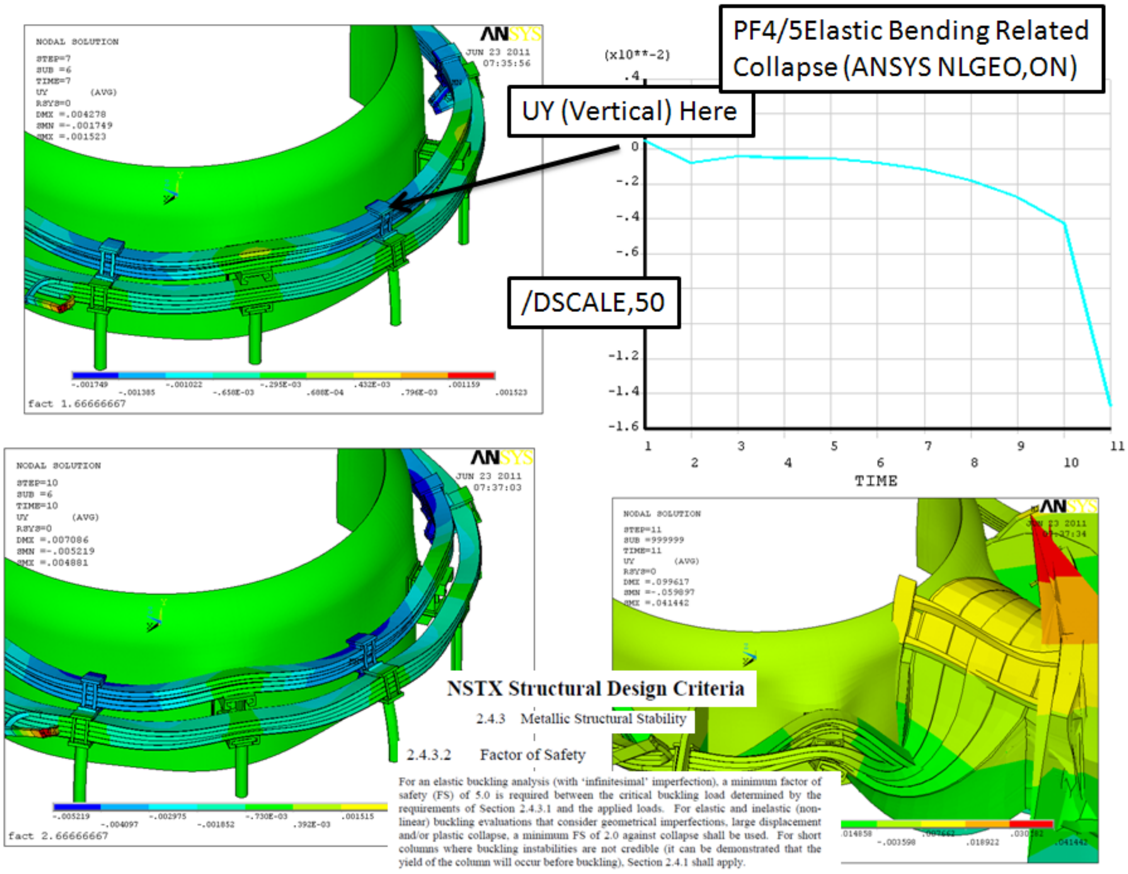


Figure 14.0-1 Large Displacement Loading of the Model to Address The Potential for Elastic or Plastic Collapse



NSTX Structural Design Criteria

2.4.3 Metallic Structural Stability

2.4.3.2 Factor of Safety

For an elastic buckling analysis (with 'infinitesimal' imperfection), a minimum factor of safety (FS) of 5.0 is required between the critical buckling load determined by the requirements of Section 2.4.3.1 and the applied loads. For elastic and inelastic (non-linear) buckling evaluations that consider geometrical imperfections, large displacement and/or plastic collapse, a minimum FS of 2.0 against collapse shall be used. For short columns where buckling instabilities are not credible (it can be demonstrated that the yield of the column will occur before buckling), Section 2.4.1 shall apply.

Figure 14.0-2 Large Displacement Loading of the Model Taken to Collapse

The design of the heavier column that will replace the existing column or strut, presented at the May Peer Review, has a shim pack at the mid height of the column. The effect on the stability of the column is a concern. The stack and flanges must be as stiff as the column. It is recommended that the shim pack be put closer to an end that could be a pin end and still be stable.

Regarding coil buckling, this load case does not produce significant compressive hoop stress in either coil. But to get compressive hoop stresses in one or the other coil, there would have to be either reversed currents or a large current in PF4. So, if you have a compressive hoop in one coil, it would have to be coupled with a tension in the other, and since they are connected together via the clamps and radial slides, the tensile loaded coil should stabilize the compressive one.

