PPPL Calculation Form

Calculation # **NSTXU-CALC-11-06-00** Revision# 0 WP # 11 (ENG-032)

Purpose of Calculation: Qualify the OBD Row 2 High Z Tiles

References : See Attached

Assumptions: See Attached

Calculation : See Attached

Conclusion: The OBD Row 2 High Z tiles are qualified to operate at the required levels as specified in the "System Requirements Document for NSTX-U High-Z Divertor Upgrade 1"

Cognizant Engineer's printed name, signature, and date

Art Brooks — Digitally signed by Art Brooks DN: cn=Art Brooks, o=PPPL, ou=Engineering Analysis, email=abrooks@pppl.gov, c=US Date: 2016.04.11 09:43:44 -04'00'

Kelsey Tresemer — Digitally signed by Kelsey Tresemer DN: cn=Kelsey Tresemer, o=PPPL, ou=Engineering, email=ktreseme@pppl.gov, c=US Date: 2016.04.12 15:29:53 -04'00'

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

Checker's printed name, signature, and date

Jingping Chen — Digitally signed by Jingping Chen Date: 2016.04.11 10:50:32 -04'00'

Analysis of OBD Row 2 High-Z Tiles

NSTX

Analysis of OBD Row 2 High-Z Tiles

NSTXU-CALC-11-06-00

March 4, 2016

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Peter Titus, Branch Head, Engineering Analysis Division

Analysis of OBD Row 2 High-Z Tiles

Executive Summary

New High-Z Tiles will replace the existing row 2 graphite tiles of the Outboard Divertor. The thermal and structural analysis presented herein qualifies the tiles for their design operation at heat fluxes of 2 MW/m2 for 5 secs. The thermal stresses are shown to drive the design - Lorentz forces from induced eddy currents following a 2 MA plasma disruption and halo current forces are shown to only modestly alter stresses.

Results also show, based on available data of the Grafoil compressibility at the pressure achieved with 1000 lbs bolt preload, the Grafoil remains compliant allowing for nearly free expansion of the tile. This allows for a fairly accurate prediction of the tile stresses using simpler, linear analysis. Analysis of forthcoming complicated tile designs that have been modified for diagnostics will take advantage of this method. Note that while the preload does not impact the thermal stresses, it is necessary to keep the tile from sliding when subjected to lateral halo current forces.

Additional analysis is presented to provide operational guidance. Higher heat fluxes are tolerable for shorter periods. The transient impact of higher heat fluxes on the tile surface and base of castellation stresses are given.

Reviewer comments which have been incorporaed are attached as and appendix.

Introduction

The NSTX-U project is undergoing an upgrade of the Outboard Divertor (OBD) Tiles that replaces some of the existing ATJ Graphite tiles with Molybdenum TZM, a High-Z material. High-Z, metallic tiles are desirable for their relevance to future power reactors where high heat flux handling capability combined with low tritium retention are desirable features. In particular, the NSTX-U project makes use of both boronization and lithiumization wall conditioning methods and neither boron nor lithium is expected to chemically interact with a high-Z metallic substrate composed of either molybdenum or tungsten.

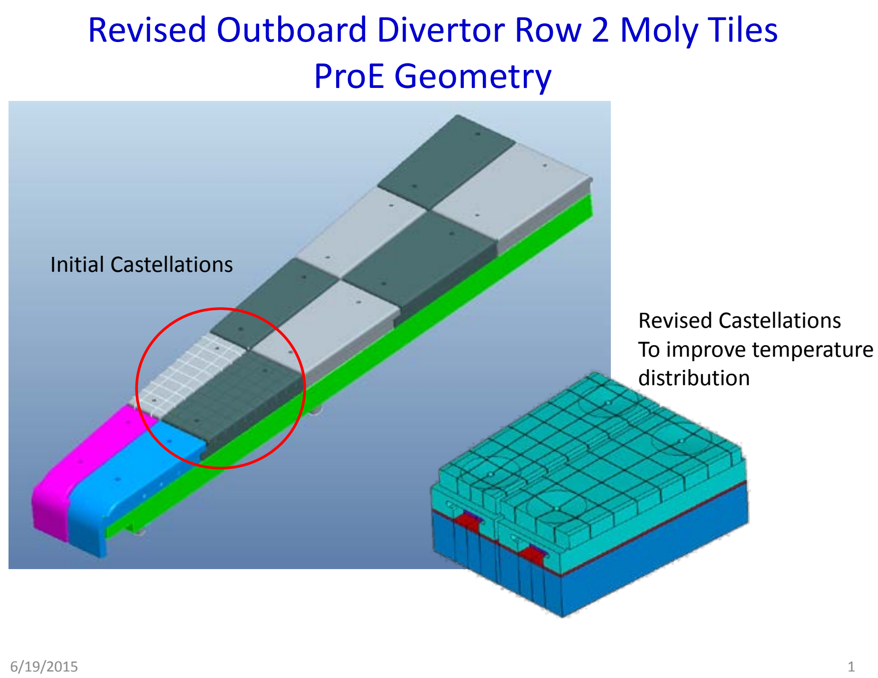
The upgrade replaces all of the current graphite tiles in the OBD row 2 with molybdenum alloy TZM tiles of similar overall geometry but with design modifications such as stress relieving castellations and shaping to enhance performance.

The purpose of the analysis is to verify the adequacy of the design to meet the minimum heat flux requirements in combination with EM forces from eddy and halo currents without exceeding the TZM stress limits. The tiles are being designed for 2 MW/m^2 for 5 seconds with higher heat fluxes (10+ MW/m^2) for shorter durations. Safe operational limits are established to assure surface heating stays below the recrystallization temperature for Mo TZM.

Scope

Analysis of OBD Row 2 High-Z Tiles

This analysis covers the design qualification of the standard OBD row 2 tiles and mounting shown below. This includes the thermal and structural response from plasma heating during normal operation combined with disruption loading. The standard tiles include cutouts only for thermocouples. Modified tiles that accommodate other diagnostics will be addressed in the future when designs become available.



In addition, other studies are performed:

- Scan of heat flux impact on tile temperature and stresses
- Impact of Tile Surface emissivity and active cooling
- Edge heating from misalignment tolerance
- Non-uniform heat flux distribution
- Impact of tile misalignment and touching on eddy currents

Assumptions

The existing tile mounting schemes was designed to permit relatively free thermal expansion, minimizing thermal stresses while providing sufficient preload to avoid tile movement from EM loading. The tiles use T-bar supports held by bolts with Belleville washers and with compliant Grafoil underneath. The bolts are preloaded to 1000 lbs (4448 N) to permit bowing of the tiles under thermal gradients without slippage for coefficients of friction as low as 0.1. There is an initial gap under the T-Bar with tolerances 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 by physics 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 a2 MA plasma may not be tolerable.

The assumption of poloidal halo currents is also implies halo currents can jump the gap between tiles. This jump is enabled by low resistance hot plasma being forced into the gap during this violent event where plasma comes in contact with the tiles. This differs from the assumption made in calculating eddy currents where the plasma at the gap remains cold and highly resistive since it does not contact the tiles.

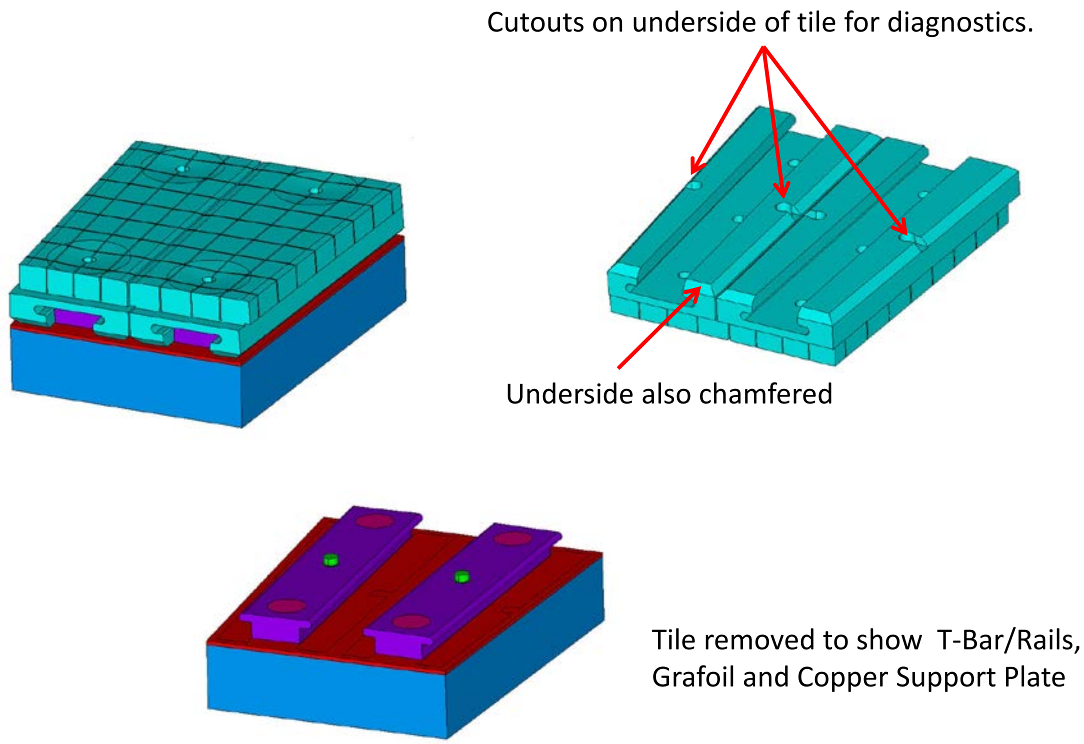
The analysis is done using the average heat fluxes associated with a14 MW plasma of 5 second duration pulse with 1200 second rep rate for 8 hours. Heat fluxes are specified normal to the tile horizontal surface and are assumed to have an impingement angle of 5 deg. This leads to much higher heat fluxes on unshaded vertical surfaces at gaps between tiles, at bolt holes and castellations. The tile shaping includes tapers that are greater than 5 deg, fully shading the vertical surfaces but enhases heating on the unshaped tapered surfaces by more than a factor of 2.

