NSTX

Stress Analysis of ATJ Center Stack Tiles and Fasteners

NSTXU-CALC-11-03-00

May 9, 2011

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PPPL Calculation Form

Calculation # **NSTXU-CALC-11-03-00** Revision #**00** WP #, if any **1707**
(ENG-032)

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

Stress Analysis of the ATJ Tiles and Supports

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

See attached report

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

See attached report

Calculation (Calculation is either documented here or attached)

See attached report

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

The Center Stack Tiles for the NSTX-CSU program are shown to be capable of withstanding the original GRD heat flux requirements using the prescribed ATJ graphite. 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.

Cognizant Engineer's printed name, signature, and date

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Checker's printed name, signature, and date

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Executive Summary

The Center Stack Tiles for the NSTX-CSU program are shown to be capable of withstanding the original GRD heat flux requirements using the prescribed ATJ graphite. 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.

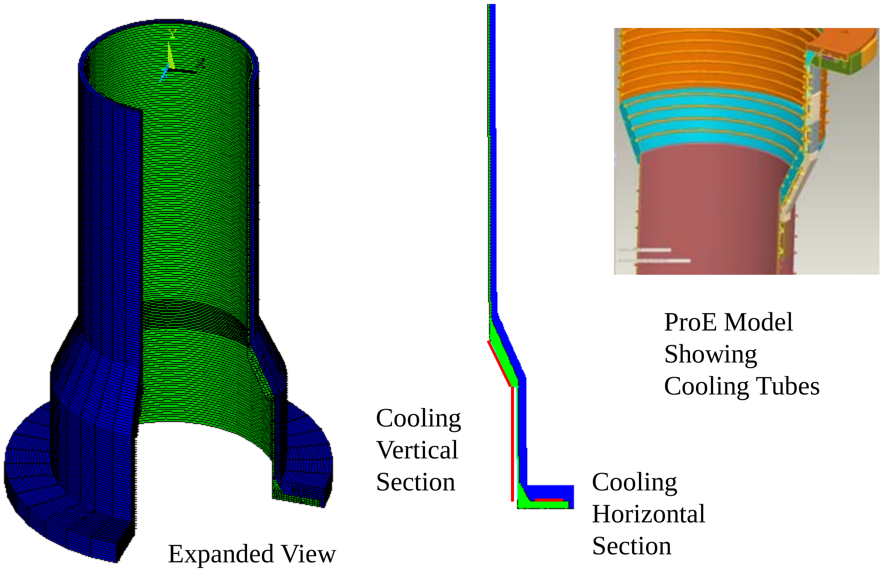
Tile Thermal and EM Stresses are within acceptable limits for ATJ graphite.

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) Tiles, and the Center Stack First Wall (CSFW) 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.

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



Expanded View

ProE Model
Showing
Cooling Tubes

Assumptions

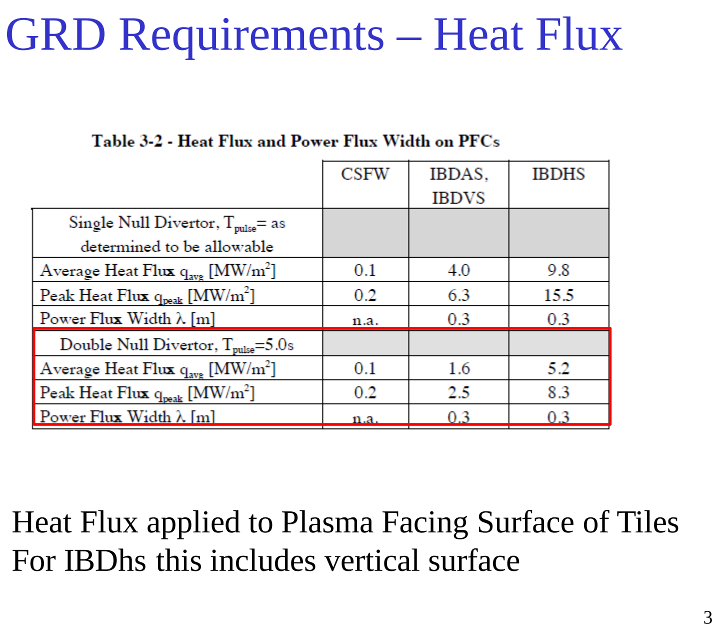
The tile mounting schemes are designed to permit relatively free thermal expansion, minimizing thermal stresses. The CSAS, IBDhs and IBDvs tiles use T-bar supports held by bolts with Belleville washers and with compliant Grafoil underneath. The bolts are lightly loaded (500 N or 112 lbs) to permit bowing 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

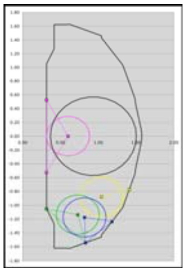
Table 3-2 - Heat Flux and Power Flux Width on PFCs

	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

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.

