NSTX

Stress Analysis of ATJ Center Stack Tiles and Fasteners

NSTXU-CALC-11-03-01

Revision 1

February 17, 2014

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PPPL Calculation Form

Calculation # TXU-Calc-11-03-00 & NSTXU-Calc-11-04-00 Revision #1

Purpose of Calculation:

This calculation is intended to qualify the thermal and structural performance of the Center Stack Tiles for operation at the heat fluxes and durations specified in the GRD except as noted.

This revision (#1) reflects the change in design of the divertor tiles at the poloidal gap between the inboard and outboard divertor tiles and inclusion of the OBD qualification. An intermediate design where the material was changed to Poco TM for the divertor tiles is not part of this calculation since the design reverted back to ATJ. The Center Stack tiles away from the gap were changed to Poco TM since there was ample margin in thermal performance.

References

1) NSTX_CSU-RQMTS-GRD General Requirements Documents, Rev 3
2) Design Point Spreadsheet "NSTX_CS_Upgrade_100504.xls"
3) NSTXU-Calc-11-01-00 Global Thermal Analysis of Center Stack Heat Balance, Dated February 15, 2011
4) ProE Model of Center Stack Tiles - aj_center_case_analysis_rev2.asm
5) Spreadsheet of Disruption Data - Disruption_scenario_currents_v2.xlsx, by Jon Menard, received 7/2/2010
6) Discussions with Stefan Gerhardt on modeling of halo currents for NSTX
7) NSTX Structural Design Criteria with proposed revisions

Assumptions

See body of report

Calculation

See body of report

Conclusion

The Center Stack Tiles, with the exception of the IBD horizontal tiles, are shown to be capable of withstanding the GRD heat flux requirements using the prescribed ATJ graphite. The heat flux to the revised IBDhs design must be further limited to 4.x MW/m2 from the prior design at 4.5 MW/m2 for the 5s duration to meet the proposed Structural Design Criteria addition for Graphite Tiles. This assumes the tiles will be classified as critical components by the GRD. If they are classified as non-critical (ie, since they can be replaced) which have higher stress allowables, they too can withstand the GRD heat flux requirements. A study was performed to investigate improvements in the tile stress as a function of the attachment bolt hole diameter and tensile stresses were improved by only 5% for larger diameter bolts. The heat flux on the bolt head would increase. However the small improvement in stress was not warranted by the potential adverse effects of the thermal loads on the bolts. Appendix A was added to provide guidance on predicting tile surface temperature from thermocouple data below the surface of the tile.

Cognizant Engineer's printed name, signature, and date

Kelsey Tresemer

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

Peter H. Titus

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Revision	Effective Date	Summary of Change
0	May 9, 2011	Original Release. All ATJ Tiles
1	Nov 26, 2013	• Tiles at CHI gap extended. • Material of CS tiles, excluding IBD horizontal, changed to Poco TM. • OBD added to analysis. • Reference to FORTRAN Code for PF Field Calcs • Two Appendices added: A - CHI Gap Thermocouple Response B - Impact of Bolt Access Hole Diameter on Stress Concentrations

Executive Summary

The Center Stack Tiles, with the exception of the IBD horizontal tiles, are shown to be capable of withstanding the GRD heat flux requirements using the prescribed Poco TM and ATJ graphite. The heat flux to the IBDhs and OBD is limited by compressive stress concentrations around the bolt access holes and corner fillets arising from thermal stresses. Heat fluxes must be limited to **3.7** MW/m2 for the 5s duration to meet the proposed Structural Design Criteria addition for Graphite Tiles and avoid surface chipping. This assumes the tiles will be classified as critical components by the GRD. If they are classified as non-critical (ie, since they can be replaced) which have higher stress allowables, they too can withstand the GRD heat flux requirements.

The tile mounting scheme, consisting of T-bar supports for the CS Angle Section (CSAS) Tiles and the Inboard Divertor Horizontal (IBDhs) and Vertical (IBDvs) Tiles, and the tray support for the Center Stack First Wall (CSFW) Tiles is adequate to support the tiles against the anticipated thermal, eddy current and halo current loads with acceptable bolt loads.

This is premised on the poloidal flowing halo current's interaction with the TF field always results in tile forces which are away from the plasma, regardless of the plasma current and TF field directions as observed in NSTX operation. While the interaction of toroidal flowing halo currents, which will be in both directions due to the Toroidal Peaking, with the PF field produce forces both toward and away from the plasma, they are shown to be small relative to the poloidal current forces and result in net forces away from the plasma. If net forces were reversed, halo currents from a 2 MA plasma may not be tolerable due to high tensile stresses in the ATJ.

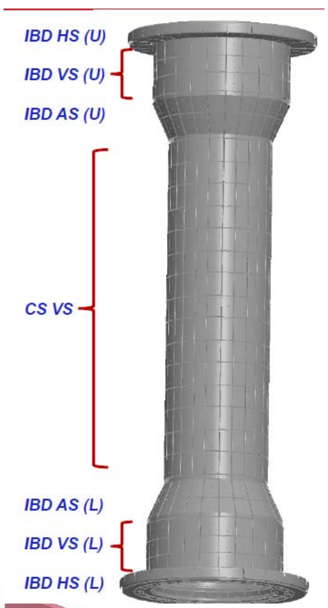
The analysis shows that the inclusion of Grafoil under the CSAS, IBDvs and IBDhs combined with the active cooling will significantly limit the thermal ratcheting of the tiles whether Li coated (with assumed emissivity of 0.3) or uncoated (with assumed emissivity of 0.7). The active cooling also offers adequate protection of the neighboring PF and OH coils and reduces the heating of the CS Casing. The flow rate and back pressure are high enough to avoid boiling of the water.

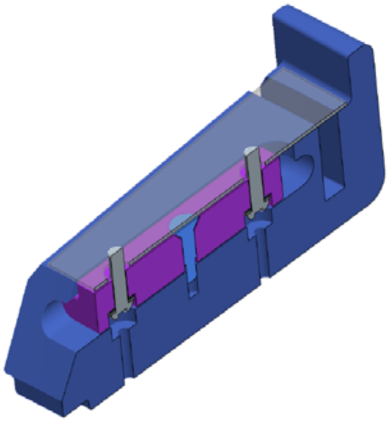
The Grafoil is shown to be structural compliant to allow relatively free thermal expansion of the tiles provided the bolts are only lightly preloaded and do not over compress the Grafoil.

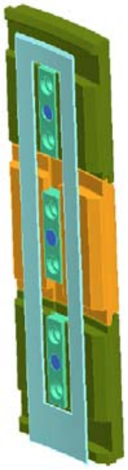
The thermocouple at the CHI Gap is shown to be response enough for pulses longer than 1 s to extrapolate the surface heating and gap heat flux.

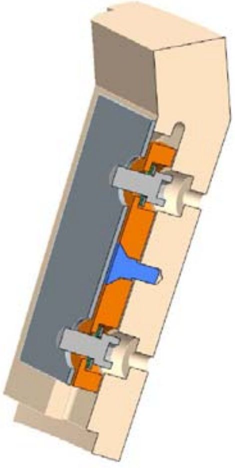
Introduction

The Center Stack Casing (CSC) Plasma Facing Components (PFC) tiles are designed to protect the Center Stack from the high heat fluxes of the plasma. They are divided into four sections of tiles referred to in the General Requirements Document (GRD) as the Inboard Divertor Horizontal (IBDhs) and Vertical (IBDvs) Tiles, the CS Angle Section (CSAS aka IBDAS) Tiles, and the Center Stack First Wall (CSFW aka CSVS) Tiles. The GRD requires all CSC PFC tiles be designed using high-grade graphite material. The use of carbon fiber composites is not permitted due to Lithium retention of the coarse weave. The available tile thickness is also dictated by the GRD. As a result the goal of the analysis is to establish safe operating limits up to the GRD desired level. Tile mounting details have been optimized within these constraints to enhance the thermal performance while withstanding the electromagnetic loading from plasma disruption induced eddy currents and halo currents.




IBD HS

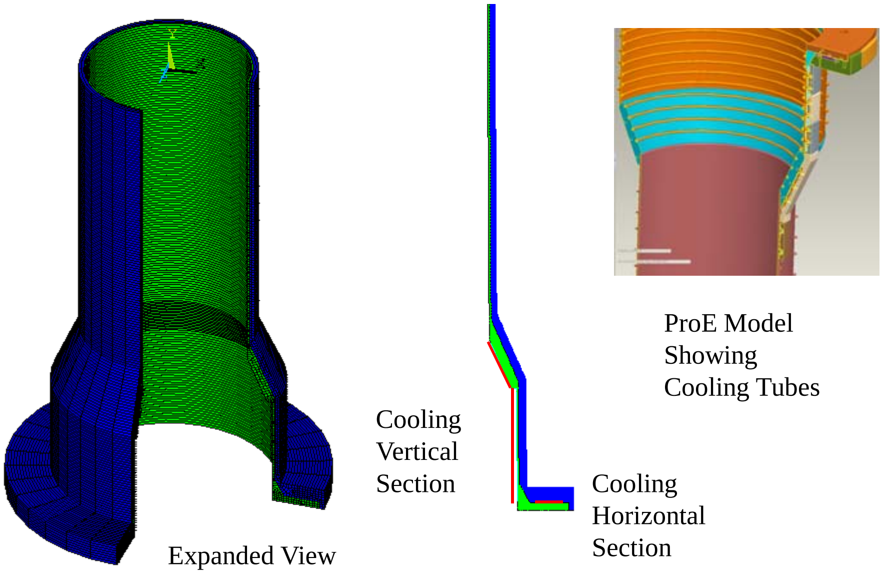

IBD VS


CS AS


CS FW

Heat is removed from the CSAS, IBDhs and IBDvs tiles by radiation to cooled outboard components (OD, PP & VV) and by the CSC water cooling system. The CSFW tiles are only radiation cooled since the CSC cooling does not extend up between the Casing and the OH coils. One of the design decisions resulting from this analysis is the use of a thermal interface material – Grafoil – between the tiles and the CSC. The original plan was to limit the heat transfer between the tiles and the CSC by not using Grafoil and relying on radiation only, out of concern about over heating the water. There are now four CSC cooling circuits in the design (two on top and two on the bottom) where there are dedicated circuits for the high heat flux IBDhs. Analysis has shown them to be adequate to safely remove the heat during the transient. The result is the water cooled tiles do not thermally ratchet with repeated pulsing. There will be ratcheting of the uncooled CSFW but the incident heat fluxes are low as would be the peak temperatures.

Axisymmetric Thermal Model of CS Tiles and Casing



Assumptions

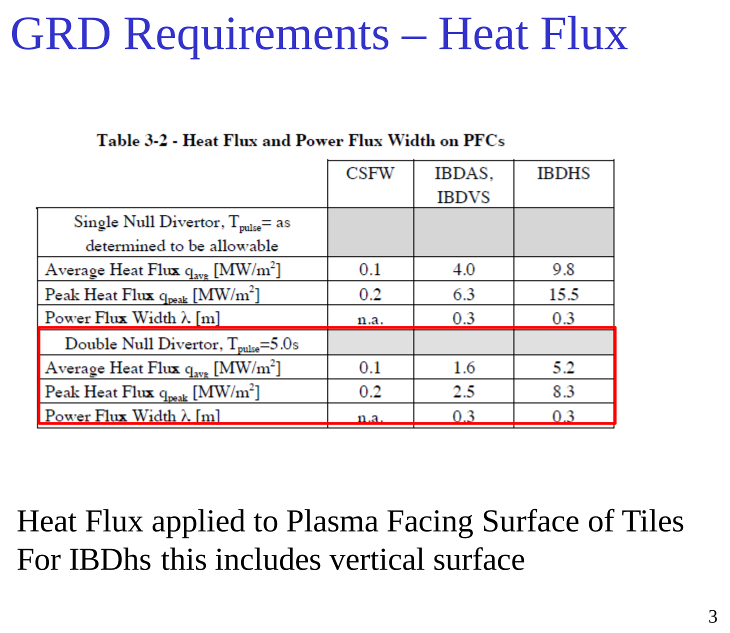
The tile mounting schemes are designed to permit relatively free thermal expansion, minimizing thermal stresses. The CSAS, IBDhs and IBDvs tiles use T-bar supports held by bolts with Belleville washers and with compliant Grafoil underneath. The bolts are lightly loaded (500 N or 112 lbs) to permit bowing of the tiles under thermal gradients. Tolerances are set to assure the load path for EM forces is directly into the Grafoil and not the bending the tile over the T-Bar.

The analysis assumes the poloidal flowing halo current's interaction with the TF field always results in tile forces which are away from the plasma, regardless of the plasma current and TF field directions as observed in NSTX operation. While the interaction of toroidal flowing halo currents, which will be in both directions due to the Toroidal Peaking, with the PF field produce forces both toward and away from the plasma, they are shown to be small relative to the poloidal current forces and result in net forces away from the plasma. If net forces were reversed, halo currents from a 2 MA plasma may not be tolerable due to high tensile stresses in the ATJ.

The analysis is done using the average heat fluxes associated with a 14 MW plasma of 5 second duration pulse with 1200 second rep rate.

Method of Analysis

ANSYS models were used to analyze the thermal and structural response of each of the four tile types. ProE models of the tile and supports were imported into ANSYS Classic. A thermal transient was run to generate the temperature distribution on the ATJ tiles.



