



## **NSTX Upgrade**

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

**NSTXU-CALC-12-05-00**

**Rev 0**

**March 2011**

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## 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 sst. 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 material ( $\mu = .05$ ), 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 \_\_\_\_\_

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

Checker's printed name, signature, and date

Irving Zatz \_\_\_\_\_

## 2.0 Table of Contents

### NSTX PF 4 and 5 Coils and Supports

	Section.Paragraph
Title Page	1.0
Table Of Contents	2.0
Executive Summary	3.0
Digital Coil Protection System	4.0
Introduction and Evolution of the Design	5.0
 Design Input,	
References	6.1
Criteria	6.2
Coil Geometry Loads and Currents and Temperatures from the Design Point	6.3
Input Currents	6.4
Materials Properties	6.5
Elastic Constants	6.6
Fatigue Data	6.7
 Analysis Models	7.0
Model elements	7.1
Fields and Forces	7.2
Link Concept	7.3
 PF 4 and 5 Coil Results	8.0
PF 4 and 5 Coil Displacement Results	8.1
PF 4 and 5 Coil Conductor Stress Results	8.2
PF4 and 5 Coil Insulation Stress	8.3
Provisions for Differential Thermal Growth of PF4 and 5	
- Results for the Link Concept	8.5
TF Ripple Loads on PF 4 and 5	8.4
Digital Coil Protection Input	9.0
PF5 Stress Influence Coefficients	9.1
PF4 Stress Influence Coefficients	9.2
Existing PF4 and 5 Bracket Weld Force Influence Coefficients (Moved to the Appendix	9.3
 Lead Support Analysis	10.0
Fatigue Analysis	11.0
 Brackets, Hardware, and Bracket to Vessel Welds	12.0
PF4/5 Existing Support Weld Stress	12.1
Bracket Welds for Upgrade Loads	12.2
PF5 Bracket Support Plate and weld, With and Without Support Column	12.3
PF4 and 5 Column Support Stress	12.4
Coil Clamp Plate Bolting	12.5
T slot Stress	12.6
Vessel Shell Stress	12.7
 Bake Out Local Thermal Stresses	13.0
Buckling Stability of Columns and Coils	14.0
 <div style="text-align: center;">Appendices</div>	
Appendix A Earlier Support Model Results	A.0
Results using only the existing Six Support Brackets	A.1
Results for Added Columns and Rubber Support Pads	A.2

	Concept which Supports TF OOP Loads off the PF4 and 5 supports	A.3
	PDR Clamp Concept	A4
	Existing PF4 and 5 Bracket Weld Force Influence Coefficients	A5
Appendix B	PF4/5 Bracket Support Weld Inspection	
Appendix	C Reference emails	



### 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.

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.

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 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.

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 sliding dovetail joint is actually used, Low friction material is required. Magna Plate is suggested. It has a friction coefficient "as low as .05". According to the design criteria document,  $\mu$  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.

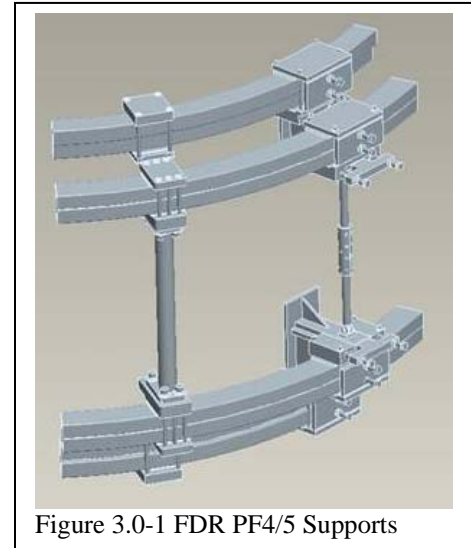


Figure 3.0-1 FDR PF4/5 Supports

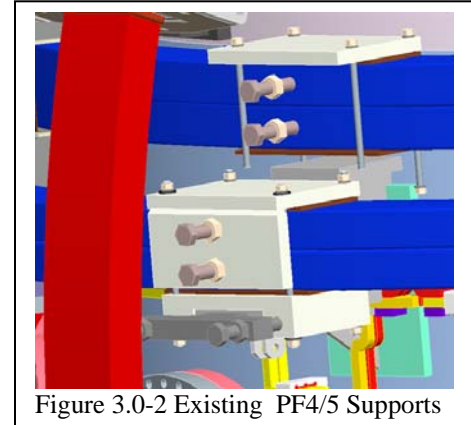
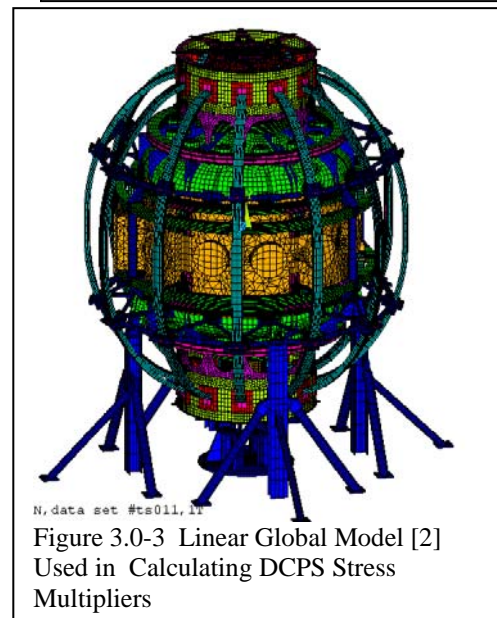


Figure 3.0-2 Existing PF4/5 Supports



N, data set #ts011, 11

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

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 sst. 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  $2/3 \cdot 95 = 63.3$  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  $0.75 \cdot \text{yield}$ ). With proper pre-tensioning, the alternating stress effecting fatigue will be small.

### 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)<sup>2</sup>.

1901	1902	1903	1904	1905	1906	1907	1908	1909	1910	1911	1912	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934	1935	1936	1937	1938	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063	2064	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074	2075	2076	2077	2078	2079	2080	2081	2082	2083	2084	2085	2086	2087	2088	2089	2090	2091	2092	2093	2094	2095	2096	2097	2098	2099	2100	2101	2102	2103	2104	2105	2106	2107	2108	2109	2110	2111	2112	2113	2114	2115	2116	2117	2118	2119	2120	2121	2122	2123	2124	2125	2126	2127	2128	2129	2130	2131	2132	2133	2134	2135	2136	2137	2138	2139	2140	2141	2142	2143	2144	2145	2146	2147	2148	2149	2150	2151	2152	2153	2154	2155	2156	2157	2158	2159	2160	2161	2162	2163	2164	2165	2166	2167	2168	2169	2170	2171	2172	2173	2174	2175	2176	2177	2178	2179	2180	2181	2182	2183	2184	2185	2186	2187	2188	2189	2190	2191	2192	2193	2194	2195	2196	2197	2198	2199	2200	2201	2202	2203	2204	2205	2206	2207	2208	2209	2210	2211	2212	2213	2214	2215	2216	2217	2218	2219	2220	2221	2222	2223	2224	2225	2226	2227	2228	2229	2230	2231	2232	2233	2234	2235	2236	2237	2238	2239	2240	2241	2242	2243	2244	2245	2246	2247	2248	2249	2250	2251	2252	2253	2254	2255	2256	2257	2258	2259	2260	2261	2262	2263	2264	2265	2266	2267	2268	2269	2270	2271	2272	2273	2274	2275	2276	2277	2278	2279	2280	2281	2282	2283	2284	2285	2286	2287	2288	2289	2290	2291	2292	2293	2294	2295	2296	2297	2298	2299	2300	2301	2302	2303	2304	2305	2306	2307	2308	2309	2310	2311	2312	2313	2314	2315	2316	2317	2318	2319	2320	2321	2322	2323	2324	2325	2326	2327	2328	2329	2330	2331	2332	2333	2334	2335	2336	2337	2338	2339	2340	2341	2342	2343	2344	2345	2346	2347	2348	2349	2350	2351	2352	2353	2354
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**"Smeared" Coil theta Stress (hoop and bending) =**

$$= (B^8*(efact-hfact)+C^8*(bfact-hfact)+D^8*(cfact-hfact)+E^8*(dfact-hfact)+F^8*(efact-hfact)+G^8*(ffact-hfact)+H^8*(gfact-hfact)+I^8*(hfact-hfact)+J^8*ifact+K^8*(jfact-hfact)+L^8*(kfact-hfact)+M^8*(lfact-hfact)+N^8*(mfact-hfact)+O^8*(nfact-hfact)+P^8*(ofact-hfact)+Q^8*(pfact-hfact))/1000000/1000000/16+hfact*16^2/1000000000000$$

The procedure for calculating the peak hoop directed tension stress is to use the stress multipliers or influence coefficients multiplied by the coil currents. Multiply the result by 37/21 to account for the local conductor cross section multiplier, then add 65 MPa thermal stress components.

**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**

## PF4 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)<sup>2</sup>.

B6= 1.00E+01 B7= 1.00E+01 B8= 1.00E+01 B9= 1.00E+01 B10= 1.00E+01 B11= 1.00E+01 B12= 1.00E+01 B13= 1.00E+01 B14= 1.00E+01 B15= 1.00E+01  
 C6= 1.00E+01 C7= 1.00E+01 C8= 1.00E+01 C9= 1.00E+01 C10= 1.00E+01 C11= 1.00E+01 C12= 1.00E+01 C13= 1.00E+01 C14= 1.00E+01 C15= 1.00E+01  
 D6= 1.00E+01 D7= 1.00E+01 D8= 1.00E+01 D9= 1.00E+01 D10= 1.00E+01 D11= 1.00E+01 D12= 1.00E+01 D13= 1.00E+01 D14= 1.00E+01 D15= 1.00E+01  
 E6= 1.00E+01 E7= 1.00E+01 E8= 1.00E+01 E9= 1.00E+01 E10= 1.00E+01 E11= 1.00E+01 E12= 1.00E+01 E13= 1.00E+01 E14= 1.00E+01 E15= 1.00E+01  
 F6= 1.00E+01 F7= 1.00E+01 F8= 1.00E+01 F9= 1.00E+01 F10= 1.00E+01 F11= 1.00E+01 F12= 1.00E+01 F13= 1.00E+01 F14= 1.00E+01 F15= 1.00E+01  
 G6= 1.00E+01 G7= 1.00E+01 G8= 1.00E+01 G9= 1.00E+01 G10= 1.00E+01 G11= 1.00E+01 G12= 1.00E+01 G13= 1.00E+01 G14= 1.00E+01 G15= 1.00E+01  
 H6= 1.00E+01 H7= 1.00E+01 H8= 1.00E+01 H9= 1.00E+01 H10= 1.00E+01 H11= 1.00E+01 H12= 1.00E+01 H13= 1.00E+01 H14= 1.00E+01 H15= 1.00E+01  
 I6= 1.00E+01 I7= 1.00E+01 I8= 1.00E+01 I9= 1.00E+01 I10= 1.00E+01 I11= 1.00E+01 I12= 1.00E+01 I13= 1.00E+01 I14= 1.00E+01 I15= 1.00E+01  
 J6= 1.00E+01 J7= 1.00E+01 J8= 1.00E+01 J9= 1.00E+01 J10= 1.00E+01 J11= 1.00E+01 J12= 1.00E+01 J13= 1.00E+01 J14= 1.00E+01 J15= 1.00E+01  
 K6= 1.00E+01 K7= 1.00E+01 K8= 1.00E+01 K9= 1.00E+01 K10= 1.00E+01 K11= 1.00E+01 K12= 1.00E+01 K13= 1.00E+01 K14= 1.00E+01 K15= 1.00E+01  
 L6= 1.00E+01 L7= 1.00E+01 L8= 1.00E+01 L9= 1.00E+01 L10= 1.00E+01 L11= 1.00E+01 L12= 1.00E+01 L13= 1.00E+01 L14= 1.00E+01 L15= 1.00E+01  
 M6= 1.00E+01 M7= 1.00E+01 M8= 1.00E+01 M9= 1.00E+01 M10= 1.00E+01 M11= 1.00E+01 M12= 1.00E+01 M13= 1.00E+01 M14= 1.00E+01 M15= 1.00E+01  
 N6= 1.00E+01 N7= 1.00E+01 N8= 1.00E+01 N9= 1.00E+01 N10= 1.00E+01 N11= 1.00E+01 N12= 1.00E+01 N13= 1.00E+01 N14= 1.00E+01 N15= 1.00E+01  
 O6= 1.00E+01 O7= 1.00E+01 O8= 1.00E+01 O9= 1.00E+01 O10= 1.00E+01 O11= 1.00E+01 O12= 1.00E+01 O13= 1.00E+01 O14= 1.00E+01 O15= 1.00E+01  
 P6= 1.00E+01 P7= 1.00E+01 P8= 1.00E+01 P9= 1.00E+01 P10= 1.00E+01 P11= 1.00E+01 P12= 1.00E+01 P13= 1.00E+01 P14= 1.00E+01 P15= 1.00E+01  
 Q6= 1.00E+01 Q7= 1.00E+01 Q8= 1.00E+01 Q9= 1.00E+01 Q10= 1.00E+01 Q11= 1.00E+01 Q12= 1.00E+01 Q13= 1.00E+01 Q14= 1.00E+01 Q15= 1.00E+01

\*Smeared\* Coil theta Stress (hoop and bending )=

$$\begin{aligned}
 &= (B6*(efact-hfact)+C6*(bfact-hfact)+D6*(cfact-hfact)+E6*(dfact-hfact)+F6*(efact-hfact)+G6*(ffact- \\
 &hfact)+I6*(gfact-hfact)+J6*(hfact-hfact)+K6*(ifact-hfact)+L6*(lfact-hfact)+M6*(lfact- \\
 &hfact)+N6*(mfact-hfact)+O6*(nfact-hfact)+P6*(ofact-hfact)+Q6*(pfact-hfact))/1000000/1000000*16 \\
 &+hfact*16^2/1000000000000
 \end{aligned}$$

The equation above includes the plasma. For "No Plasma" the p factor should be set to zero.  
The procedure for calculating the peak hoop directed tension stress is to use the stress multipliers or influence coefficients multiplied by the coil currents, Multiply the result by 37/21 to account for the local conductor cross section multiplier, then add 55 MPa thermal stress components.

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

## 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.

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

## PF4/5 Coil and Support Analysis Page 9

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).  $S_m$  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  $S_m$  value is 156 MPa. and the bending allowable is 233 MPa

- From: 2.4.1.1 Design Tresca Stress Values ( $S_m$ ), NSTX\_DesCrit\_IJ\_080103.doc [3]
- • (a) For conventional (i.e., non-superconducting) conductor materials, the design Tresca stress values ( $S_m$ ) 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  $1.5 \times 156$  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  $0.9 S_y$ .

## 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  $241 \times 21/36 = 140 \text{ MPa} = 20 \text{ ksi}$  (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

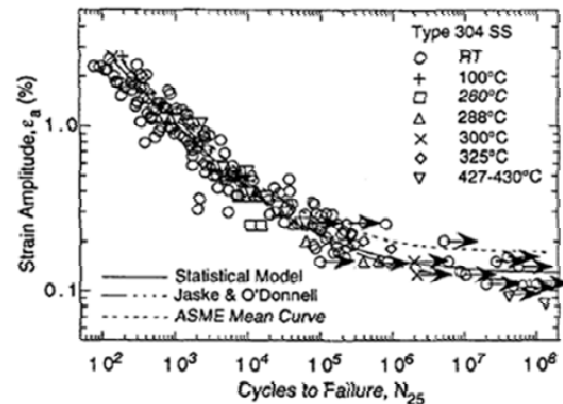
For fillets divide weld area by  $\sqrt{2}$

**Fatigue:**

for a nominal 60,000 cycles, the strain range allowable is  $\sim .175\%$   
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 for a modulus of  $200 \times 10^9$  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

### 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 I<sup>2</sup>T, 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

## 6.4 Materials Properties

Material	Yield 4 deg K (MPa)	Ultimate 4 deg K, (Mpa)	Yield, 80 deg. K (MPa )	Ultimate , 80 deg. K (MPa)	Yield, 292 deg K (MPa)	Ultimate , 292 deg K (MPa)
304 SST 50% CW			1344 (195 ksi)	1669	1089	1241
304 Stainless Steel (Bar,annealed)	404	1721	282	1522	234	640

Coil Structure Room Temperature (292 K) Maximum Allowable Stresses,  $S_m$  = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5\* $S_m$

Material	$S_m$	1.5 $S_m$
304 Stainless Steel (Bar,annealed)	156MPa(22.6ksi)	234 MPa (33.9ksi)



Avesta Sheffield Plate Inc.

## Certificate of Analysis and Tests

OUR ORDER 106101 - 01

HEAT &amp; PIECE 87893-3B 5/13/98

SOLD TO: PROCESS SYSTEMS INTERNATIONAL  
20 WALKUP DRIVESHIP TO: NEW ENGLAND STEEL TANK  
111 BROOK ROAD

PSI MIC NO. 69923

WESTBOROUGH

MA 01581

SOUTH QUINCY  
737001-06

MA 02169

YOUR ORDER &amp; DATE

558635

3/18/98

TAG# PART #V077P001

ITEM DESCRIPTION

HEAT &amp; 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, ASME SA240-96AD  
NO WELD REPAIR ON MATERIAL  
ASTM A262-93A PRAC A

ASTM A480-96, ASME SA480-96AD  
MAG PERM <1.05 ASTM A342 (6)  
ASTM A262-93A PRAC E

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

MECHANICAL &amp; 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 ✓

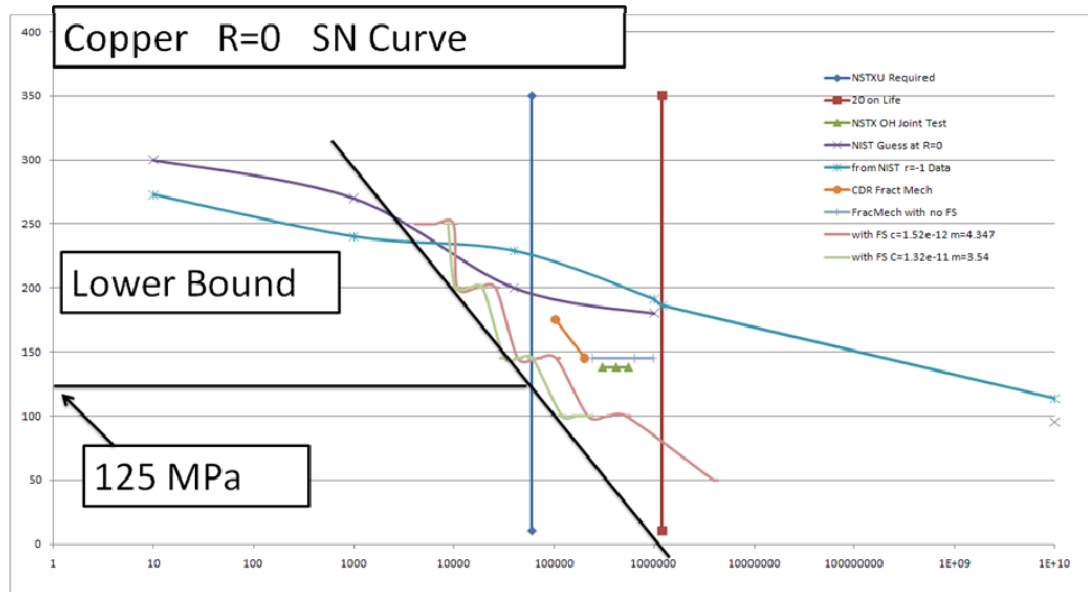
Vessel Material Mill Certifications for the 304 Vessel Show a 45 ksi Yield

## ASTM A193 Bolt Specs from PortlandBolt.com

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



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)

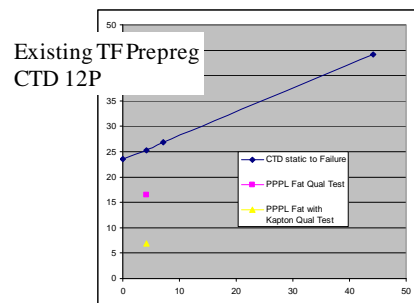
- From Criteria Document:
- I-5.2.1.3 Shear Stress Allowable
- The shear-stress allowable,  $S_s$ , for an insulating material is most strongly a function of the particular material and processing method chosen, the loading conditions, the temperature, and the radiation exposure level. The shear strength of insulating materials depends strongly on the applied compressive stress. Therefore, the following conditions must be met for either static or fatigue conditions:

$$S_s = [2/3 \text{ to } ] + [c_2 \times S_c(n)]$$

$$2/3 \text{ of } 32.5 \text{ MPa} = 21.7 \text{ MPa}$$

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

From NSTX TF Test Report:

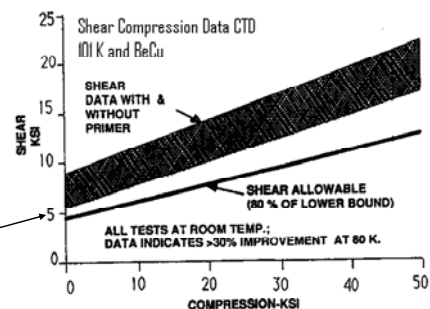


2/3 of 24 = **16 MPa (Static)**

C2~.44

Should be Further De-rated for Fatigue

From an October 27 2009 email from Dick Reed



## 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.

## MAGNAPLATE HMF®

For Most Base Metals

The coating creates an ultra-hard, mirror-smooth, highly reflective surface that exhibits a uniquely low coefficient of friction, exceptional wear properties and high temperature resistance.

Up to R<sub>a</sub> 68.  
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.

Recommended for packaging machines,  
closure devices, chutes, hoppers, folders,  
rolls, lathe beds, ball valves, and areas  
where high wear is encountered, as well  
as for products where a microfinish  
and/or static reduction is vital.

### I-5.2.2 Coefficient of Friction

The allowable coefficient of friction ( $\mu$ ) 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

$$\mu_{min} = \mu - 0.15 \text{ but } \geq 0.02$$

$$\mu_{max} = \mu + 0.15$$

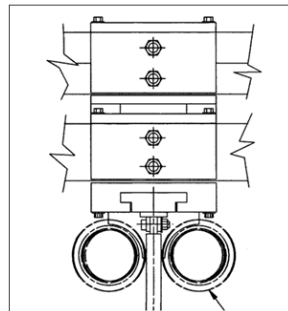
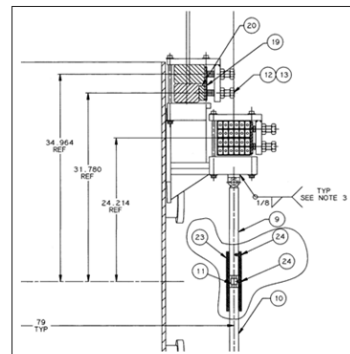
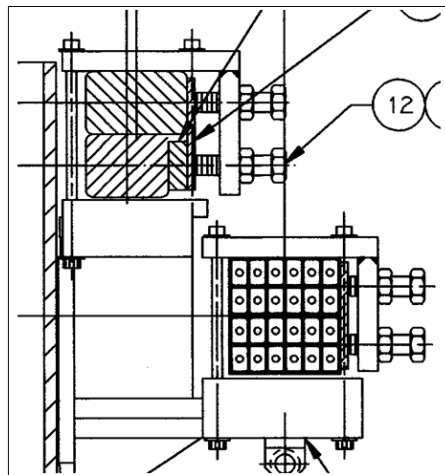
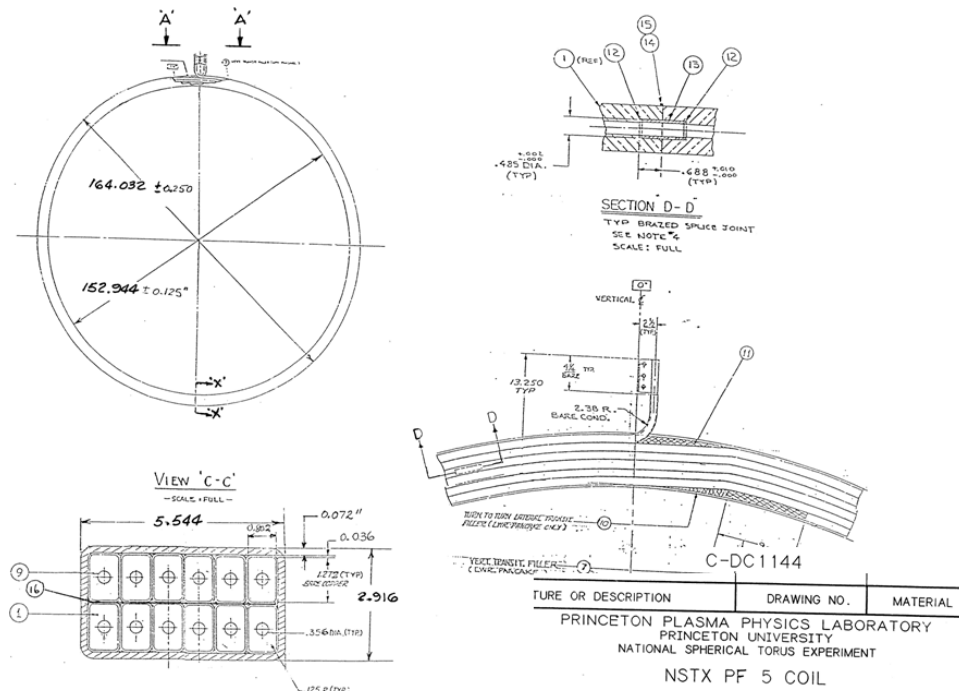
Friction values outside the range 0.1-0.4 require exceptional justification. The case of friction coefficient extremes must be considered as anticipated upset conditions in the design.

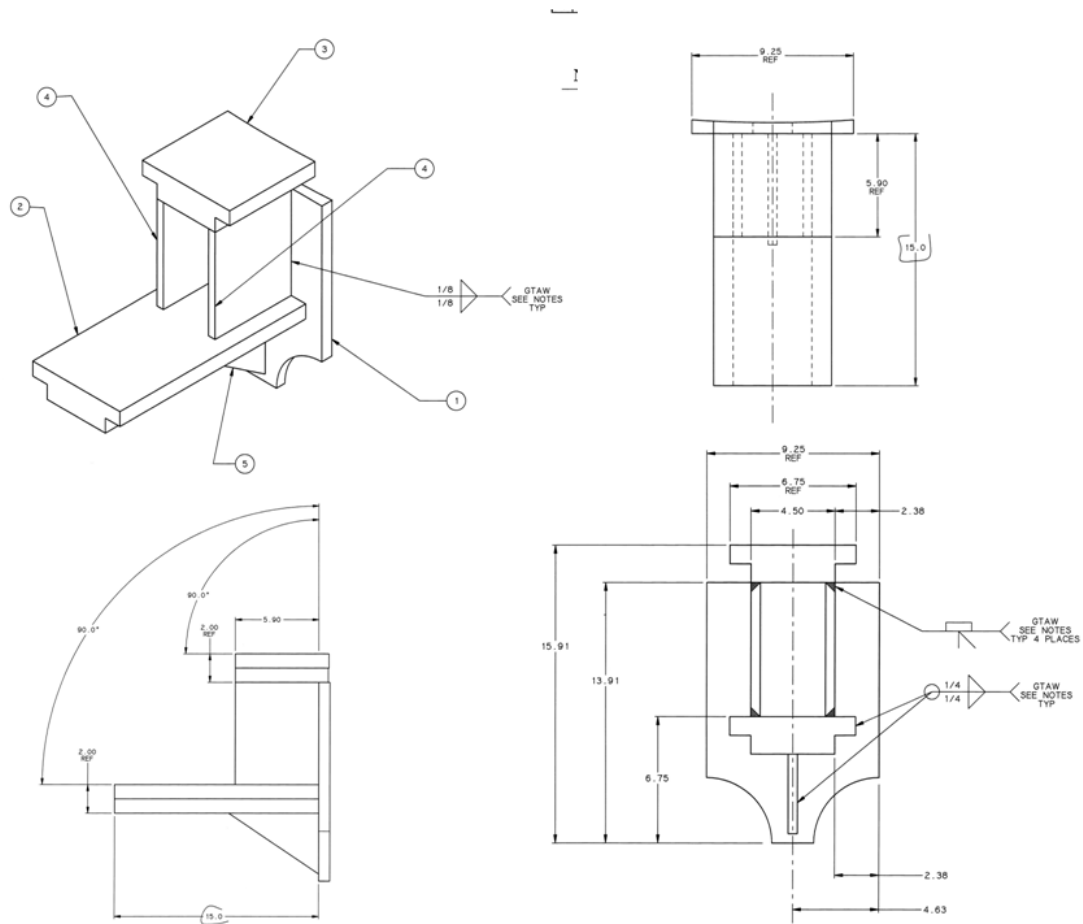


## General Magnaplate

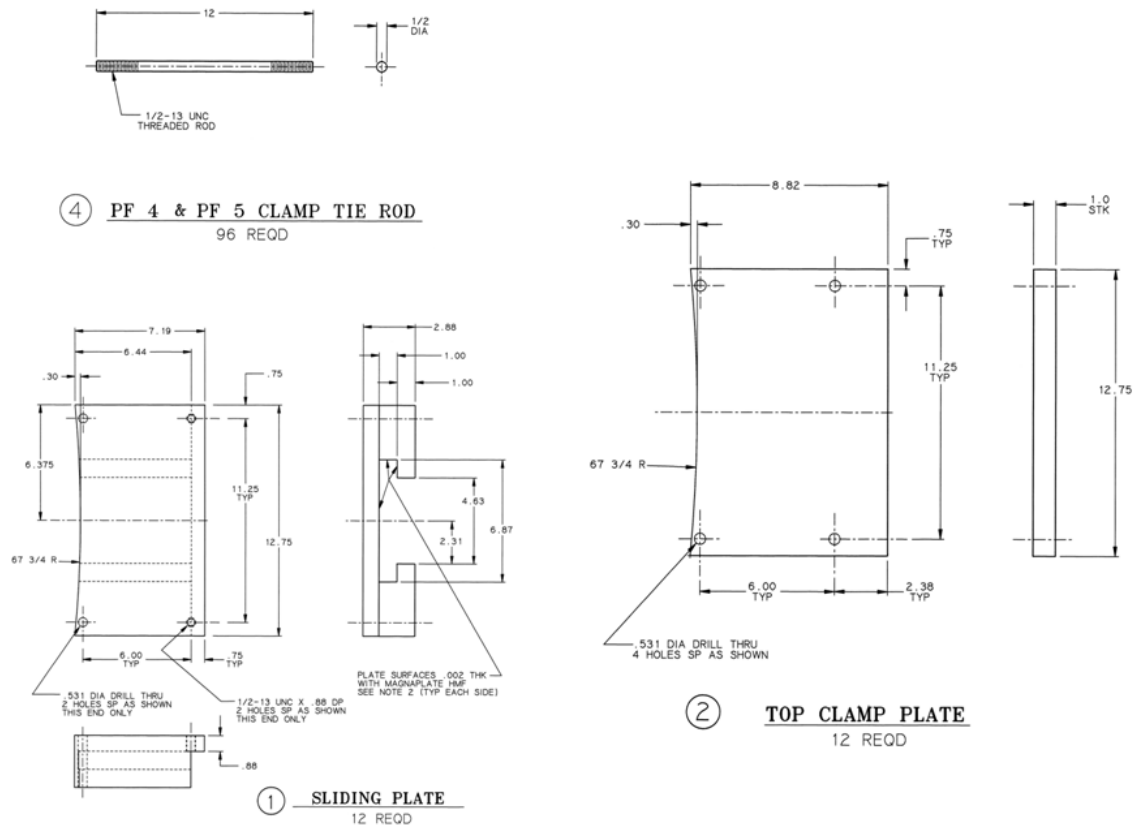
General Magnaplate Corp.  
1331 Route 1, Linden, NJ 07036  
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## 6.5 Coil Geometry and Currents