Requirements – EM Loads
Eddy Currents



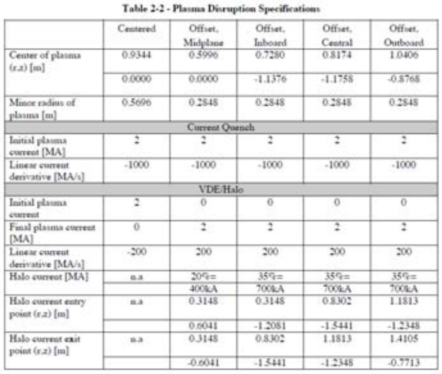
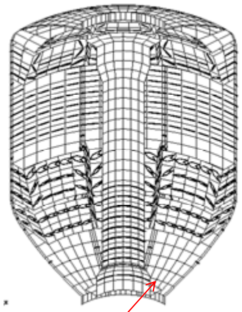


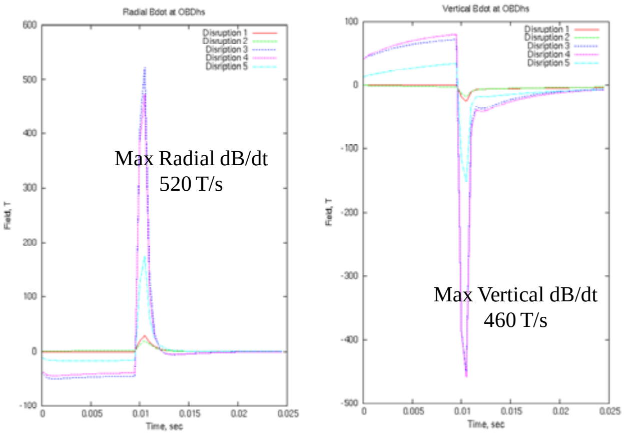
Table 2-2 - Plasma Disruption Specifications

	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



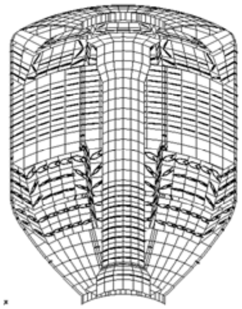
SPARK Scan of above disruptions yielded
Max dB/dt = 520 T/s Radial, 460 T/s Vertical
at diverter

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



Max Radial dB/dt
520 T/s

Max Vertical dB/dt
460 T/s



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:

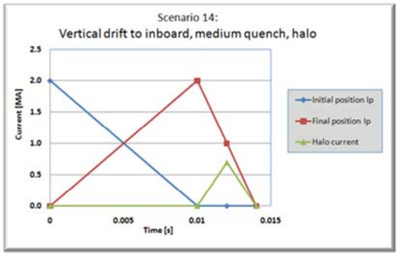
Max Br = 0.5 T
Max Bz = -0.57 T

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



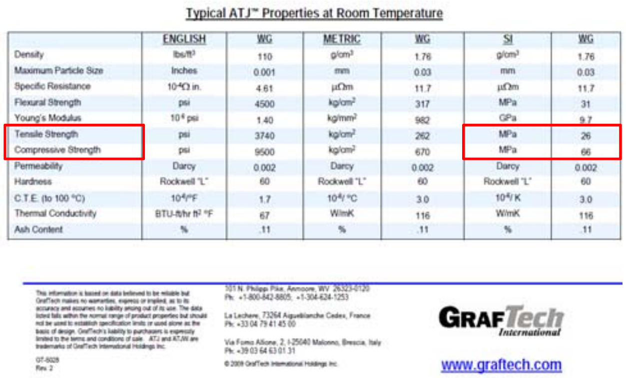
Excepted from
Disruption_scenario_currents_v2.xlsx

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	10⁻⁴Ω in.	4.61	μΩm	11.7	μΩm	11.7
Flexural Strength	psi	4500	kg/cm²	317	MPa	31
Young's Modulus	10⁶ 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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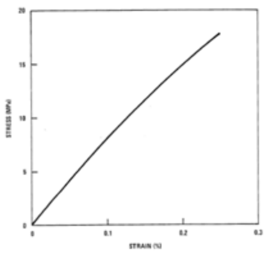


Fig. 3.3-4 Tensile stress-strain curve for 2020 graphite

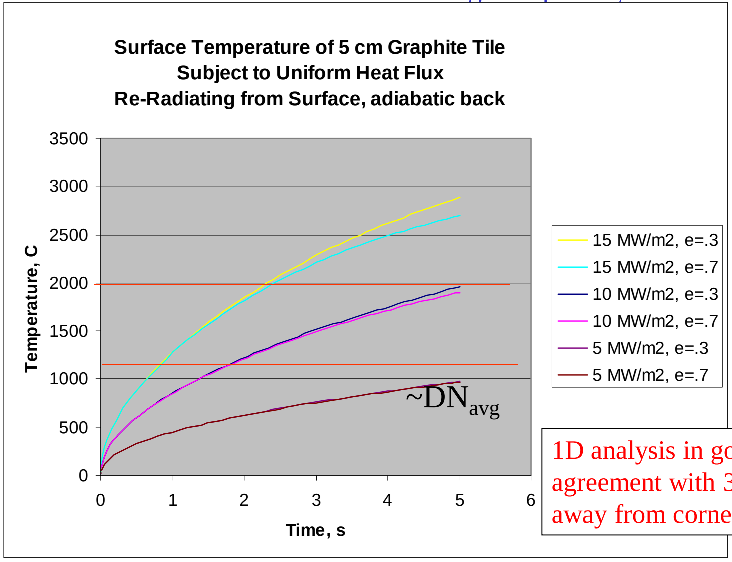
ATJ very brittle – Yield strength close to Ultimate

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

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.

