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Analysis Efforts Supporting NSTX Upgrades

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The National Spherical Torus Experiment (NSTX) is a low aspect ratio, spherical torus (ST) configuration device which is located at Princeton Plasma Physics Laboratory (PPPL) This device is presently being updated to enhance its physics by doubling the TF field to 1 Tesla and increasing the plasma current to 2 Mega-amperes. The upgrades include a replacement of the centerstack and addition of a second neutral beam.

The upgrade analyses have two missions. The first is to support design of new components, principally the centerstack, the second is to qualify existing NSTX components for higher loads, which will increase by a factor of four. Cost efficiency was a design goal for new equipment qualification, and re-analysis of the existing components. Showing that older components can sustain the increased loads has been a challenging effort in which designs had to be developed that would limit loading on weaker components, and would minimize the extent of modifications needed. Two areas representing this effort have been chosen to describe in more details: analysis of the current distribution in the new TF inner legs, and, second, analysis of the out-of-plane support of the existing TF outer legs.

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I. Introduction

The National Spherical Torus Experiment (NSTX) is a low aspect ratio, spherical torus (ST) configuration device located at Princeton Plasma Physics Laboratory (PPPL). From previous research, with lower collisionality ν* high fusion neutron fluxes and fluencies could be achievable in very compact ST devices [1]. These researches motivate the upgrade of NSTX to higher TF field B_T from 0.55 to 1 Tesla, increase the plasma current I_P from 1 to 2 Mega-amperes and pulse length from 1 to 7 seconds. Addition of a second neutral beam injection (NBI) would increase heating power from 5 to 10 Mega-watt. To achieve this higher B_T, TF current has to increase from 71.2KA per turn to 130KA per turn and loads will increase by a factor of four. A new centerstack (CS) with doubled outer diameter would replace the existing CS [1,2].

The upgrade analyses have two missions. The first is to support design of new components, principally the centerstack. The second is to qualify existing NSTX components for higher loads, which will increase by a factor of four, and structure change, such as 2nd NBI port on the vacuum vessel. Cost efficiency was a design goal for new equipment qualification, and re-analysis of the existing components. Showing that older components can sustain the increased loads has been a challenging effort in which designs had to be developed that would limit loading on weaker components, and would minimize the extent of modifications needed. Two areas representing this effort have been chosen to describe in more details: analysis of the current distribution in the new TF inner legs, and, second, analysis of the out-of-plane support of the existing TF outer legs.

A current diffusion analysis is carried out to calculate the temperature and stresses during toroidal field (TF) coil ramp up, flat top and ramp down. Current distribution in the TF coil depends on the coil resistance, inductance and contact pressure between the contact joint of flag and arch. Water cooling is included to study the coolant parameters and cooling time. The result can be cross validated by Tom Willard's paper at this conference, in which only the resistive part is modeled.

Because the TF current is increased to 130KA, the umbrella structure is not sufficient to take the out-of-plane (OOP) loads even after reinforcement. Rings were added to reduce the pull-out (in-plane) loads. Since the machine is already crowded, interference was a severe problem limiting the addition of trusses to help sustain the OOP loads. Also to avoid transferring too much load to the vacuum vessel (VV), springs are used to transfer load from TF to VV so as to limit the shear load on VV clevises to be less than 5,000lbs. Loads also will be limited by a new digital coil protection system. Modifications use the territory presently taken up by the existing turn buckles and tie bars. In this way, the attachment to VV only requires modest modification and shear stress in coil turn to turn bond is less than the allowable. Some of these support details may be found in a paper by Mark Smith at this conference.

II. TF Coupled Thermal Electromagnetic Diffusion Analysis

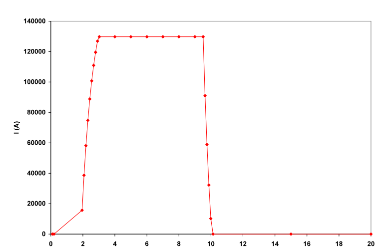

Figure 1: NSTX Normal Operation Waveform.

The objective of this analysis is to calculate the temperature and stresses during TF coil ramp up, flat top and ramp down (Fig. 1). PF field is not considered. This analysis is based on the coupled field electromagnetic and thermal analysis for a simple model [3], [4].