Type B Bracket Details



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

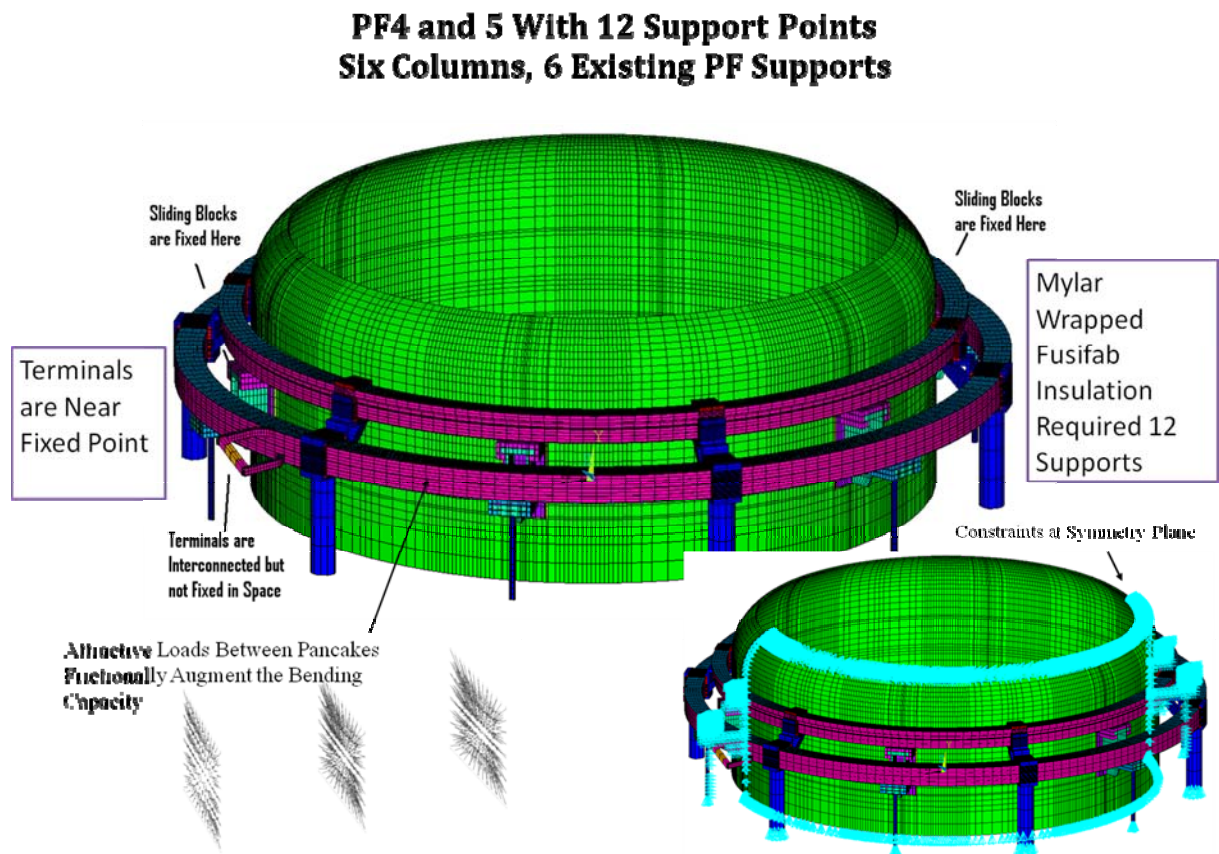


Fig. 7.1-1 180 Symmetry Model with 12 Supports



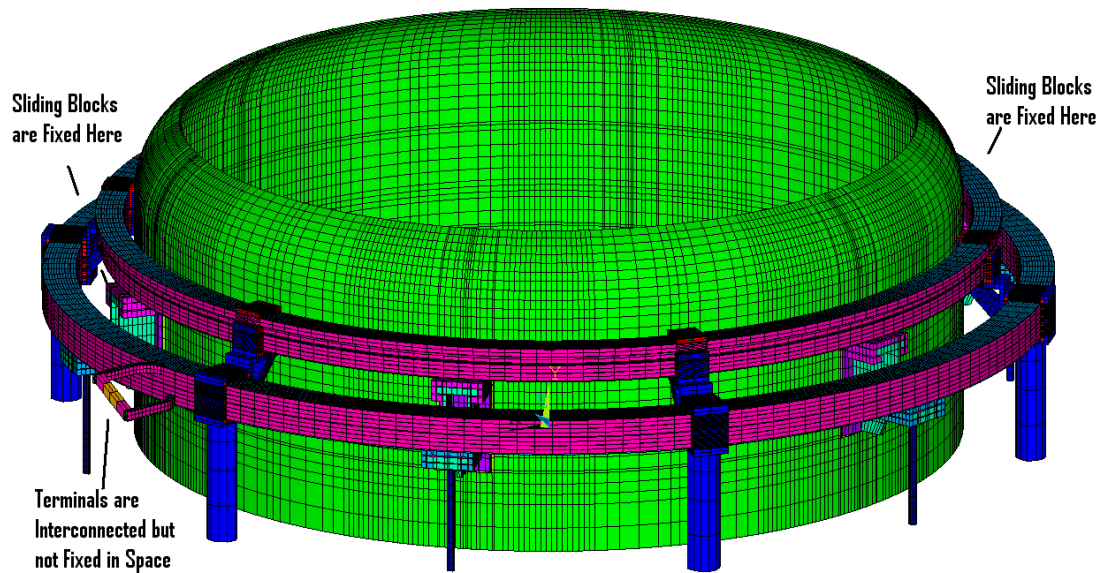


Fig.

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.

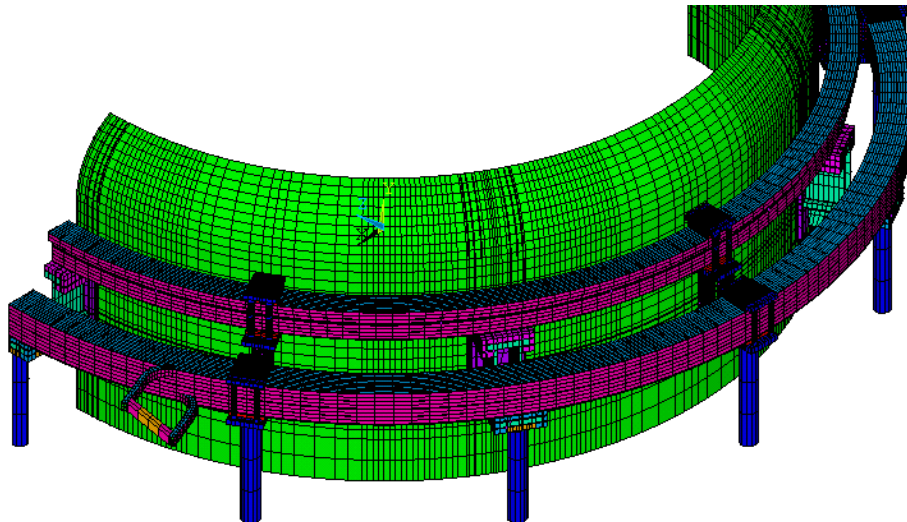


Fig. 7.1-3 June 2011 Model of the PF4/5 Support System with Heavier Columns all Around

## 7.2 Fields and Forces

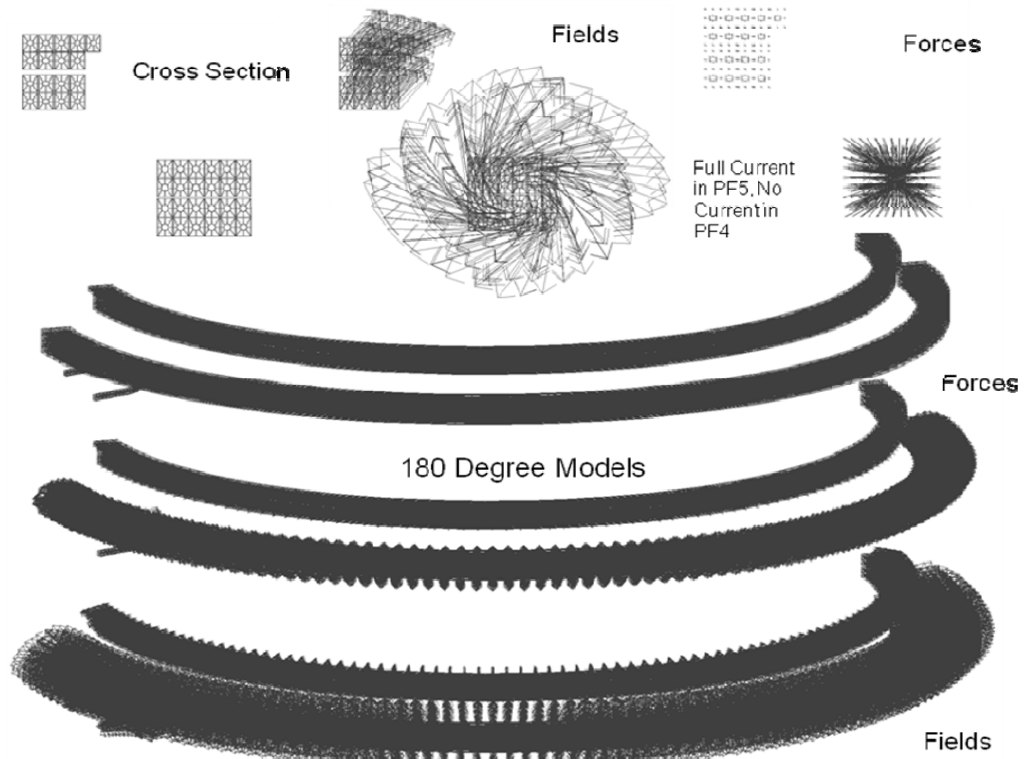


Figure 7.2-1 Fields and Forces for the 180 degree Symmetry Model with Full Current in PF5 and zero current in PF4

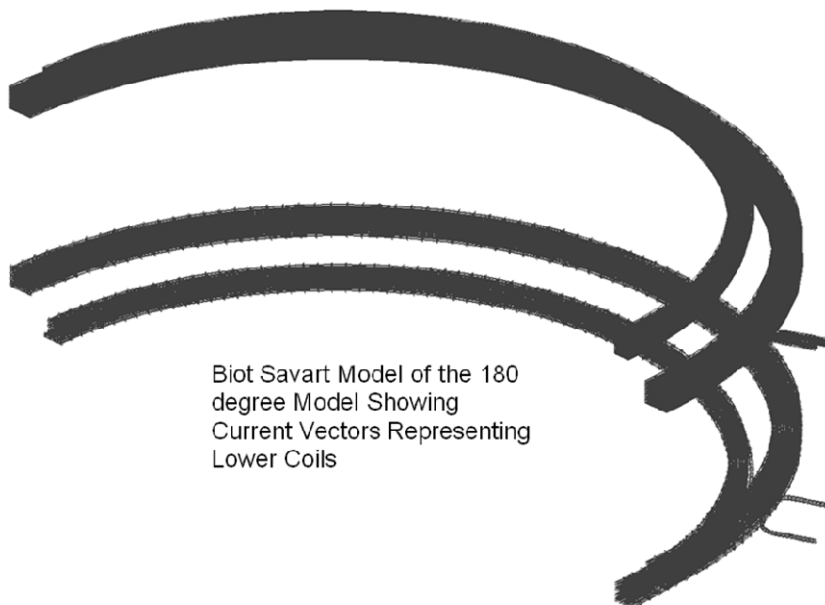


Figure 7.2-2 Biot Savart Model showing the current sticks modeling the lower coils - These are deleted in the structural model and up-down symmetry is assumed for this model. Up down asymmetries are evaluated from loads in the Design Point Spreadsheet.

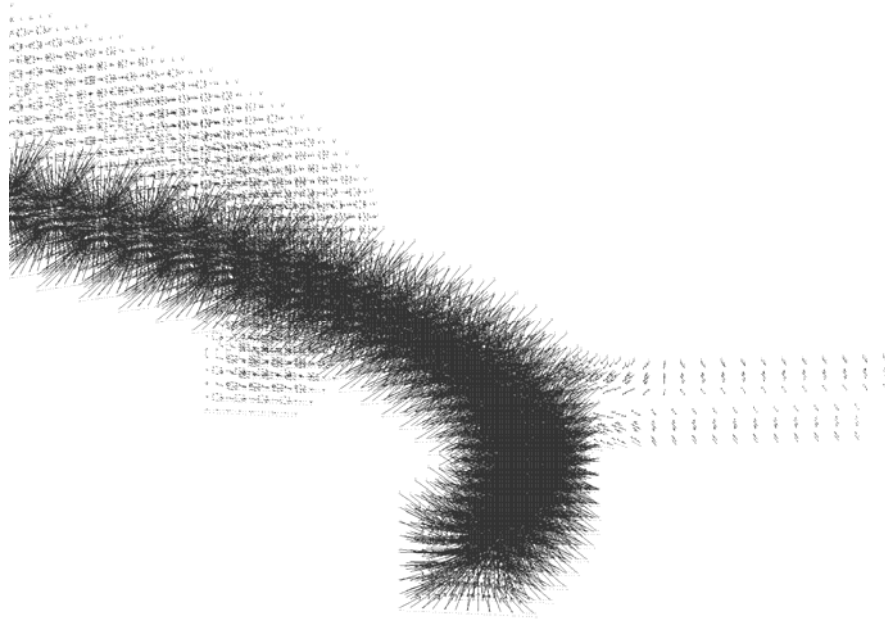


Figure 7.2-3 Local Detail of the Lorentz Forces at the Coil Leads

### 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.

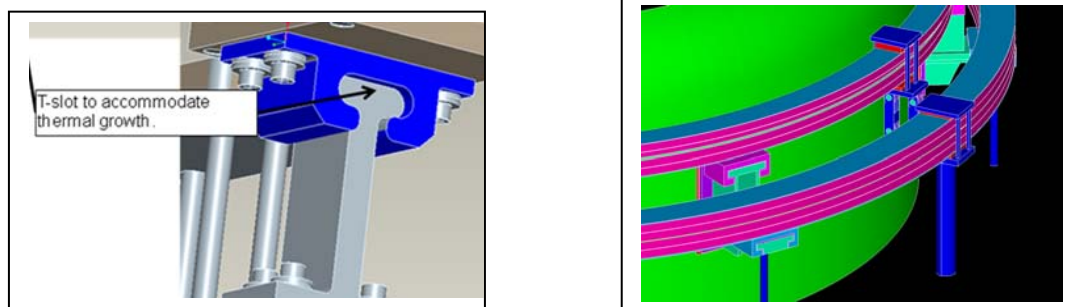


Figure 7.3-1 Left: Final Design Dovetail Slide, Right: The link Design, Mechanically Similar to the Dovetail

### 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.

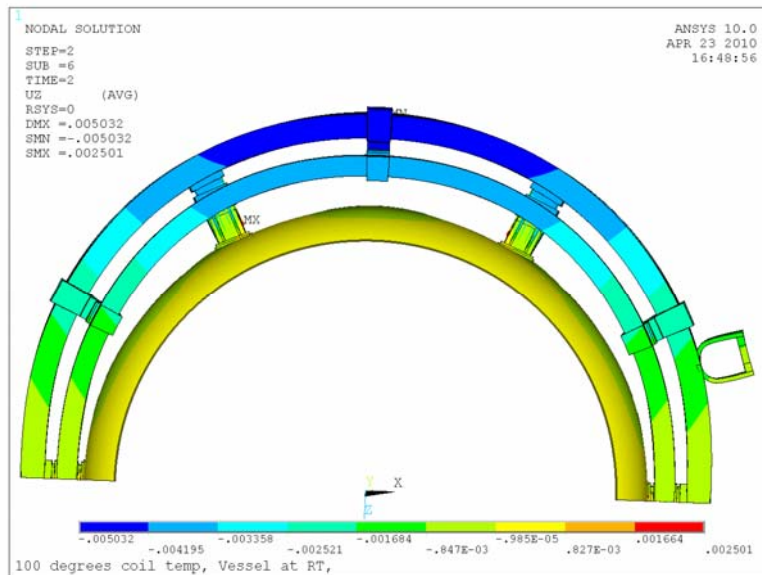


Figure 8.1-1 Coils held radially at left and right. Existing supports free to slide. Coils at 100C

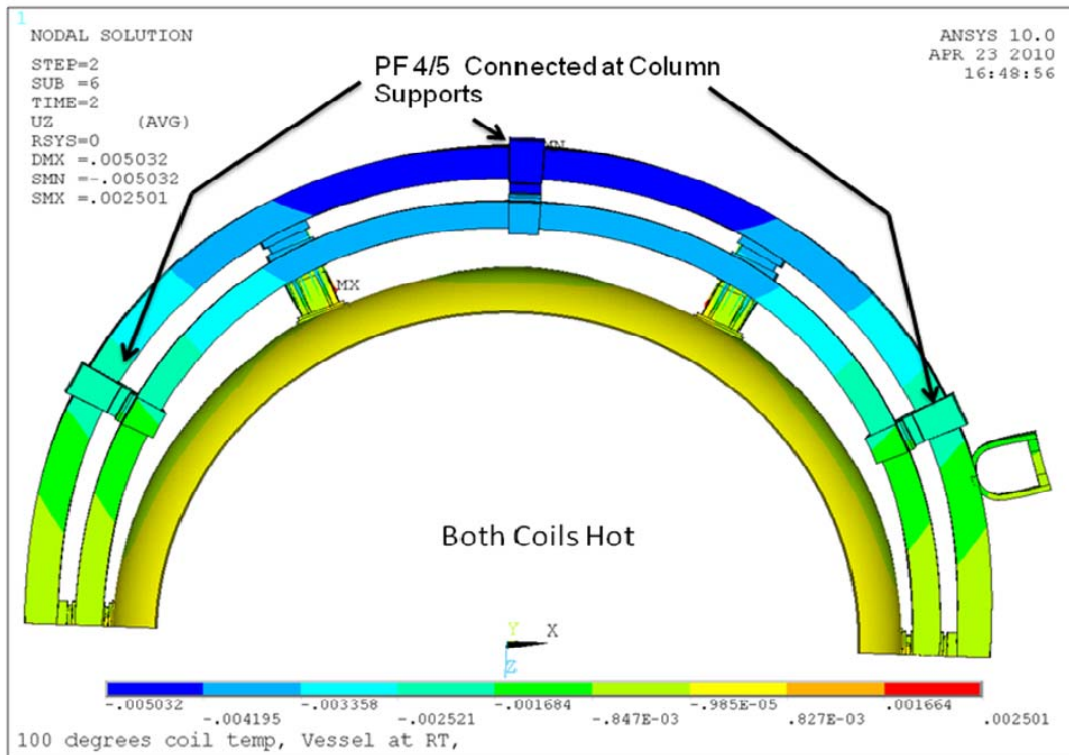


Figure 8.1-2 Coils held radially at left and right. Existing supports free to slide. Coils at 100C

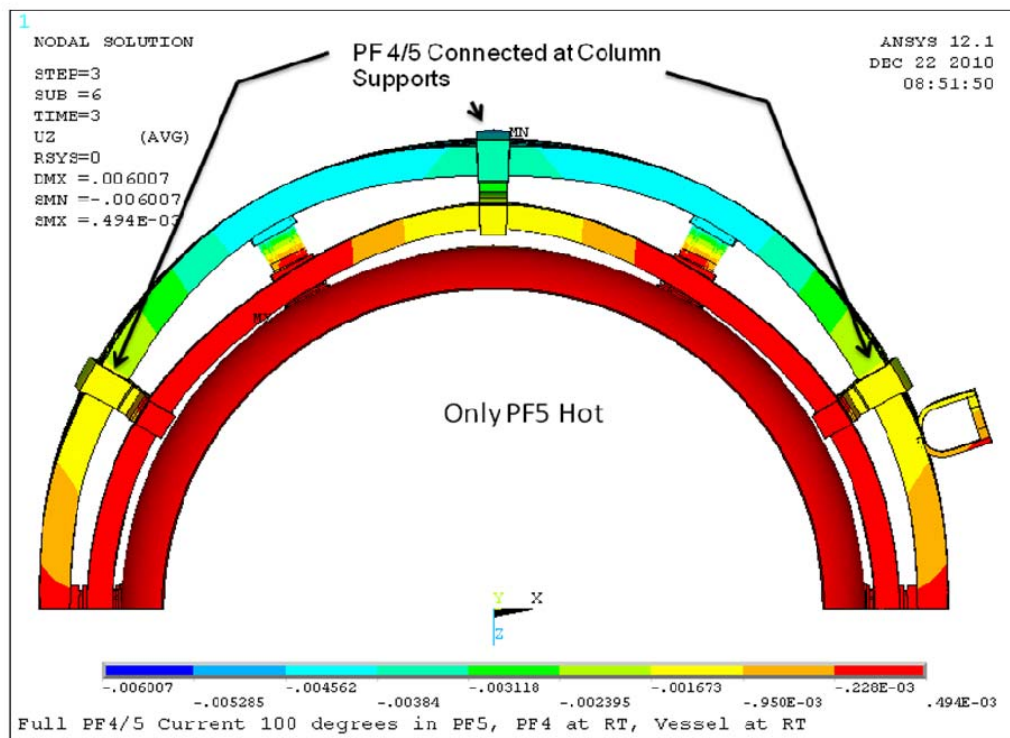


Figure 8.1-3 Coils held radially at left and right. Other supports free to slide. PF5 at 100C, PF4 and 5 clamped together at added support columns



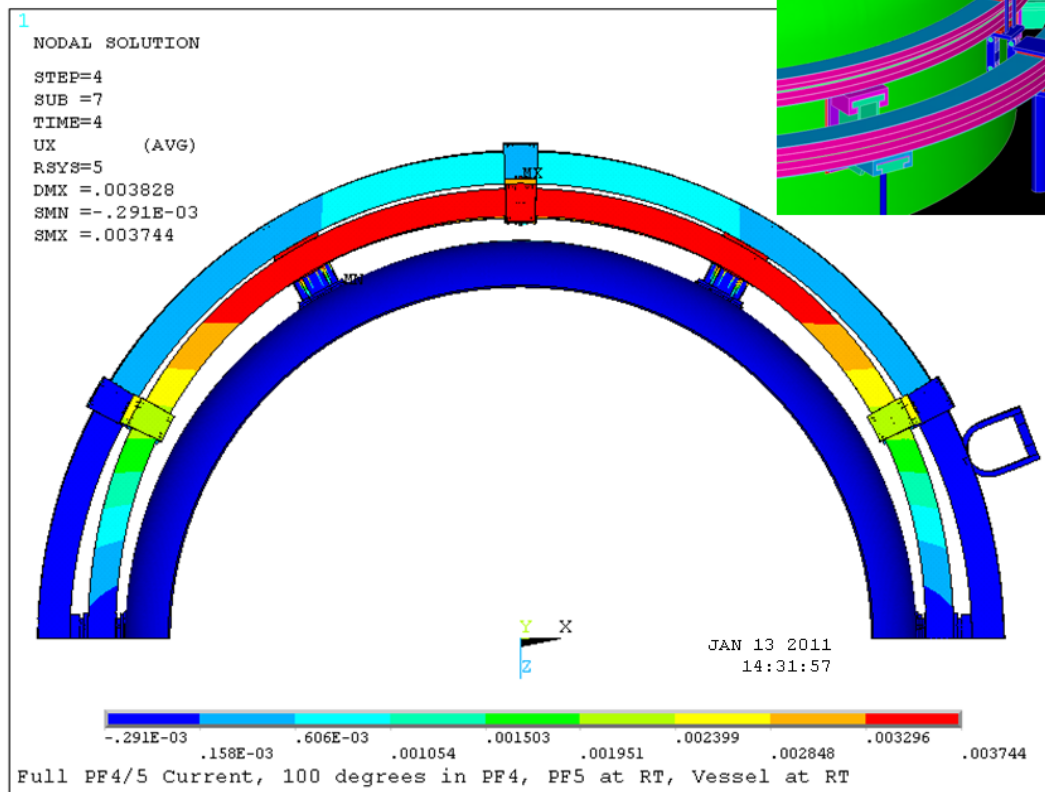


Figure 8.1-4 Coils held radially at left and right. All other supports free to slide. PF4 at 100C PF 5 at RT

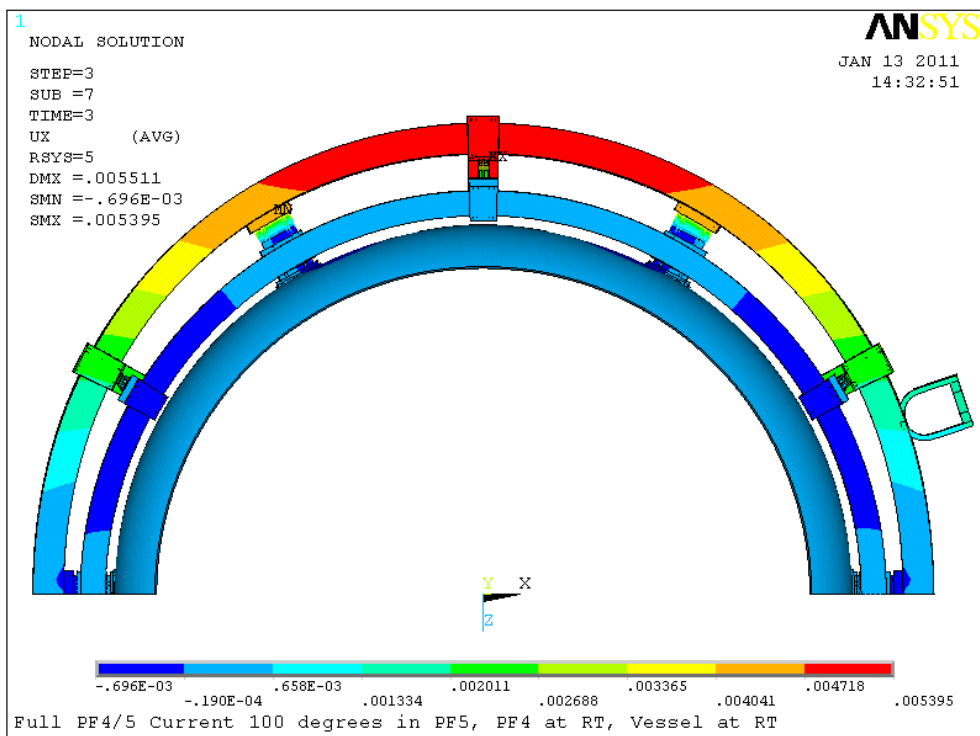


Figure 8.1-5 Coils held radially at left and right. All other supports free to slide. PF5 at 100C, PF4 at RT

## 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.

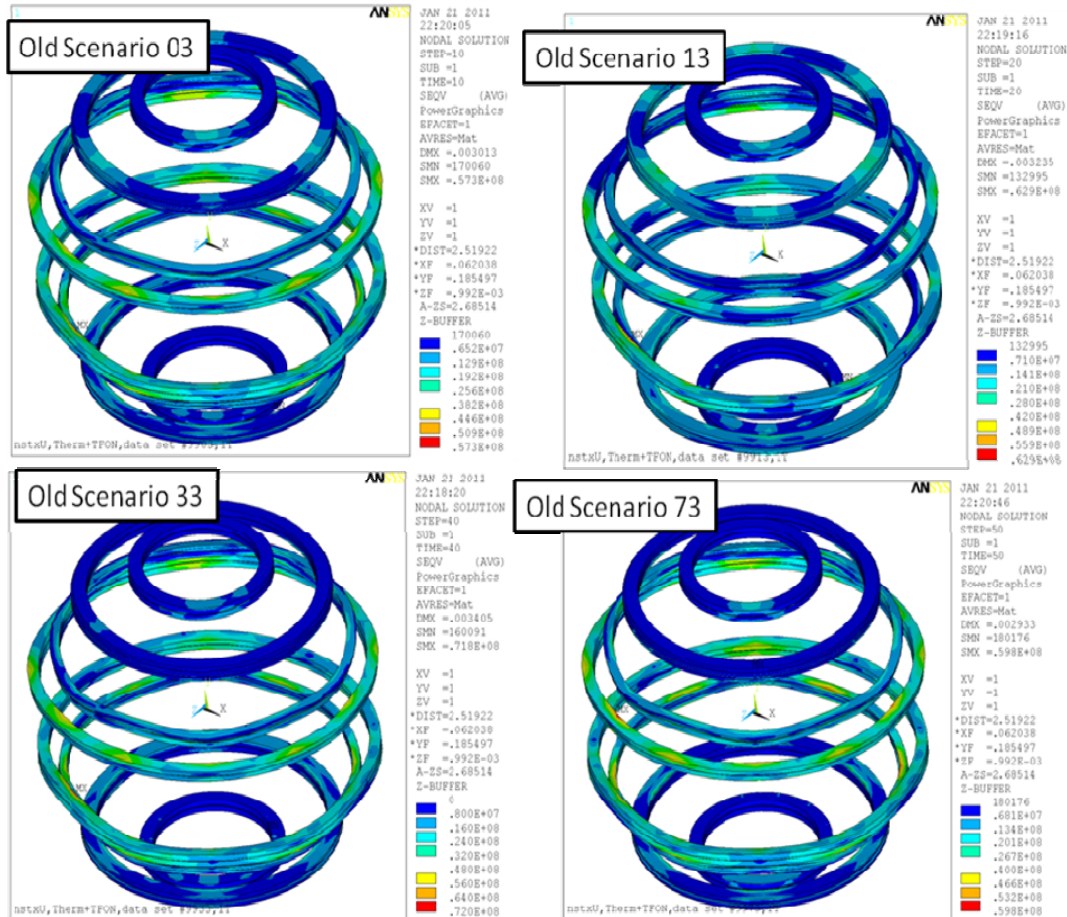
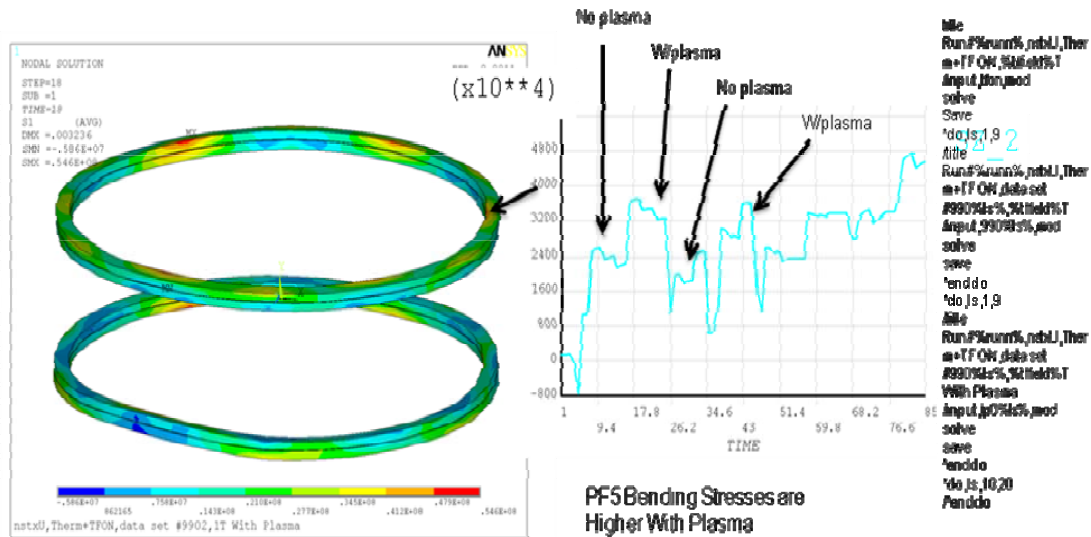


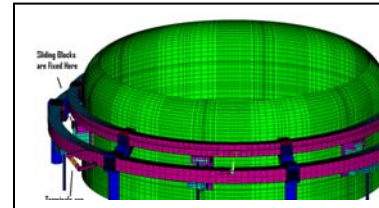
Fig 8.2-1 Global Model Results for PF4 and 5, ref [2]

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.