GRD Requirements – Heat Flux

Table 3-2 - Heat Flux and Power Flux Width on PFCs

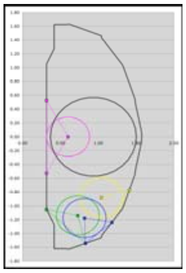
	CSFW	IBDAS, IBDVS	IBDHS
Single Null Divertor, T_{pulse}= as determined to be allowable			
Average Heat Flux q_{avg} [MW/m^2]	0.1	4.0	9.8
Peak Heat Flux q_{peak} [MW/m^2]	0.2	6.3	15.5
Power Flux Width λ [m]	n.a.	0.3	0.3
Double Null Divertor, T_{pulse}=5.0s			
Average Heat Flux q_{avg} [MW/m^2]	0.1	1.6	5.2
Peak Heat Flux q_{peak} [MW/m^2]	0.2	2.5	8.3
Power Flux Width λ [m]	n.a.	0.3	0.3

Heat Flux applied to Plasma Facing Surface of Tiles
For IBDhs this includes vertical surface

3

Eddy currents were calculated using max values of dB/dt (vertical and radial) at the tile locations found from scanning the 5 disruption scenarios given in Table 2.2 of the GRD. The scans were done using the SPARK code with previously generated models of the VV, CS and PP. A resistive distribution is assumed based on the very short time constant for the tiles. For ATJ tiles with an electrical resistivity of 11.7e-6 Ohm-m, max thickness of 5 cm, and 17 cm width, the time constant is less than 0.1 ms.

Requirements – EM Loads
Eddy Currents



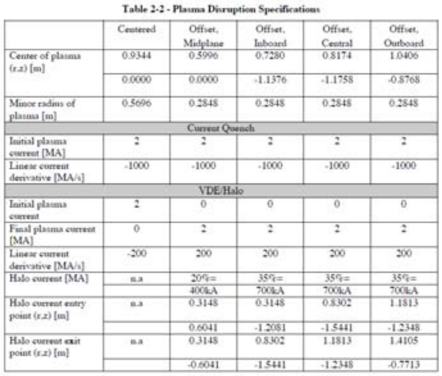
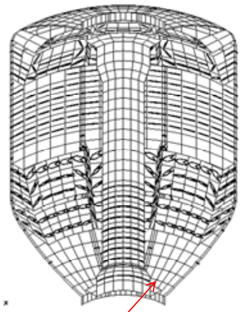


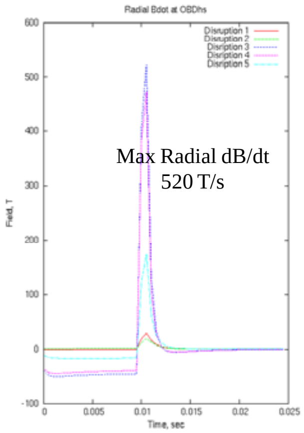
Table 2-2 - Plasma Disruption Specifications

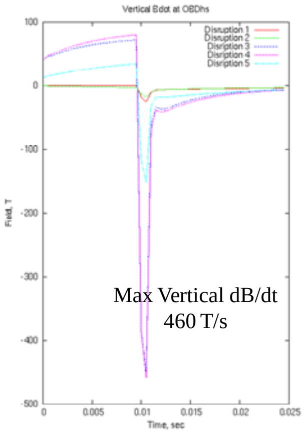
	Centered	Offset, Midplane	Offset, Inboard	Offset, Central	Offset, Outboard
Center of plasma (r,z) [m]	0.9344	0.5996	0.7280	0.8174	1.0406
	0.0000	0.0000	-1.1376	-1.1758	-0.8768
Minor radius of plasma [m]	0.5696	0.2848	0.2848	0.2848	0.2848
Current Quench					
Initial plasma current [MA]	2	2	2	2	2
Linear current derivative [MA/s]	-1000	-1000	-1000	-1000	-1000
VDE/Halo					
Initial plasma current	2	0	0	0	0
Final plasma current [MA]	0	2	2	2	2
Linear current derivative [MA/s]	-200	200	200	200	200
Halo current [MA]	n.a	20%=	35%=	35%=	35%=
		400kA	700kA	700kA	700kA
Halo current entry point (r,z) [m]	n.a	0.3148	0.3148	0.8302	1.1813
		0.6041	-1.2081	-1.5441	-1.2348
Halo current exit point (r,z) [m]	n.a	0.3148	0.8302	1.1813	1.4105
		-0.6041	-1.5441	-1.2348	-0.7713

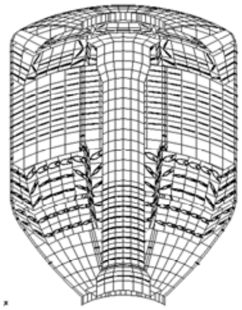


SPARK Scan of above disruptions yielded
Max dB/dt = 520 T/s Radial, 460 T/s Vertical
at diverter

dB/dt scan from Plasma at Horizontal Inboard Diverter During Disruptions







Based on 2 MA for NSTX CSU

The background maximum field values were obtained by scanning thru the 96 operating scenarios specified in the Design Point Spreadsheet “NSTX_CS_Upgrade_100504.xls” using a FORTRAN code built on the Magnetics Library routine FICOI. This was found to be in agreement with results generated by others using the OPERA code.

Requirements – Peak Background Fields

Coil	R (center)	dR	Z (center)	dZ	nR	nZ	Turns	Fill
	(cm)	(cm)	(cm)	(cm)				0.0000
OH (half-plane)	24.2083	6.9340	106.0400	212.0800	4.0	110	442	0.7013
PF1a	31.9300	5.9268	159.0600	46.3533	4.0	16	64	0.8594
PF1b	40.0380	3.3600	180.4200	18.1167	2.0	16	32	0.7938
PF1c	55.0520	3.7258	181.3600	16.6379	2.0	10	20	0.8560
PF2a	79.9998	16.2712	193.3473	6.7970	7.0	2	14	0.7409
PF2b	79.9998	16.2712	185.2600	6.7970	7.0	2	14	0.7409
PF3a	149.4460	18.6436	163.3474	6.7970	7.5	2	15	0.6928
PF3b	149.4460	18.6436	155.2600	6.7970	7.5	2	15	0.6928
PF4b	179.4612	9.1542	80.7212	6.7970	2.0	4	8	0.7525
PF4c	180.6473	11.5265	88.8086	6.7970	4.5	2	9	0.6723
PF5a	201.2798	13.5331	65.2069	6.8580	6.0	2	12	0.7733
PF5b	201.2798	13.5331	57.8002	6.8580	6.0	2	12	0.7733

Btf = 1T at 0.9344m

PF Configuration from NSTX_CS_Upgrade_100504.xls
Scan of 96 scenarios in same spreadsheet used to establish max fields:

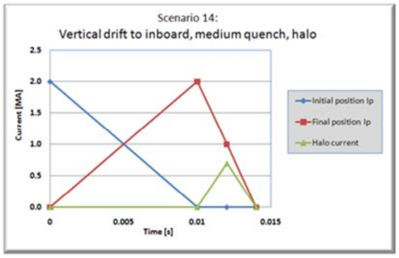
Max Br = 0.5 T
Max Bz = -0.57 T

Avg Btf ~ 2 T at IBDhs
Max Btf ~ 3 T at CS

Halo currents in the tiles are based on the resistive sharing of poloidal currents with the CSC. While the tiles themselves are not poloidally continuous, it is postulated that during a halo current strike plasma fills the gaps between the participating tiles and shorts them out. At an estimate temperature of 10ev, plasma resistivity is comparable to ATJ graphite.

Requirements - Halo

Analysis Priority [1=high]	Scenario index and analysis sequence	Scenario category	Disruption scenario description	Initial Ip [MA]	Initial position index	Final position index	Drift time [s]	Quench time [s]	Ip quench rate [GA/s]	Halo fraction f_h
1	1	1	Centered disruption, fast quench	2	1	1	0.01	0.001	2	0
1	2	2	Initiated shifted to CS, fast quench, no halo	2	2	2	0.01	0.001	2	0
1	6	2	Inward drift to CS, very slow quench, halo	2	1	2	0.01	0.1	0.02	0.2
1	3	3	Initiated shifted down to inboard, fast quench, no halo	2	3	3	0.01	0.001	2	0
1	7	3	Vertical drift to inboard, very slow quench, halo	2	1	3	0.01	0.1	0.02	0.35
1	4	4	Initiated shifted down to middle, fast quench, no halo	2	4	4	0.01	0.001	2	0
1	8	4	Vertical drift to middle, very slow quench, halo	2	1	4	0.01	0.1	0.02	0.35
1	5	5	Initiated shifted down to outboard, fast quench, no halo	2	5	5	0.01	0.001	2	0
1	9	5	Vertical drift to outboard, very slow quench, halo	2	1	5	0.01	0.1	0.02	0.35



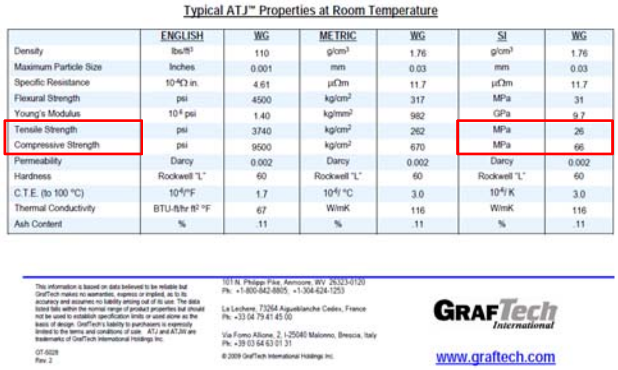
Excepted from
Disruption_scenario_currents_v2.xlsx

For IBDhs,
Halo = **35 kA** per 15 deg Tile
(2MA/24Tiles*.35HCF*1.2TPF)

Halo current assumed to take longest path across TF for worse case loading unless justification can be made not to.

The tile thermal and structural performance is based on the use of ATJ graphite who’s properties are given below.

ATJ Graphite Properties



Typical ATJ™ Properties at Room Temperature

	ENGLISH	WG	METRIC	WG	SI	WG
Density	lbs/ft³	110	g/cm³	1.76	g/cm³	1.76
Maximum Particle Size	Inches	0.001	mm	0.03	mm	0.03
Specific Resistance	10^{-4}Ω in.	4.61	µΩm	11.7	µΩm	11.7
Flexural Strength	psi	4500	kg/cm²	317	MPa	31
Young's Modulus	10^{6} psi	1.40	kg/mm²	982	GPa	9.7
Tensile Strength	psi	3740	kg/cm²	262	MPa	26
Compressive Strength	psi	9500	kg/cm²	670	MPa	66
Permeability	Darcy	0.002	Darcy	0.002	Darcy	0.002
Hardness	Rockwell "L"	60	Rockwell "L"	60	Rockwell "L"	60
C.T.E. (to 100 °C)	10^{-6}/°F	1.7	10^{-6}/ °C	3.0	10^{-6}/ K	3.0
Thermal Conductivity	BTU-ft/hr ft² °F	67	W/mK	116	W/mK	116
Ash Content	%	.11	%	.11	%	.11

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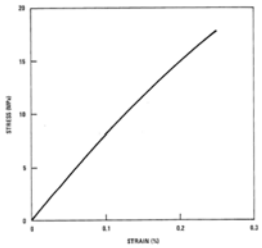


Fig. 3.3-4 Tensile stress-strain curve for 2020 graphite

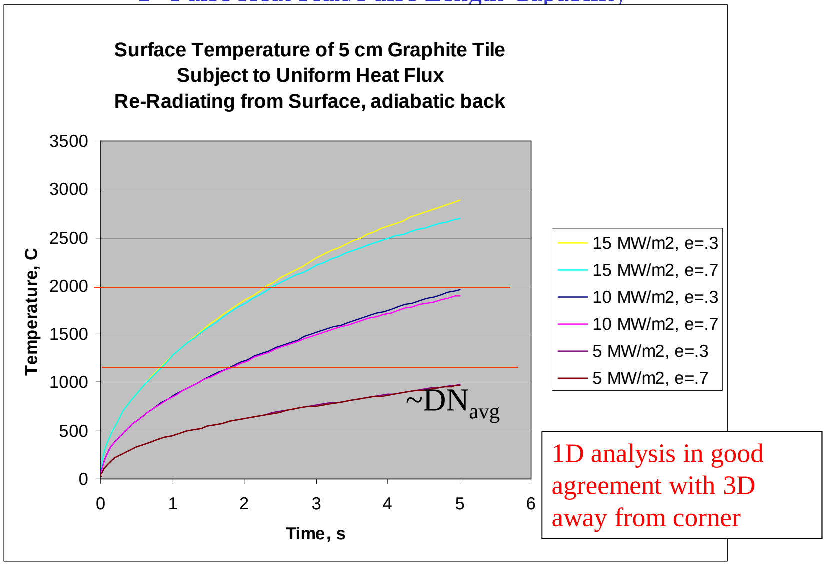
Representative Tensile Stress-Strain Curve from GRAPHITE DESIGN HANDBOOK GA 1988 (for 2020 graphite)

8

Results

A 1-D thermal performance of ATJ Graphite was generated at heat fluxes varying from 5 15 MW/m2 (DN) to 15 MW/m2 (SN) for comparison. It suggests that the design which is governed per the GRD by the DN operation for 5 sec would limit single null operation to under 1 sec.