Method of Analysis

Geometry

The geometry imported from ProE and used for final analysis is shown below. This is considered the basic tile that includes diagnostic cutouts for thermocouples.

ANSYS Geometry of a Diagnostic Tile



Modeling

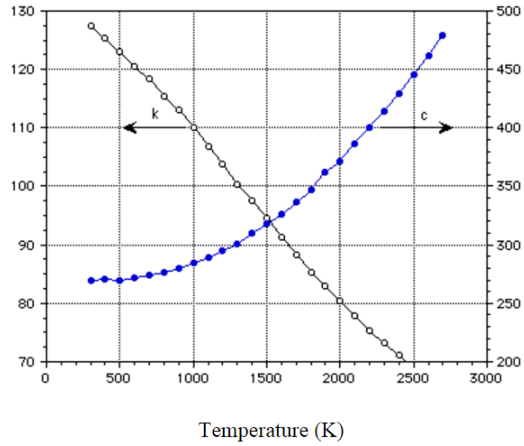
Several ANSYS models were generated to capture the performance of the tiles since attempting to mesh the full model at the level needed to accurately resolve stresses - particular at the castellations – leads to prohibitively large models particularly for nonlinear contact analysis. A global nonlinear model of the tile - with simple castellations - and supporting T-bars is used to evaluate the behavior of the assembly when subject to combined thermal and EM forces, verifying the ability of the T-bars to hold the tiles without slippage. A local model of a section of the tile in the high stress regions is used to resolve detailed stresses at the base of the castellations and near the diagnostic cutouts. This model is also used to scan the impact of heat flux magnitude and duration on surface heating and stresses. These models were created using ANSYS APDL scripts. The final ProE model of the tile and supports was also imported into ANSYS Classic for verification of earlier results. This model was used for linear analysis only – that is the contacts were either open, closed and sliding or fixed. A thermal analysis was run to generate the transient temperature distribution on the TZM tiles. The thermal stresses are evaluated at a number of time points. Halo currents

Material Properties

Analysis of OBD Row 2 High-Z Tiles

The material properties for the Moly TZM were taken from Advanced Energy Technology Group, Center for Enegy Research at UCSD (http://www-ferp.ucsd.edu/LIB/PROPS/PANOS/moa.html)

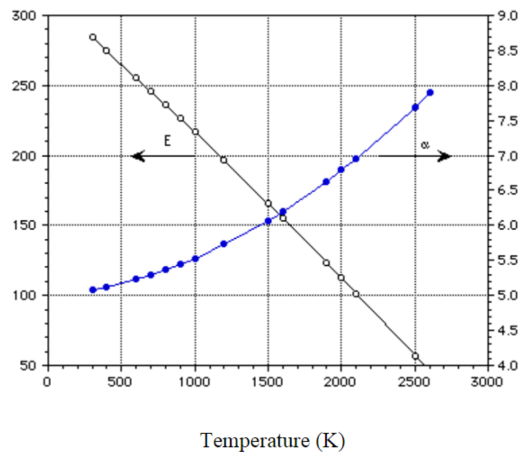
Thermal Conductivity, w/m-K



Specific Heat, J/kg-K

Figure 1 : Thermal conductivity and specific heat of TZM.

Elastic Modulus, GPa



Coefficient of
Thermal Expansion, m/m-K

Figure 2 : Elastic modulus and coefficient of thermal expansion of TZM.

Yield Strength, MPa

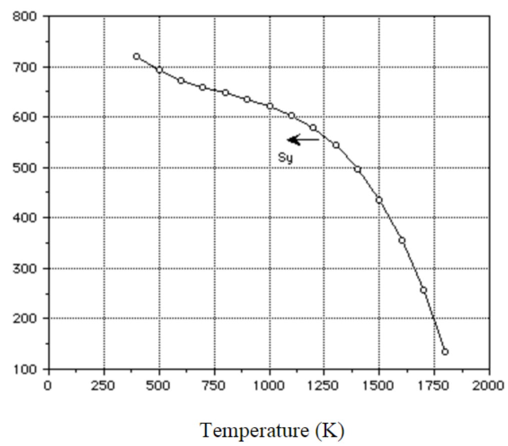


Figure 3 : Yield Stress of TZM.

Loads and Boundary Conditions

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 models of the VV, CS and PP previously generated for the analysis of the CS Tiles (ref 8). For TZM tiles with an electrical resistivity of 5.5e-8 Ohm-m, max thickness of 5 cm, and 17 cm width, the time constant is ~14 ms, much longer than the plasma disruption time of ~0.1 ms for graphite. This means the eddy currents induced in the TZM tiles will be limited by the total flux swing thru the tile (the inductive limit) rather than the dB/dt (the resistive limit).

Requirements – EM Loads
Eddy Currents

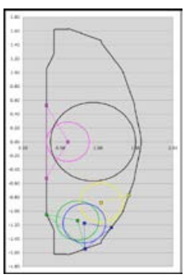
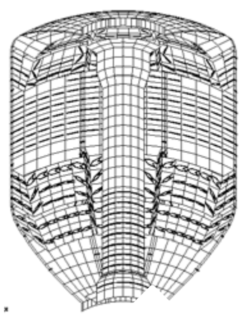


Table 2-2 - Plasma Disruption Specifications

	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



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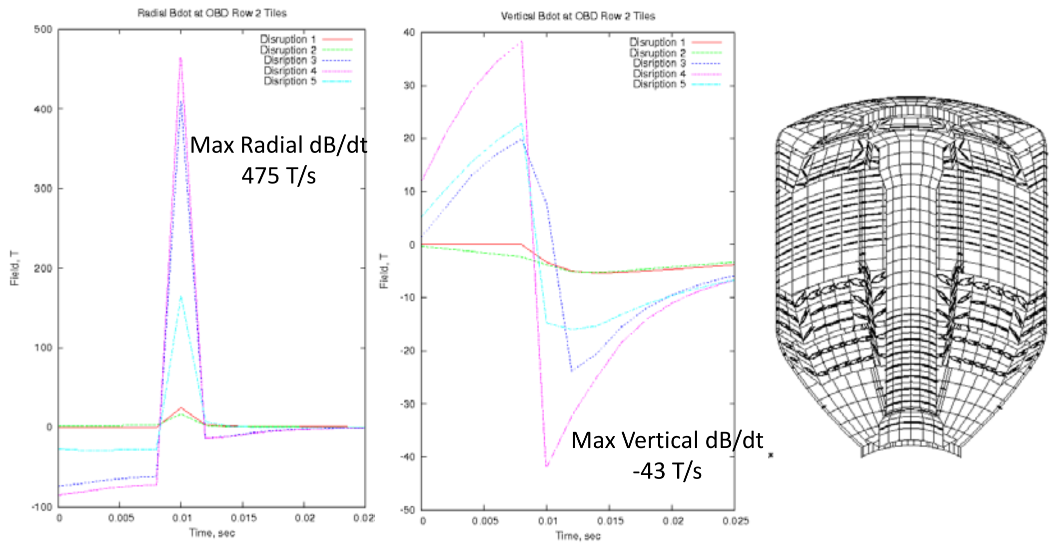
dB/dt Scan during Plasma Disruptions at Outboard Diverter Row 2 Tiles



Based on 2 MA for NSTX CSU 5

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” (ref 2) 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 = 0.24 T
Max Bz = -0.77 T

Max Btf ~ 0.8 T at OBD Row 2 (r=.735m)

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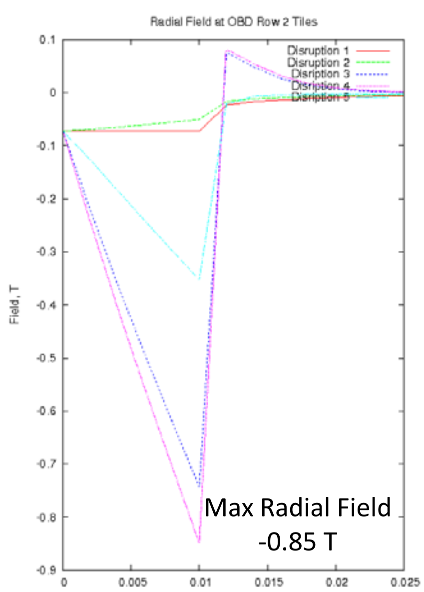
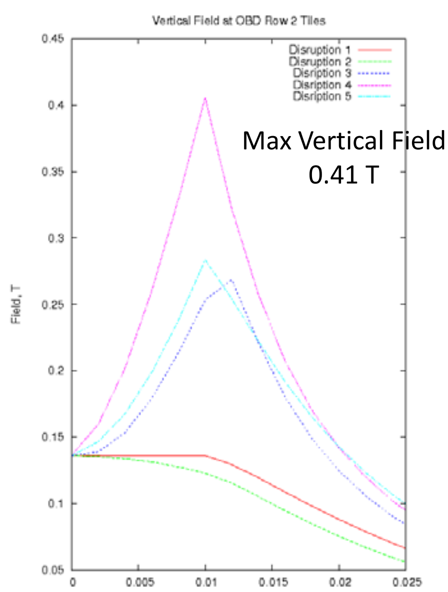
Field Scan during Plasma Disruptions at Outboard Diverter Row 2 Tiles





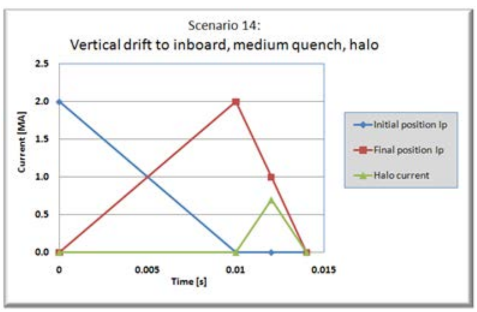
Analysis of OBD Row 2 High-Z Tiles

Halo currents are assumed to flow poloidally in the tiles. 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 still fairly low.