II.1. Modeling

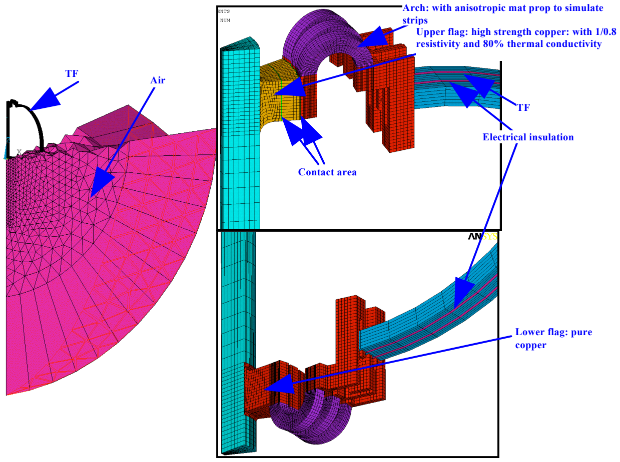

Figure 2: Electromagnetic Model (with air).

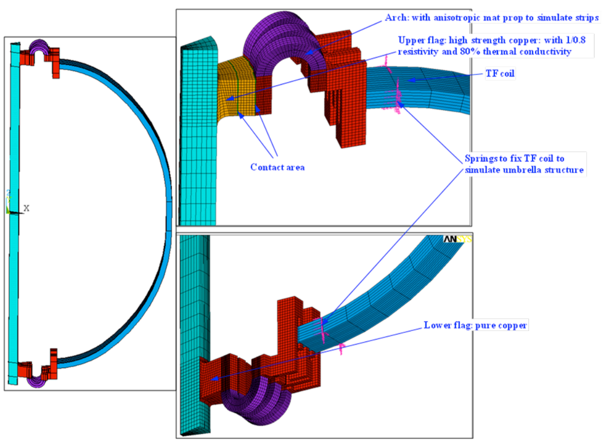

Figure 3: Thermal and Structural Model (without air and add fixation).

This is a transient and coupled field analysis. An electromagnetic model (Fig. 2) is used to calculate current diffusion effect and transfer the generated heat and Lorenz force to thermal and structural model (Fig. 3). The thermal and structural model calculates the temperature, displacement, thermal stress, contact pressure at contact areas, and then transfer these data back to electromagnetic model. The materials have temperature dependent material properties, including electrical resistivity, thermal conductivity, specific heat, coefficients of thermal expansion. The arches have anisotropic resistivity and thermal conductivity to simulate the straps. Because the arch is made of many straps and not a solid copper, it becomes much more compliant. The modulus of the arch is based on the results of [5]. The upper flag uses high strength copper which has 1/0.8 resistivity and 80% thermal conductivity of pure copper. In next section, the results show that using high-strength copper or pure copper doesn't have much difference. The lower flag uses pure copper. In the electromagnetic model, the contact regions have pressure dependent resistivity and the data are from [6] (Table I).

Table I: Contact Resistance Data [6].

CONTACT PRESSURE(Pa)	CONDUCTIVITY (S/m^2)	CONTACT PRESSURE(Pa)	CONDUCTIVITY (S/m^2)
1.00000E+00	1.00000E+00	3.16044E+07	1.89971E+10
1.37359E+06	5.35411E+08	3.38778E+07	2.30742E+10
1.47681E+06	5.38476E+08	3.61694E+07	2.74988E+10
1.83862E+06	5.53310E+08	3.84064E+07	3.19775E+10
2.36282E+06	5.78873E+08	4.06156E+07	3.62419E+10
3.07523E+06	6.15297E+08	4.28283E+07	4.10335E+10
3.95984E+06	6.66688E+08	4.49190E+07	4.57280E+10
4.99175E+06	7.53410E+08	4.69450E+07	4.97211E+10
6.18883E+06	8.75474E+08	4.88533E+07	5.30157E+10
7.52698E+06	1.15148E+09	5.06903E+07	5.58498E+10
9.01059E+06	1.79136E+09	5.23996E+07	5.86168E+10
1.06360E+07	2.83763E+09	5.40124E+07	6.09994E+10
1.24087E+07	3.85840E+09	5.54407E+07	6.28324E+10
1.42633E+07	4.79779E+09	5.67574E+07	6.43307E+10
1.62207E+07	5.97101E+09	5.79004E+07	6.54035E+10
1.82582E+07	7.14651E+09	5.89026E+07	6.62942E+10
2.03965E+07	8.29712E+09	5.97272E+07	6.69859E+10
2.26062E+07	9.47304E+09	6.04046E+07	6.74716E+10
2.48285E+07	1.09843E+10	6.08813E+07	6.77217E+10
2.71058E+07	1.29688E+10	6.11718E+07	6.80843E+10
2.93977E+07	1.58780E+10		