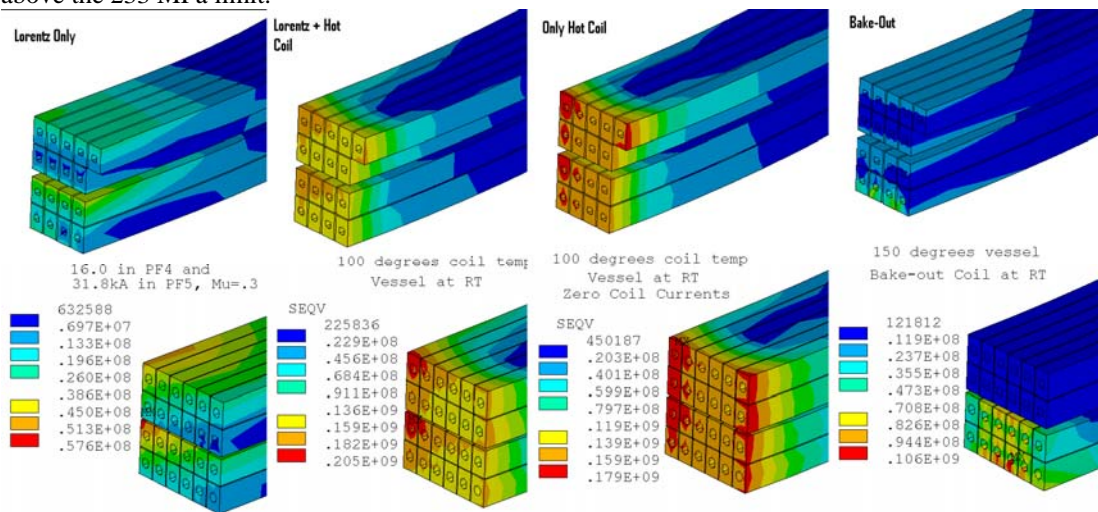


## Coil Conductor Stress

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.

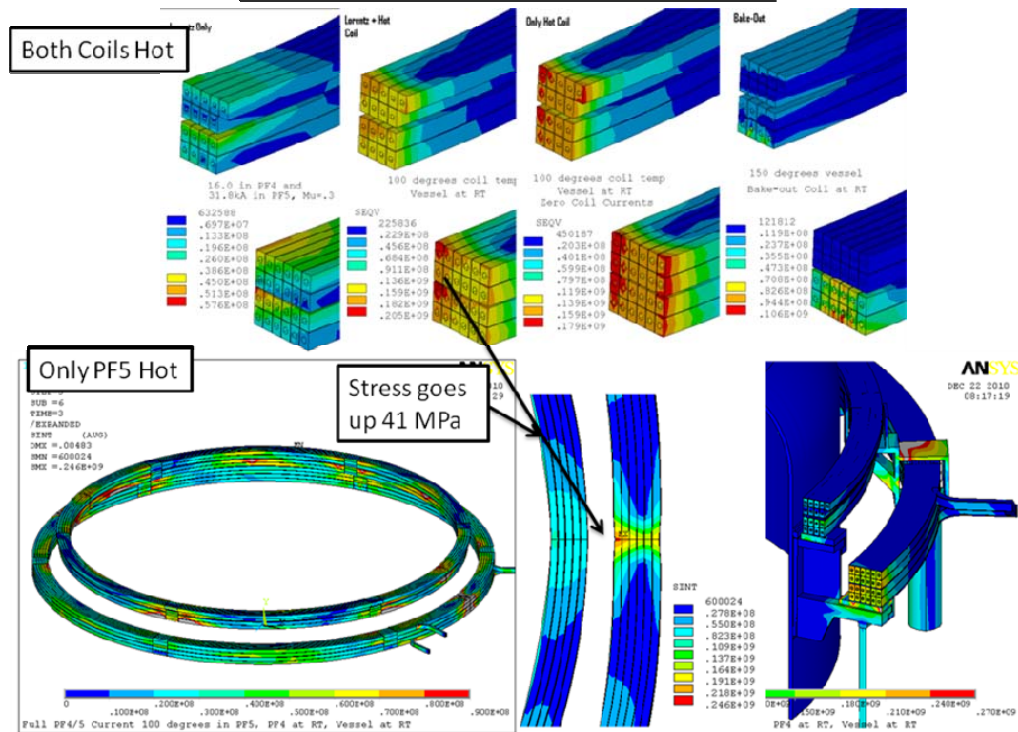


The  $S_m$  value for the coil cold worked copper is expected to be similar to the TF specs or  $S_m$  is 156 MPa with the bending allowable at 233 MPa (see the criteria in section 6). Fatigue is addressed in section 11. Peak Stresses below are all above the 233 MPa limit.

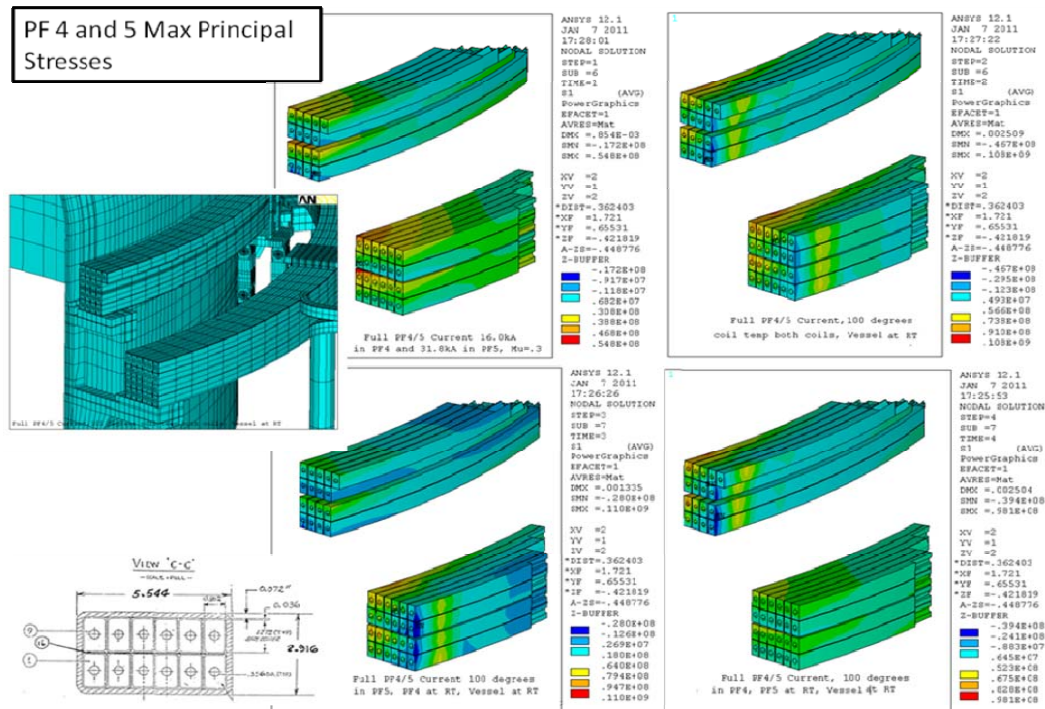




### PF 4 and 5 Connected at Column Supports



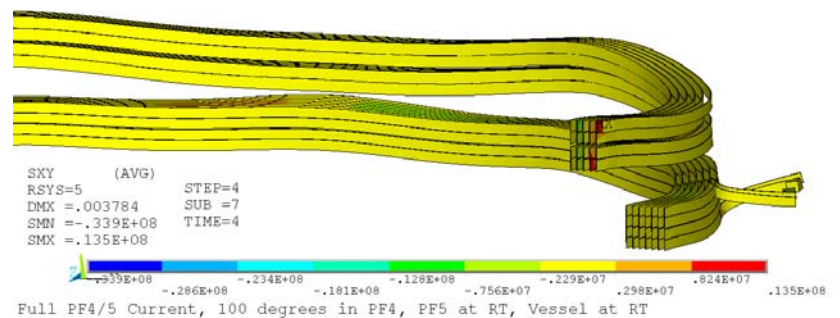
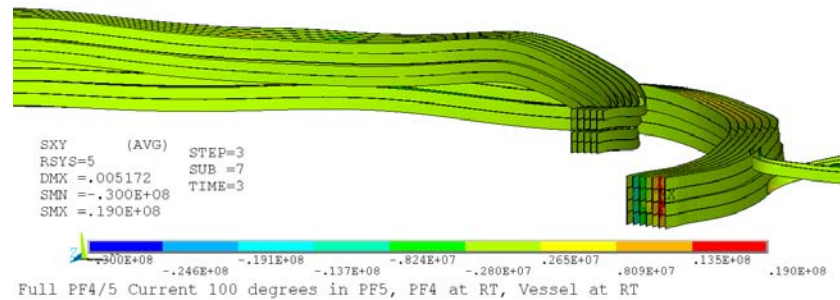
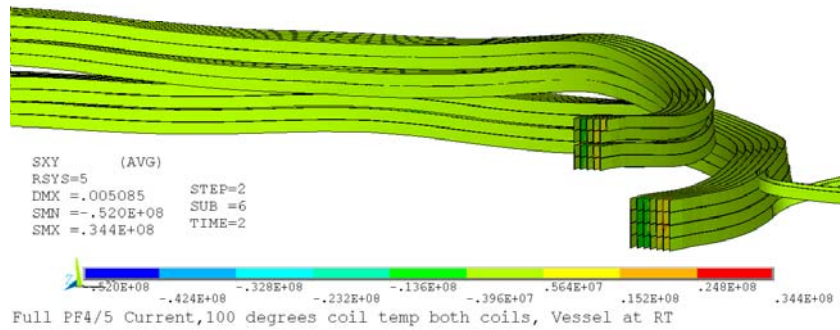
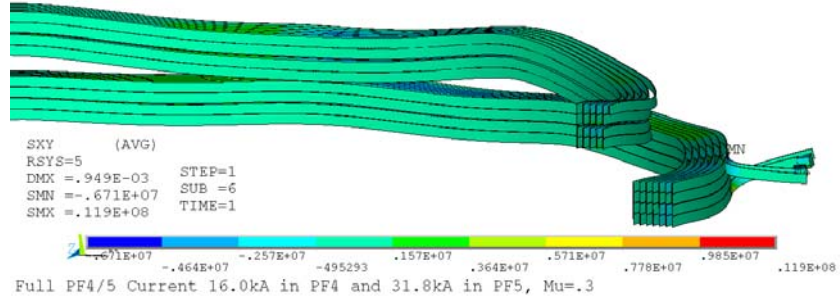
With PF4 and 5 rigidly connected at the added support column locations, and only PF5 hot, the stress goes up 41 MPa and is above the 233 MPa static limit.

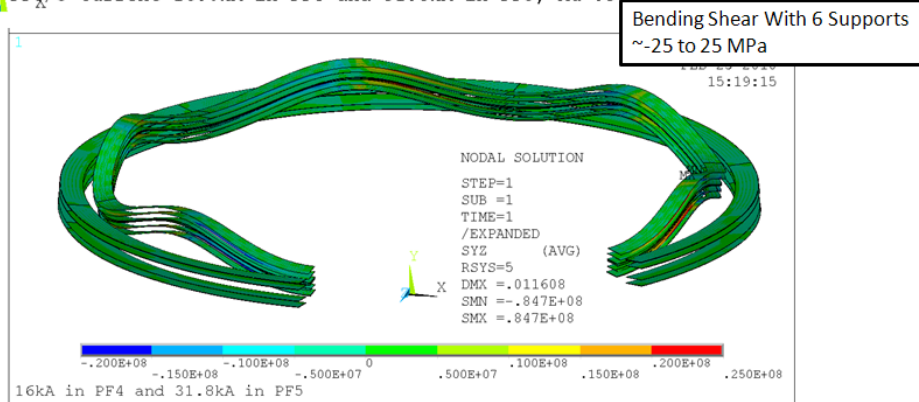
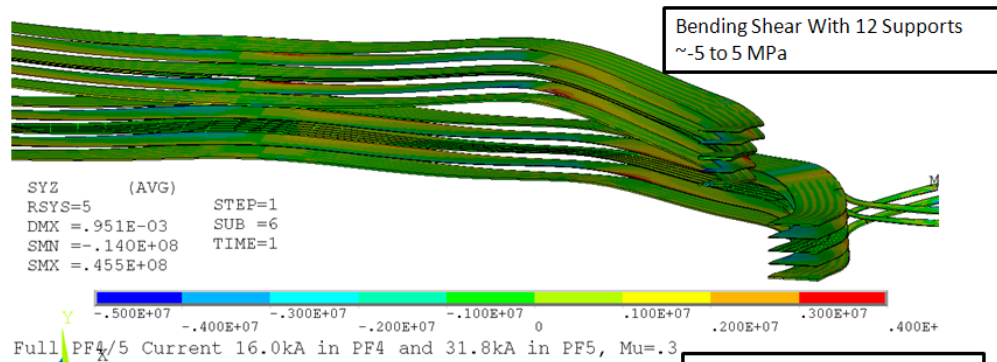
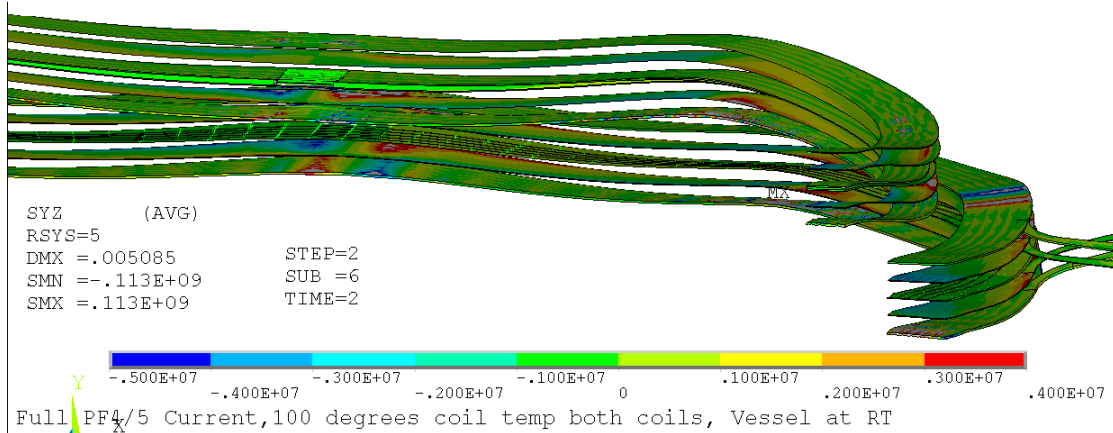
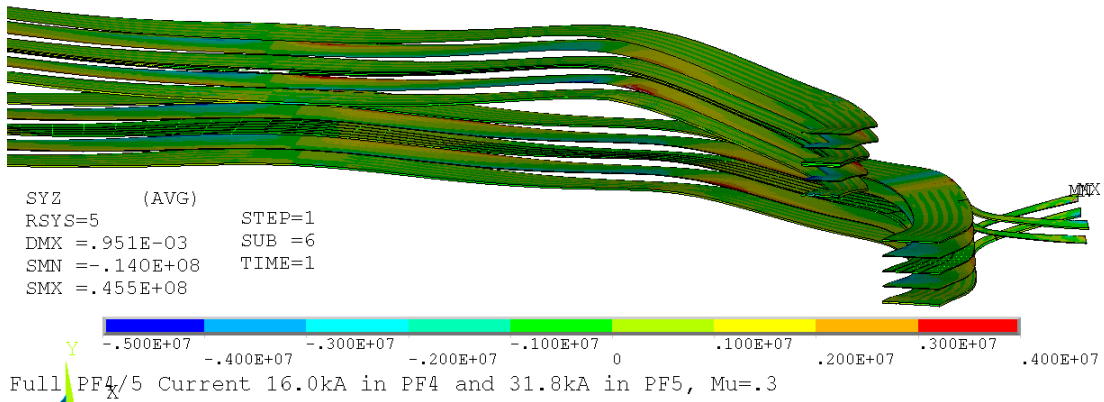


Conductor stress with a mechanism to allow differential radial motion of PF4 and 5

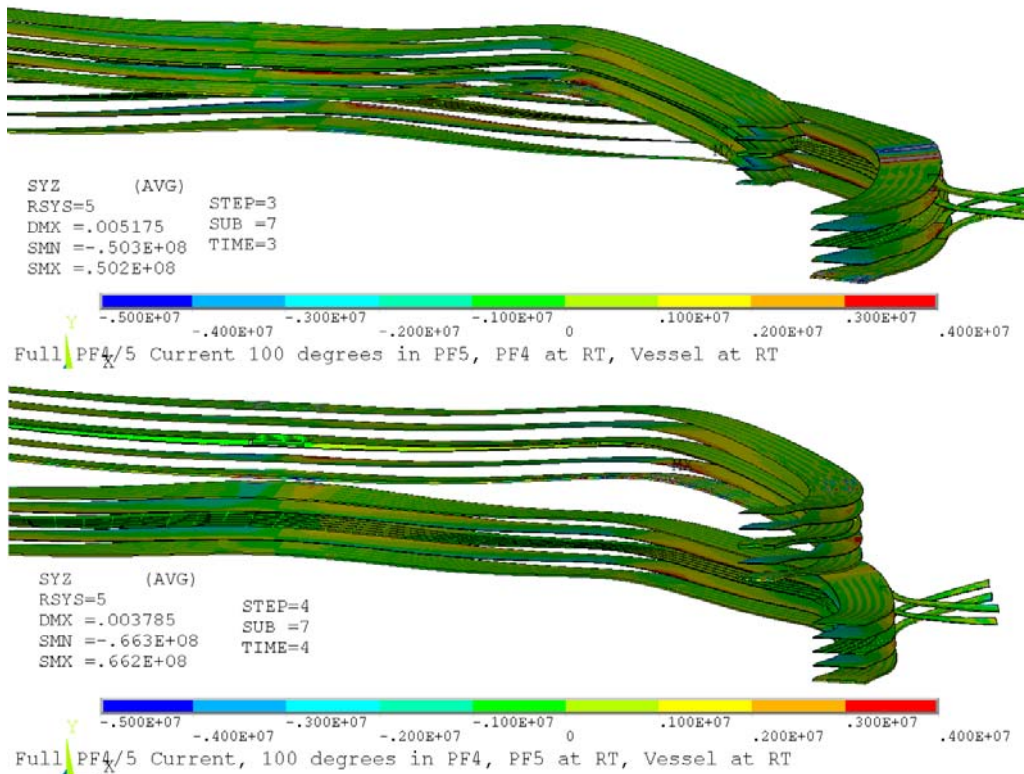
### 8.3 PF4 and 5 Coil Insulation Stress

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.

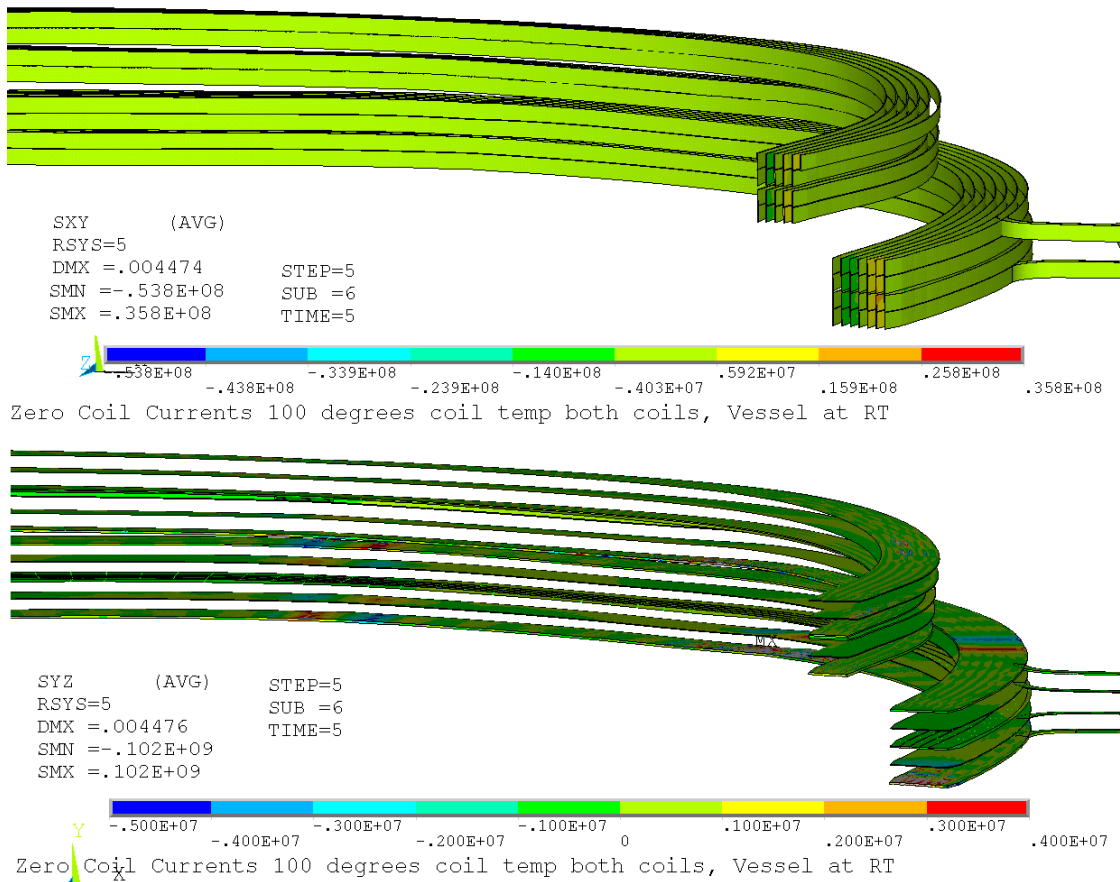






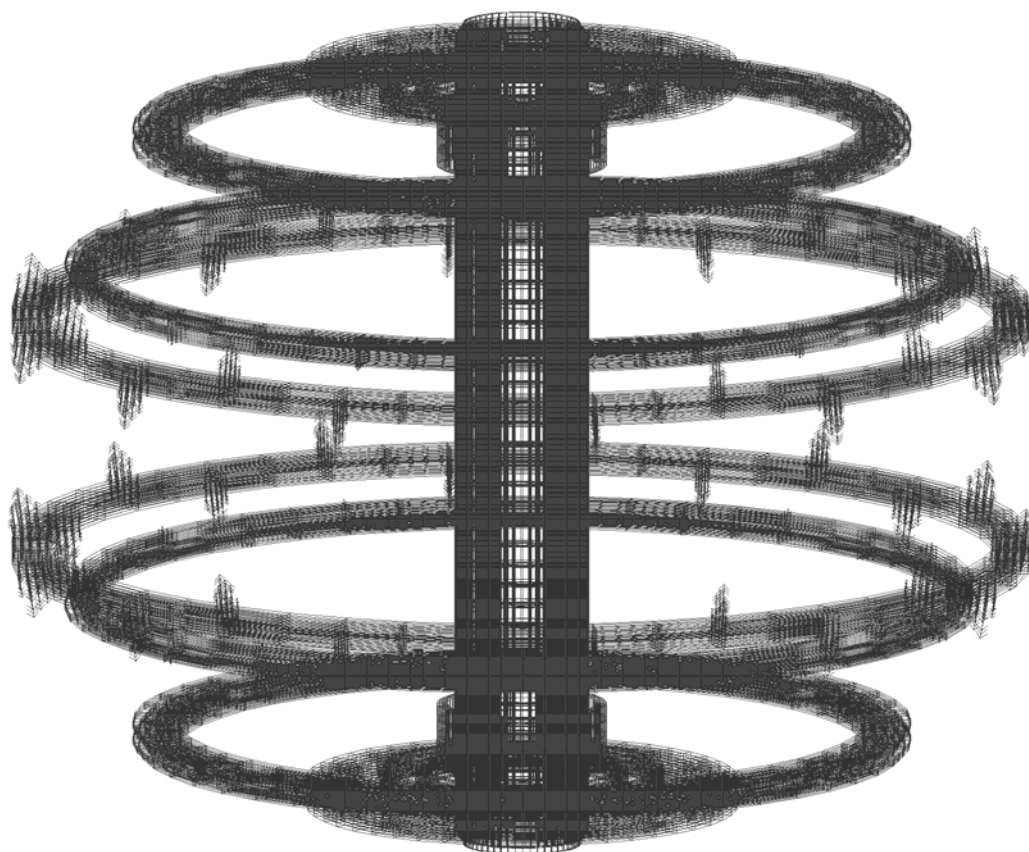


Lowering insulation stress was a significant driver in the decision to provide 12 support points. In the figure above, the shear stress due to bending between supports is reduced from about 25 MPa to 5 MPa in PF4. PF4 is divided into two pancakes and interacts strongly with PF5. With PF4 and 5 upper 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.

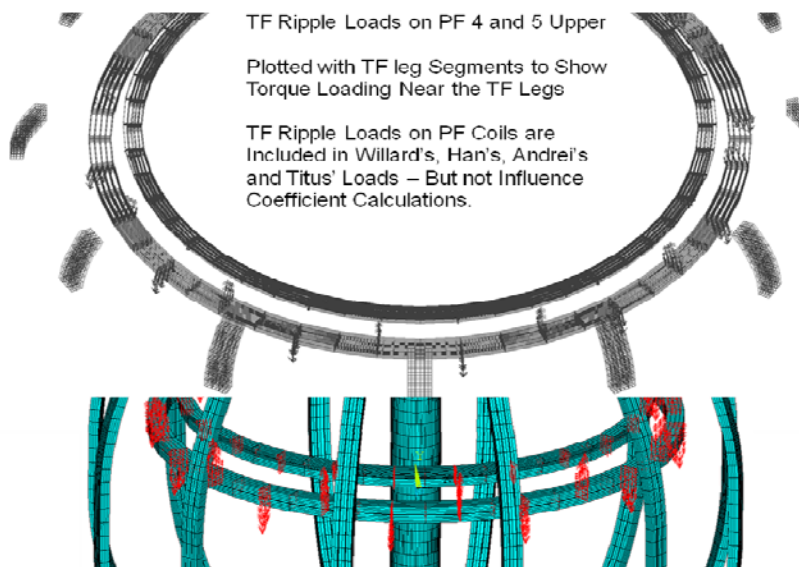


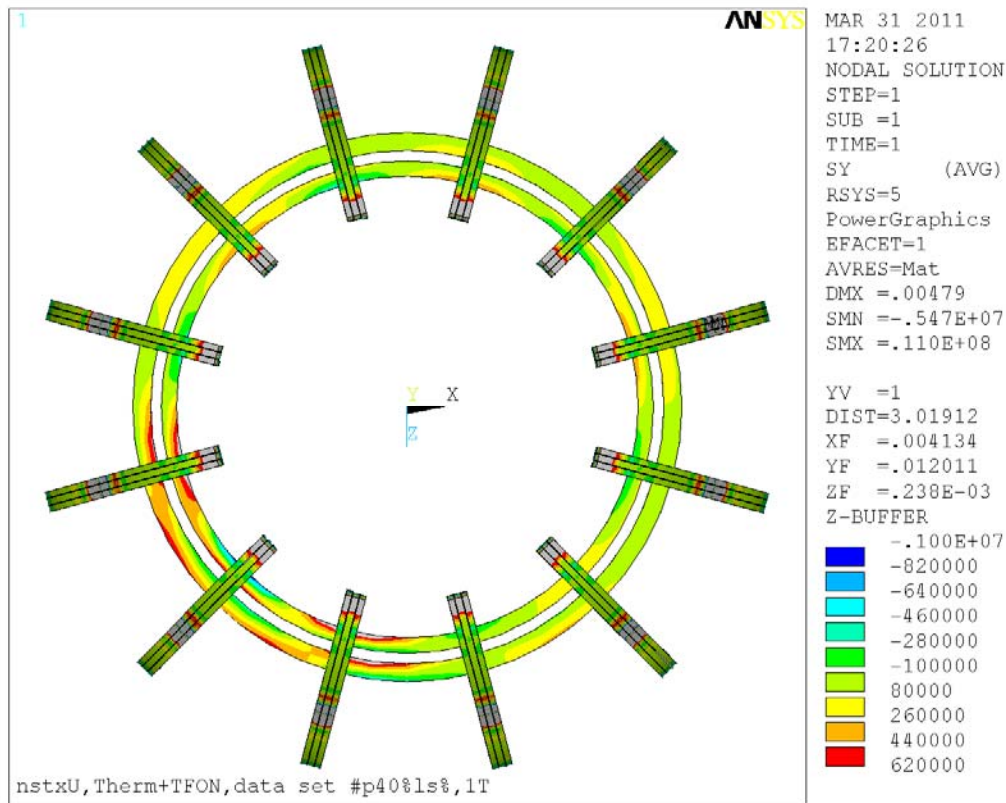
#### 8.4 TF Ripple Loads on PF 4 and 5

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.



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 remain.





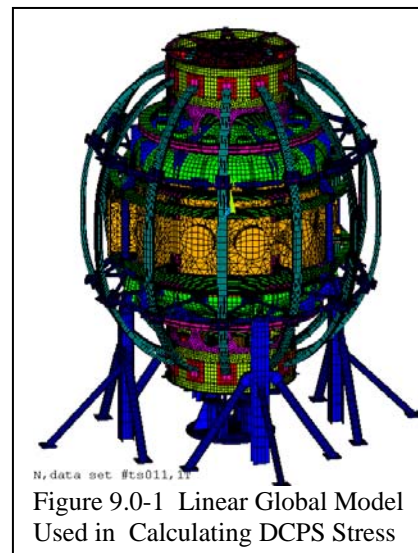
Hoop Directed Stress - Bending Stress Due to TF Ripple. - Less than 11 MPa at most locations. The asymmetry is due to local support bracket and port modeling.

## 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.

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

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.