The peak halo current in a tile is determined by the plasma current (2 MA), halo current fraction (HCF=0.35) and the toroidal peaking fractor (TPF=1.2) as specified by physics (ref 5). With 96 tiles toroidally the peak halo current is 8.75 kA.

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 OBD_Row2,
Halo = **8.75 kA** per 3.75 deg Tile
(2MA/96Tiles*.35HCF*1.2TPF)

Halo current assumed to take longest path across TF for worse case loading unless justification can be made not to. Current resistively distributed between tile and support plate

The combined loading to the tiles is summarized below.

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)

Structural Load Summary for Tile

- Thermal
  - At 2 MW/m2 for 5 sec the Surface Temperature varies from less than 175 C in the shaded regions to just under 500 C on the tapered regions where heating is enhanced.
  - There is ~450 C max thermal gradient thru thickness of the tile.
- Eddy Currents
  - With Moly TZM low electrical resistivity, eddy currents do not reach the resistive limit (~85 kA) as given from the max dB/dt so a more realistic current based on the inductive limit is used (25kA) determined from the total flux swing thru the tile
  - With the peak fields of .8T, the edge load is 2.6 kN and the radial moment is 257 N-m
- Halo Currents
  - The 8.75 kA give a Lorentz force of 910 N normal (pushing tile into support plate) as well as 910 N lateral (sliding tile on plate)
- Structural
  - Rails supporting tile are held by ¼" bolts assumed preloaded to 1000 lbs (4.448 kN) with Belleville washers to allow moment
  - Tile will arch away from plate pushing down at corners of tile at Grafoil and pulling up at the middle of the rail. Behavior is simulated with contact elements with friction (mu=0.3)
  - Lateral motion will tend to shear bolts if friction and/or normal forces are not high enough to prevent slippage
    - Preload plus Halo normal forces total 9.7 kN should be sufficient to hold .9 kN lateral force with less than mu=0.3

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Acceptance Criteria

The TZM Yield Strength and Fatigue Limits vary with temperature as shown below. In general, the base of the castellations are significantly cooler than the surface so will have a higher allow stress than the surface. The design will be limited by the fatigue allowable of 500 MPa at temperatures below 500 C. It is also desirable to keep peak surface temperatures below the recrystallization temperature of the TZM assumed to be 1400 C. SN data is not available at that temperature and may become an issue for high powered shots (in present results that qualify the tiles at 2 MW/m2 for 5 sec 500 C is not exceeded). Since the dominate stress is from thermal load cycling from pulse to pulse, stresses vary linearly from 0 to their max (not thermal load reversal) so R=0 data is appropriate. Preload and EM will have only a small effect on R

TZM Yield Strength and S-N Curve

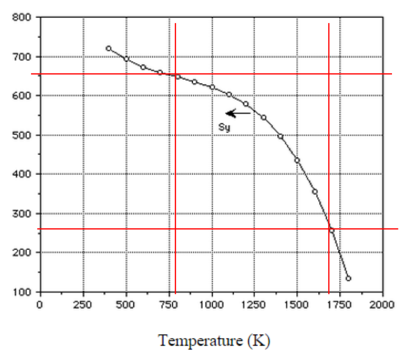
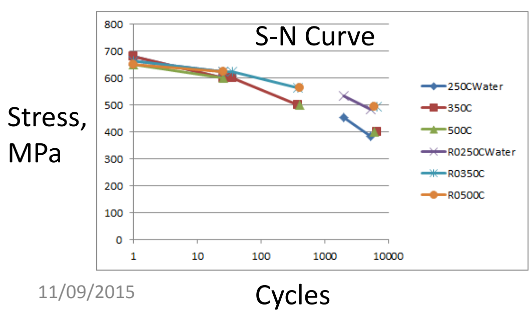


Figure 3 : Yield Stress of TZM.

Sy=650 MPa at 500 C (773 K)
Allowable Secondary Stress =1300 MPa

Sy=260 MPa at 1400 C (1673 K)
Allowable Secondary Stress = 520 MPa



At 500 C, 500 Mpa R=0 Tension We should expect 6000 Cycles

SN data from Peter Titus
Based on Load Controlled, not Strain Controlled

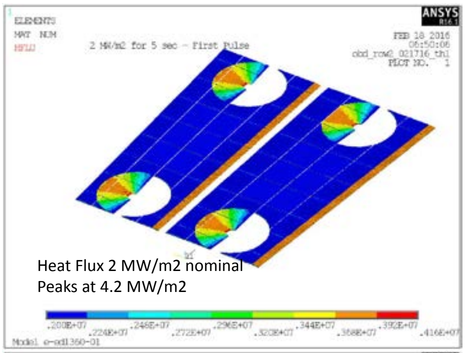
11/09/2015 6

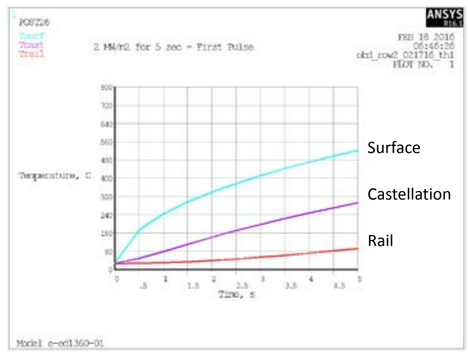
Analysis of OBD Row 2 High-Z Tiles

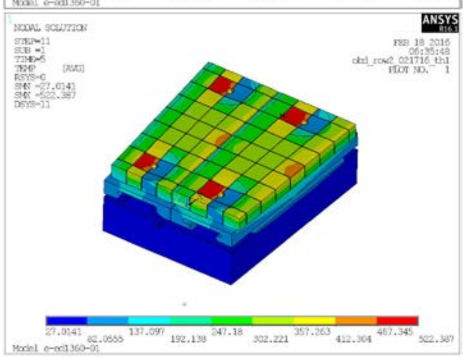
Results

Results are given first for the final global model for just thermal loading which has been shown to dominate.

Temperature Response, 2 MW/m2 Nominal for 5 sec





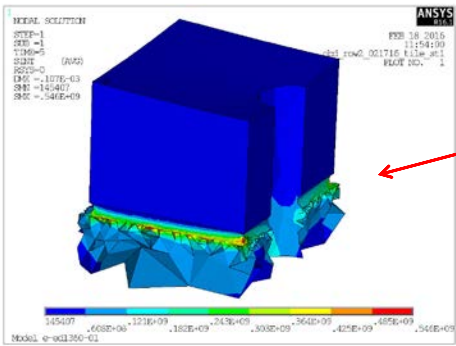


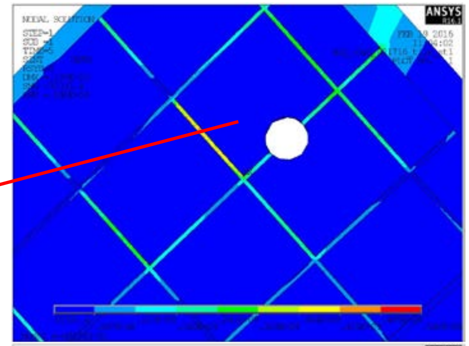
Note: Simulation run to end of pulse
Castellation may get hotter and heat soaks in

The plots above show the first pulse thermal response for the design load of 2 MW/m2 for 5 sec over the entire surface. Note the 2 MW/m2 is assumed to be the normal component of a much higher heat flux parallel to the field lines which are at 5 deg to the nominal surface. The upper left hand plot shows the resultant heat flux distribution when the surface angles and shading are factored in.

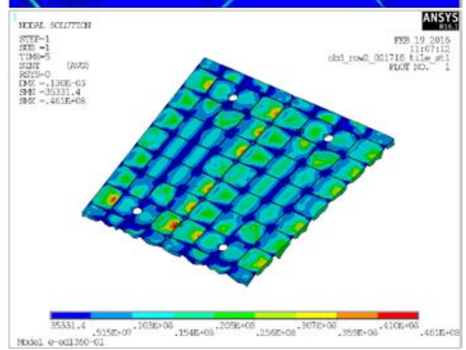
Analysis of OBD Row 2 High-Z Tiles

Thermal Stress in Free Expansion Tiles





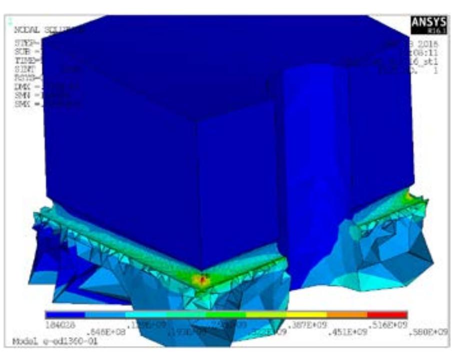
Stress at Sharp Corners formed where Castellations Cross only slightly less than with Clamped Tiles. Peak Stress 546 Mpa.



Surface Stress much lower 46.1 MPa

The resulting thermal only stresses are shown for two different boundary conditions – tiles free to expand (above) and tiles clamped flat (below).