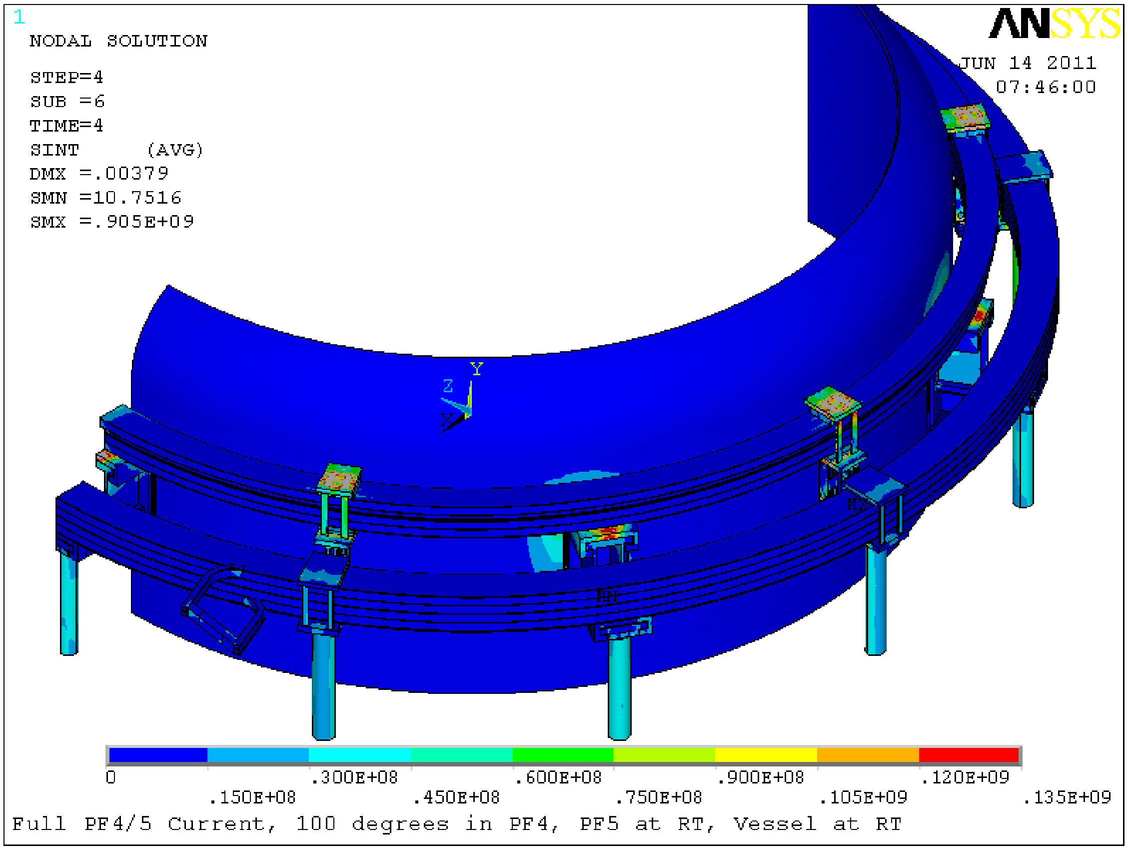


Figure 14.0-3 Initial Loading Tresca Results with a Load Multiplier of 1.0

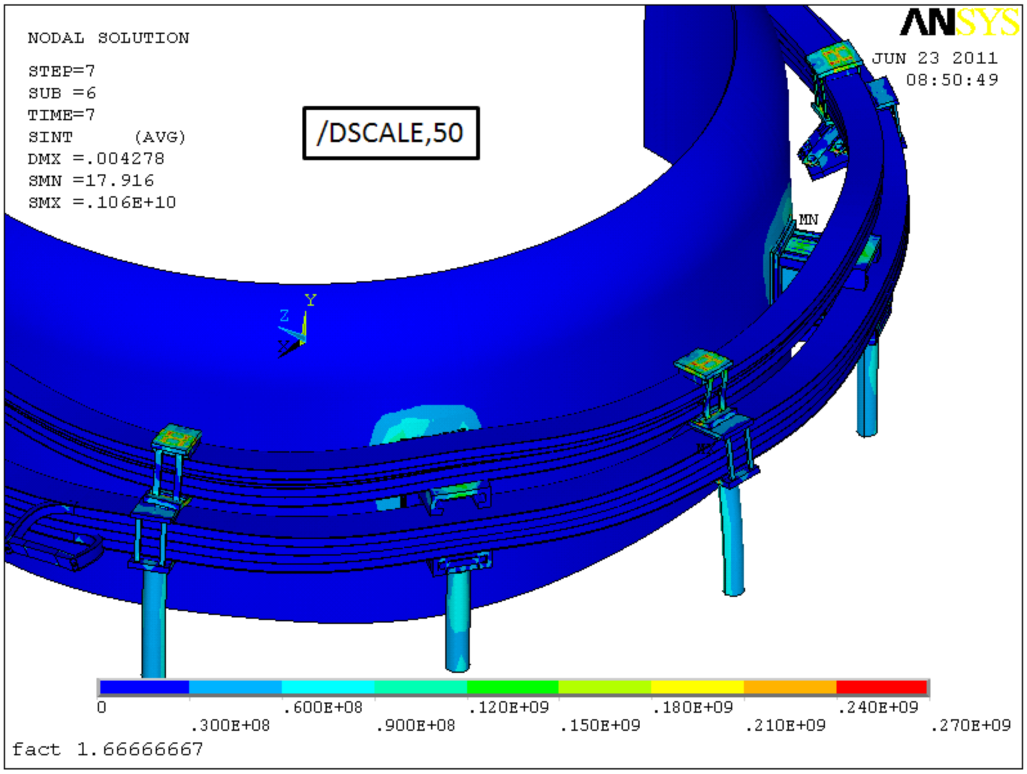


Figure 14.0-4 Initial Loading Tresca Results with a Load Multiplier of 1.7

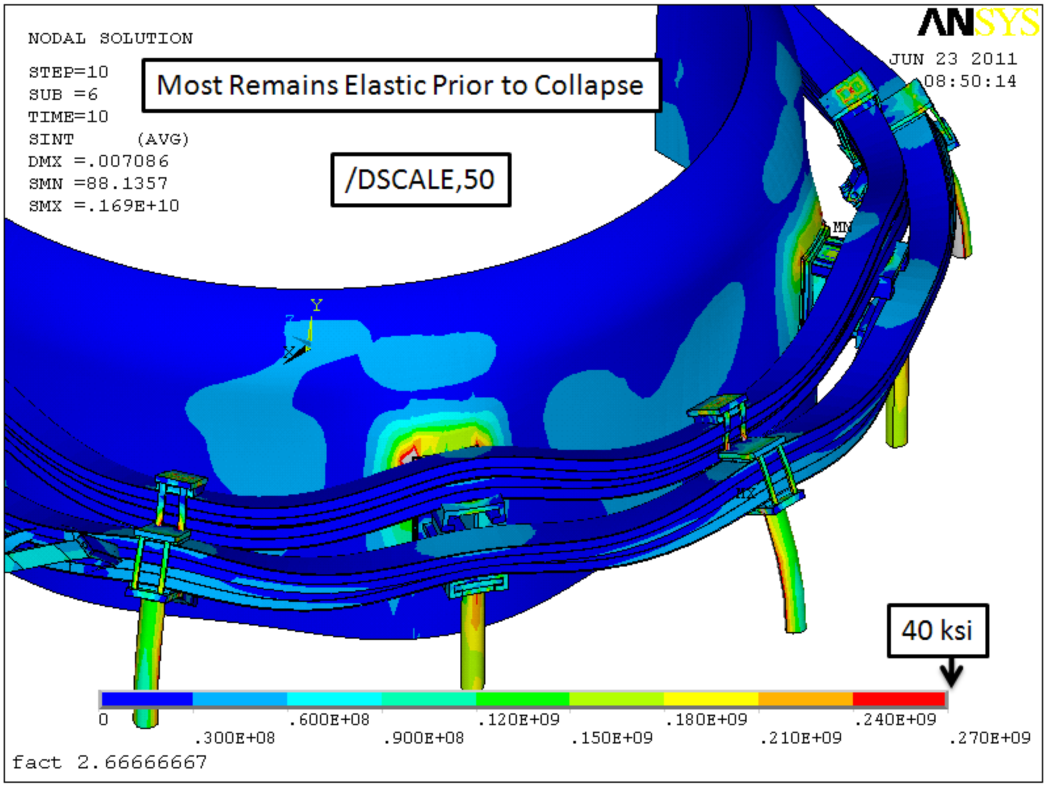


Figure 14.0-5 Large Displacement Tresca Results with a Load Multiplier of 2.6

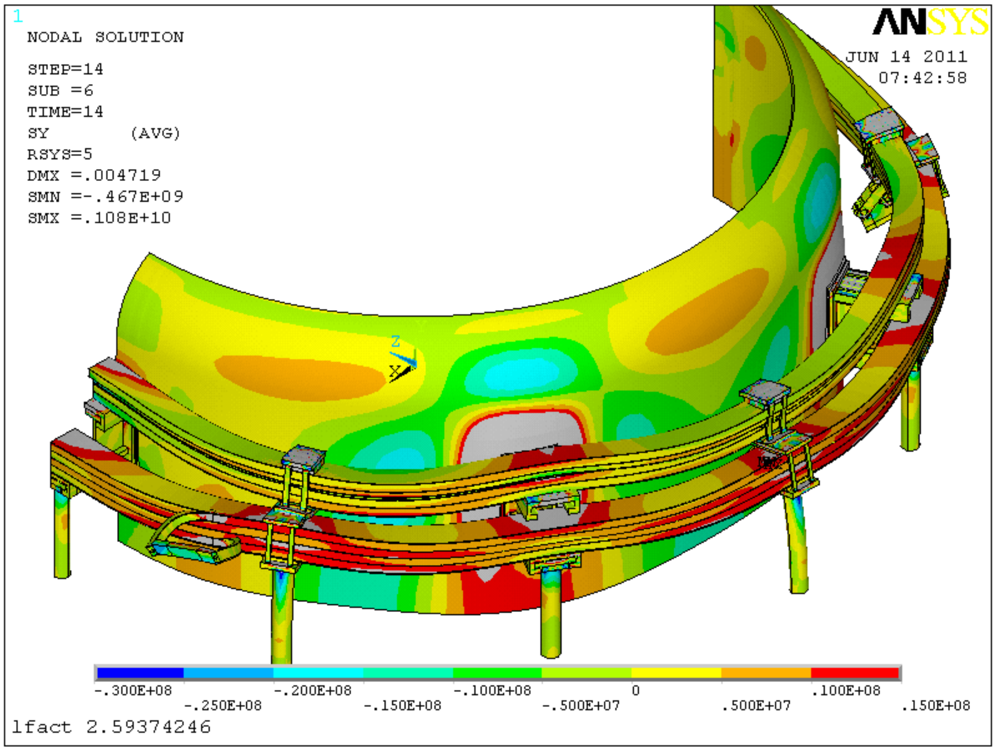


Figure 14.0-6 Vertical Stress with a load multiplier of 2.6

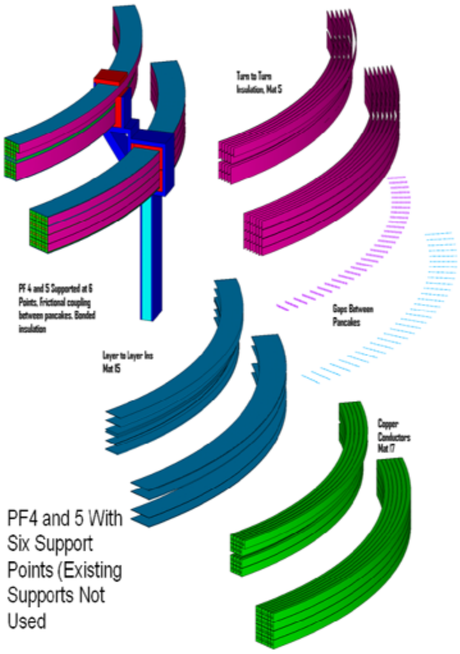
Appendix A Analysis of Earlier Concepts

A.1 Feasibility of 6 vs. 12 Support Points

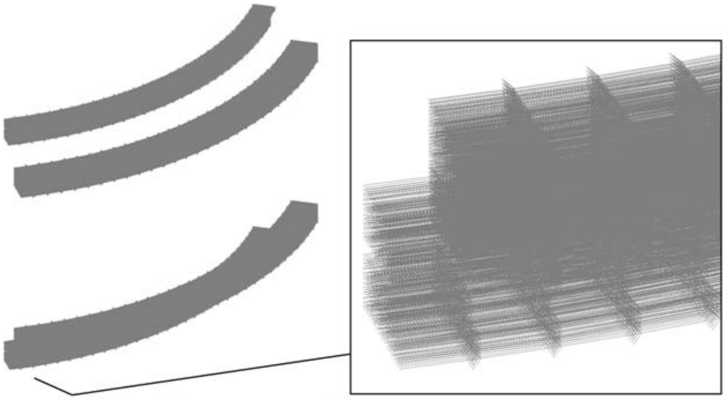
Currently (2011), both PF4 and 5 are supported by six support brackets welded to the vessel shell (12 including uppers and lowers). This study investigated the use of 6 supports for the upgrade loads. The PF5 insulation system is a mylar wrapped fusifab epoxy system. Because of the poor bonding of the mylar to epoxy and to the copper conductors, and because of copper stresses - particularly in PF4, twelve supports are necessary for the upgrade to reduce the spans and resulting bending stress.

Table a.1-1 Design Point Vertical Loads at the time of the Study

Fz(lbf)	PF4U	PF5U	PF5L	PF4L
Min	-204724	-241452	-50636	-85361
Worst Case Min	-423491	-523610	-191878	-151945
Max	85361	50636	241452	186601
Worst Case Max	151945	191878	523610	423491

