Calculation No: NSTXU-CALC-11-14-00 **Revision No:** 0

***Title:** Calculation of Thermal and Structural on Row 3 Tiles and Variants Styles 1 and 2*

Purpose of Calculation: (Define why the calculation is being performed.)
Qualify Outboard Divertor Row 3 Tile and Attachments

Codes and versions: (List all codes, if any, used)
ANSYS 19.0, 19.1, 19.2

References (List any source of design information including computer program titles and revision levels.)
1. NSTX-U-RQMT-GRD-001-02, GENERAL REQUIREMENTS DOCUMENT, Stefan, Gerhardt, 2018.
2. NSTX-U-RQMT-RD-003-01, NSTX-U Disruption Analysis Requirements, Stefan, Gerhardt, 2018.
3. NSTXU-CALC-55-03-00, PFCs Fields and dBdts, Art Brooks, October 13, 2017.
4. NSTX Structural Design Criteria Document, NSTX_DesCrit_IZ_080103.doc, I. Zatz, 2016.
5. NSTX-U-RQMT-SRD-003-02, System Requirements Document on Plasma Facing Component, Stefan, Gerhardt, July 2018.
6. PFCR-MEMO-005-00, Impact of faceting on heat flux to the outboard divertor PFCS, M. Reinke, June 2017.

Assumptions (Identify all assumptions made as part of this calculation.)
Assume that all the OBD345 tiles without cooling underneath should have the repetition period of 40 minutes.

Calculation (Calculation is either documented here or attached)
The transient thermal and structural models with halo and eddy loads have been analyzed to check the design qualification of OBD345tiles. See the attached report for details.

Conclusion (Specify whether or not the purpose of the calculation was accomplished.)
All tiles meet their design requirements.

Cognizant Individual (or designee) printed name, signature, and date

Preparer's printed name, signature and date

Brian C Linn
9/27/18
Brian C Linn
Digitally signed by Brian C Linn
Date: 2018.09.27 17:59:32 -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 Jiarong Fang
Digitally signed by Jiarong Fang
Date: 2018.09.27 18:32:37 -04'00'

Revised 9/10/18

National Spherical Torus eXperiment - Upgrade

NSTX-U

Calculation of Thermal and Structural on Row 3 Tiles and Variants Styles 1 and 2

NSTXU-CALC-11-14-00

September 27, 2018

Brian C Linn
Digitally signed by Brian C Linn
Date: 2018.09.27 17:59:53 -04'00'

Prepared By
Brian C. Linn, Engineering Analyst

Jiarong Fang
Digitally signed by Jiarong Fang
Date: 2018.09.27 18:33:12 -04'00'

Reviewed By
Jiarong Fang, Engineering Analyst

Michael Jaworski
Digitally signed by Michael Jaworski
Date: 2018.09.28 23:21:59 -04'00'

Approved By – Responsible Engineer
Michael A. Jaworski, Research Physicist

NSTX-U CALCULATION

Record of Changes

Rev.	Date	Description of Changes	Revised by
0	9/17/18	Initial Release	

Overview

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 T953 graphite stress limits. The allowable stress limits for T953 graphite are half of the ultimate tensile and compressive strength, consistent with the brittle material requirements specified in the NSTX-U Structural Design Criteria (NSTX_CRIT-0001-02B). Vendor provided data gives an ultimate compressive strength of 110MPa for T953. Published values of the UTS of T953 were not available and material testing was performed to establish UTS of 40MPa for T953. The heat flux requirement for OBD tiles is defined in requirements in NSTX-U-RQMT-SRD-003-02 tables 4.4-2 (row 3) and 4.4-3 (rows 4 and 5).

Thermal analysis presented here was performed based on the worst-case thermal transient required. Electromagnetic forces analyzed in these analyses were calculated from the NSTX-U Disruption Requirements document, NSTX-U-RQMT-RD-003-00. Halo current forces were implemented as either (1) a force applied to the tile plasma facing surface(s) corresponding to the component-average nodal forces determined by eddy current analysis or (2) as a body-distributed force applied at mesh nodes. The type of EM load defined in each analysis is indicated in each variant subreport.

Similar to previous designs, the OBD3-5 tiles use T-bar supports held by bolts with Belleville washers and with compliant Grafoil underneath. The new design OBD mounting structure incorporates several minor modifications aimed at allowing the tile to more freely expand when thermally loaded and thus minimize internal stresses induced in the tile. All analyses assumed hold-down bolts preloaded to 500lbs (2670N); this reduced preload was specified to permit thermal deformation while still preventing movement of the assembly under disruption electromagnetic loads.

This analysis covers the design qualification of the standard OBD row 3 tiles and mounting shown below. This includes the thermal and structural response from plasma heating during normal operation combined with disruption loading. Variants of each standard cutout accommodating embedded diagnostic sensors were also analyzed. Tables 1 and 2 provide a summary of the peak stresses determined for all variants analyzed in this report. The detailed results for each variant are given in the applicable section of this report.

The subreports for each tile variant were done for global model that did not include chamfers on the plasma facing surface of the bolt hole chamfers. The values of minimum principle stresses reported in subreports is unrealistically high, as a chamfer has been incorporated to these edges and was optimized in an independent local model. The results for the local chamfer model are given in Section 6.

PPPL Dwg. No.	Description	Max Temp	Max S1 MPa	Min S3 MPa	Comments
E-ED1403-1	R3 style 1 base tile	1264C	15.5	-50.5	Analysis subreport given for tile model which was subsequently changed to increase the depth of hold-down bolt counterbores. The initial stress profiles matched those of the thermocouple variant, E-ED1403-6. Subsequent analysis of this tile not necessary - the results presented for the thermal couple variant (ED1403-3) are also valid for this tile. The S3 value reported is based on the chamfer incorporated on the bolt hole and is shown in Section 6 of this report.
E-ED1403-2	Mirnov	N/A	N/A	N/A	Analysis not required; analysis of R5 Style 1 Mirnov variant (E-ED1406-2) showed that the probe cutout will not drive design. See calculation report NSTXU-11-16-00.
E-ED1403-3	Thermocouple	1264C	15.5	-50.5	
E-ED1403-4	Langmuir Probe (2x)	N/A	N/A	N/A	Analysis not required; qualification via R3 Style 2 Langmuir Probe variant (E-ED1402-4). The S3 value reported is based on the chamfer incorporated on the bolt hole and is shown in Section 6 of this report.
E-ED1403-6	RF Langmuir Probe	1264C	15.5	-50.5	*Reported values based on incorporation of stress reduction features analyzed with E-ED1403-3. The S3 value reported is based on the chamfer incorporated on the bolt hole and is shown in Section 6 of this report.

Table 1 – Summary of analysis results for OBD Row 3 Style 1 tiles. All tiles are made from T953 Graphite; allowables: S1=20MPa, S3=-55MPa.

PPPL Dwg. No.	Description	Max Temp	Max S1 MPa	Min S3 MPa	Comments
E-ED1402-1	R3 style 2 base tile	1227C	19.5	-50.5	The S3 value reported is based on the chamfer incorporated on the bolt hole and is shown in Section 6 of this report.
E-ED1402-3	Thermocouple	N/A	N/A	N/A	Analysis not required; analysis of R3 Style 1 thermocouple variant (E-ED1403-3) showed that the probe cutout will not drive design. This tile can be considered qualified by qualification of its' base design
E-ED1402-4	Langmuir Probe (2x)	1352C	19.5	-50.5	*Reported values based on incorporation of stress reduction features analyzed with E-ED1402-1. The tile was also modified (chamfer introduced) to address the compressive stress reported right. The S3 value reported is based on the chamfer incorporated on the bolt hole and is shown in Section 6 of this report.

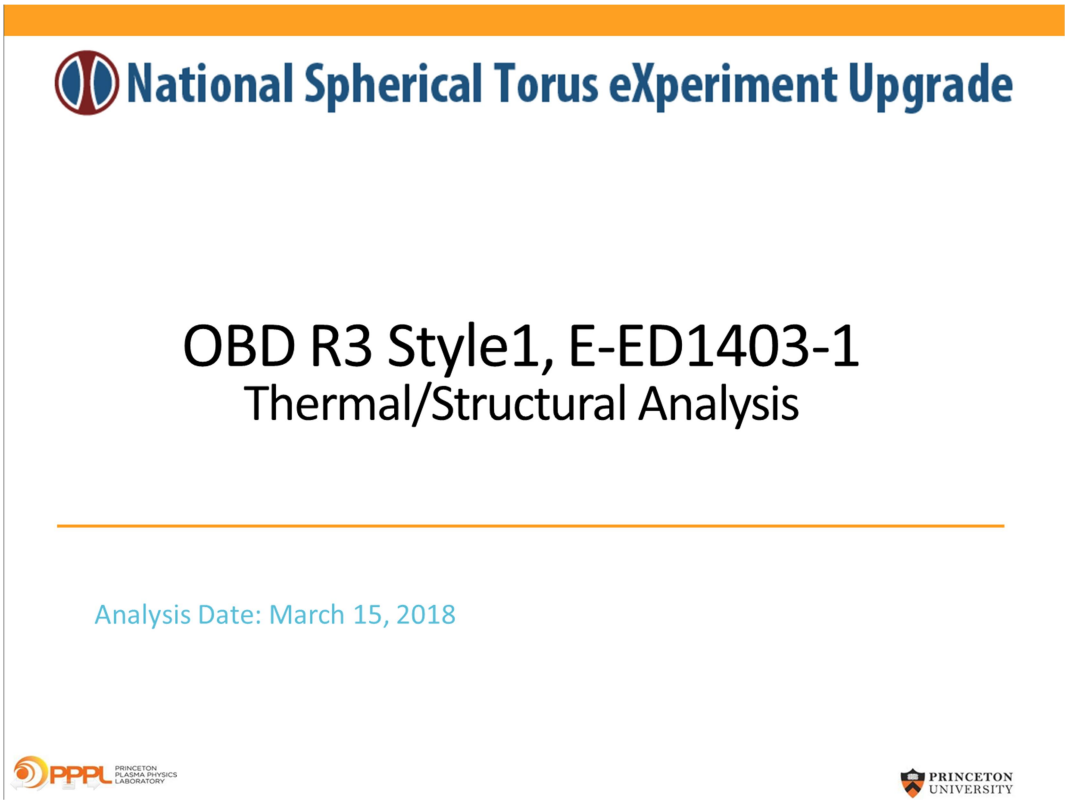
Table 2 – Summary of analysis results for OBD Row 3 Style 2 tiles. All tiles are made from T953 Graphite; allowables: S1=20MPa, S3=-55MPa.

Contents

1 Subreport E-ED1403-1, R3 Style 1 Base Tile

The results shown in this subreport are for an outdated version of the R3 Style 1 base tile (E-ED1403-1). The tile design was subsequently changed to (1) increase the depth of hold-down bolt counterbores (2) add a slot from the forward edge of the tile to the first bolt access hole, and (3) chamfer the under-tile step at the OBD R2 interface. These changes are detailed and shown in the subreport for the R3 Style 1 thermocouple variant (E-ED1403-3). At the time this analysis was completed, the stress profiles the E-ED1403-1 and E-ED1403-3 tile designs were very similar. Subsequent analysis of the E-ED1403-1 tile was not necessary as the key features are captured by analysis of the thermocouple variant.

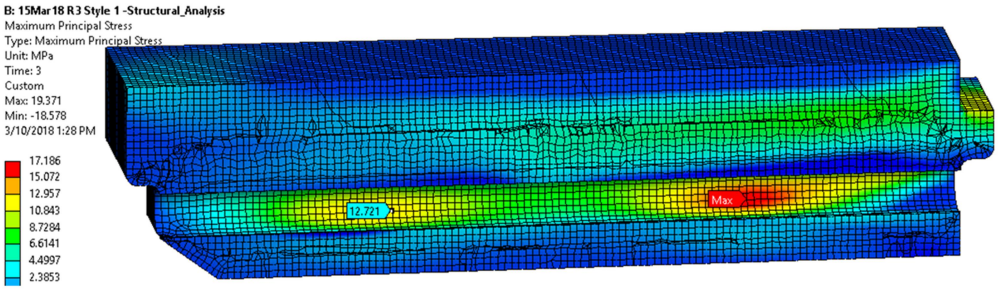
Please see E-ED1403-3 subreport for the stresses expected in this tile.



Tbar Slot Stresses

Max S1 = 17.2 MPa
Acceptable

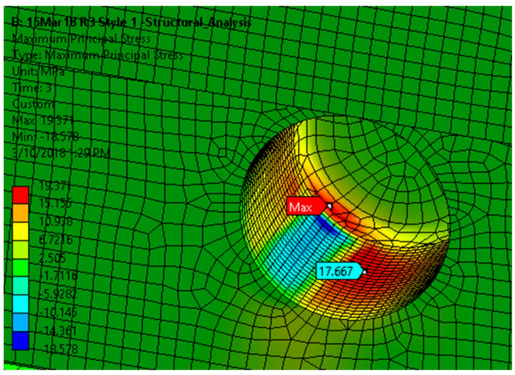
Max S3 = -14 MPa
Acceptable

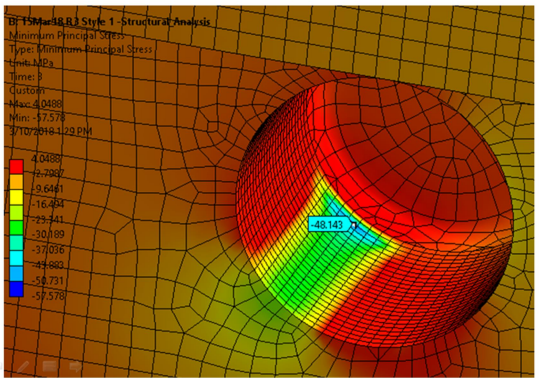


T953 Allowables: S1 = 20 MPa, S3 = -55 MPa

Shear Pin Hole Stresses

Max S1 = 19.4 MPa
Acceptable

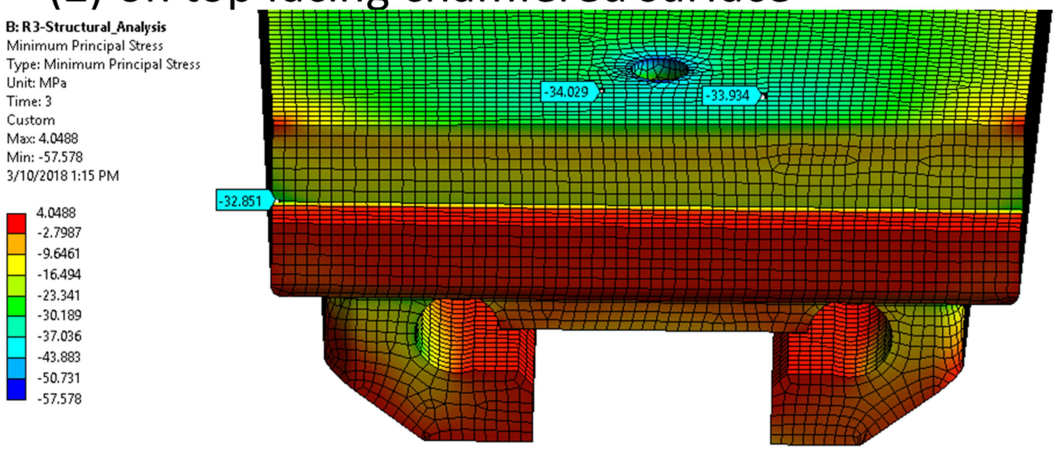




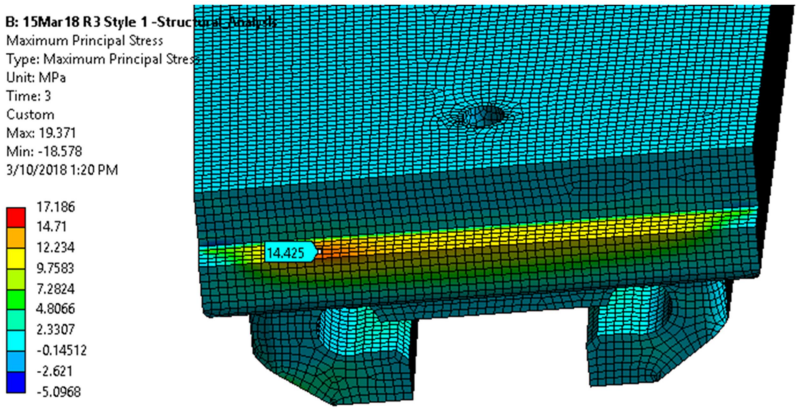
Max S3 = -57.6 MPa
Acceptable – localized peak

Notable Features - 1

Peak S3 occur at:
(1) sharp corner along topmost shelf surface
(2) on top facing chamfered surface



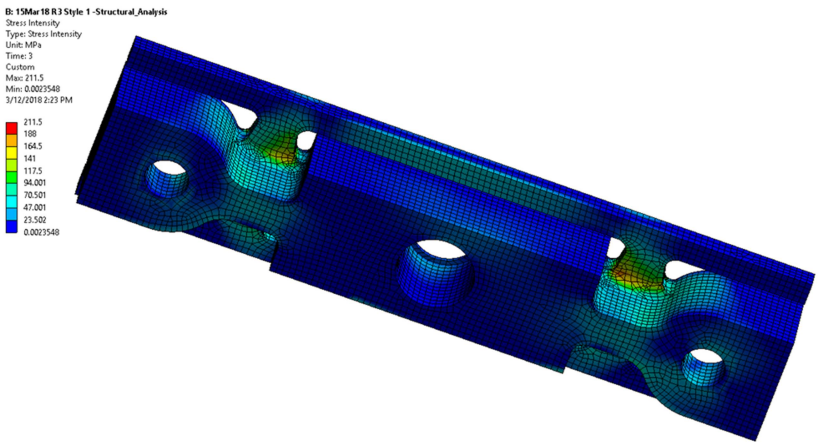
Notable Features - 3



S1 in the interface “shelf” at R2 tolerable

Tbar Stress

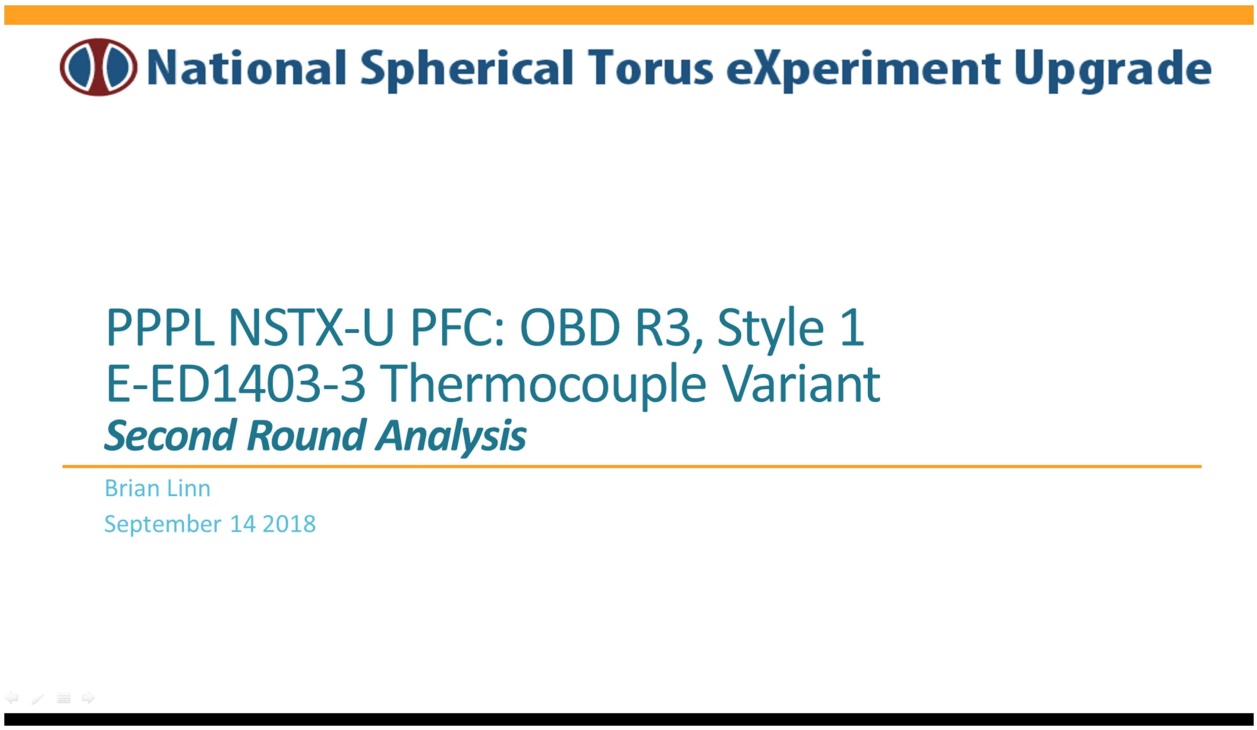
Tbar stress intensity is acceptable



2 Subreport E-ED1403-3 R3 Style 1 Thermocouple Variant

This subreport is broken up into two sections to provide design history. The first section gives the results for the current tile design of E-ED1403-3, which incorporated several modifications to the tile's design. The second section presents the analysis of an outdated version of the E-Ed1403-3 tile design. The peak stresses shown in the outdated tile design were alleviated by the geometric changes outlined below.

2.1 Analysis of Current E-ED1403-3 Tile



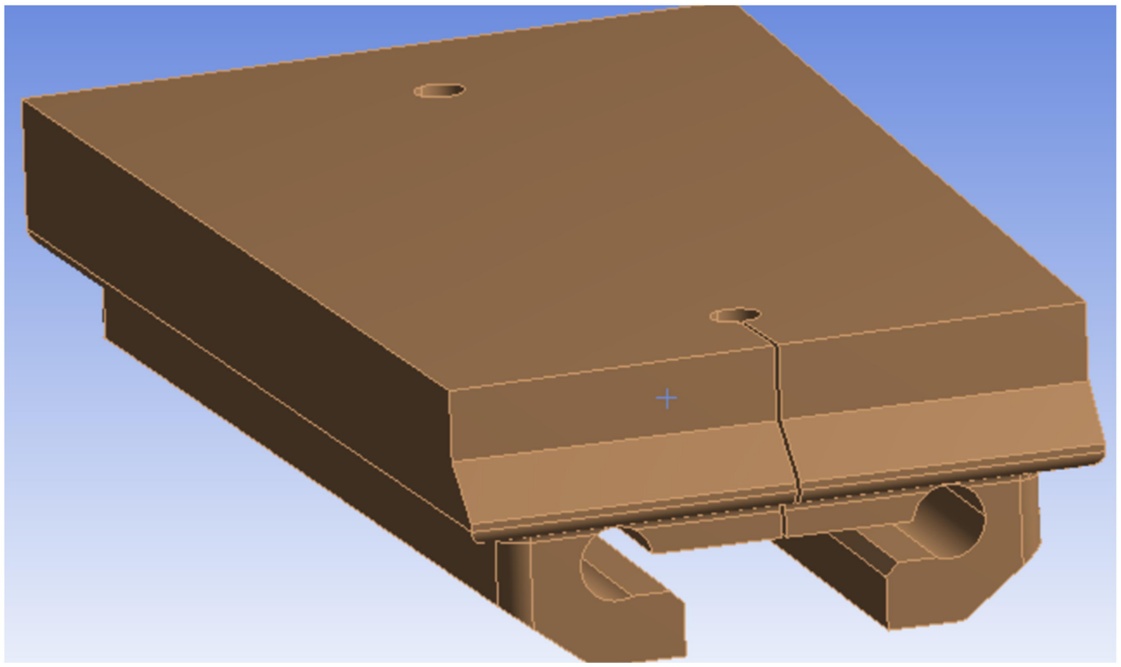
Results Summary – R3 Style 1 ED1403-3

This *second round analysis* of ED1403-3 reflects tile design modifications to alleviate issues ascertained from the Initial 1403-3 Analysis Report. The modifications to the tile design are summarized here, however, no ANSYS settings were changed from the original analysis. For a full description of the analysis setup, see the initial report.

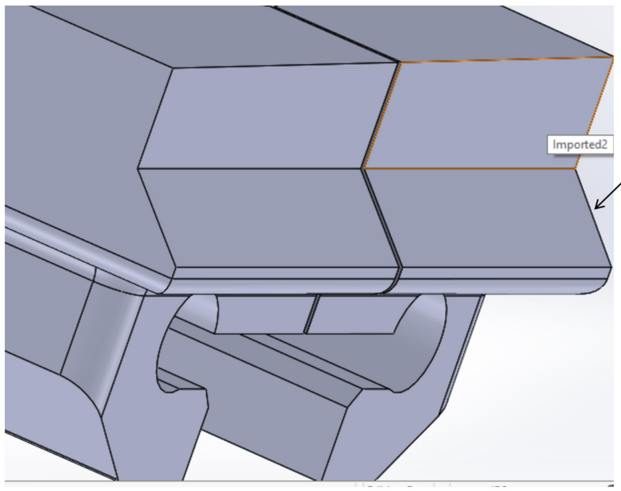
- **Result Overview for Tile (T953)**
  - T_{max} = 1264°C
  - $S1_{allow}$ / $S1_{max}$ = 20 MPa / 15.5 MPa → **SF ~ 1.29**
  - $S3_{allow}$ / $S3_{min}$ = -55 MPa /-39 MPa → **SF ~ 1.41**

- Notes
  1. The above stresses occur at load step 1. Halo Force & Eddy Moment loads serve to reduce peak stresses.
  2. Minimum principal stress around bolt access holes are artificially high as the chamfer on the plasma facing surface was not modeled. Minimum principle stresses in all other regions were shown to be acceptable.

Modified R3 S1 Tile Geometry

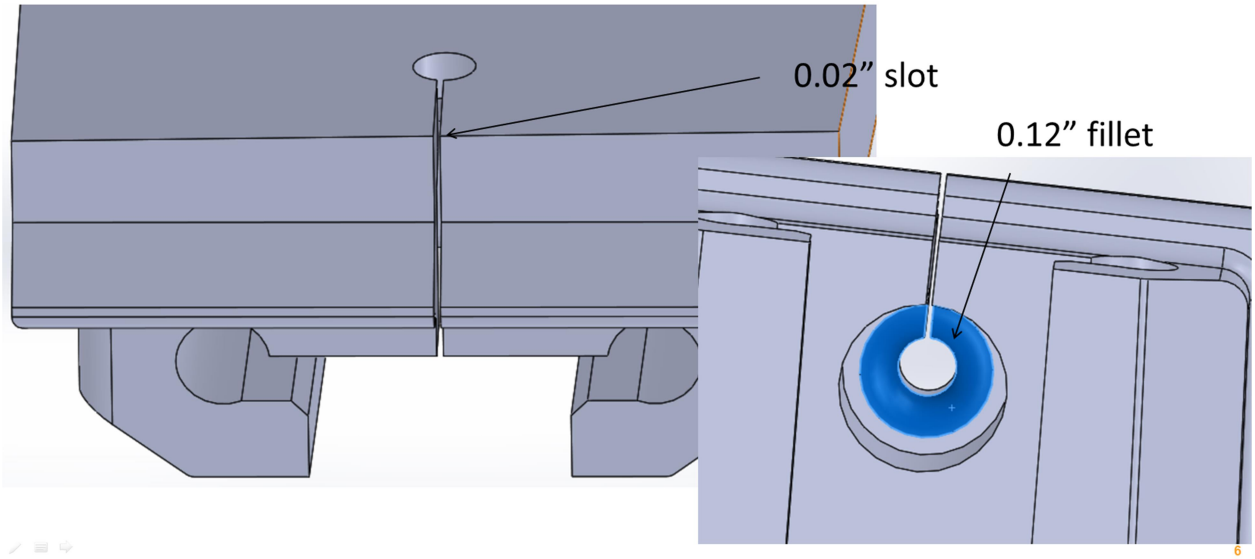


Geometry Changes



45 degree chamfer

Geometry Changes Continued



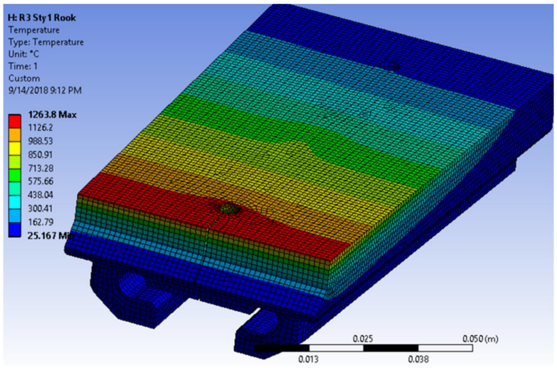
0.02” slot

0.12” fillet

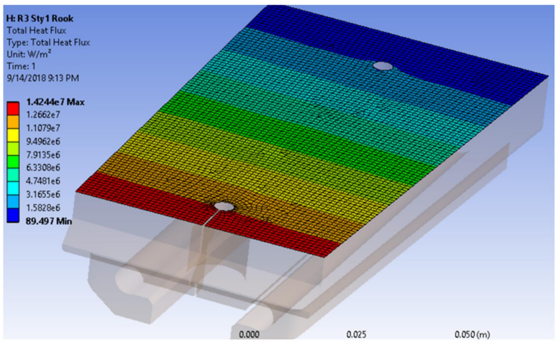
Round 2 Analysis Results
Row 3 Style 2, ED1403-3

Thermal Transient Results

Maximum Temperature

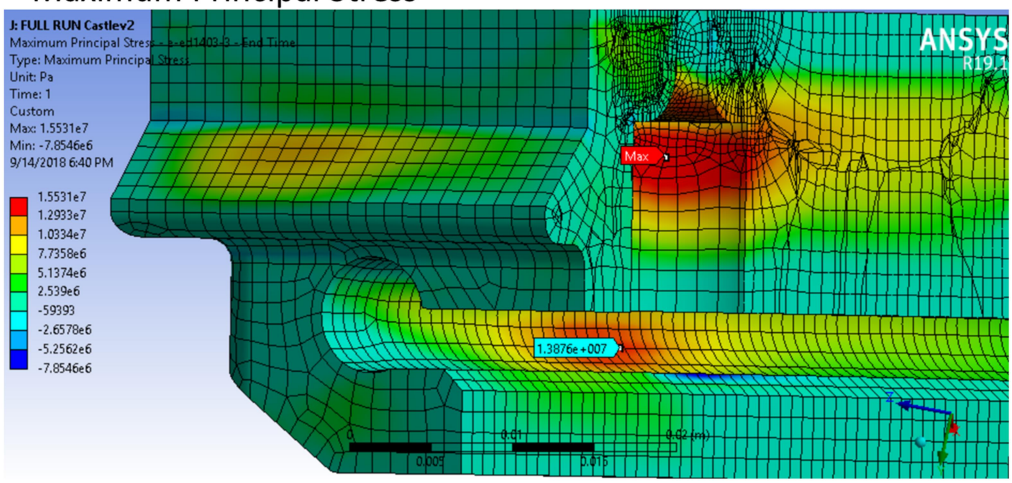


Directional Heat Flux



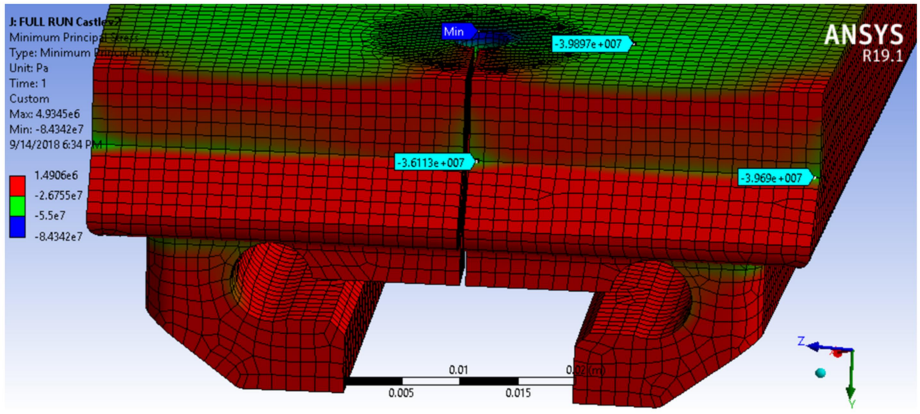
Structural Analysis Results

- Tile – Maximum Principal Stress



Structural Analysis Results

- Tile – Minimum Principal Stress



2.2 FOR INFORMATION ONLY – Analysis of outdated E-ED1403-3 tile design

PPPL NSTX-U PFCs

OBD345 R3, S1

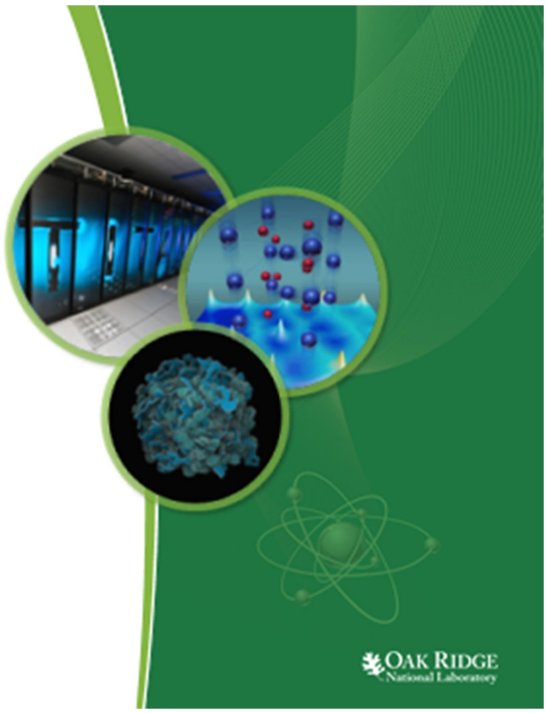
E - ED1403 - 3 Thermocouple Variant

Joseph B. Tipton, Jr.