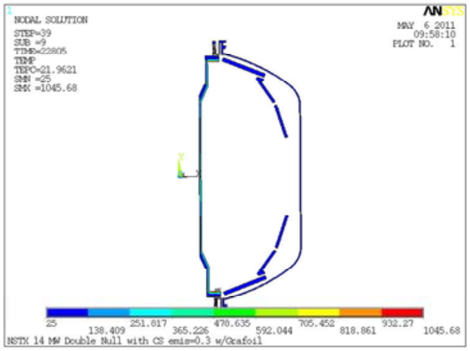
1st Pulse Heat Flux/Pulse Length Capability

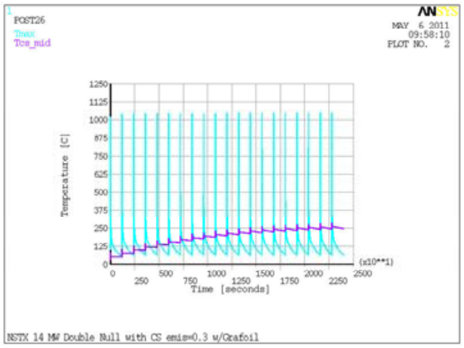


1D analysis in good agreement with 3D away from corner

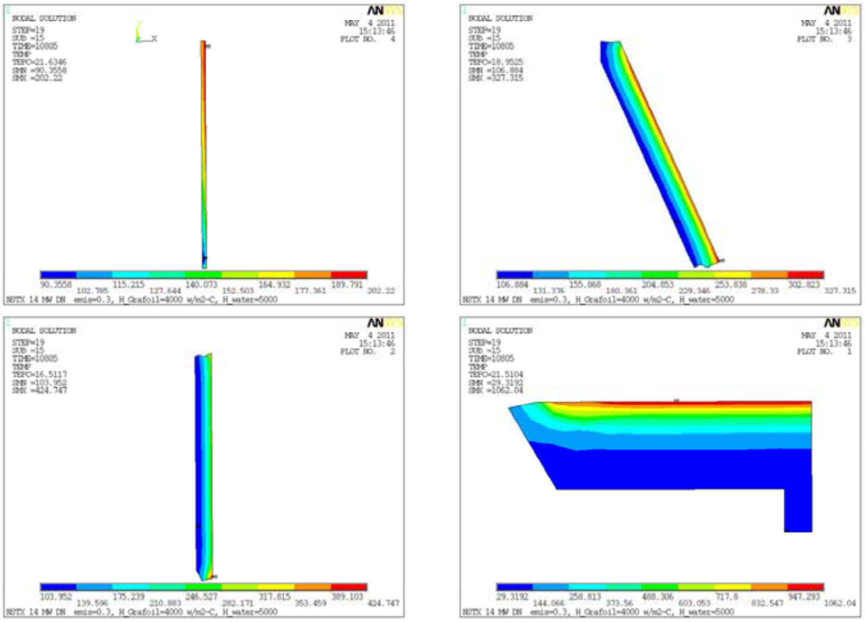
11 Single pulse without ratcheting with ATJ Graphite

A 2-D axisymetric thermal model to the previously run was modified to reflect the use of Grafoil under the tiles. The model was also modified to include the effect of water transport (using ANSYS fluid116 elements) instead of just using an effective film coefficient as used in earlier analyses. This limited the thermal ratcheting while still providing adequate limits on the water temperature rise as shown below.

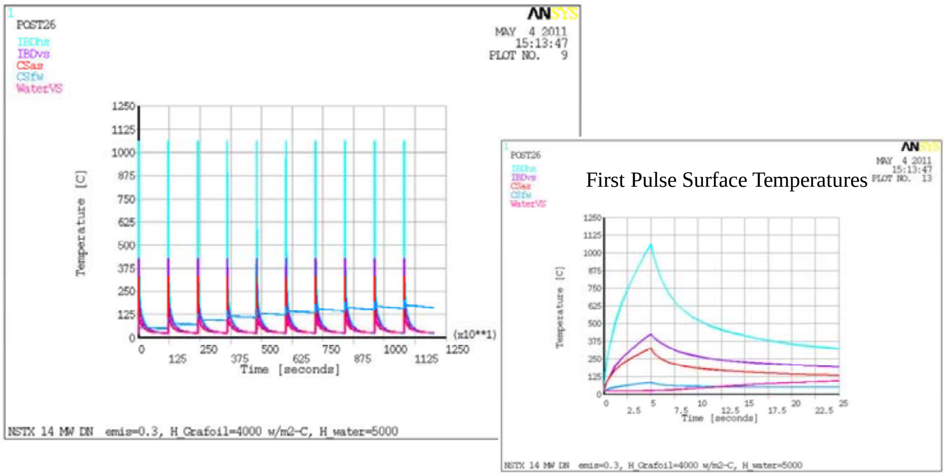




Tile Ratcheted Temperatures



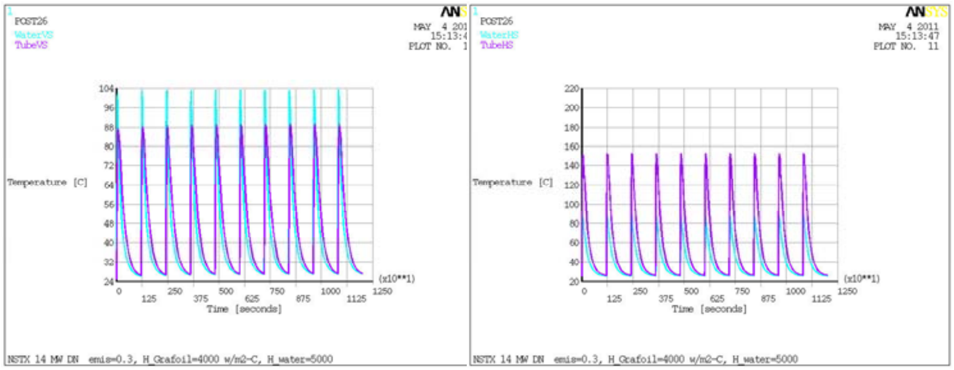
No Ratcheting on Water Cooled Tiles
Only on Radiation Cooled CSFW

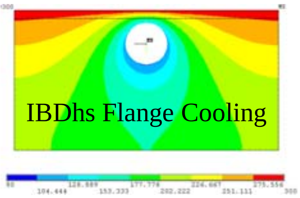


First Pulse Surface Temperatures

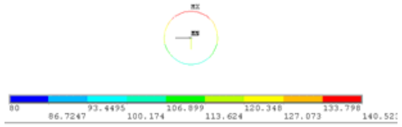
Water in Cooling Loops stays below ~100 C

Neighboring Case Temperature Higher





IBDhs Flange Cooling



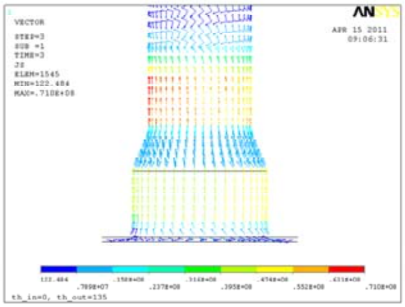
IBDhs Flange Cooling Tube Surface

A halo current distribution model was also created to investigate the direction of forces on the tile. This was crucial to the structural performance. Results show that forces are always away from the plasma and into the supporting CSC which limits the tile stresses since the tile is effective supported off it base and not the thin sections at the T-Bar.

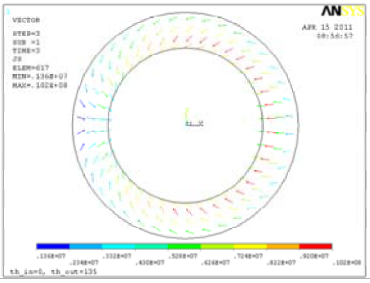
Halo Currents and Force Directions in the CS

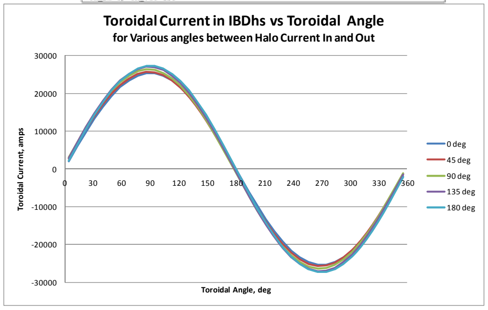
- The halo currents and associated Lorentz forces & directions are based on the following:
  - Halo Currents are resistively distributed.
  - Halo Currents are predominantly poloidal
    - Studies show this to be true even with large toroidal peaking (TPF) with in and out strike points at different toroidal angles
    - The exception is near the strike points where current quickly redistributes
  - The tiles are assumed shorted to each other (at least locally) by plasma filling the gaps
    - It is estimated that at a temperature of 10ev, the plasma electrical resistivity is very close to ATJ graphite (thou it may not penetrate very deep into the gap)
  - As a result of the above, there is current sharing between the tiles and CS casing based on the relative resistance
- Per Stefan Gerhardt, the interaction of the halo currents with the TF is always such as to press tiles toward VV wall or CS Casing
  - This is this is true even when the TF direction is opposite the plasma current.
- The interaction with the PF should result in some forces pulling tiles away from the wall where there is a component of halo current flowing in opposite toroidal directions (see next slide)

Halo Current Distribution with TPF=1.5 Strike on IBDhs



Current Direction is fairly poloidal in IBDvs, CSAS and CSFW but has sizable toroidal currents in both directions due to Halo Toroidal Peaking Factor

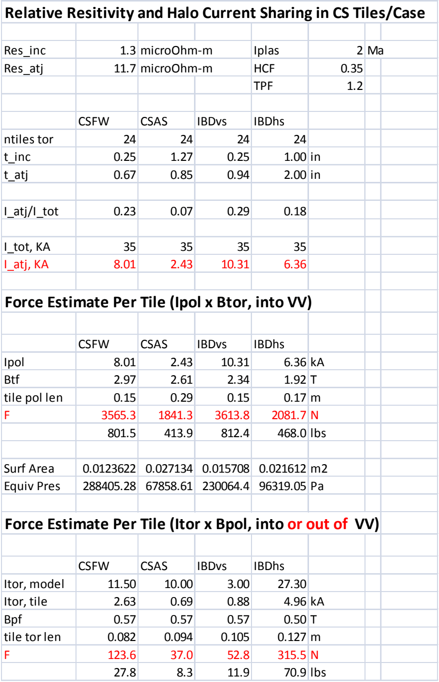




As a result of Toroidal Peak, there is a resistive redistribution of current primary in the low resistance section of the IBDhs. When crossed with the radial PF this will cause some tiles to experience forces into the wall and others away from the wall. The IBDhs current toroidal distribution is driven more by the TPF than by the assumed toroidal angle between strike in and out. Peak toroidal current in IBDhs is 27.3 kA of which 4.9 kA flows thru the ATJ tile assuming a resistive distribution between tile and casing.

Current Sharing and Tile Forces

- Tiles share less than 30% of Halo currents based on relative resistance
- Forces due to the toroidal flow of halo currents are small compared to the poloidal component.
- Net Forces will remain into the VV/CS



Relative Resitivity and Halo Current Sharing in CS Tiles/Case

Res_inc	1.3	microOhm-m		Iplas	2	Ma
Res_atj	11.7	microOhm-m		HCF	0.35	
				TPF	1.2	
	CSFW	CSAS	IBDvs	IBDhs		
ntiles tor	24	24	24	24		
t_inc	0.25	1.27	0.25	1.00	in	
t_atj	0.67	0.85	0.94	2.00	in	
I_atj/I_tot	0.23	0.07	0.29	0.18		
I_tot, KA	35	35	35	35		
I_atj, KA	8.01	2.43	10.31	6.36		

Force Estimate Per Tile (Ipol x Btor, into VV)

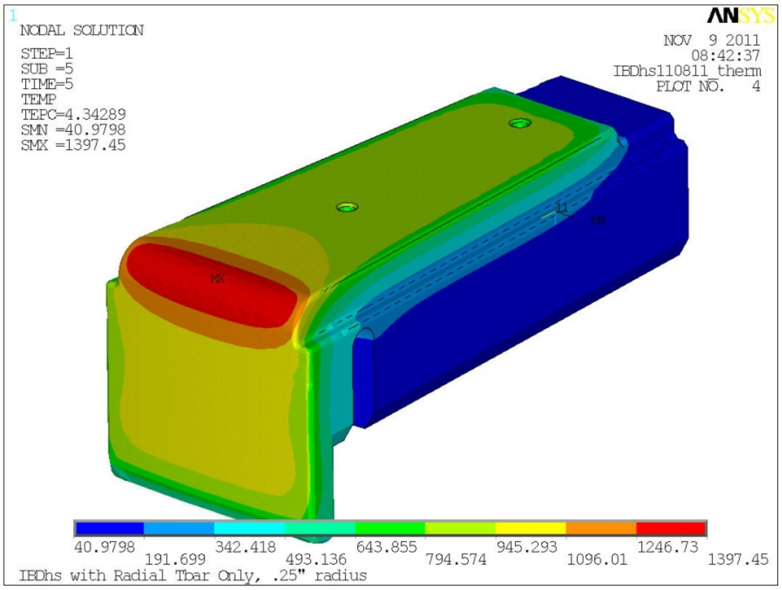
	CSFW	CSAS	IBDvs	IBDhs	
Ipol	8.01	2.43	10.31	6.36	kA
Btf	2.97	2.61	2.34	1.92	T
tile pol len	0.15	0.29	0.15	0.17	m
F	3565.3	1841.3	3613.8	2081.7	N
	801.5	413.9	812.4	468.0	lbs
Surf Area	0.0123622	0.027134	0.015708	0.021612	m2
Equiv Pres	288405.28	67858.61	230064.4	96319.05	Pa

Force Estimate Per Tile (Itor x Bpol, into or out of VV)

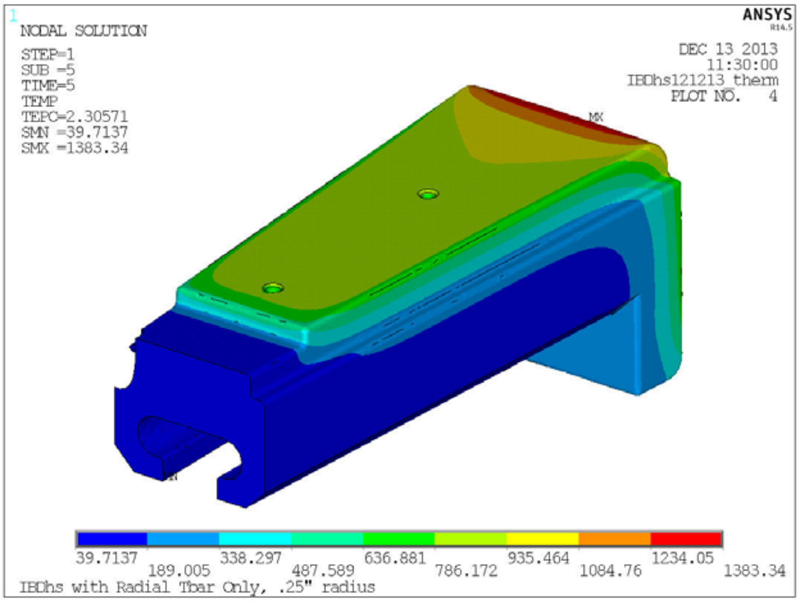
	CSFW	CSAS	IBDvs	IBDhs	
Itor, model	11.50	10.00	3.00	27.30	
Itor, tile	2.63	0.69	0.88	4.96	kA
Bpf	0.57	0.57	0.57	0.50	T
tile tor len	0.082	0.094	0.105	0.127	m
F	123.6	37.0	52.8	315.5	N
	27.8	8.3	11.9	70.9	lbs