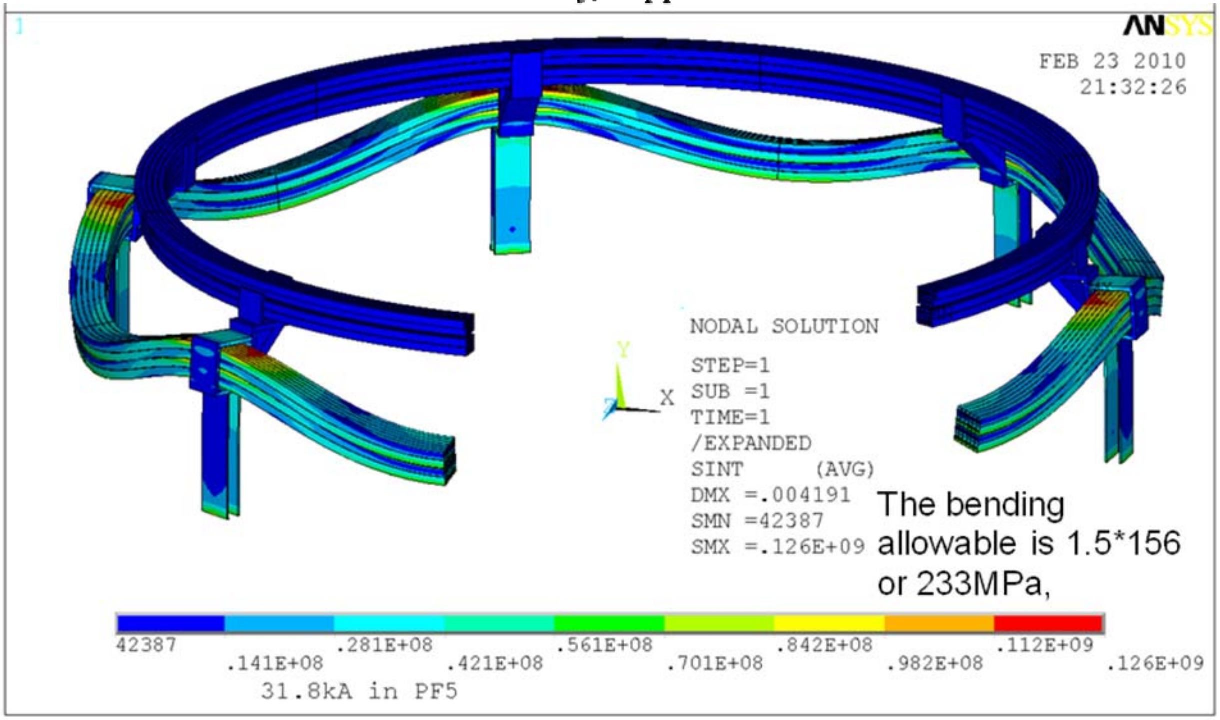


Biot Savart
Current Sticks
and Net Loads,
60 Degree
Models



	ANSYS Reaction Load for 60 degree	ANSYS Full Coil	NSTX Design Point Spreadsheet 96 Scenarios
PF 4,5 U&L Fully Energized PF416kA PF5 31.8kA	244724 N	330083	291786
PF5 U&L at 31.8kA	154370	208214 46700lbs	241452

PF5 Currents Only, Copper Tresca Mu=.3



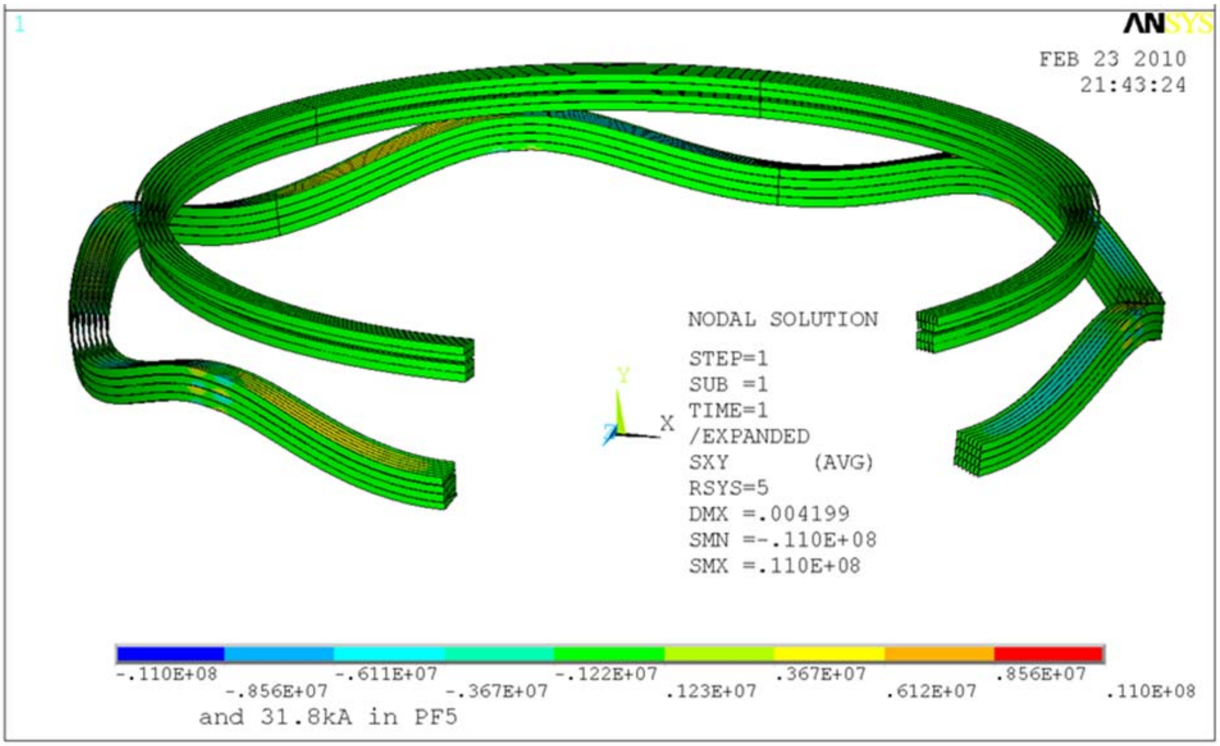
```
NODAL SOLUTION

STEP=1
SUB =1
TIME=1
/EXPANDED
SINT      (AVG)
DMX =.004191
SMN =42387
SMX =.126E+09
```

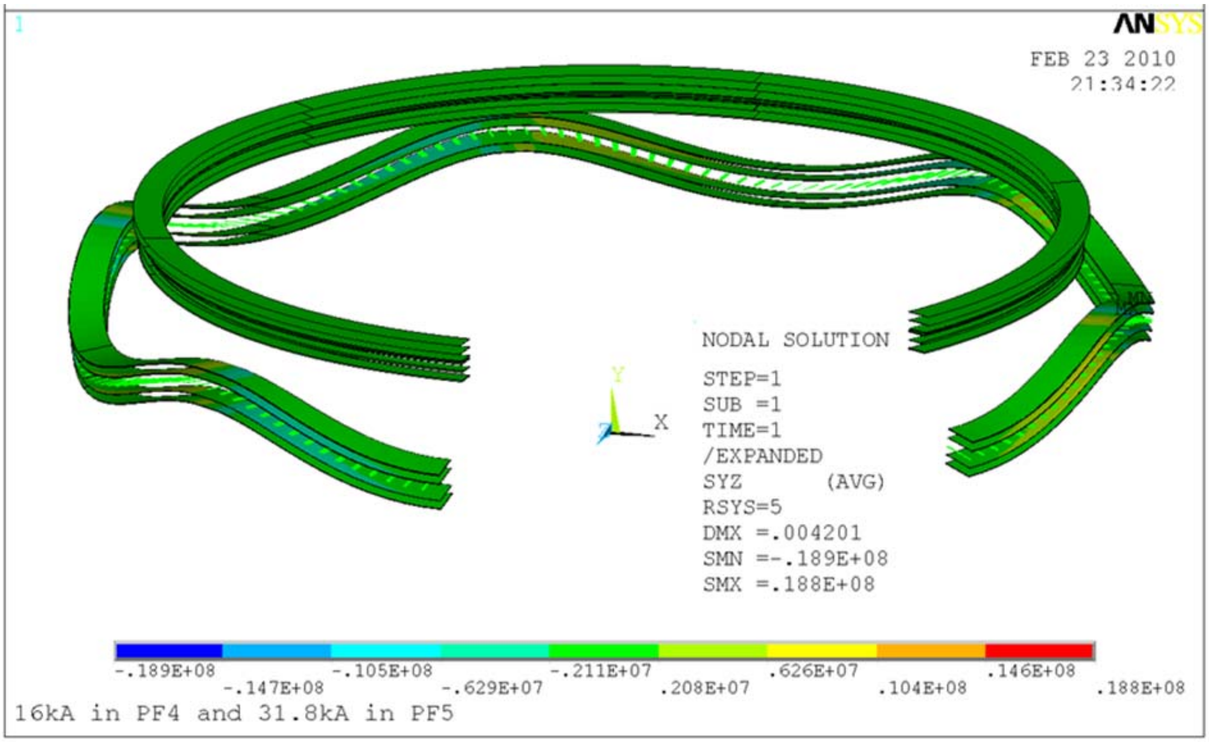
The bending allowable is 1.5*156 or 233MPa,

31.8kA in PF5

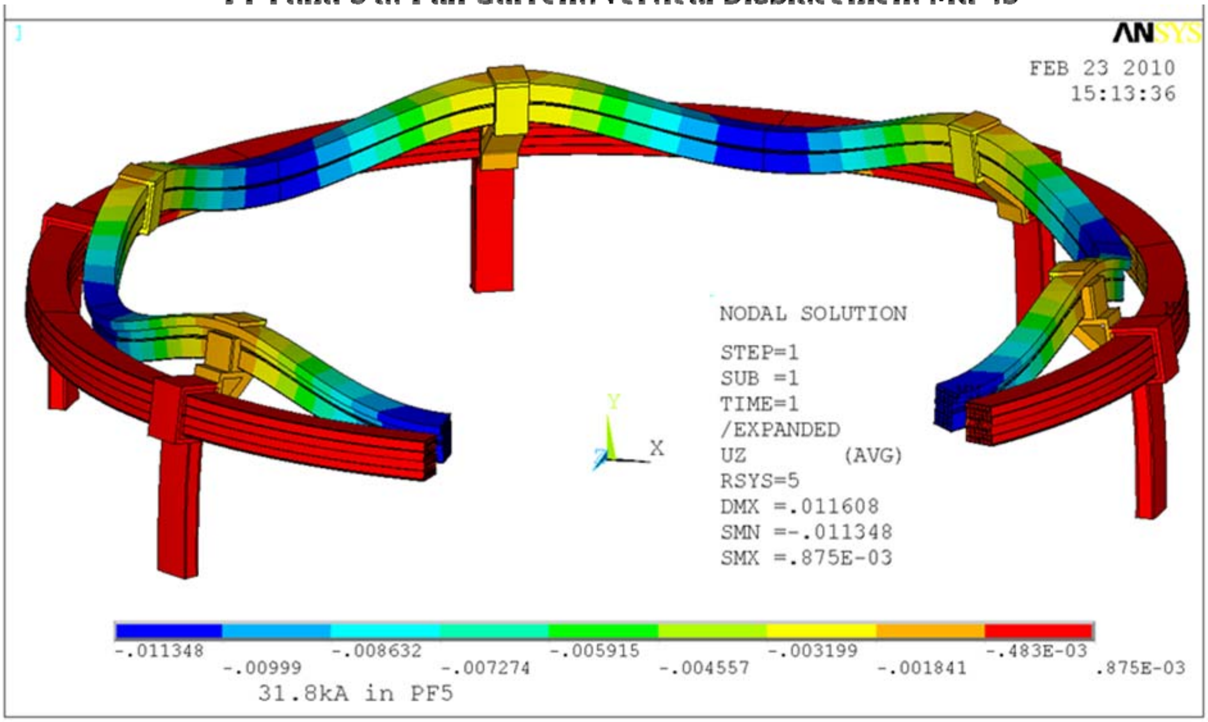
PF5 Currents Only, Rad-Theta Shear on Turn to Turn Insulation Mu=.3