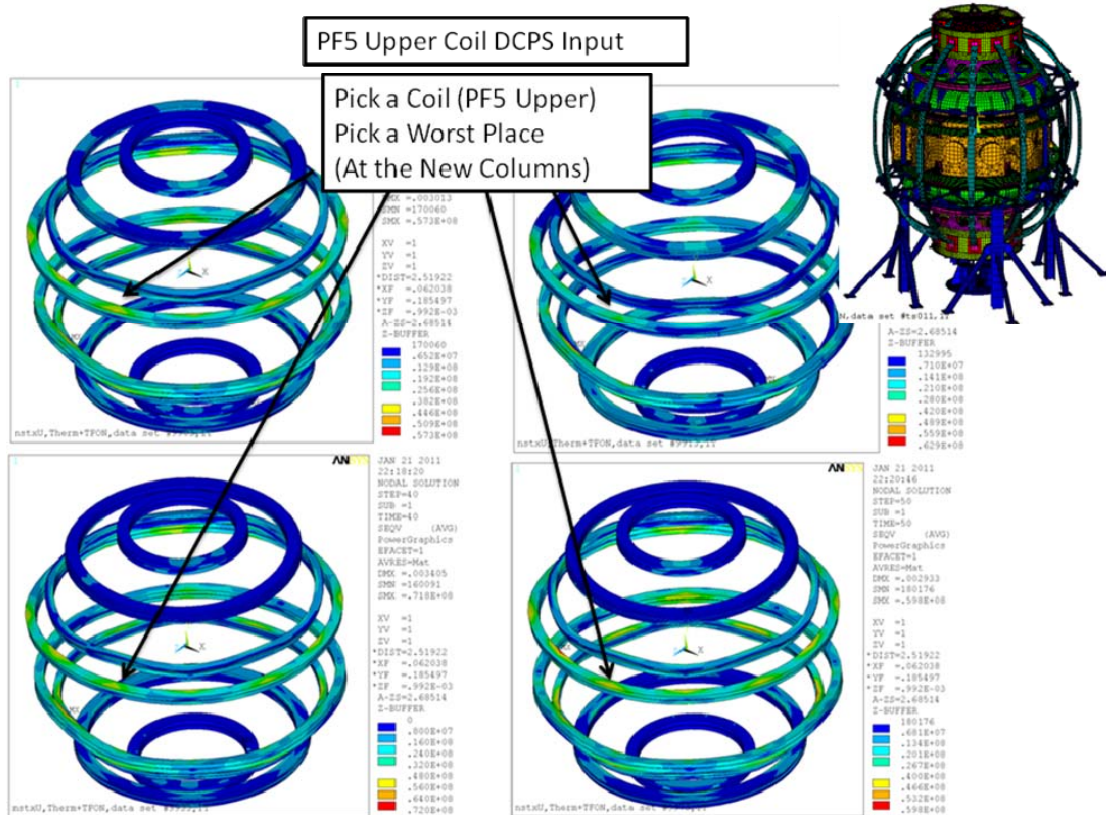
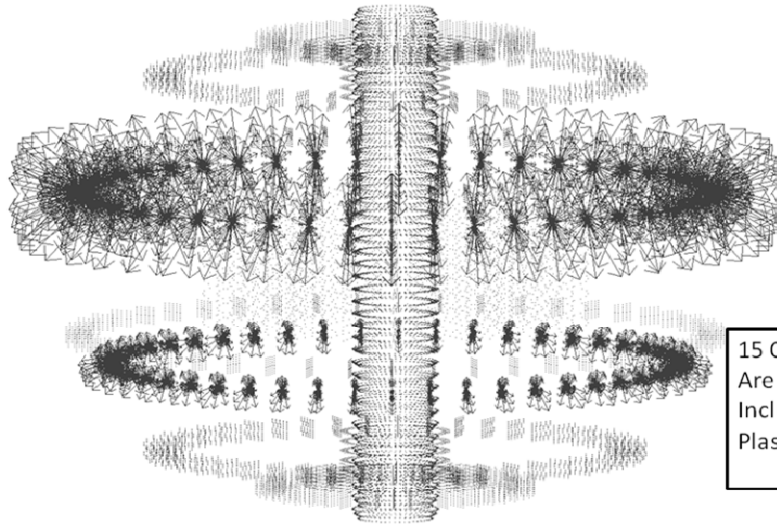


Figure 9.1-1 Finding a Worst Case Location For Which to Calculate Coefficients



Forces on PF5 (and 4) due to Unit Terminal  
Currents (actually 1000A) in PF 4 and 5



15 Other Sets of Loads  
Are Calculated,  
Including one for the  
Plasma

Figure 9.1-2 Unit Current Biot Savart Load Calculation

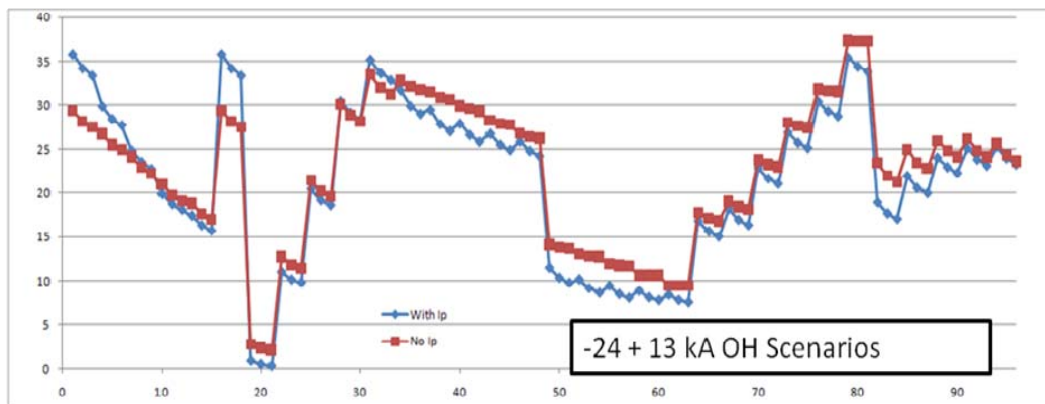
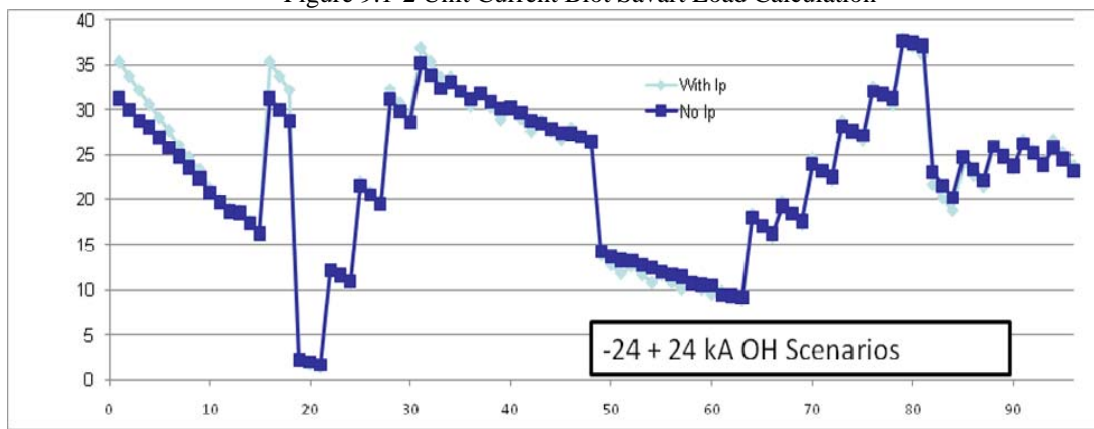
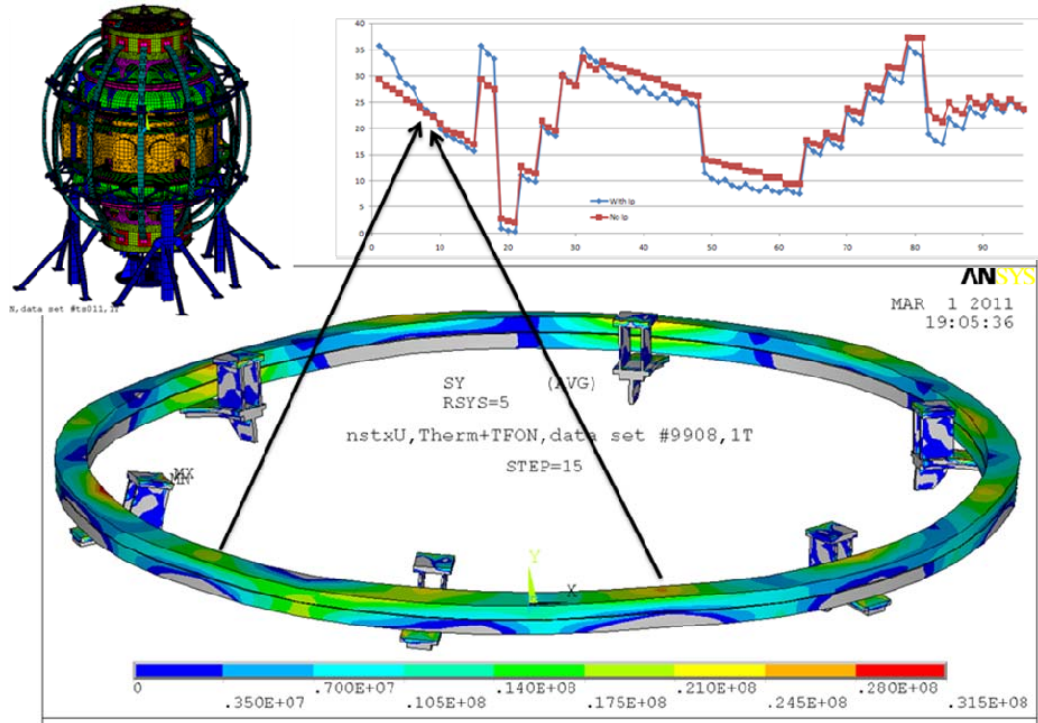
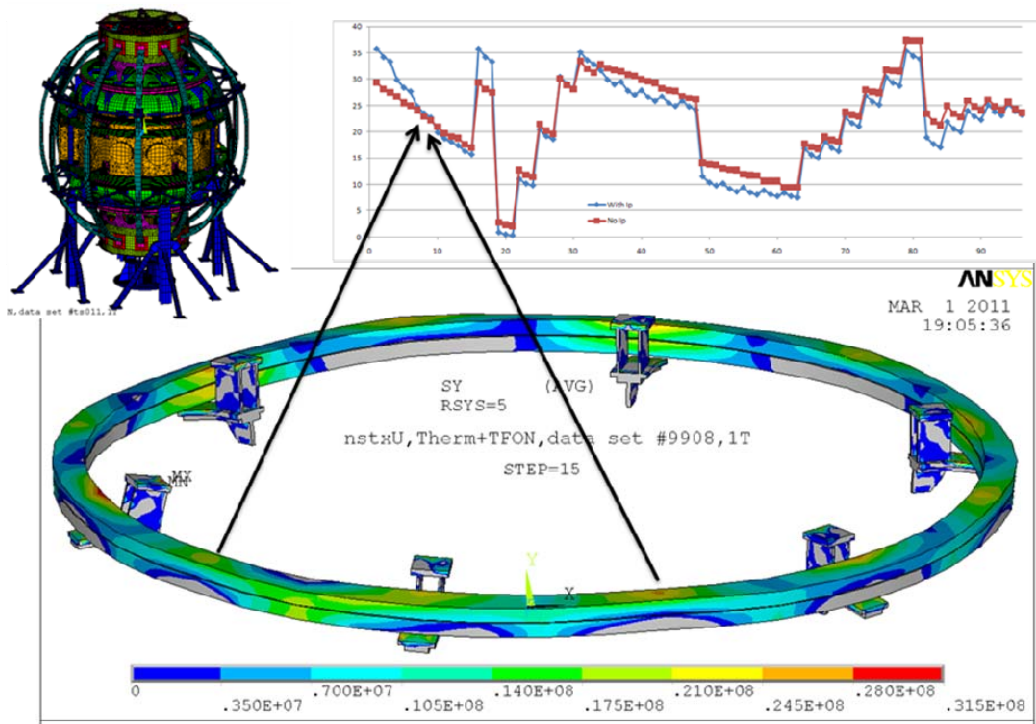


Figure 9.1-3 Application of Stress Coefficients to the Old Scenario



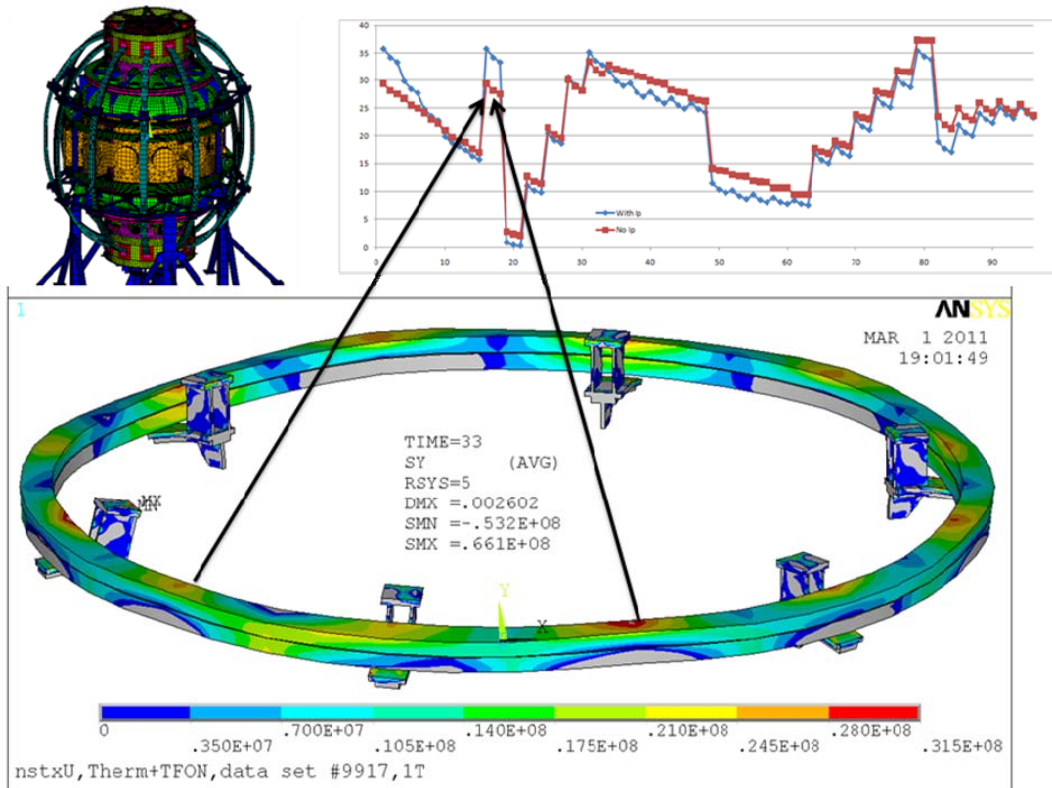
Check Influence Coefficients Against Global Model

Figure 9.1-4 Comparison with Global Model Results



Check Influence Coefficients Against Global Model

Figure 9.1-5 Another Comparison with Global Model Results



### Check Influence Coefficients Against Global Model

Figure 9.1-6 Another Comparison with Global Model Results

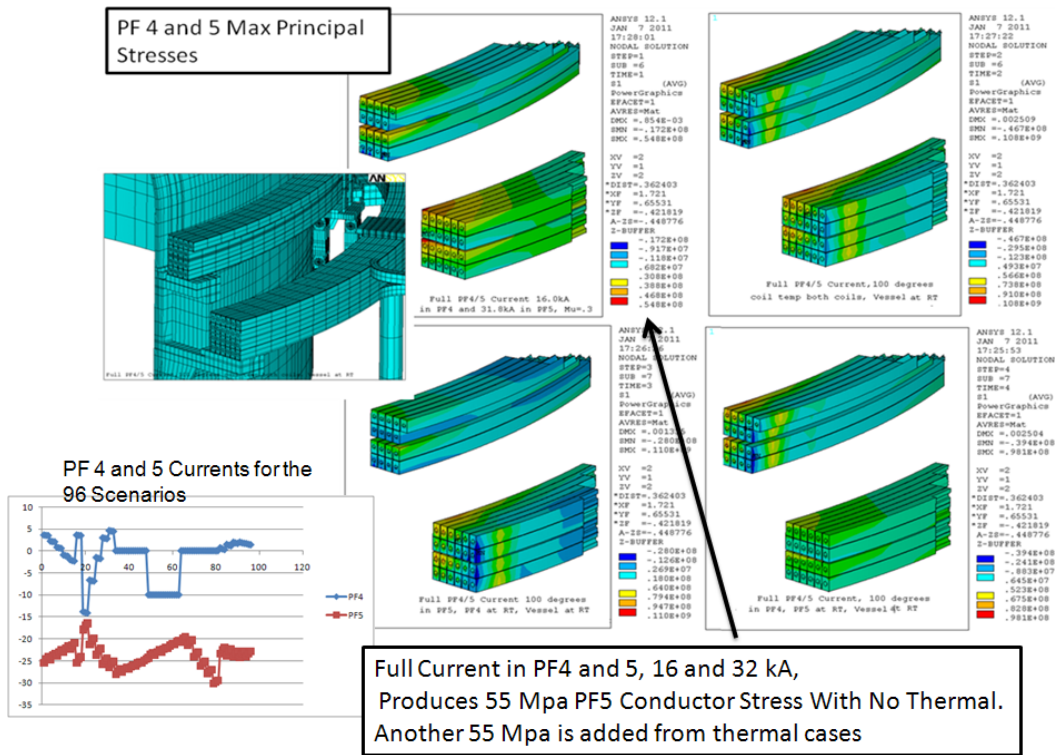


Figure 9.1-7 Compare Results from Influence Coefficients to the Detailed Local Model of the Coils

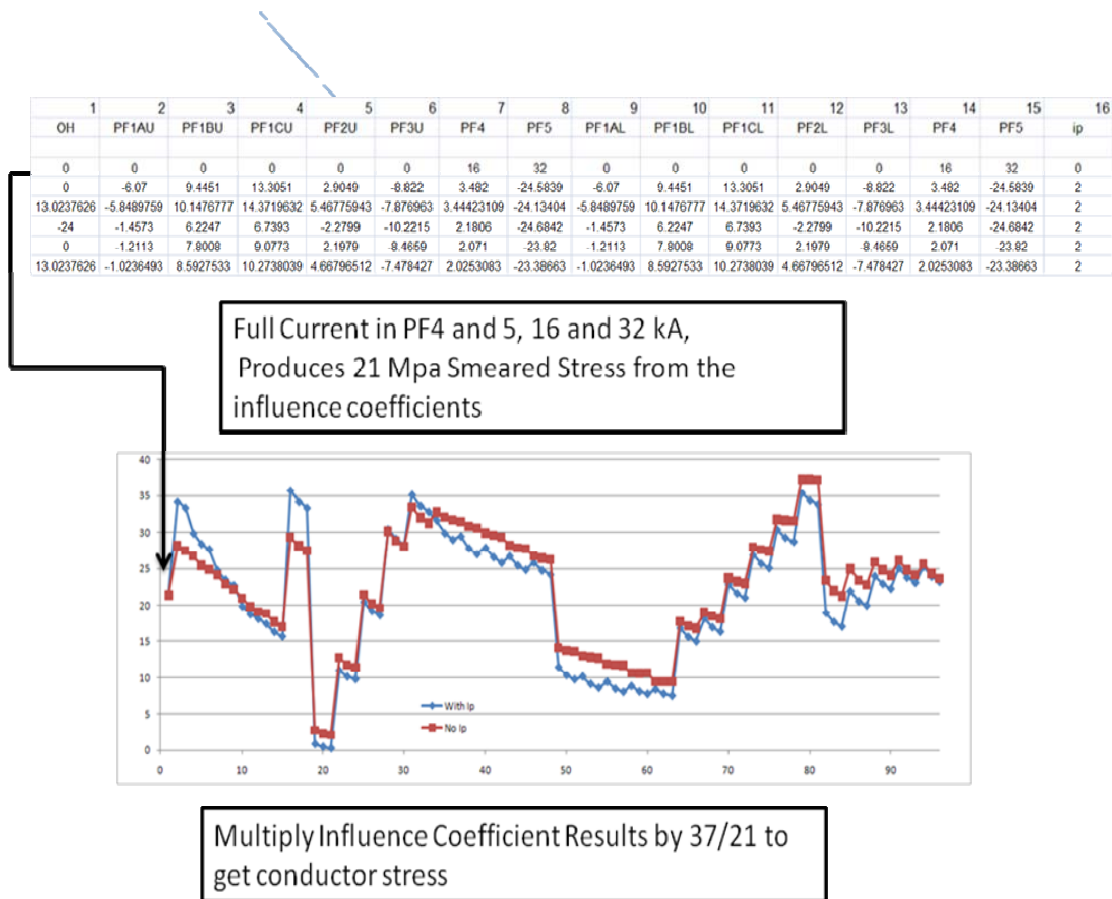


Figure 9.1-8 Using a Scenario/Current Set Consistent with the Local Model, Calculate a Stress Multiplier for the Conductor Stress

The procedure for calculating the peak hoop directed tension stress is to use the stress multipliers or influence coefficients multiplied by the coil currents, Multiply the result by 37/21 to account for the local conductor cross section multiplier, then add the 55 MPa thermal stress components. The peak stress in the plots of all scenarios is 38 MPa and the peak stress is then :

$$= 38 \times (37/21) + 55 = 122 \text{ MPa}$$

This is a tension stress representative of the principal stress which needs to be compared with a fatigue allowable (see Section 11).

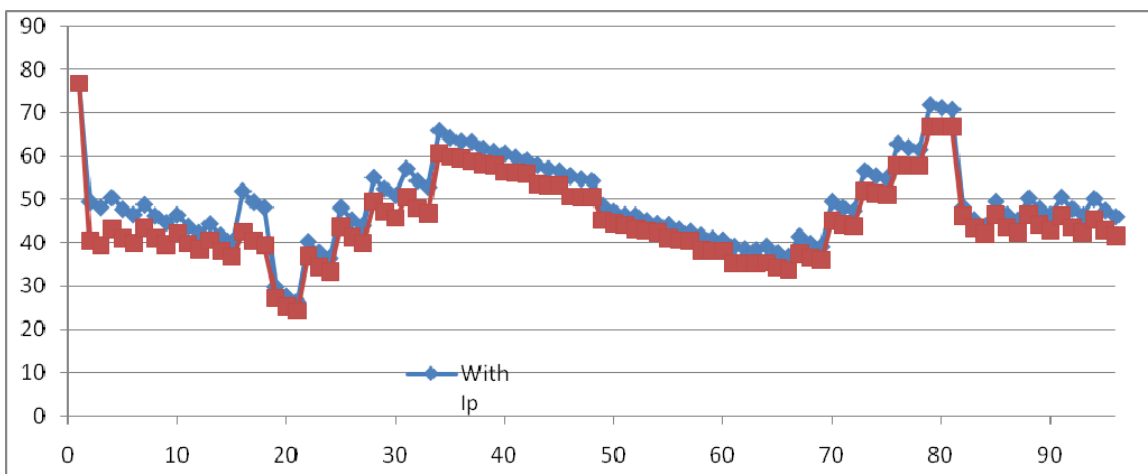
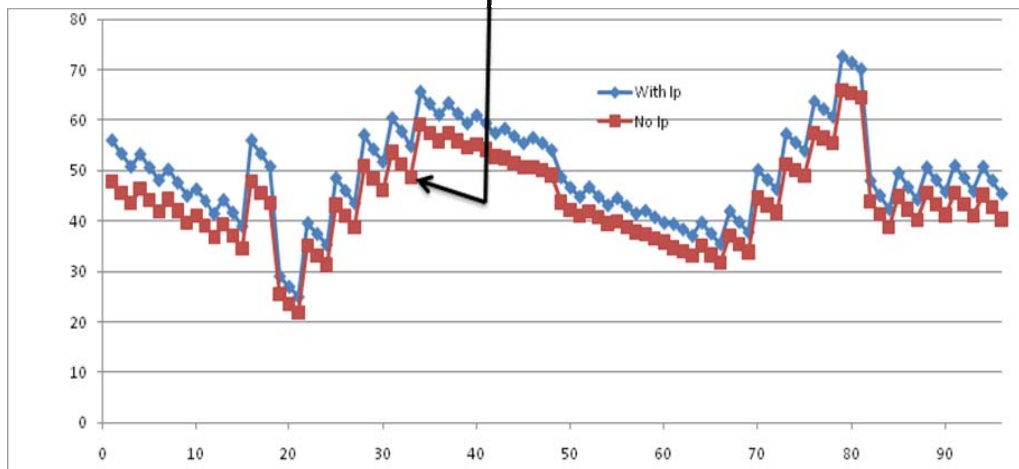
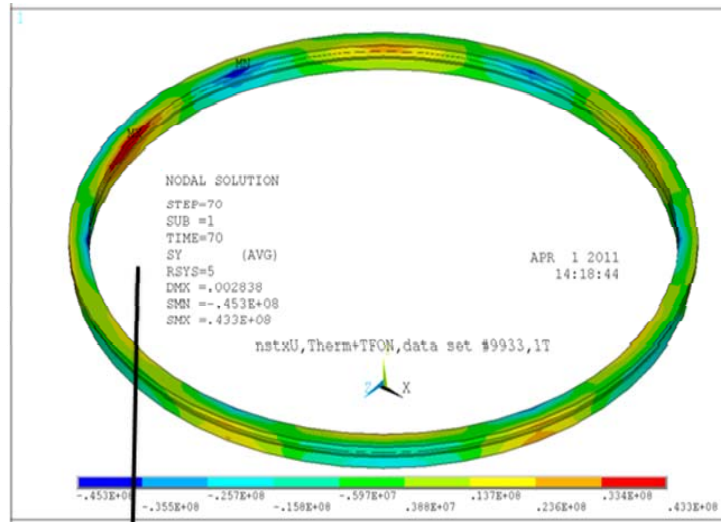
## 9.2 PF4 Coil Stress DCPS Input

The procedure outlined above is applied to PF4 in this next section.



# PF4 Check of Influence Coefficient Calculation vs. Global Model

Old +/-24 kA  
Scenario

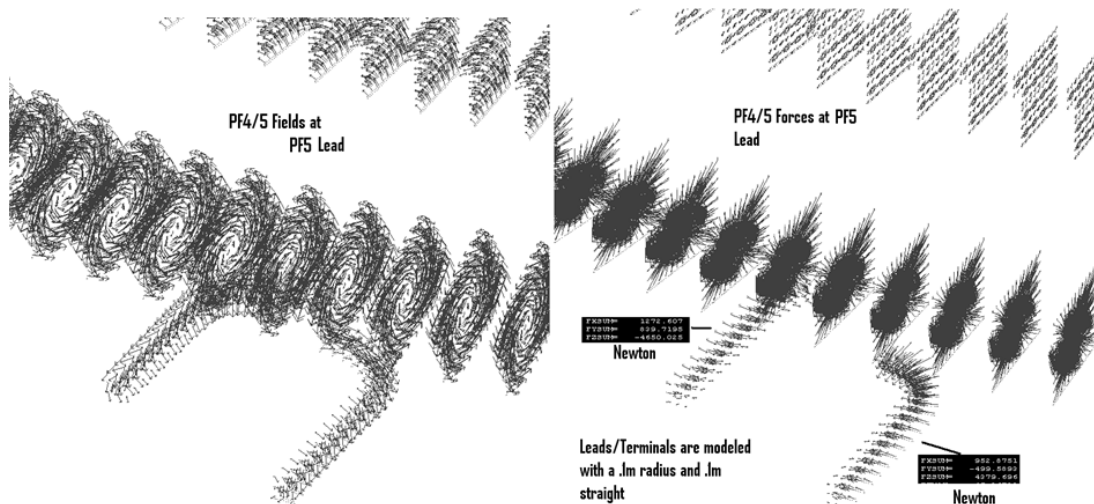


## 9.3 Existing Support Weld Stress Multipliers

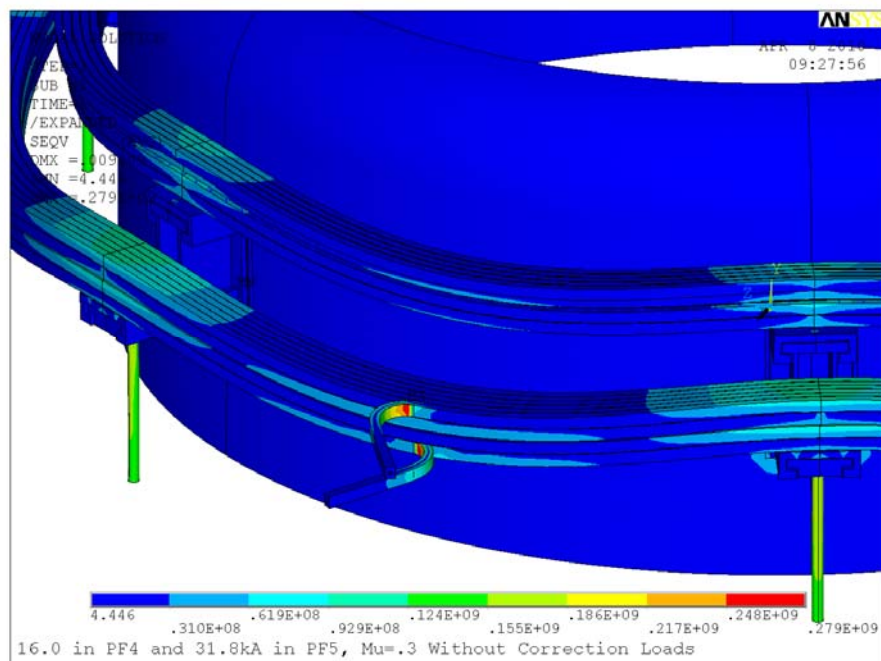
This section derives (from Reference 9) an analysis of coefficients to relate PF4 and 5 loads to the weld stress of the bracket pad. This is pertinent to the upgrade because it was used for a protection system that was implemented in 2010 in NSTX. This same approach can be translated to the DCPS requirements.

## 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.



Cantilevered, un-supported leads produced excessive bending stresses due the Lorentz Loads caused by the local coil fields. The unsupported lead stresses are shown below.



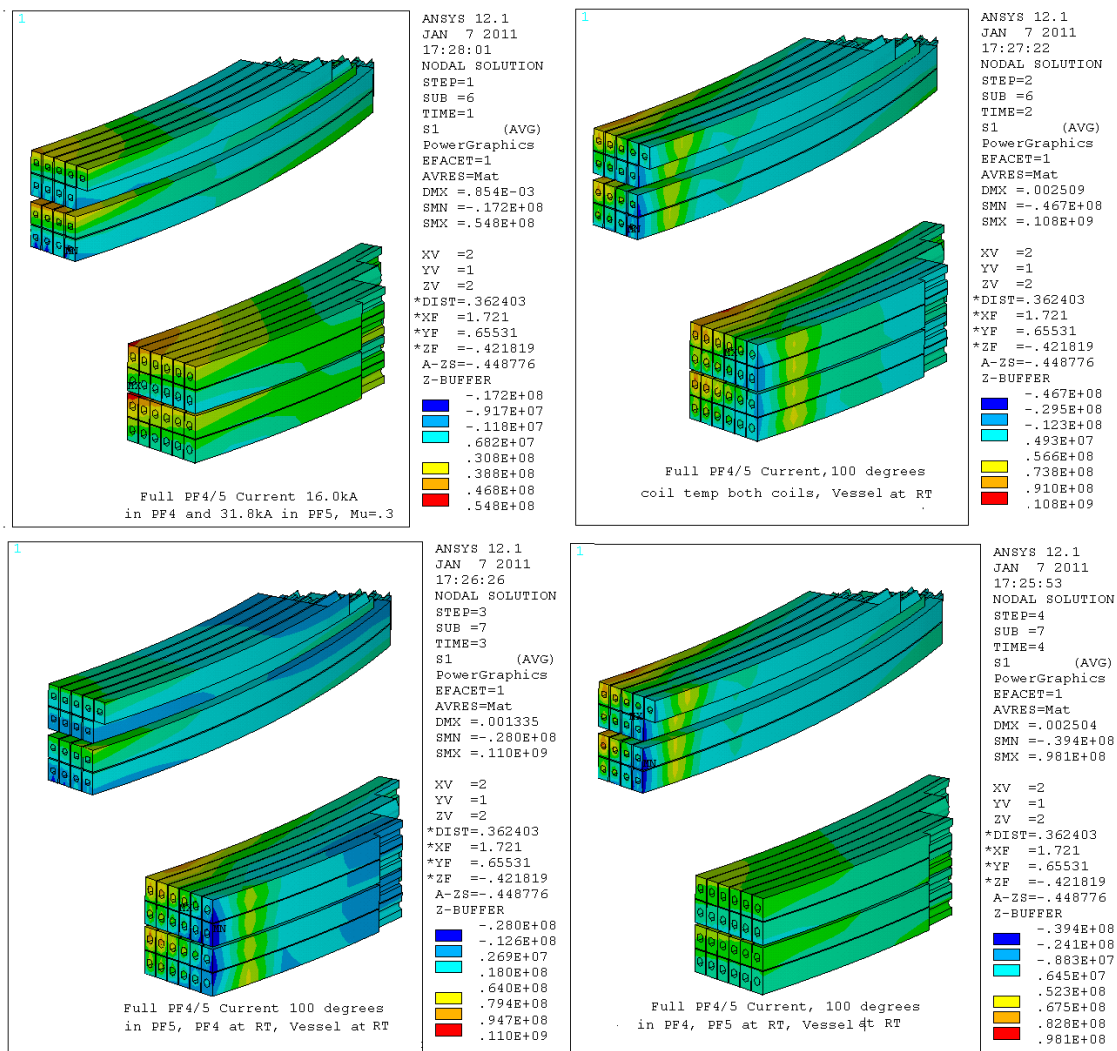
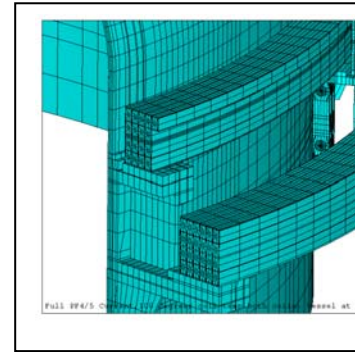
The bending stress would be relieved by taking credit for the connection to the bus bars on the unistrut at the support platform. This was modeled by displacement constraints. These would produce stresses if the coils move relative to the bus bar support. The PF4/5 support concept imposes fixity at two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



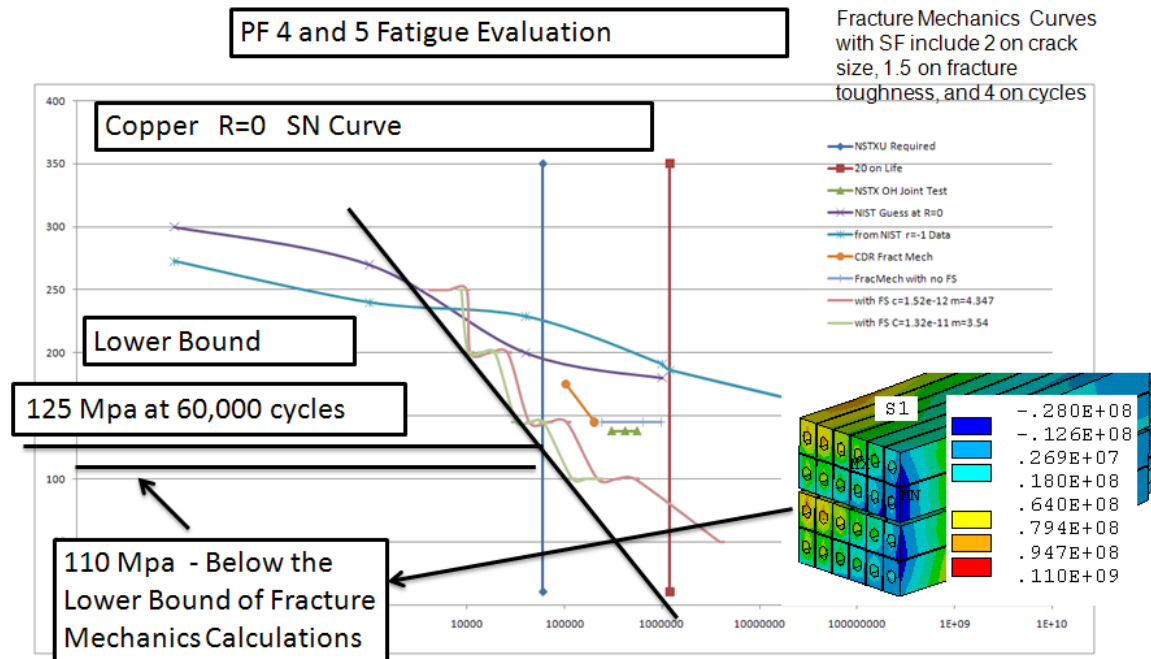
degrees apart. Choosing one fixed point near the lead break-out will limit the differential displacement stress in the leads.