Results for Individual Tiles:

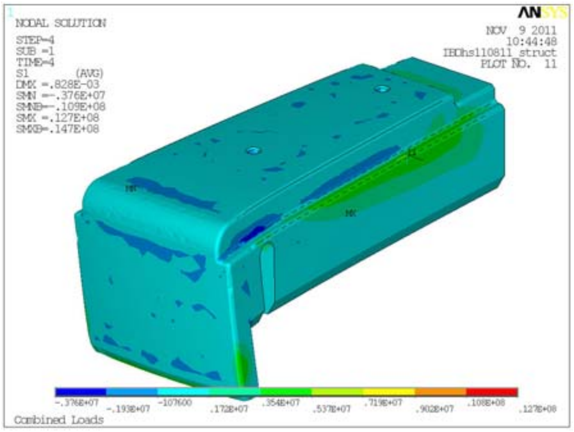
IBDhs

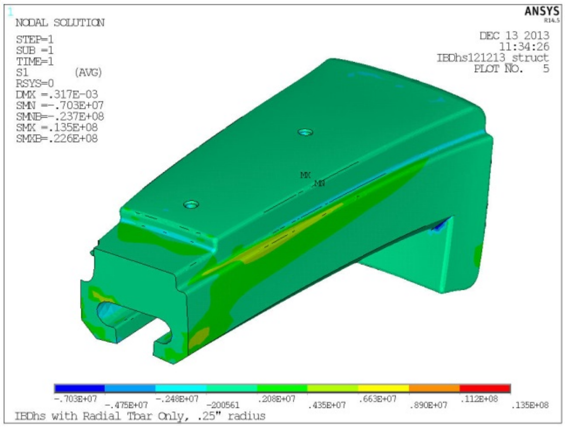


The temperature response for a 5 second pulse at 5 MW/m2 on the top horizontal surface, the vertical surface at the gap and the large corner radius. The results are perhaps conservative in the sense that the same heat load is applied concurrently to all three surfaces. However it ignores the possible increased heating at the toroidal gaps between tiles. The change in design below shows comparable temperatures as expected.

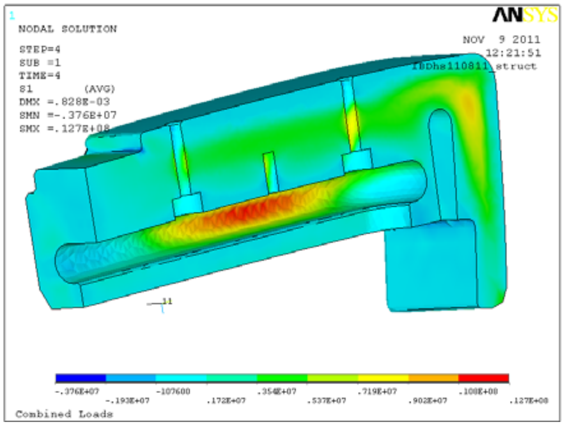


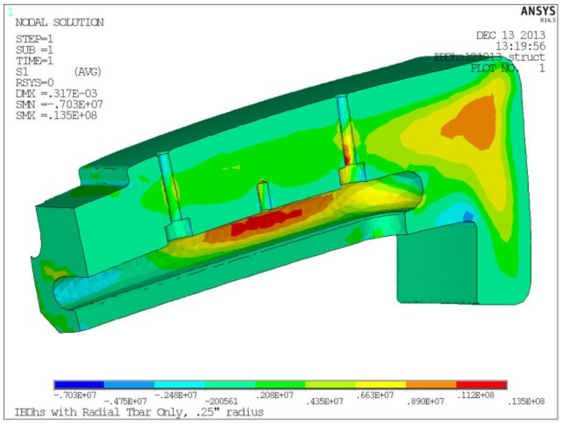
IBDhs – Combined Loading (Eddy, Halo & Thermal)

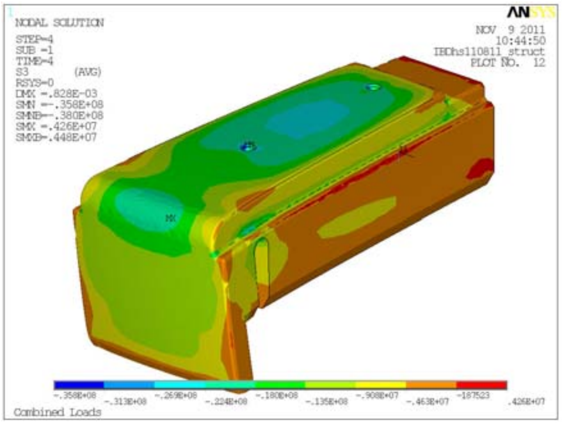


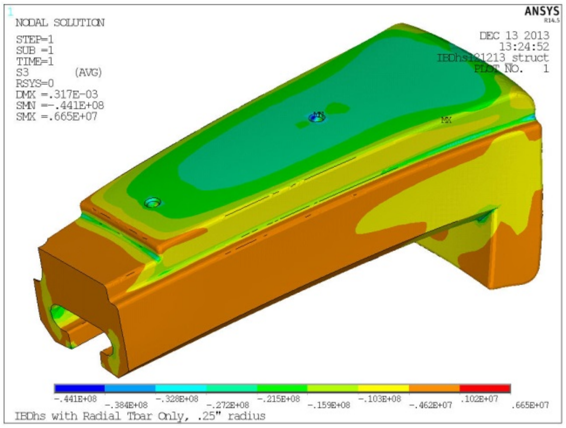


The IBDhs tile shows highest tensile stresses of 12.7 MPa (old design left) for combined loading in the T-slot increased to 13.5 MPa (new design right) as revealed in the sectioned view below.

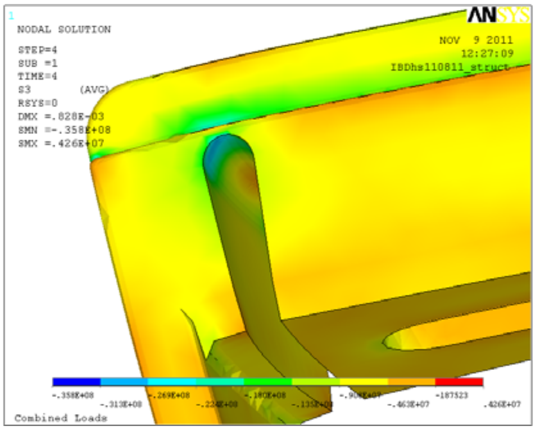


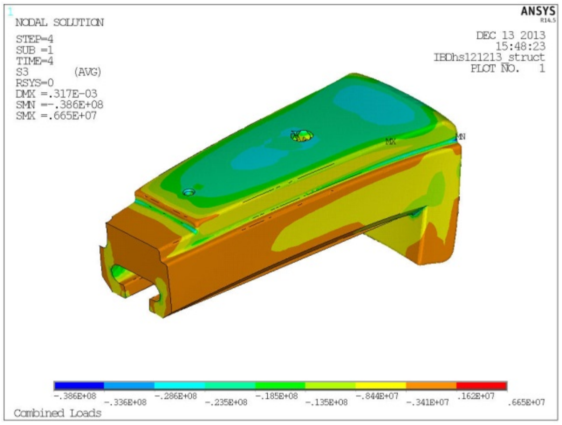






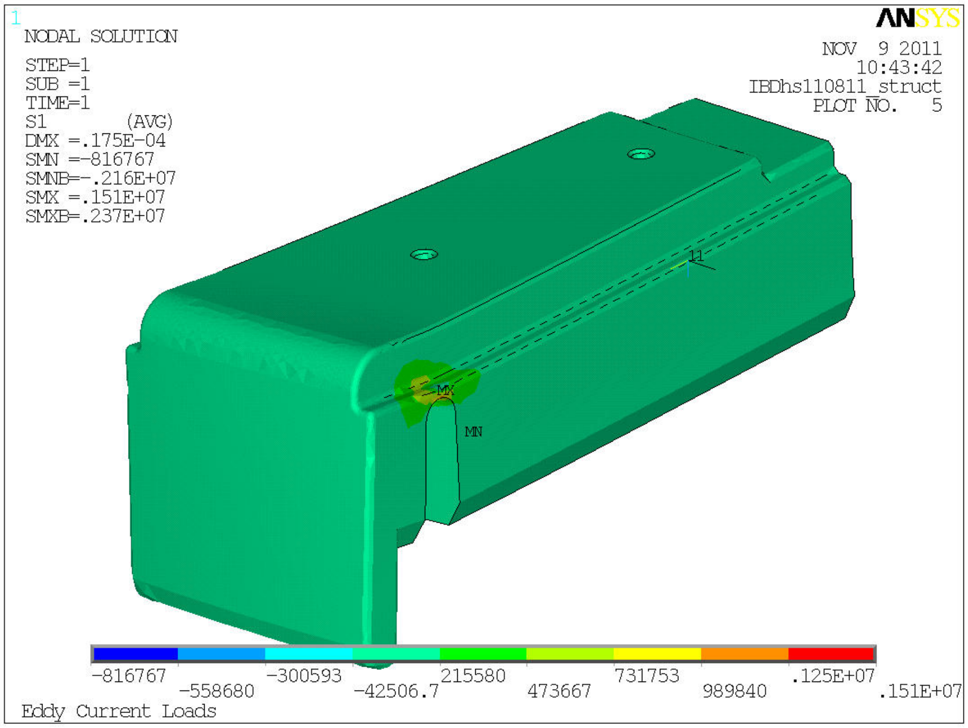
The highest compressive stresses of -35.8 MPa (old design left) are at the top heated surfaces as expected, peaking at the chamfer on the bolt access holes due to the local stress concentration. The stresses increase to -44.1 MPa (new design right). Away from the countersink at the holes the stress are reduce to -38.6 MP at the ends of the fillets (below right). The old design had a toroidal slot for the Rogowski coil (below left). This feature is not part of the new design and contributed to the increase in compressive stress magnitude.