PF5 Currents Only, Vert-Theta Shear on Layer Insulation Mu=.3

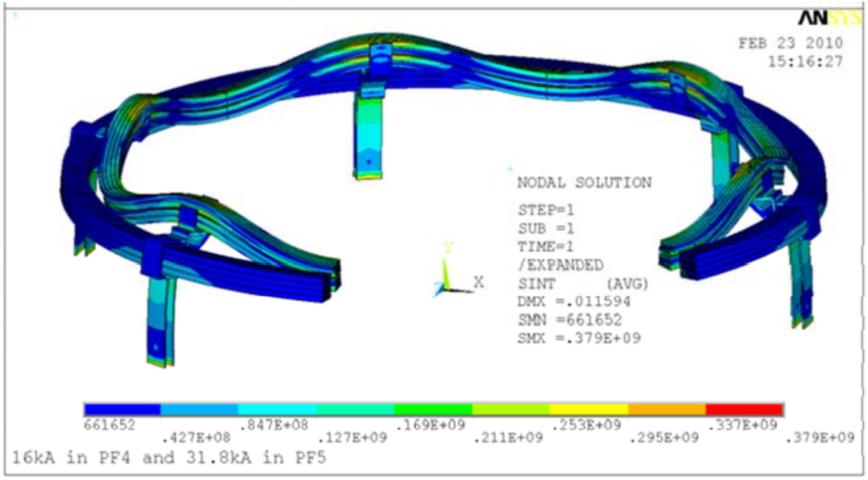


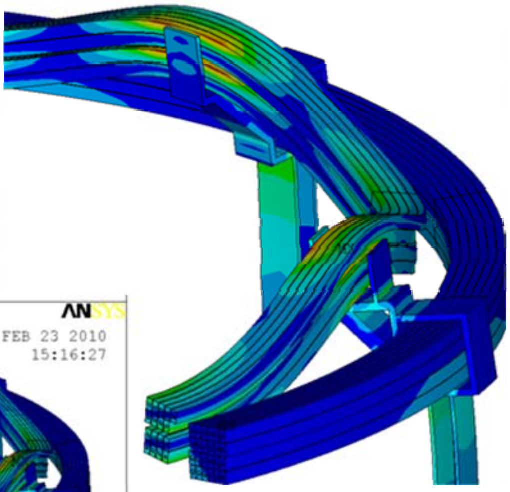
PF4 and 5 at Full Current. Vertical Displacement Mu=.3



PF4 and 5 at Full Current, Tresca Stress Mu=.3

The Bending allowable is 1.5*156 or 233MPa,

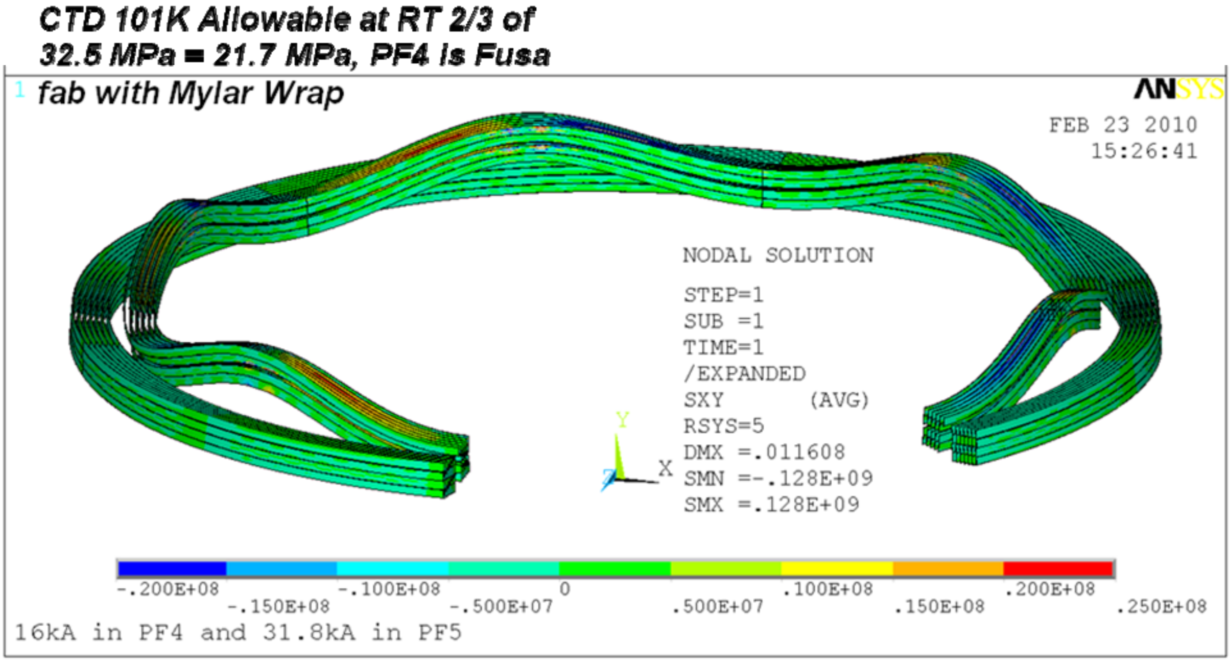




PF4 is Overstressed

With Mu=0.0 the PF4 conductor stress did not change. PF4 Pancakes appear to be separating

PF4 and 5 at Full Current, Insulation Radial Theta Shear on Turn to Turn Insulation Mu=.3



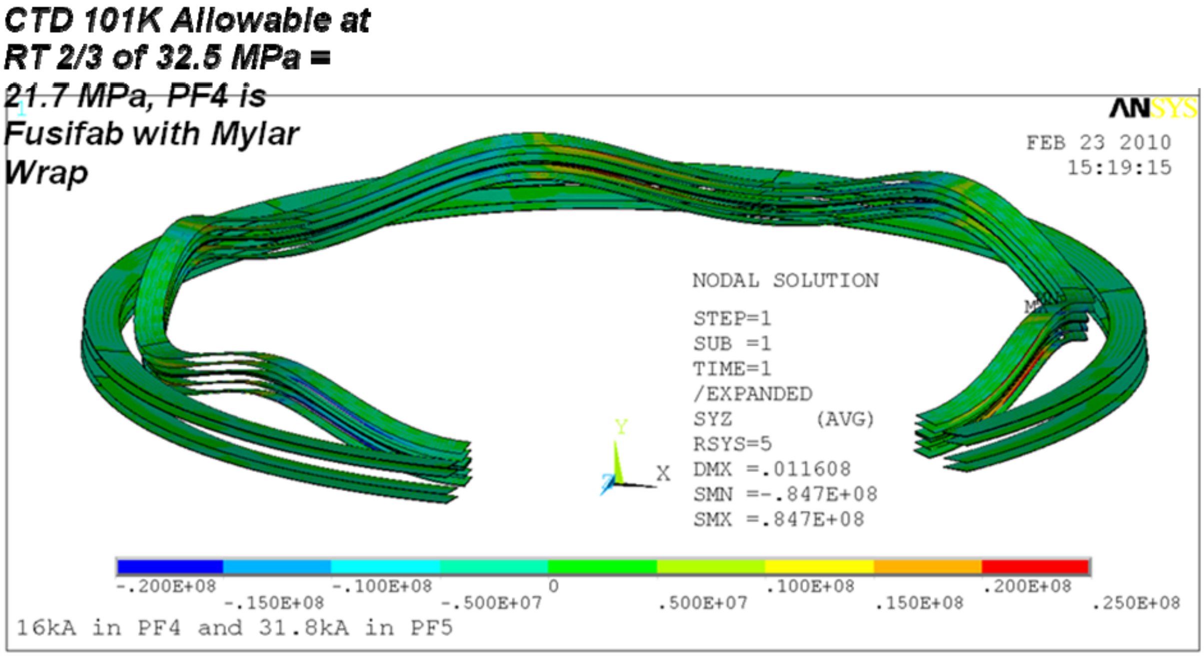
CTD 101K Allowable at RT 2/3 of 32.5 MPa = 21.7 MPa, PF4 is Fusa fab with Mylar Wrap

```
NODAL SOLUTION

STEP=1
SUB =1
TIME=1
/EXPANDED
SXY       (AVG)
RSYS=5
DMX =.011608
SMN =-.128E+09
SMX =.128E+09
```

16kA in PF4 and 31.8kA in PF5

PF4 and 5 at Full Current, Insulation Vertical Theta Shear on Layer Insulation Mu=.3



CTD 101K Allowable at RT 2/3 of 32.5 MPa = 21.7 MPa, PF4 is Fusifab with Mylar Wrap

```
NODAL SOLUTION

STEP=1
SUB =1
TIME=1
/EXPANDED
SYZ       (AVG)
RSYS=5
DMX =.011608
SMN =-.847E+08
SMX =.847E+08
```

16kA in PF4 and 31.8kA in PF5

A.2 Results for Added Columns and Rubber Support Pads

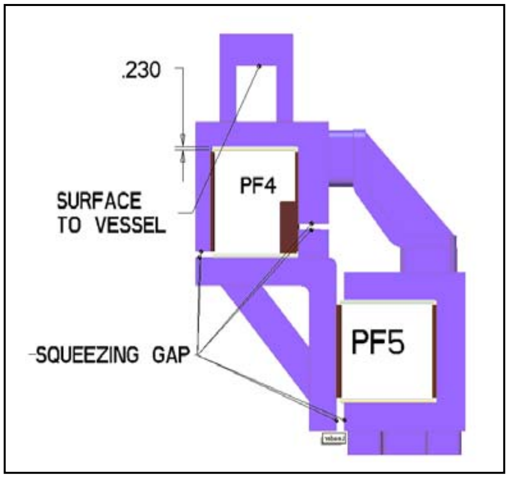
With the agreement that 12 columns were needed and that the existing columns would be used, the effort turned to providing centering features that would accommodate the differential heat-up of PF4 and 5. Rubber blocks were suggested to allow differential motion between the coils at the added support columns/brackets. The pads that were analyzed had too high a shear stiffness and didn't allow the needed compliance. Links and dovetail joints were suggested.