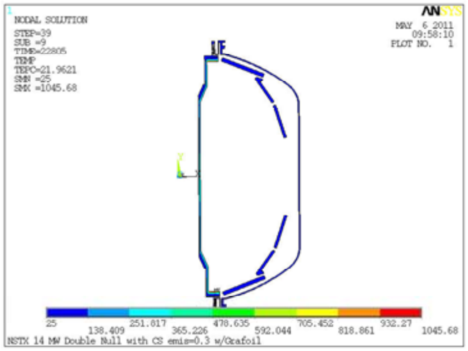
1st Pulse Heat Flux/Pulse Length Capability

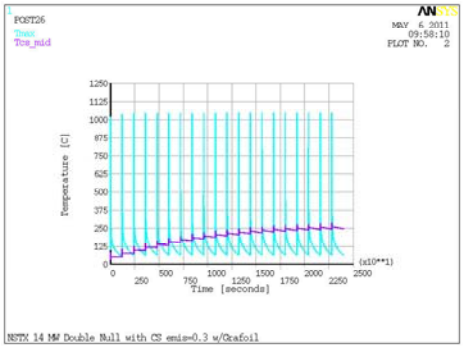


1D analysis in good agreement with 3D away from corner

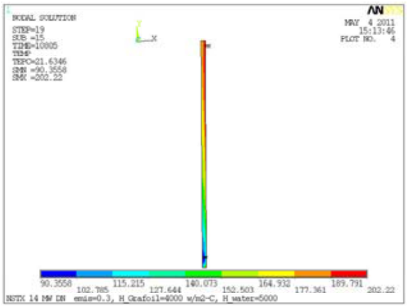
Single pulse without ratcheting with ATJ Graphite

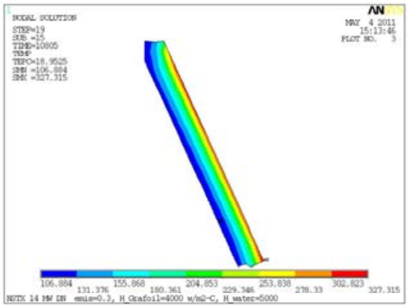
A 2-D axisymetric thermal model to the previously run was modified to reflect the use of Grafoil under the tiles. The model was also modified to include the effect of water transport (using ANSYS fluid116 elements) instead of just using an effective film coefficient as used in earlier analyses. This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