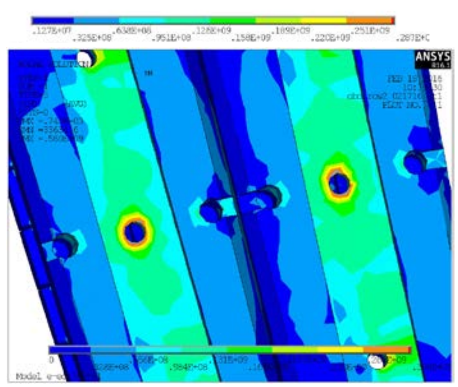
Thermal Stress in Clamped Tiles*



Sharp Corners formed where Castellations Cross. Need to be Rounded. Peak Stress 580 Mpa.

Away from sharp corners, stresses are less than half

Stresses at Diagnostic Cutouts < 287 MPa

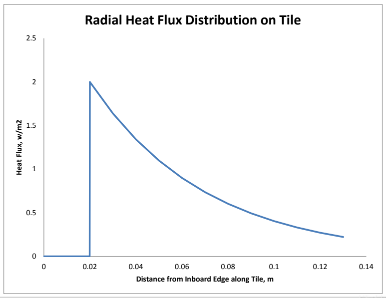


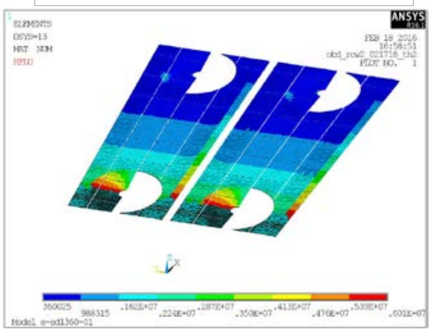
Locating Pin Hole Stress higher 407 MPa

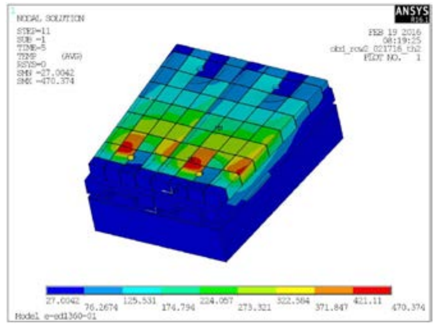
The bolt preload of 1000 lbs was shown to be sufficient to keep tile in contact with Grafoil at 2 MW/m2 for 5 s

Analysis of OBD Row 2 High-Z Tiles

Temperatures from Variable Heat Flux over Tile Surface

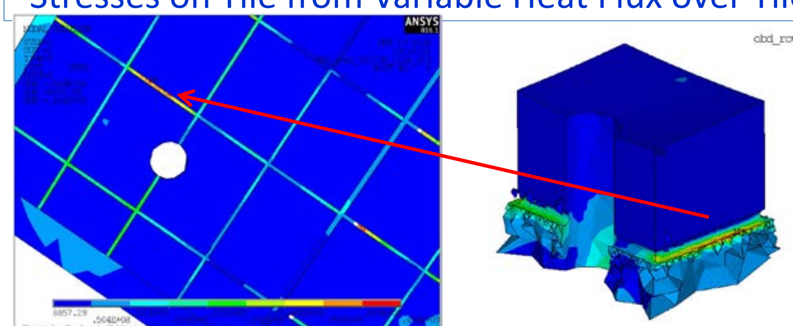




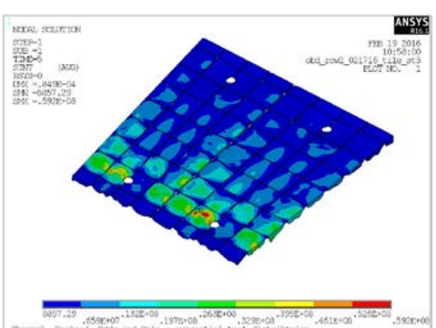


Similar results are obtained for non-uniform heat flux. As shown above the heat flux drops off exponential in the radial direction, peaking at the inboard bolt hole and decaying with a decay length of 5 cm resulting in large thermal gradients radially. The corresponding stresses are given below.

Stresses on Tile from Variable Heat Flux over Tile Surface



Peak Stress at Castellations 454 MPa

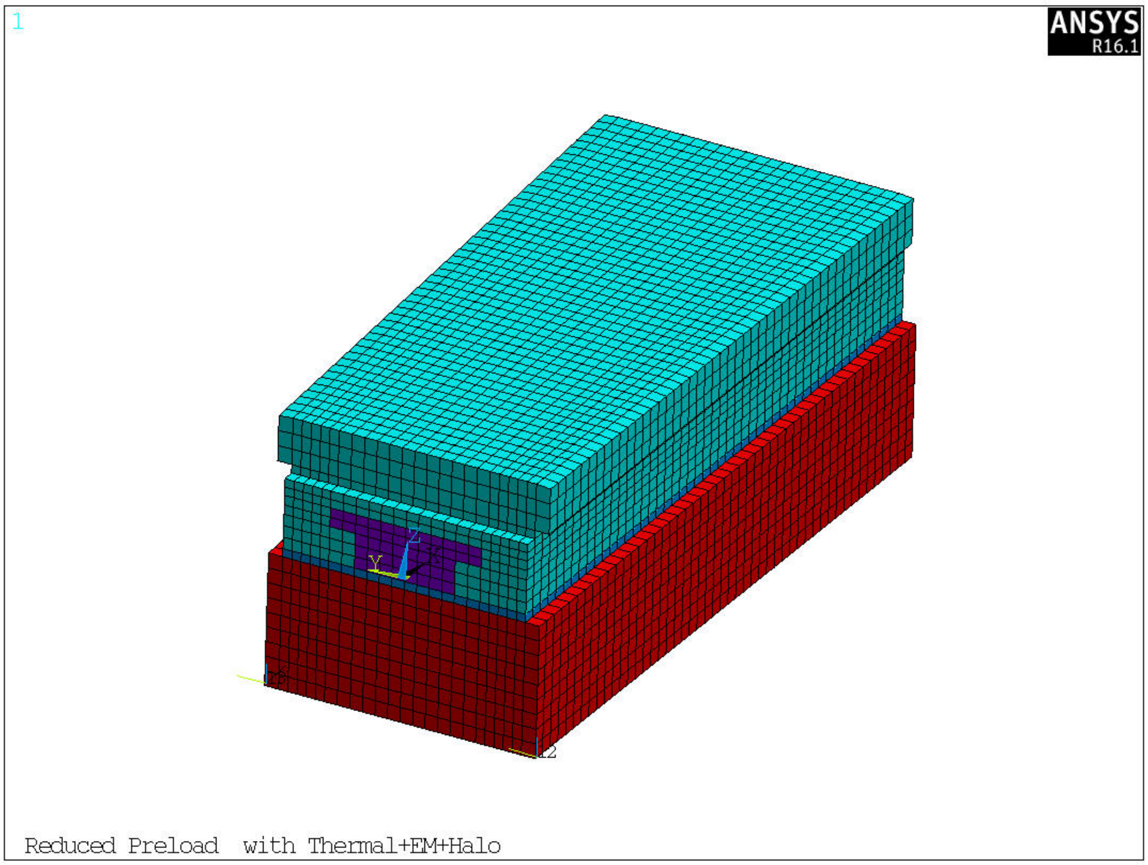


Surfaces Stress much lower
59 MPa

Analysis of OBD Row 2 High-Z Tiles

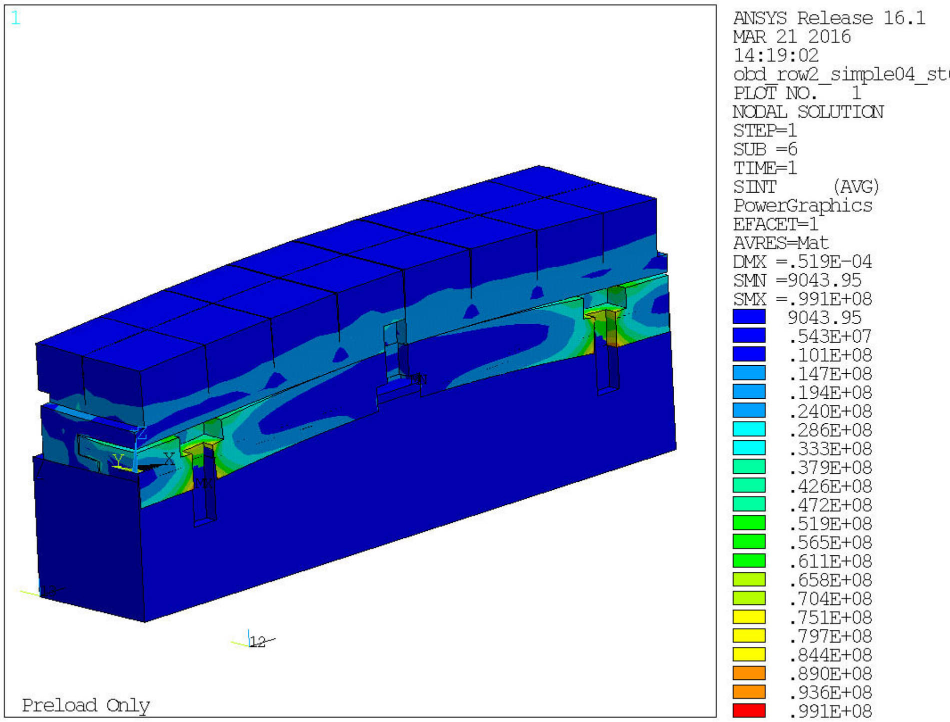
The tiles are supported by a T-bar that runs through the length of the tile. The T-bar is held to the copper backing plates with bolts and Belleville washers preloaded to 1000 lb each. This keeps the tile in contact with the Grafoil that fills the gap between the tile and backing plate providing improved thermal conductance to the plate. Heat is rejected off the back of the plate either radiatively or actively cooled if needed. The preload also restrains the tile from the lateral halo forces.