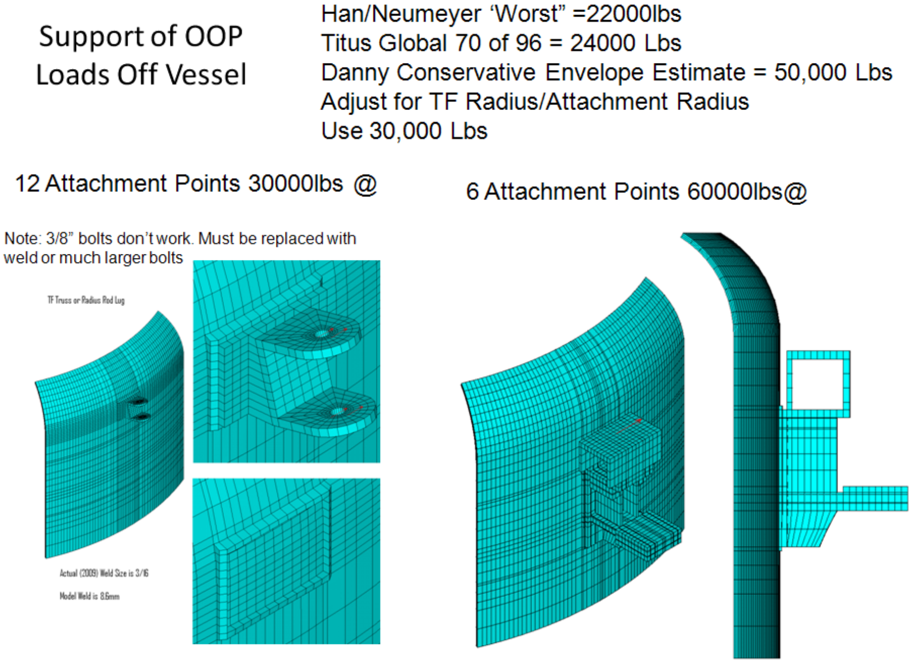
A.3 Support Concept in which the TF OOP loading is supported off the PF4 and 5 supports

This was a concept that attempted to transfer the out-of-plane loading to the vessel through the PF 4 and 5 support brackets. It put a twisting moment on the bracket and the weld stresses were unacceptable.

Table A.2-1 Net Loads on the PF4 and 5 Assembly

Fz(lbf)	(PF4U+PF5U)-(PF4L+PF5L)
Min	-502240
Worst Case Min	-1065883
Max	-108545
Worst Case Max	44617





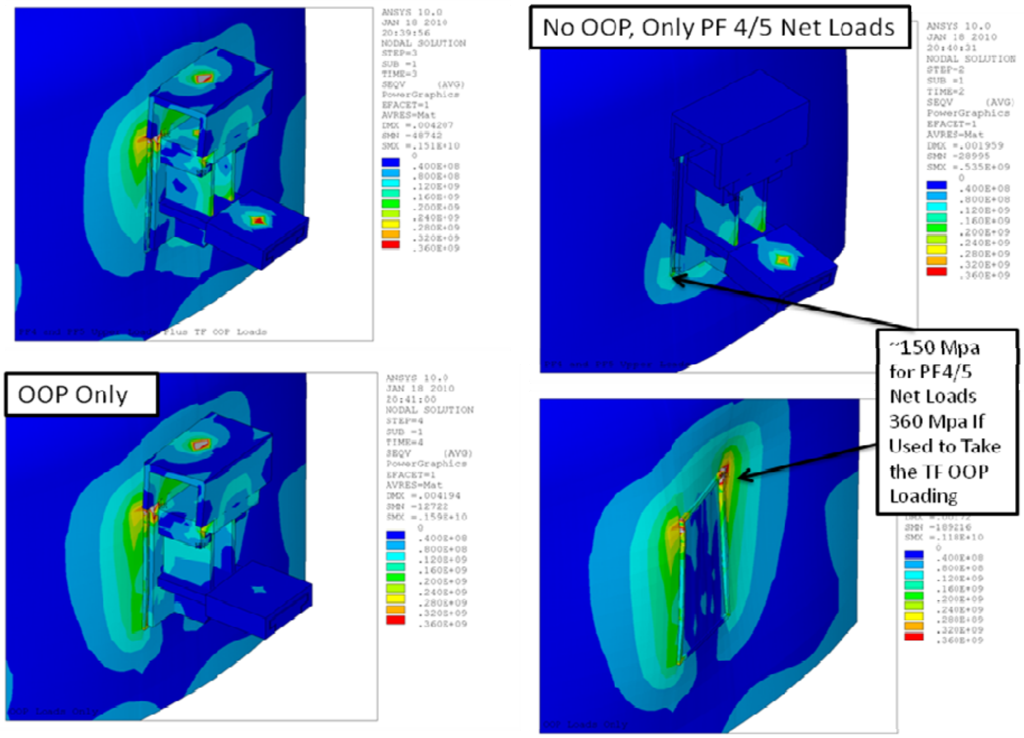
Support of OOP Loads Off Vessel

Han/Neumeyer 'Worst" =22000lbs
Titus Global 70 of 96 = 24000 Lbs
Danny Conservative Envelope Estimate = 50,000 Lbs
Adjust for TF Radius/Attachment Radius
Use 30,000 Lbs

12 Attachment Points 30000lbs @

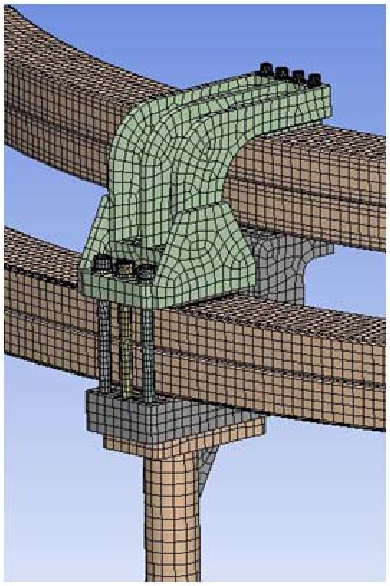
6 Attachment Points 60000lbs@

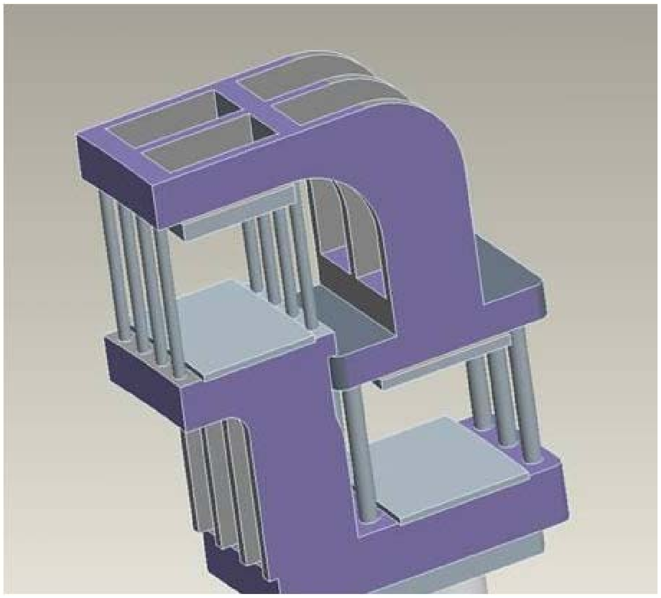
Note: 3/8" bolts don't work. Must be replaced with weld or much larger bolts


No OOP, Only PF 4/5 Net Loads
OOP Only
~150 Mpa for PF4/5 Net Loads 360 Mpa If Used to Take the TF OOP Loading
PF4 and PF5 Upper Loads Plus TF OOP Loads
ANSYS 10.0
JAN 18 2010
20:39:56
NODAL SOLUTION
STEP=3
SUB =1
TIME=3
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.004207
SMN =48742
SMX =.151E+10
ANSYS 10.0
JAN 18 2010
20:40:31
NODAL SOLUTION
STEP=2
SUB =1
TIME=2
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.001959
SMN =28995
SMX =.535E+09
ANSYS 10.0
JAN 18 2010
20:41:00
NODAL SOLUTION
STEP=4
SUB =1
TIME=4
SEQV (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.004194
SMN =12722
SMX =.159E+10
SMN =189216
SMX =.118E+10
0
.400E+08
.800E+08
.120E+09
.160E+09
.200E+09
.240E+09
.280E+09
.320E+09
.360E+09

A.4 PDR Clamp Concept

This clamp detail, which was presented at the PDR, did not have a feature that would have allowed PF5 and PF4 to have different operating temperatures. Also the clamping behavior was difficult to implement and analyze because a common clamp was used for both coils. This was analyzed by Larry Bryant and there was difficulty obtaining convergence, consistent with the mechanical uncertainty of how the single clamp would interact with the two coils. .