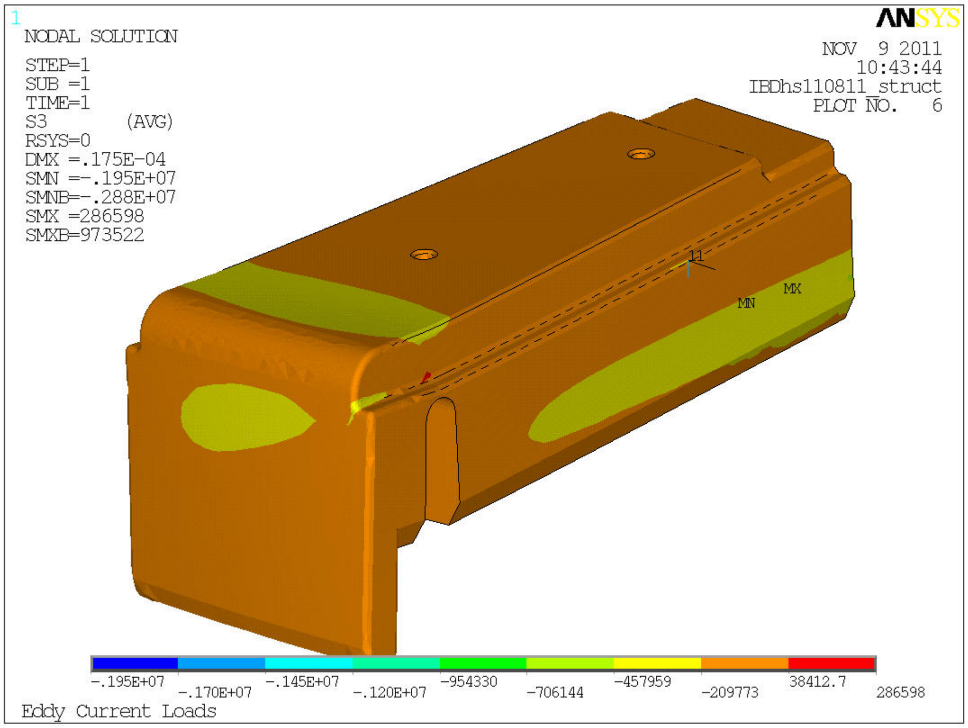




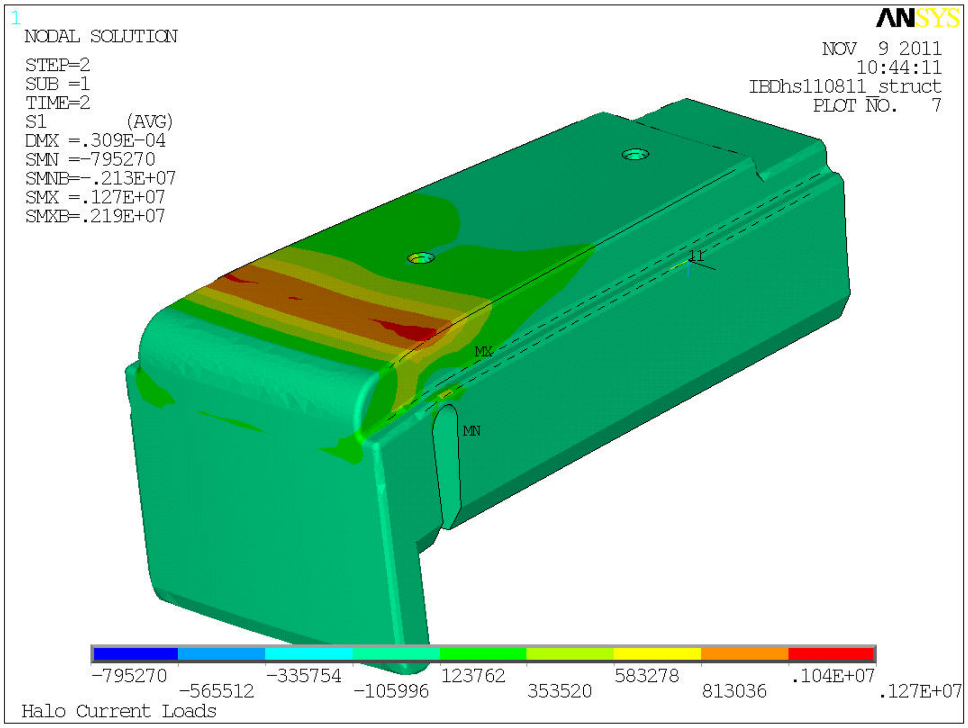
IBDhs –Eddy Current Loading

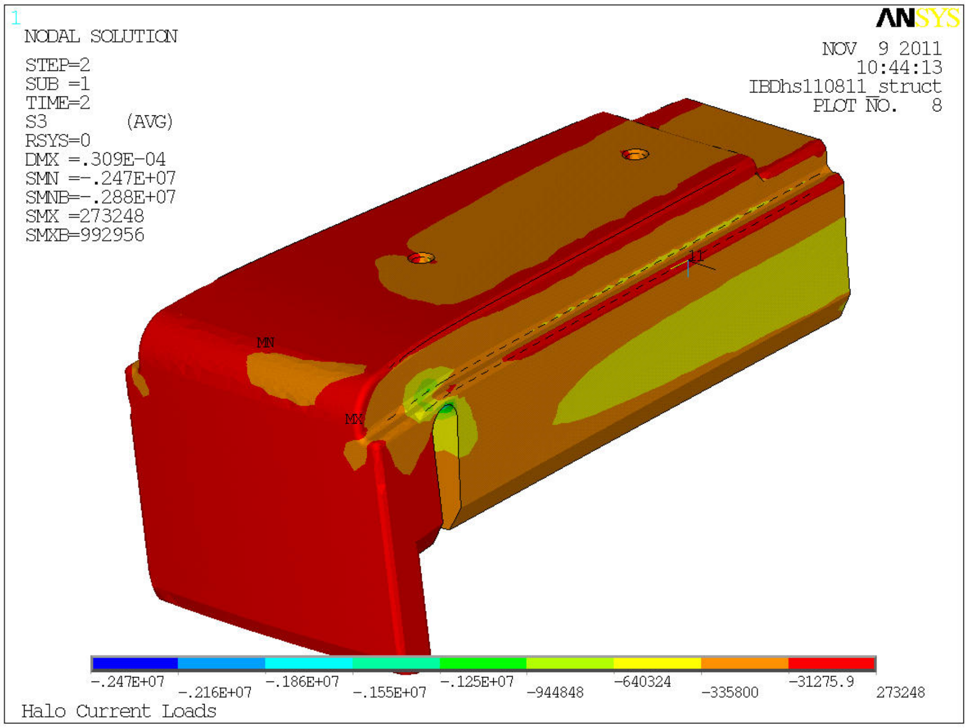
The figures which follow give principal stress (S1 & S3) results for each load case. Thermal loads are shown to dominate.



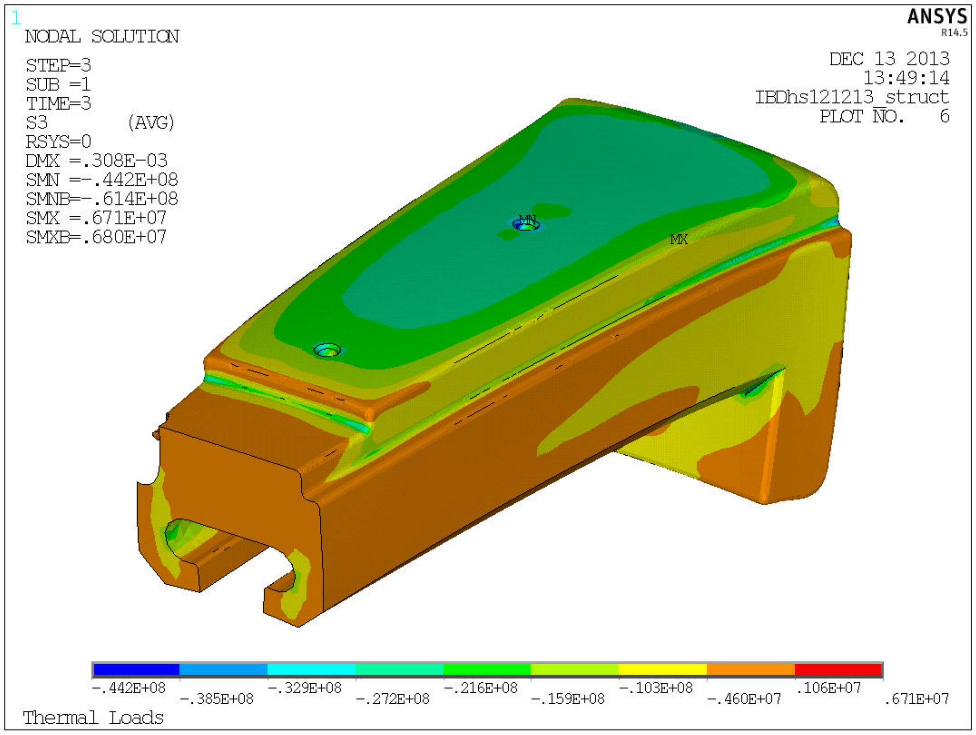


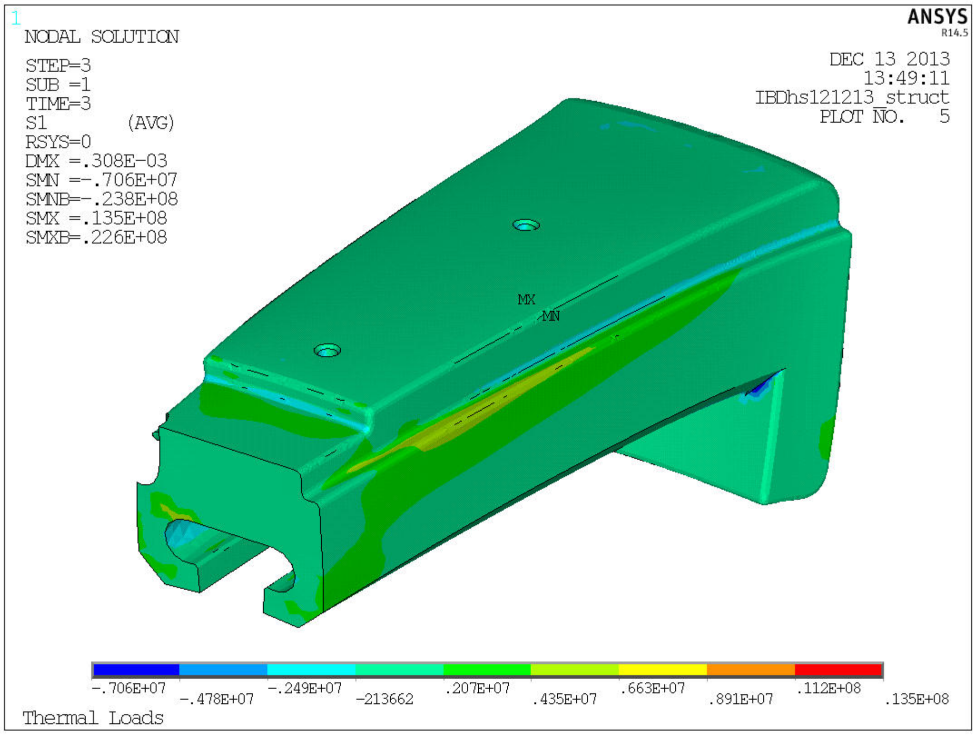
IBDhs –Halo Current Loading





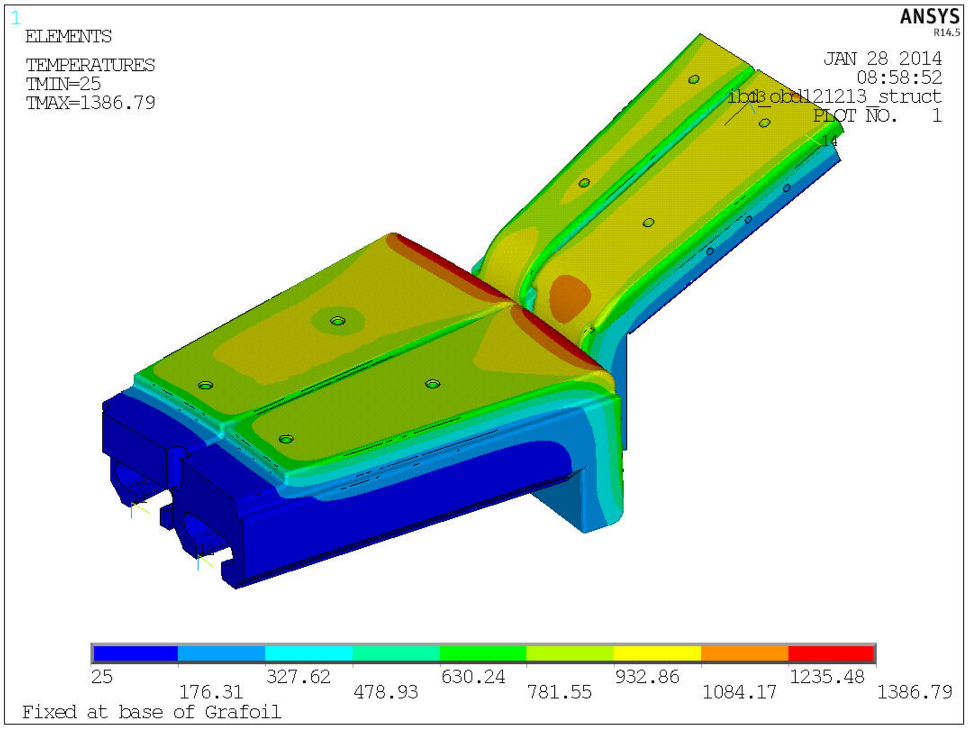
IBDhs –Thermal Loading



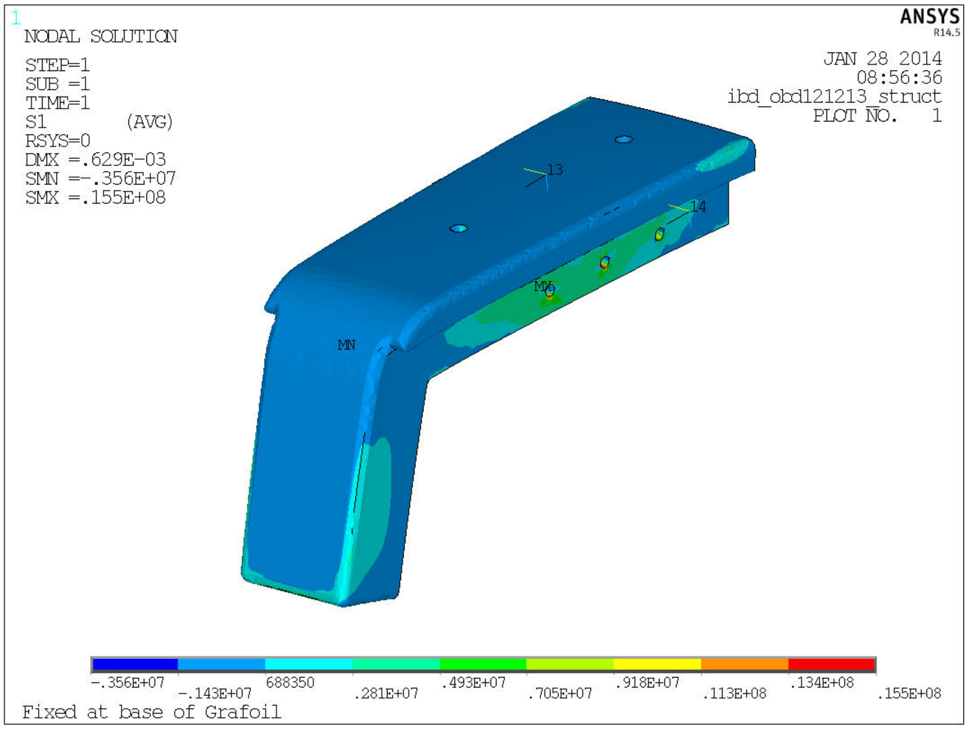


The thermal stresses above dominate, driving the high tensile stresses in the t-slot and the high compressive stresses on the surface.

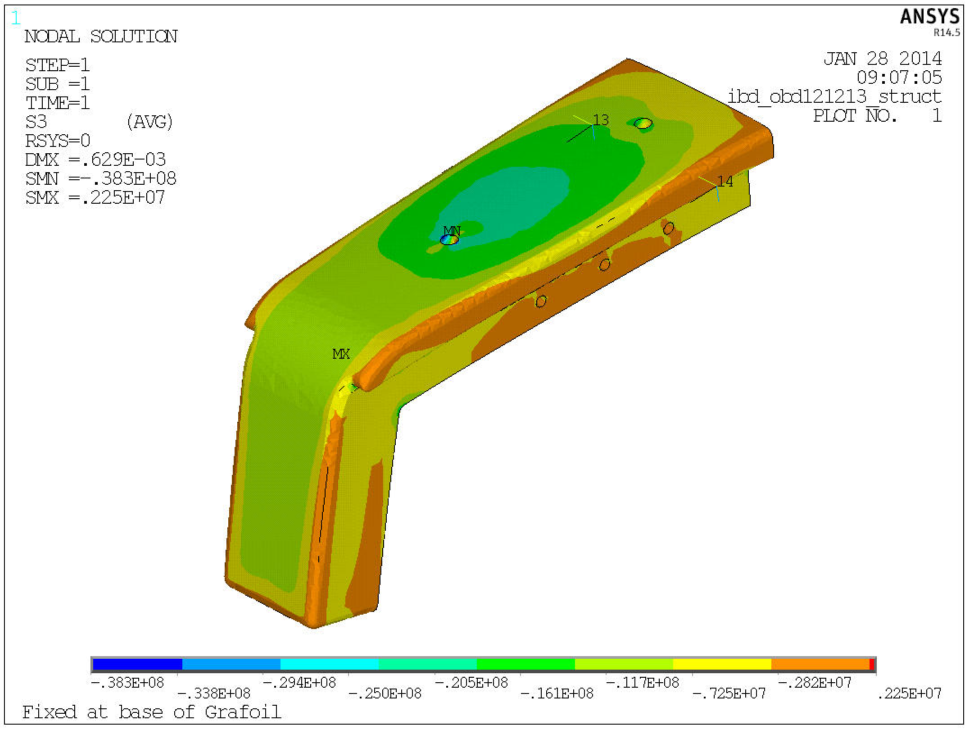
Outboard Divertor (OBD)



The OBD temperature response for the same heat flux as the IBDhs results in lower peak temperatures due to the larger corner radius. Again the results are perhaps conservative in the sense that the same heat load is applied concurrently to all three surfaces. However, as with the IBDhs, it ignores the possible increased heating at the toroidal gaps between tiles.