II.5.Results

The distribution of current in TF coil depends on the resistance, inductance and contact pressure in the contact area. Coil temperature reaches highest at the end of the pulse, i.e., 10.136s for normal operation. Without active cooling during pulse, maximal temperature of inner leg is 117ºC, at the inner side of lower flag. Comparing with [2], 101ºC temperature rise, this analysis with current diffusion effect results in a little higher temperature. Upper flag has more material and thus the max temperature is a little lower, 112 ºC. With active water cooling (0.25" diameter tube, 3m/s flow rate and inlet temperature of 12 ºC), the maximal temperature of lower flag drops to 113.4 ºC and that of upper flag is 110.8 ºC (Fig. 4).

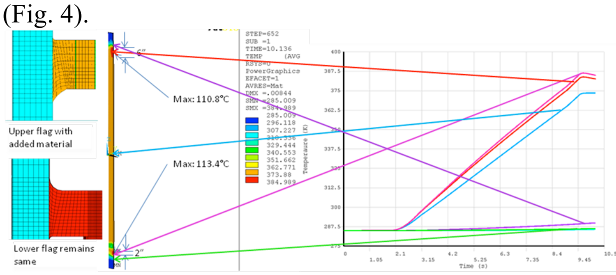

Figure 4: Temperature rise in TF inner leg upon normal operation waveform with water cooling.

TF inner legs are wrapped with fiber glass and bonded using epoxy. The epoxy is reported to be able to work normally until 115 ºC. But the different thermal expansion coefficient between copper and epoxy may cause delamination. Two positions of the cooling lines are evaluated. Fig. 5 shows that putting cooling line at side results in lower S_{theta} of 90MPa (i.e. stress to cause delamination) than cooling lines in the middle, because putting cooling tubes in the middle will cool the coil down faster and result in more difference in shrinkage. In this analysis, 0.3” tube is used with flow rate 3m/s and it takes 5 minutes to cool the inner leg down to room temperature. If slow down the cooling process, for example, using 0.25” tube and same flow rate, the stress S_{theta} can be reduced to 48MPa (Fig. 6).

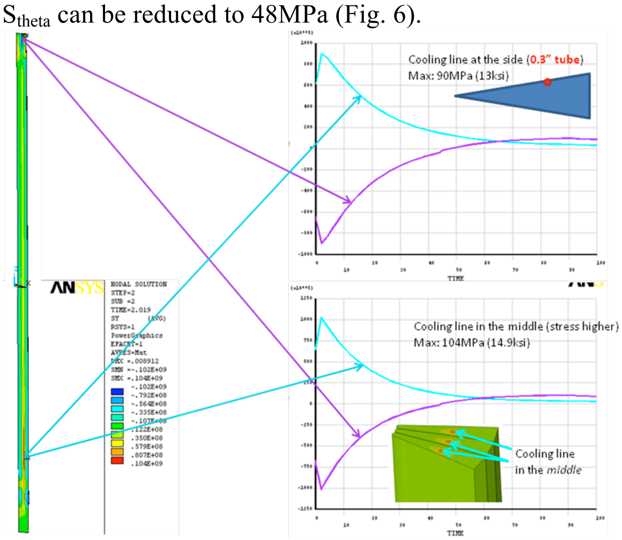

Figure 5: History plot of delamination stress S_{theta} (Pa) after pulse with water cooling.

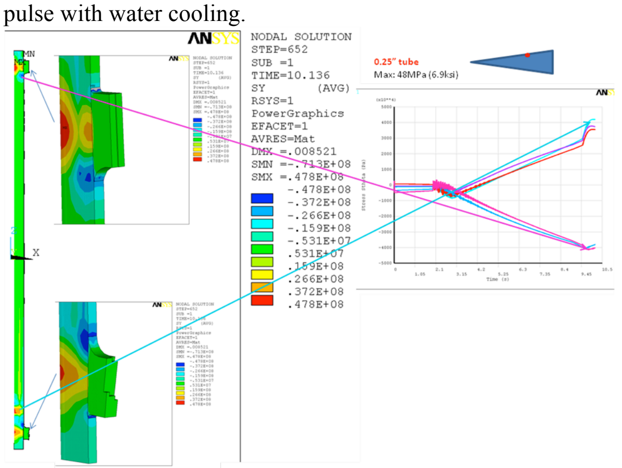

Figure 6: History plot of delamination stress S_{theta} (Pa) during pulse with water cooling.