Appendix A5
Stress Multipliers for the PF4 and 5 Clamp Weld in the Existing NSTX (2010)

The existing PF 4 and 5 supports were modeled and loads based on the upgrade design were applied. This analysis is representative of only the up-down symmetric attractive loads. The loads that were applied are shown in the table below. These are 1/6th the loading that would be appropriate for the whole of PF4U and PF5U coils. These loads produced 30,555 psi in the weld that holds the bracket to the vessel. The allowable stress in the weld is a function of the weld profile and the QA/inspection level applied to the weld. For visual inspection, a weld efficiency of 0.7 was assumed. If the weld was liquid penetrant inspected, a weld efficiency of 1.0 would be assumed.

Applied Loads on the model with a Resulting Weld Stress of 30555 psi	Allowable Load based on Visual weld inspection and an allowable weld stress of 14ksi	Allowable Load based on Visual Plus Penetrant weld inspection and an allowable weld stress of 20ksi
Due to PF4U: 17,000 Lbs Plus PF5U: 20,000 Lbs = 37000 lbs	16,900 Lbs	24,200 Lbs

Applied Loads on the model with 22,200 Lbs in the Strut	Allowable Load based on minimum AISC A307 bolting double shear allowable of 8.84 kips	Allowable Load based on Fy=36ksi steel, (e.g., A-36) for a double shear allowable of 9.54 kips
PF4U: +PF5U = 37000 lbs,	14,700 Lbs	15,900 Lbs

The strut bolt stress is limiting for the case where the loads in PF4/5 are just attractive. Weld stresses double for the same loading if the strut is removed. If there is a net load on the PF4/5U + PF4/5L assembly, then the strut does not contribute to supporting this load component, and the allowable load from only a net assembly load would be 8 kips top and bottom or 16 kips total. So one rule or guide would be the following:

The (Attractive Load on PF4/5U to PF4/5L + the net load on PF4/5U and L assembly) should be less than 16 kips.

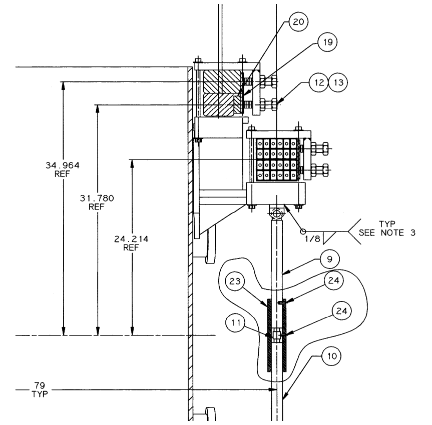


Fig 9.3-1 Existing PF4 and 5 Support

In this analysis, PF4 and 5 loads are grouped together. PF5 loading has a larger moment arm and has a bigger effect on the weld and strut bolt stress. To be strictly correct, the PF5/PF4 load ratio should be as assumed in the analysis. Only the bracket to vessel weld and the strut end bolts were looked at. It is assumed that the buckling of the strut was addressed when it failed, and that there is adequate margin against buckling at present. Also, it is assumed that only compression loads are taken by the strut (the 1/8-inch welds that connect the strut clevis to the bracket are too small). (Note that a new, larger column is being used in the upgrade)

Analysis

The weld is nominally 5/16-inch, but the QA report recommends that it be treated as an effective ¼ inch weld. To facilitate meshing the weld, an arbitrary cross section is used then the weld stress is scaled by the ratio of the weld section in the model to the actual weld section. In this case, the weld was intended as a fillet, but material has been added to accommodate the vessel curvature, and the resulting weld was derated. The weld is assumed to have a larger cross section than a fillet, so the standard 0.707 factor was not applied. The weld allowable is a function of the level of inspection that is applied. At PPPL, only visual inspection is routine. ASME would require a weld efficiency of 0.7 or lower.

```
/title,PF4 and PF5 Upper Loads
!Remove OOP Loads
bf,all,temp,20
f,436,fz,-204000/12/.2248
f,1098,fz,-241000/12/.2248
Solve
```

PF4/5 Weldment
Nominal Weld = 5/16 in.
QA Effective Weld = 1/4
FEA Weld Model Thick =10mm
Weld Stress =90*(.01*39.37)/.25
=142 MPa = 30555 psi

Ron: Scale Weld Stress by ratio of your forces to those that I applied

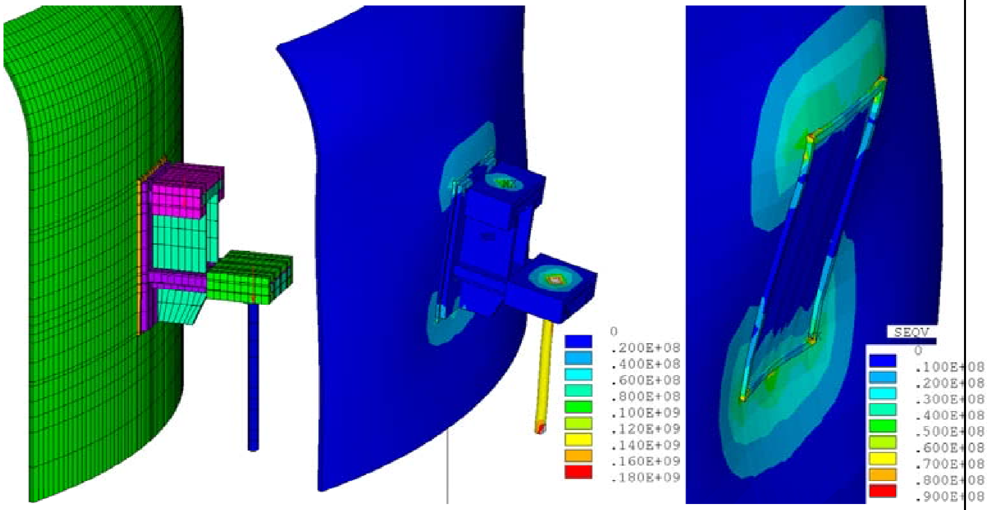


Fig 9.3- 2 - In-Plane PF4U and 5U Loads With Strut

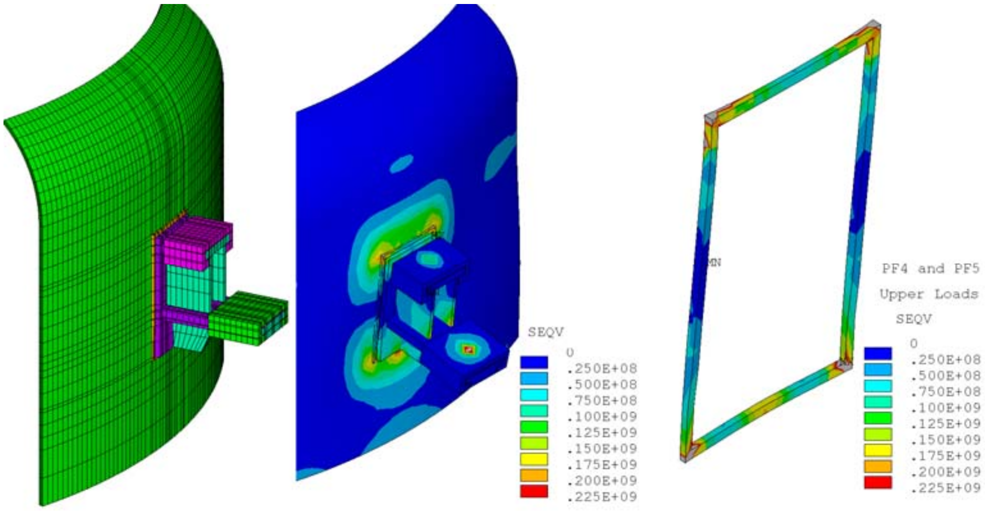


Fig 9.3-3 - If the strut is removed, the weld stresses approximately double.

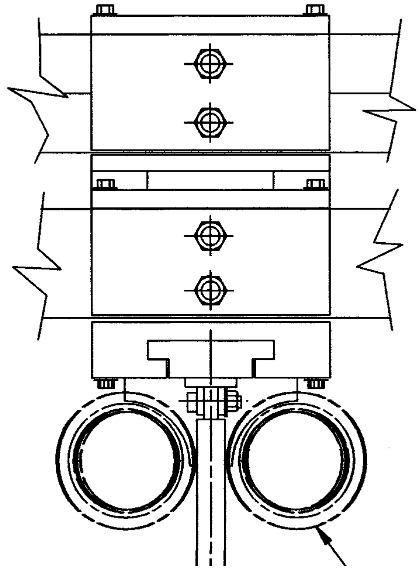
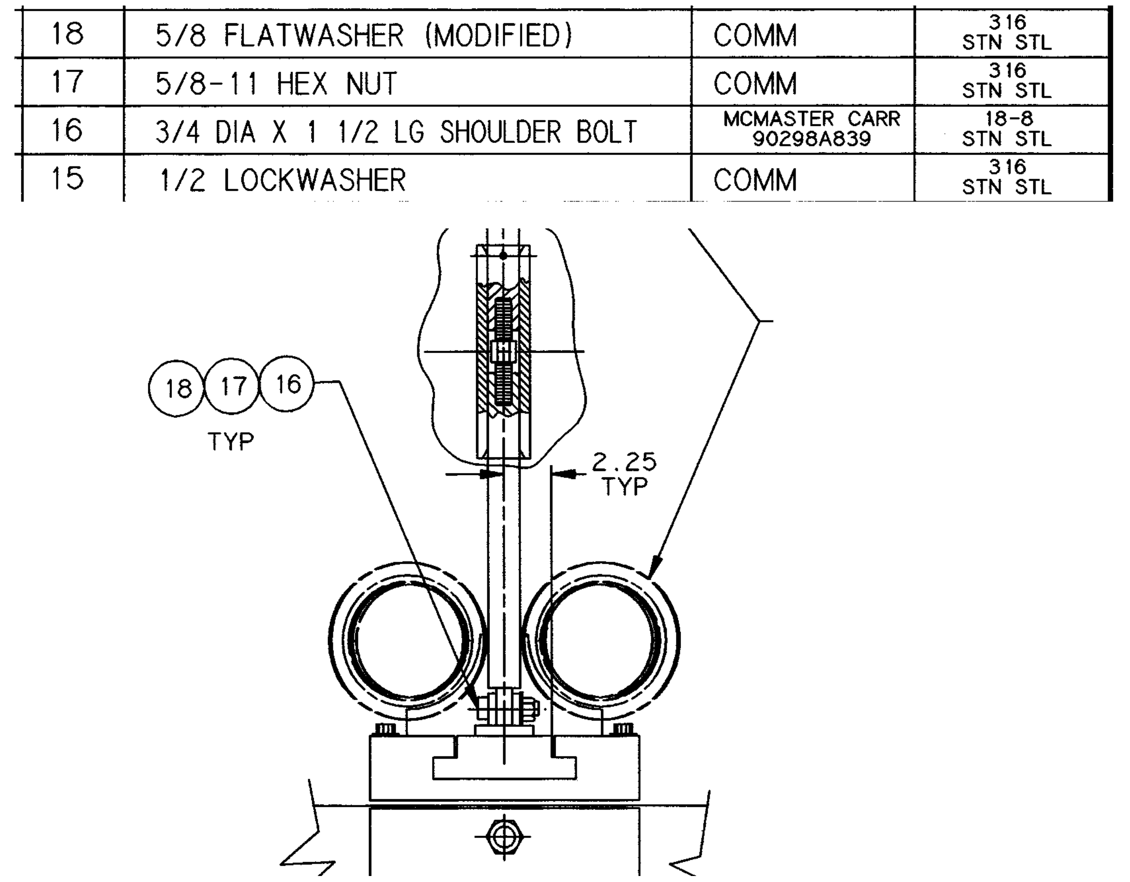