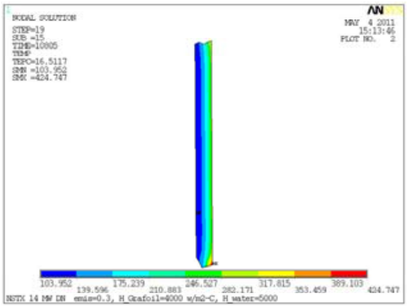


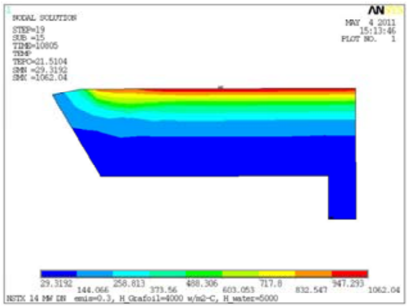


Tile Ratcheted Temperatures

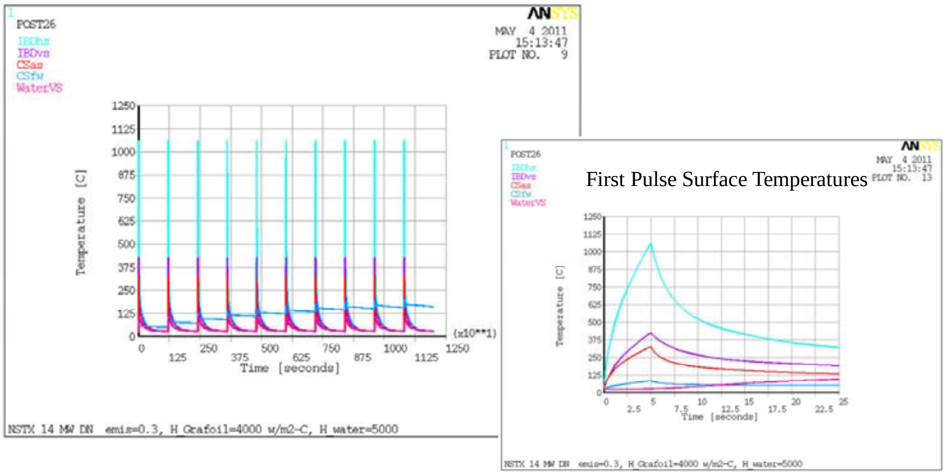






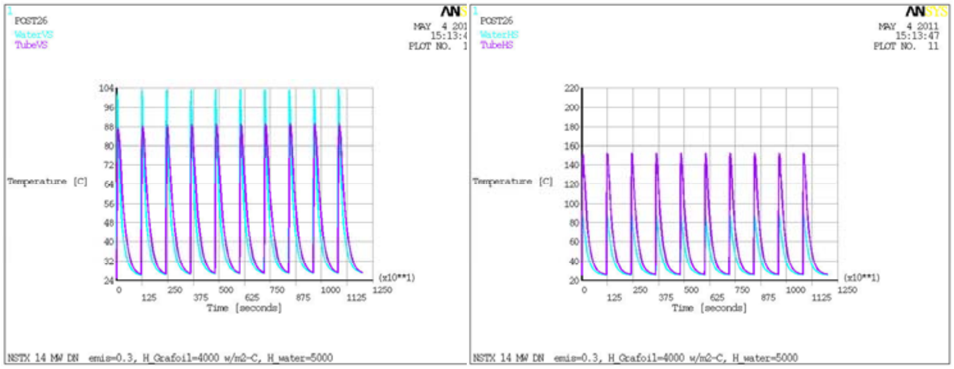


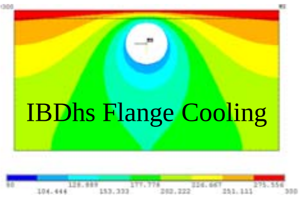
No Ratcheting on Water Cooled Tiles
Only on Radiation Cooled CSFW



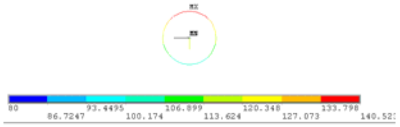
First Pulse Surface Temperatures

Water in Cooling Loops stays below ~100 C
Neighboring Case Temperature Higher





IBDhs Flange Cooling



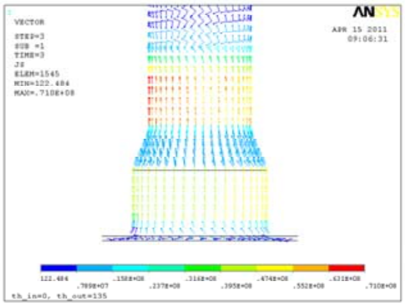
IBDhs Flange Cooling Tube Surface

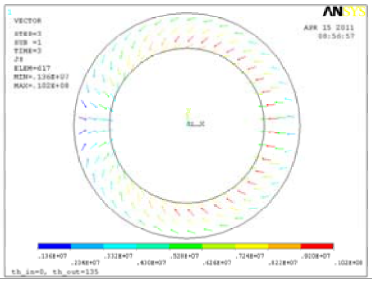
A halo current distribution model was also created to investigate the direction of forces on the tile. This was crucial to the structural performance. Results show that forces are always away from the plasma and into the supporting CSC which limits the tile stresses since the tile is effective supported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

Halo Currents and Force Directions in the CS

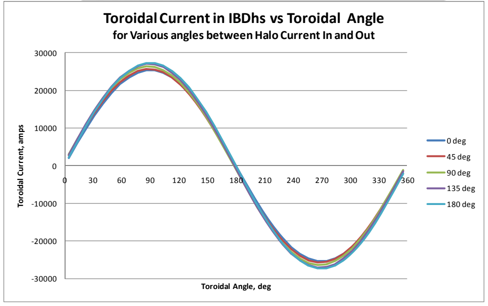
- The halo currents and associated Lorentz forces & directions are based on the following:
  - Halo Currents are resistively distributed.
  - Halo Currents are predominantly poloidal
    - Studies show this to be true even with large toroidal peaking (TPF) with in and out strike points at different toroidal 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





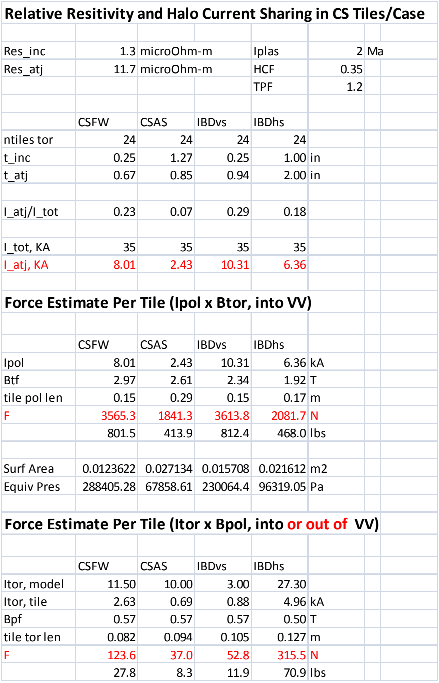
Current Direction is fairly poloidal in IBDvs, CSAS and CSFW but has sizable toroidal currents in both directions due to Halo Toroidal Peaking Factor



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)