The dominant tensile thermal stresses for the OBD are at the retaining holes running toroidally thru the base of the tiles, again due to stress concentrations, reaching 15.5 MPa. As with the IBDhs tiles, the compressive stresses peak on the surface with a stress concentration around the bolt access holes of -38.3 MPa.



IBDhs - Stress Summary

	Old Design		New Design	
	Principal Stresses, MPa		Principal Stresses, MPa	
	S1	S3	S1	S3
Eddy Currents	1.5	-2.0	-	-
Halo Currents	1.3	-2.5	-	-
Thermal	12.7	-36.5	13.5	-44.2
Combined	12.7	-35.8	13.5	-44.1
Ultimate Strength	26	-66		
Stress Allowable				
Critical Components	13.00	-33.00		
Non-Critical Components	19.5	-49.5		

The table above summaries the peak stresses in the preceding plots and the allowable stress based on the criteria discussed below. The compressive stresses from the thermal loading will limit the operation if the tiles are ultimately categorized as critical components by the GRD as discussed below. Note the new design was not run with separate load cases for just eddy or halo currents, only combined.

Design Criteria

The NSTX CSU is design to meet the NSTX Structural Design Criteria. However the existing criteria is silent on brittle materials. A revision to the criteria has been proposed specifically to address graphite tiles:

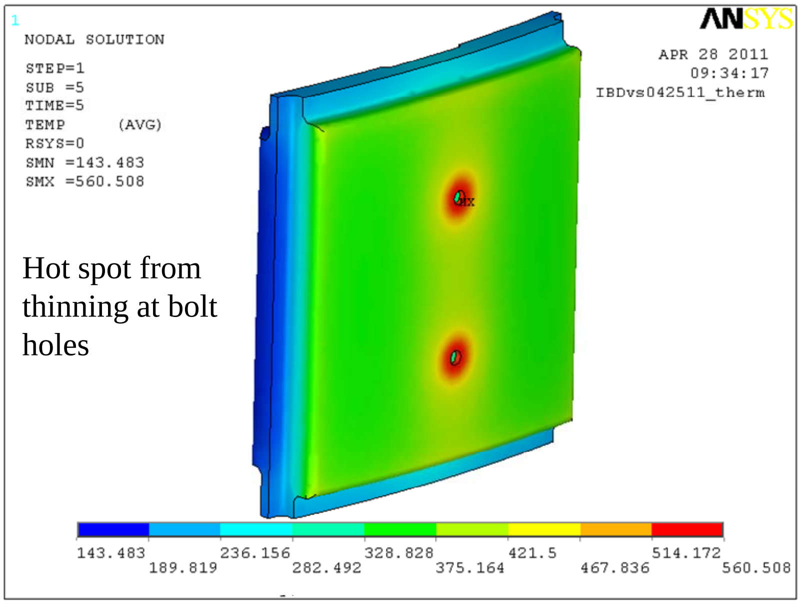
“This section describes the design criteria for carbon and carbon fiber composite (CFC) tiles. For static stresses, the design allowable stress of critical components (as defined by the GRD) shall be limited to **1/2 of the ultimate** tensile and compressive stresses at temperature. Note that these materials generally have much lower tensile limits than compressive limits. This must be taken into consideration when defining allowable stresses. Non-critical components (as defined by the GRD) shall be limited to **3/4 of the ultimate** tensile and compressive stresses at temperature. There shall be no relief for secondary stresses.

For other potentially brittle materials (e.g., ceramics), with an established lack of ductility, for static stresses, the design allowable stress shall be limited to 1/3 of the ultimate tensile and compressive stresses at temperature. These materials also generally have much lower tensile limits than compressive limits which must be taken into consideration when defining allowable stresses. There shall be no relief for secondary stresses.”

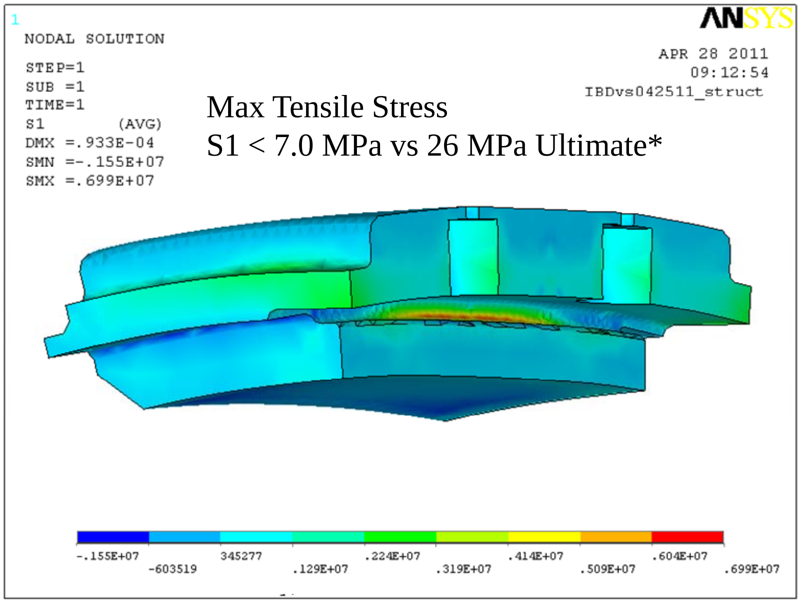
As of this writing, the above is not formally approved. Nor is the classification of tiles by the GRD as critical or non-critical components. Therefore the more conservative criteria of ½ ultimate will be applied.

The IBDhs tiles fall short of this criteria. To meet the criteria, the peak heat load that would tolerable would drop from 5.0 to 3.7 MW/m2 (Higher heat loads could be tolerated for shorter pulses though stresses do not scale linearly with pulse time).

IBDvs

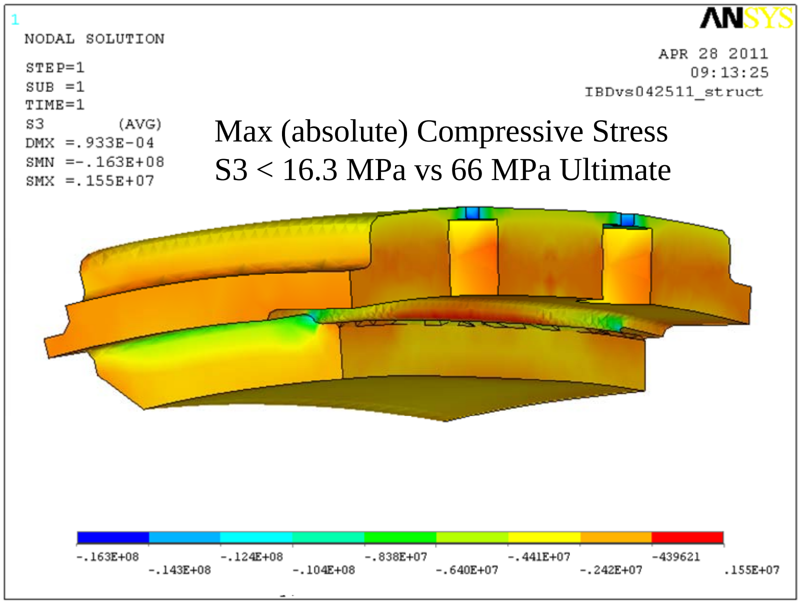


Hot spot from thinning at bolt holes



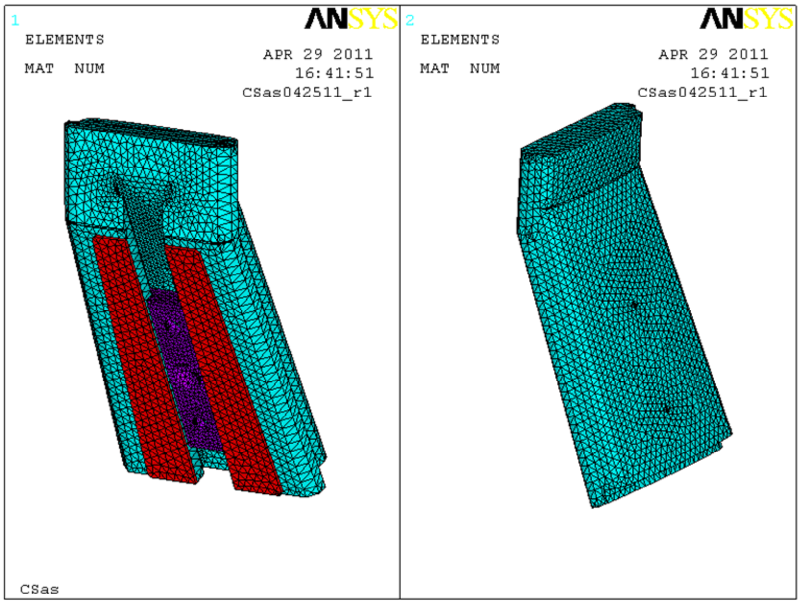
Max Tensile Stress
S1 < 7.0 MPa vs 26 MPa Ultimate*

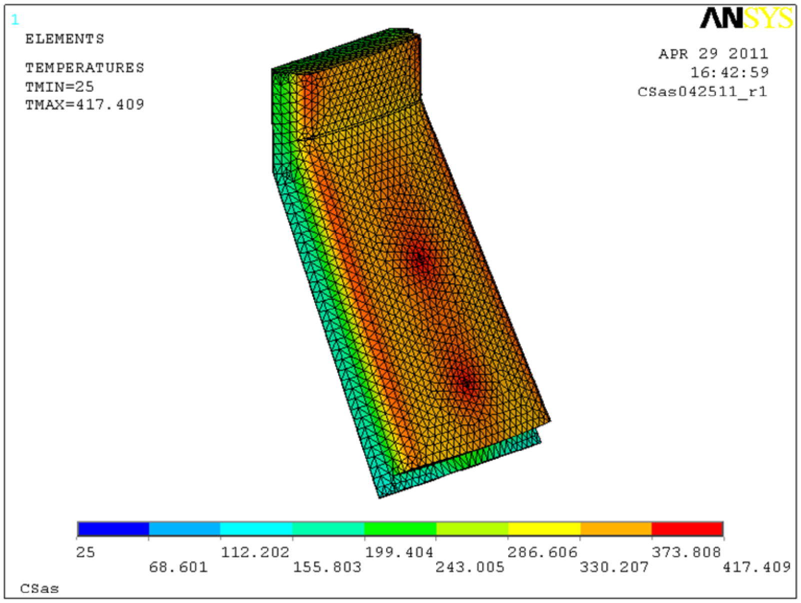
*ATJ stated value. Testing suggest limits may be less



Max (absolute) Compressive Stress
S3 < 16.3 MPa vs 66 MPa Ultimate

CSAS


1
ELEMENTS
MAT NUM
APR 29 2011
16:41:51
CSas042511_r1
2
ELEMENTS
MAT NUM
APR 29 2011
16:41:51
CSas042511_r1
CSas


1
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112.202
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243.005
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330.207
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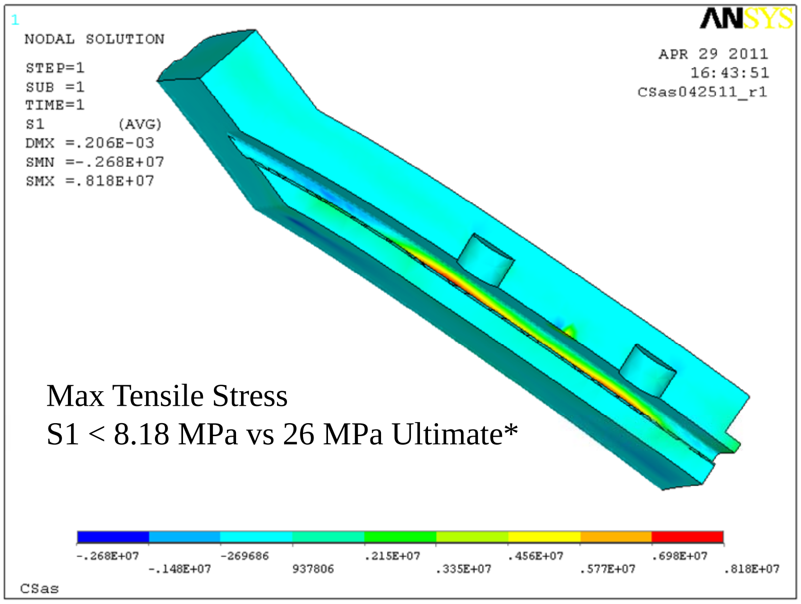
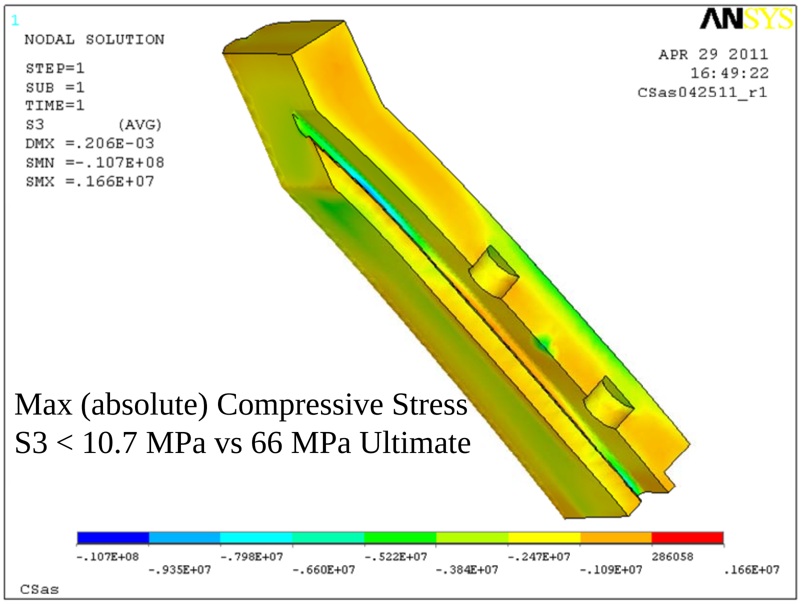
417.409
CSas