Figure 9.3-5 PF4 and 5 Strut Bolting Detail

Bolt capacity

The strut is modeled as 3 cm in diameter. For the upgrade loads, the stress in the strut is about 140 MPa, so the load is 98.9l kN or 22,200 lbs.

The shoulder bolt that takes the strut compression load is a ¾ inch 304 SST bolt in double shear. The AISC allowable for an A307 bolt is 8.84 kips (or 9.54 kips for Fy=36ksi steel, like A-36) in double shear. 304SS bolting could have a 30 ksi yield, but is likely closer to the A36 yield due to roll forming of the bolt.



18	5/8 FLATWASHER (MODIFIED)	COMM	316 STN STL
17	5/8-11 HEX NUT	COMM	316 STN STL
16	3/4 DIA X 1 1/2 LG SHOULDER BOLT	MCMASTER CARR 90298A839	18-8 STN STL
15	1/2 LOCKWASHER	COMM	316 STN STL

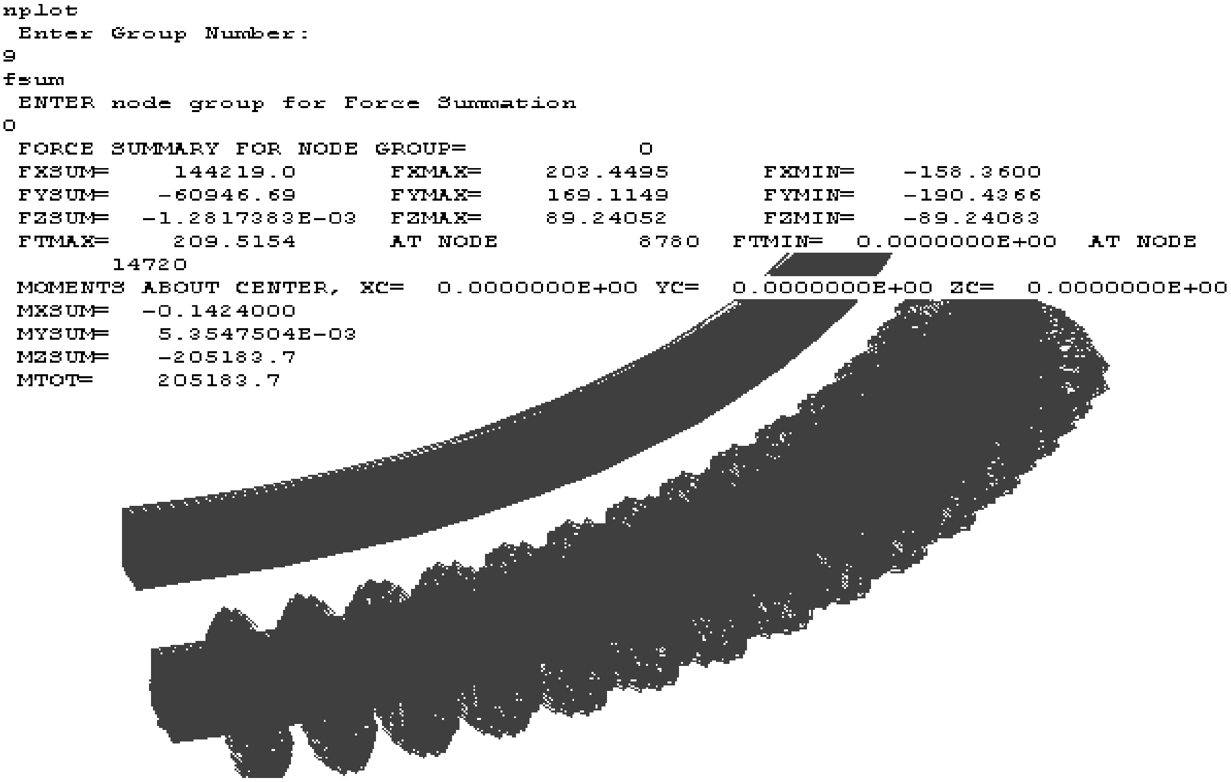
The Weld Allowable is 20 ksi with inspection and an efficiency of 1.0 and 14 ksi with a weld efficiency of .7 These are discussed in Figure 6.3-4 in Section 6.

Table 9.1-1 NSTX Centerstack Upgrade PF Loads

Fz(lbf)	PF4U	PF5U	PF5L	PF4L
Min	-204724	-241452	-50636	-85361
Worst Case Min	-423491	-523610	-191878	-151945
Max	85361	50636	241452	186601
Worst Case Max	151945	191878	523610	423491

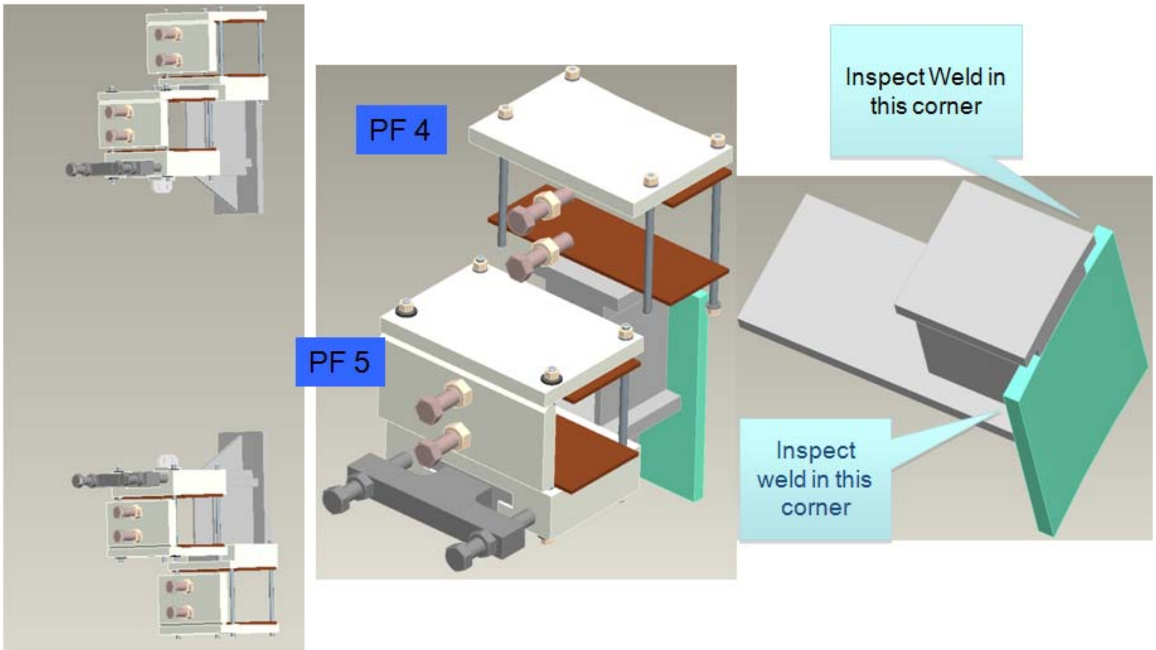
Benchmark Check of 20 kA Current Operation of PF5 with Existing supports.

The calculation below only has PF 4 and 5 upper and lower modeled. With only currents in PF5, the analysis below shows 60 kN compared with 80 kN from Ron Hatcher's calculation with all PF currents active.