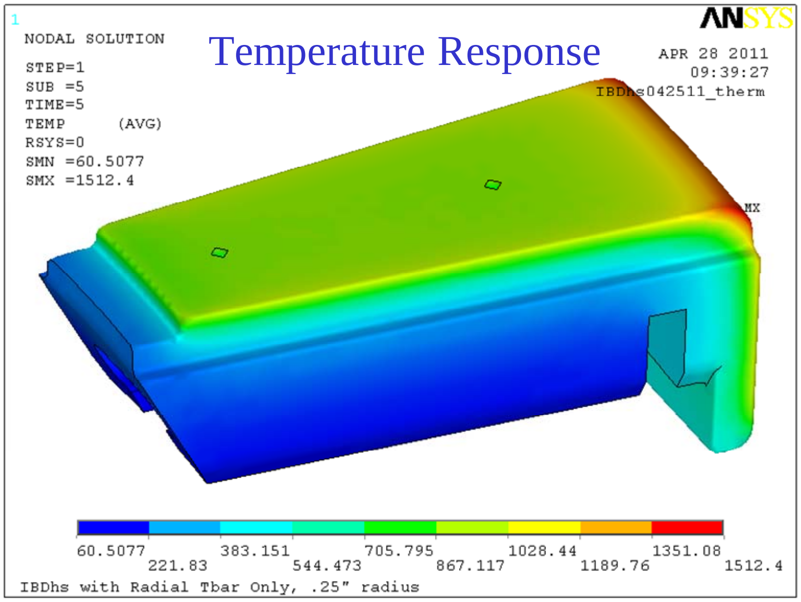
	CSFW	CSAS	IBDvs	IBDhs	
Ipol	8.01	2.43	10.31	6.36	kA
Btf	2.97	2.61	2.34	1.92	T
tile pol len	0.15	0.29	0.15	0.17	m
F	3565.3	1841.3	3613.8	2081.7	N
	801.5	413.9	812.4	468.0	lbs
Surf Area	0.0123622	0.027134	0.015708	0.021612	m2
Equiv Pres	288405.28	67858.61	230064.4	96319.05	Pa

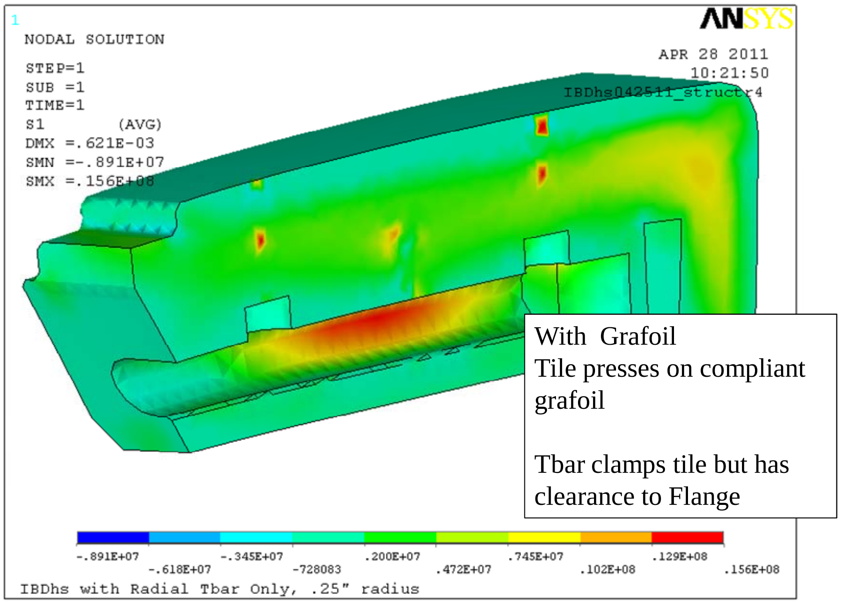
Force Estimate Per Tile (Itor x Bpol, into or out of VV)