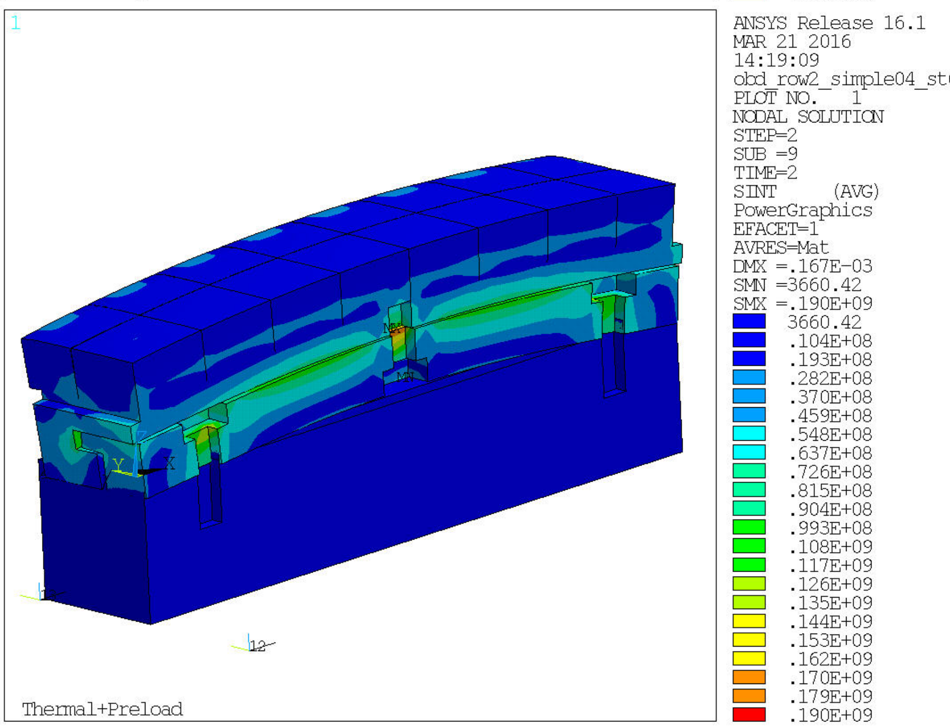
A simplified model (shown below) of the TZM tile, Inconel T-bar, Grafoil and Copper back plate was used to simulate the response of the assembly to preload, thermal stresses, plasma disruption eddy current forces and halo current forces. The model contains gap elements with friction. The loads are applied sequentially to see the incremental impact.



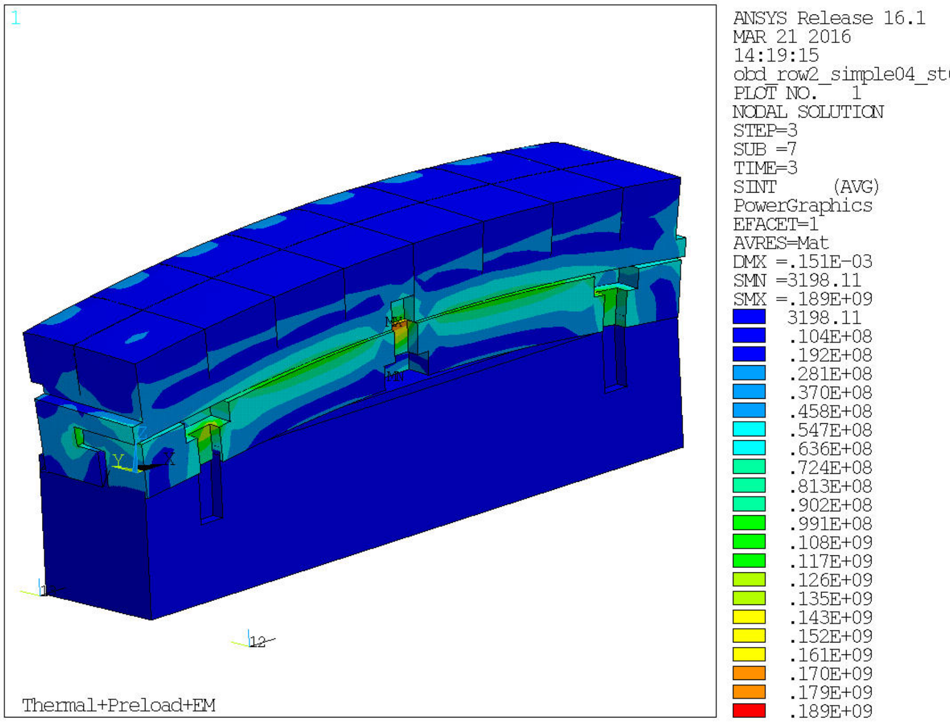
The following four plots show results for preload only, 2 MW/m2 thermal + preload, eddy currents + thermal + preload, and finally halo currents + eddy currents + thermal + preload respectively. The stresses are shown to be dominated by the thermal loading – the addition of eddy current and halo current forces do not significantly alter the peak stress. The peak stress is shown to be ~190 MPa, well within the 500 MPa limit. However, the main purpose of this model is to show the tile stresses can be reasonable determined from assuming simplified boundary conditions with just thermal loading as was done earlier with the detailed modeling. This justifies the assumption made there.

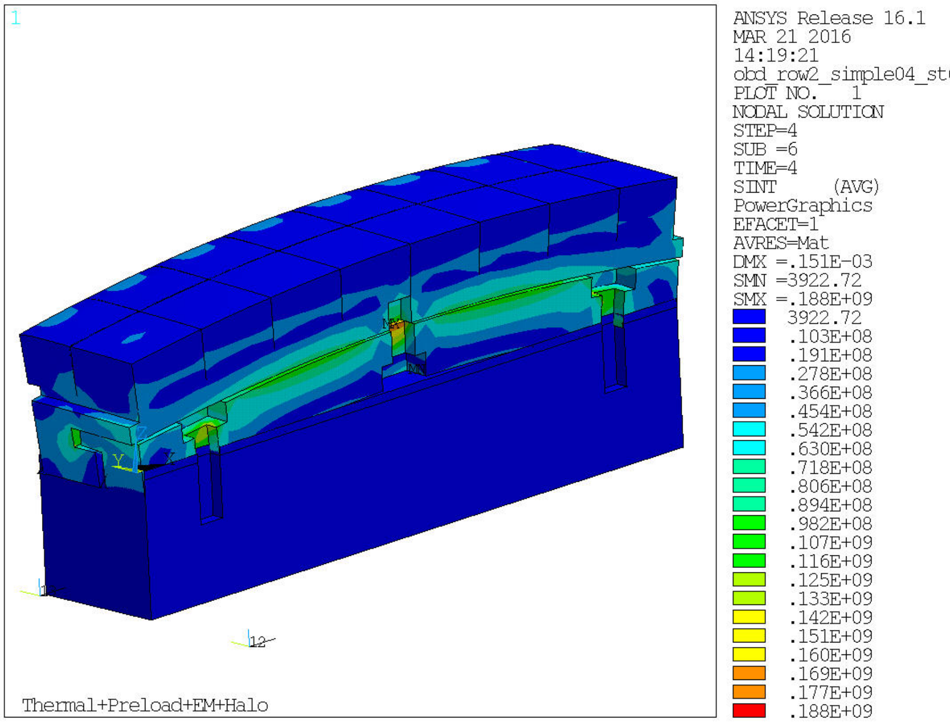
Analysis of OBD Row 2 High-Z Tiles





Analysis of OBD Row 2 High-Z Tiles



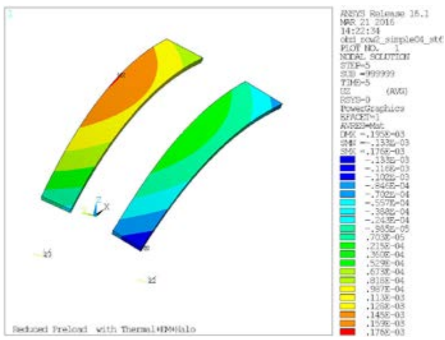


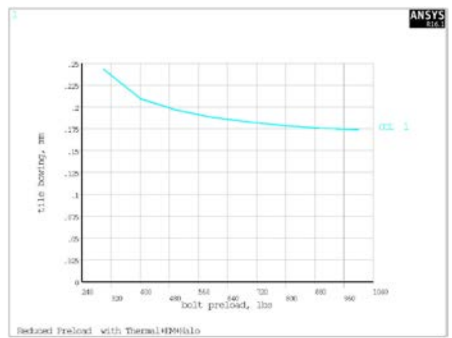
Analysis of OBD Row 2 High-Z Tiles

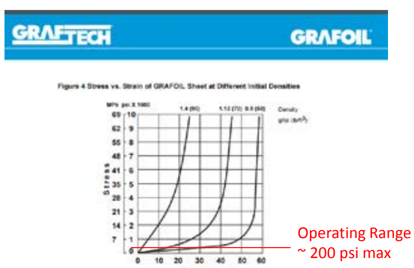
The preload does not have a significant impact on the tile stresses (unless it becomes much larger than the 1000 lb assumed). This is due to the compliancy of the Grafoil. At 1000 lb preload the pressure is ~200 psi (1.4 MPa) which, looking at the GRAFTECH plot below, puts it on the low end of the curve with an effective modulus of less than 10 MPa. At higher preloads the strain in the Grafoil would flatten out, losing its compliancy.

As mentioned earlier the preload is required to restrain the tile from lateral moment under halo forces with uncertain coefficients of friction between the TZM and Grafoil. With a coefficient of friction of 0.3, the tile could slip if the preload dropped below 300 lbs. The 1000 lbs gives some protection against lower coefficients.