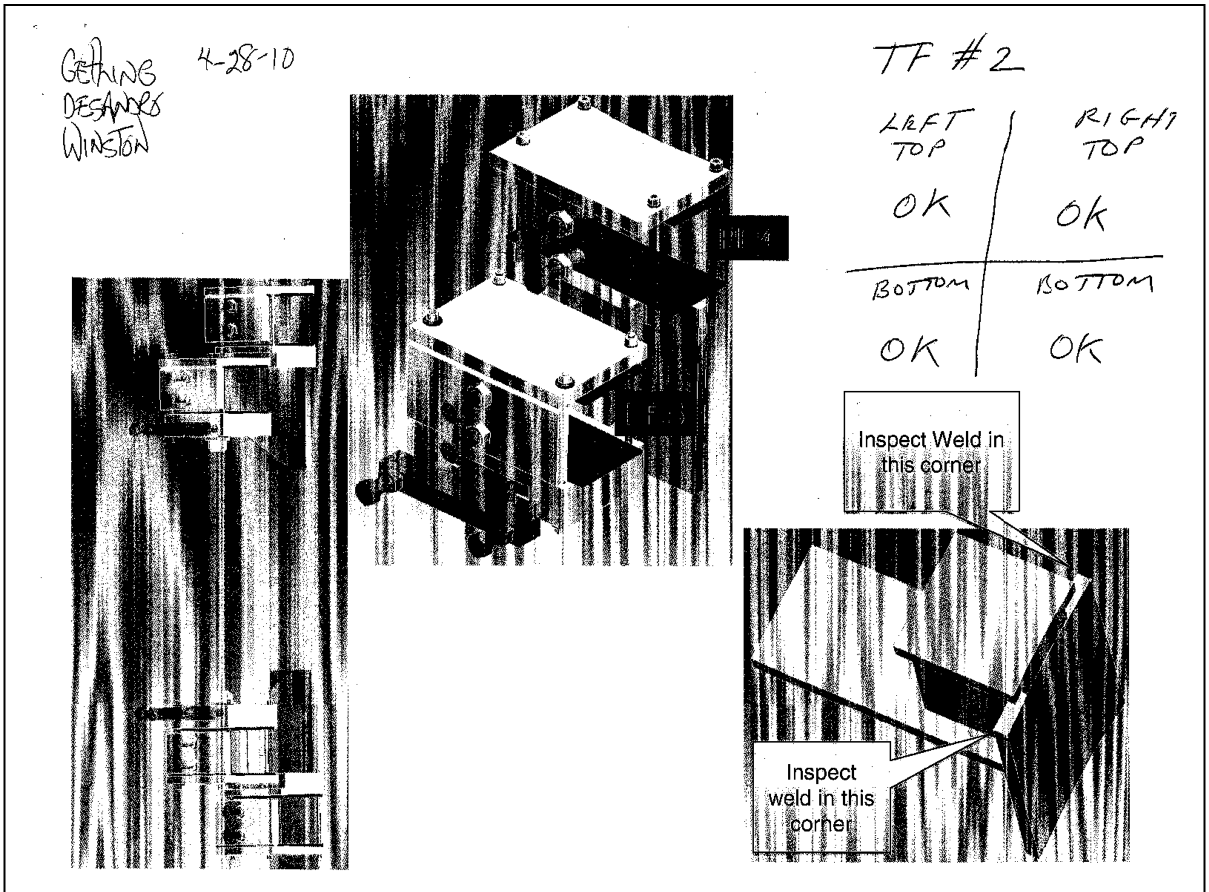


```
nplot
 Enter Group Number:
9
fsum
 ENTER node group for Force Summation
0
 FORCE SUMMARY FOR NODE GROUP=            0
 FXSUM=     144219.0       FXMAX=     203.4495       FXMIN=    -158.3600
 FYSUM=    -60946.69       FYMAX=     169.1149       FYMIN=    -190.4366
 FZSUM=   -1.2817383E-03   FZMAX=     89.24052       FZMIN=    -89.24083
 FTMAX=     209.5154       AT NODE            8780   FTMIN=   0.0000000E+00   AT NODE
       14720
 MOMENTS ABOUT CENTER, XC=  0.0000000E+00 YC=   0.0000000E+00 ZC=   0.0000000E+00
 MXSUM=   -0.1424000
 MYSUM=    5.3547504E-03
 MZSUM=    -205183.7
 MTOT=     205183.7
```

Appendix B
PF4/5 Bracket Support Weld Inspection



Pete,
The machine techs were able to get into several of the PF 4/5 support brackets with a borescope to inspect the welds. They looked at the brackets under TF coils 2,4,6,8,10,12. They were able to inspect the upper corners in all cases and the lower corners in most cases. No signs of any cracks or distress. Winston said if we wanted to look at some in person they could get in again on Thursday evening.
Larry

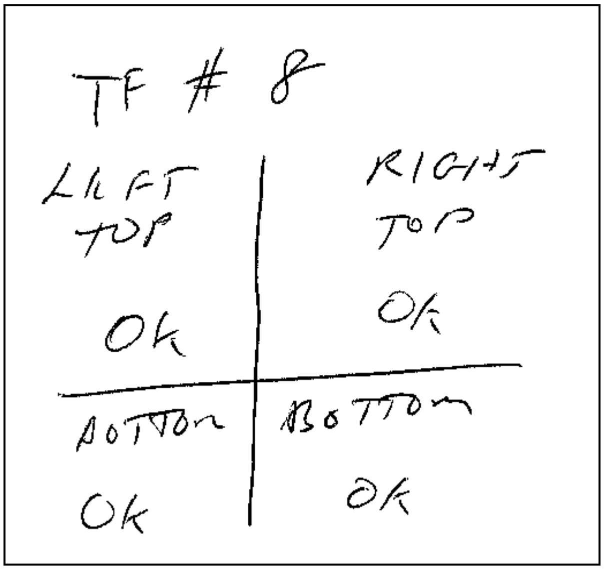


GETHING
DESANDRO
WINSTON

4-28-10

TF #2

LEFT TOP OK	RIGHT TOP OK
BOTTOM OK	BOTTOM OK



TF # 8

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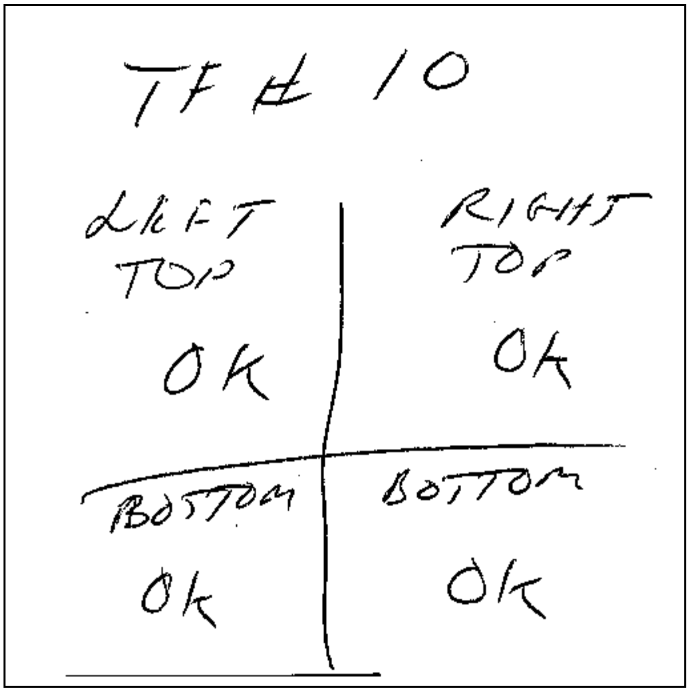
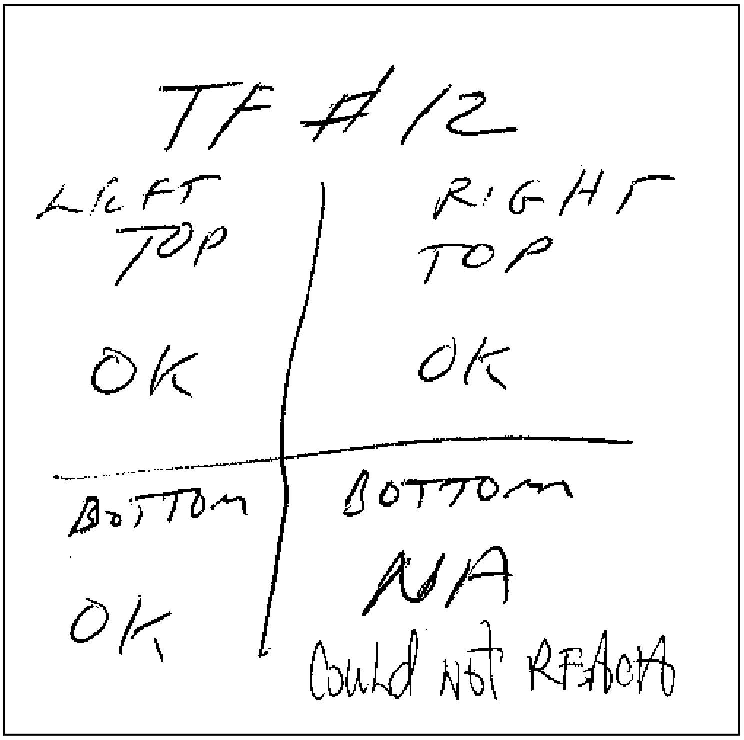
BOTTOM Ok	BOTTOM Ok



TF # 10

LEFT TOP OK	RIGHT TOP Ok
BOTTOM Ok	BOTTOM Ok



TF # 12

LEFT TOP OK	RIGHT TOP OK
BOTTOM OK	BOTTOM NA Could not REACH

Appendix C References

Reference 11

Pete,

"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.

So, these two cases bracket how the machine will operate.

You can see this here:

http://www.pppl.gov/~neumeyer/NSTX_CSU/PF_Coil_Summary.htm

I have not put this in the GRD, but I can if you like. In fact the SPFI condition is probably the design driver for many of the out-of-plane loads because it pushes the OH to -24kA second swing. The GRD calls for an OH flux of 2.0 Wb which we supply in the LPPI case. With the SPFI case and the full second swing we get 2.3Wb.

Chas

On Mar 29, 2011, at 2:27 PM, Peter Titus wrote:

Charlie: What do these mean? Long Pulse something? Short Pulse Someithing?
-Peter

Tmax_LPPI Tmax_SPFI

Charles L. Neumeyer
Princeton University, Plasma Physics Laboratory
Forrestal Campus, U.S. Route #1 North at Sayre Drive
P. O. Box 451
Princeton, N. J. 08543
Tel: 609-243-2159
Mobile: 609-313-4738
Fax: 609-243-3266

Reference 12

April 5 2011 email from Jim Chrzanowski:

Pete

FYI- The PF-2, PF-3 and PF-4 were all manufactured by PPPL. Their insulation scheme is (4) half-lapped layers of Mylar insulation, followed by (2) half-lapped layers of Fusa-Fab" B-stage insulation.

Jim