	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

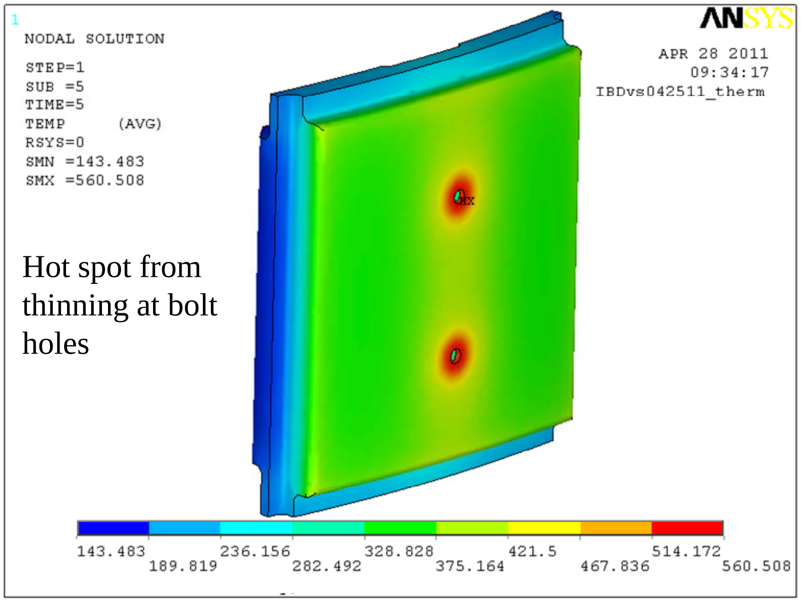




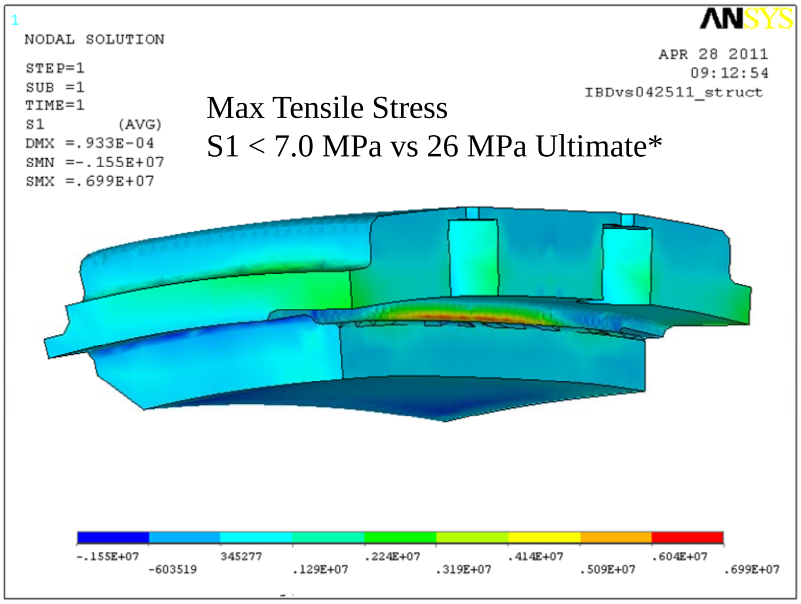
With Grafoil
Tile presses on compliant grafoil