ORISE Faculty Researcher at ORNL

Higher Education Research Experiences (HERE) for Faculty Program

ORNL is managed by UT-Battelle for the US Department of Energy



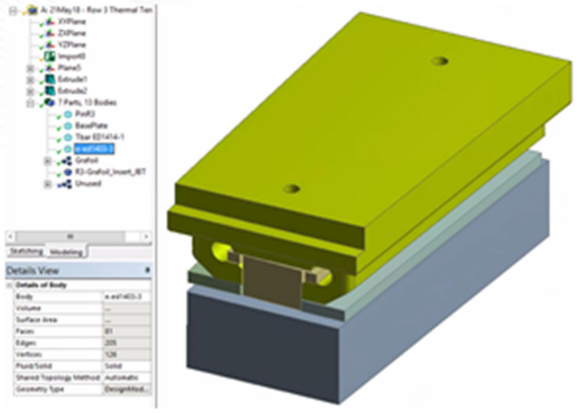
Results Summary

- Tile (T953)
  - T_{max} = 1250°C
  - $S1_{allow}$ / $S1_{max}$ = 25 MPa / 19.9 MPa → **SF ~ 1.25**
  - $S3_{allow}$ / $S3_{min}$ = -55 MPa /-78.2 MPa → **SF ~ 0.70**
- T-bar (IN625)
  - $1/3\sigma_{UTS}$ = 1/3*782 MPa = 261 MPa
  - $2/3\sigma_{YS}$ = 2/3*397 MPa = 265 Mpa
  - $\sigma_{VM,max}$ = 164 MPa → **SF ~ 1.59**
- Notes
  1. The above stresses occur at load step 1. Halo Force & Eddy Moment loads serve to reduce peak stresses.
  2. Minimum principal stress could be lowered via chamfer on tile hole.

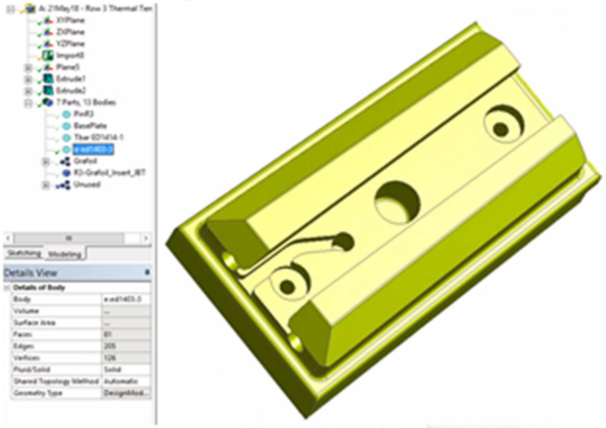
Geometry

Geometry

Tile (T953)



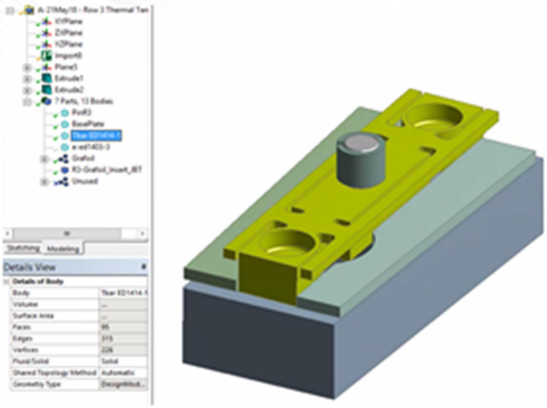
Thermocouple Variant



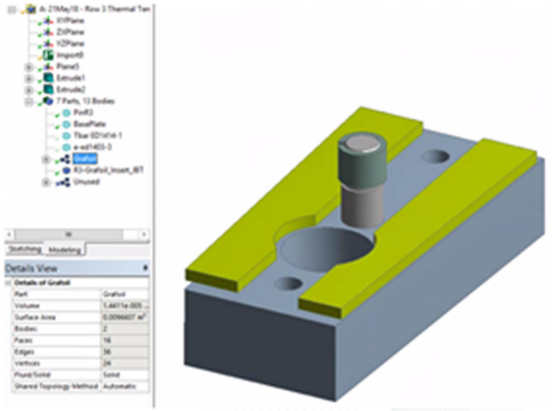
OAK RIDGE National Laboratory

Geometry

T-Bar (IN625)



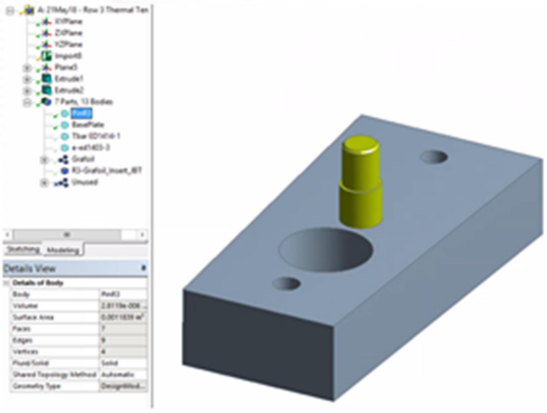
Grafoil



OAK RIDGE National Laboratory

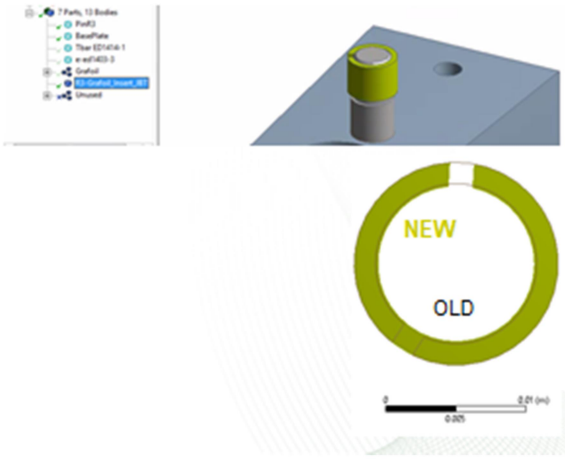
Geometry

Pin (IN718)



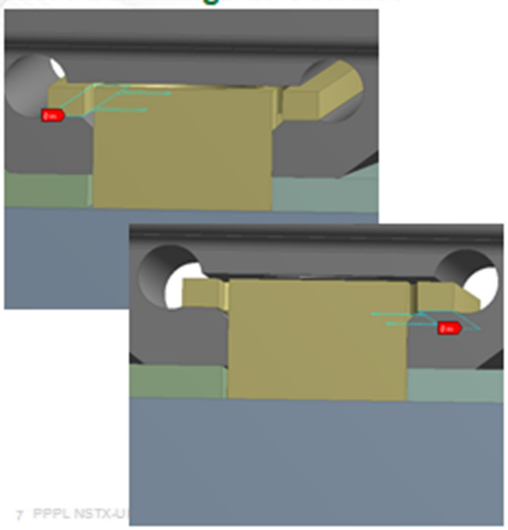
Insert (Grafoil)

- Replaced with custom geometry to remove inner gap.

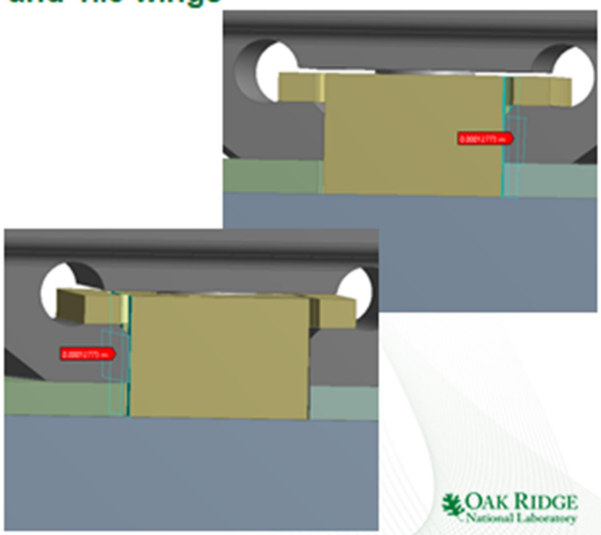


Geometry

Tile/T-bar Wings in Contact



0.13 mm Gap between T-bar sides and Tile wings

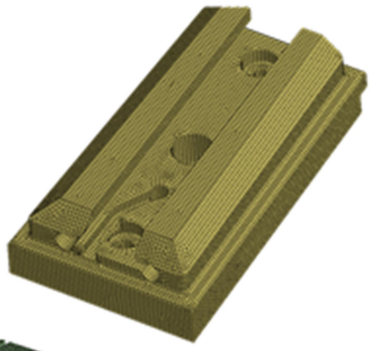


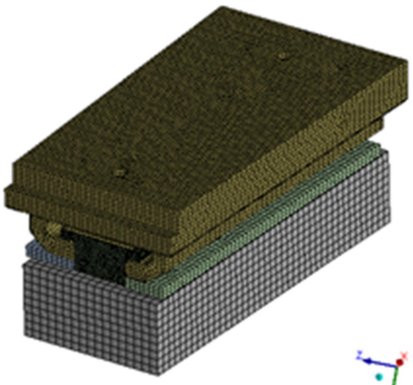
Discretization

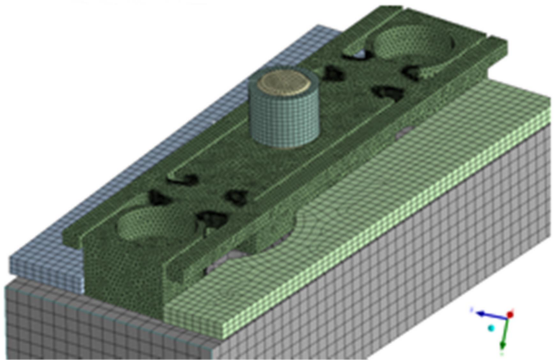
OAK RIDGE National Laboratory

Discretization

- HEX dominant
- Nodes = 866865
- Elements = 409597



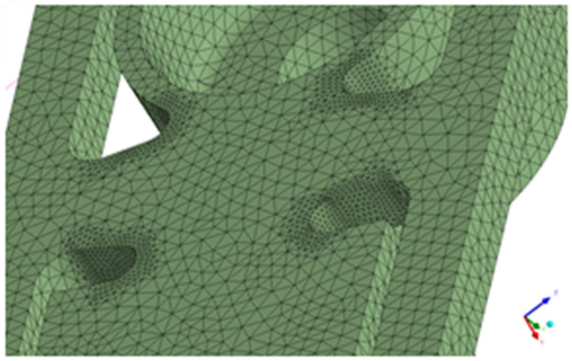


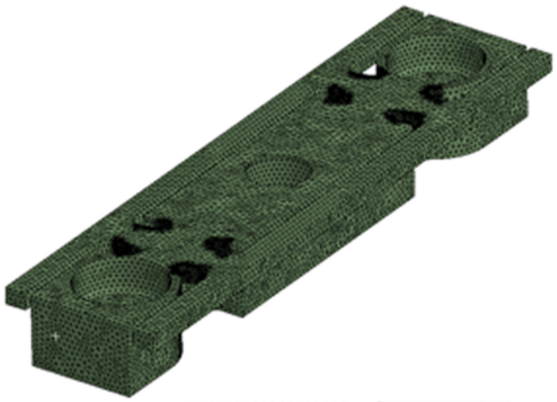


OAK RIDGE National Laboratory

Discretization

- T-bar is TET dominant
- Refinement level 2 along faces of cantilever support

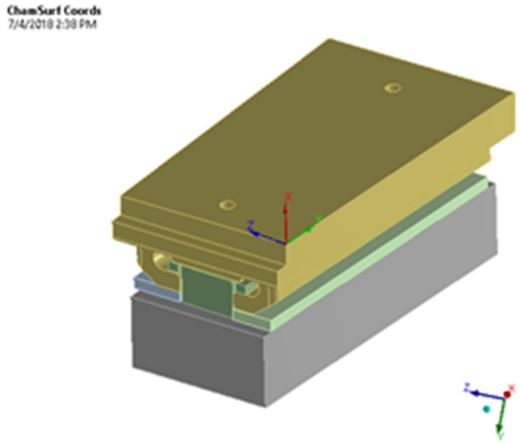




Thermal Model

Coordinate Systems

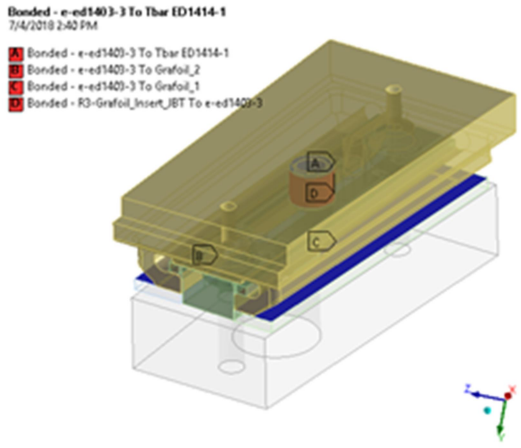
ChamSurf



OAK RIDGE National Laboratory

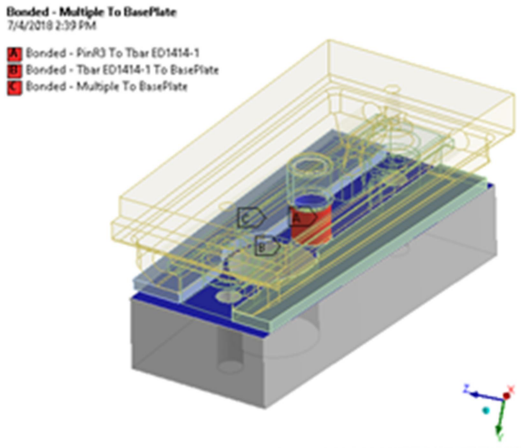
Contacts

Tile Contacts



Hardware Contacts

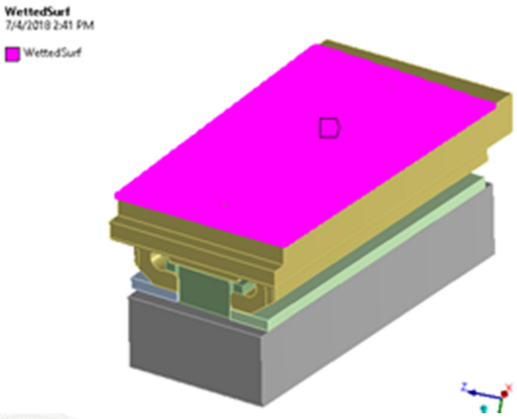
- Note no contact between Insert and Pin



Heat Flux

WettedSurf

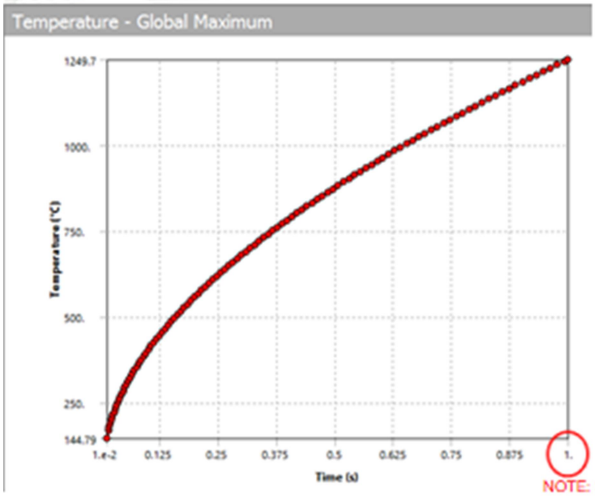
- WettedSurf = ChamSurf(Y ≤ 0.11 m)
- SFGRAD,HFLUX,13,Y,0,-125803640
- SF,WettedSurf,HFLUX,13838400



OAK RIDGE National Laboratory

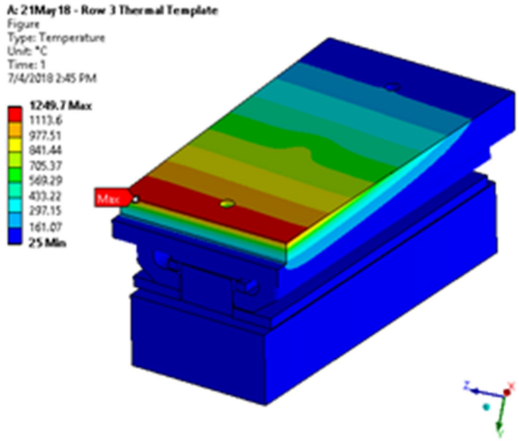
Results

Temperature



NOTE: Simulation runs to 1 second.

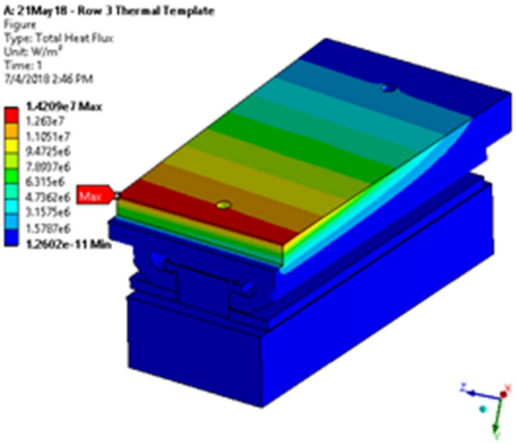
Temperature



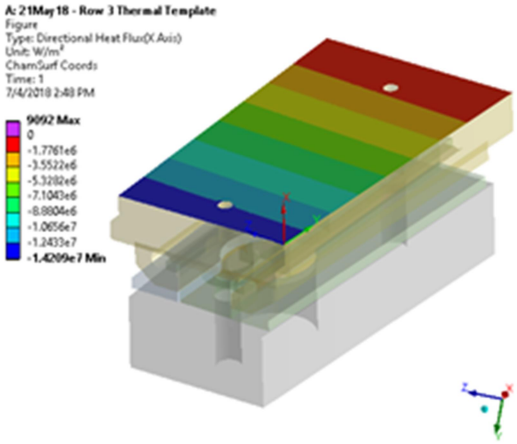
OAK RIDGE National Laboratory

Results

Total Heat Flux



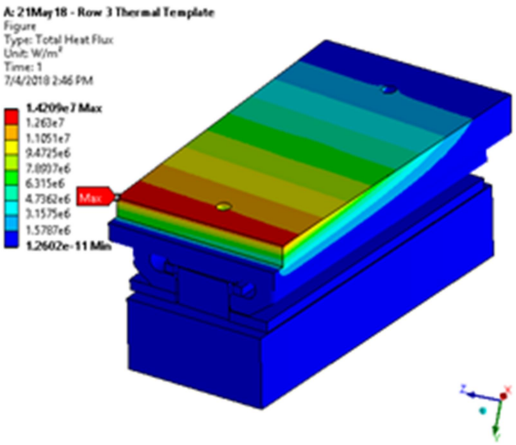
Directional Heat Flux



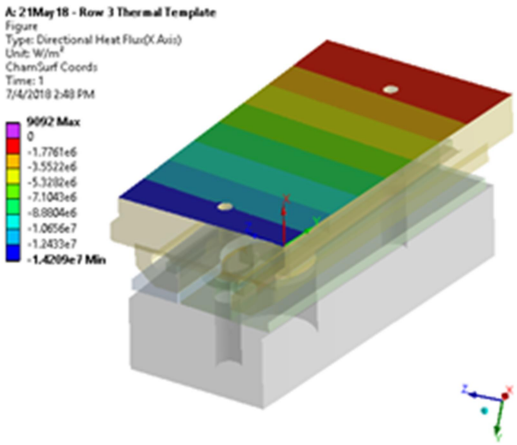
OAK RIDGE National Laboratory

Results

Total Heat Flux



Directional Heat Flux



16 PPPL NSTX-U PFC CBD R3, S1 (E-ED1403-3)

OAK RIDGE National Laboratory

Structural Model

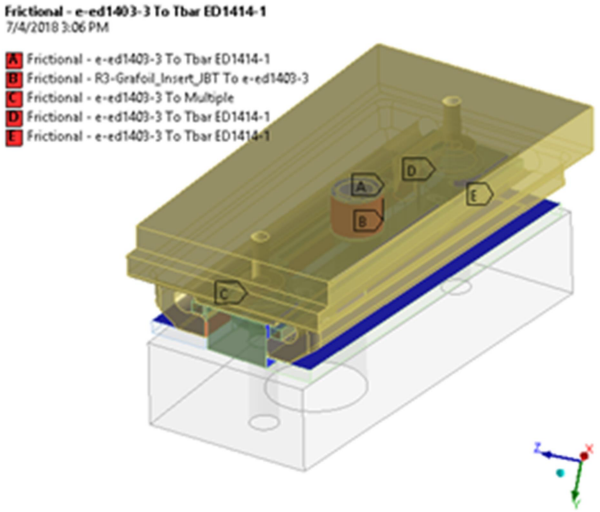
OAK RIDGE National Laboratory

Contacts

Tile Contacts

- A,C,D,E: Friction Coefficient = 0.1
- C: "Adjust-to-Touch"
- A,D,E: Removed "Adjust-to-Touch"

- B: Friction Coefficient = 0.01
  (NOTE: This was given as 0.1 in the R4, S1 template.)
- B: Update Stiffness = Aggressive
- B: Removed "Adjust-to-Touch"

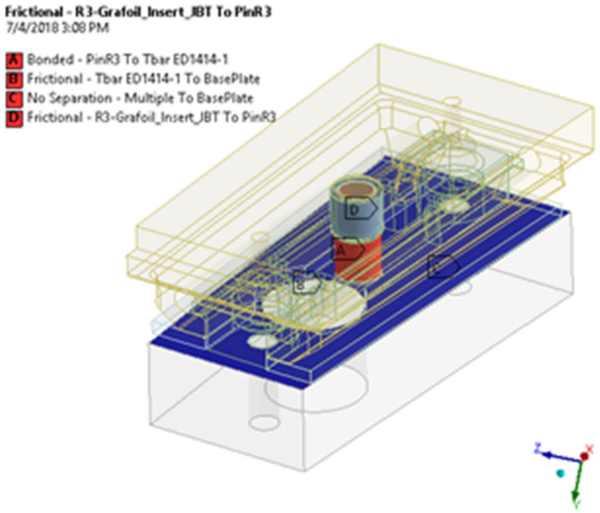


OAK RIDGE National Laboratory

Contacts

Hardware Contacts

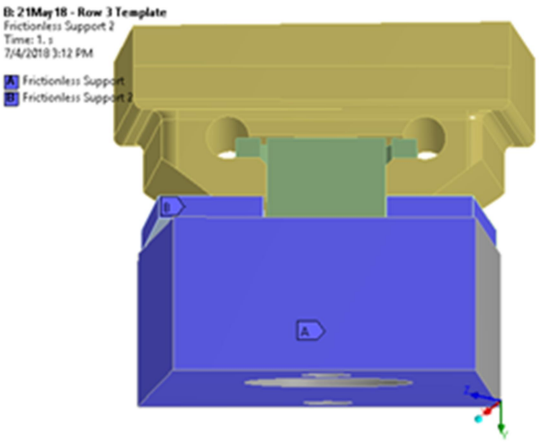
- B: Frictional Coefficient = 0.3
- D: Frictional Coefficient = 0.01
- D: Made R45Pin the target surface
- D: Update Stiffness = Aggressive
- D: Removed "Adjust-to-Touch"



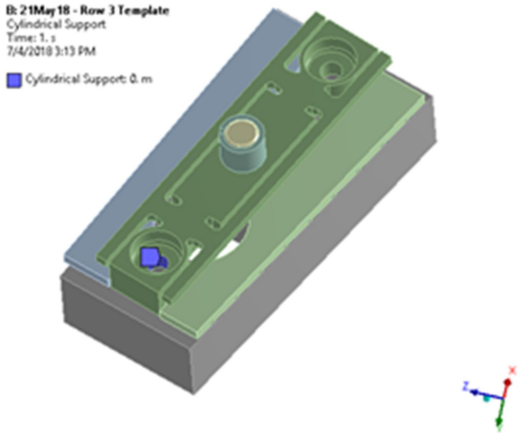
OAK RIDGE National Laboratory

Supports

Frictionless Supports



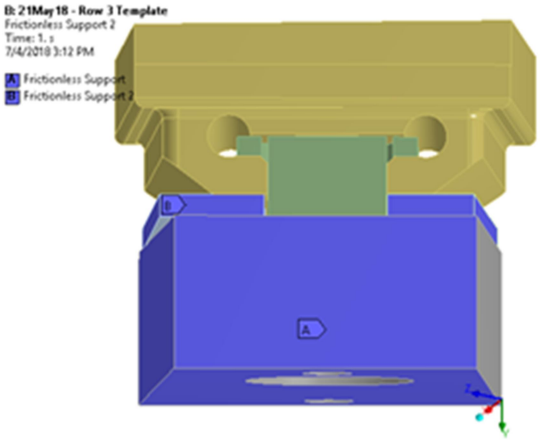
Fixed Supports



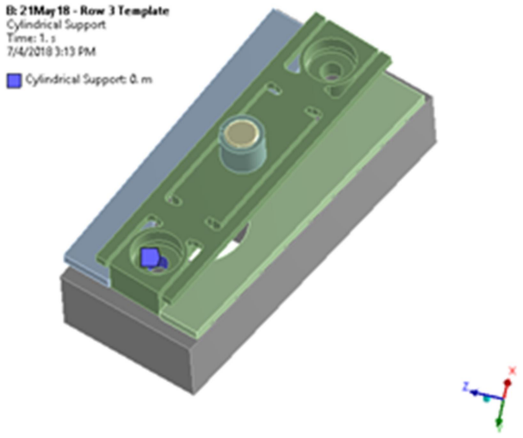
OAK RIDGE National Laboratory

Supports

Frictionless Supports



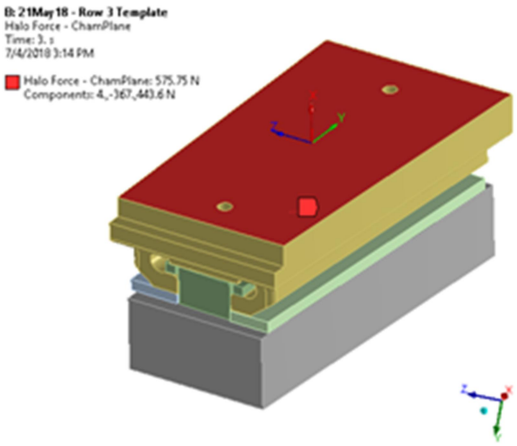
Fixed Supports



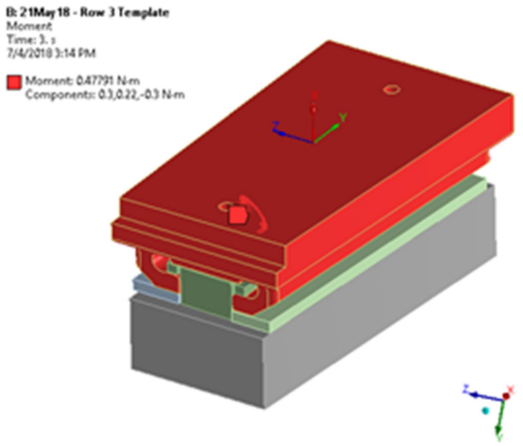
OAK RIDGE National Laboratory

Loads

Halo Forces



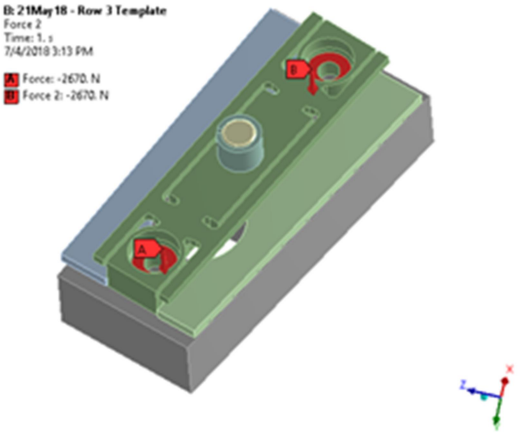
Eddy Moments



OAK RIDGE National Laboratory

Loads

Bolt Pretension

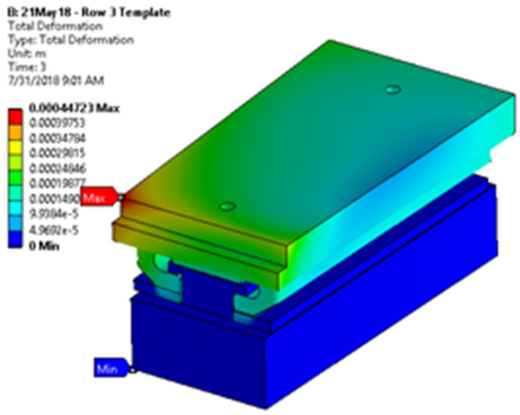


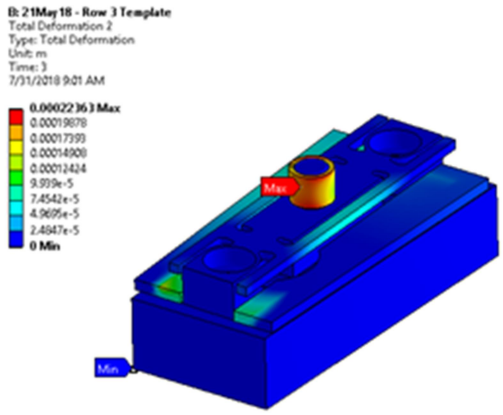
Thermal Loads

- Imported body temperatures from thermal solution.