Impact of Preload on Tile Stress and Deflection



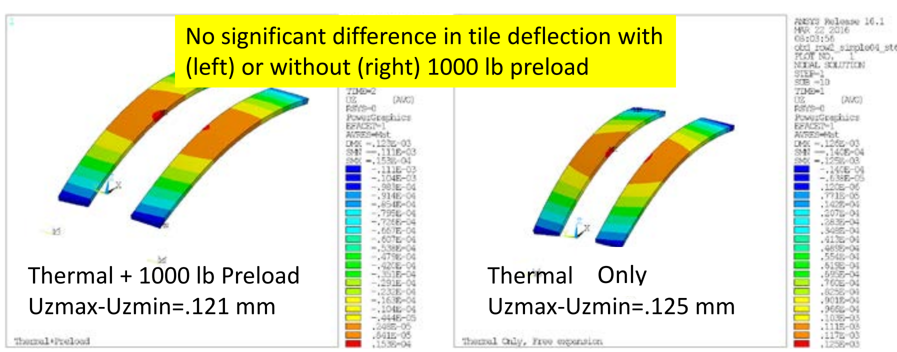




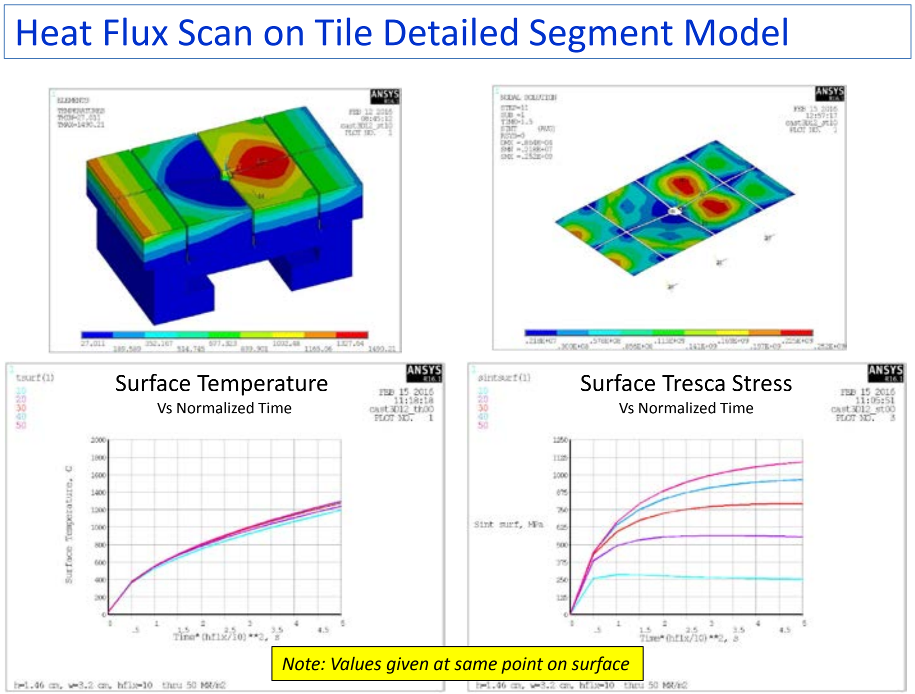
The Grafoil has a very low effective modulus at the pressure from 1000 lb preloads (200 psi or 1.4 MPa) making it very compliant to tile deformation.

Preload is needed mainly to keep tile from slipping with halo current forces

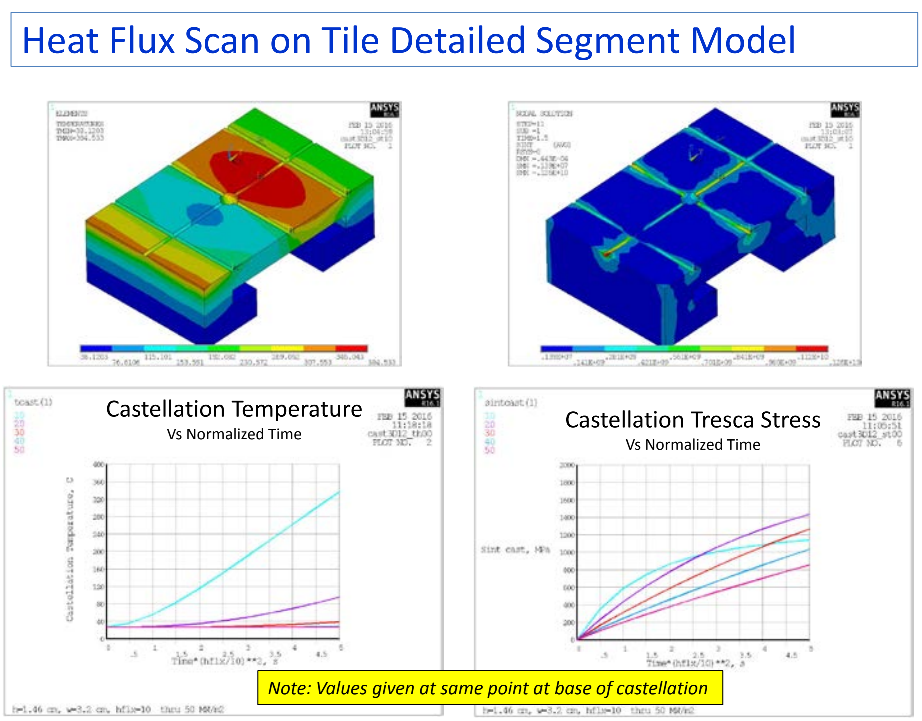
Below the deflection of the base of a tile is compared with and without preload. The pattern is the same as is the difference between the max and min displacement. The preload only changes the free body motion of the tile as it compresses the Grafoil.



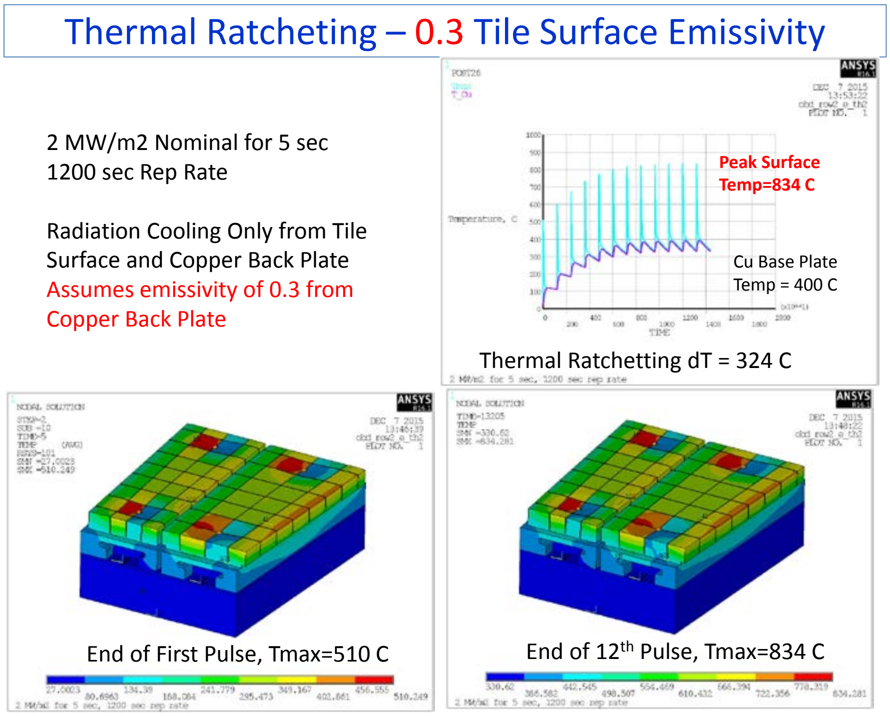
Analysis of OBD Row 2 High-Z Tiles



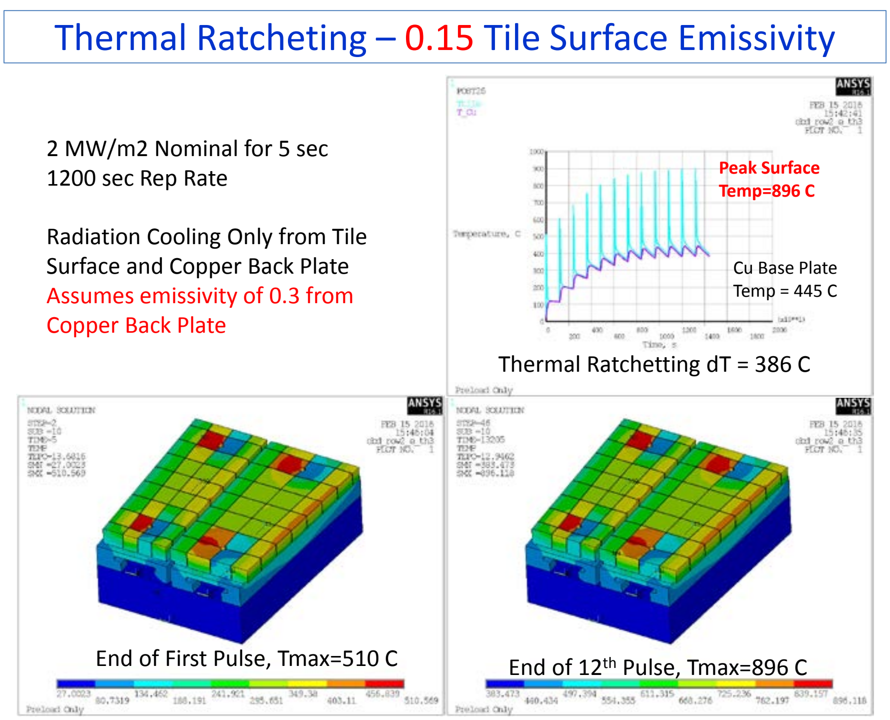
The detailed local model was used to perform a scan of high heat flux impact on temperature and stress response at the tile surface (above) and at the root of the castellations (below). Heat fluxes for 10, 20, 30, 40 and 50 MW/m2 are given. Note the time scale has been normalized (stretched out) to 10 MW for 5 sec. So the 50 MW/m2 is actually run for only 5*(10/50)^2=0.2 sec but produces the same surface heating.