The max temperature in outer leg reaches only 47ºC at the end of pulse. But to avoid further temperature rise upon following pulses, active cooling is simulated. With cooling line of 0.5” tube diameter, 3m/s flow rate and tube attached to the surface of outer leg, the coil can be cooled down to 25ºC in 5 minutes.

In this model, the arch is modeled by two solid pieces. But in reality, they are made of many straps. So the arches in this model have anisotropic material properties (mechanical properties are based on the local structure model results of [5]), Current density, magnetic flux density and temperature from this analysis have been provided for a detailed simulation of the joint.

Because the upper flag has two contact regions, using high strength copper as the flag material can help to maintain high and uniform contact pressure and also lower contact resistance. But high strength copper has higher resistance and lower thermal conductivity. Fig. 7 gives the comparison. Using high strength copper (1/0.8 resistivity and 80% thermal conductivity) causes temperature difference of less than 1ºC. Thus high strength copper can be used if required to increase the pressure of joint bolt insert over the capacity of pure copper.

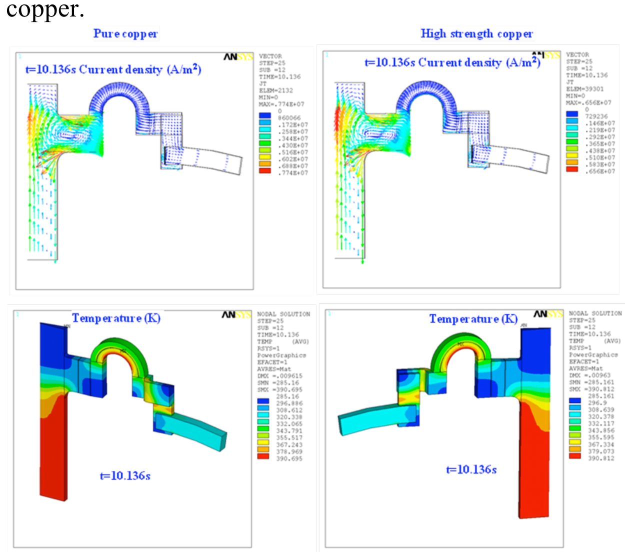

Figure 7: Comparison of current density and temperature between pure copper and high strength copper.

Toroidal field contours have been provided for use in other calculations—in particular the background field in the antenna calculation.

III. ANALYSIS OF TF OUTER LEG

The objective of this analysis is to study what kind of additional support structure can help to take some of the in-plane and out-of-plane (OOP) force of TF outer leg.

The upgrade of NSTX CSU will increase the TF current to 130KA. Upon TF self field and poroidal field, TF outer leg will have in-plane (i.e. in the plane of TF outer leg) force and OOP (i.e. perpendicular to the plane of TF outer leg) force. TF outer leg is supported by the umbrella structure (Fig. 8). From previous analysis, with the worst case PF currents, the umbrella structure will have very high stress of >1GPa (145 ksi). The umbrella structure has a cylindrical shape and radial load should not be a problem. The Aluminum blocks are bolted to the umbrella structure and must take the radial load. Analysis for Al. blocks was done separately. Vertical load will be transferred to vacuum vessel. OOP load will make the umbrella structure twist and produce high stress on the arches, especially double arch. So it is necessary to add additional support structure to take some OOP load so as to reduce the load to umbrella structure and also reinforce umbrella structure.

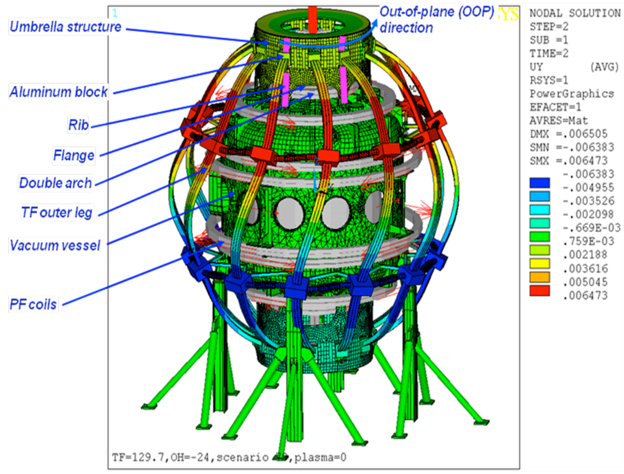

Figure 8: Modeling of TF outer leg and support structure, umbrella structure and vacuum vessel.