Results

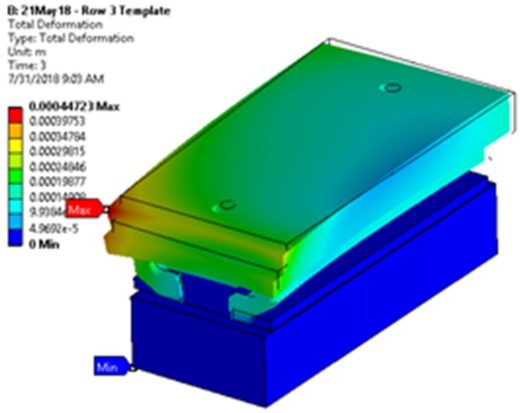
Total Deformation

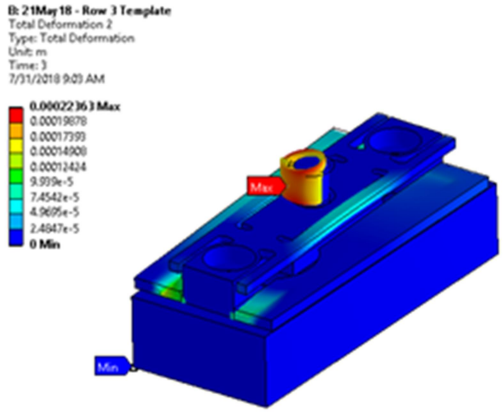




Results – Deformation (Exaggerated)

Total Deformation

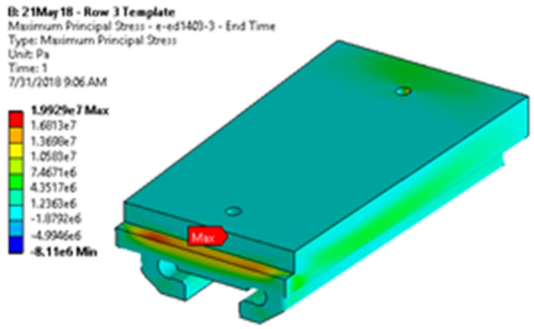


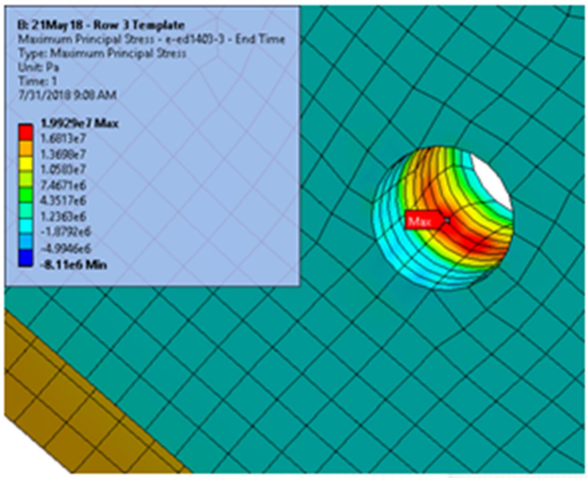


OAK RIDGE National Laboratory

Results

Tile – Maximum Principal Stress

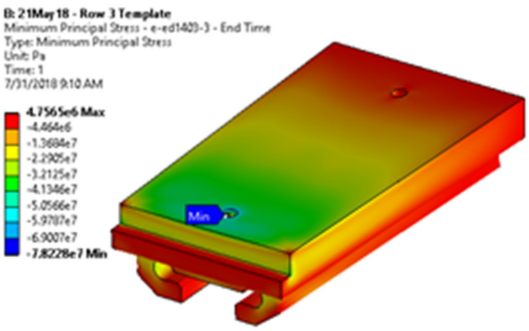


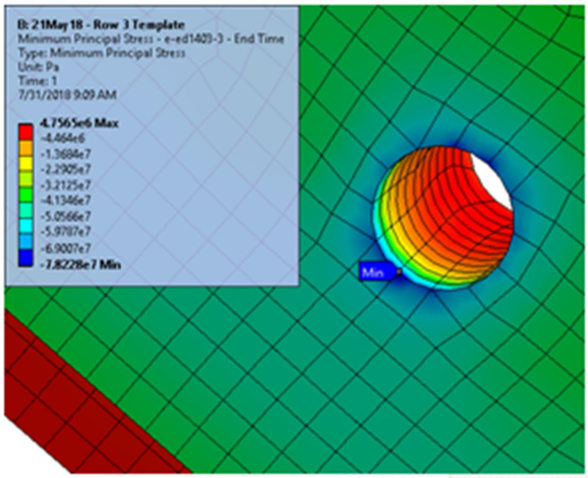


OAK RIDGE National Laboratory

Results

Tile – Minimum Principal Stress

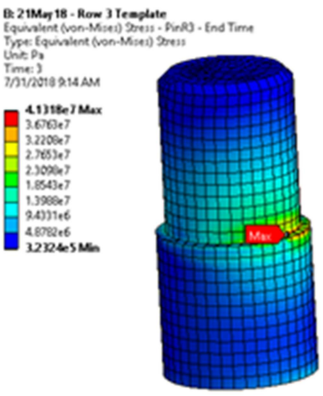




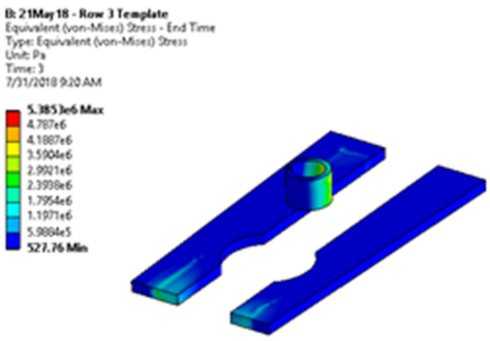
OAK RIDGE National Laboratory

Results

Pin



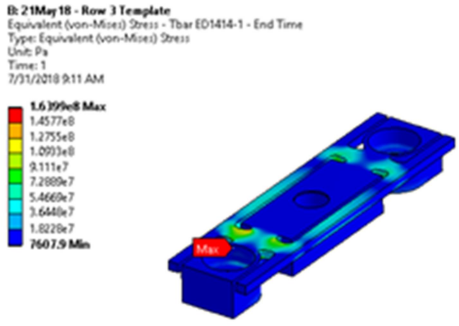
Grafoil

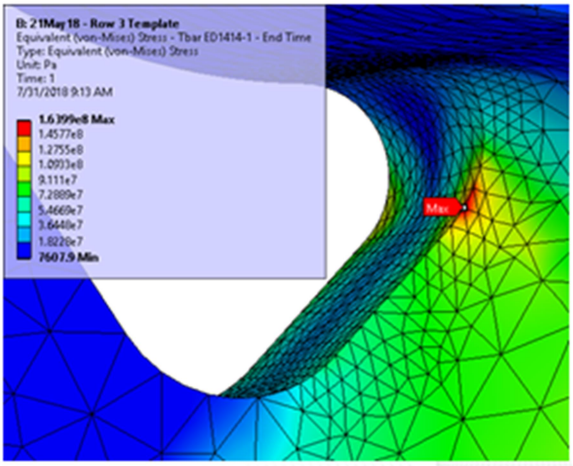


OAK RIDGE National Laboratory

Results

T-bar

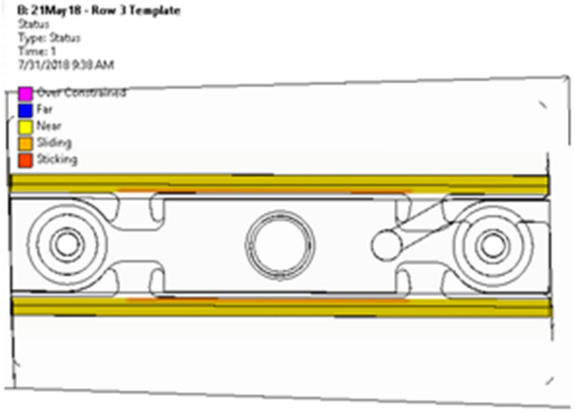




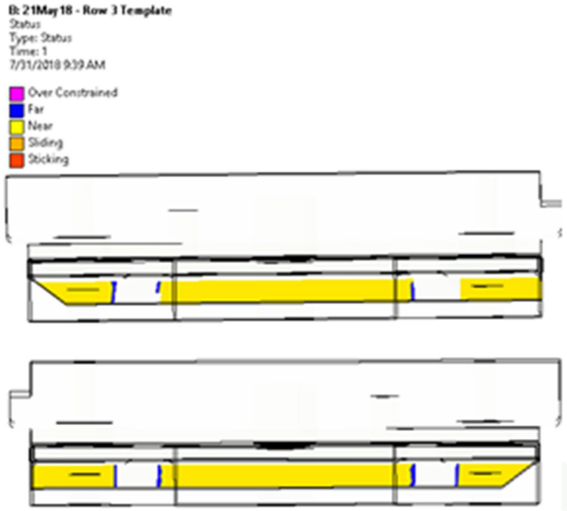
OAK RIDGE National Laboratory

Results

Tile/T-bar Contact

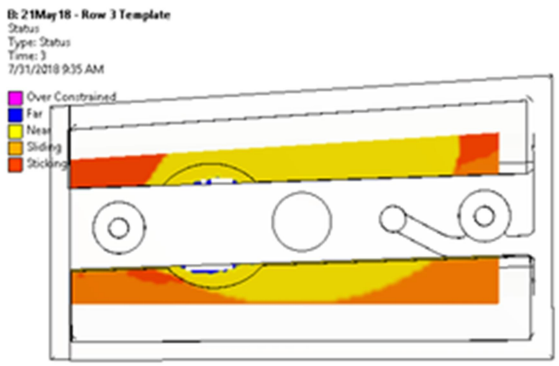


No Contact on Tile Wings

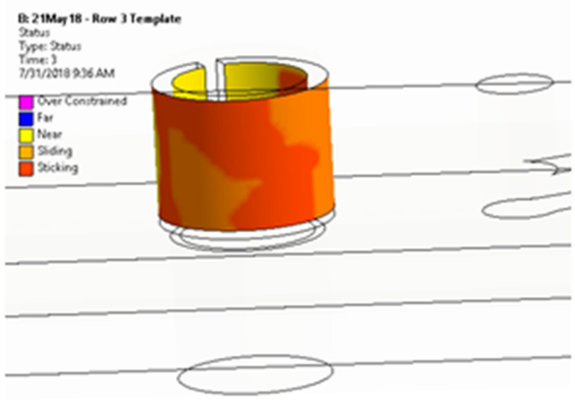


Results

Grafoil/Baseplate Contact



Pin/Insert/Tile Contact



OAK RIDGE National Laboratory

Results Summary

- Tile (T953)
  - T_{max} = 1250°C
  - $S1_{allow}$ / $S1_{max}$ = 25 MPa / 19.9 MPa → **SF ~ 1.25**
  - $S3_{allow}$ / $S3_{min}$ = -55 MPa /-78.2 MPa → **SF ~ 0.70**
- T-bar (IN625)
  - $1/3\sigma_{UTS}$ = 1/3*782 MPa = 261 MPa
  - $2/3\sigma_{YS}$ = 2/3*397 MPa = 265 Mpa
  - $\sigma_{VM,max}$ = 164 MPa → **SF ~ 1.59**
- Notes
  1. The above stresses occur at load step 1. Halo Force & Eddy Moment loads serve to reduce peak stresses.
  2. Minimum principal stress could be lowered via chamfer on tile hole.

OAK RIDGE National Laboratory

3 Subreport E-ED1403-6 R3 Style 1 RF Langmuir Probe Variant

The E-ED1403-6 tile design was revised after this analysis to reflect the changes detailed in the subreport for the R3 Style 1 thermocouple variant (E-ED1403-3). Analysis of preliminary tile design showed RFLP features minimally impact design and the resulting stress profile was analogous to that of the E-ED1403-1 tile design. The stress reduction features incorporated and analyzed with E-ED1403-1 were also incorporated into this tile and additional analysis of this variant are not warranted. The results presented in this subreport provide the justification for not re-analyzing this tile after making the R3 Style 1 design changes.

Please see E-ED1403-3 subreport for the stresses expected in this tile.

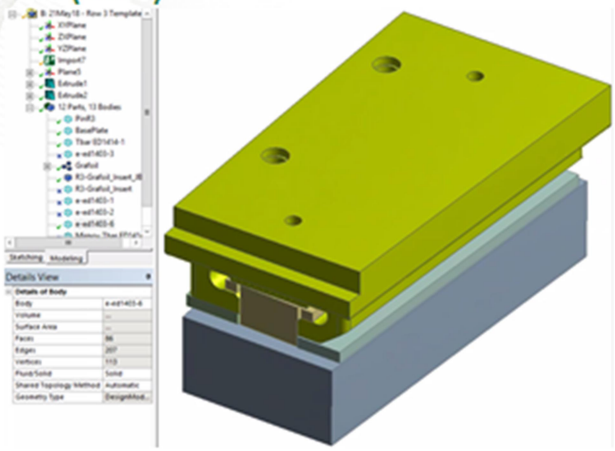
Results Summary

- Tile (T953)
  - T_{max} = 1250°C
  - $S1_{allow}$ / $S1_{max}$ = 25 MPa / 23.2 MPa → **SF ~ 1.07**
  - $S3_{allow}$ / $S3_{min}$ = -55 MPa /-79.0 MPa → **SF ~ 0.69**
- T-bar (IN625)
  - $1/3\sigma_{UTS}$ = 1/3*782 MPa = 261 MPa
  - $2/3\sigma_{YS}$ = 2/3*397 MPa = 265 Mpa
  - $\sigma_{VM,max}$ = 217.4 MPa → **SF ~ 1.2**
- Notes
  1. $S1_{max}$ and $\sigma_{VM,max}$ occur at load step 1. Halo Force & Eddy Moment loads serve to reduce peak stresses.
  2. Maximum principal stress might be lowered by reducing tile wing contact with sides of T-bar.
  3. Minimum principal stress could be lowered via chamfer on tile hole.

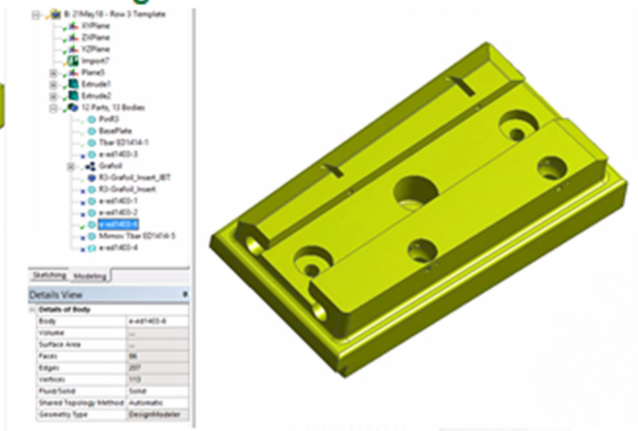
Geometry

Geometry

Tile (T953)

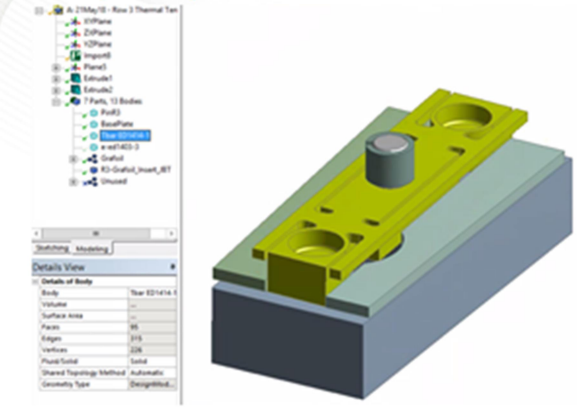


RF Langmuir Probe Variant

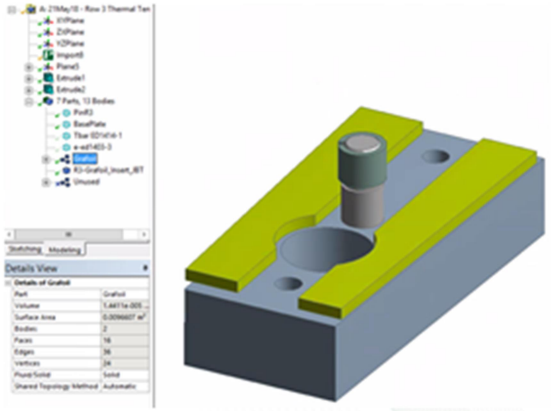


Geometry

T-Bar (IN625)

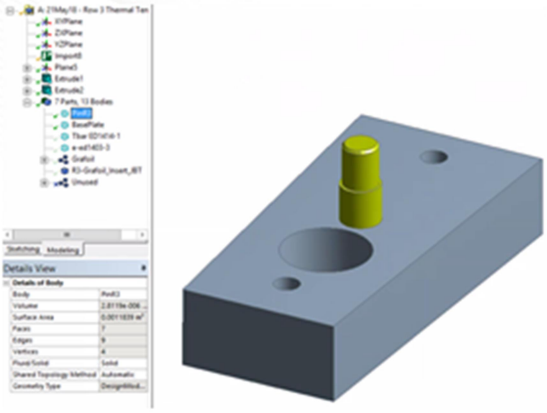


Grafoil



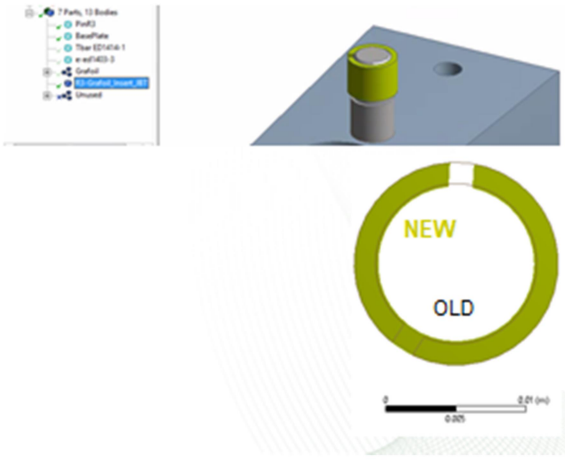
Geometry

Pin (IN718)



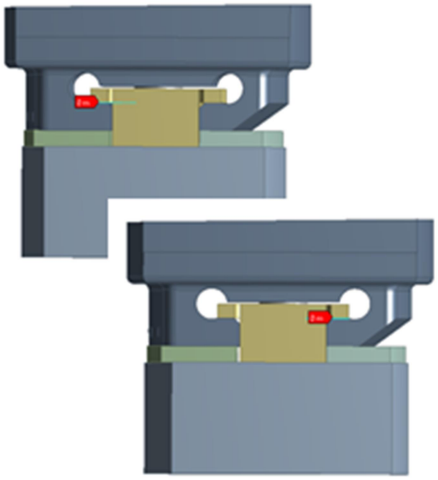
Insert (Grafoil)

- Replaced with custom geometry to remove inner gap.

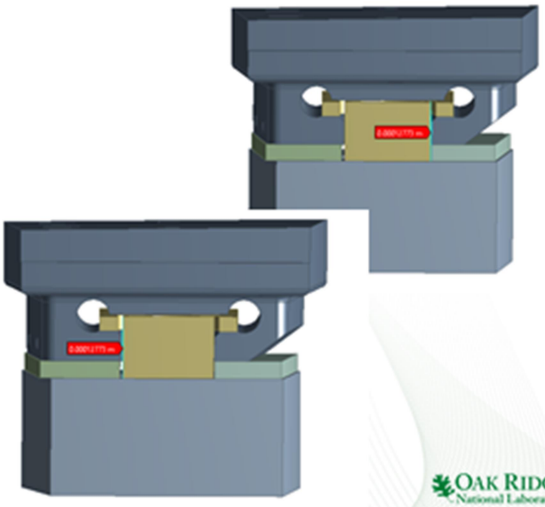


Geometry

Tile/T-bar Wings in Contact



0.13 mm Gap between T-bar sides and Tile wings

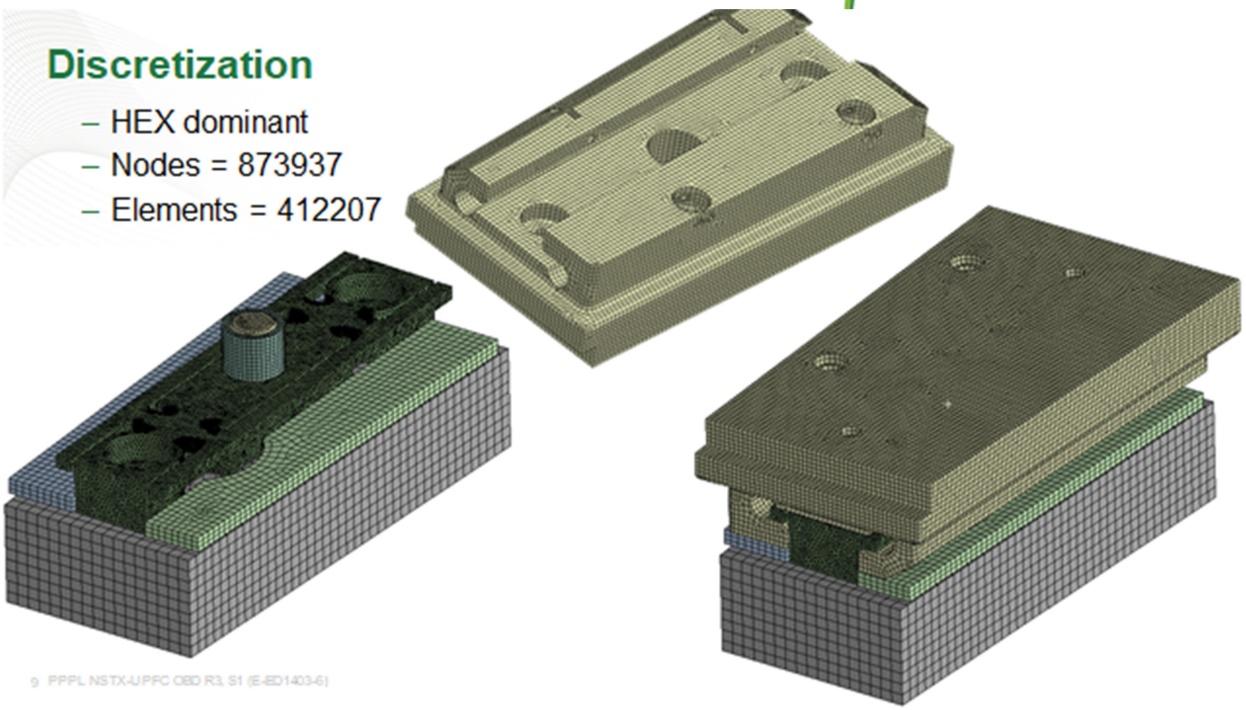


Discretization

OAK RIDGE National Laboratory

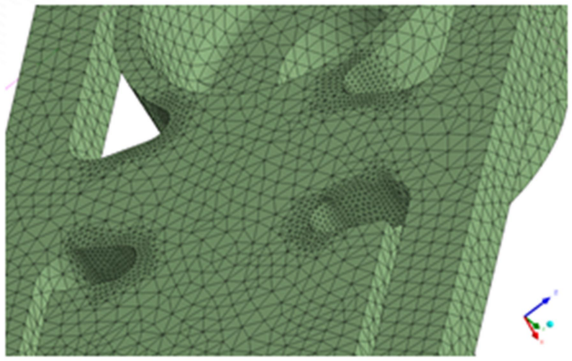
Discretization

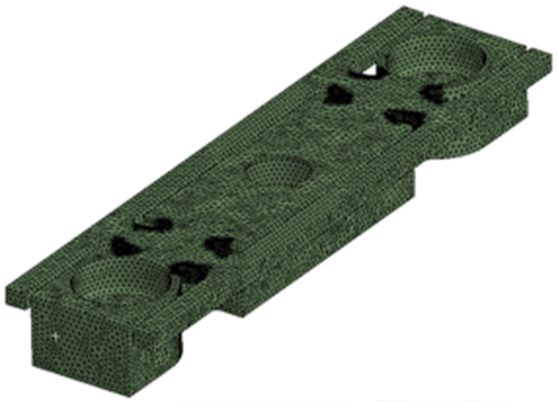
- HEX dominant
- Nodes = 873937
- Elements = 412207



Discretization

- T-bar is TET dominant
- Refinement level 2 along faces of cantilever support



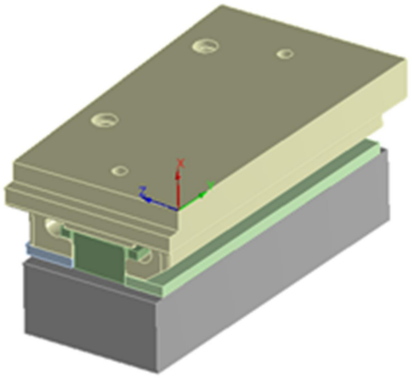


Thermal Model

Coordinate Systems

ChamSurf

ChamSurf Coords
7/9/2018 10:12 AM



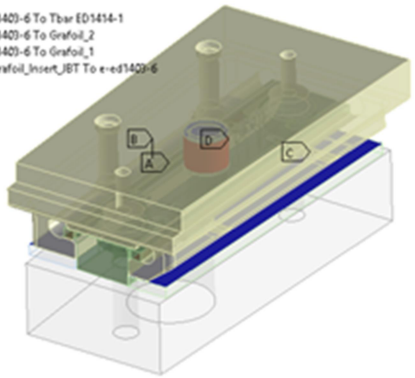
OAK RIDGE National Laboratory

Contacts

Tile Contacts

Bonded - e-ed1403-6 To Tbar ED1414-1
7/9/2018 10:13 AM

A Bonded - e-ed1403-6 To Tbar ED1414-1
B Bonded - e-ed1403-6 To Grafoil_2
C Bonded - e-ed1403-6 To Grafoil_1
D Bonded - R3-Grafoil_Insert_IBT To e-ed1403-6

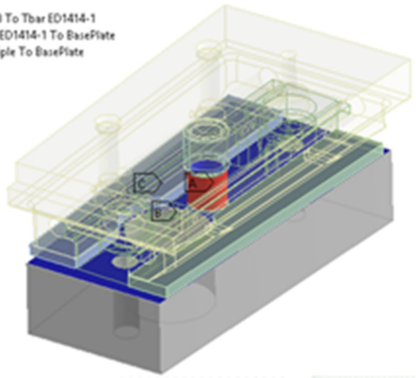


Hardware Contacts

- Note no contact between Insert and Pin

Bonded - Multiple To BasePlate
7/9/2018 10:14 AM

A Bonded - PinR3 To Tbar ED1414-1
B Bonded - Tbar ED1414-1 To BasePlate
C Bonded - Multiple To BasePlate

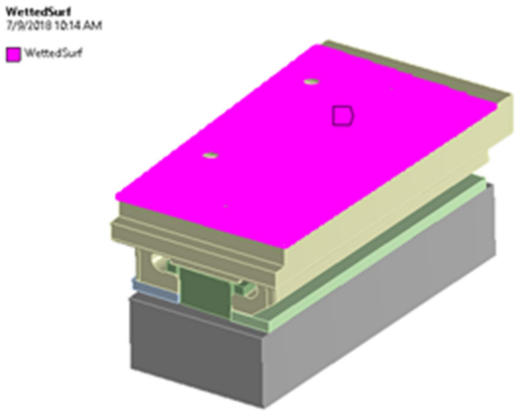


OAK RIDGE National Laboratory

Heat Flux

WettedSurf

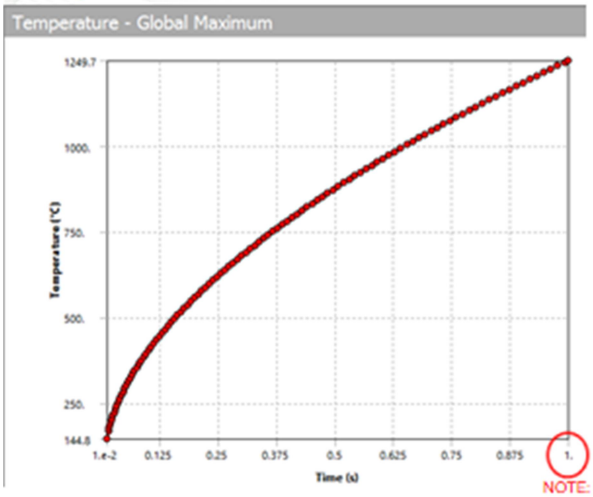
- WettedSurf = ChamSurf(Y ≤ 0.11 m)
- SFGRAD,HFLUX,13,Y,0,-125803640
- SF,WettedSurf,HFLUX,13838400



OAK RIDGE National Laboratory

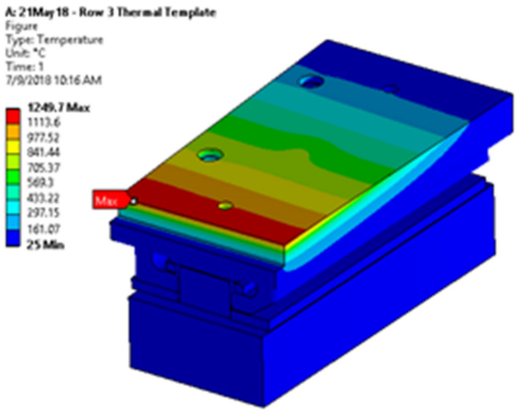
Results

Temperature



NOTE: Simulation runs to 1 second.