Analysis of OBD Row 2 High-Z Tiles



A sensitivity of the Tile surface emissivity and active cooling to thermal ratcheting was also performed. With radiation cooling only, the tile surface ratchets up to 834 C with 0.3 surface emissivity after a few hours of pulsing. At 0.15 surface emissivity the tile surface ratchets up to 896 C. The base of the castellations stay below 500 C in both cases (400 C at e=.3 and 445 C at e=.15)

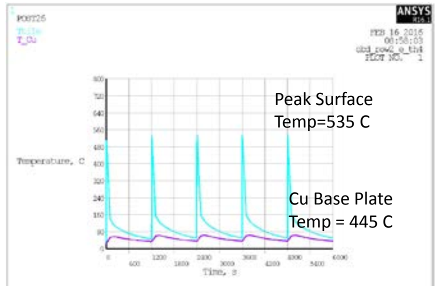


Analysis of OBD Row 2 High-Z Tiles

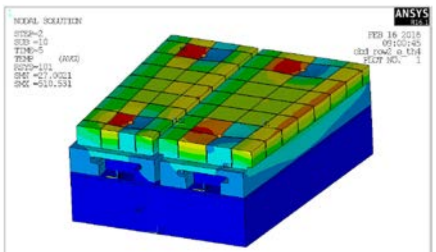
Thermal Ratcheting – Active Cooling

2 MW/m2 Nominal for 5 sec
1200 sec Rep Rate

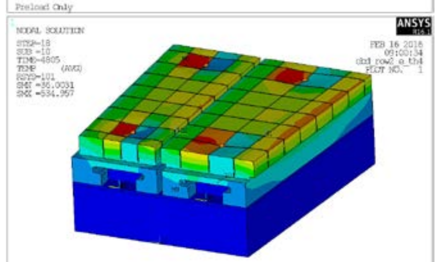
Radiation Cooling from Tile Surface, emis=.15
Radiation Cooling from Copper Back Plate, emis=0.3, plus active cooling, heff=300 w/m2-C



Thermal Ratchetting dT = 25 C

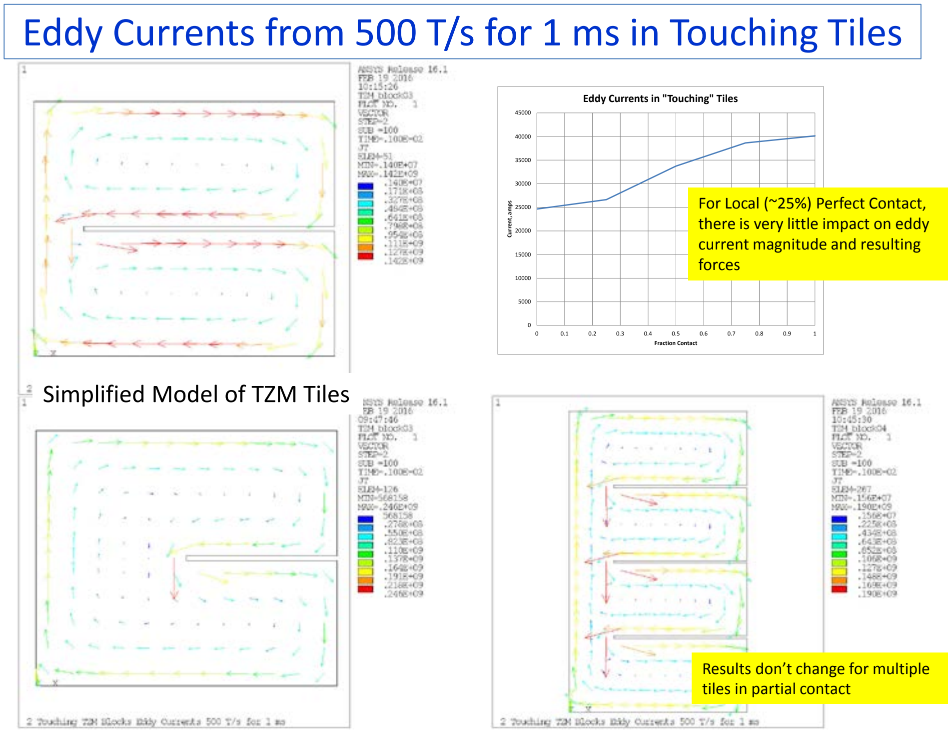


End of First Pulse, Tmax=510 C

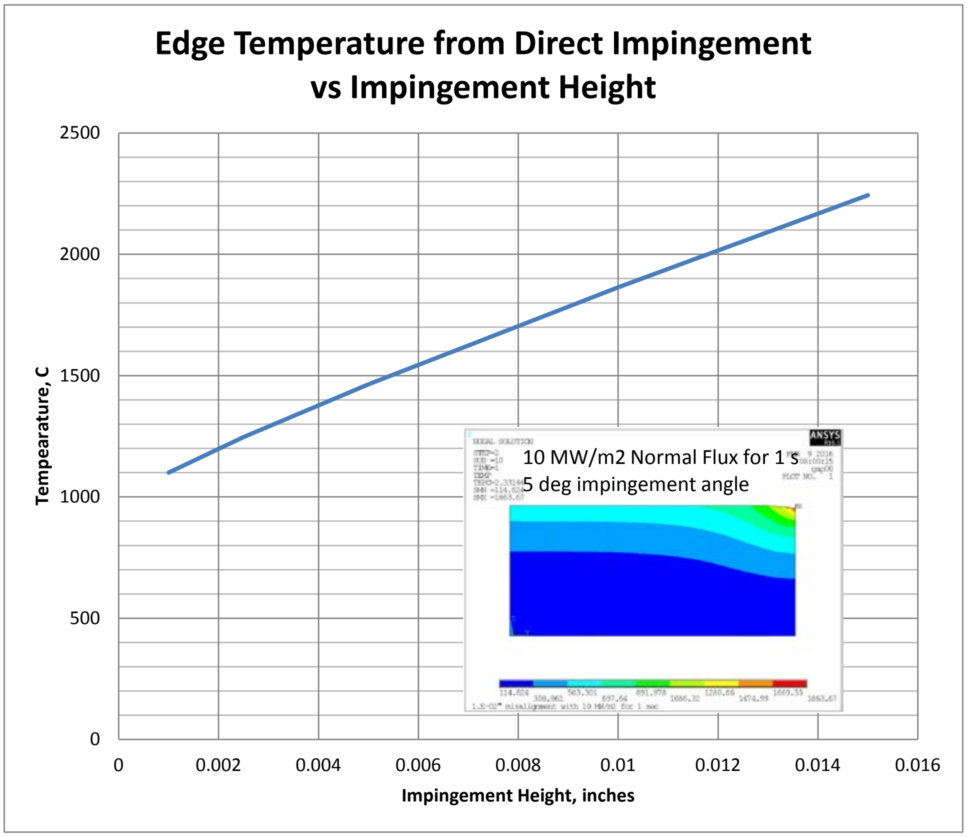


End of 5th Pulse, Tmax=535 C

Analysis of OBD Row 2 High-Z Tiles



Tolerances can possibly lead to tile misalignment that causes contact between tiles. This could occur if adjacent tiles rotated in opposite directions, contacting at one end. This has the potential effectively increasing the size and magnitude of eddy current loops. The plots above show loads would increase modestly if this occurs.



The tiles have been shaped to avoid edge heat of the gaps between tiles. However the assembly alignment tolerance of tiles could lead to edge heating if tolerances are large. The plot above shows the temperatures that result for different tolerances (aka impingement height). The project has chosen .01 inch as the assembly tolerance.

Summary

Results for the OBD row2 Moly TZM basic tiles analyzed herein show the tiles can withstand the 6000 cycles for pulsing with nominal heat loads of 2 MW/m2 for 5 secs without exceeding the 500 MPa fatigue limit.

References

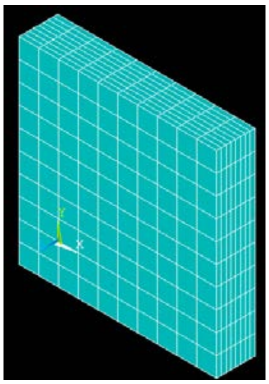
1) NSTX_CSU-RQMTS-GRD General Requirements Documents, Rev 3
2) Design Point Spreadsheet “NSTX_CS_Upgrade_100504.xls”
3) http://www-ferp.ucsd.edu/LIB/PROPS/PANOS/moa.html
4) ProE Model of OBD Row 2 Tiles

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-CRIT-0001-02 “NSTX Structural Design Criteria”
8) NSTXU-CALC-11-03-00 “Stress Analysis of ATJ Center Stack Tiles and Fasteners”
9) “System Requirements Document for NSTX-U High-Z Divertor Upgrade 1”

Appendix I – Reviewers Comments (Jingping Chen)

Analysis of OBD Row 2 High-Z Tiles
NSTX
Review recommendations

1. Based on the report, heat flux is the dominant load to the structure, so a simplified model was developed to verify the thermal results.