## 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.



From Section 9, the peak Max Principal Stress in PF5 for all scenarios is  $= 38 \cdot (37/21) + 55 = 122$  MPa.



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 122 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.

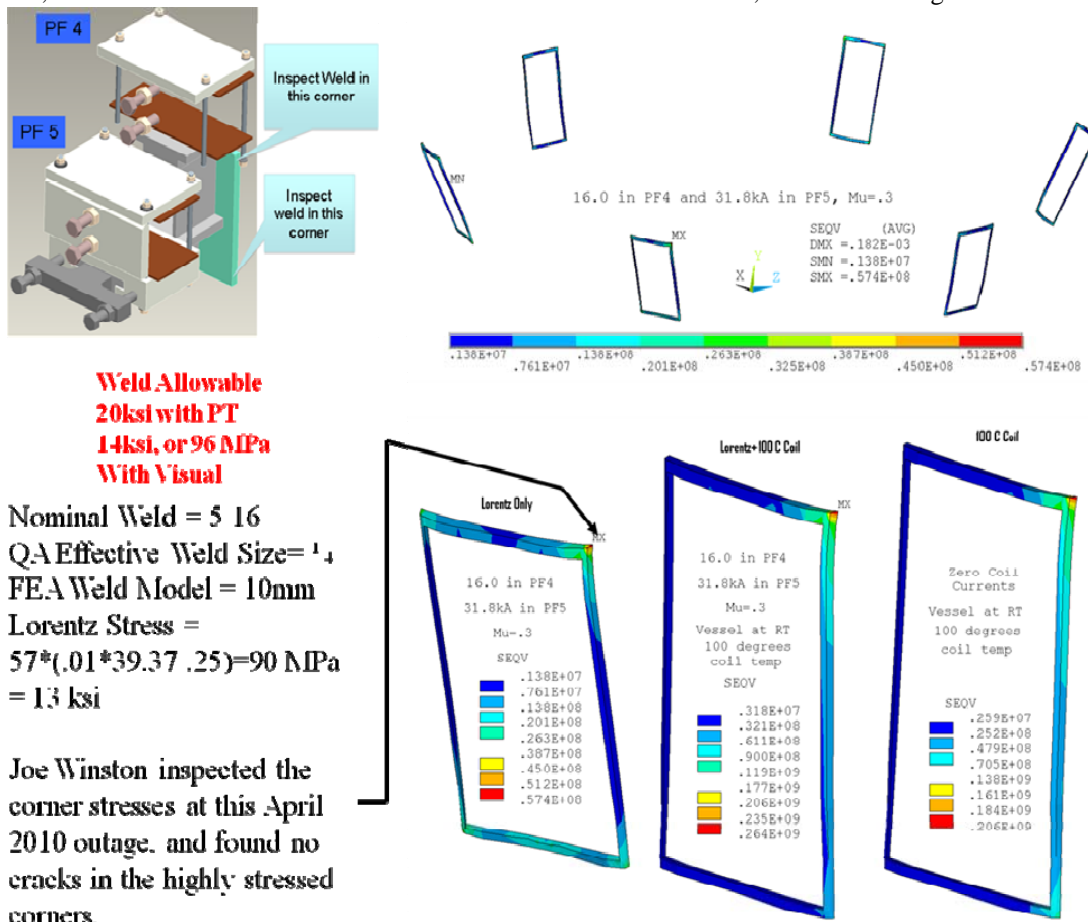
It should be emphasized that this evaluation conservatively assumed that all 60,000 pulses utilize the scenario that produces the worst case stress, and that this stress occurred when the thermal stresses are at a peak.

## 12.0 Brackets, Hardware and Bracket-to-Vessel Welds

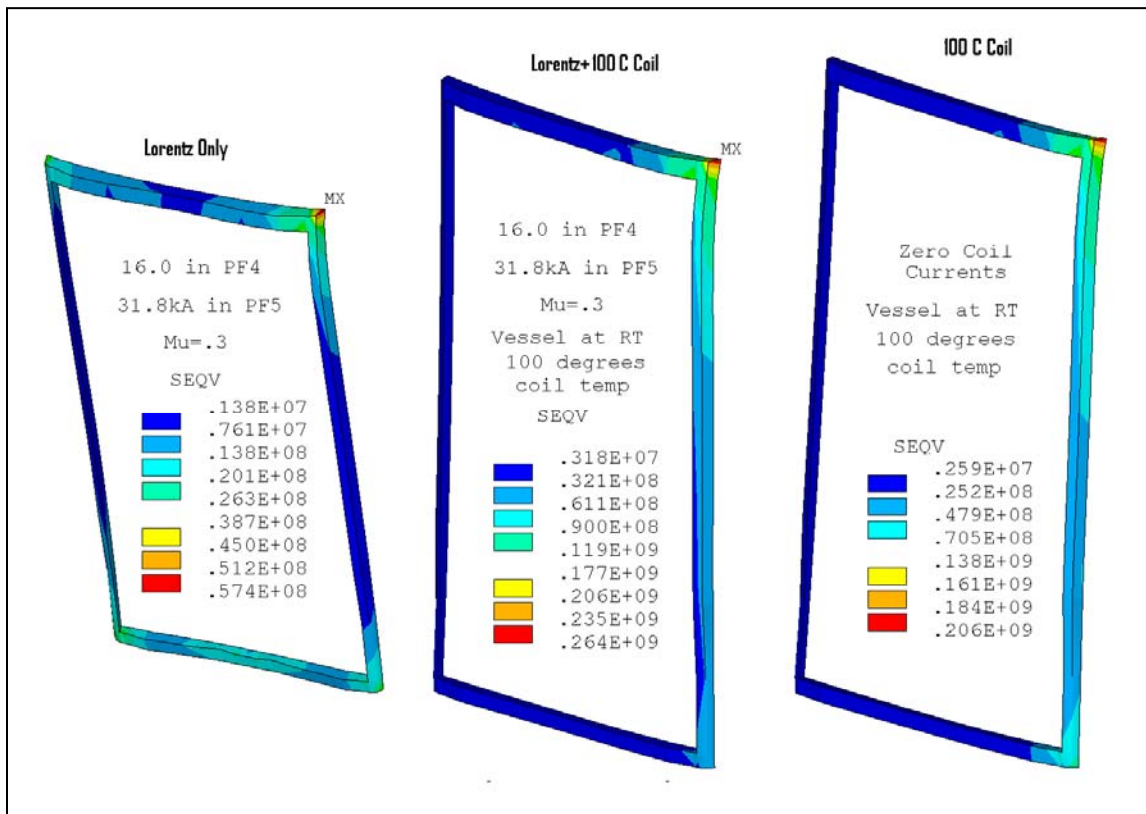
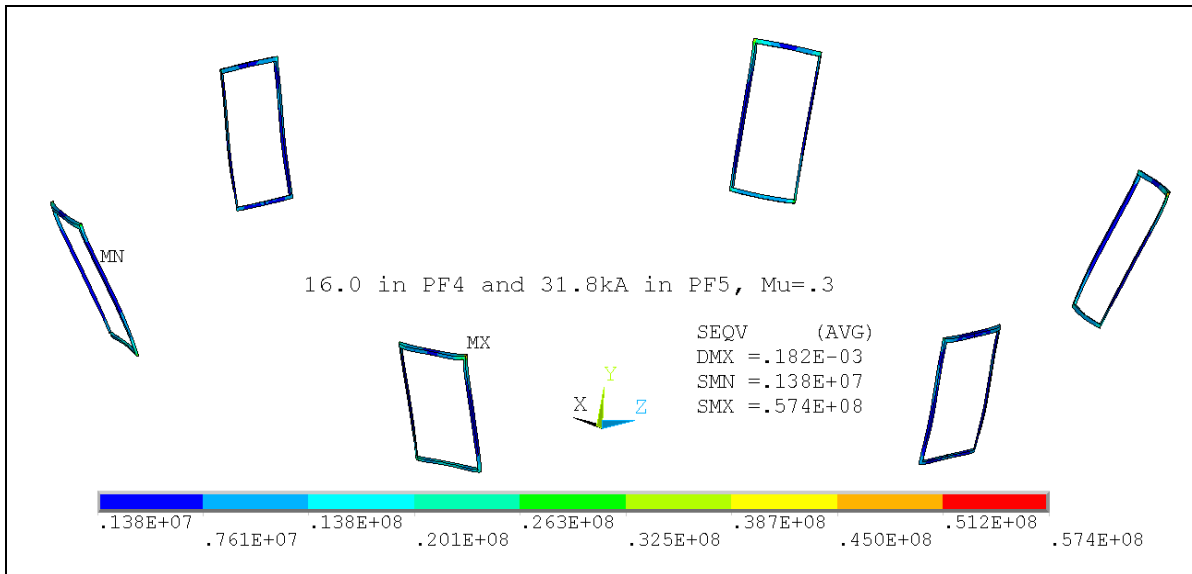
### 12.1 Existing Bracket to Vessel Welds

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 1/4 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.



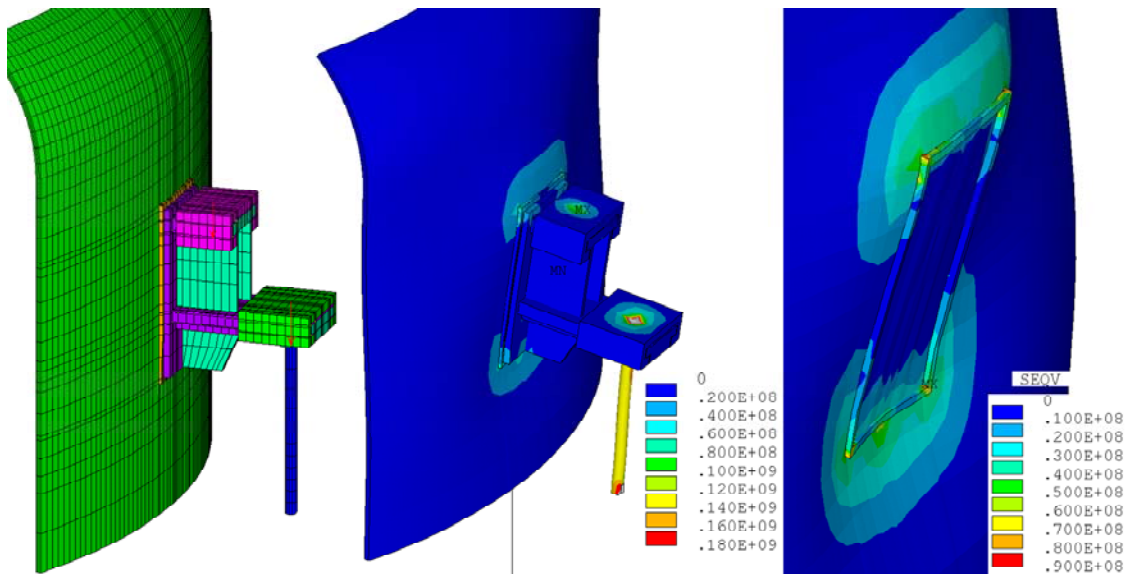
The weld is assumed to have a larger cross section than a fillet, so the .707 factor was not applied. Weld allowable is a function of the level of inspection that is applied. At PPPL, only visual inspection is routine. ASME would require a weld efficiency of 0.7 or lower.



/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  
 $\text{Weld Stress} = 90 * (.01 * 39.37) / .25$   
 $= 142 \text{ MPa} = 30555 \text{ psi}$

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



In-Plane PF4 and 5U Loads With Strut

## 12.2 Bracket Welds for Upgrade Loads

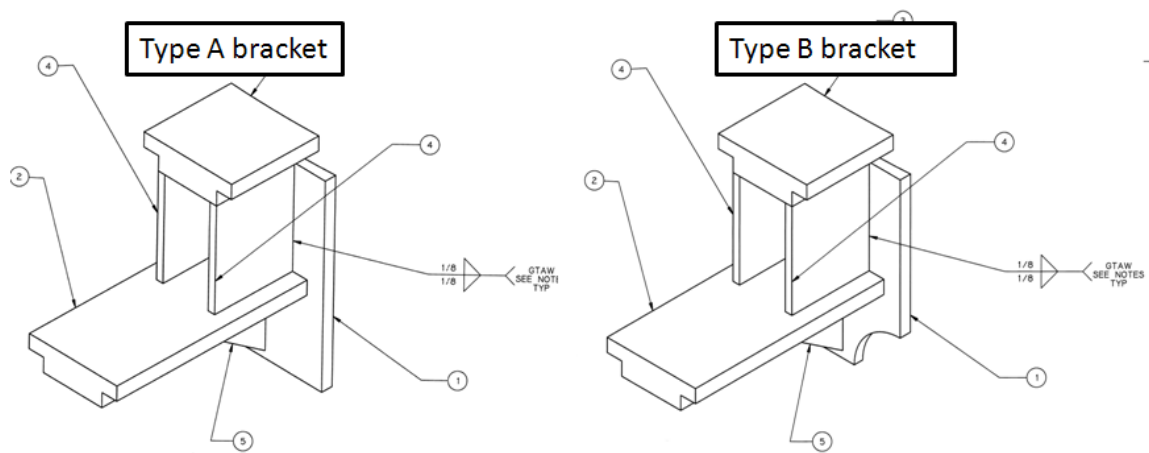


Figure 12.2-1 Bracket Types and Weld Specifications

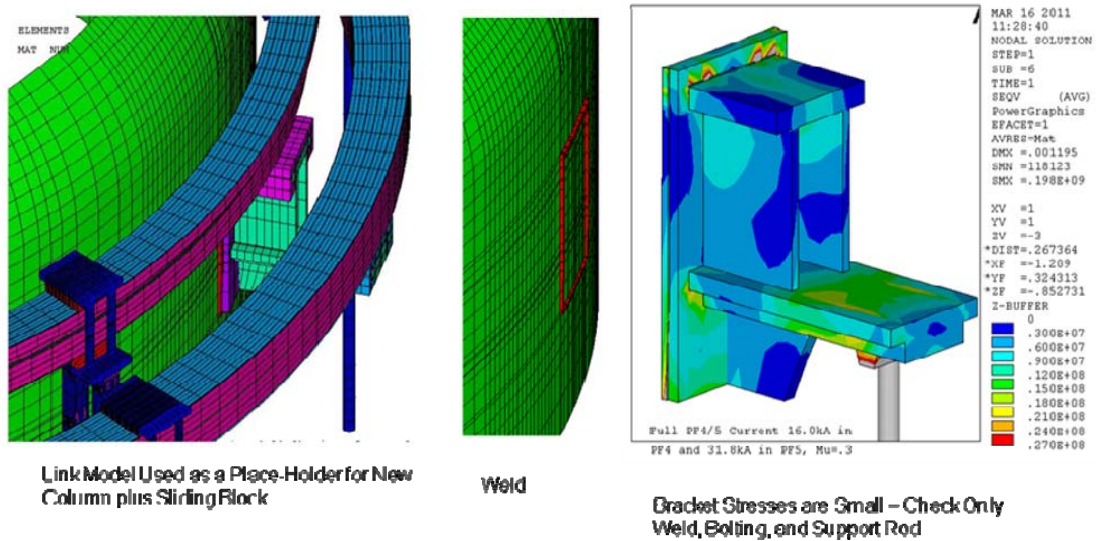


Figure 12.2-2 Analysis Model Weld Details



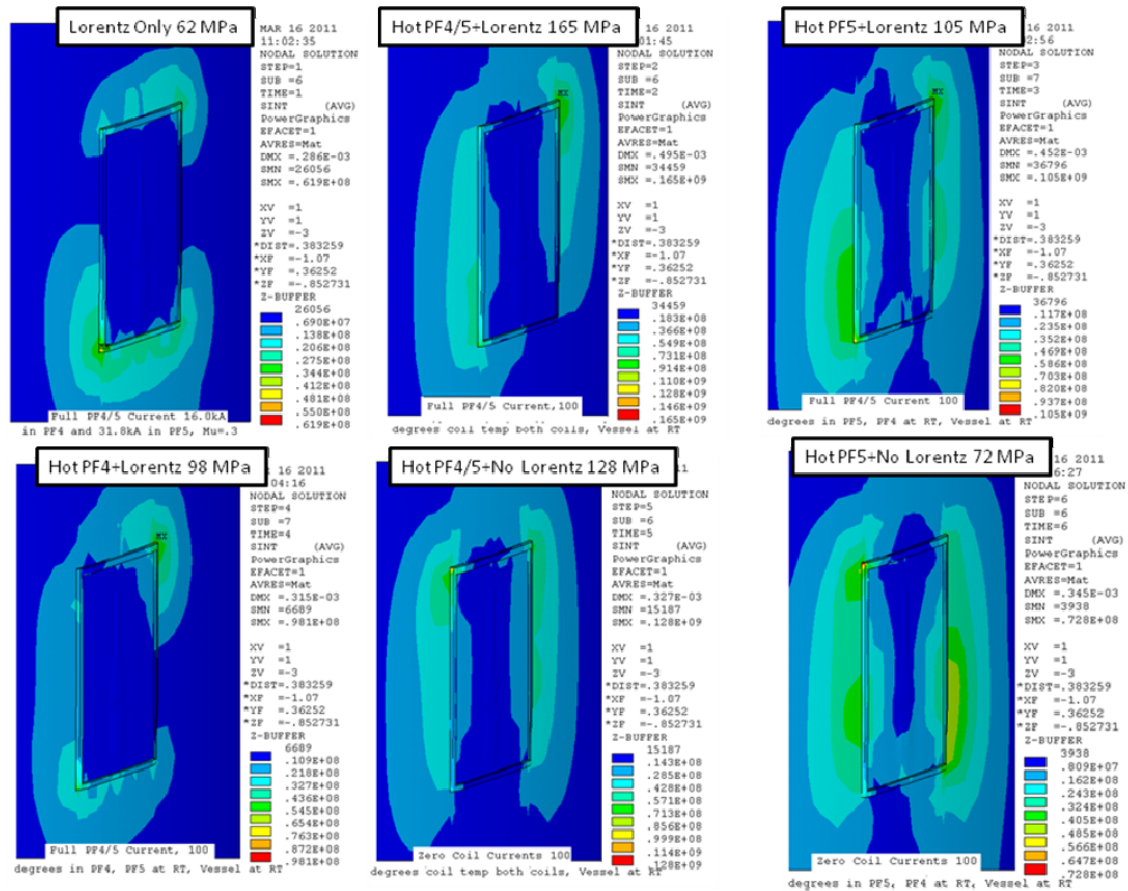
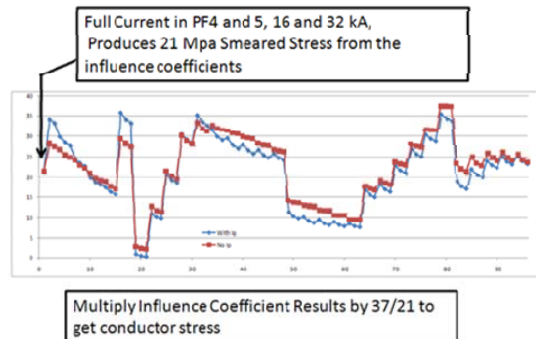


Figure 12.2-3 Weld Stresses from the Local Model of the Bracket  
Weld Stresses Scaled From Coil Hoop Direction Stress Influence Coefficient

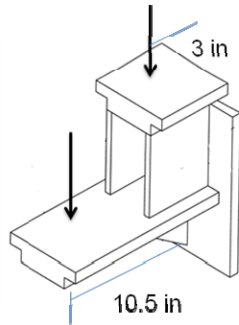
#### FEA Weld Multiplier

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



	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		Weld Allowable based on Visual Plus Penetant weld inspection			
14ksi		20ksi			

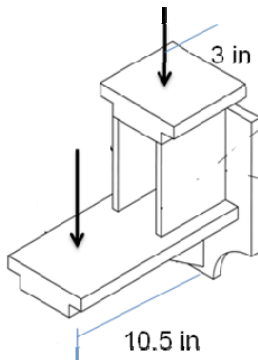
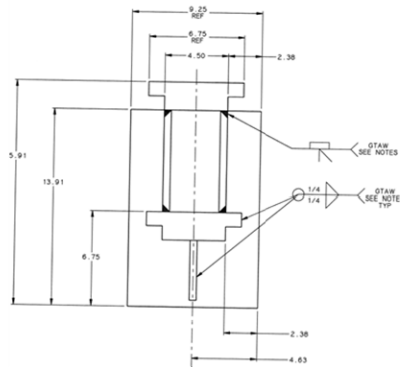
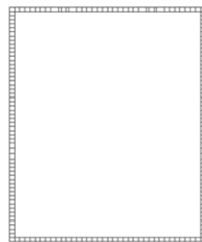
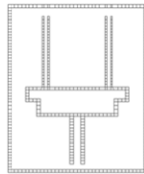
Figure 12.2-4 Weld Stresses Scaled from the Local Model and Influence Coefficients



Type A bracket

```

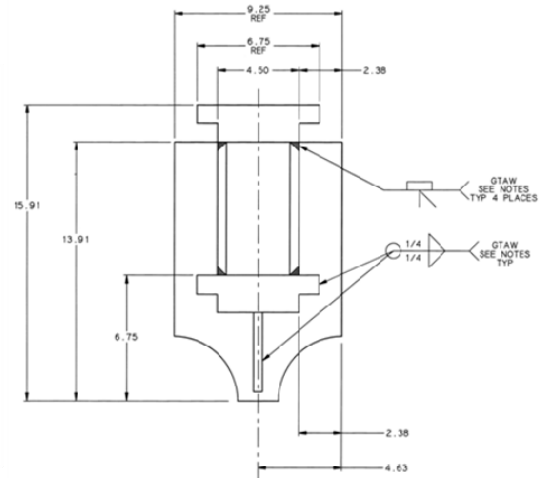
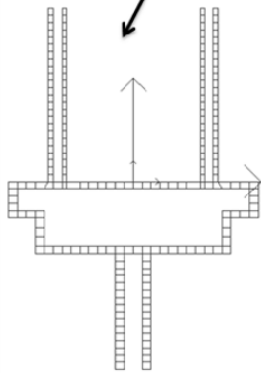
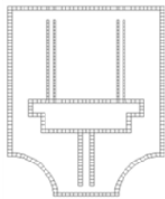
Section Properties for Group Number: 0
AREA= 11.62500 INX = 182.8204 IYY = 341.2735
MAX DISTANCE TO EXTREME FIBER, CX= 4.750000 CY= 7.125000
RINX= 182.8204 SINX= 39.48051 RAD OF GYR= 3.965663
RINY= 341.0918 SINY= 47.87254 RAD OF GYR= 5.416755
PRODUCT OF INERTIA ABOUT ORIGIN=RIXYT= 0.0000000E+00
PRODUCT OF INERTIA ABOUT NEUTRAL AXIS=IXY= 0.0000000E+00
ROTATION ANGLE TO PRINCIPAL MOMENTS OF INERTIA = 0.0000000E+00
COORDINATES OF THE CENTROID, XBAR= 0.0000000E+00 YBAR= -0.1250000
  
```

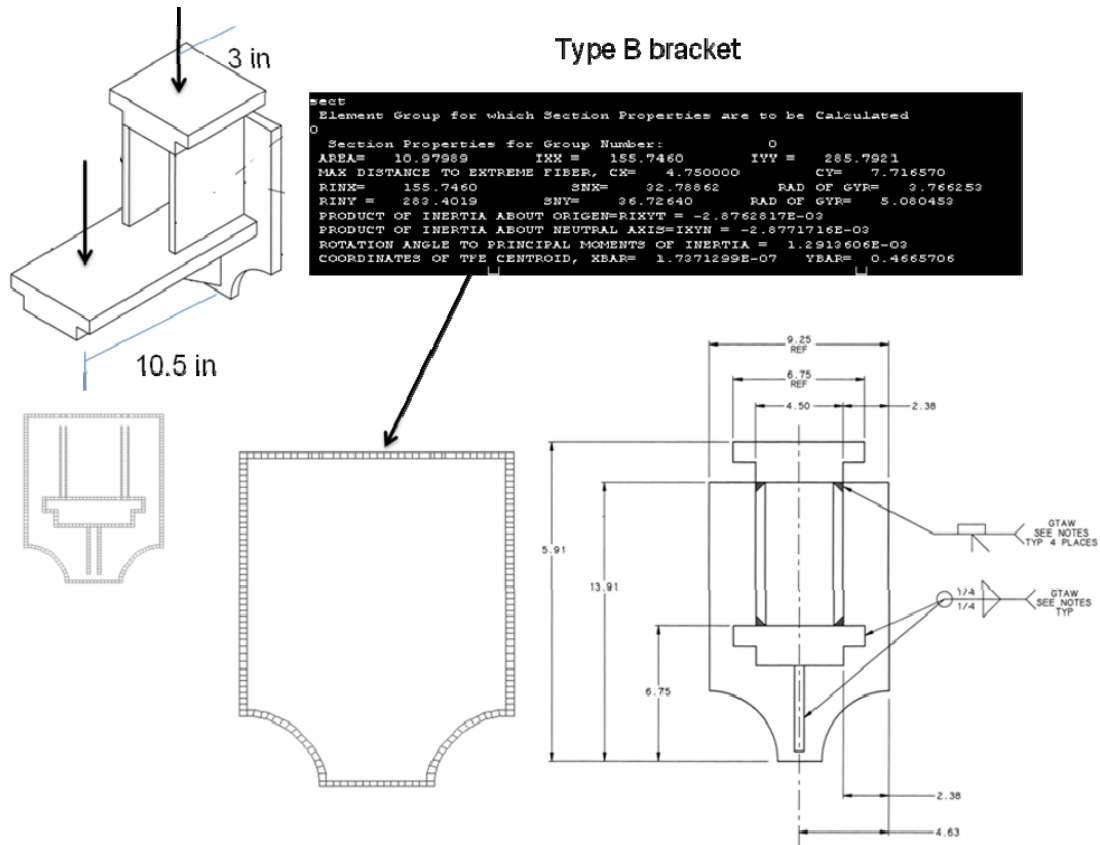


Type B bracket

```

Section Properties for Group Number: 4
AREA= 9.500000 INX = 36.82293 IYY = 89.32858
MAX DISTANCE TO EXTREME FIBER, CX= 3.500000 CY= 6.542763
RINX= 36.82293 SINX= 10.52084 RAD OF GYR= 1.968781
RINY= 89.32858 SINY= 13.22682 RAD OF GYR= 3.018190
PRODUCT OF INERTIA ABOUT ORIGIN=RIXYT= -5.7220459E-06
PRODUCT OF INERTIA ABOUT NEUTRAL AXIS=IXY= -5.4622264E-06
ROTATION ANGLE TO PRINCIPAL MOMENTS OF INERTIA = 6.2960294E-06
COORDINATES OF THE CENTROID, XBAR= 5.0192285E-08 YBAR= -0.5427632
  
```





## Weld Stresses Calculated From Weld Section Properties

	Worst Net PF4,5,U,L	Moment Sum for 6 Supports (12 U&L), 10.5" Lever	Section Modulus (in <sup>3</sup> )	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

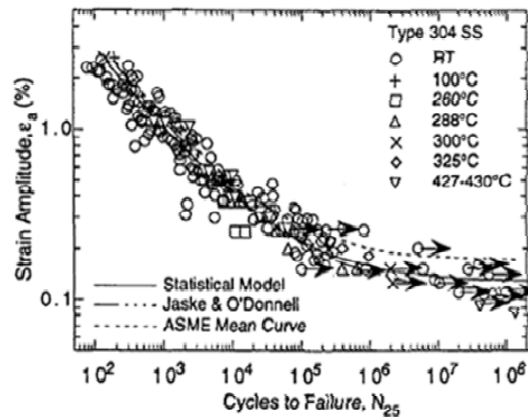
From Charlie's Design Point Spreadsheet	Fz(lbf)	(PF4U+PF5U)+(PF4L+PF5L)	Conservatively uses PF5 moment arm and .707 factor on 1/4 in weld
	Min w/ o Plasma	-81947	
	Min w/ Plasma	-81953	
	Min Post-Disrupt	-58992	
	Min	-81953	
	Worst Case Min	-513255	
	Max w/ o Plasma	0	
	Max w/ Plasma	17	
	Max Post-Disrupt	15	
	Max	17	
	Worst Case Max	513255	

## 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 from 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

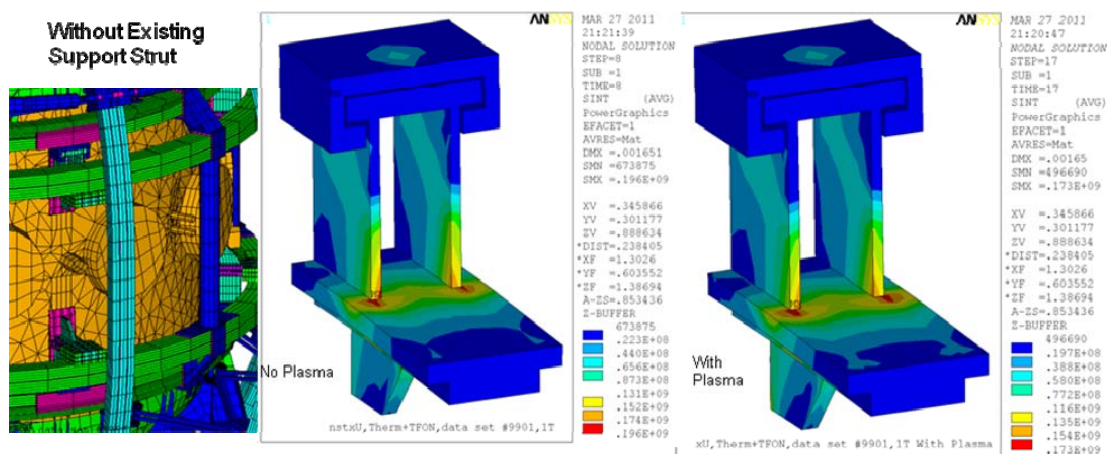
"Estimation of Fatigue Strain-Life Curves for Austenitic In Light Water Reactor Environments Stainless Steels", Argonne Nat. Lab, 1998

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.