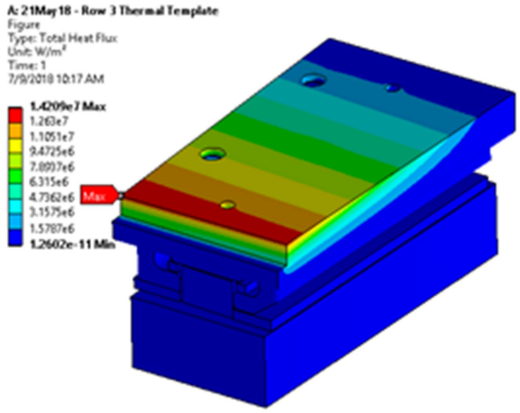
Temperature



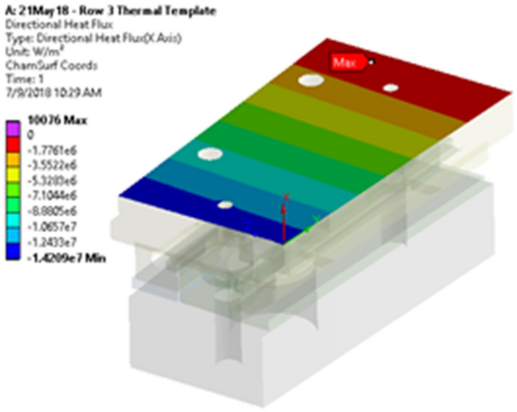
OAK RIDGE National Laboratory

Results

Total Heat Flux



Directional Heat Flux



OAK RIDGE National Laboratory

Structural Model

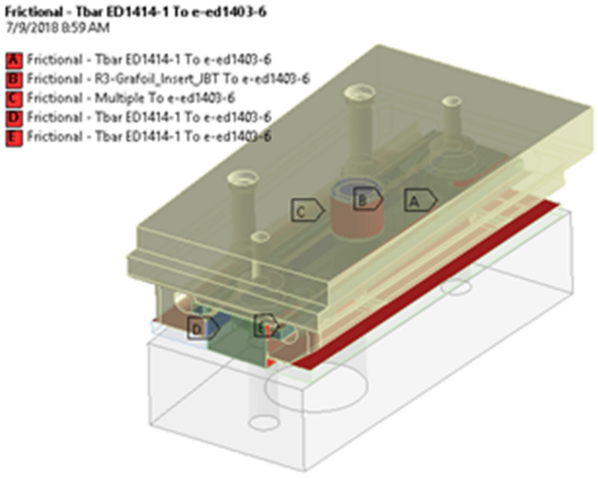
OAK RIDGE National Laboratory

Contacts

Tile Contacts

- A,C,D,E: Friction Coefficient = 0.1
- C: "Adjust-to-Touch"
- A,D,E: Removed "Adjust-to-Touch"

- B: Friction Coefficient = 0.01
  (NOTE: This was given as 0.1 in the R4, S1 template.)
- B: Update Stiffness = Aggressive
- B: Removed "Adjust-to-Touch"



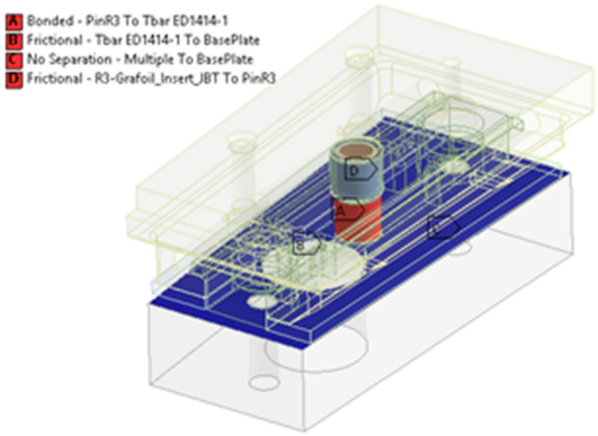
OAK RIDGE National Laboratory

Contacts

Hardware Contacts

- B: Frictional Coefficient = 0.3

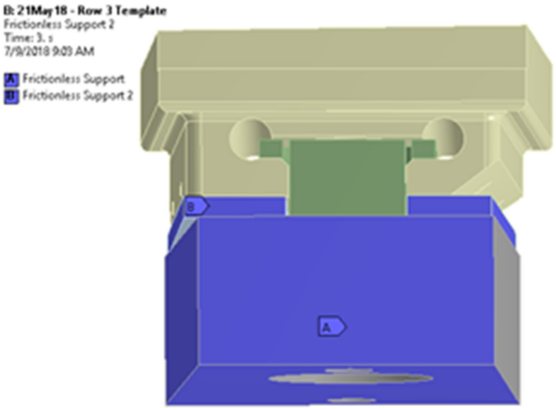
- D: Frictional Coefficient = 0.01
- D: Made R45Pin the target surface
- D: Update Stiffness = Aggressive
- D: Removed "Adjust-to-Touch"



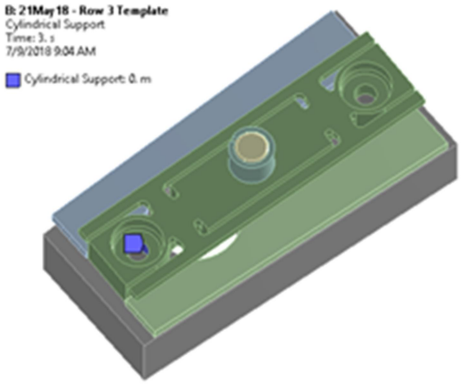
OAK RIDGE National Laboratory

Supports

Frictionless Supports



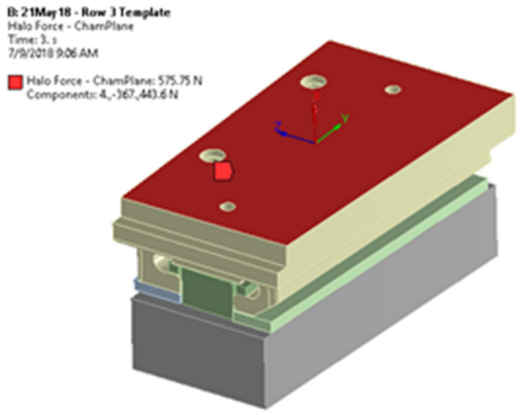
Fixed Supports



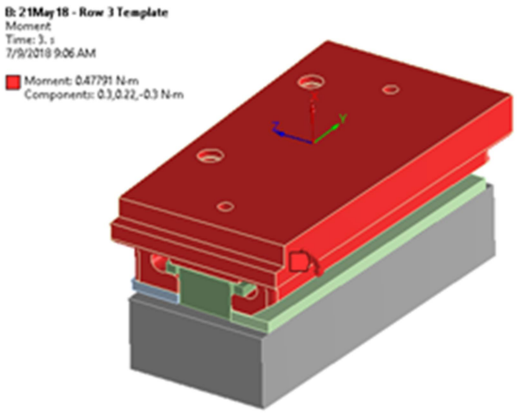
OAK RIDGE National Laboratory

Loads

Halo Forces



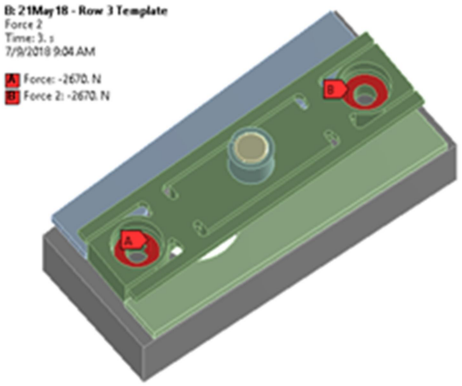
Eddy Moments



OAK RIDGE National Laboratory

Loads

Bolt Pretension

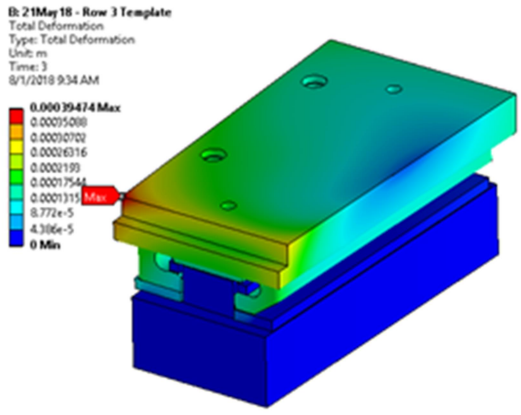


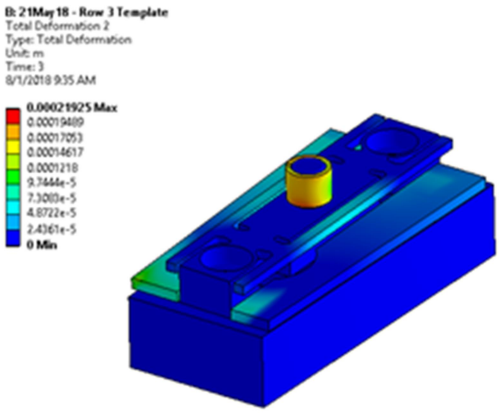
Thermal Loads

- Imported body temperatures from thermal solution.

Results

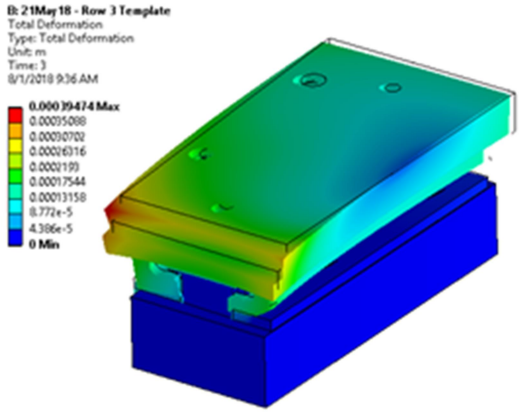
Total Deformation

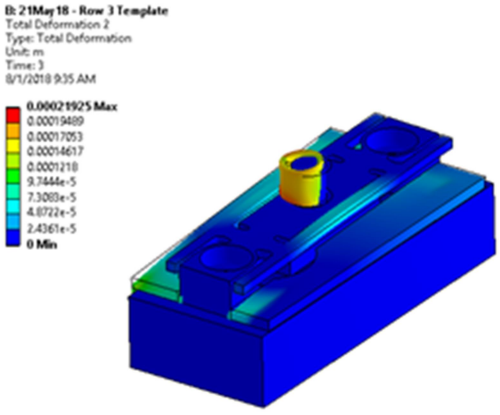




Results

Total Deformation (w/ Exaggerated Deflection)

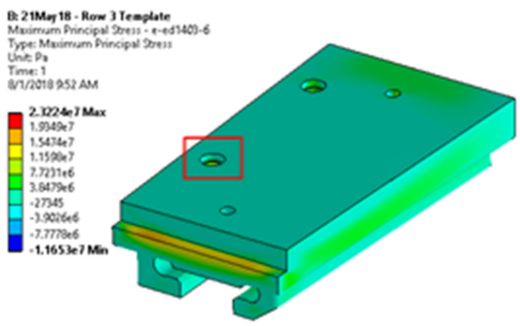


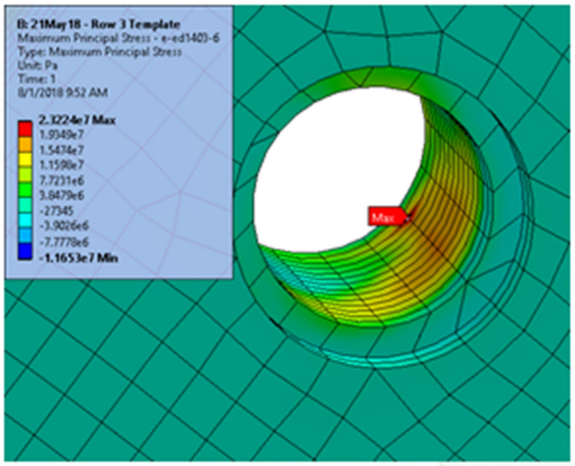


OAK RIDGE National Laboratory

Results

Tile – Maximum Principal Stress

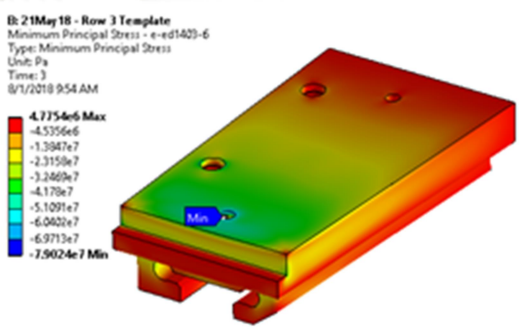


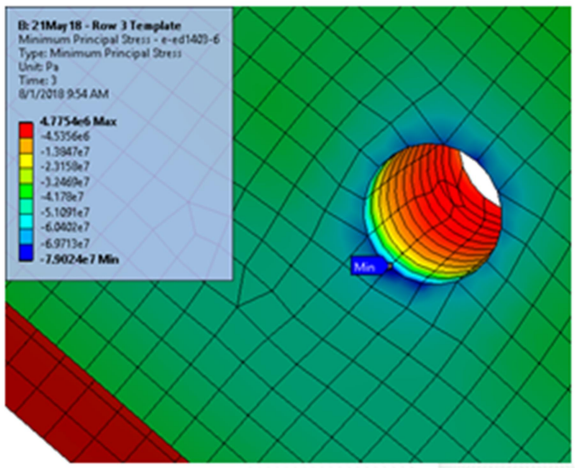


OAK RIDGE National Laboratory

Results

Tile – Minimum Principal Stress

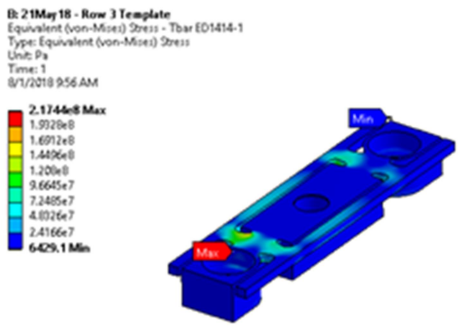


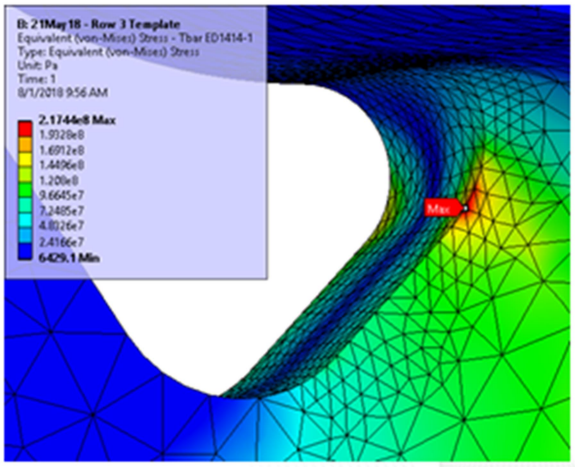


OAK RIDGE National Laboratory

Results

T-bar

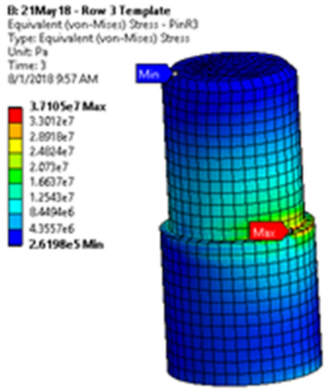




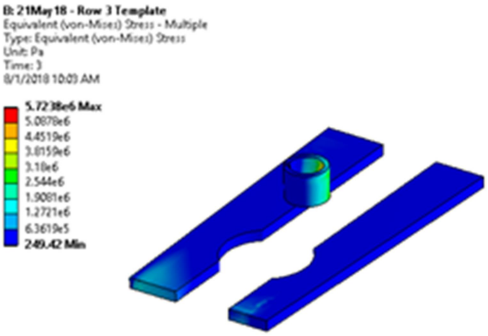
OAK RIDGE National Laboratory

Results

Pin



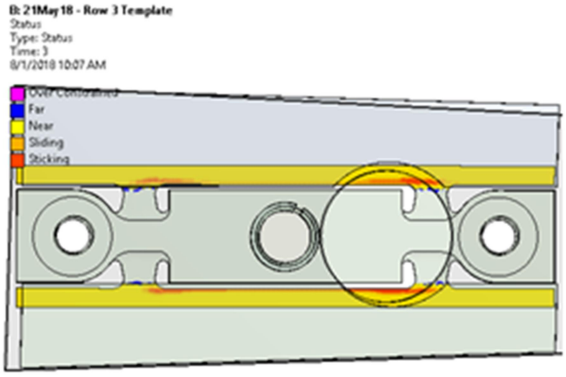
Grafoil



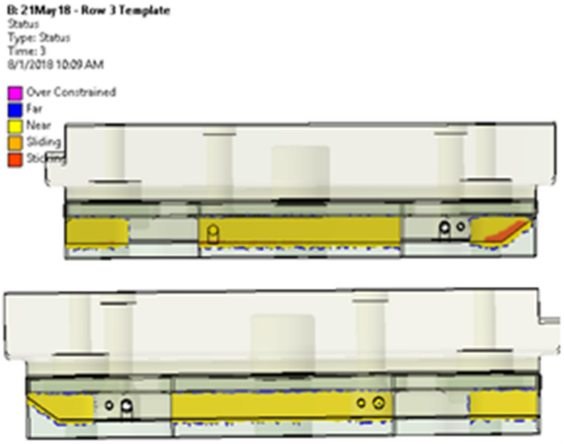
OAK RIDGE National Laboratory

Results

Tile/T-bar Contact

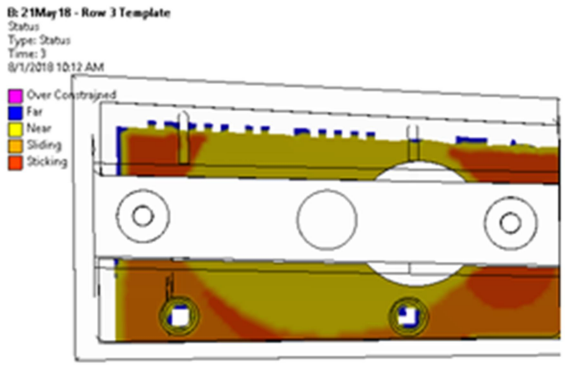


No Contact on Tile Wings

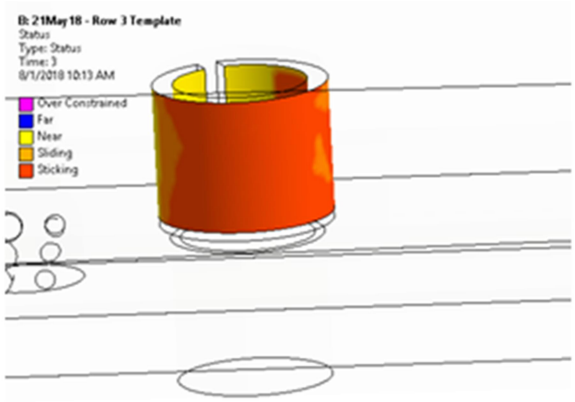


Results

Grafoil/Baseplate Contact



Pin/Insert/Tile Contact



OAK RIDGE National Laboratory

Results Summary

- Tile (T953)
  - T_{max} = 1250°C
  - $S1_{allow}$ / $S1_{max}$ = 25 MPa / 23.2 MPa → **SF ~ 1.07**
  - $S3_{allow}$ / $S3_{min}$ = -55 MPa /-79.0 MPa → **SF ~ 0.69**
- T-bar (IN625)
  - $1/3\sigma_{UTS}$ = 1/3*782 MPa = 261 MPa
  - $2/3\sigma_{YS}$ = 2/3*397 MPa = 265 Mpa
  - $\sigma_{VM,max}$ = 217.4 MPa → **SF ~ 1.2**
- Notes
  1. $S1_{max}$ and $\sigma_{VM,max}$ occur at load step 1. Halo Force & Eddy Moment loads serve to reduce peak stresses.
  2. Maximum principal stress might be lowered by reducing tile wing contact with sides of T-bar.
  3. Minimum principal stress could be lowered via chamfer on tile hole.

OAK RIDGE National Laboratory

4 Subreport E-ED1402-1 R3 Style 2 Base Tile

This subreport is broken up into two sections to provide design history. The first section gives the results for the current tile design of E-ED1403-1, which incorporated several modifications to the tile's design. The second section presents the analysis of an outdated version of the E-ED1403-1 tile design. The peak stresses shown in the outdated tile design were alleviated by the geometric changes outlined below.

4.1 Analysis of Current E-ED1402-1 Tile Design

National Spherical Torus eXperiment Upgrade

PPPL NSTX-U PFC: OBD R3, Style 2
E-ED1402-1 Base Tile
Second Round Analysis

Brian Linn

September 14 2018

Results Summary – R3 Style 2 ED1402-1

This *second round analysis* of ED1402-1 implements the tile design modifications to alleviate issues ascertained from the Initial 1403-3 Analysis Report. Results and modifications to the tile design are summarized here, however, no ANSYS settings were changed from the original analysis. For a full description of the analysis setup, see the referenced report.

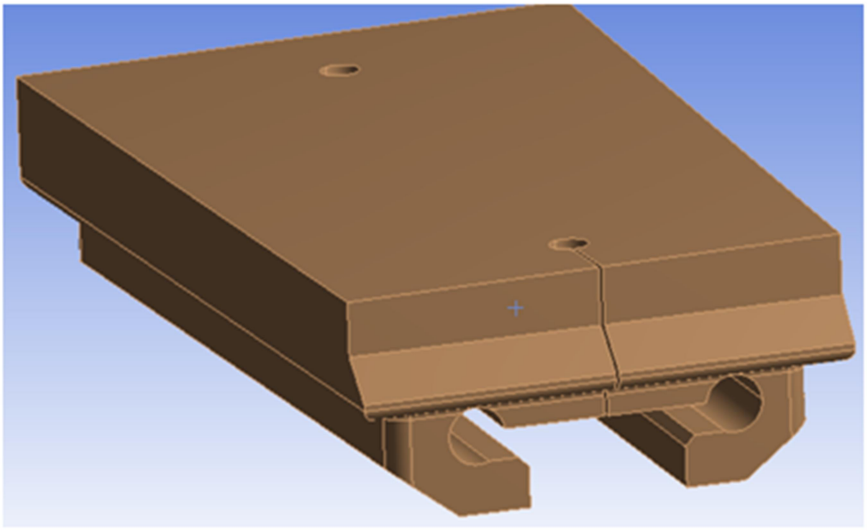
- **Result Overview for Tile (T953)**
  - T_{max} = 1227°C
  - $S1_{allow}$ / $S1_{max}$ = 20 MPa / 19.5 MPa → **SF ~ 1.29**
  - $S3_{allow}$ / $S3_{min}$ = -55 MPa /-39 MPa → **SF ~ 1.41**

- Notes
  1. The above stresses occur at load step 1. Halo Force & Eddy Moment loads serve to reduce peak stresses.
  2. Minimum principal stress around bolt access holes are artificially high as the chamfer on the plasma facing surface was not modeled. Minimum principle stresses in all other regions were shown to be acceptable.

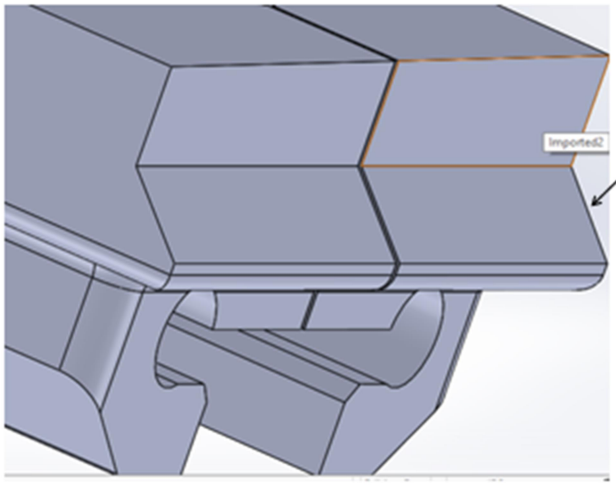
Row 3 Tile Design Change Summary

Implemented in all Style 1 and Style 2 Tiles

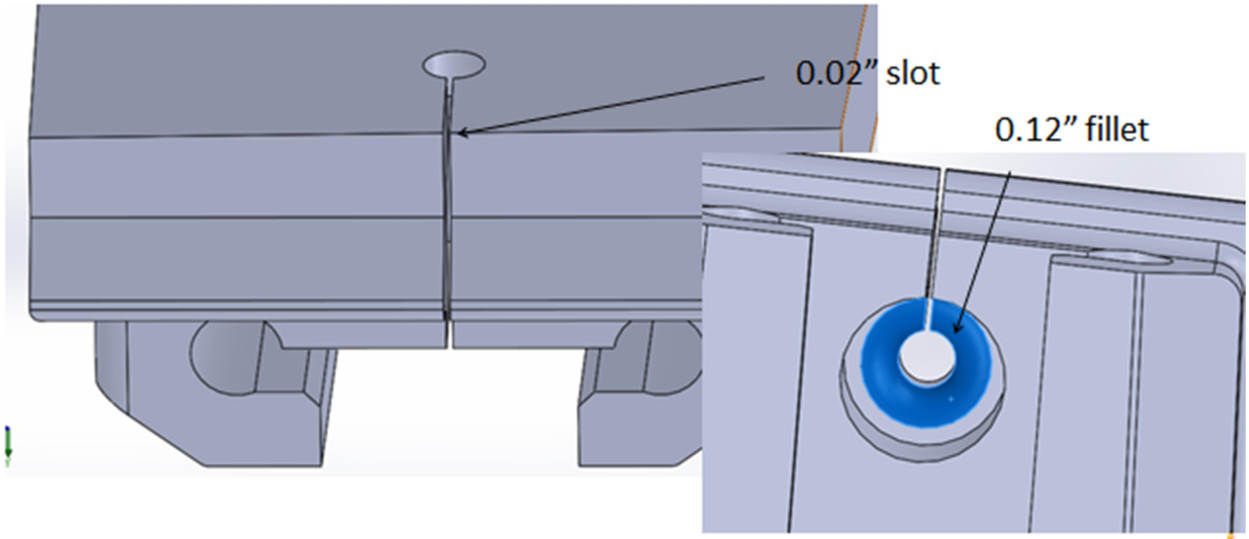
Modified R3 S1 Tile Geometry



Geometry Changes



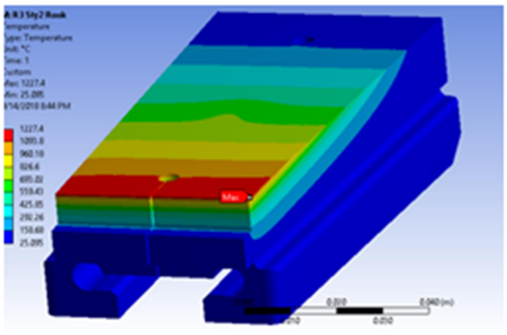
Geometry Changes Continued



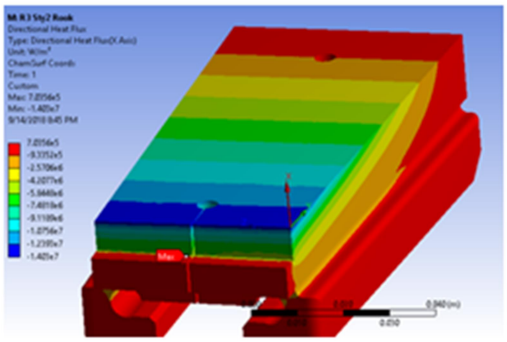
Round 2 Analysis Results
Row 3 Style 2, ED1402-1

Thermal Transient Results

Maximum Temperature

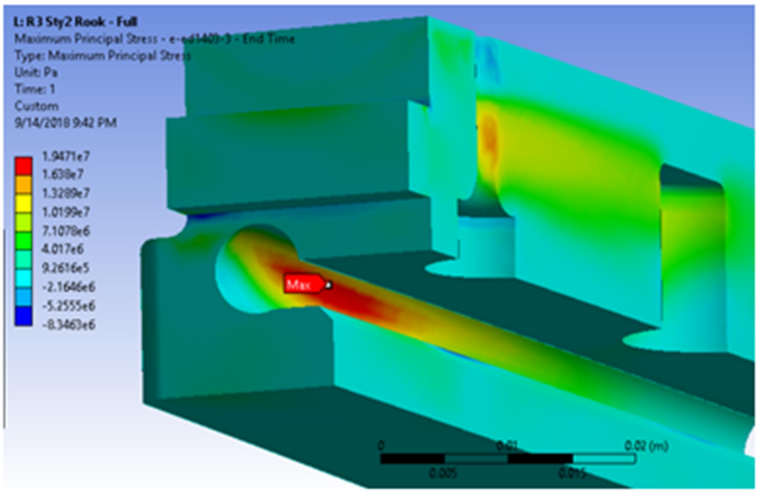


Directional Heat Flux



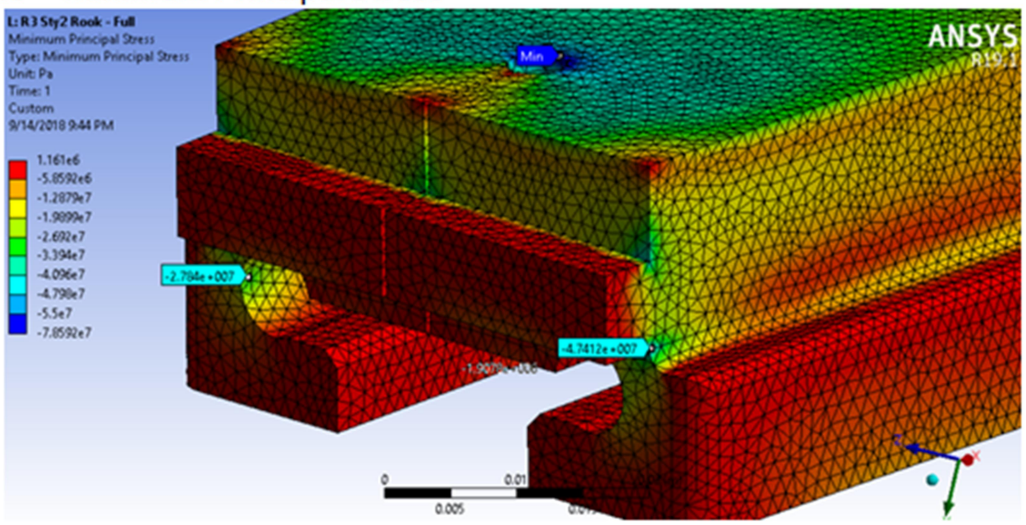
Structural Analysis Results

- Tile – Maximum Principal Stress



Structural Analysis Results

- Tile – Minimum Principal Stress



4.2 FOR INFORMATION ONLY – Analysis of Outdated E-ED1402-1 Tile Design

ORNL Analyst: William Smith

Summary:

The minimum principal stress in the chamfer of one of the bolt holes exceeds its allowable. See Figure 36. Peak stresses in all components are reported in Table 8, Table 9, and Table 10. The components considered in the analysis are shown below in Figure 20 and Figure 21.