- 2 MW heat flux to one of the side surface to simulate average heat flux
- 4.12 MW heat flux to simulate peak heat flux
- 0.3 emissivity used for thermal ratcheting simulation
- 300K is assumed to be initial temperature

   The detailed results of this model are summarized at the end of this document.
   Conclusions: the results from this simplified model are perfectly consistent to the report's results.
2. In page 6, please add unit to the figures.
3. In page 12, regarding S-N curve and thermal stress, it is good to add a brief justification why the R=0 fatigue data can be used to judge the thermal stress.
4. In page 19, the label in bottom right figure should be thermal without preload
5. In page 23, regarding the eddy current analysis
   Because both Eddy current and HALO current happen during plasma disruption, and in HALO analysis we assume plasma fill into the gaps and short the tiles, should we also assume the same condition in Eddy current calculation?

Analysis of OBD Row 2 High-Z Tiles

Results from the simplified model:

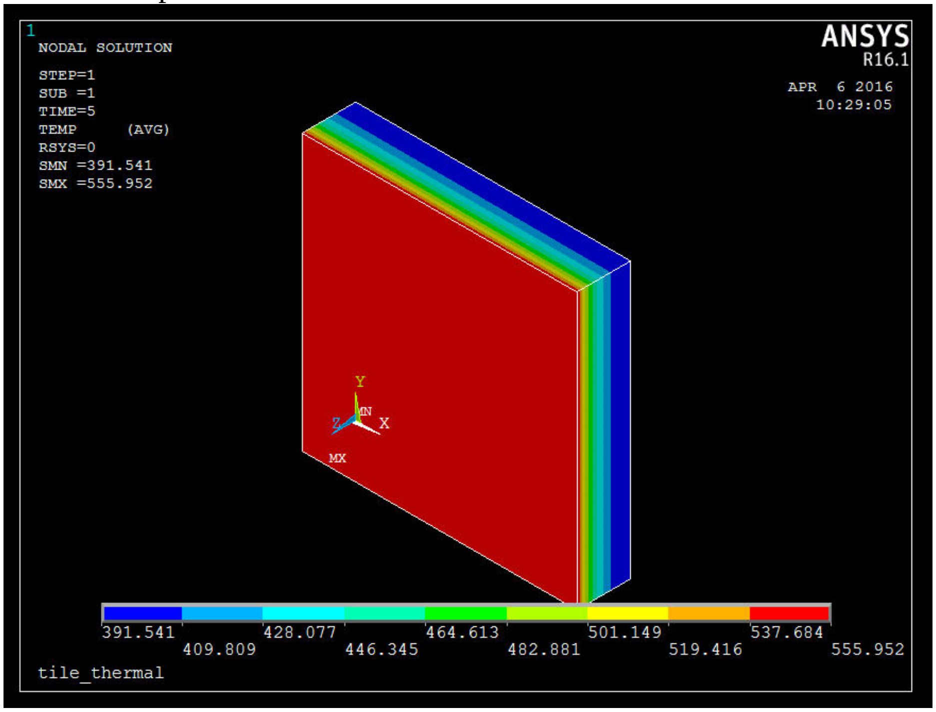


Fig.1 temperature plot for 2MW heat flux to the left surface for 5 s.

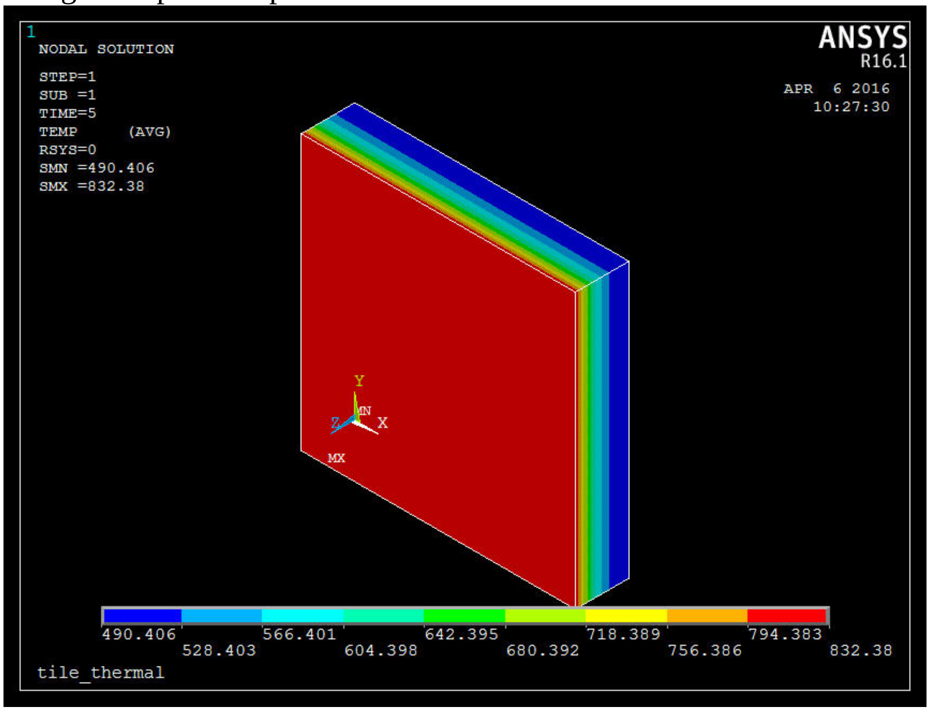


Fig.2 temperature plot for 4.16 MW heat flux to the left surface for 5 s.

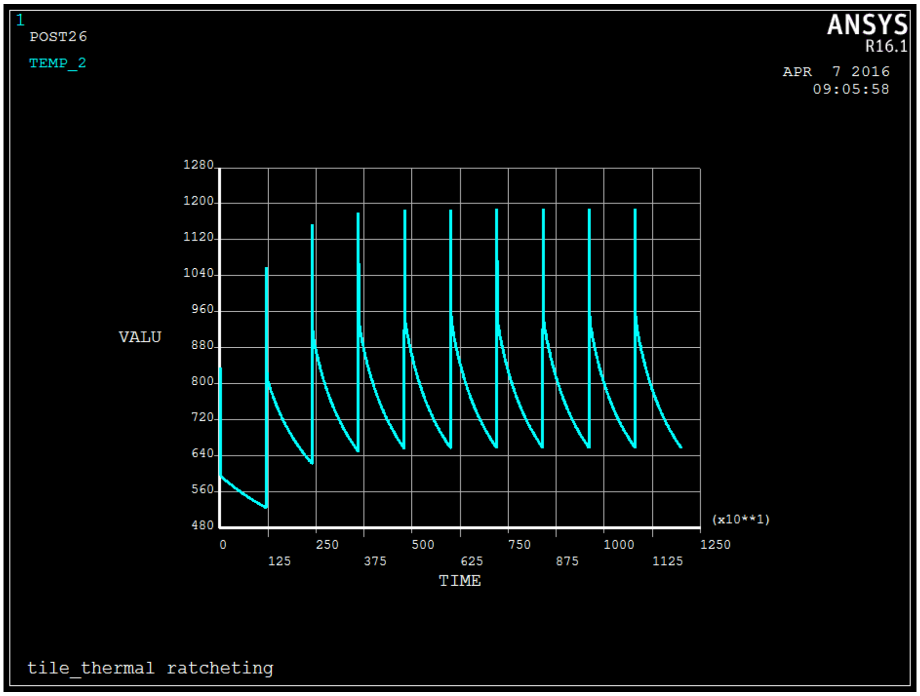


Fig.3 Thermal ratcheting at peak surface (4.2MW, 0.3emis, $T_{init.}$ 300K, 1200s rep time)

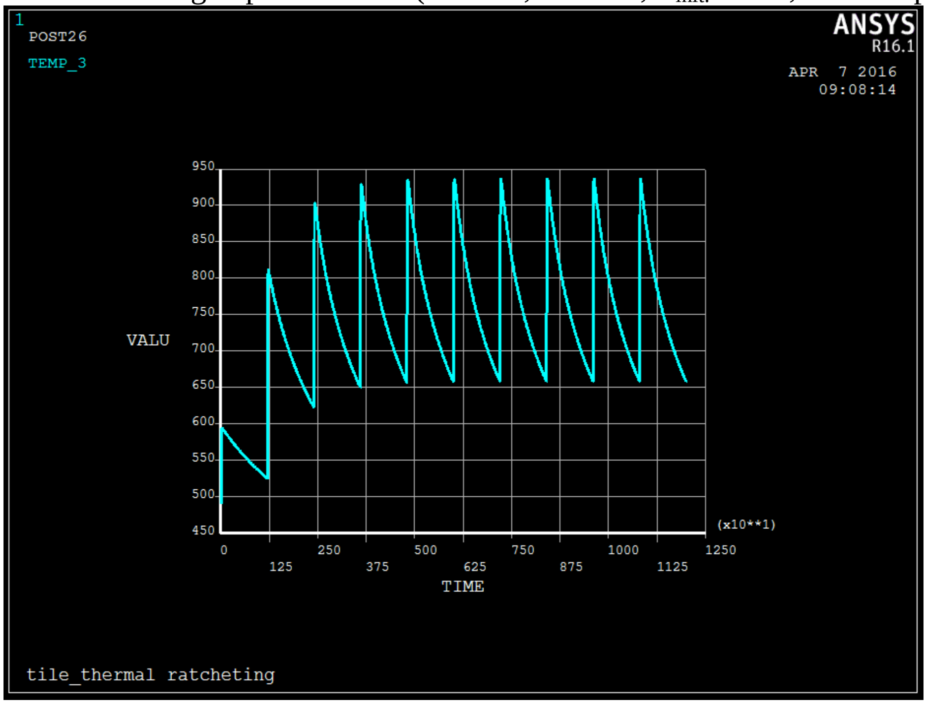


Fig.4 Thermal ratcheting at back surface (4.2MW, 0.3emis, $T_{init.}$ 300K, 1200s rep time)