The idea is to use ring and tie springs. They occupy the space of existing turn buckle. They can transfer the OOP load to vacuum vessel and effective on both symmetric and asymmetric PF currents. In these analyses, rings were added to reduce the pull-out (in-plane) loads at the umbrella structure. Various spring constant was tried and plotted so as to select the optimal parameters to satisfy the requirements in copper bond shear stress, coil stress, clevis shear load and max OOP displacement etc.. Since the machine is already crowded, interference was a severe problem limiting the addition of trusses. Although it is not the first choice to transfer more load to vacuum vessel, up-down asymmetric currents and resulting net twist required an attachment to the vessel. Tie springs can take the net twist and also provided adequate OOP support for symmetric case. They use the existing territory of turn buckle and there is enough room for them. Loads in the tie springs allow attachment to the vessel with only modest modification and max shear load to clevis to be within 5000 lbs. Vessel stresses are acceptable and the umbrella structure requires only modest modification. Because the springs are soft, they would load the coil but only a little during vessel bake out and no need to be disconnected.

III.1. Modeling

A full model is built including TF outer leg, outer leg support, PF and OH coils, vacuum vessel, umbrella structure and support legs (Fig. 8, 9). But centerstack, pedestal assembly and crown for umbrella structure are not included. Also the ports and arches in the umbrella structure are still simplified. Existing TF clamp is not strong enough to connect to the ring. A new clamp is added to hold the current one and connect to ring and tie springs. The tie springs connect to clevis which is fixed to vessel by six 3/8” bolts. The total shear load for these six bolts has to be within 5000 lbs. This design is effective on both symmetric and asymmetric PF currents. Because the vessel model and TF coil model are separately built and the mesh is not matched, the nodes on Aluminum block have to be coupled to the umbrella structure. Also the clevis is fixed to vacuum vessel in the same way. Since the double arch area on the umbrella structure has highly concentrated stress, 3” high 3” wide ribs are welded to reinforce these areas (Fig. 8).

A.

B.

C.

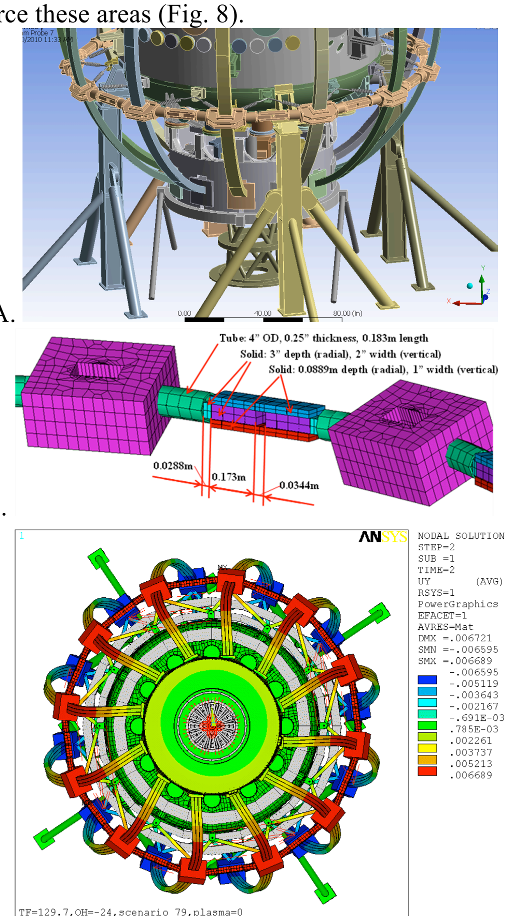

Figure 9: (A)Lower half of the machine showing the design of outer leg support structure; (B)Modeling of TF clamp and ring; (C)Top view of the machine and coil OOP displacement.