CSAS, continued

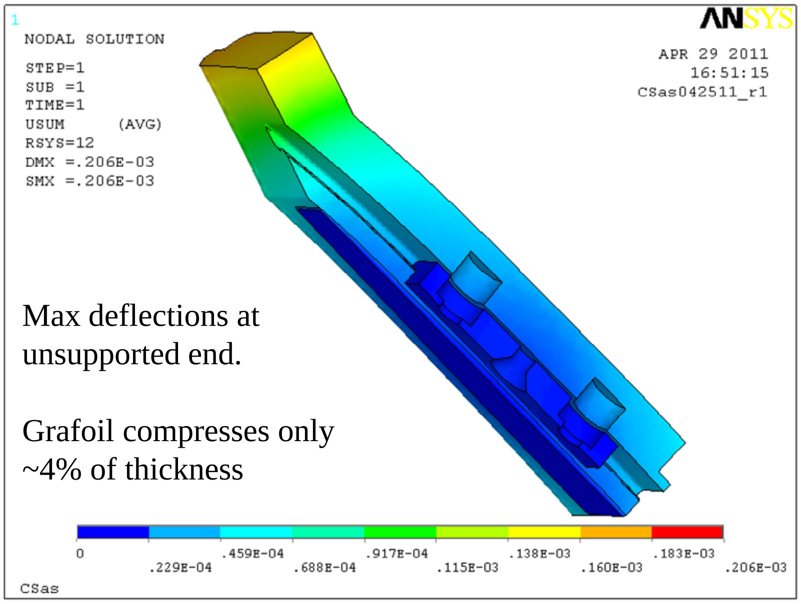


Max Tensile Stress
S1 < 8.18 MPa vs 26 MPa Ultimate*



Max (absolute) Compressive Stress
S3 < 10.7 MPa vs 66 MPa Ultimate

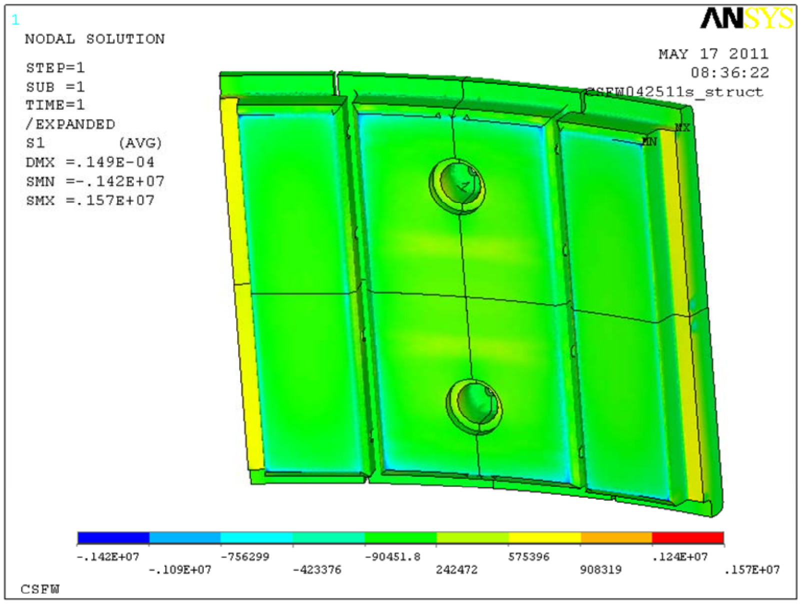
CSas, Continued



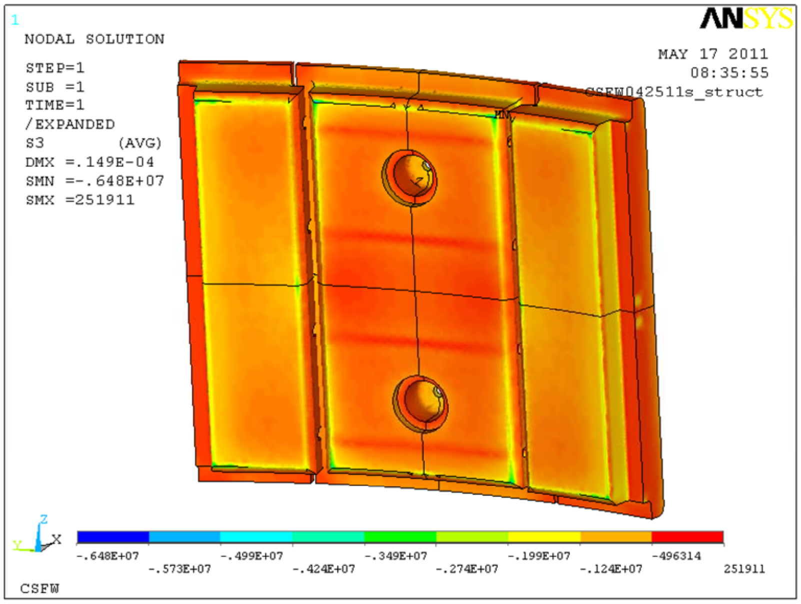
Max deflections at unsupported end.

Grafoil compresses only ~4% of thickness

CSFW



CSFW, continued



Summary

The tables below summarize the peak temperatures and stresses from the analysis for the given heat load:

	Summary of Tile Thermal Structural Response				
	Heat Flux for 5s	Ratcheted Temperature	Peak Tensile Principal Stress, S1	Peak Compress Principal Stress, S3	Max Deflection
	mw/m2	C	MPa		mm
IBDhs, surface	5.0	1062	**13.5**	**-44.1**	0.6
Hot Spot at Corner		**1383**			
IBDvs, surface	1.6	425	7.0	-16.3	0.1
Hot Spot at Hole		560			
CSAS, surface	1.6	327	8.2	-10.7	0.2
Hot Spot at Hole		417			
CSFW	0.2	260	1.6	-6.5	0.01

The Center Stack Tiles, with the exception of the IBDhs and OBD, are shown to be capable of withstanding the original GRD heat flux requirements using the prescribed ATJ graphite with Tensile Strength of 26 MPa and Compressive Strength of 66 MPa. The IBDhs fall short based on the assumption they will classified as critical components in the GRD. Peak tensile stresses are 52% of the ultimate strength; peak compresses stresses are 67% of ultimate. For the OBD tiles, peak tensile stresses are 60% of the ultimate strength; peak compresses stresses are 58% of ultimate To meet the proposed criteria, a proportional reduction in the heat flux, from 5 MW/m2 to 3.7 MW/m2 is required, or, if the high surface compression stress region at the lip of the bolt access hole is ignored and chipping tolerated, the allowable heat flux increases to 4.2 MW/m2. If the tiles are classified as non-critical the stress limit is 75% ultimate and the criteria can be met at the 5 MW/m2 heat load.

Results are based on average Tile surface heating. The IBDhs shows a hot spot at the corner of the tile closest to the X-point due to assumed heating from both faces which may be (or may not be) conservative.

The tile mounting scheme, consisting of T-bar supports for the CS Angle Section (CSAS) Tiles and the Inboard Divertor Horizontal (IBDhs) and Vertical (IBDvs) Tiles, and the tray support for the Center Stack First Wall (CSFW) Tiles is adequate to support the tiles against the anticipated thermal, eddy current and halo current loads with acceptable bolt loads. The load paths are such as to dump the net tile forces from Halo and Eddy Currents directly into the CSC. The supports offer flexible constraint on the tile thermal expansion without carrying significant load.

To repeat what was said earlier, the EM load direction is premised on the poloidal flowing halo current’s interaction with the TF field always results in tile forces which are away from the plasma, regardless of the plasma current and TF field directions as observed in NSTX operation. While the interaction of toroidal flowing halo currents, which will be in both directions due to the Toroidal Peaking, with the PF field produce forces both toward and away from the plasma, they are shown to be small relative to the poloidal current forces and result in net forces away from the plasma. If net forces were reversed, halo currents from a 2 MA plasma may not be tolerable due to high tensile stresses in the ATJ.

The analysis shows that the inclusion of Grafoil under the CSAS, IBDvs and IBDhs combined with the active cooling will significantly limit the thermal ratcheting of the tiles whether Li coated (with assumed emissivity of 0.3) or uncoated (with assumed emissivity of 0.7). The active cooling also offers adequate protection of the neighboring PF and OH coils and reduces the heating of the CS Casing. The flow rate and back pressure are high enough to avoid boiling of the water.

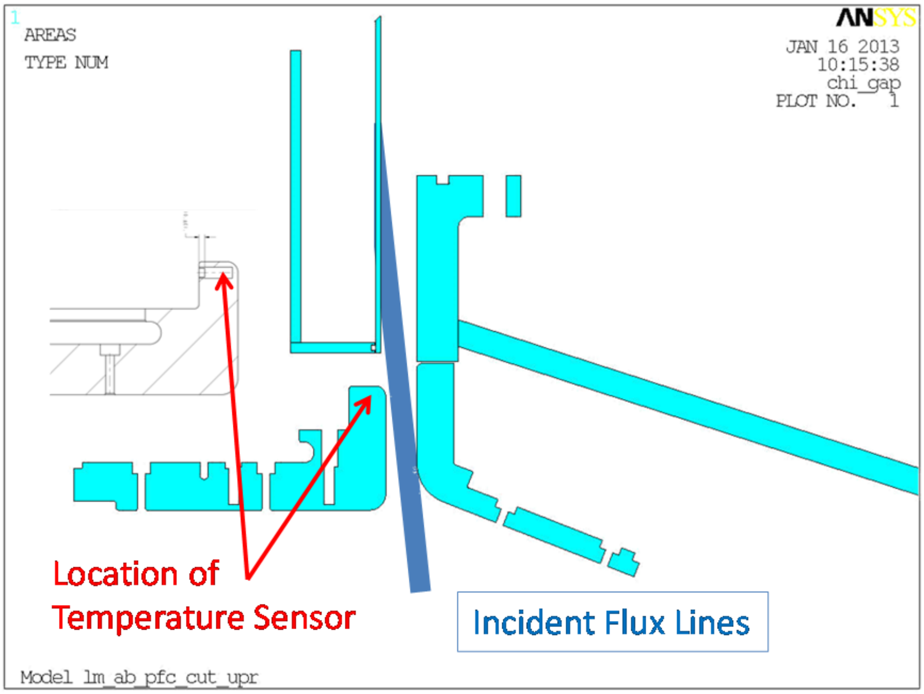
The Grafoil is shown to be structural compliant to allow relatively free thermal expansion of the tiles provided the bolts are only lightly preloaded and do not over compress the Grafoil.

References

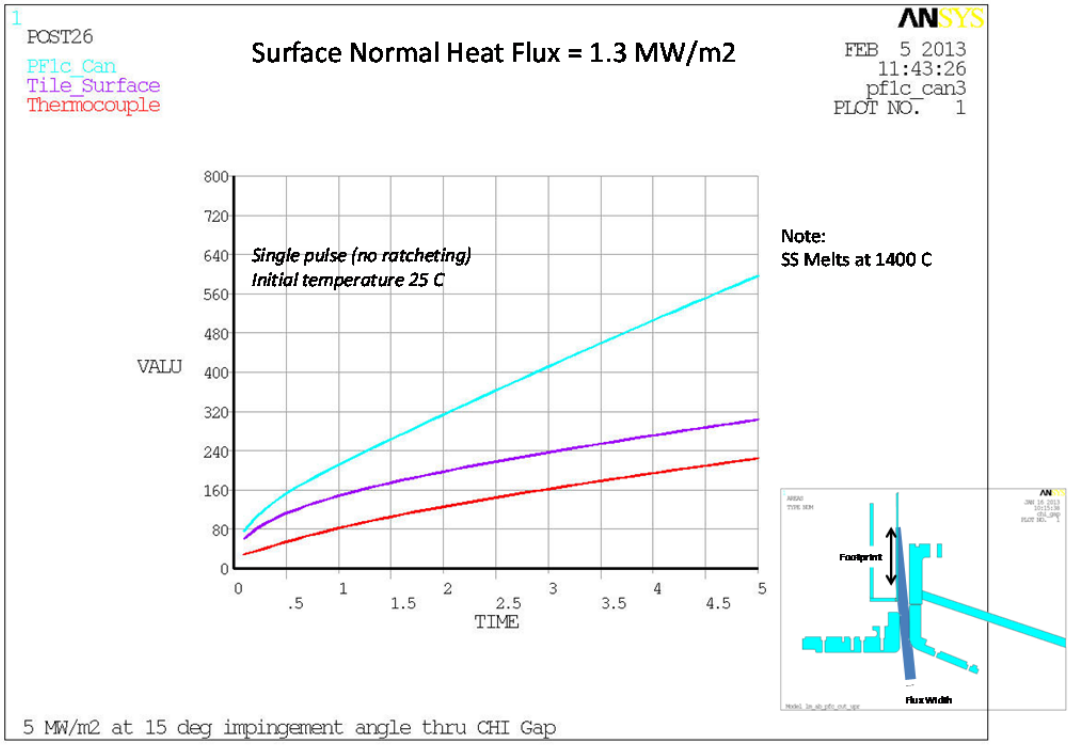
1) NSTX_CSU-RQMTS-GRD General Requirements Documents, Rev 3
2) Design Point Spreadsheet “NSTX_CS_Upgrade_100504.xls”
3) NSTXU-Calc-11-01-00 Global Thermal Analysis of Center Stack Heat Balance, Dated February 15, 2011
4) ProE Model of Center Stack Tiles - aj_center_case_analysis_rev2.asm
5) Spreadsheet of Disruption Data - Disruption_scenario_currents_v2.xlsx, by Jon Menard, received 7/2/2010
6) Discussions with Stefan Gerhardt on modeling of halo currents for NSTX
7) NSTX Structural Design Criteria with proposed revisions
8) Fortran Code for PF field calculations based on PPPL Magnetics Library FICOI routine. PFCalc3.f resides on Unix Cluster at “/p/eaddata/abrooks/nstx_csu/pfcalc /pfcalc3.f”

Appendix A
CHI Gap Thermocouple Response

The CHI Gap between the IBD and OBD permits heat flux to impinge on the PF1c coil canister. Direct measurement of the thermal response of the canister is being considered by thermal imaging. In parallel, thermocouples are installed in the IBDhs tile as close to the canister as possible. The response of the thermocouple will be used to estimate the surface heat fluxes in the CHI Gap. Since the thermocouple is imbedded in the tile its response will be delayed. The temperature response of the thermocouple location was compared below to surface temperature to verify the response time was adequate to protect the canister and coil.