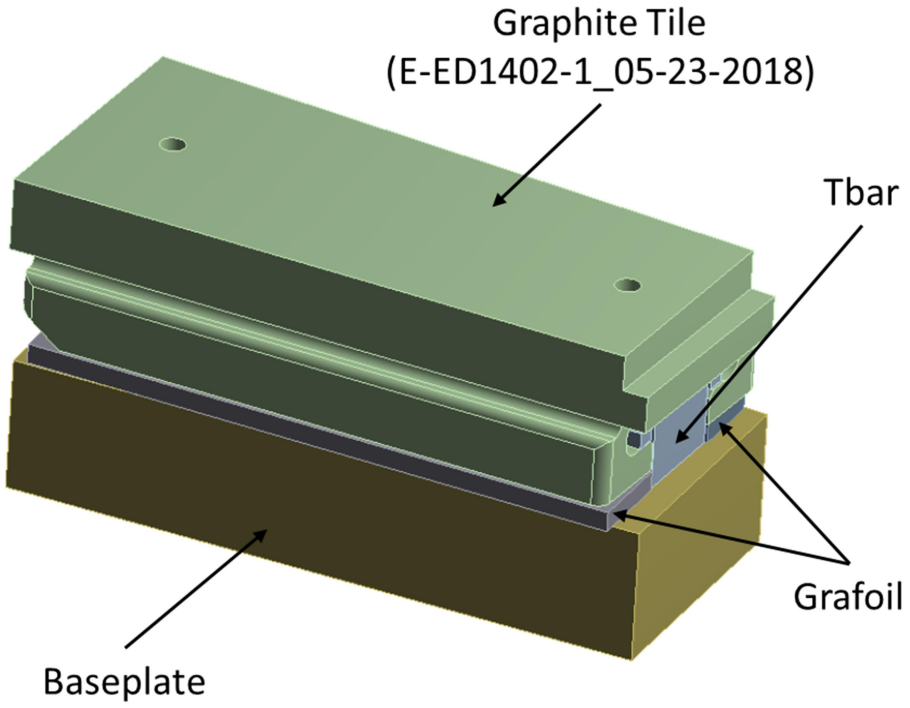


Figure 1: Outboard Diverter Row 3 (1402-1).

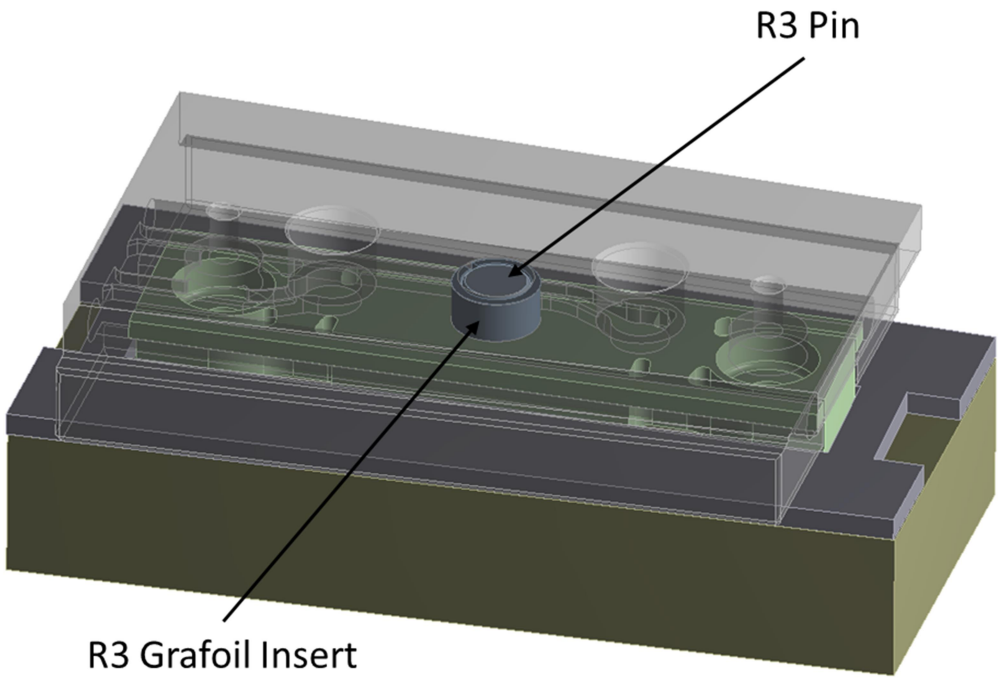


Figure 2: Outboard Diverter Row 3 (1402-1) components.

The total number of nodes and elements for the complete assembly is 491,176 and 125,780.
Figure 22 shows the mesh used in the analysis with and without the graphite tile. Figure 23 shows the mesh of the mounting side of the graphite tile.

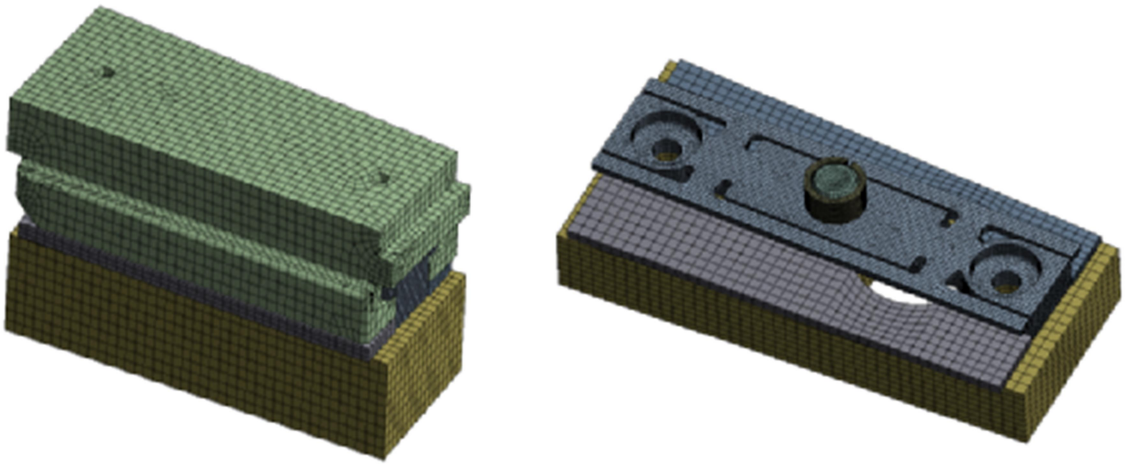


Figure 3: Mesh of the Outboard Diverter Row 3 (1402-1)

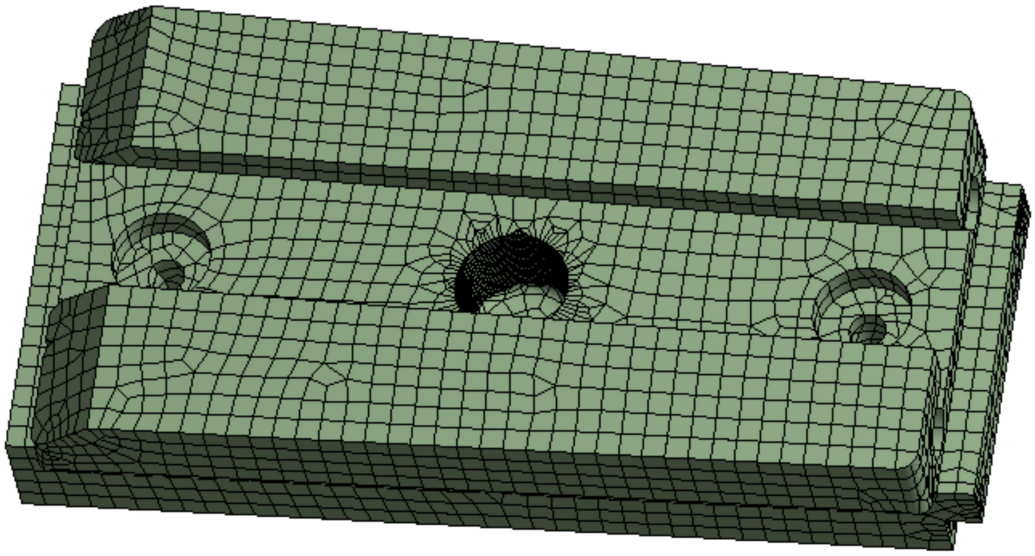


Figure 4: Mounting side of the graphite tile.

Table 6 lists each component of the assembly and its material.

Table 1: Components Material Definitions

Component	Material
Graphite Tile (E-ED1402-1 05-23-2018)	T953
Grafoil Slides	Grafoil
Baseplate	Pure Copper
R3-Grafoil Insert	Grafoil
R3 Pin	Inconel 718
Tbar	Alloy 625

Thermal Analysis

The following boundary conditions were used for the thermal analysis.

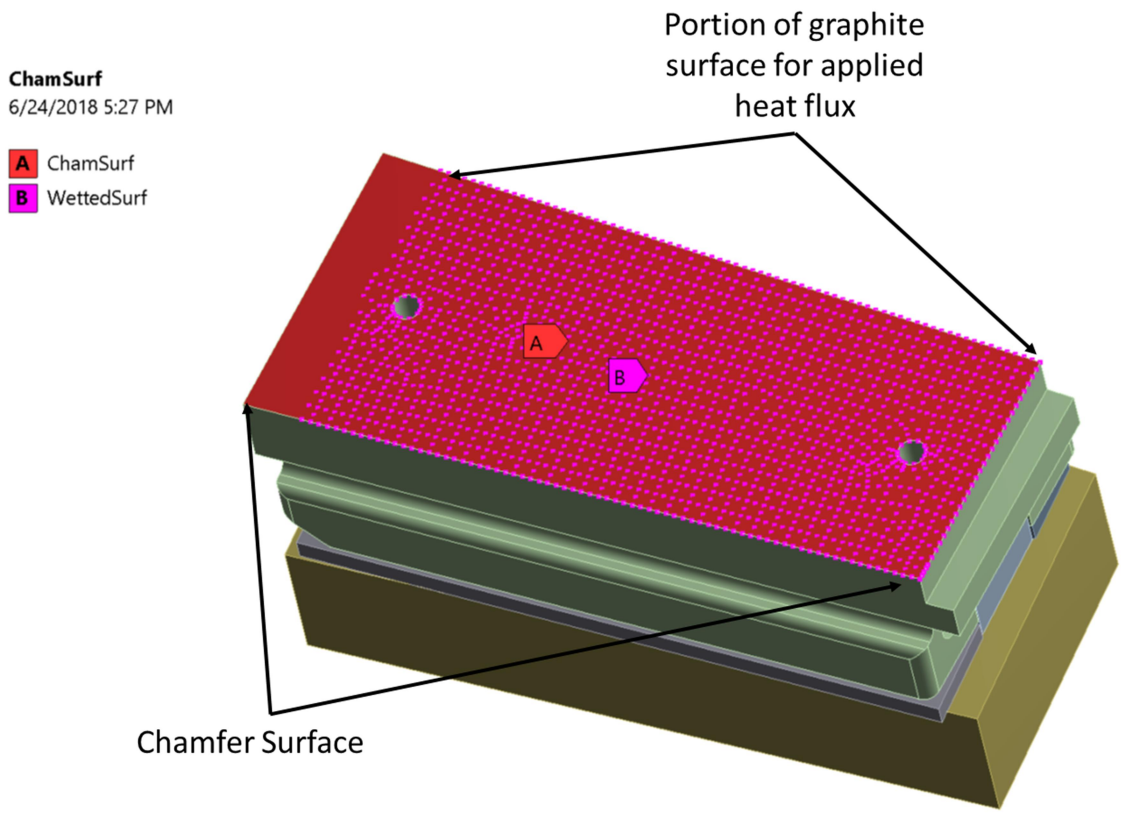


Figure 5: Thermal boundary conditions

Total bolt hole heat flux = 1.3689E07 W/m^2

Total top surface heat flux = 1.5094E07 W/m^2 with a maximum gradient heat flux along the ChamSurf coordinate Y-direction (see Figure 9 for coordinate system) of 1.8059E06 W/m^2/°

The peak temperature in the assembly is 1341.8 °C and is found on the graphite tile's surface.

Figure 25 and

Figure 26 shows the temperature contour due to the applied heat fluxes. Table 7 lists the peak temperature for each component over all time steps.

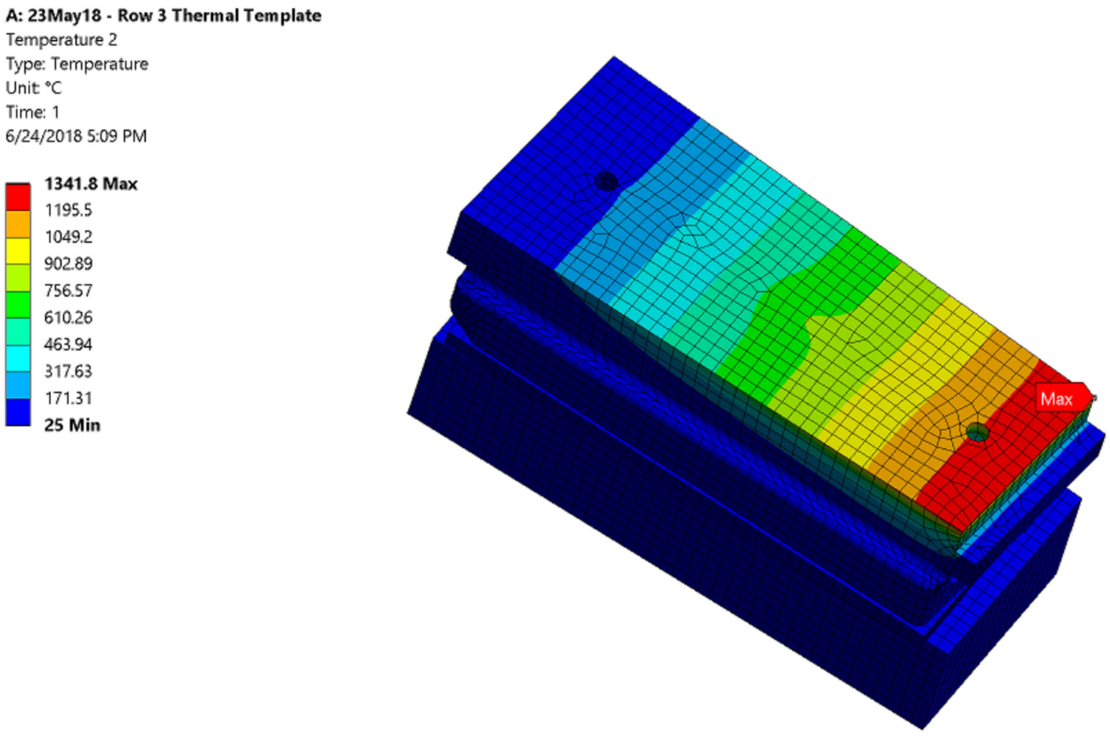


Figure 6: Temperature contour plot of the Outboard Diverter Row 3 (1402-1)

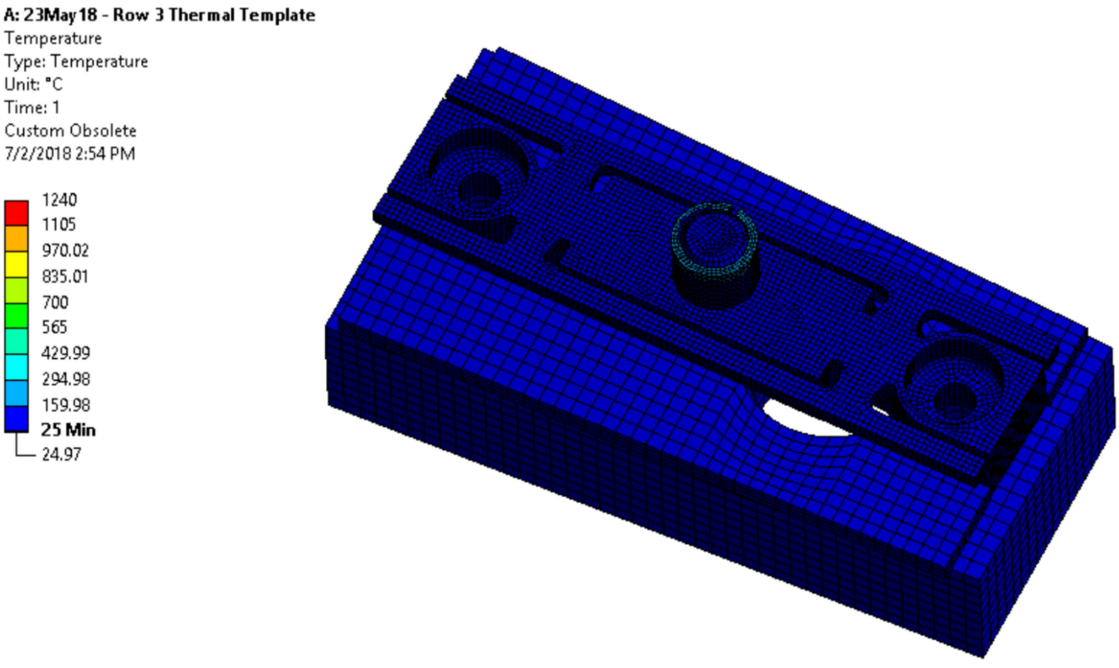


Figure 7: Temperature contour plot of Outboard Diverter Row 3 (1402-1) without graphite tile

Table 2: Peak temperature over time for each component

Component	Peak Temperature (°C)
Graphite Tile (E-ED1402-1 05-23-2018)	1341.8
Grafoil	28.396
Baseplate	25.479
Grafoil Insert	227.0
R3 Pin	25.003
Tbar	25.085

4.3 Structural-Thermal Analysis

Preload force of 2670 N applied to both fastener locations on the Tbar as shown in Figure 27. Figure 28 shows the eddy moment and halo force loading applied to the graphite tile.

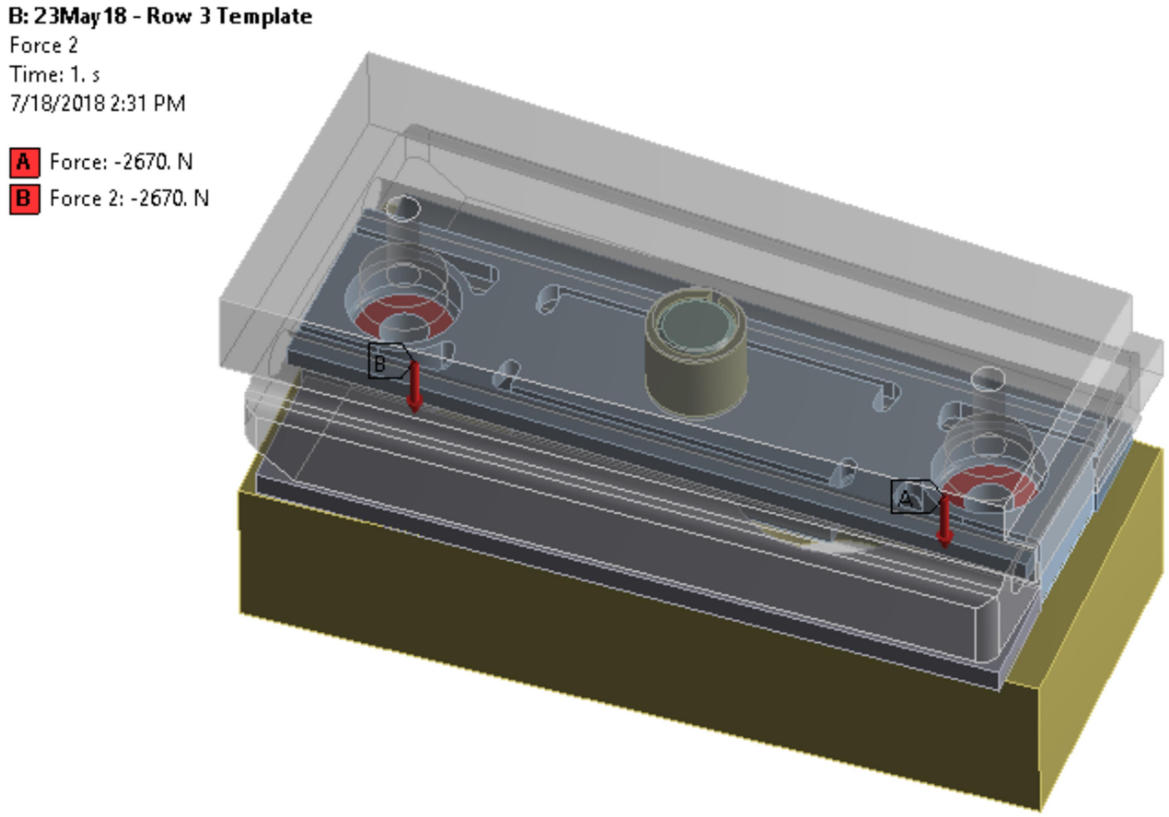


Figure 8: Bolt preload force applied to the Tbar.

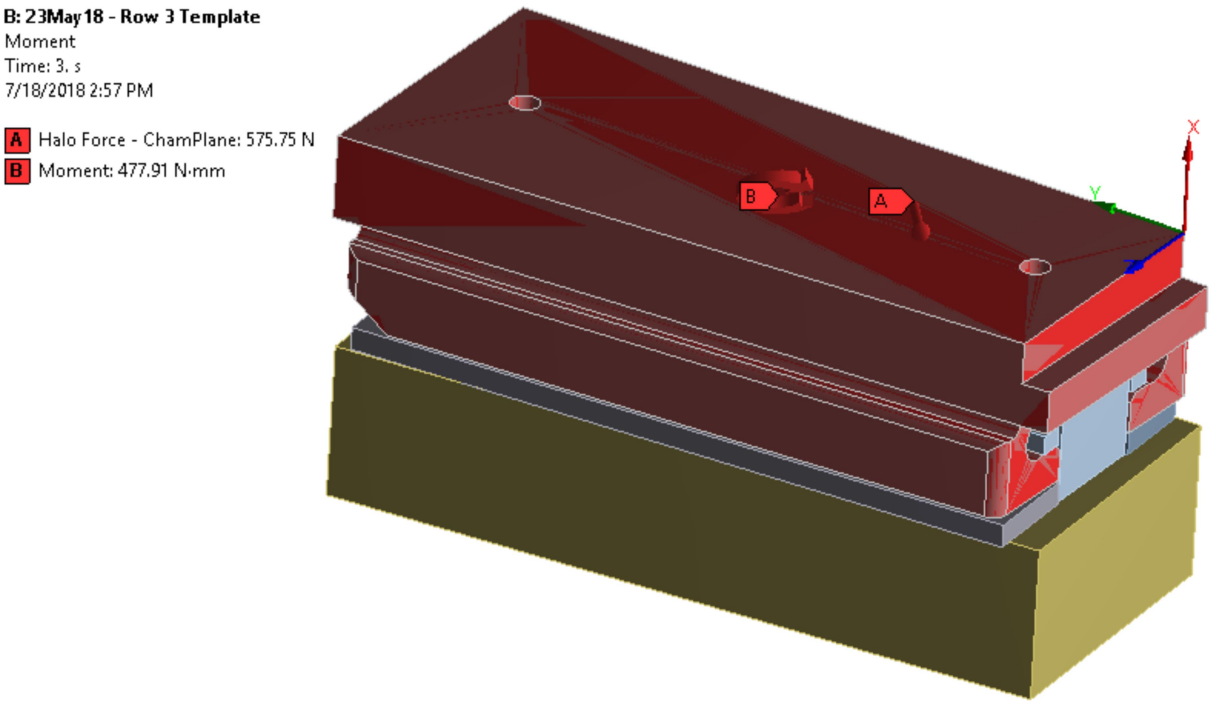


Figure 9: Eddy moment (A) and Halo force (B) applied to the graphite tile.

Frictionless constraints were applied to three sides of the baseplate and two sides of the grafoil.
Figure 29 shows the location of these constraints highlighted in blue.

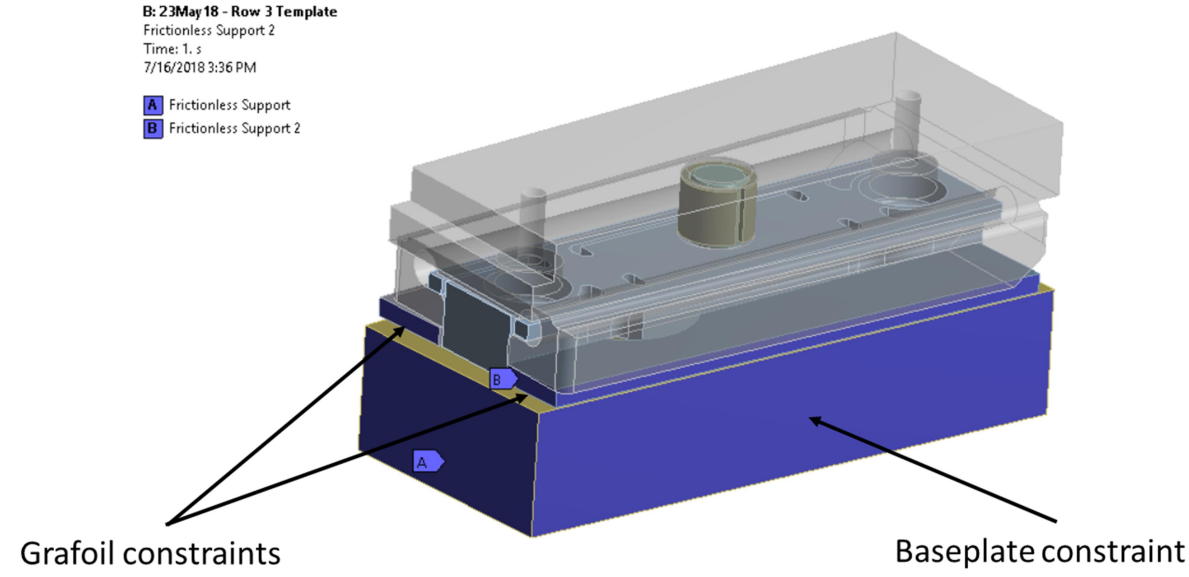


Figure 10: Frictionless boundary condition locations on the baseplate and grafoil.

The graphite tile is connected to the grafoil, R3-grafoil insert, and Tbar through frictional contact with a coefficient of friction of 0.1.
Figure 30 shows the surfaces in contact with each other labeled A through E.

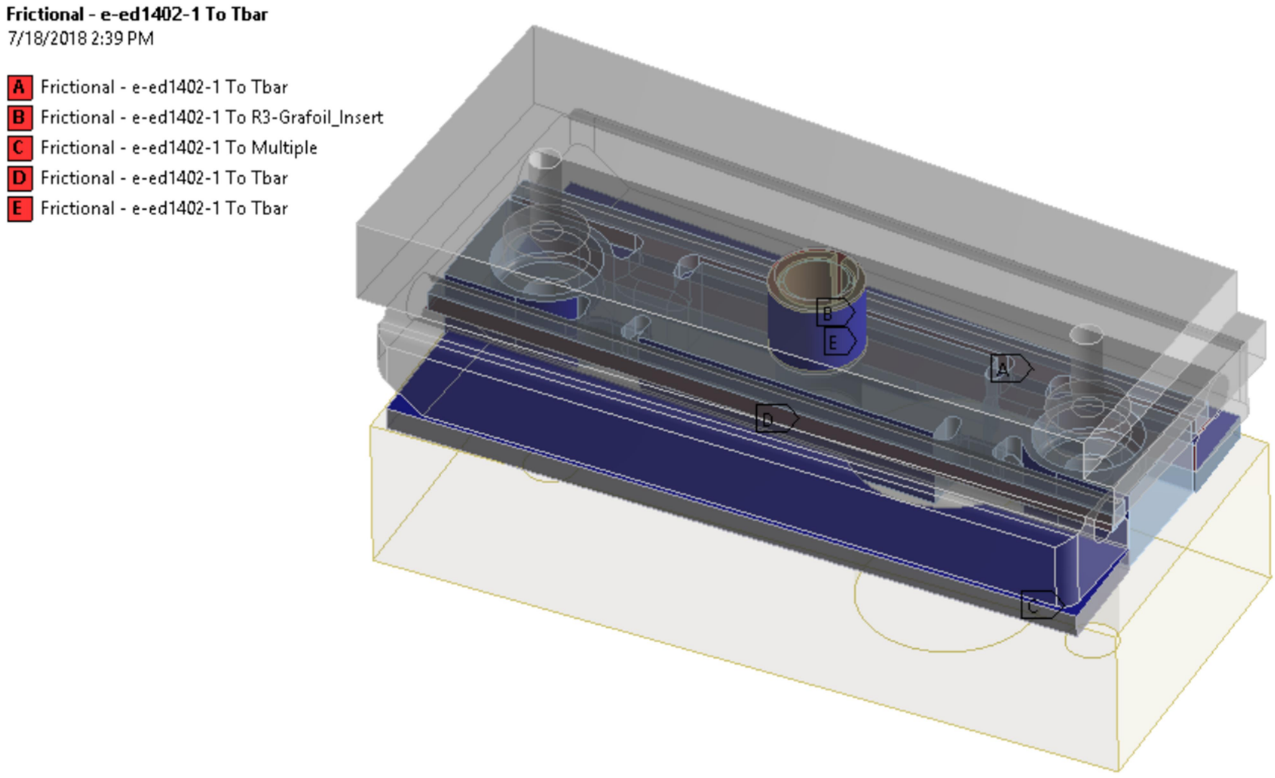


Figure 11: Frictional contact between the graphite tile and support structure.

The R3 pin is bonded to the Tbar. The contact between the R3 pin and R3-grafoil insert is frictional with a coefficient of friction of 0.01. The Tbar is in frictional contact with the baseplate with a coefficient of friction of 0.3. The grafoil and baseplate are in contact with the no separation condition.
Figure 31 shows the surfaces in contact with each other labeled A through D.

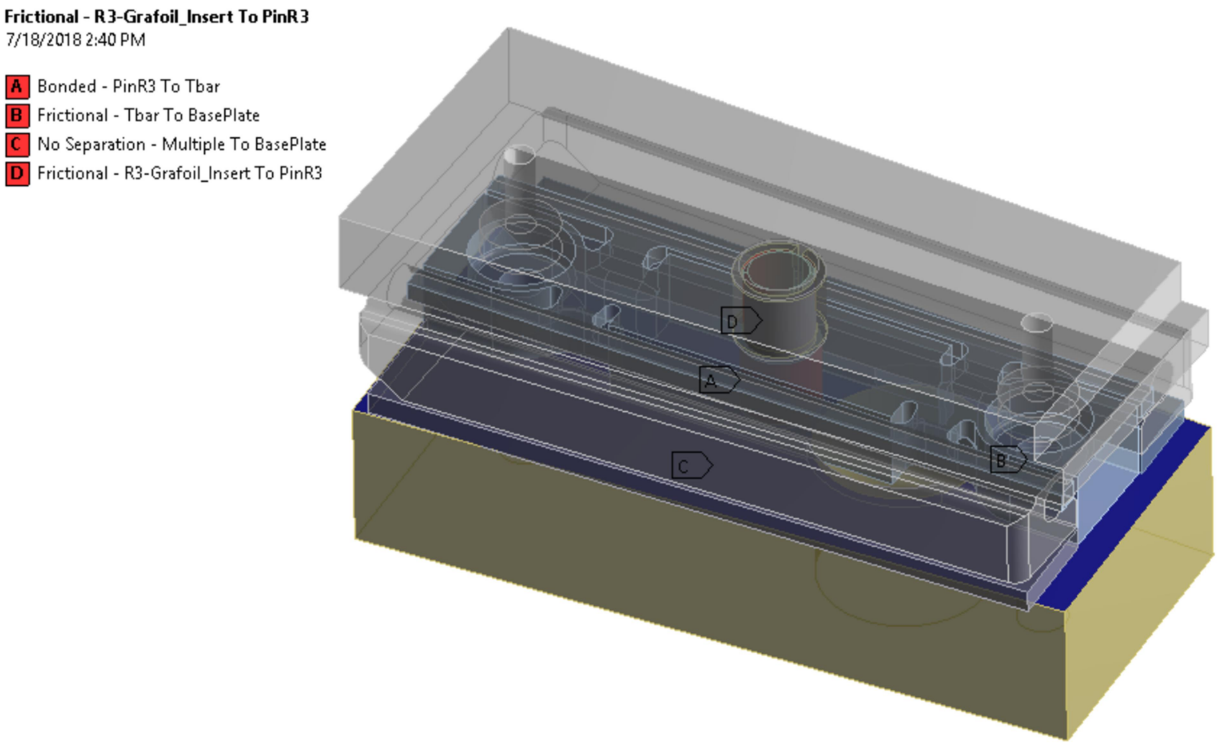


Figure 12: Frictional contact between the support structure.