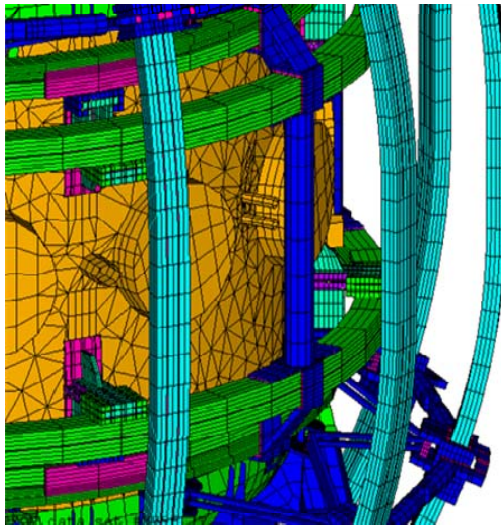
Without the strut, bending stress concentrates at the corners of the gusset plate weld. The global Model [2]



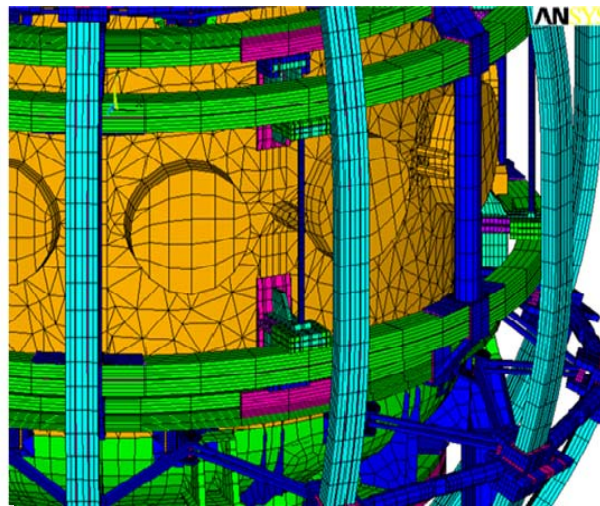
was run with and without the support strut.



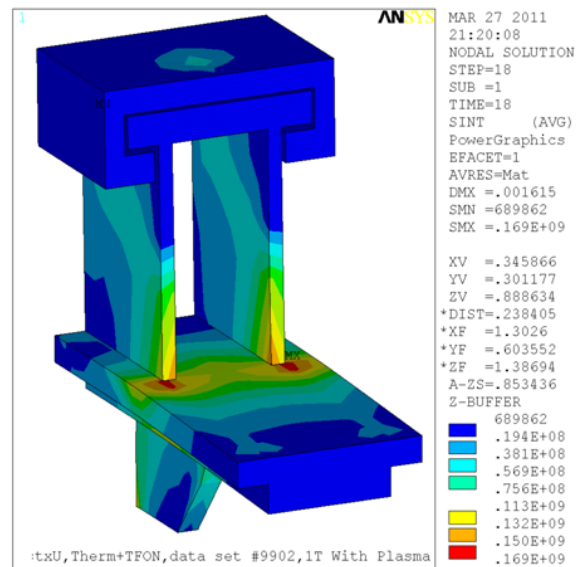
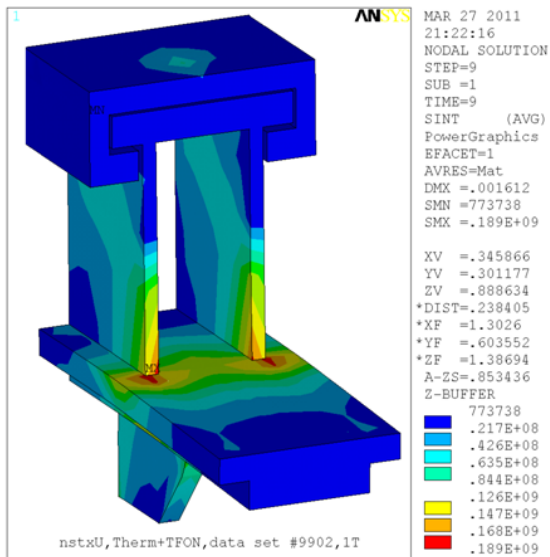
Without Existing Support Strut, Run#27

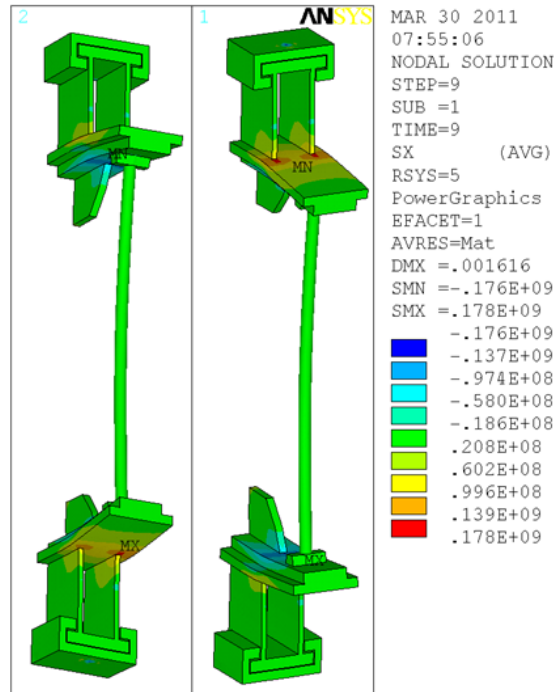
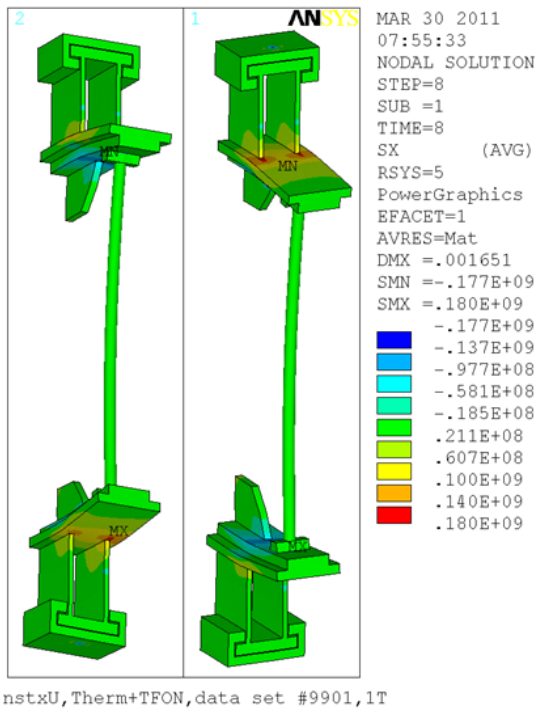
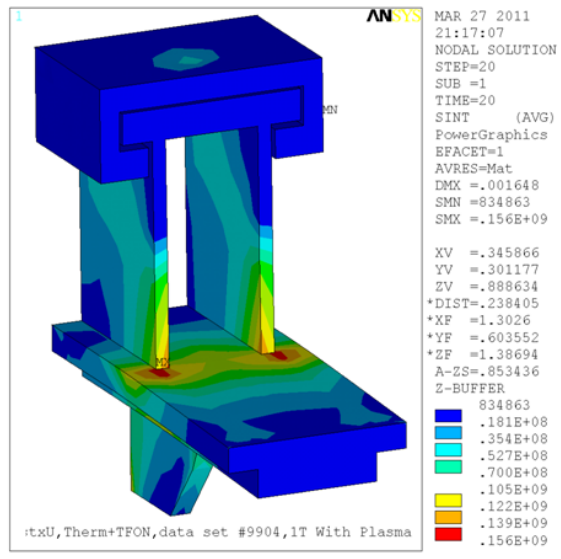
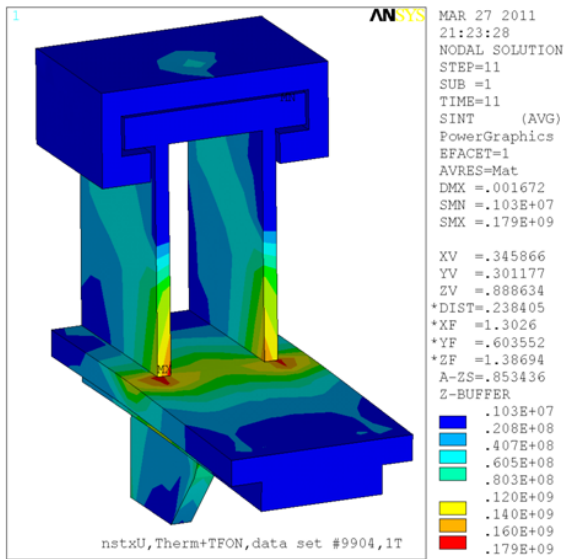


With Existing Support Strut, Run#28



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.





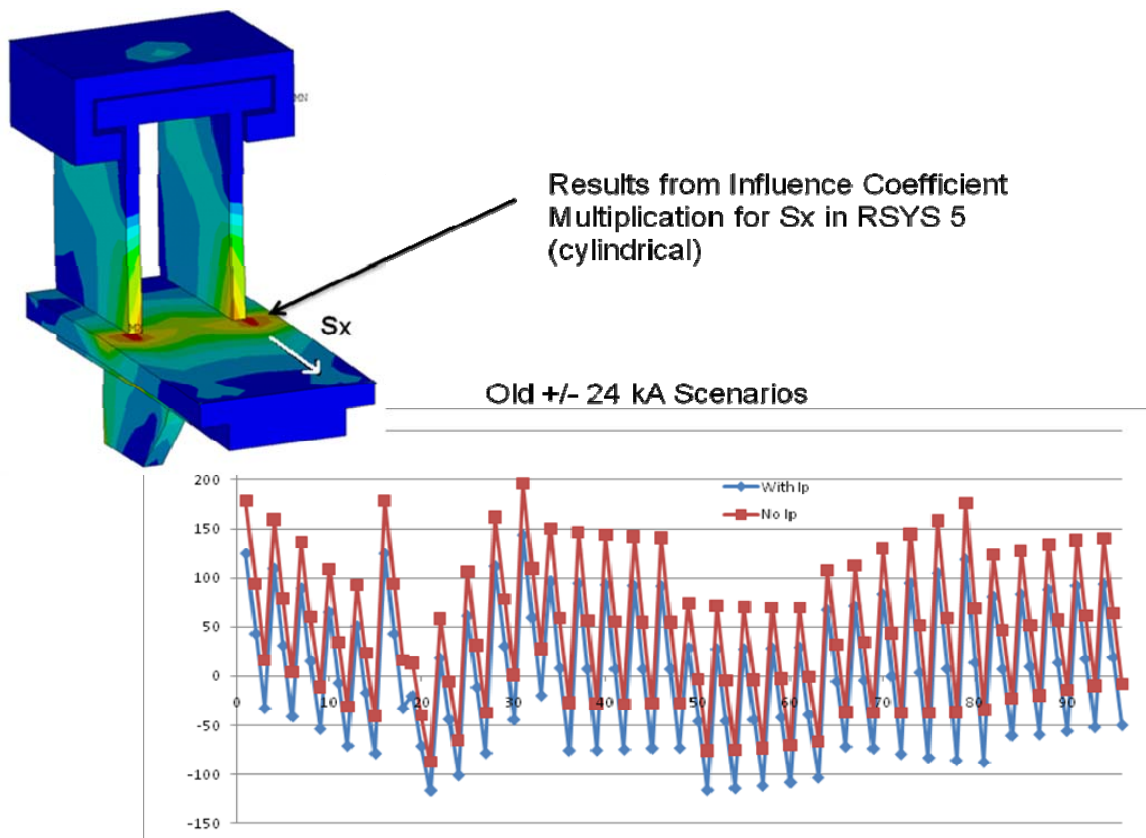
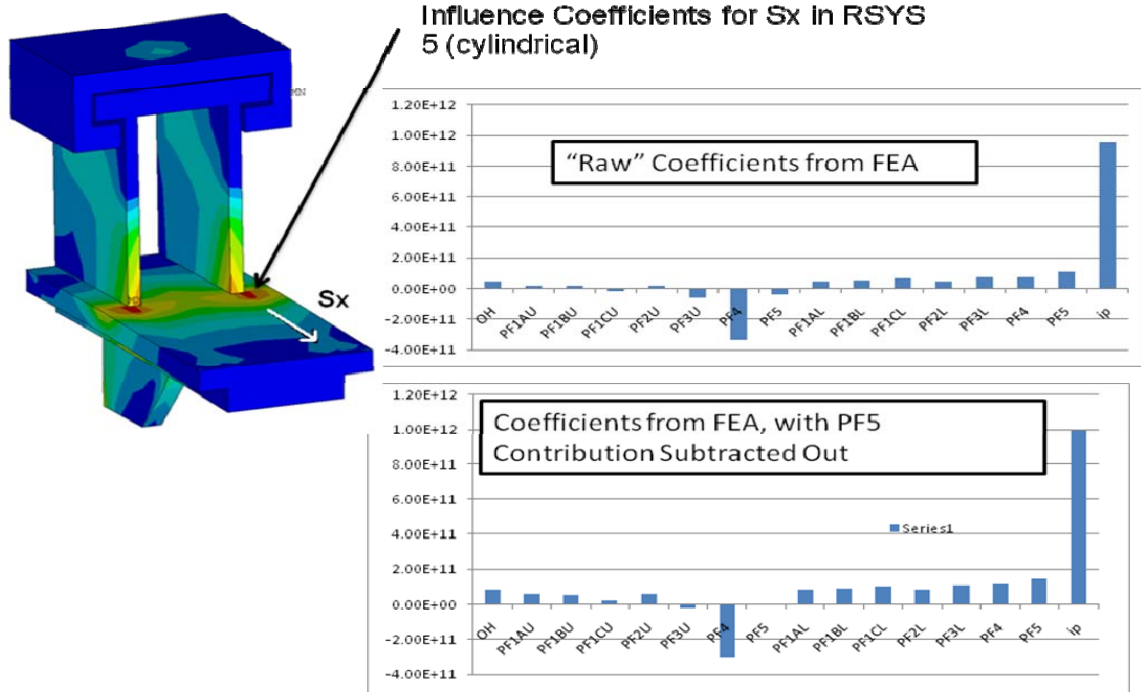
It is evident from this plot that the small diameter column does little to resist the cantilever bending of the PF5 support plate. A stiffer section is needed. A heavier column was added in May, 2011 and a model including this has been run and reduces the bending stress on the cantilever section substantially.

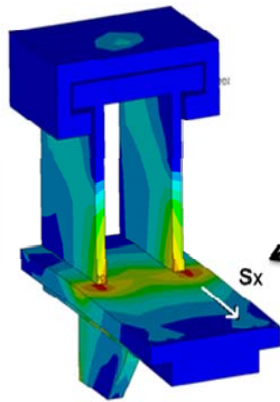
## Bracket Stress by Influence Coefficients

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



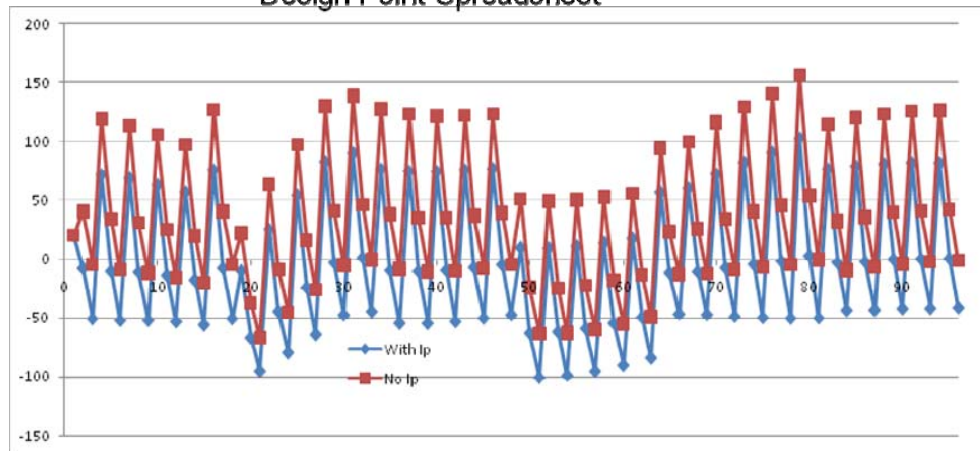
section is not included in the DCPS for this reason, but it allows consideration of all 96 scenarios, with and without a plasma.





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

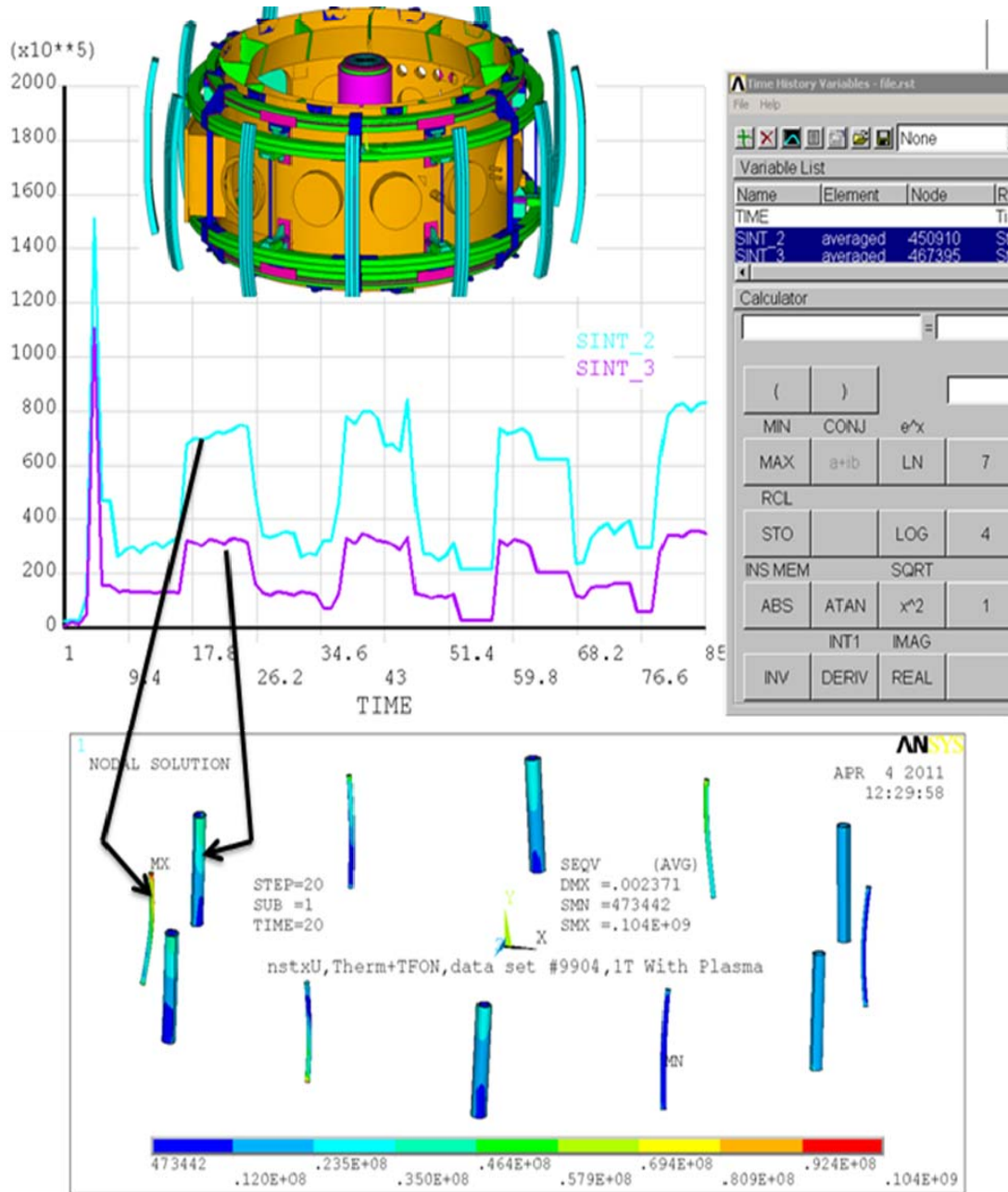
+13kA/- 24 kA Scenario from Latest ( as of March 2011)  
Design Point Spreadsheet

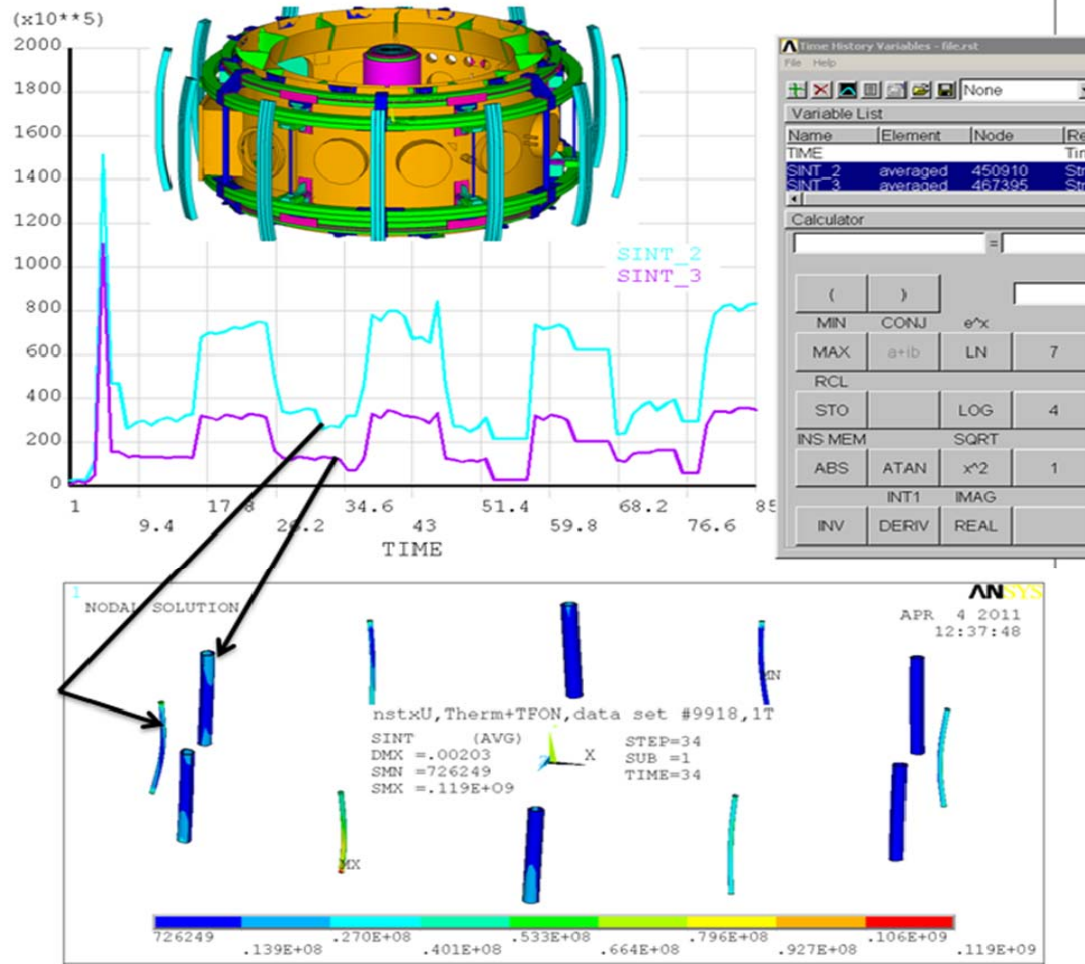


The peak stress in the plate near the weld toe is less than 150 MPa, which is within the static allowable for the bracket material, but is probably a concern with respect to weld fatigue. This is another reason why the existing column/rod should be stiffened.

## 12.4 Column Stresses from the Global Model

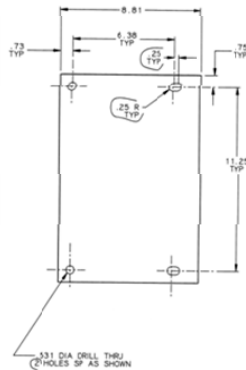
The global model [2] is available to provide column stresses in both the added column and the existing column. While the existing column/rod is not stiff enough to help the brackets welded to the vessel shell, the stresses in the columns and rods are small (less than 120 MPa in the rod and 30 MPa in the 3 inch pipe column). This stress level does not require any further evaluation or consideration in the DCPS.





## 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

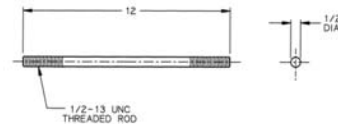
For loading that is up-down symmetric, that is the upper coils are being loaded upward and the lower loads are being loaded downward, then all 12 supports will resist the loads. Then there are four studs per clamp plate and 12 sets of clamp plates. The present FDR design used 3/4-inch bolts on the added 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		



④ PF 4 & PF 5 CLAMP TIE ROD  
96 REQD

ASTMA193 B8M Class 2

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

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.

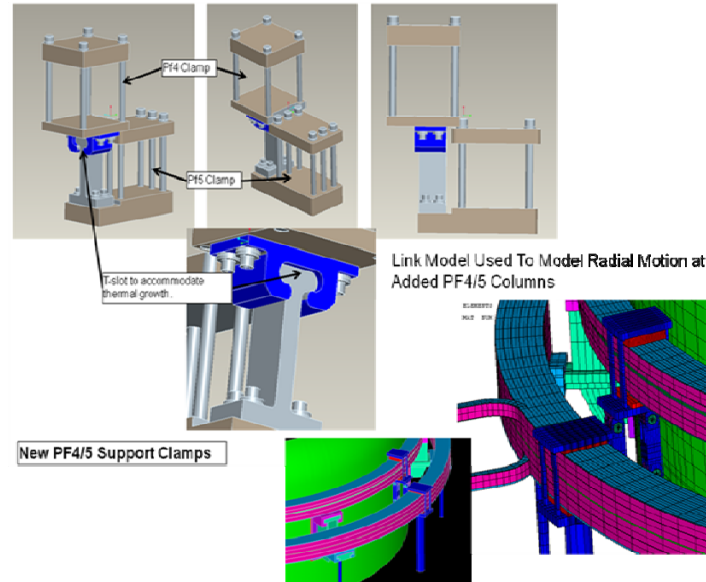


Figure 12.6-1 Dovetail or T slot sliding Block and Link Model Used to Simulate the Radial motion of the sliding block.

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 see about 4000 lbs (see table above). The T slot shown below will see the loads from four studs or 16000 lbs.



Added Column T Slot Joint

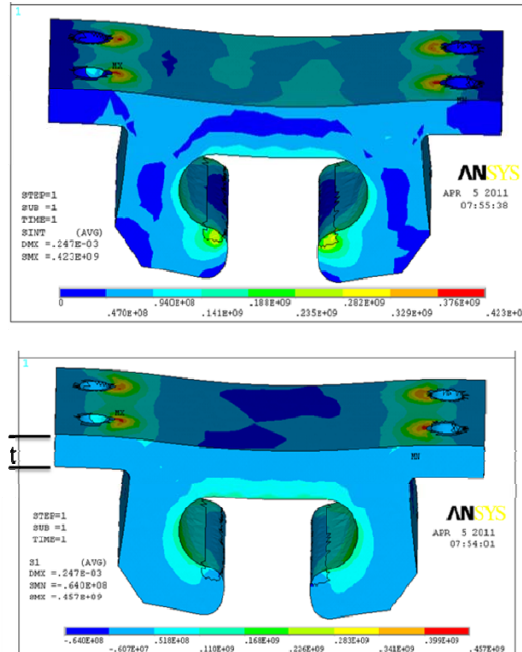
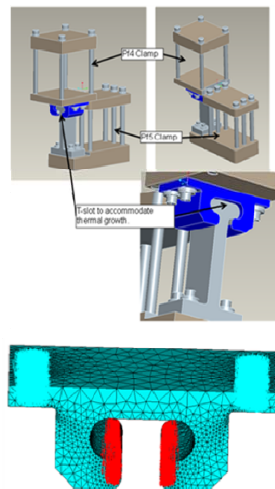
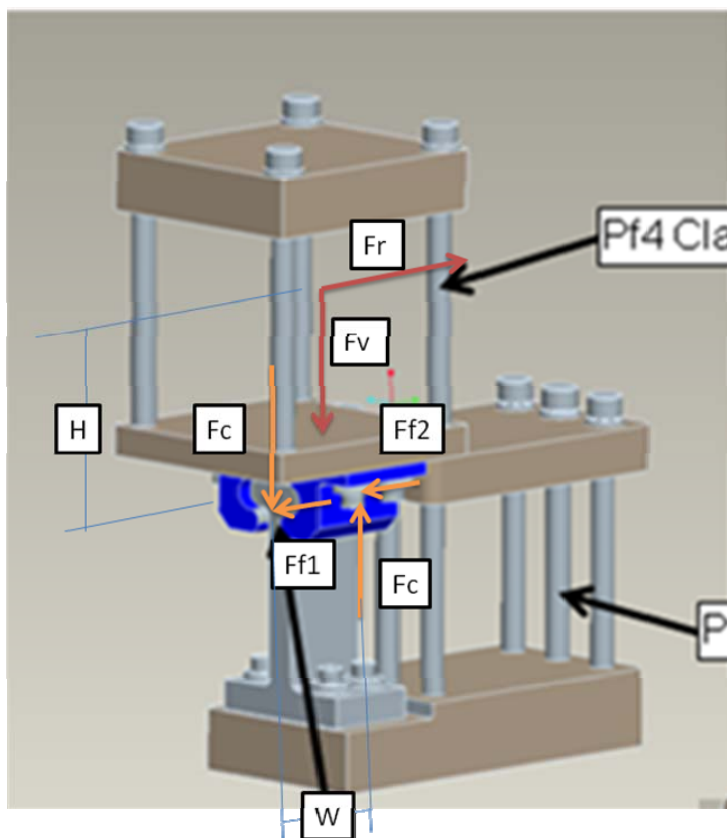


Figure 12.6-2 Dovetail Stress Analysis

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



Sum Moments:  
 $Fr \cdot H = Fc \cdot W$   
 $Fc = Fr \cdot H / W$

$Fr = 2 \cdot \mu \cdot Fc$

For Lock-Up with Only Fr

$\mu u = W / H / 2$

Or  $\mu$  must be less than  
 .25 for  $W / H \sim 1/2$

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 =  $\mu * 203125 + 2 * \mu * h/w * 289472$

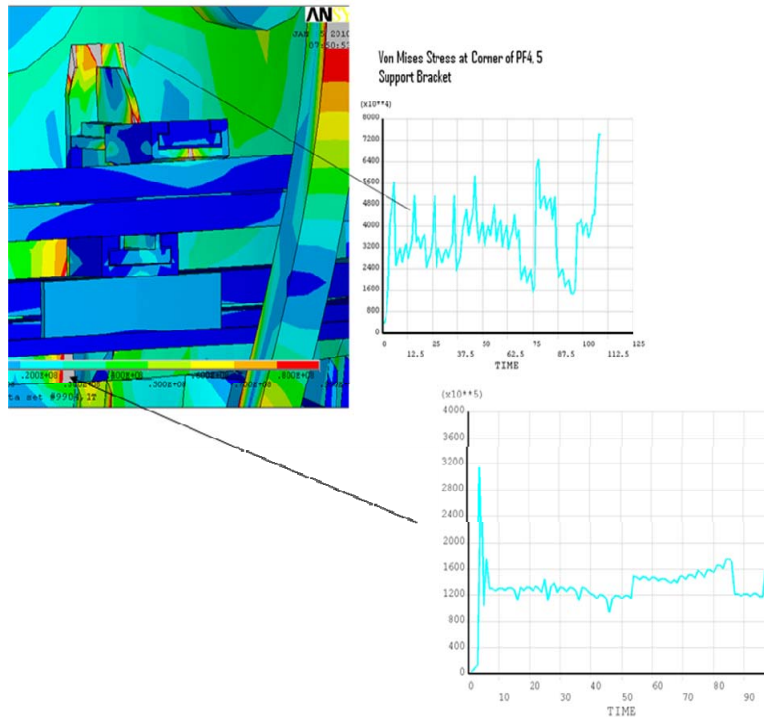
To allow radial growth under Lorentz loads the radial load must be greater than the frictional restraining force, or:  $289472 > \mu * (203125 + 2 * h/w * 289472)$

Or  $\mu$  must be less than  $289472 / (203125 + 2 * h/w * 289472) = .213$

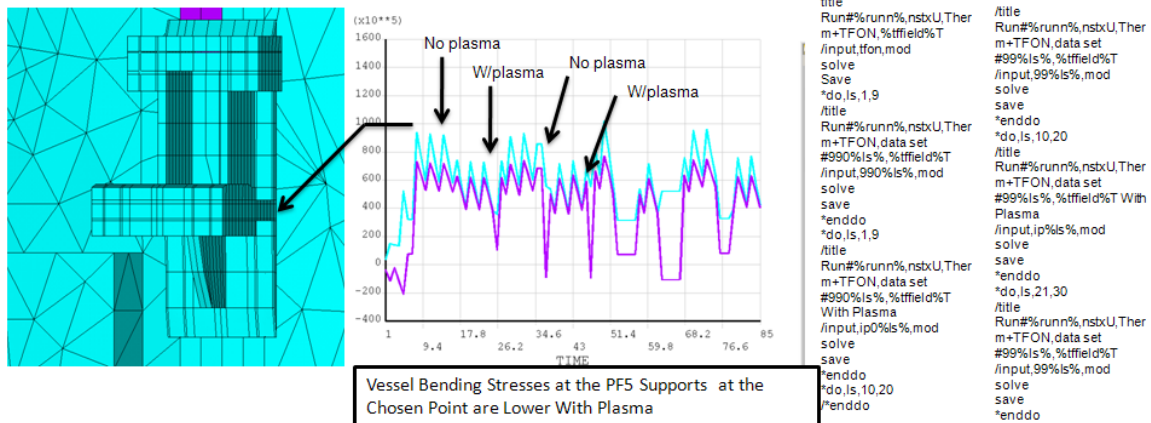
Or  $\mu$  must be less than .1 for  $H/W \sim 4$

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



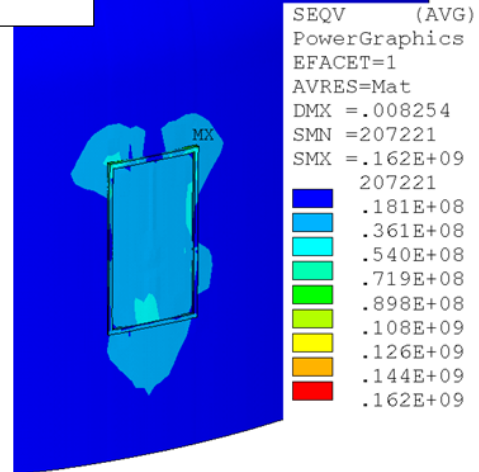
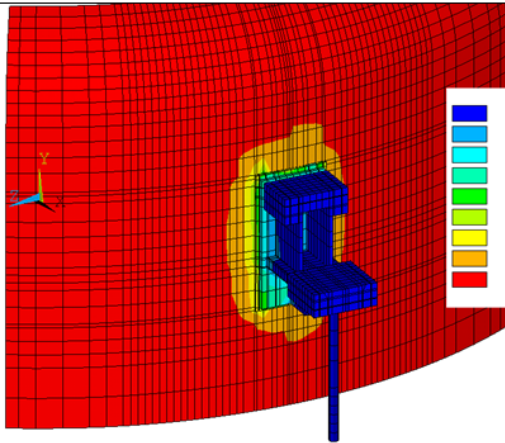
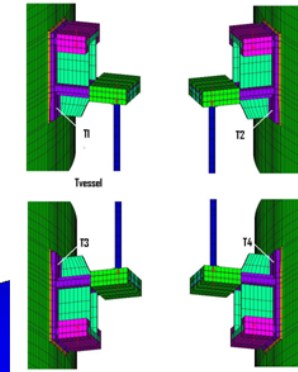
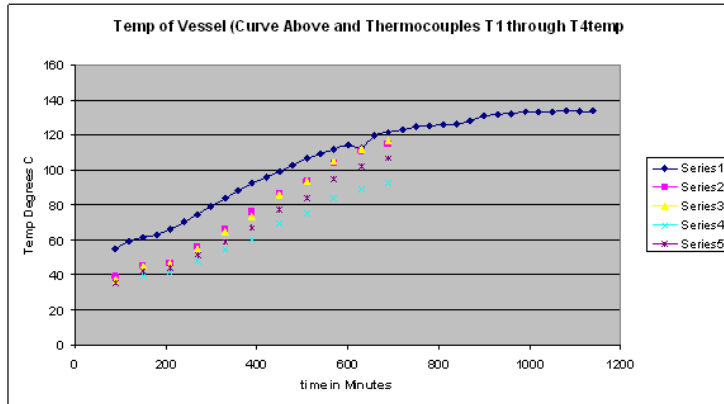
Vessel stresses are 160 MPa at the bottom and 64 MPa at the top (from the Jan 6, 2011, meeting presentation).