The results show the thermocouple response appears adequate to extrapolate the tile surface temperature, and associated heat flux, for long pulses (ie greater than 1 sec).

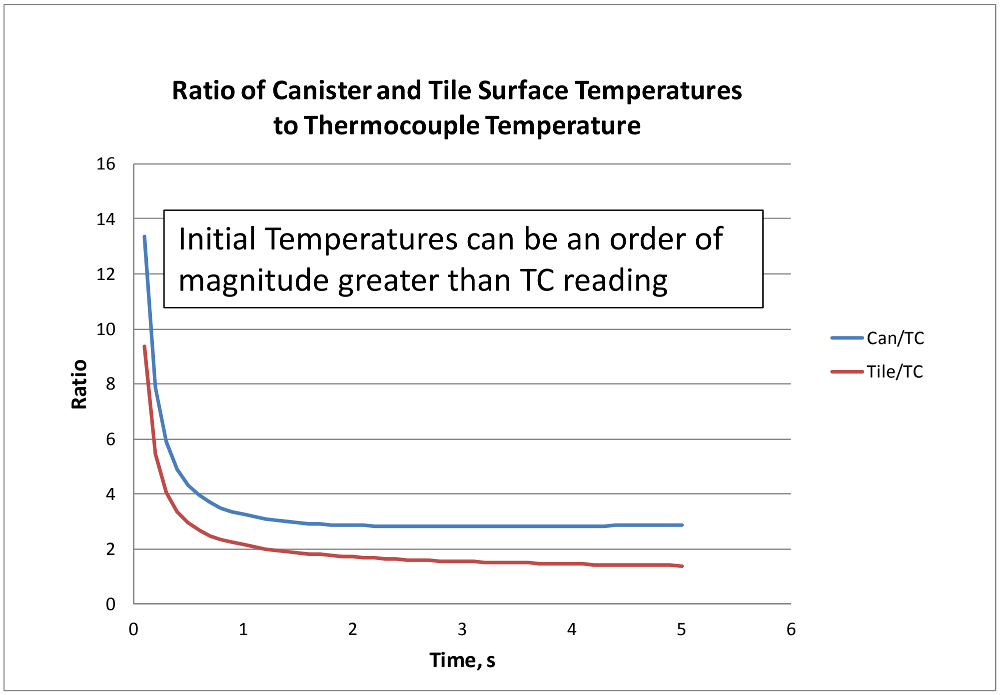


Surface Normal Heat Flux = 1.3 MW/m2

Single pulse (no ratcheting)
Initial temperature 25 C

Note:
SS Melts at 1400 C

5 MW/m2 at 15 deg impingement angle thru CHI Gap

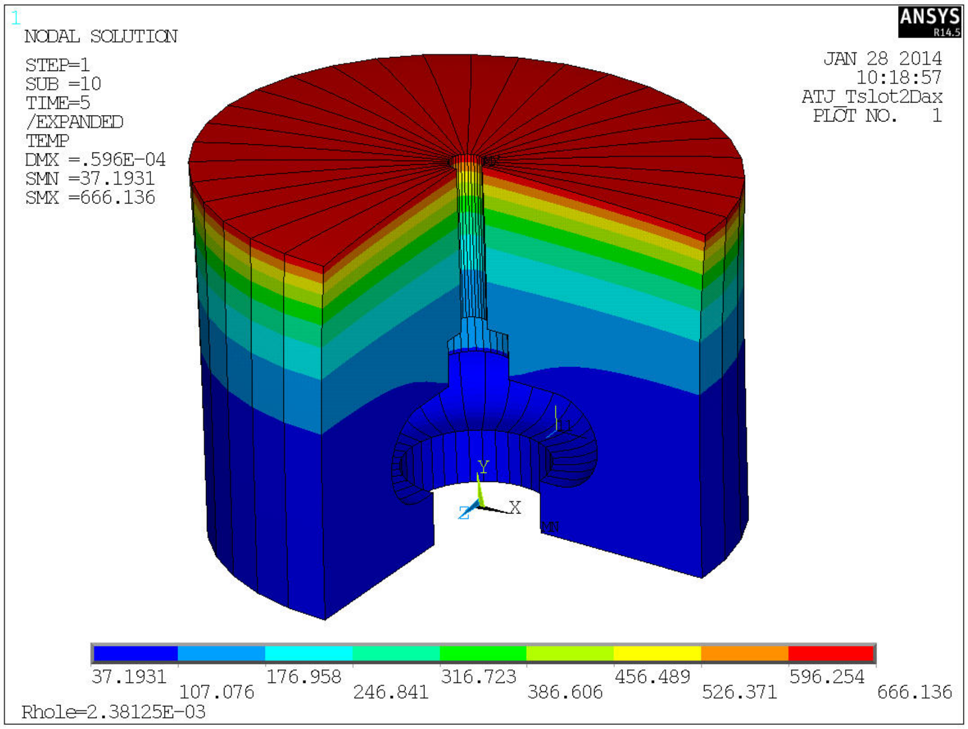


Ratio of Canister and Tile Surface Temperatures to Thermocouple Temperature

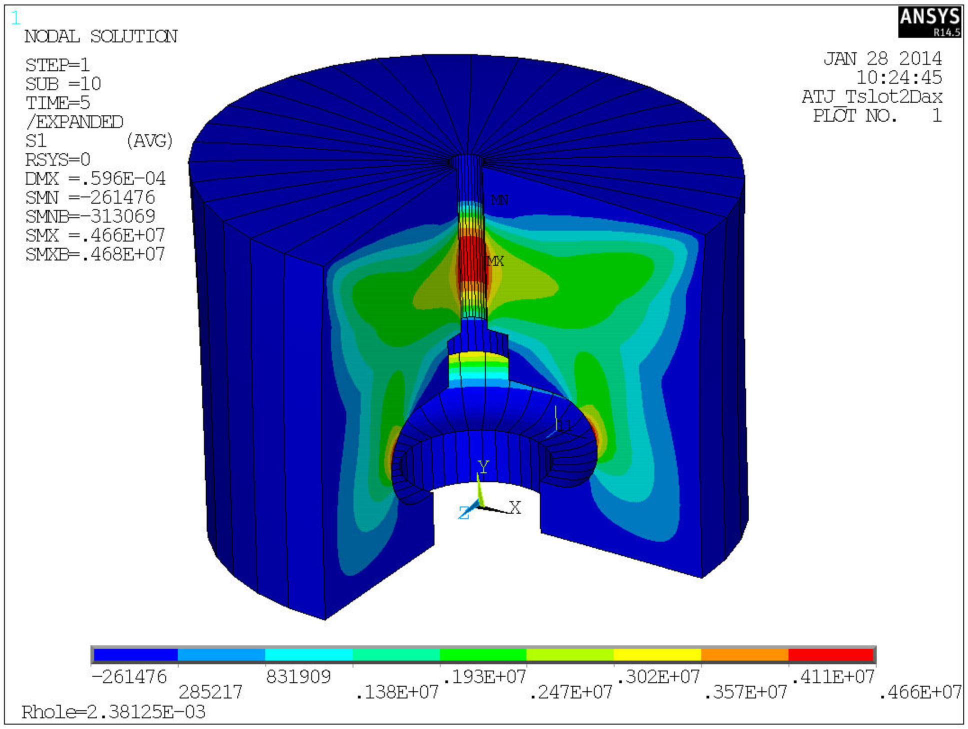
Initial Temperatures can be an order of magnitude greater than TC reading

Appendix B
Impact of Bolt Access Hole Diameter on Stress Concentrations

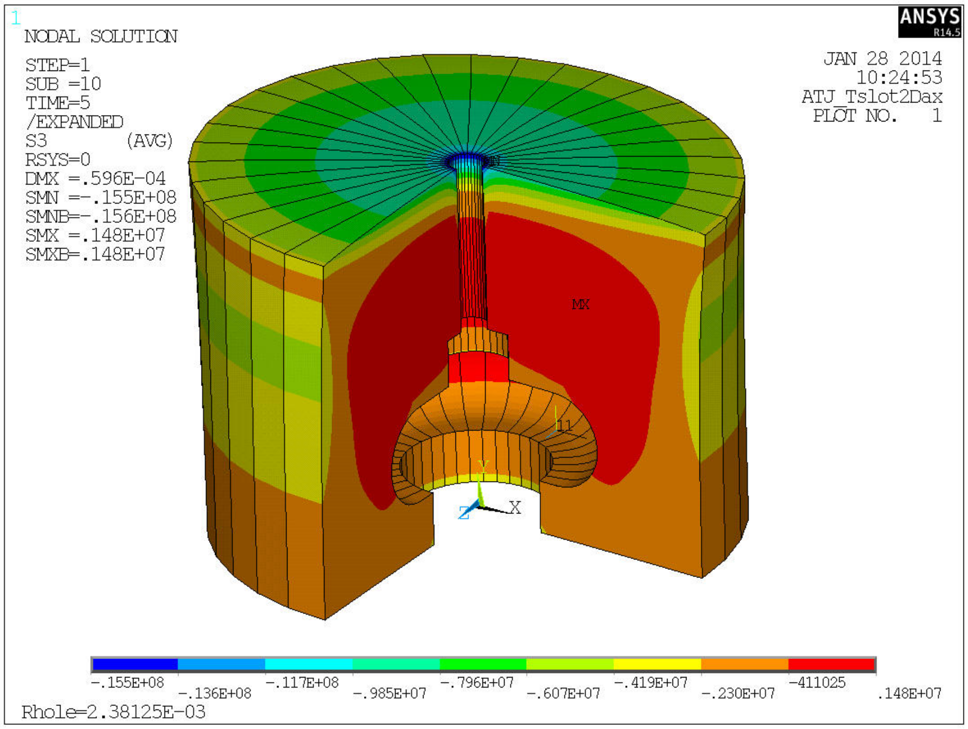
The high stresses that limit operation occur due to stress concentrations at the bolt access holes. A simple study was done to assess the impact of larger holes. An axisymmetric model of a tile with a T-slot and a single bolt hole was run varying the hole diameter. A 5 MW/m2 heat flux was applied for 5 s on the freely supported tile.



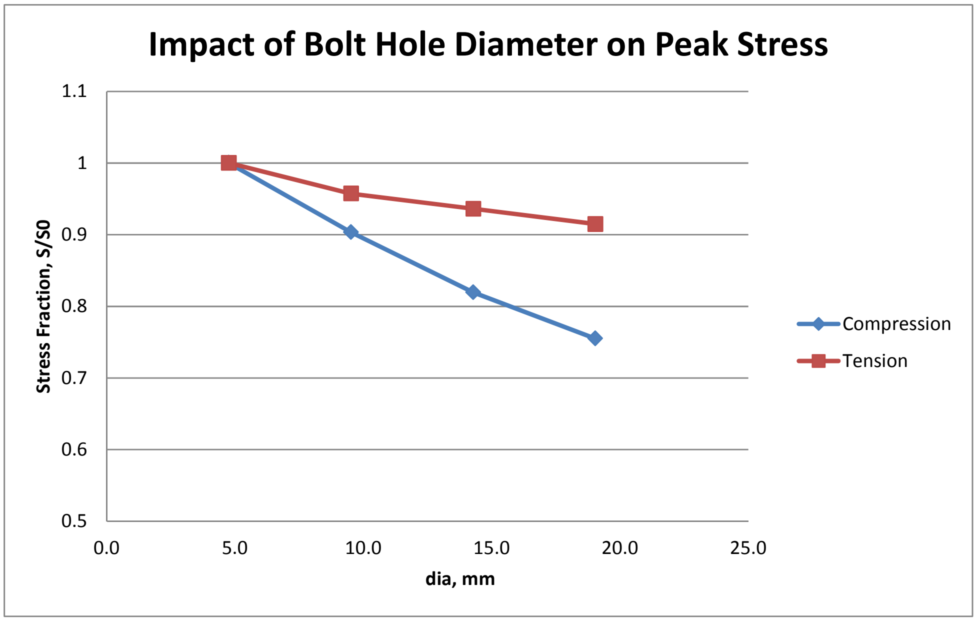
Temperature Response



Peak Tensile Stress occurs half way thru hole. Increasing hole diameter beyond 2x moves peak stress to T-slot



Peak Compressive Stress occurs at surface stress concentration.



Doubling bolt hole diameter can reduce compressive stress concentration at surface ~10%, but only~5% on tensile stress concentration at center of tile.

Increasing the bolt hole diameter may expose the bolt head to more radiant heat flux unless the hole is plugged.