Results

Total deformation contour plot of the assembly is shown in Figure 32. X, Y, Z deformation contour in the assembly is shown Figure 33, Figure 34, and Figure 35.

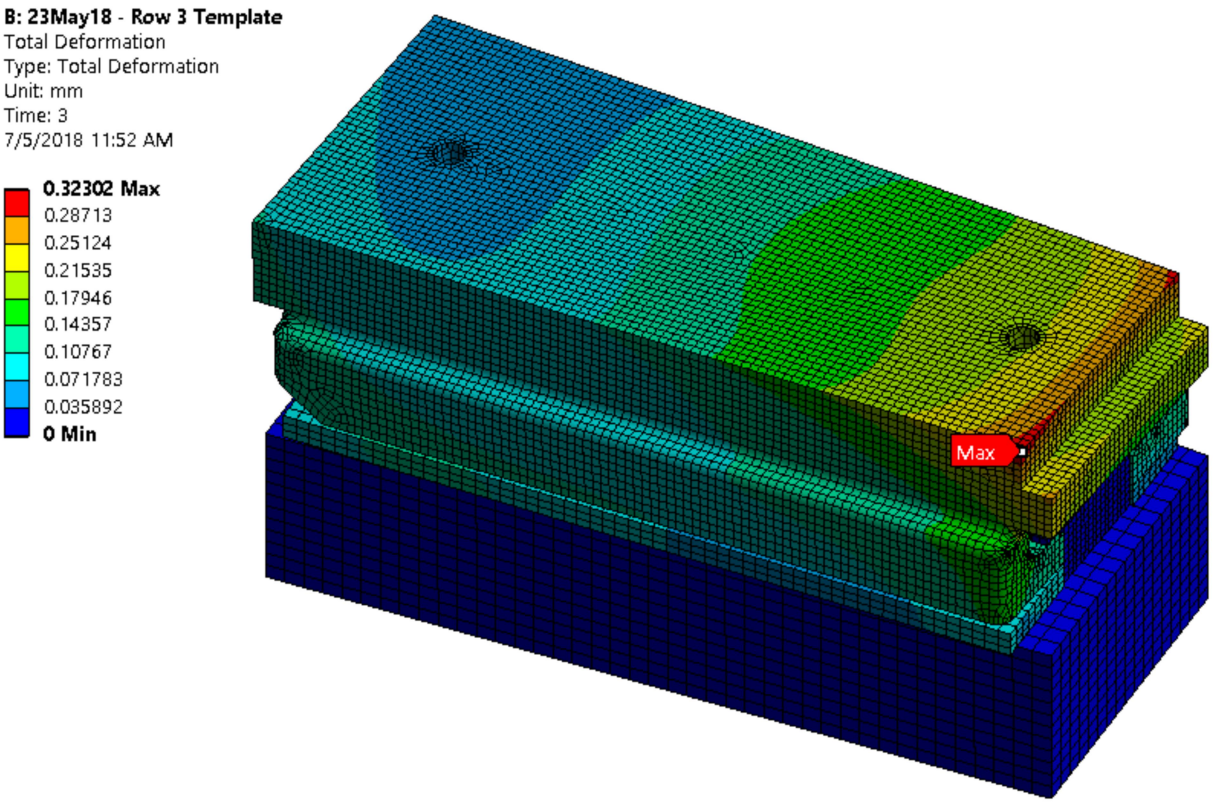


Figure 13: Total deformation of the assembly

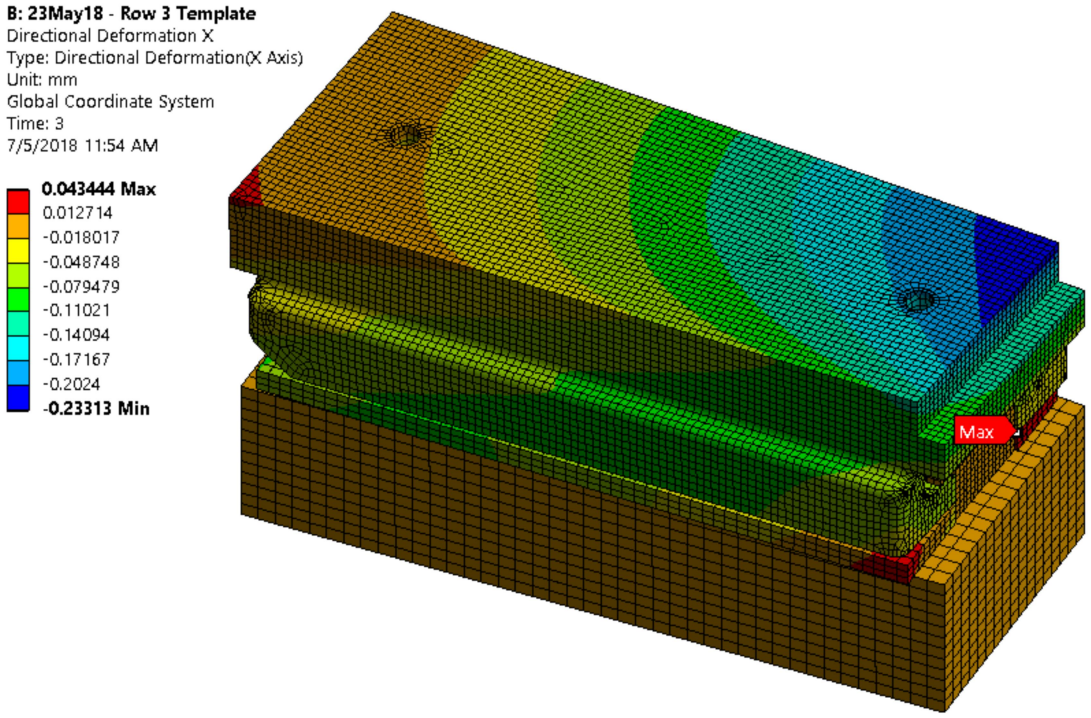


Figure 14: X-direction displacement

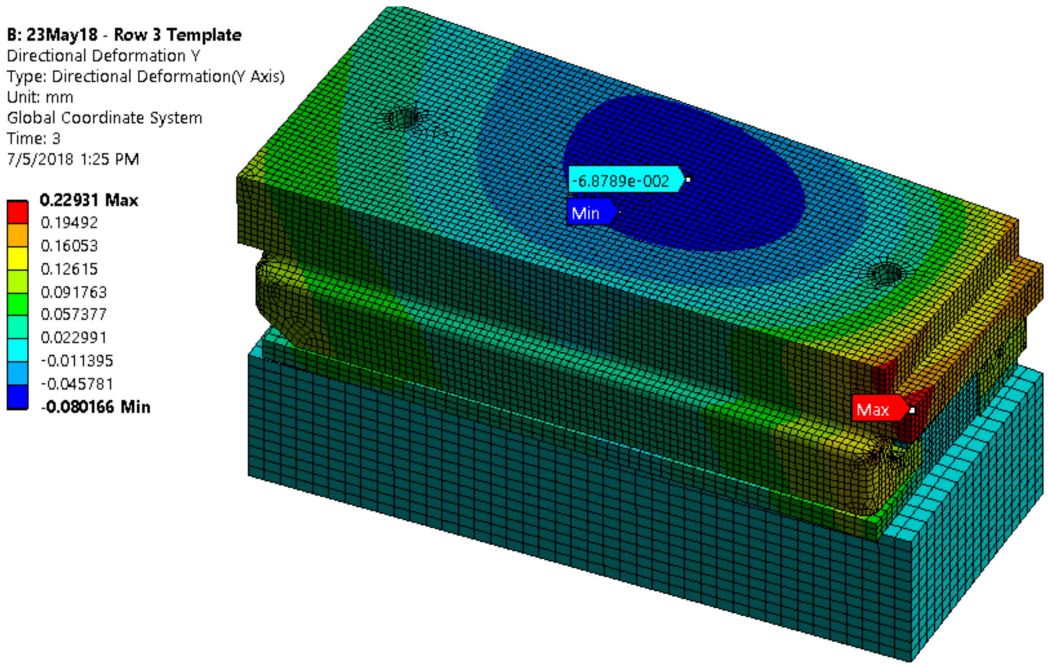


Figure 15: Y-direction displacement

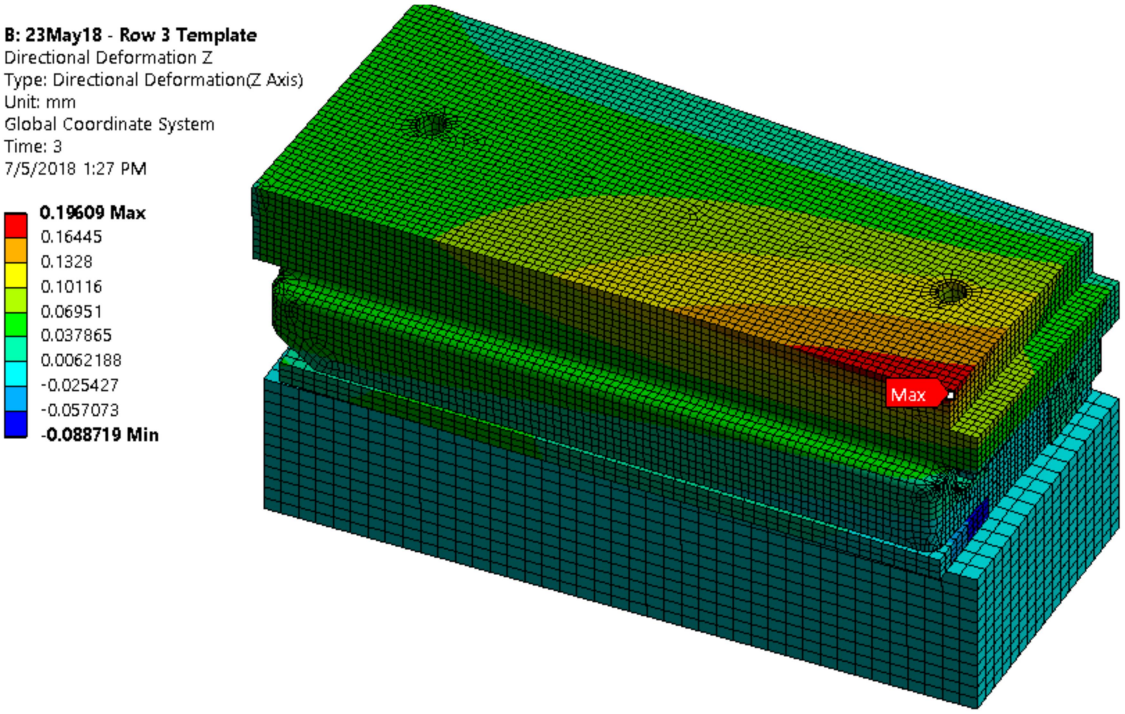


Figure 16: Z-direction displacement

Table 8 and Table 9 list the peak maximum and minimum principal stress and the corresponding allowable in the components made of graphite. Table 10 lists the peak equivalent stress and the corresponding allowable for the components made from metal.

Table 3: Maximum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1402-1 05-23-2018)	28.17	20	1.69 to 2.02
Graphite Tile – Tbar Slot	28.17	20	1.69 to 2.02
Graphite Tile – Shear Pin Hole	13.18	20	2.67 to 3.00
Grafoil	1.31	20	0.72 to 1.04
Grafoil Insert	0.51	20	2.02 to 2.35

Table 4: Minimum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1402-1 05-23-2018)	-80.28	-55	0.07 to 0.39
Graphite Tile – Tbar Slot	-36.94	-55	2.67 to 3.00
Graphite Tile – Shear Pin Hole	-19.75	-55	1.04 to 1.37
Grafoil	-2.38	-55	1.70
Grafoil Insert	-2.19	-55	2.67 to 3.00

Table 5: Equivalent Stress of metallic components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Baseplate	34.88	??	2.78 to 3.00
Pin	23.05	??	2.78 to 3.00
Tbar	195.94	261	1.89 to 2.11

The minimum principal stress in the chamfer of the bolt hole, shown in Figure 36, exceeded its allowable stress. The maximum principal stress also exceeded its allowable and occurred in the tile tbar slot as shown in Figure 37.

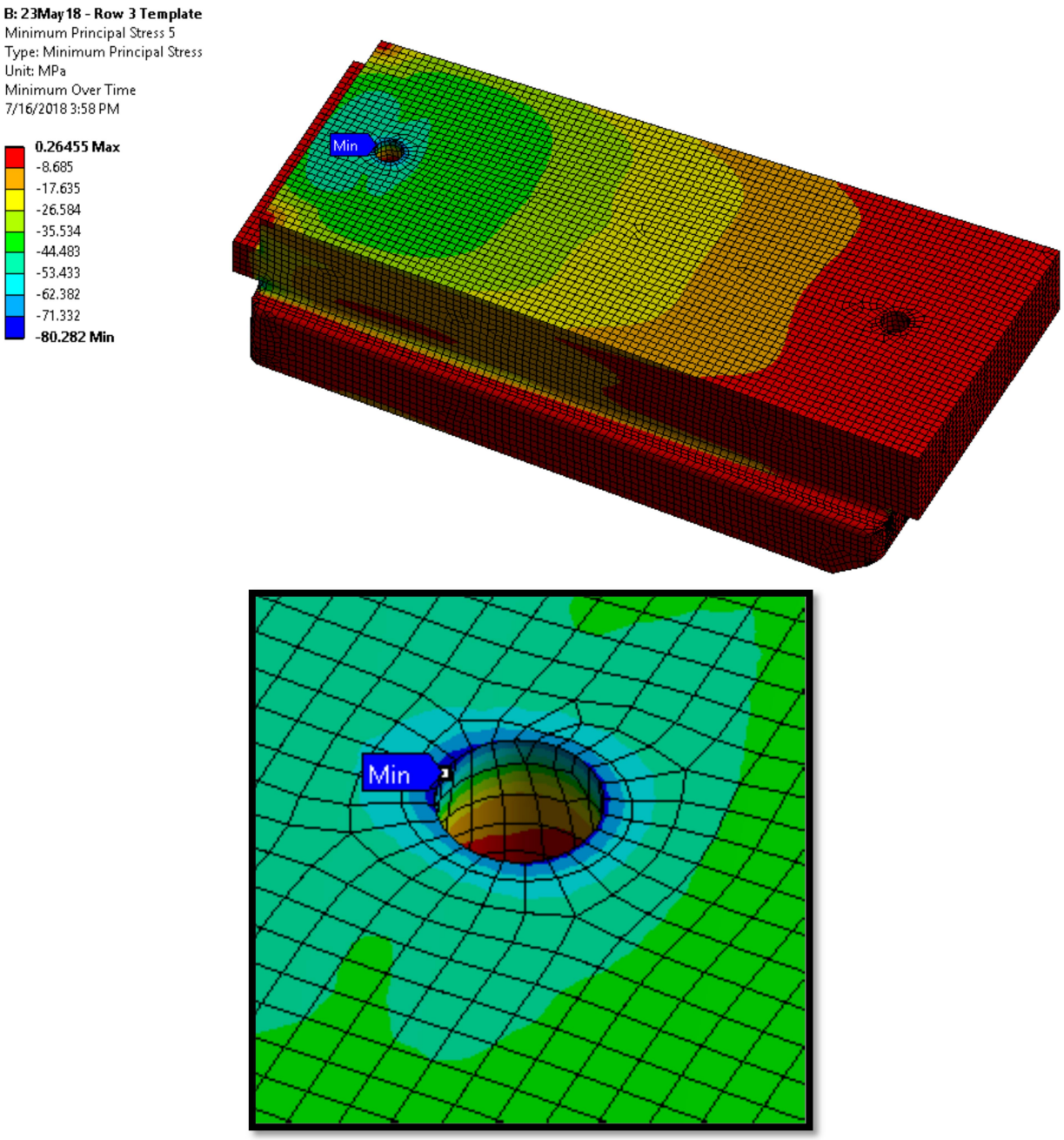


Figure 17: Location of peak minimum stress in graphite tile.

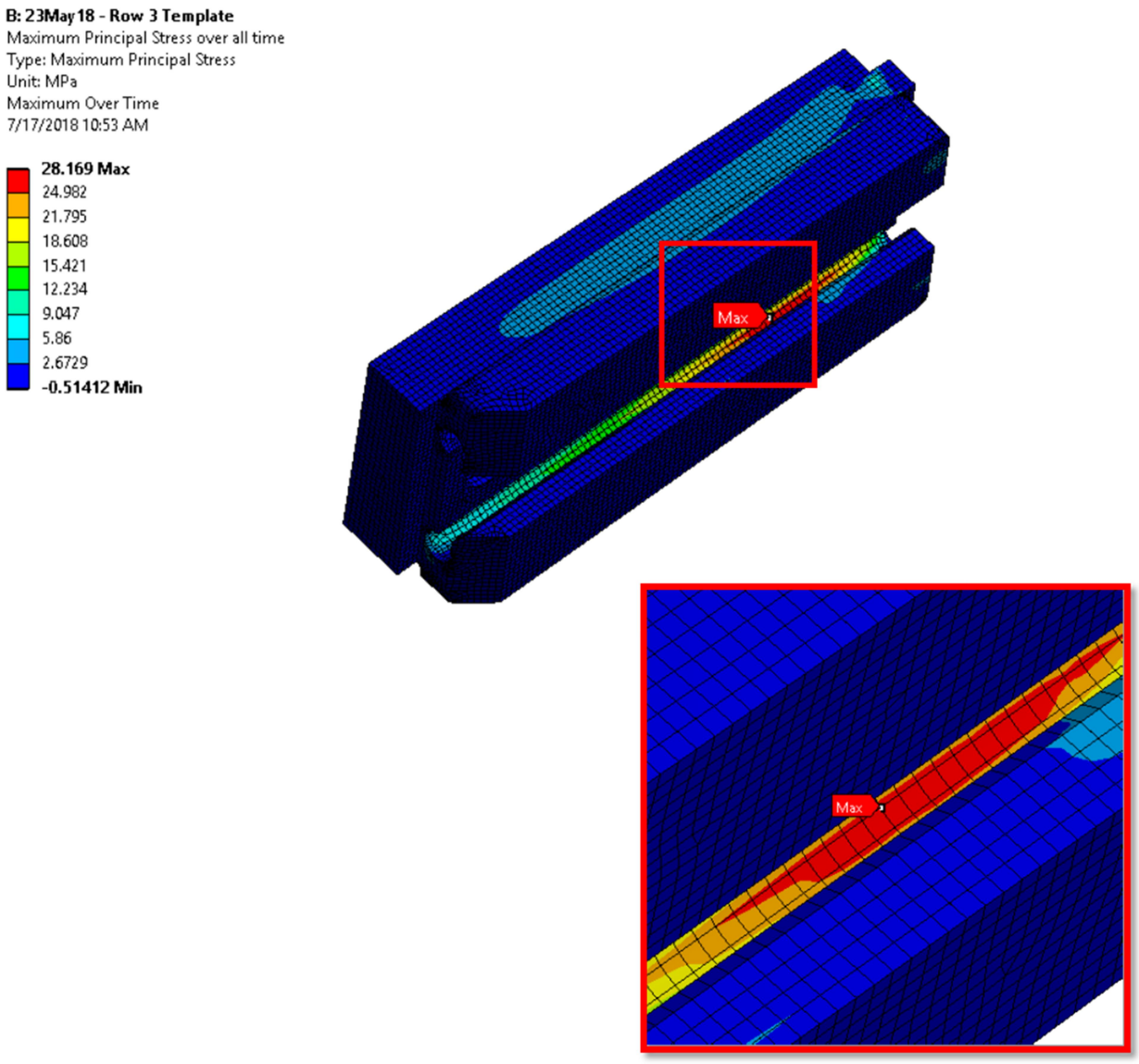


Figure 18: Location of peak maximum principal stress.

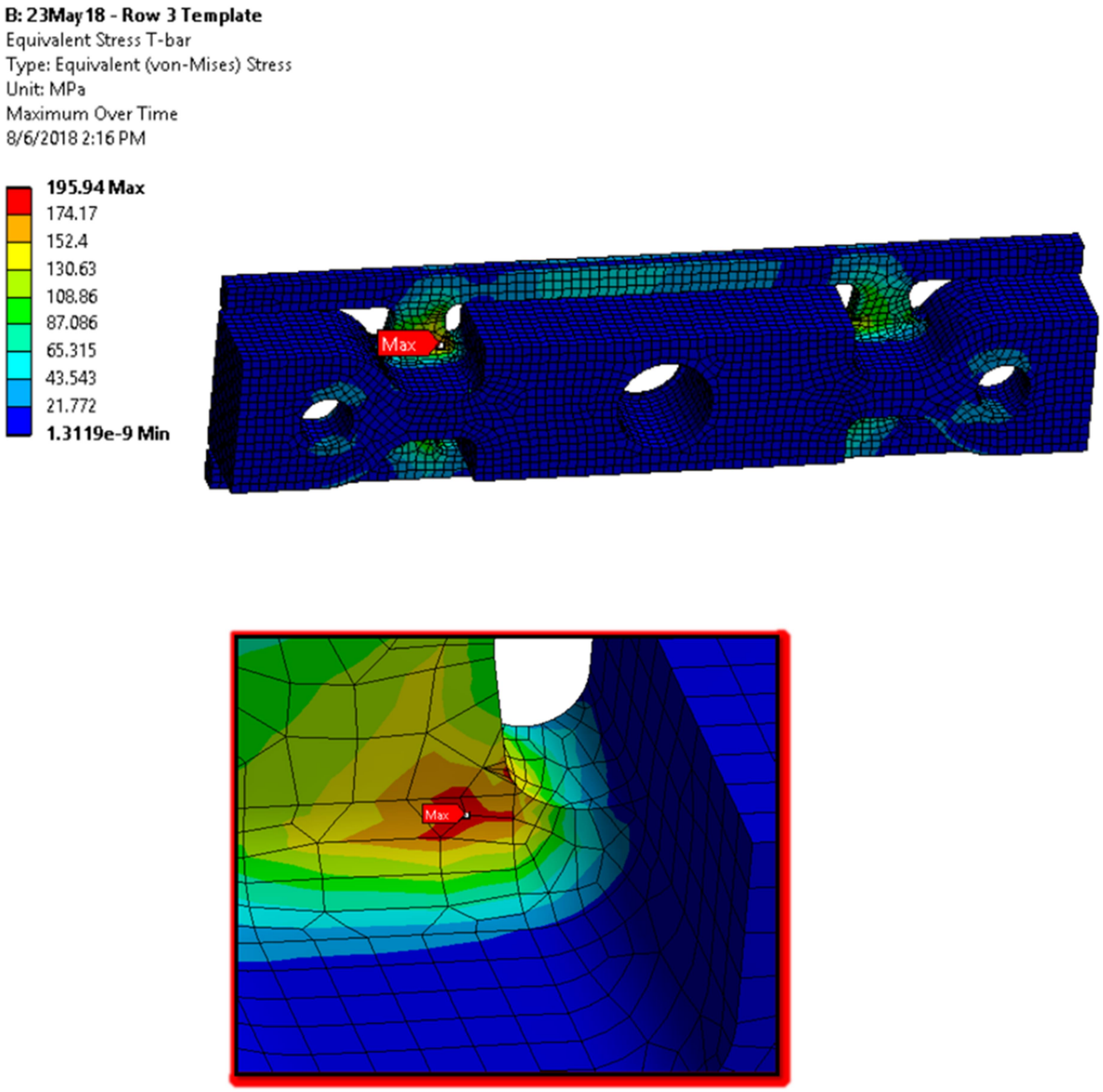


Figure 19: Location of peak equivalent stress

5 Subreport E-ED1402-4 Row 3 Style 2 Langmuir Probe Variant

The E-ED1402-4 tile design was revised after this analysis to incorporate the changes detailed in the subreport for the R3 Style 2 base tile. Analysis of preliminary tile design showed that the Langmuir probe cutouts will not drive this variant's design. The stress reduction features incorporated and analyzed with E-ED1402-1 were also incorporated into this tile. The results presented in this subreport provide the justification for not re-analyzing these changes.

Please see E-ED1403-3 subreport for the stresses expected in this tile.

Analysis of Outboard Diverter Row 3 style 2 variant (1402-4)

ORNL Analyst: Jason Cook

Summary:

The minimum principal stress in the chamfer of one of the bolt holes exceeds its allowable. See Figure 36. I do not have the allowable stress for pure copper. Peak stresses in all components are lists in Table 8, Table 9, and Table 10. The components considered in the analysis are listed below in Figure 20 and Figure 21.

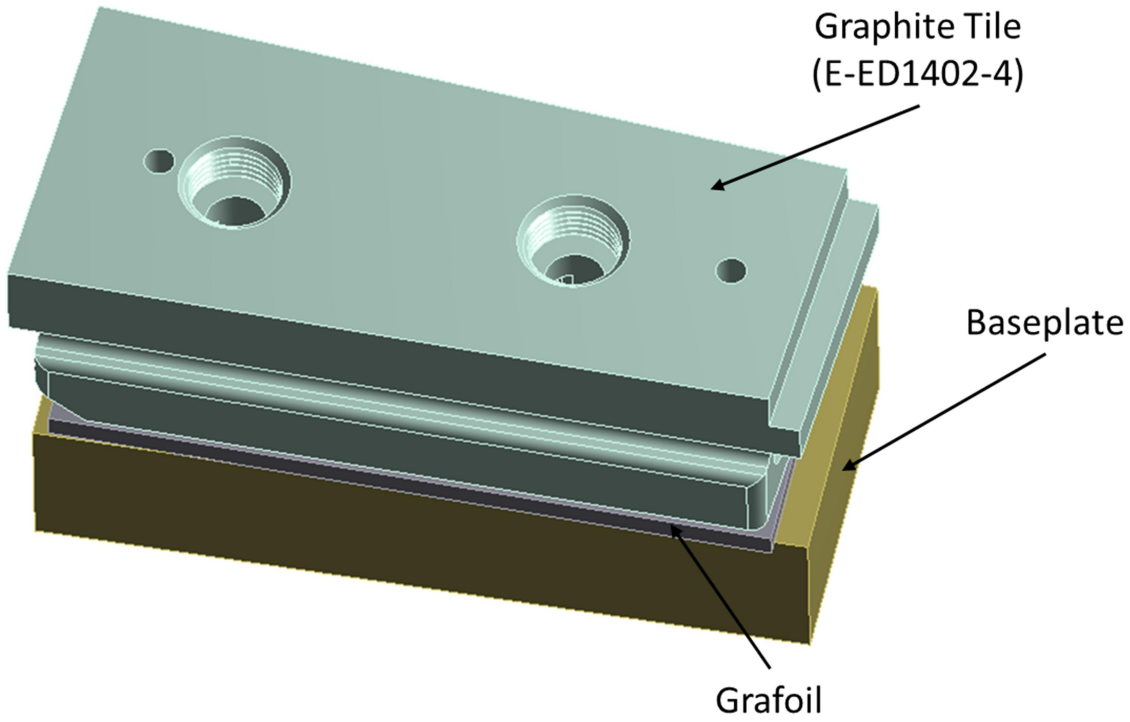


Figure 20: Outboard Diverter Row 3 style 2 variant (1402-4)

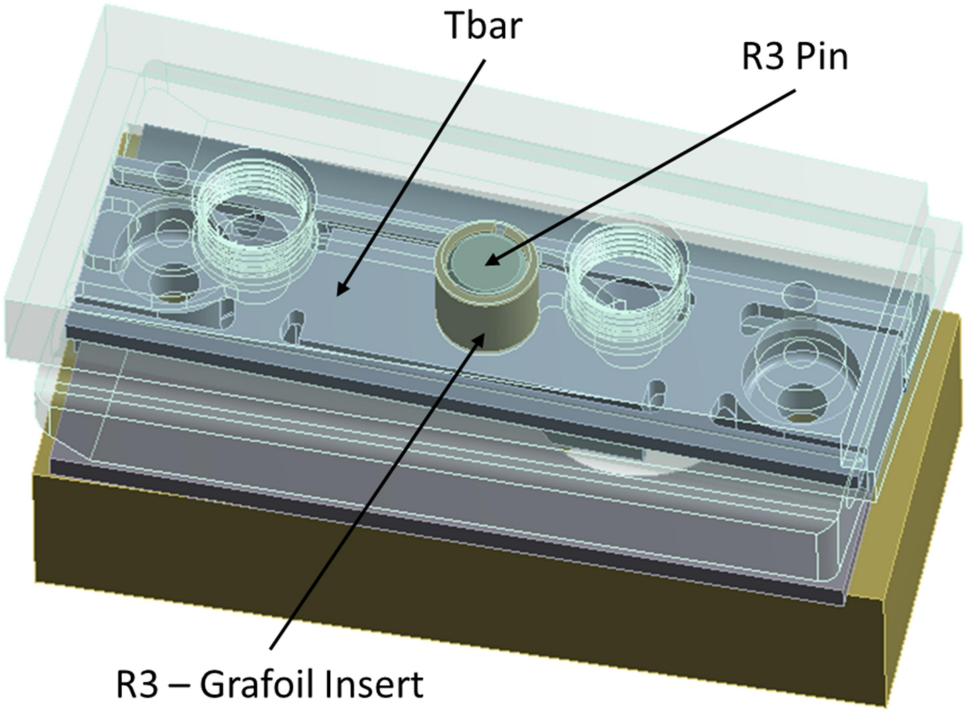


Figure 21: OBD Row 3 style 2 variant (1402-4) components considered in analysis.

The total number of elements and nodes for the whole assembly is 160,863 and 579,133 respectively.

Figure 22 shows the mesh used in the analysis with and without the graphite tile. Figure 23 shows the mesh of the mounting side of the graphite tile and the bottom of the baseplate.