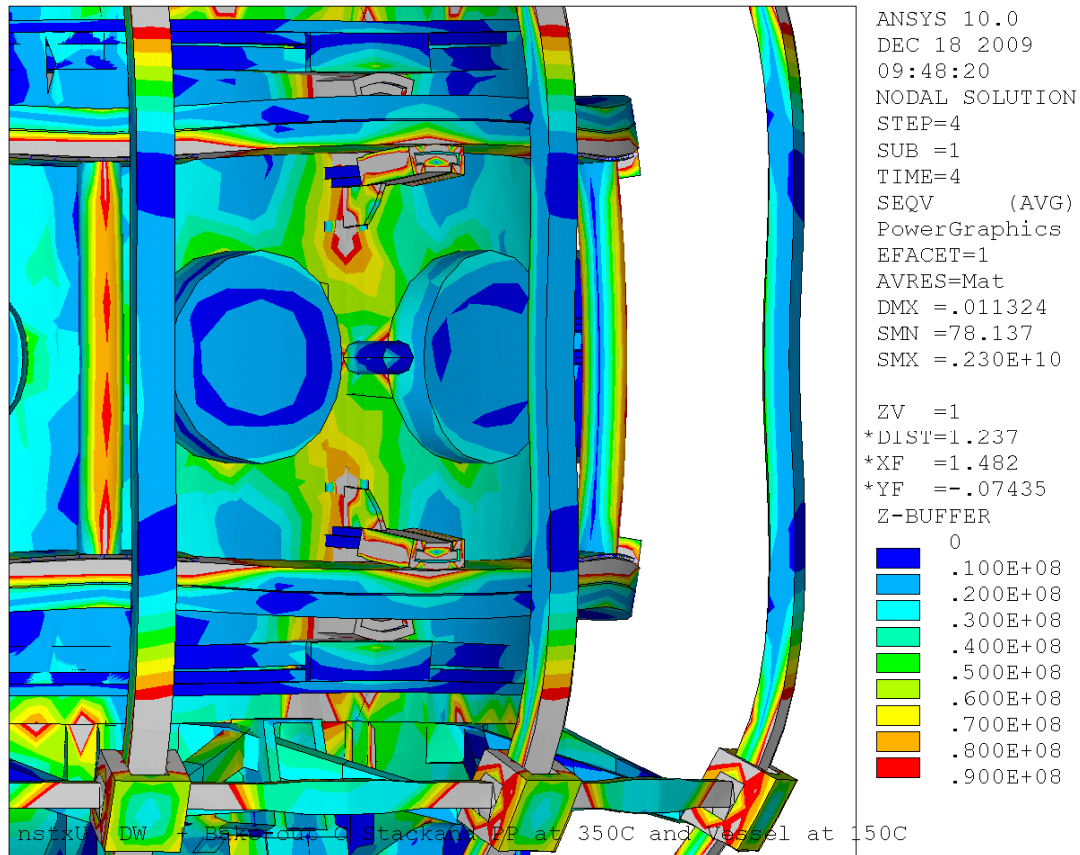


These results show the shell stress slightly higher with no plasma. In the load sequence, first 10 load cases without plasma are analyzed then 10 load cases with plasma are analyzed. The trend in coil tensile stress is the opposite - see Section 9 - but the differences aren't great.

### 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.





Bake-out stresses 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.

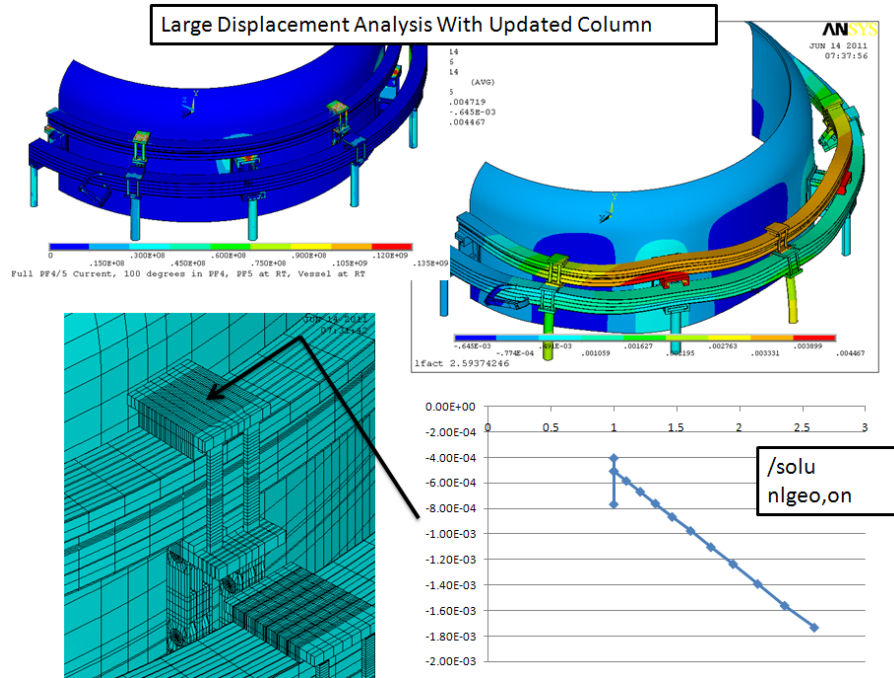


Figure 14.0-1 Large Displacement Loading of the Model to Address The Potential for Elastic or Plastic Collapse

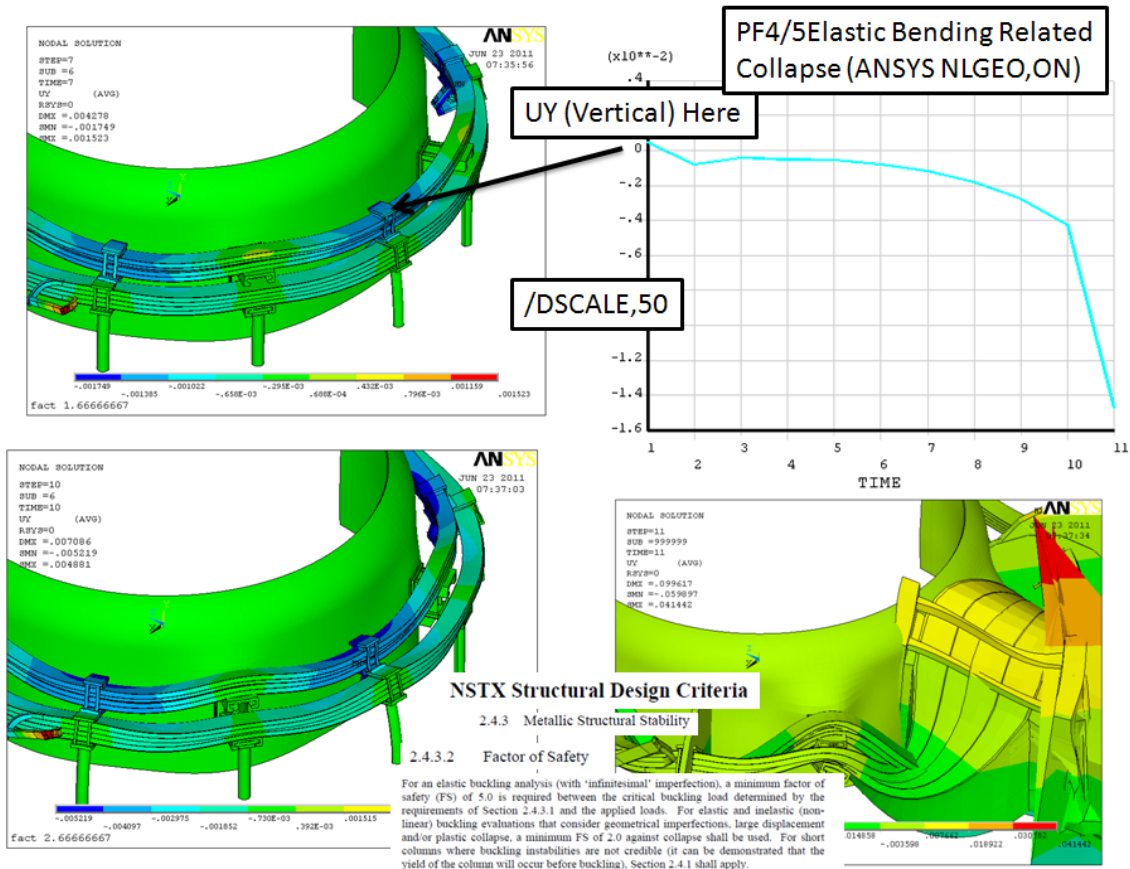


Figure 14.0-2 Large Displacement Loading of the Model Taken to Collapse



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.

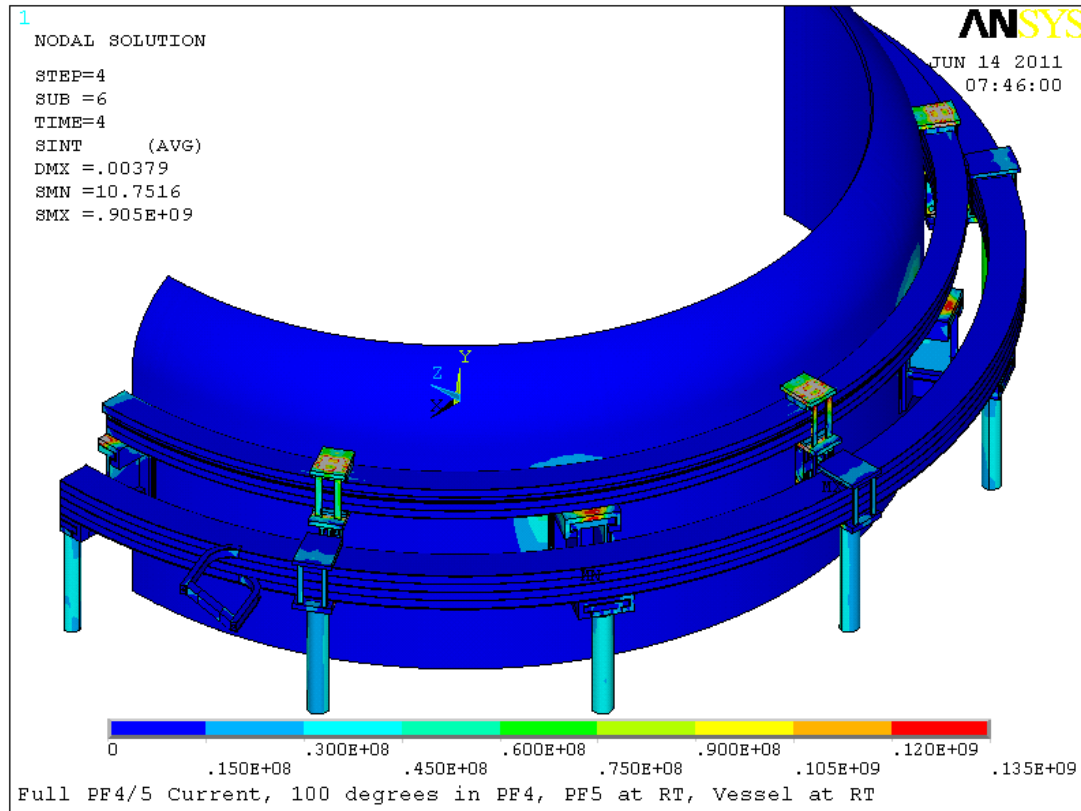


Figure 14.0-3 Initial Loading Tresca Results with a Load Multiplier of 1.0

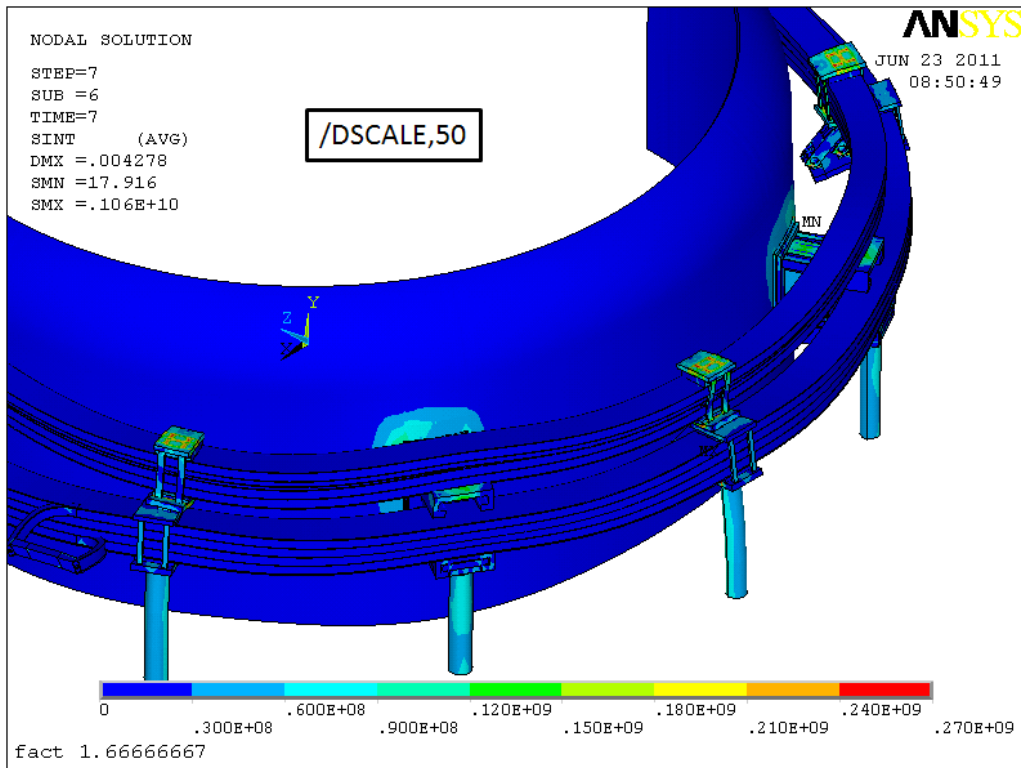


Figure 14.0-4 Initial Loading Tresca Results with a Load Multiplier of 1.7

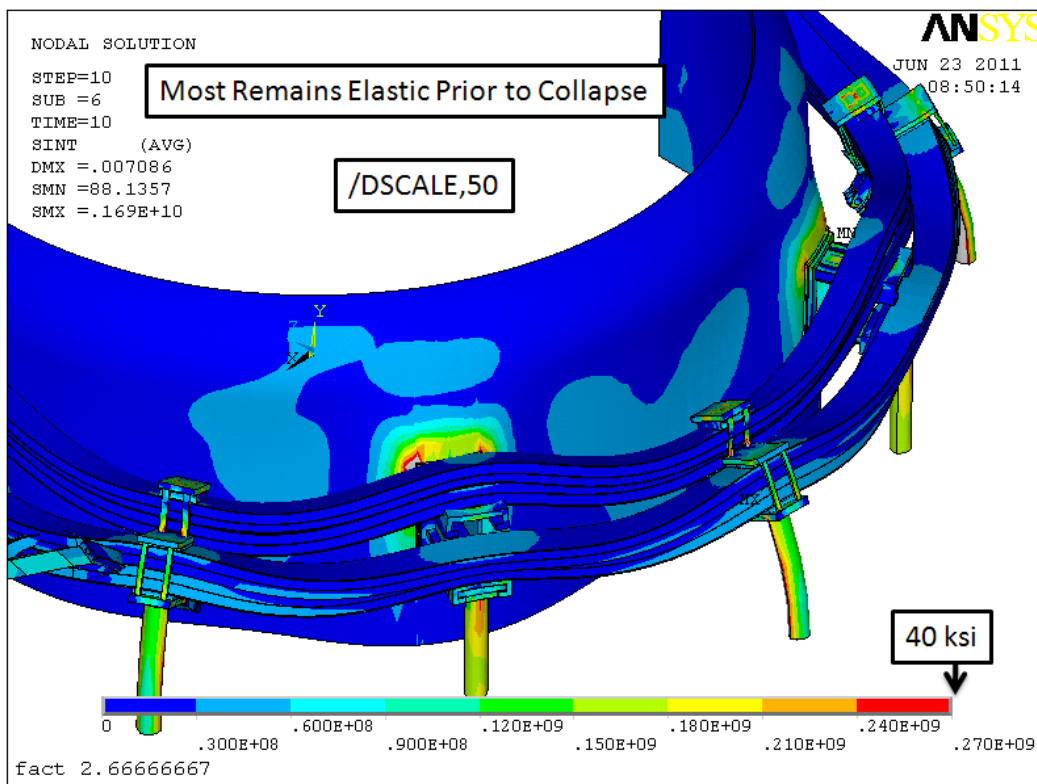


Figure 14.0-5 Large Displacement Tresca Results with a Load Multiplier of 2.6

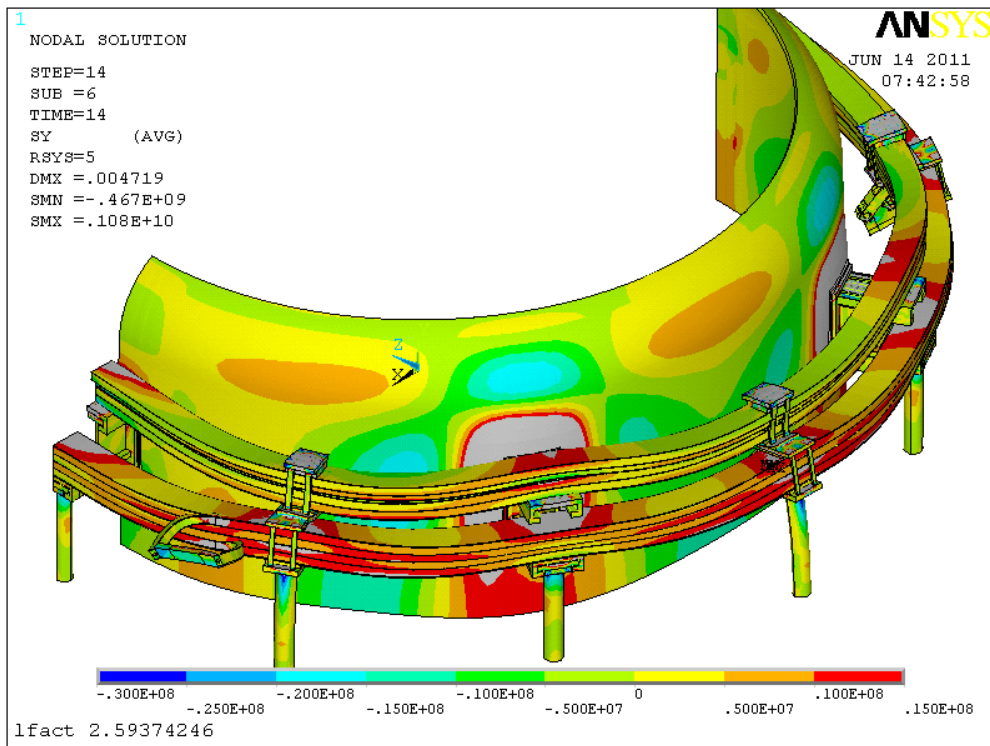


Figure 14.0-6 Vertical Stress with a load multiplier of 2.6

## Appendix A Analysis of Earlier Concepts

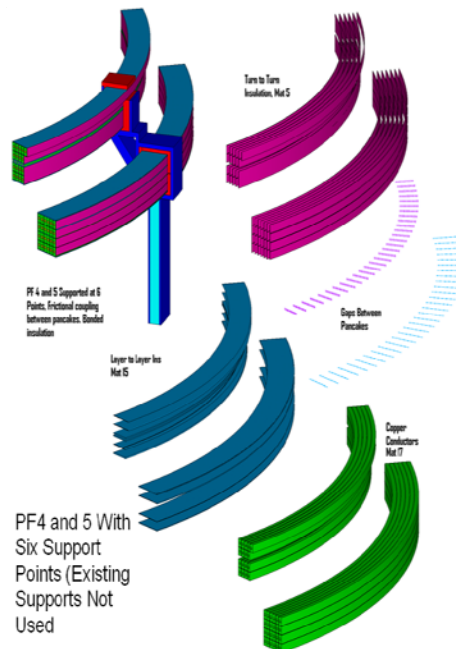
Feasibility of 6 vs 12 Support Points	A.1
Results for Added Columns and Rubber Support Pads	A.2
Concept which Supports TF OOP Loads off the PF4 and 5 supports	A.3
PDR Clamp Concept	A.4
Stress Multipliers for the PF4 and 5 Clamp Weld in the Existing NSTX (2010)	A.5

### A.1 Feasibility of 6 vs. 12 Support Points

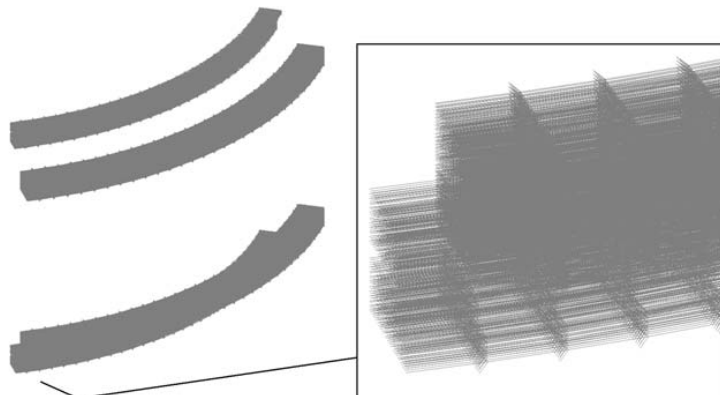
Currently (2011), both PF4 and 5 are supported by six support brackets welded to the vessel shell (12 including uppers and lowers). This study investigated the use of 6 supports for the upgrade loads. The PF5 insulation system is a mylar wrapped fusifab epoxy system. Because of the poor bonding of the 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

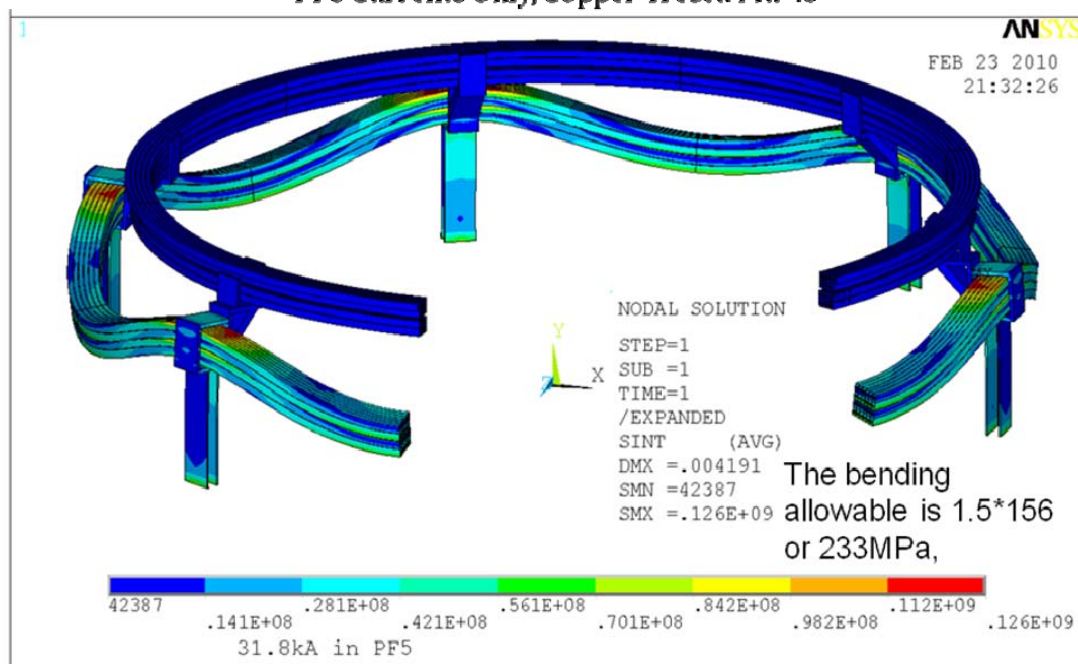


Biot Savart  
Current Sticks  
and Net Loads,  
60 Degree  
Models

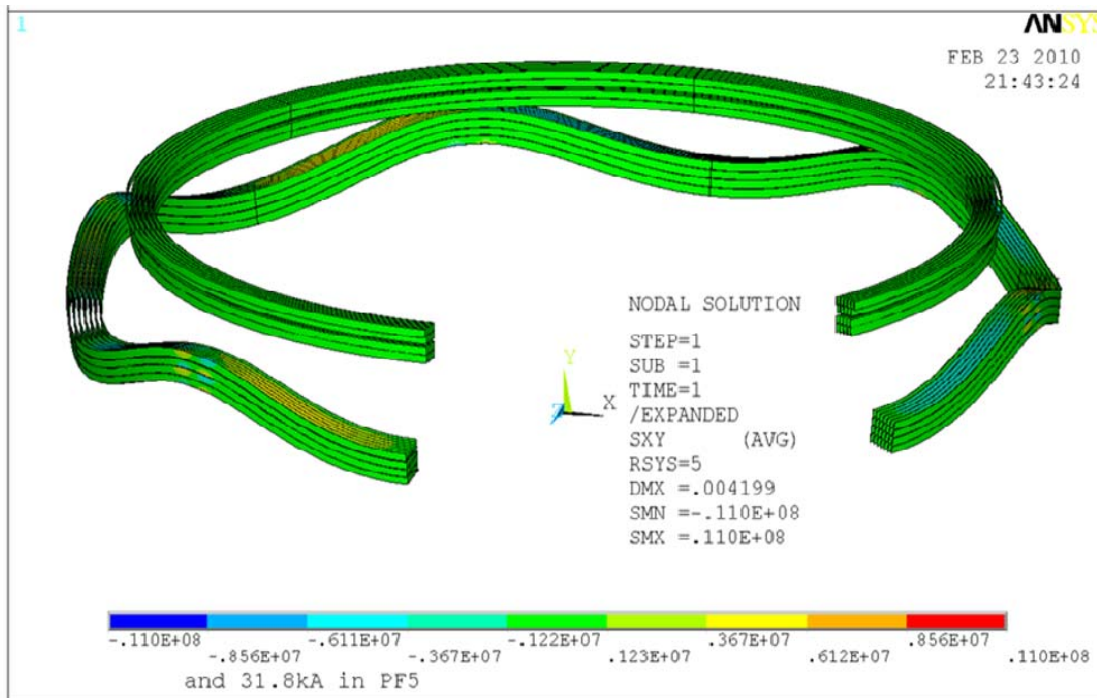


	ANSYS Reaction Load for 60 degree	ANSYS Full Coil	NSTX Design Point Spreadsheet 96 Scenarios
PF 4,5 U&L Fully Energized PF4 16kA PF5 31.8kA	244724 N	330083	291786
PF5 U&L at 31.8kA	154370	208214 46700lbs	241452

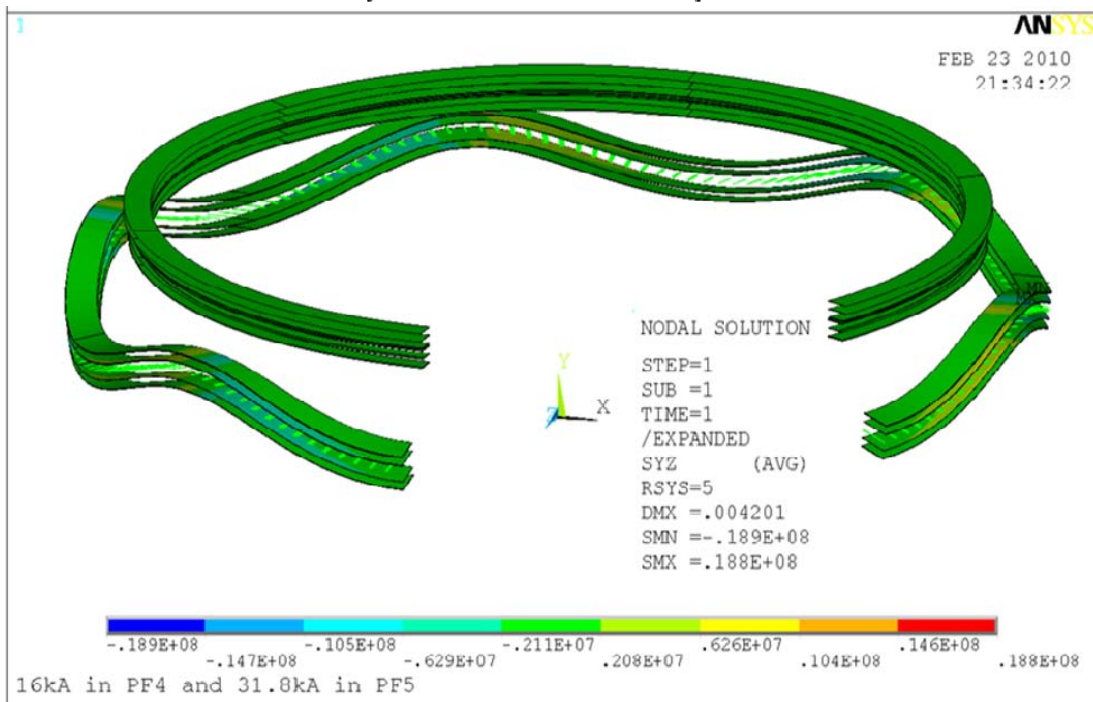
### PF5 Currents Only, Copper Tresca $\mu=.3$