III.2.Results

Table II shows the results for three scenarios, 49, 79 and 82, which have larger OOP loads in TF outer leg. Total 96 scenarios may be run later. In Table III clevis shear load, coil stress, copper bond shear stress, and so on are listed with different spring stiffness for scenario 79. Due to a recent update for all the scenario currents, the PF currents for Table II and III have a little difference and thus the results are slightly different too. According to the criteria document [8], the stresses in TF outer legs are within allowable of 233MPa. The highest stress 175MPa for scenario 79 is at the connection between TF coil and ring (Fig. 10). The model uses solid bond between coil and clamp. In reality, there is a thick epoxy layer between them that may further reduce the stress. The vessel stress at Aluminum block is too high (Figure 11). It is mainly because the direct coupling of nodes of Al. block and umbrella structure so as to cause element discontinuity. This should be further analyzed by a detailed model. Stress in vessel arch area is too high before reinforcement (304MPa or 44ksi) and drops down to 190MPa (28ksi), within allowable when adding ribs and flanges (Fig. 8). But more work on the detailed design of the reinforcement will be done later.

Vacuum vessel bake out to 150°C will cause vessel expansion and load TF coil through the springs. Analysis shows that vessel expands 4mm in radial direction and loads on the clevis pin results in average stress of 40MPa (5.8ksi). Max coil stress is 106MPa (15.4ksi) at the joint of coil and umbrella structure (Fig. 13).

Table II: Results of different scenarios.

scenario	spring stiffness (klbs/in)	tie bar load (KN)	clevis shear load (KN)	Utheta (mm)	coil stress (MPa)	Max Cu bond shear stress (Mpa)	Max arch stress (Mpa)
49	17.37	12	23	6.77	171	11.5 (mid-plane)	194
79	17.37	12	22	6.47	175	12 (mid-plane)	218
82	17.37	9	18	5.22	154	9.3 (mid-plane)	225

Table III: Results of different spring stiffness upon scenario 79.

spring stiffness (klbs/in)	modulus (Pa)	clevis shear load (KN)	Utheta (mm)	coil stress (Mpa)	Cu bond shear stress Sxy (Mpa)	Cu bond shear stress Syz (Mpa)	Max Cu bond shear stress (Mpa)
22.33	9.E+08	28	6.52	153	7.63	12.3	12.6
17.37	7.E+08	24	7.26	161	7.67	13.1	13.3
12.41	5.E+08	19	7.84	170	7.86	14.1	14.1

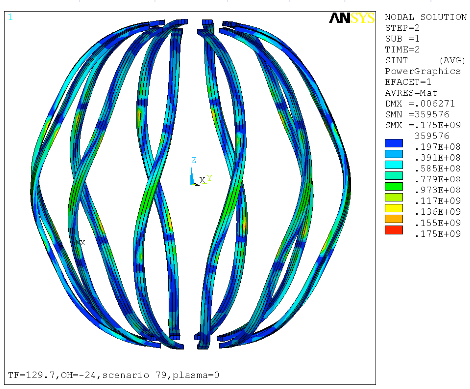

Figure 10: Coil stress upon scenario 79.

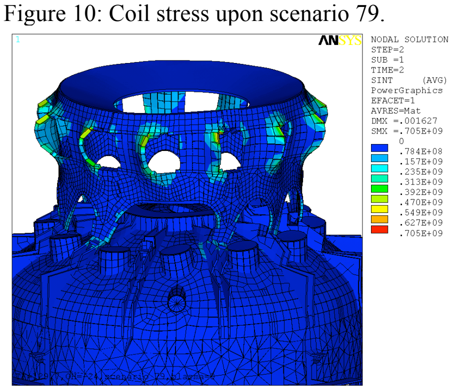

Figure 11: Umbrella structure stress upon scenario 79.

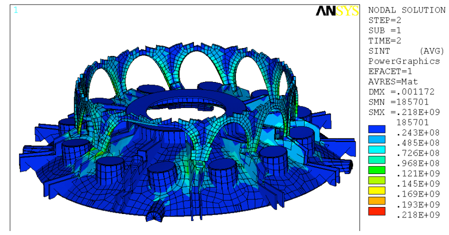

Figure 12: Arch area stress upon scenario 79.

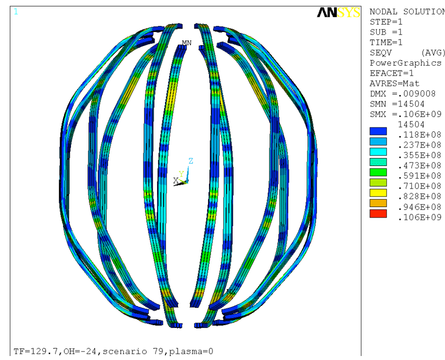

Figure 13: Coil stress in vacuum vessel bake out to 150°C.

ACKNOWLEDGMENTS

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