Tbar clamps tile but has clearance to Flange

IBDvs

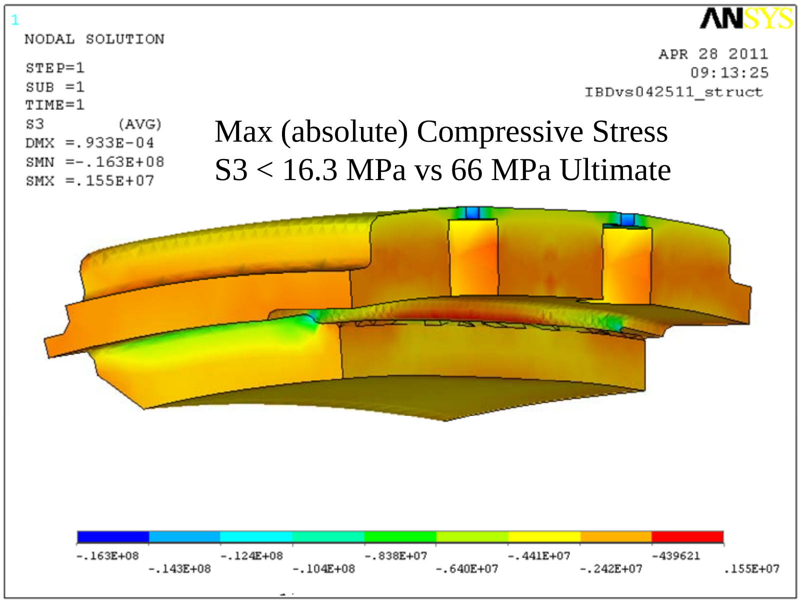


Hot spot from thinning at bolt holes

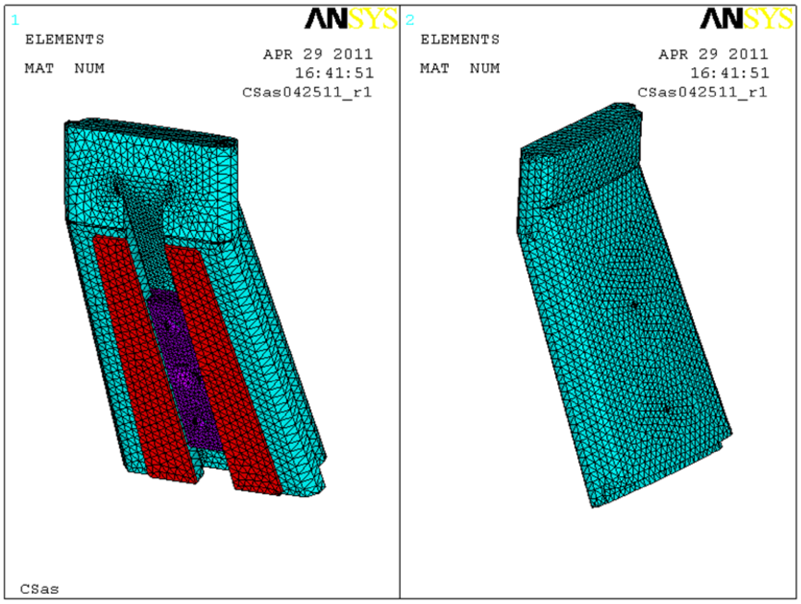


Max Tensile Stress
S1 < 7.0 MPa vs 26 MPa Ultimate*

*ATJ stated value. Testing suggest limits may be less



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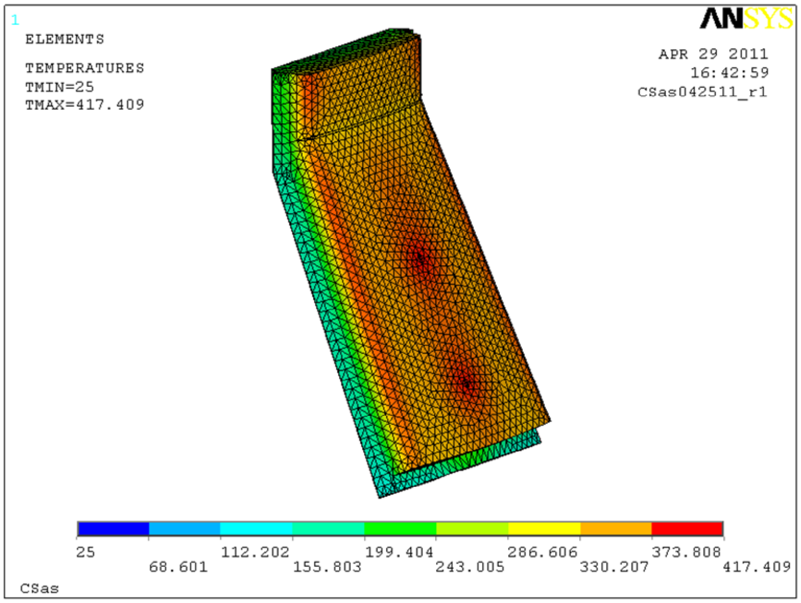
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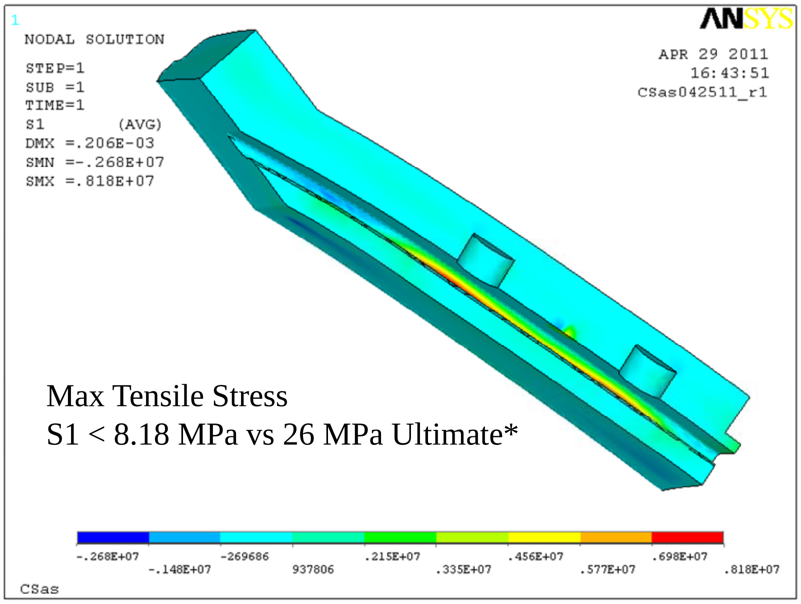
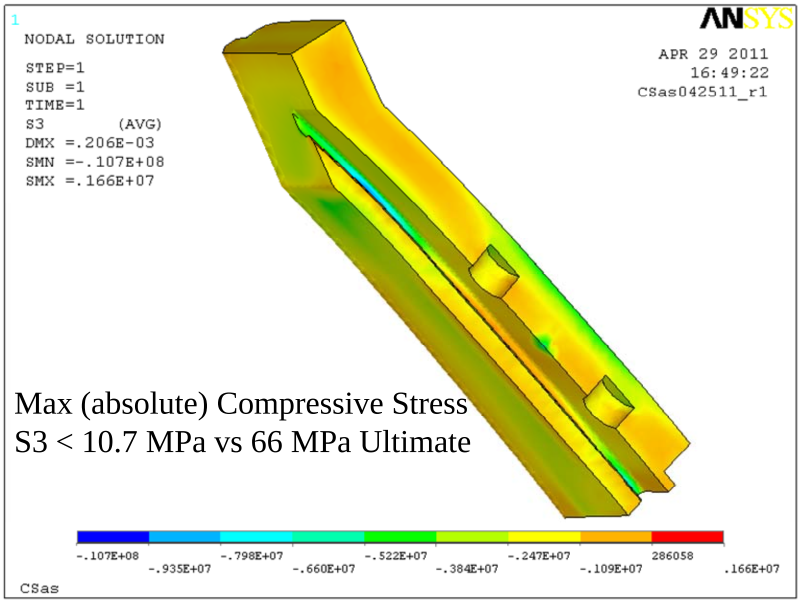
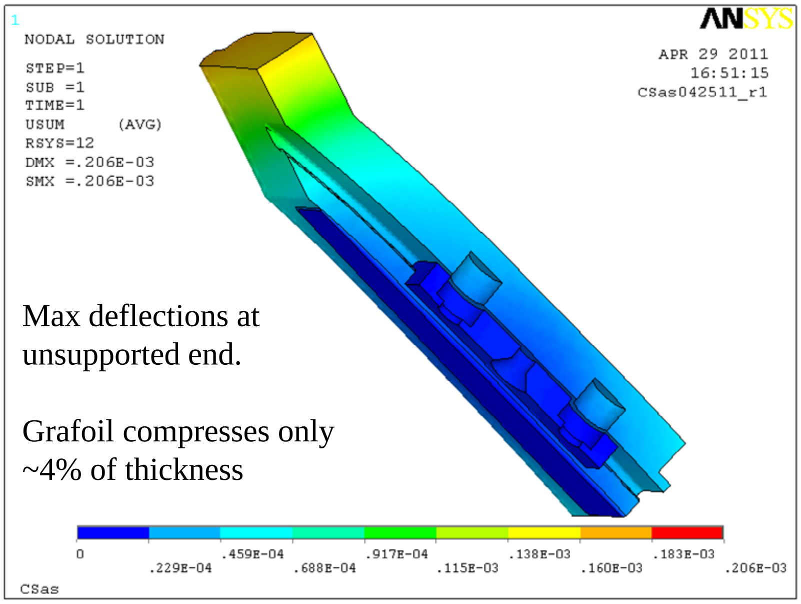