### PF5 Currents Only, Rad-Theta Shear on Turn to Turn Insulation $\mu=3$

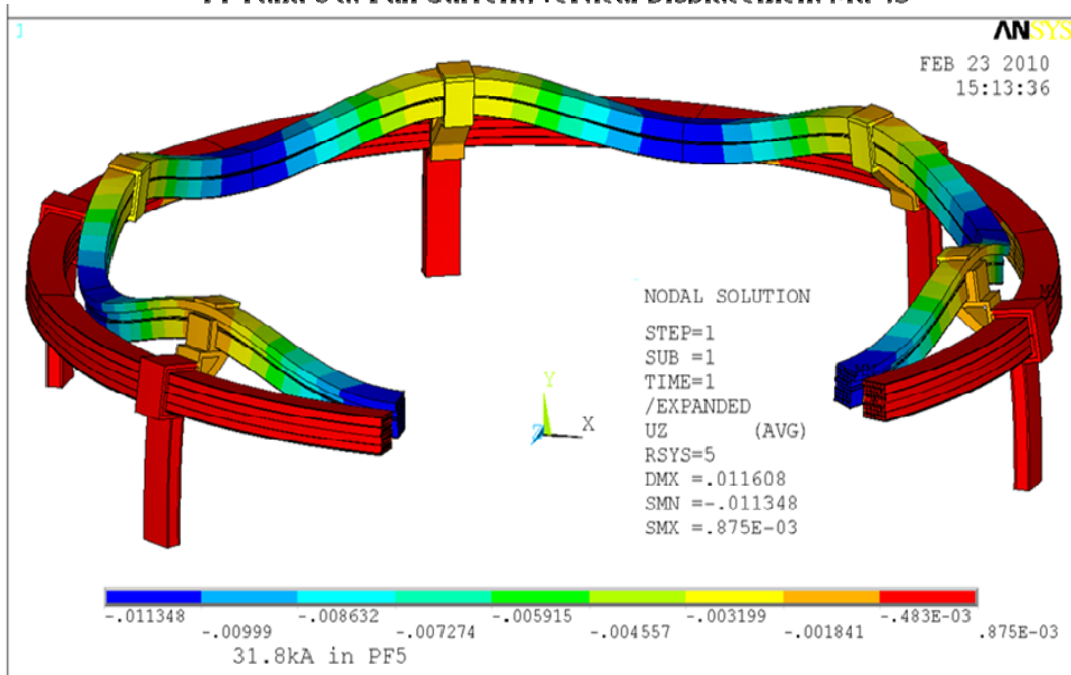


### PF5 Currents Only, Vert-Theta Shear on Layer Insulation $\mu=3$



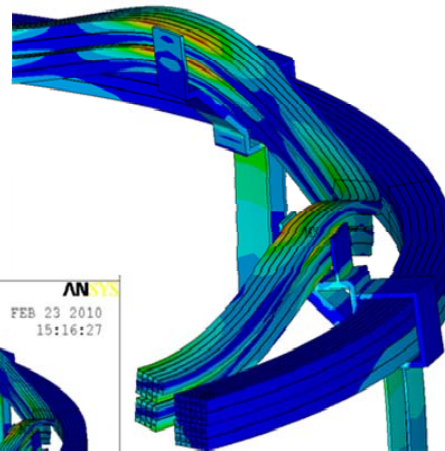
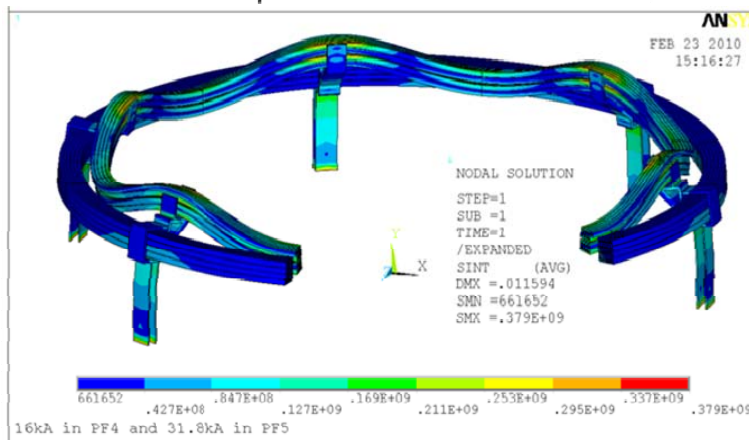


# PF4 and 5 at Full Current, Vertical Displacement $\mu=.3$



## PF4 and 5 at Full Current, Tresca Stress $\mu=.3$

The Bending  
allowable is  $1.5 \times 156$   
or 233MPa,

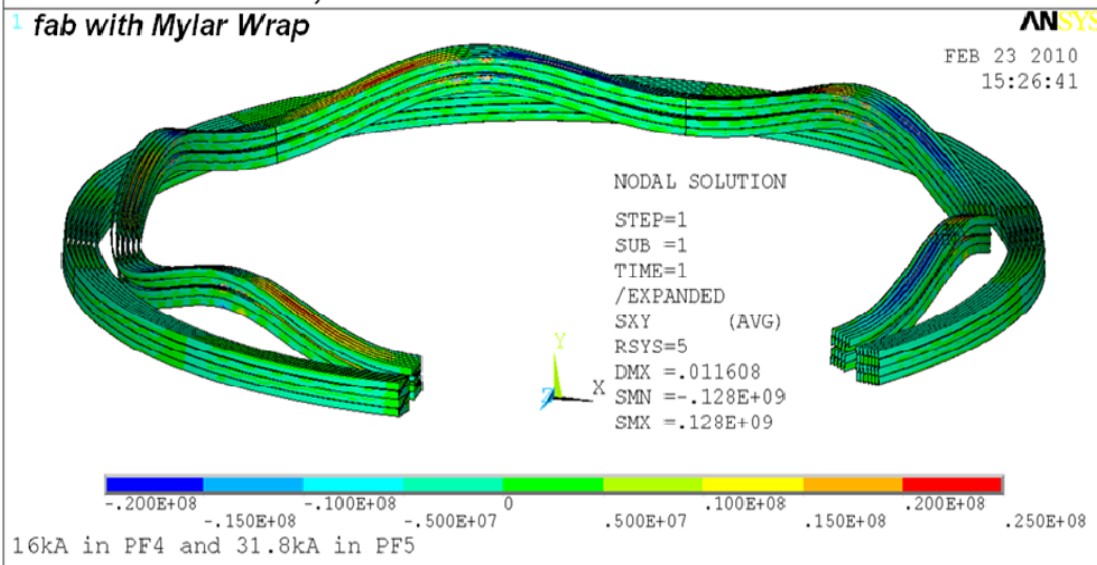


**PF4 is Overstressed**

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

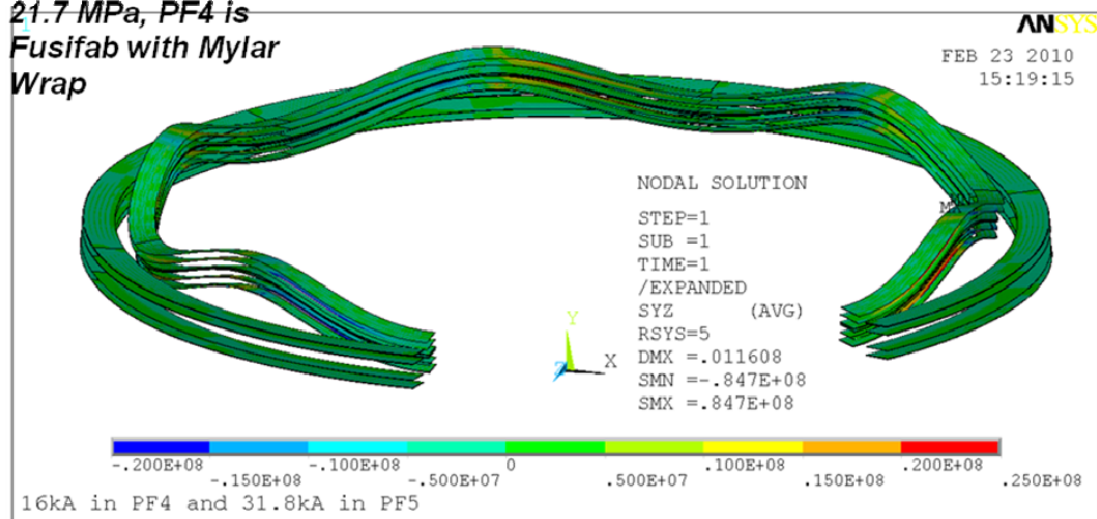
## PF4 and 5 at Full Current, Insulation Radial Theta Shear on Turn to Turn Insulation $\mu=.3$

**CTD 101K Allowable at RT 2/3 of 32.5 MPa = 21.7 MPa, PF4 is Fusa**



## 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**



### 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

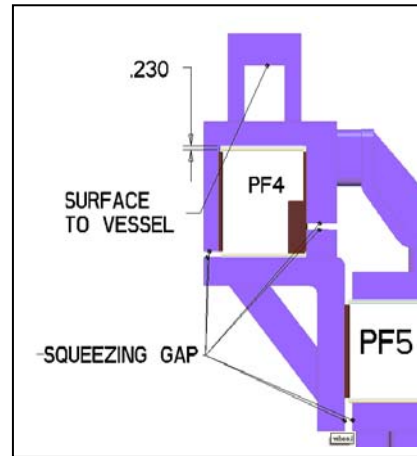
columns/brackets. The pads that were analyzed had too high a shear stiffness and didn't allow the needed compliance. Links and dovetail joints were suggested.

### 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

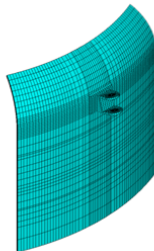
Han/Neumeyer 'Worst' = 22000lbs  
 Titus Global 70 of 96 = 24000 Lbs  
 Danny Conservative Envelope Estimate = 50,000 Lbs  
 Adjust for TF Radius/Attachment Radius  
 Use 30,000 Lbs

12 Attachment Points 30000lbs @

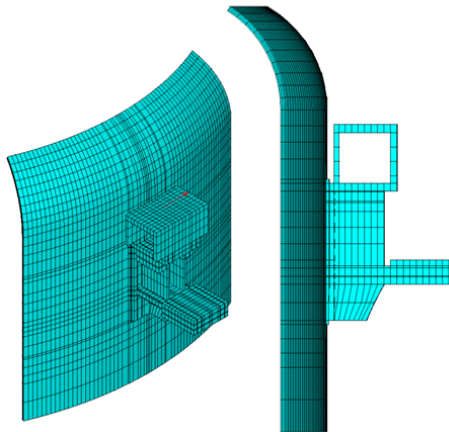
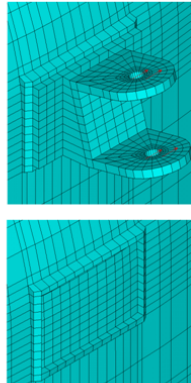
6 Attachment Points 60000lbs@

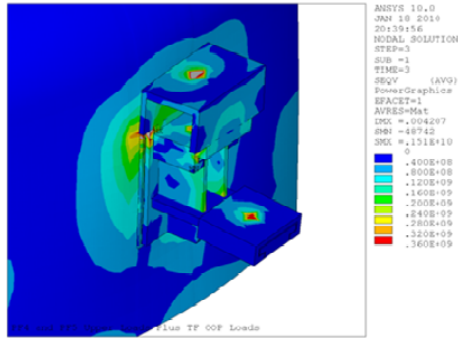
Note: 3/8" bolts don't work. Must be replaced with weld or much larger bolts

TF Truss or Radius Rod Leg

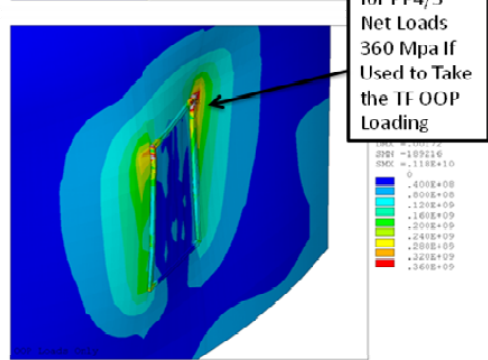
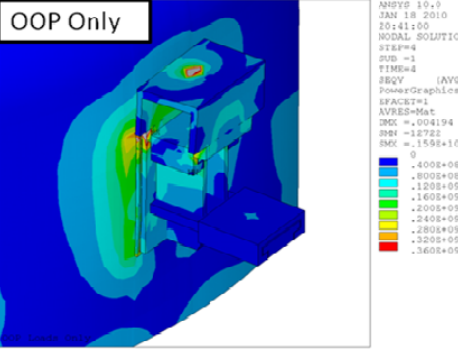
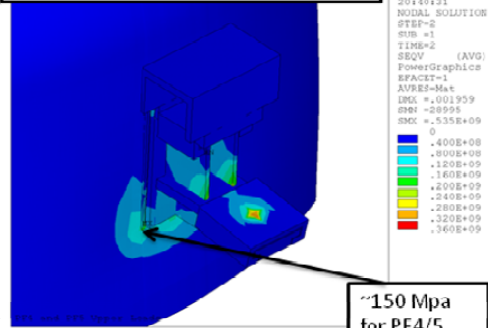


Actual (2008) Weld Size is 3/16  
 Model Weld is 0.05mm





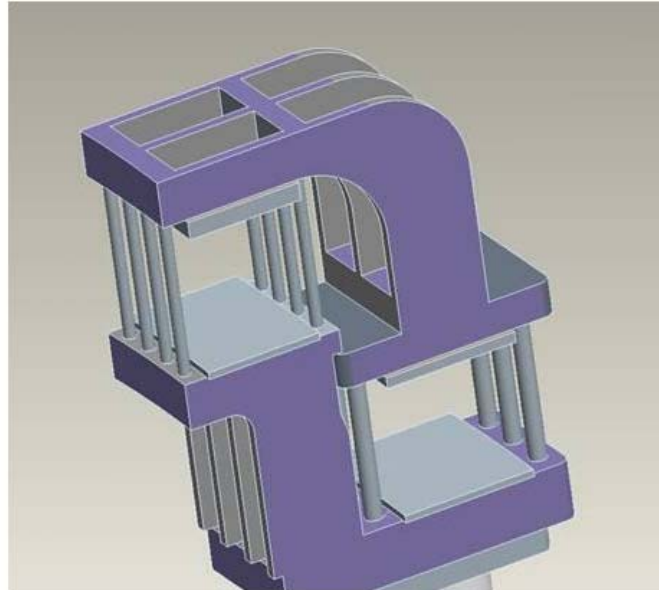
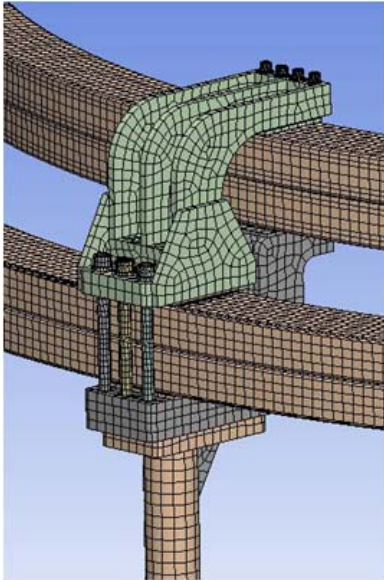
No OOP, Only PF 4/5 Net Loads



~150 Mpa  
for PF4/5  
Net Loads  
360 Mpa If  
Used to Take  
the TF OOP  
Loading

#### 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 1/6<sup>th</sup> 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.***

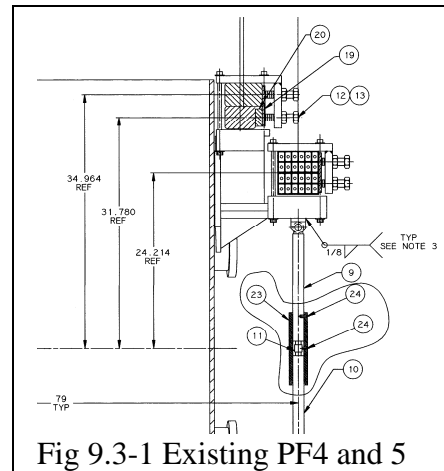


Fig 9.3-1 Existing PF4 and 5

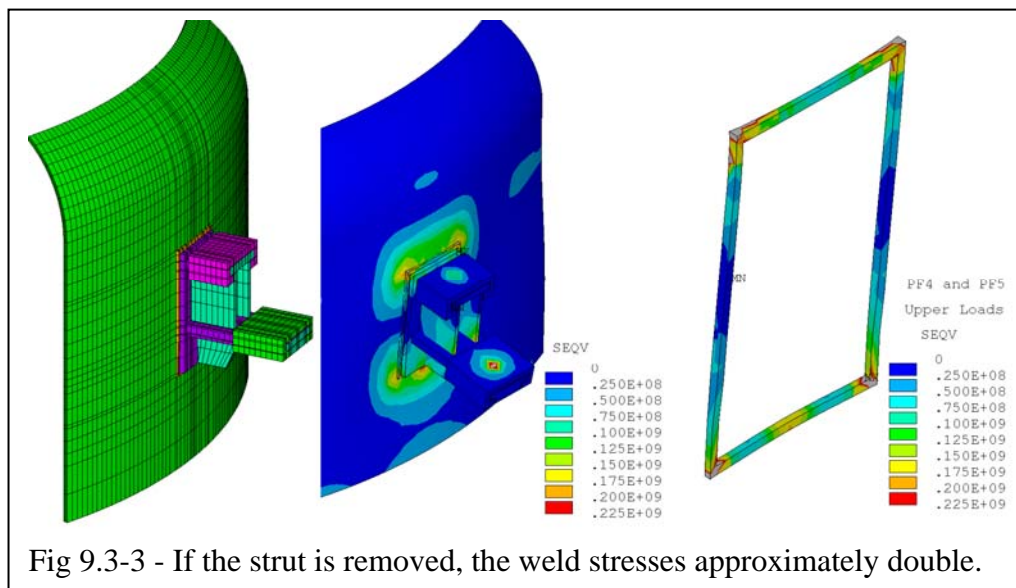
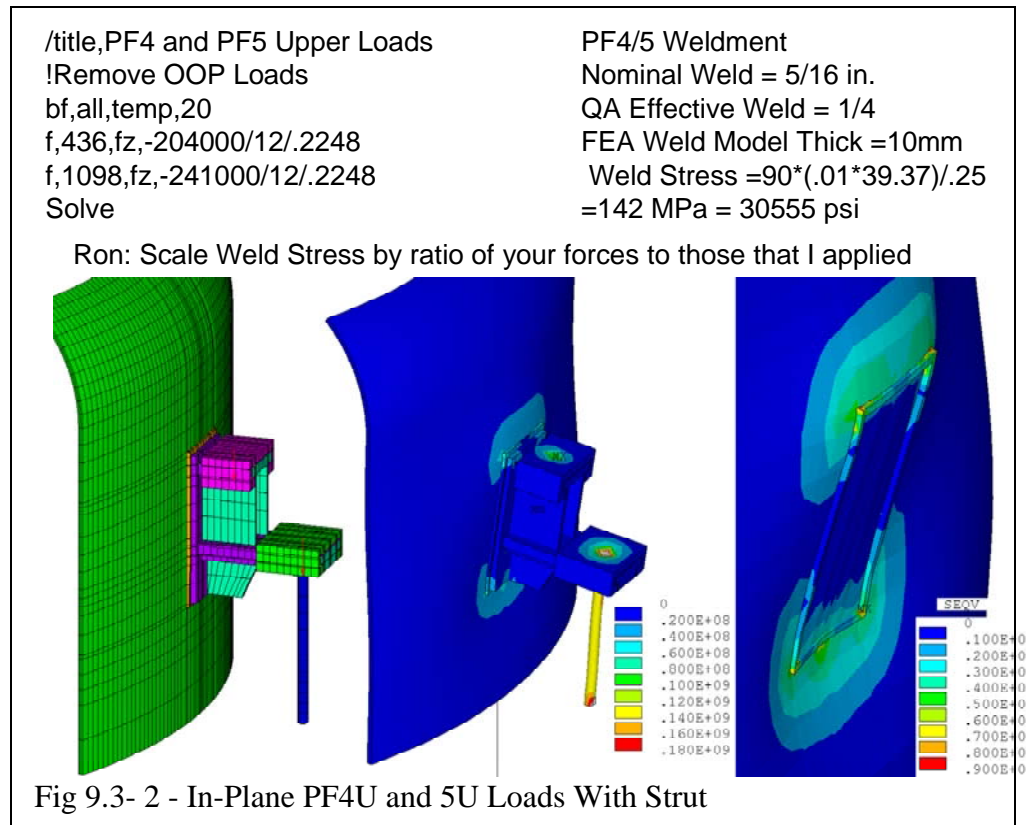
In this analysis, PF4 and 5 loads are grouped together. PF5 loading has a larger moment arm and has a bigger effect on the weld and strut bolt stress. To be strictly correct, the PF5/PF4 load ratio should be as assumed in the analysis. Only the bracket to vessel weld and the strut end bolts were looked 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 1/4 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.



## 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 98.91 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  $F_y=36\text{ksi}$  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.

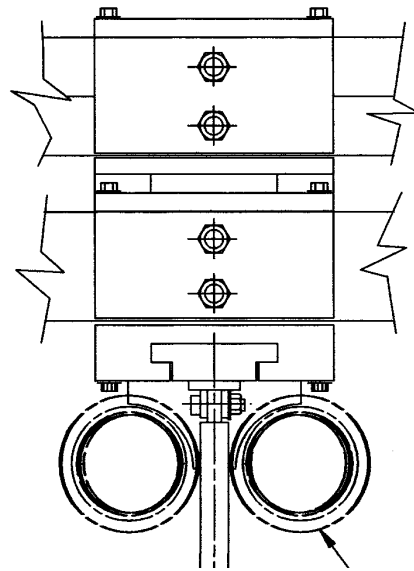
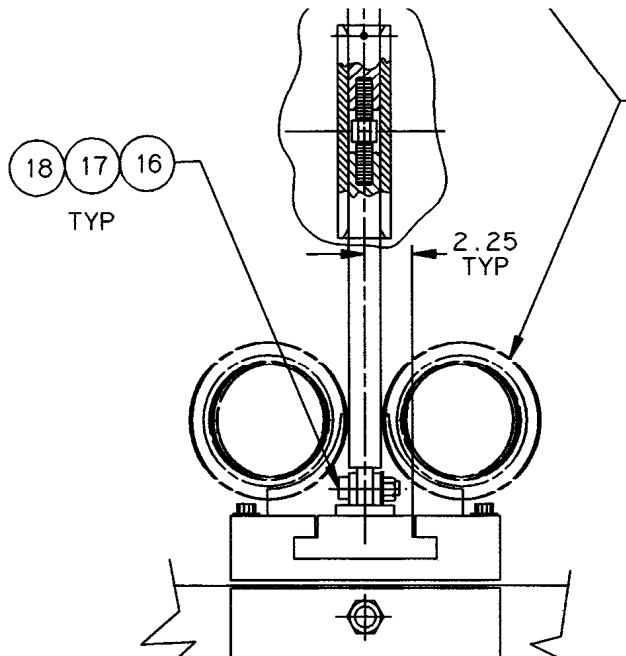


Figure 9.3-5 PF4 and 5 Strut Bolting Detail

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.

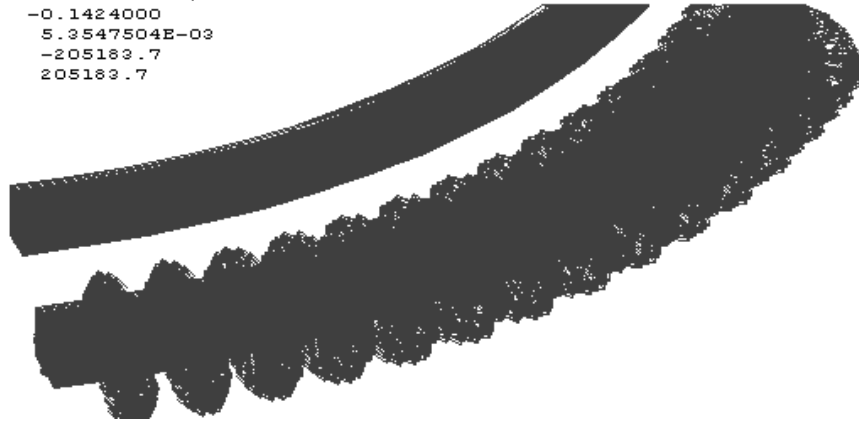
Table 9.1-1 NSTX Centerstack Upgrade PF Loads

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

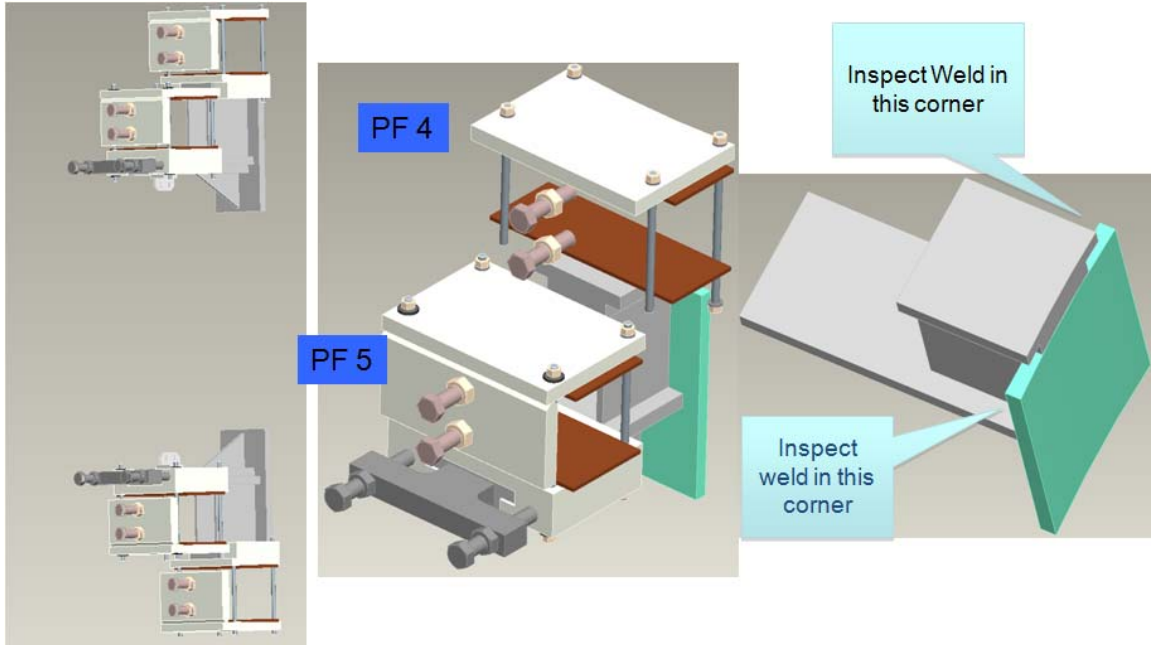
### Benchmark Check of 20 kA Current Operation of PF5 with Existing supports.

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.

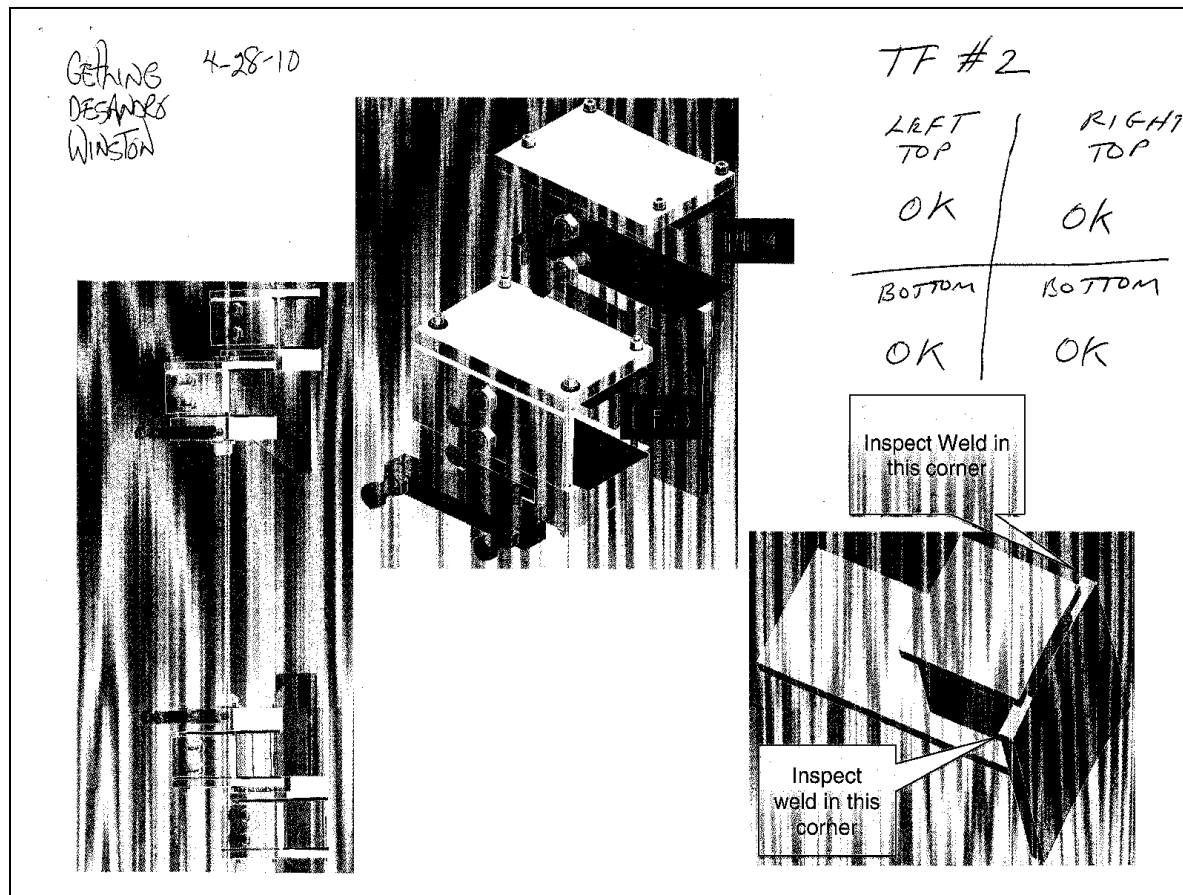
```
nplot
Enter Group Number:
9
fsum
ENTER node group for Force Summation
0
FORCE SUMMARY FOR NODE GROUP=      0
FXSUM=    144219.0    FXMAX=    203.4495    FXMIN=   -158.3600
FYSUM=   -60946.69    FYMAX=    169.1149    FYMIN=   -190.4366
FZSUM=   -1.2817383E-03    FZMAX=    89.24052    FZMIN=   -89.24083
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=   -205182.7
MTOT=    205182.7
```



## 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 coners 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



TF # 8	
LEFT TOP	RIGHT TOP
OK	OK
BOTTOM	BOTTOM
OK	OK

TF # 10	
LEFT TOP	RIGHT TOP
OK	OK
BOTTOM	BOTTOM
OK	OK

TF # 12	
LEFT TOP	RIGHT TOP
OK	OK
BOTTOM	BOTTOM
OK	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](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 Something?

-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