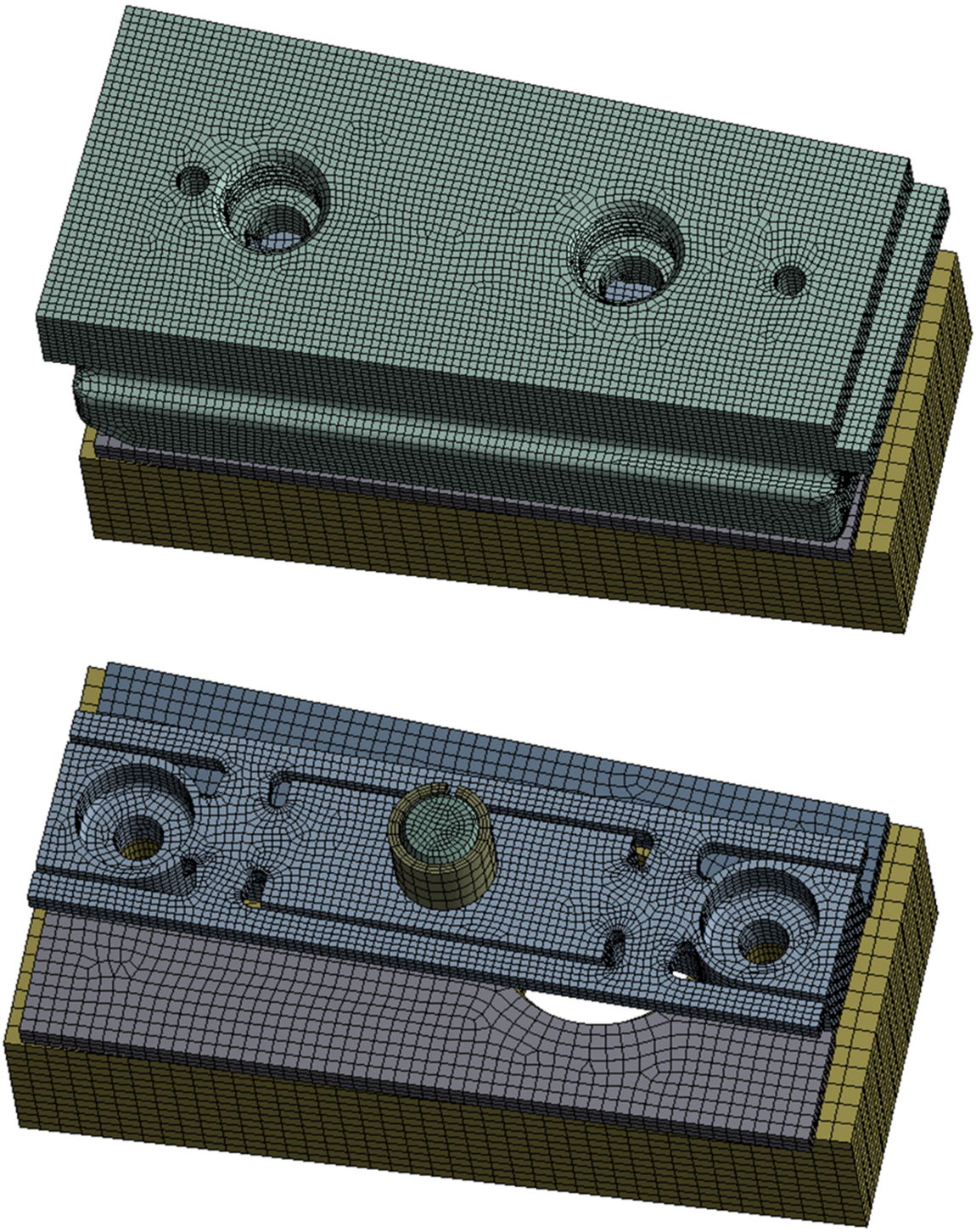


Figure 22: Mesh of the Outboard Diverter Row 3 style 2 variant (1402-4)

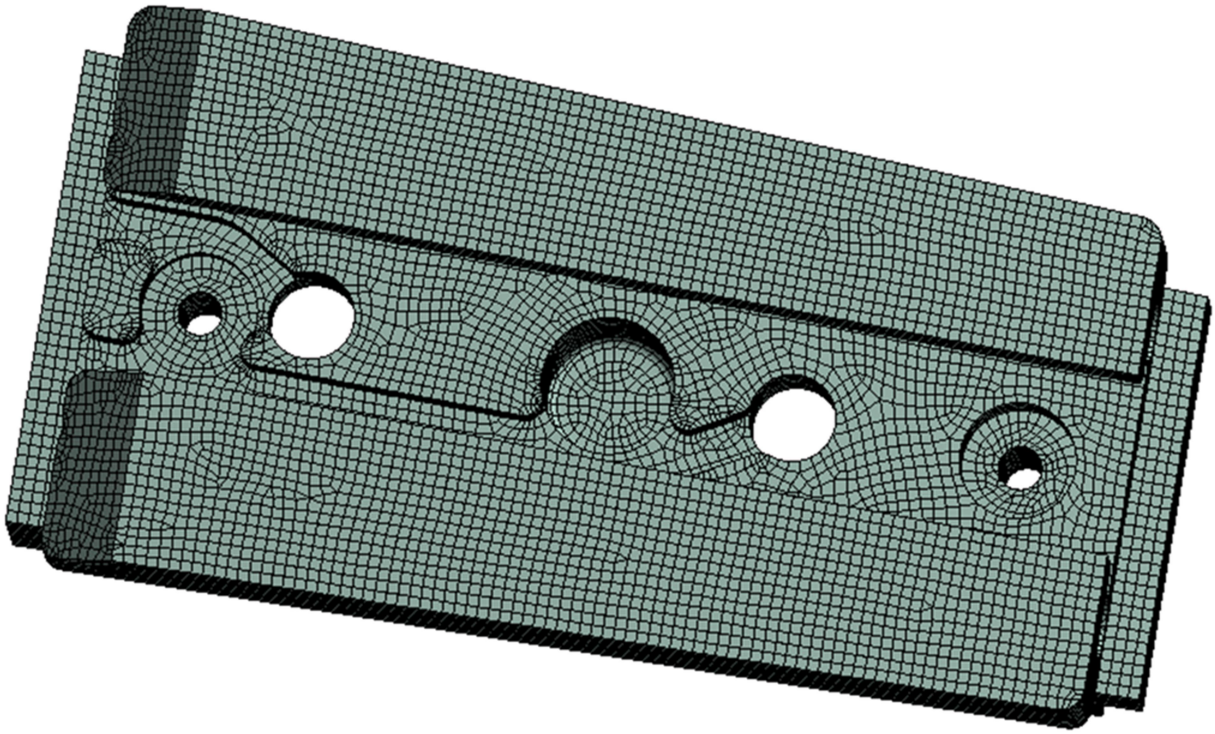


Figure 23: Mounting side of the graphite tile and bottom of baseplate.

Table 6 lists each component of the assembly and its material.

Table 6: Components and their materials.

Component	Material
Graphite Tile (E-ED1402-4)	T953
Grafoil	Grafoil
Baseplate	Pure Copper
R3-Grafoil Insert	Grafoil
R3 Pin	Inconel 718
Tbar	Alloy 625

Thermal Analysis

The following boundary conditions were used for the thermal analysis.

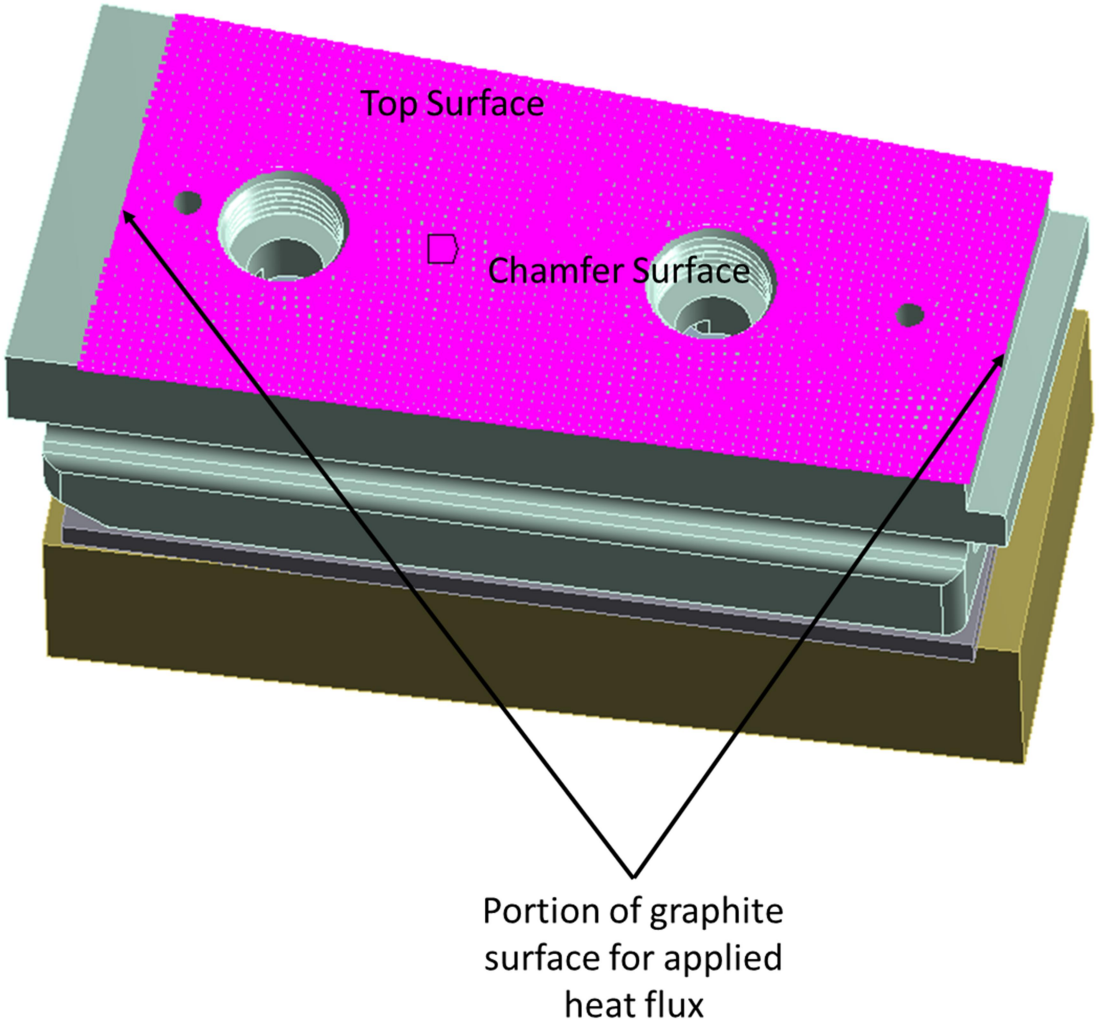


Figure 24: Thermal boundary conditions

Top Surface heat flux = 15,125,544 W/m^2 with a gradient heat flux along the y-direction of –137,504,948 W/m^2/° with the extent being 0.11 m.

The peak temperature in the assembly was 858 °C in the graphite tile.

Figure 25 and Figure 26 shows the temperature contour because of the applied heat fluxes. Table 7 shows lists the peak temperature for each component.

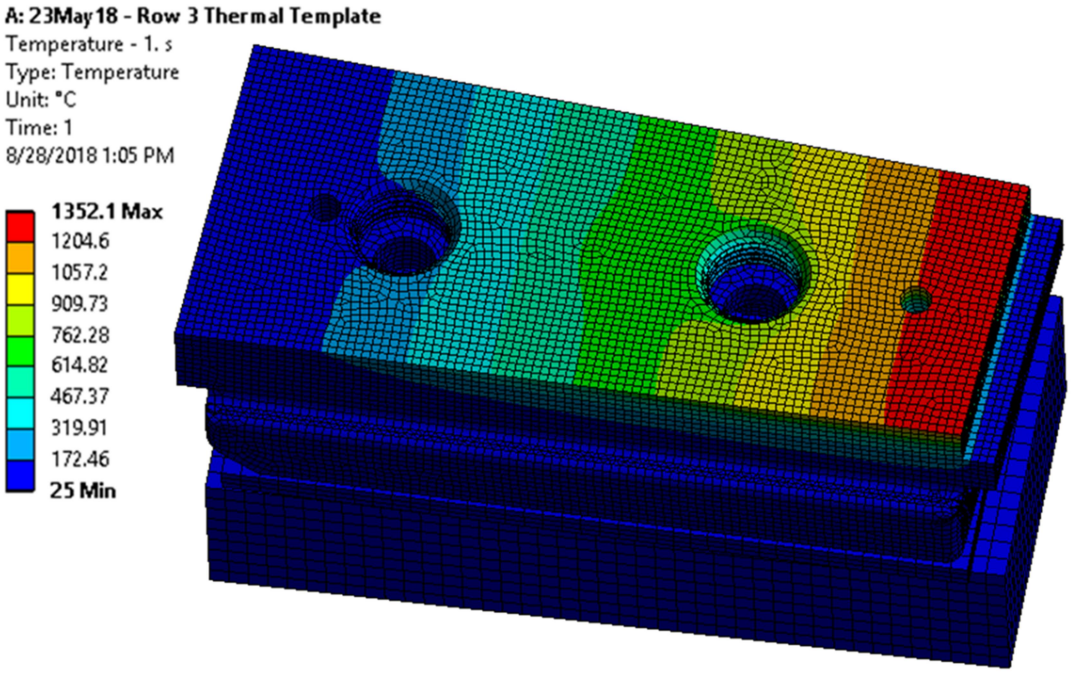


Figure 25: Temperature contour plot of the Outboard Diverter Row 3 style 2 variant (1402-4)

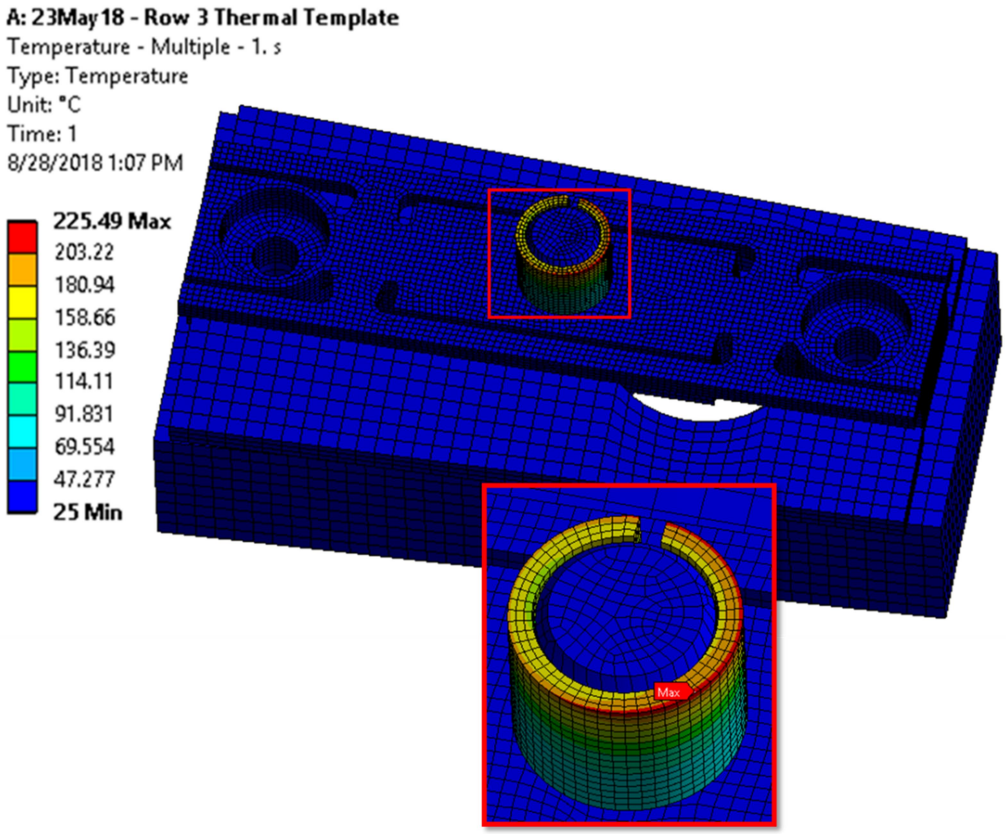


Figure 26: Temperature contour plot of the Outboard Diverter Row 3 style 2 variant (1402-4) without graphite tile

Table 7: Peak temperature for each component

Component	Peak Temperature (°C)
Graphite Tile (E-ED1402-4)	1352
Grafoil	28
Baseplate	25
R3-Grafoil Insert	225
R3 Pin	25
Tbar	25

Structural-Thermal Analysis

Preload force of 2670 N applied to both fastener locations on the Tbar as shown in Figure 27. Figure 28 shows the eddy moment and halo force loading applied to the graphite tile.

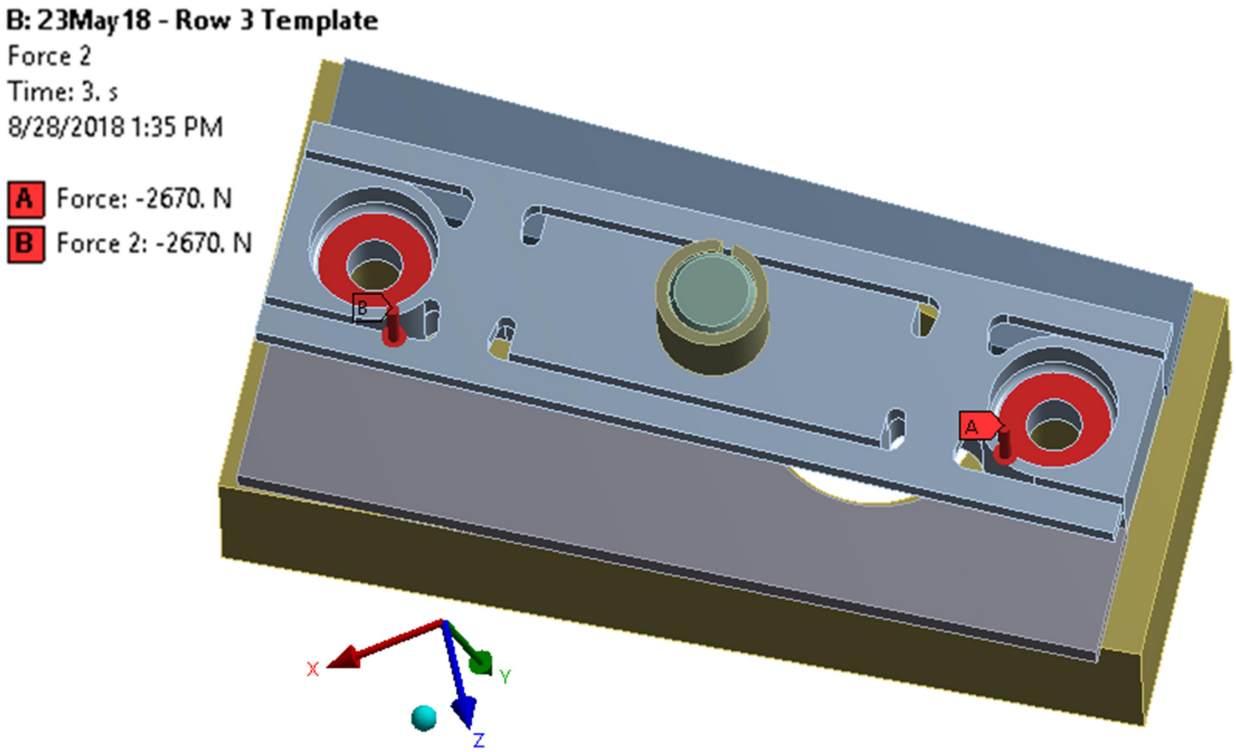


Figure 27: Bolt preload force applied to the Tbar.

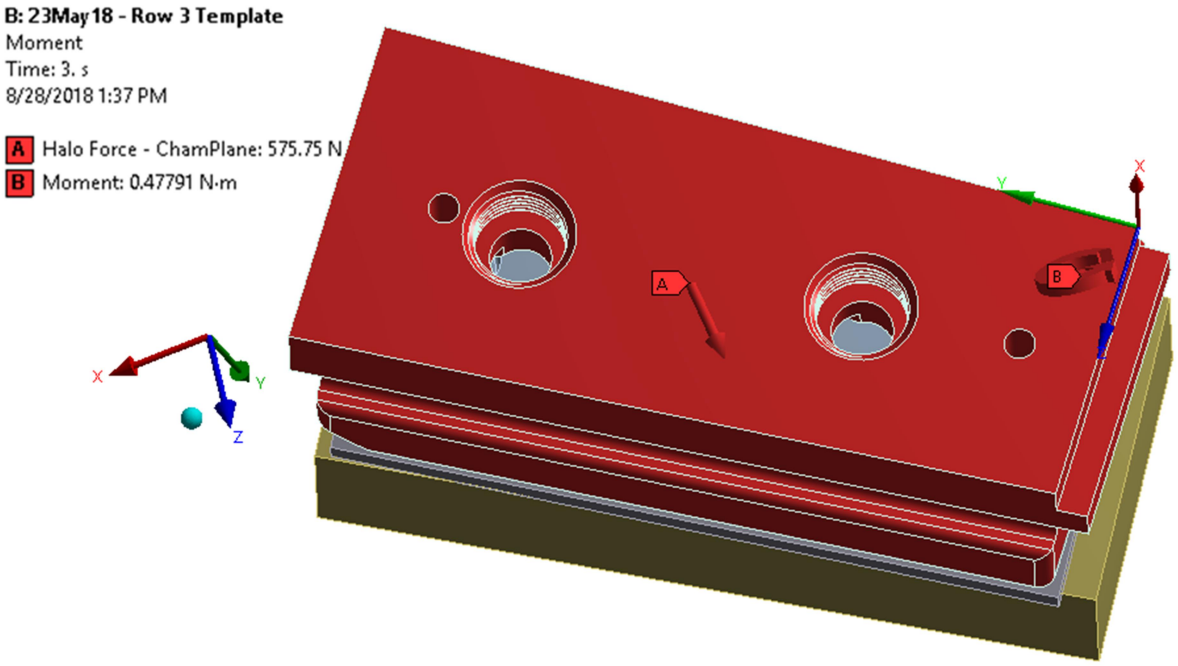


Figure 28: Eddy moment (A and B) and Halo force (C) applied to the graphite tile.

Frictionless constraints were applied to three side of the baseplate and three sides of the grafoil.
Figure 29 shows the location of these constraints highlighted in blue.

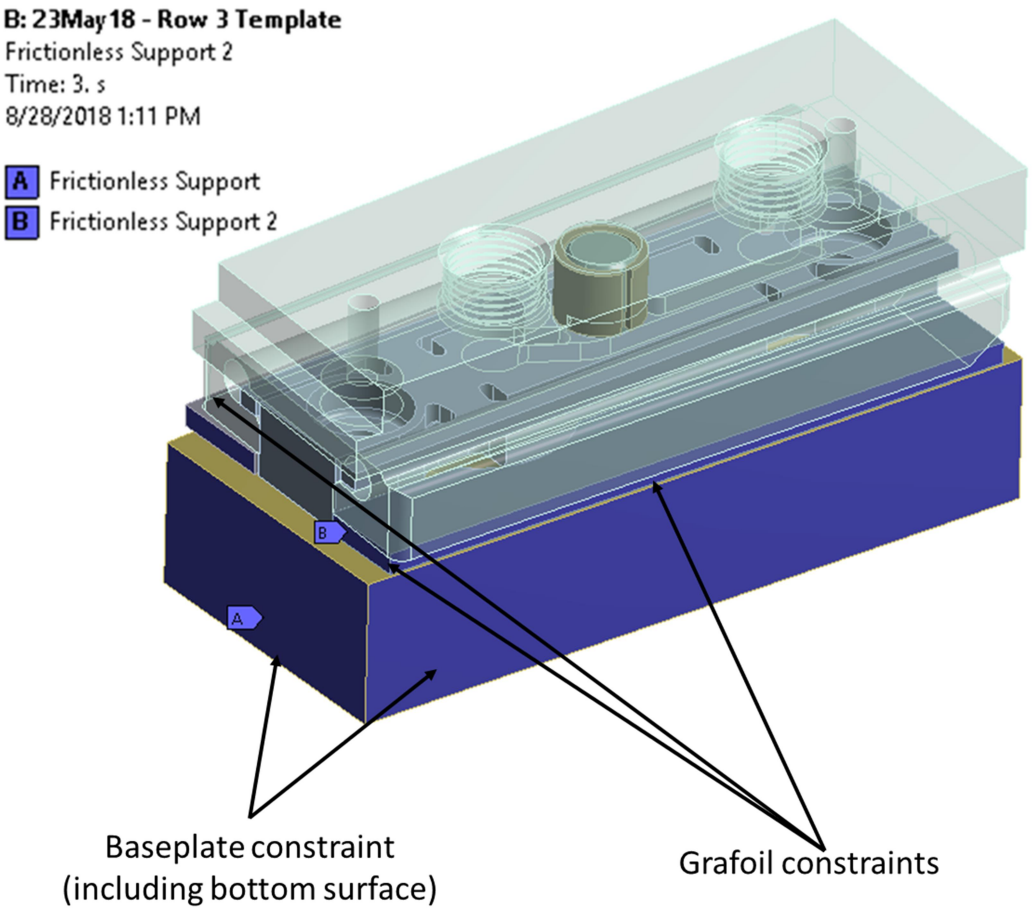


Figure 29: Frictionless boundary condition locations on the baseplate, grafoil, and bolt hole.

The graphite tile is connected to the grafoil and Tbar through frictional contact with a coefficient of friction of 0.1. The grafoil pin insert is connected through frictional contact to the tile with a coefficient of friction of 0.01.
Figure 30 shows the surfaces in contact with each other labeled A through E.

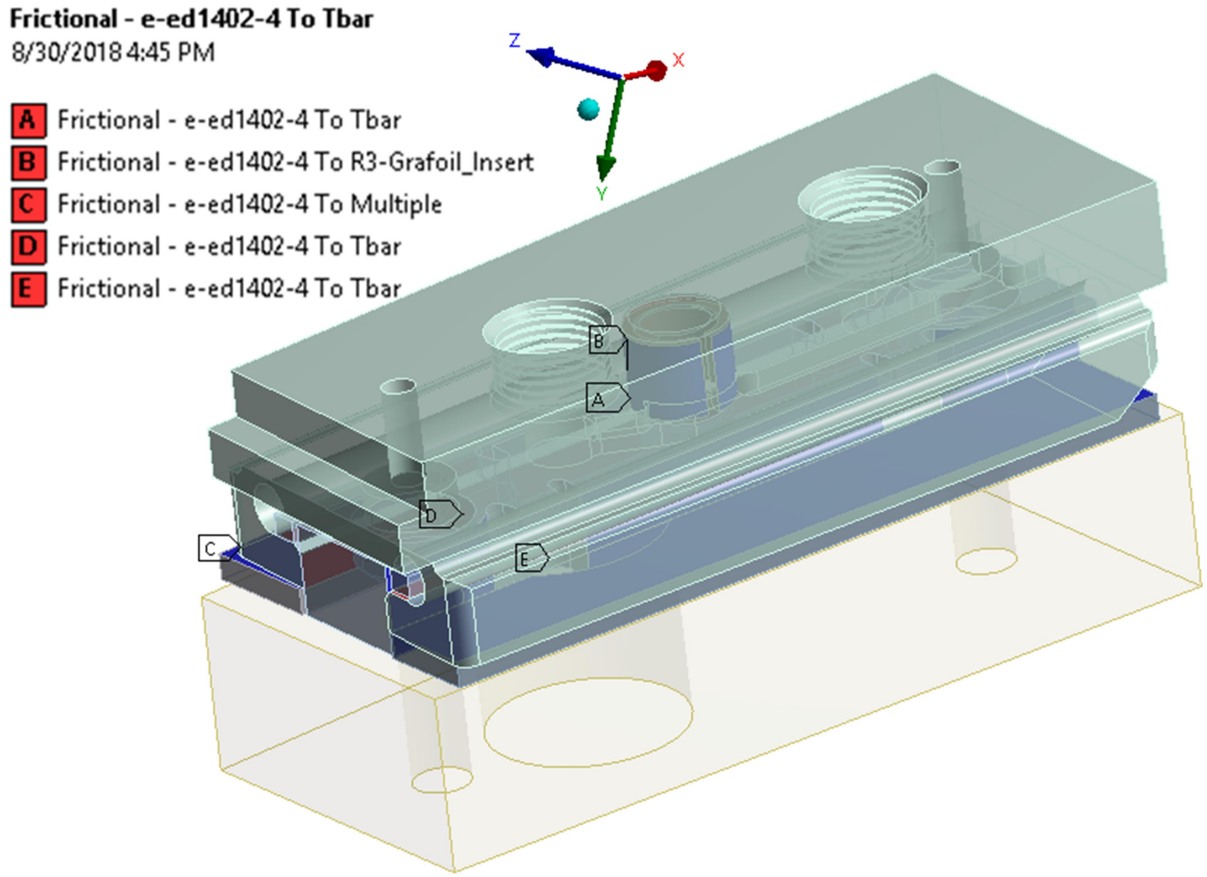


Figure 30: Frictional contact between the graphite tile and support structure.

The R45 pin is bonded to the Tbar. The contact between the R45 pin and R45-grafoil insert is frictional with a coefficient of friction of 0.01. The Tbar is in frictional contact with the baseplate with a coefficient of friction of 0.3. The grafoil and baseplate are in contact with the no separation condition.

Figure 31 shows the surfaces in contact with each other labeled A through D.

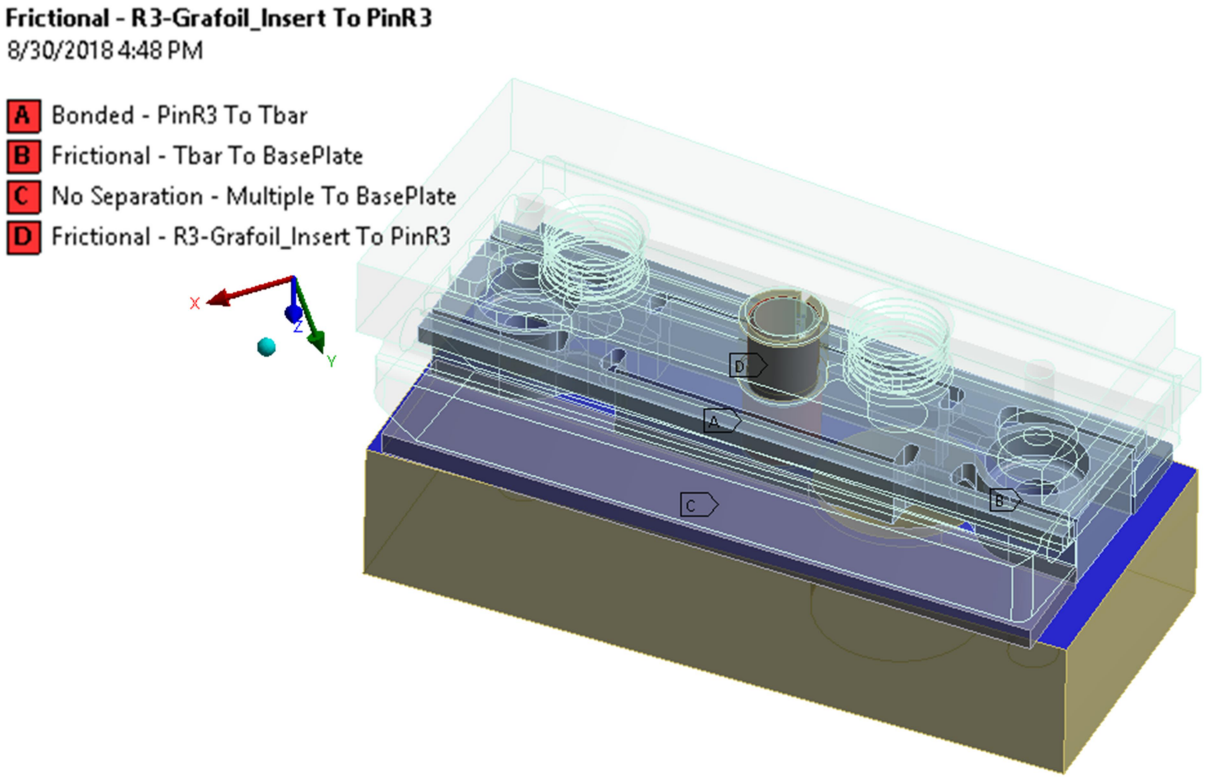


Figure 31: Frictional contact between the support structure.