Max Tensile Stress
S1 < 8.18 MPa vs 26 MPa Ultimate*



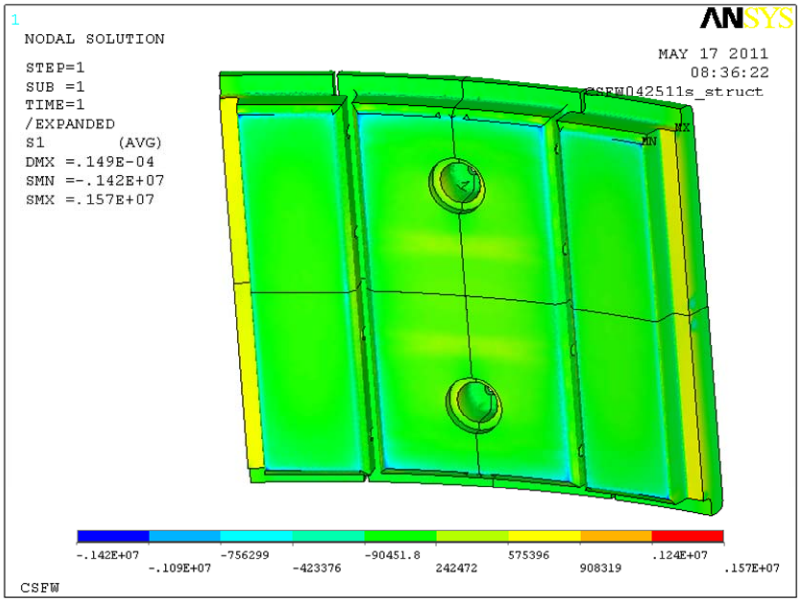
Max (absolute) Compressive Stress
S3 < 10.7 MPa vs 66 MPa Ultimate

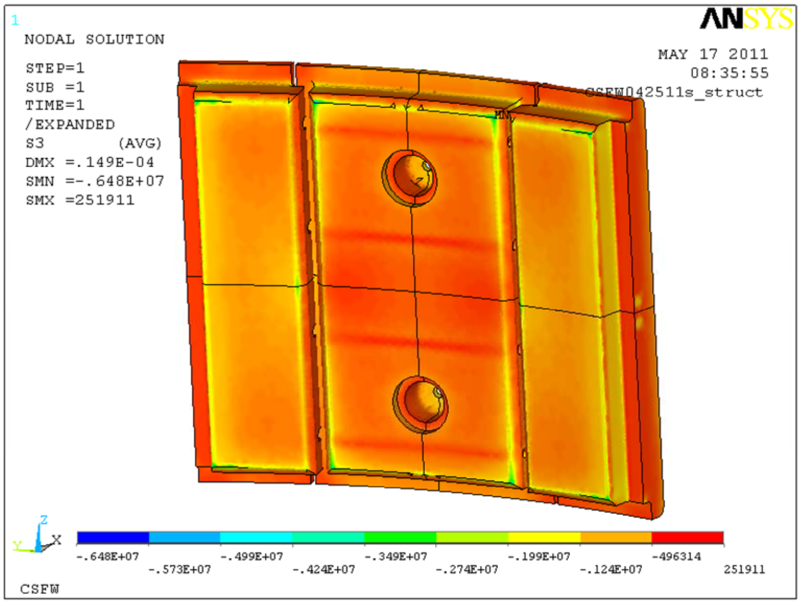


Max deflections at unsupported end.

Grafoil compresses only ~4% of thickness

CSFW





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	15.6	-58.0	0.6
Hot Spot at Corner		1512			
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 for the NSTX-CSU program 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. 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.

IBhs and IBDvs (top) and CSAS and CSFW (bot) Thermal and EM Stresses are within acceptable limits for ATJ graphite.

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