Results

Total deformation contour plot of the assembly is shown in Figure 32. X, Y, Z deformation contour in the assembly is shown Figure 33, Figure 34, and Figure 35.

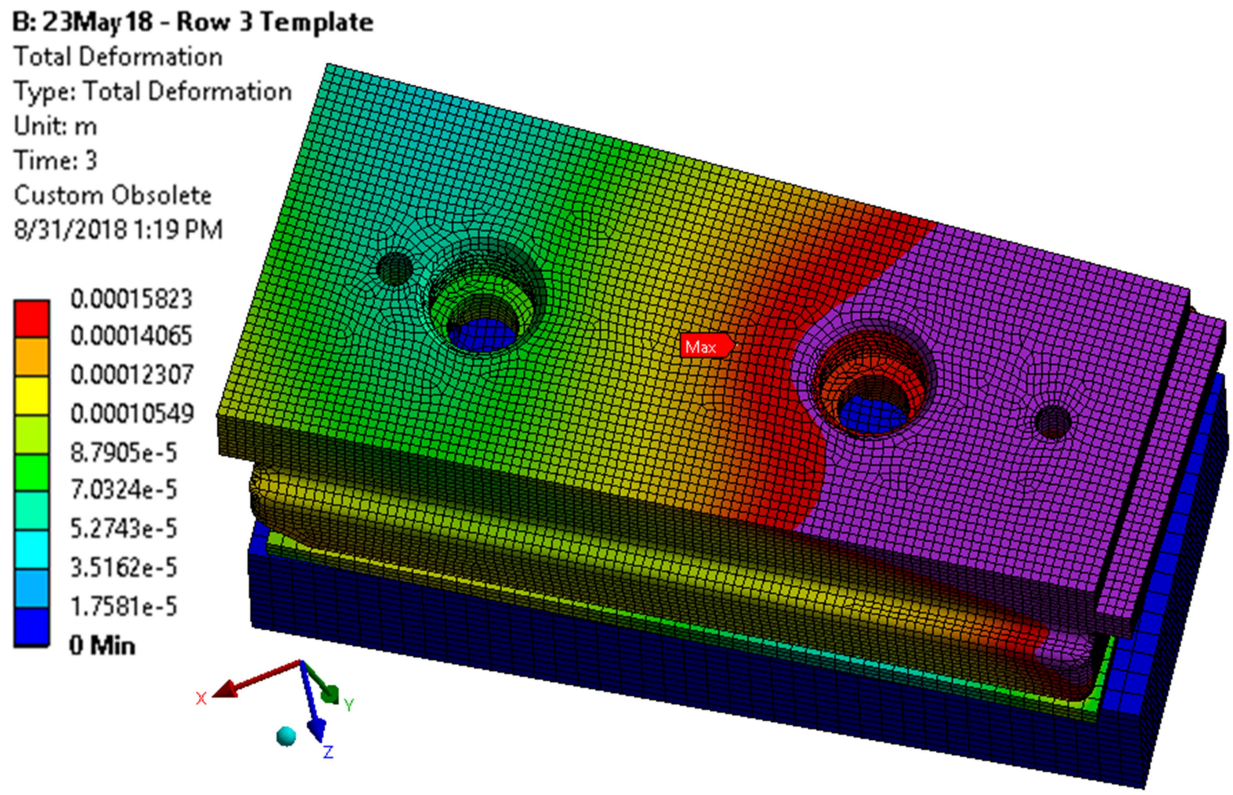


Figure 32: Total deformation of the assembly

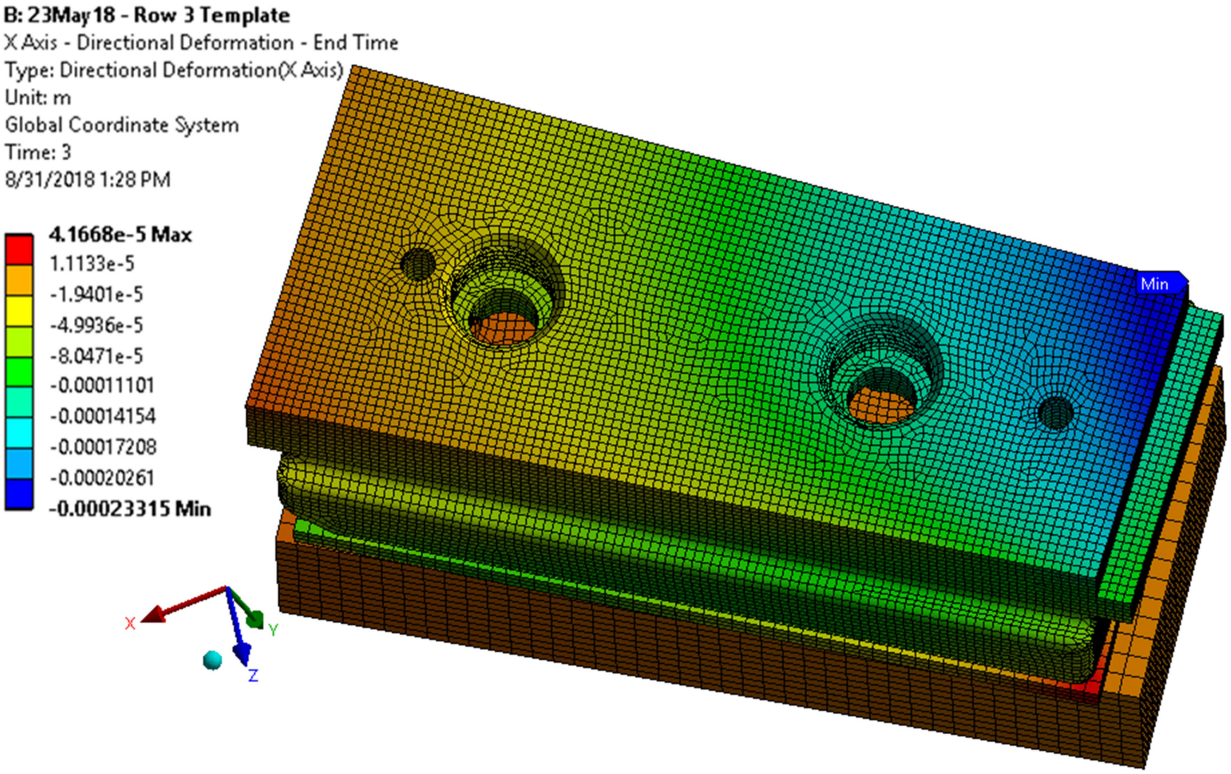


Figure 33: X-direction displacement

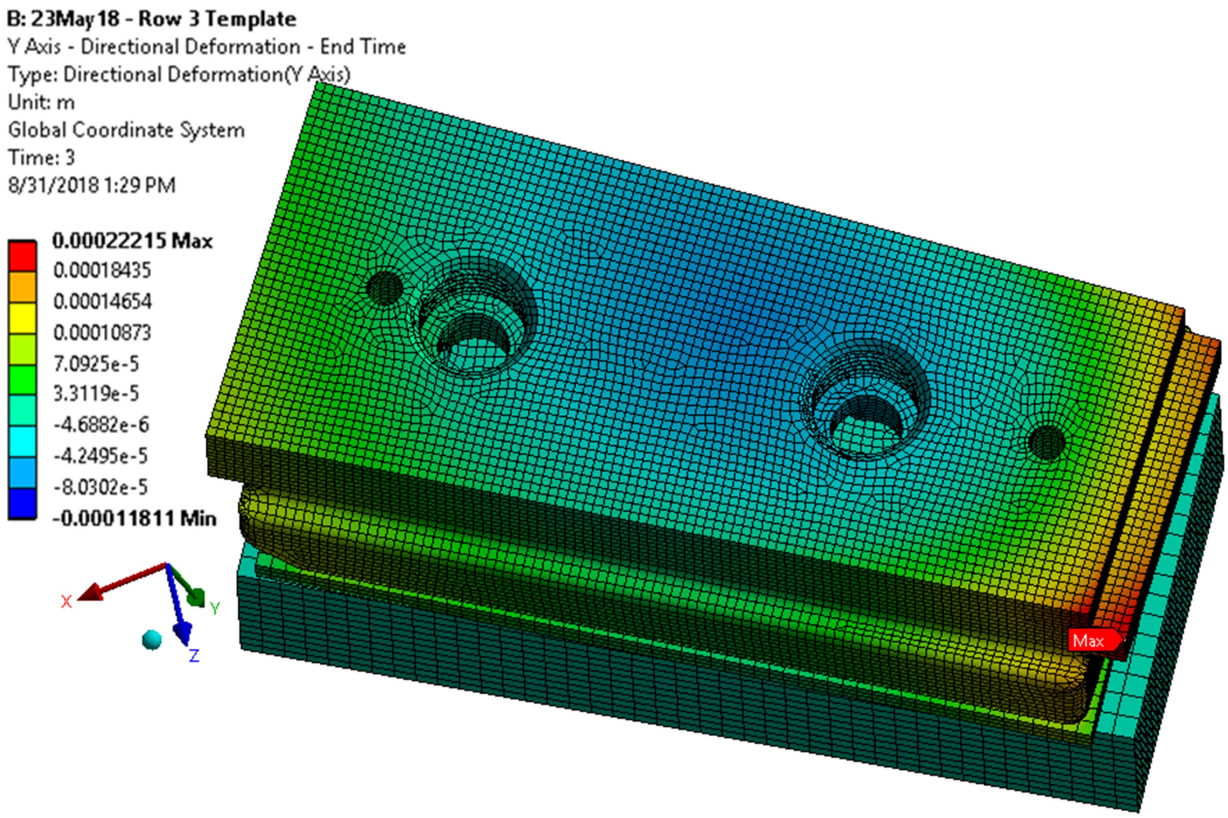


Figure 34: Y-direction displacement

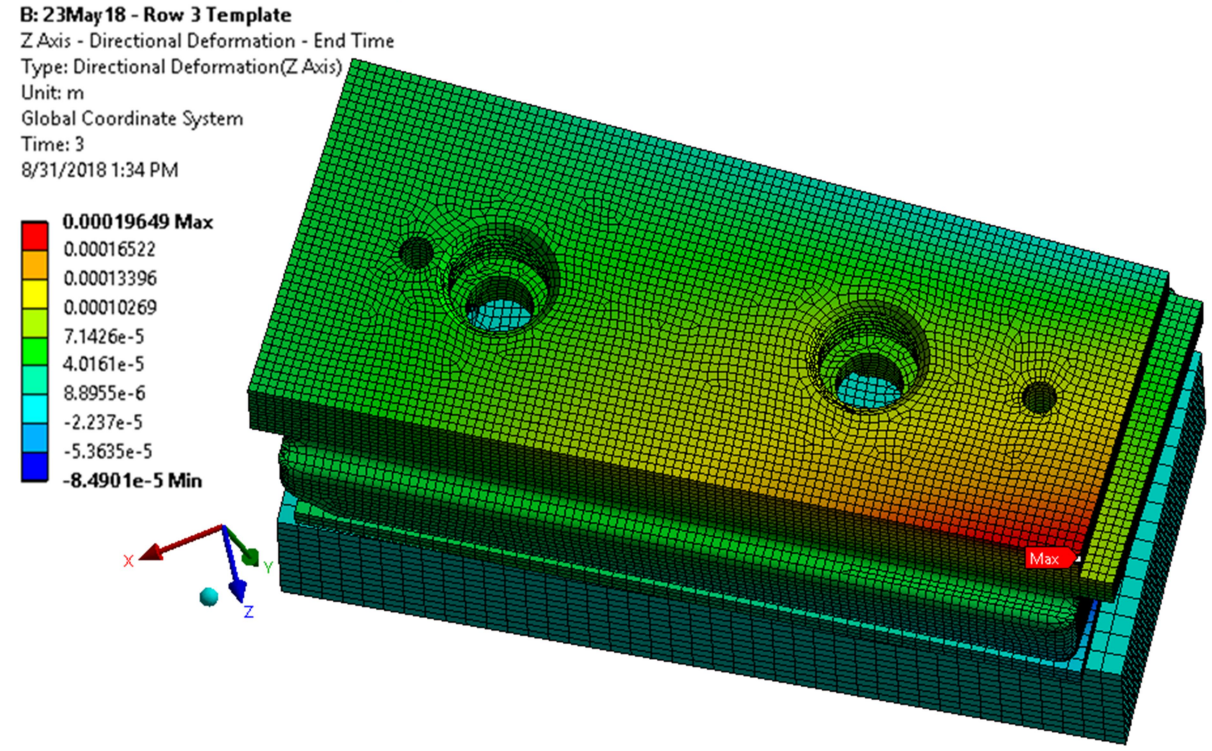


Figure 35: Z-direction displacement

Table 8 and Table 9 list the peak maximum and minimum principal stress and the corresponding allowable in the components made of graphite. Table 10 lists the peak equivalent stress and the corresponding allowable for the components made from metal. Note that BPL – bolt preload, Halo – halo forces, and Eddy – eddy current induced moment.

Table 8: Maximum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1402-4)	28.33	20	BPL+Halo
Graphite Tile – Tbar Slot	28.33	20	BPL+Halo
Graphite Tile – Shear Pin Hole	12.42	20	BPL+Halo+Eddy
Grafoil	1.26	20	BPL+Halo
R45-Grafoil Insert	1.95	20	BPL+Halo

Table 9: Minimum Principal Stress of Graphite Components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Graphite Tile (E-ED1402-4)	-82.93 (unchamfered hole)	-55	BPL+Halo
Graphite Tile – Tbar Slot	-15.54	-55	BPL
Graphite Tile – Shear Pin Hole	-35.71	-55	BPL+Halo
Grafoil	-2.3	-55	BPL+Halo
R45-Grafoil Insert	-2.45	-55	BPL+Halo+Eddy

Table 10: Equivalent Stress of metallic components

Component	Peak Stress (MPa)	Allowable (MPa)	Load Step
Baseplate	33.68	??	BPL+Halo
R45 Pin	23.11	??	BPL+Halo+Eddy
Tbar (ED1414-2 R4)	186.94	261	BPL+Halo

The tbar slot stress in the tile exceeded its allowable. All other stress values were below their respective allowables. Figure 36 shows the location of the peak minimum principal stress with bolt preload and the halo load. The location of maximum principal stress with bolt preload and the halo load is shown in Figure 37. The location of peak equivalent stress with bolt preload and the halo load is shown in **Figure 38**.

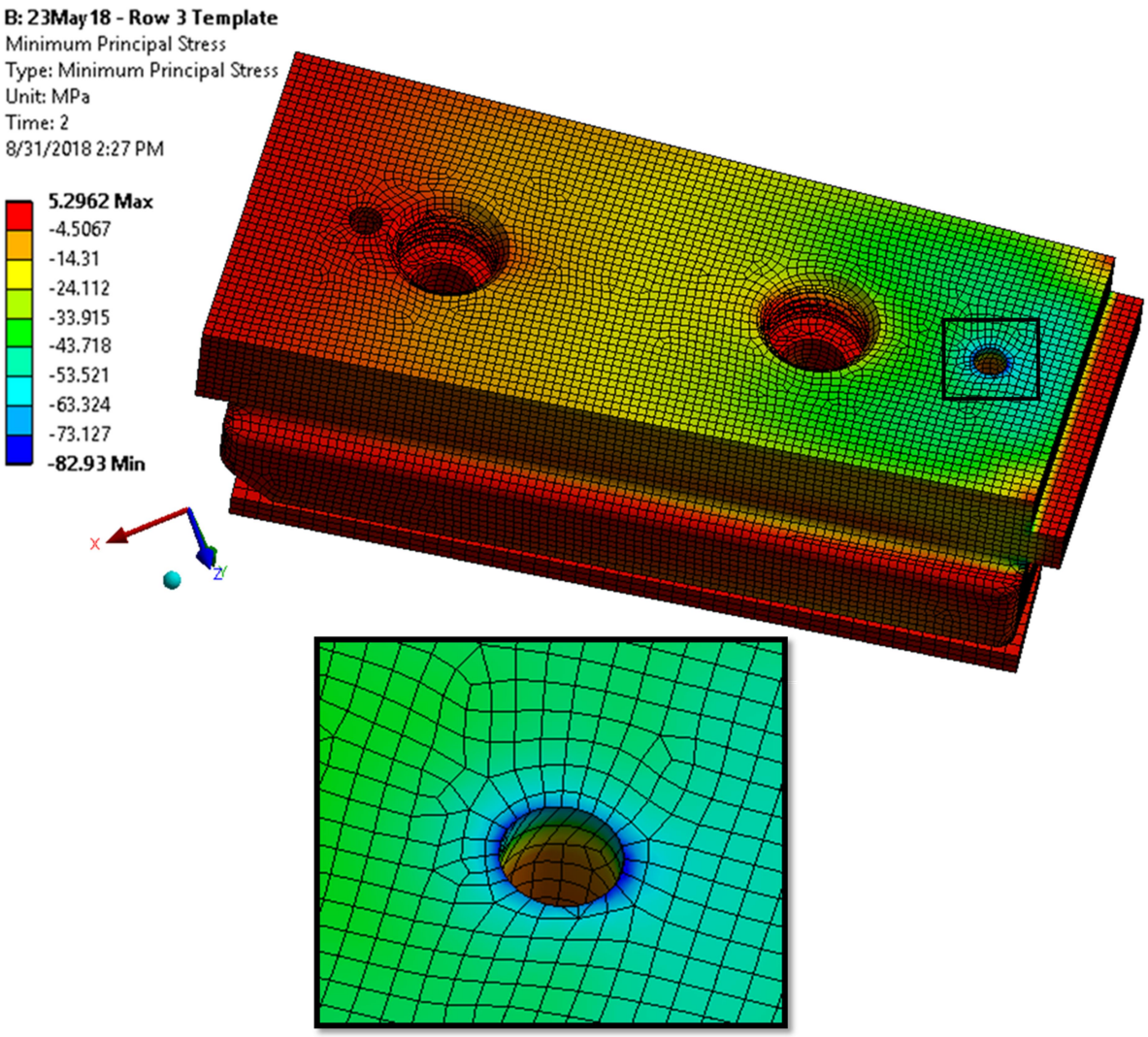


Figure 36: Location of peak minimum stress in OBD Row 3 style 2 -10

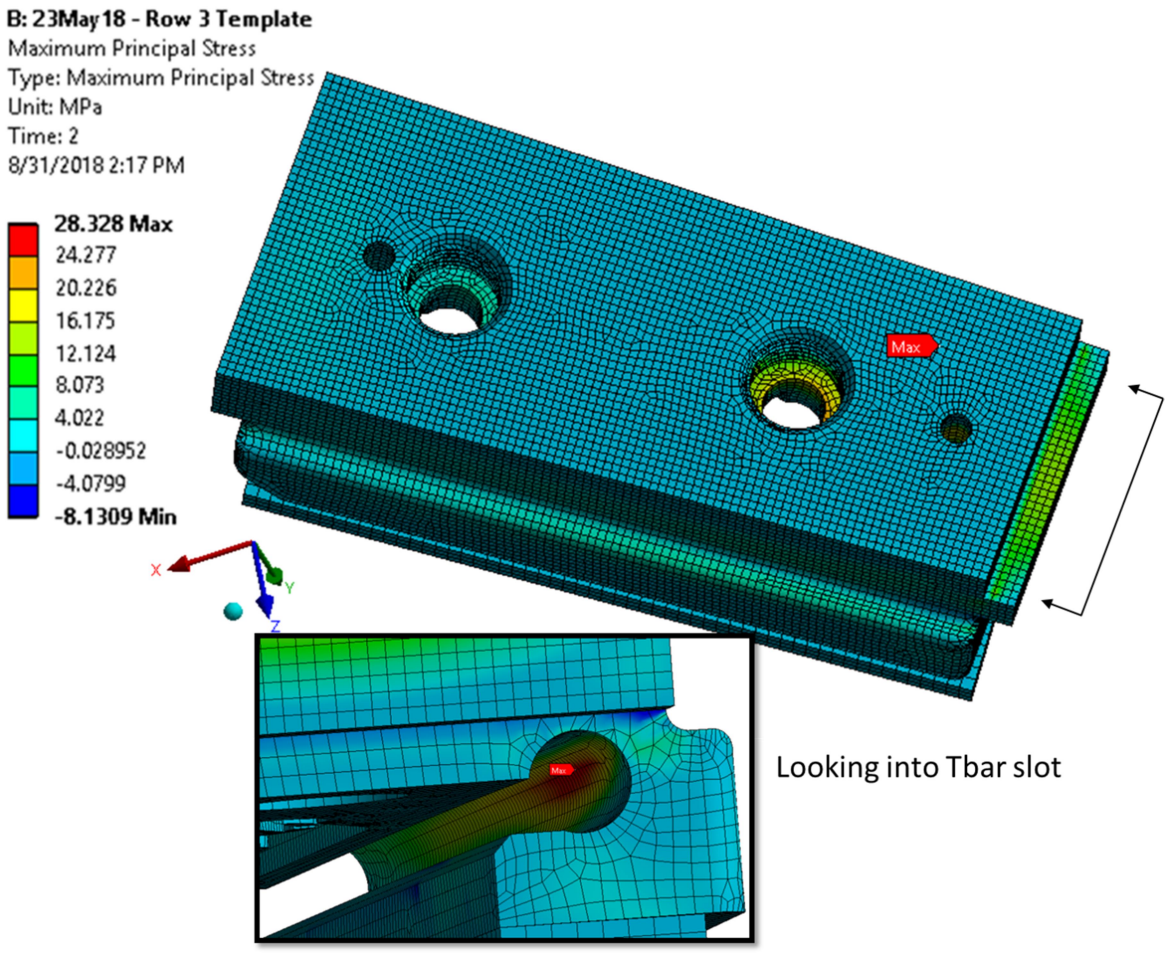


Figure 37: Location of peak maximum principal stress.

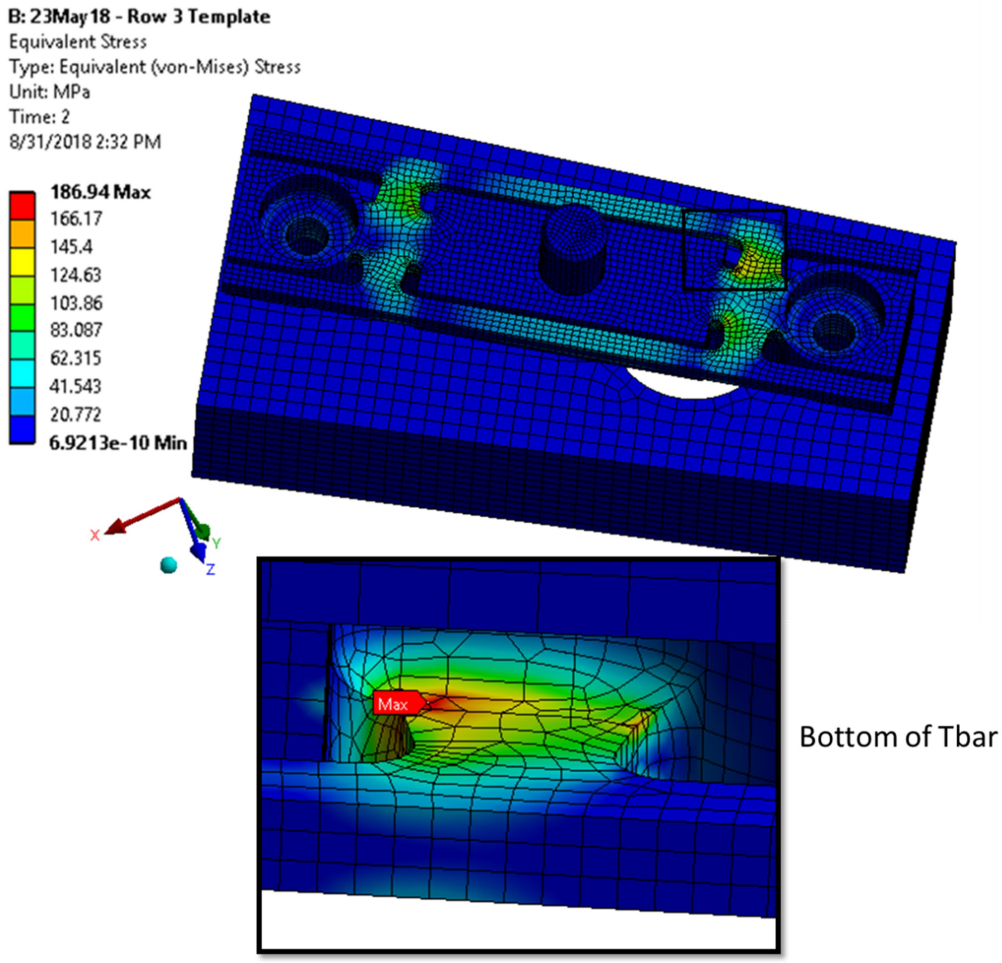
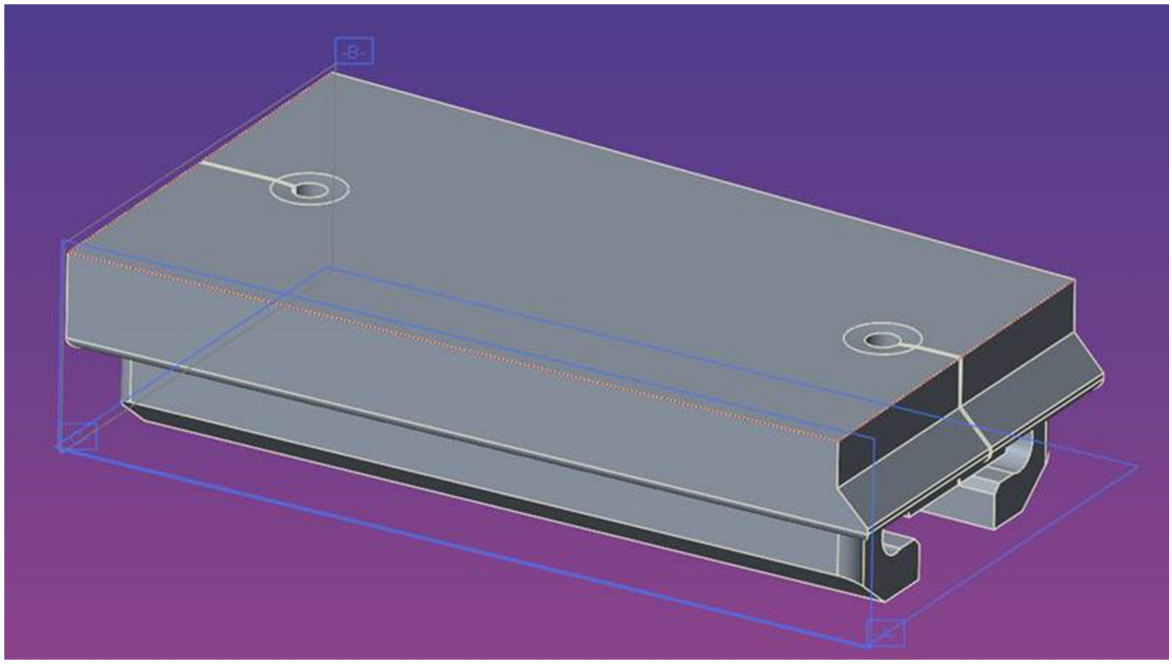


Figure 38: Location of peak equivalent stress for combined loading.

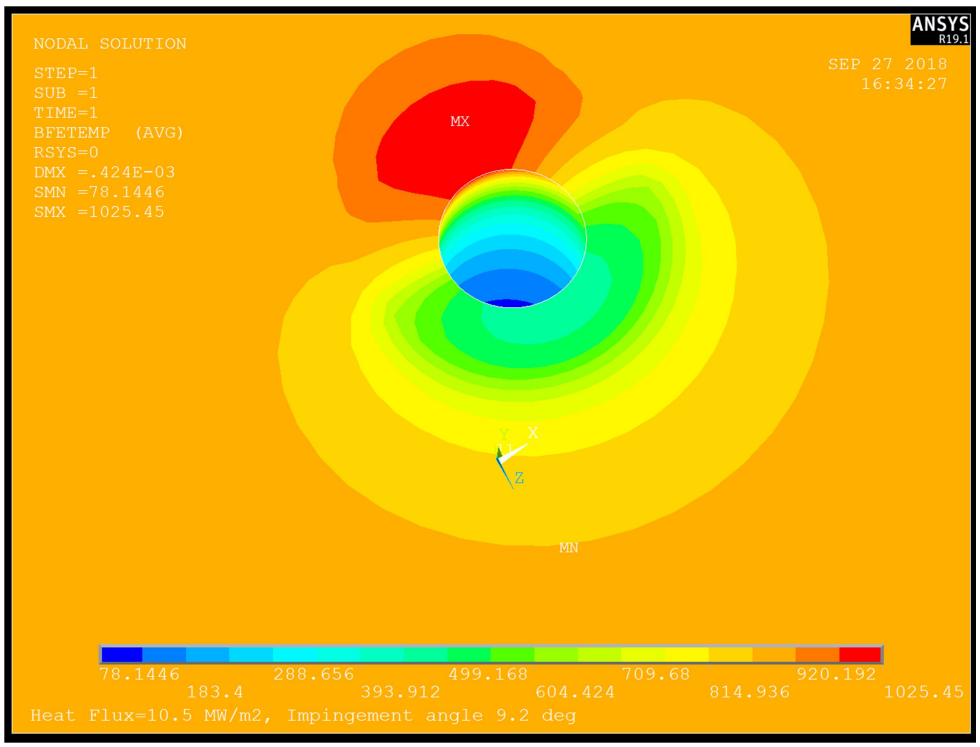
6 Row 3 Bolt Access Hole Chamfer Calculation

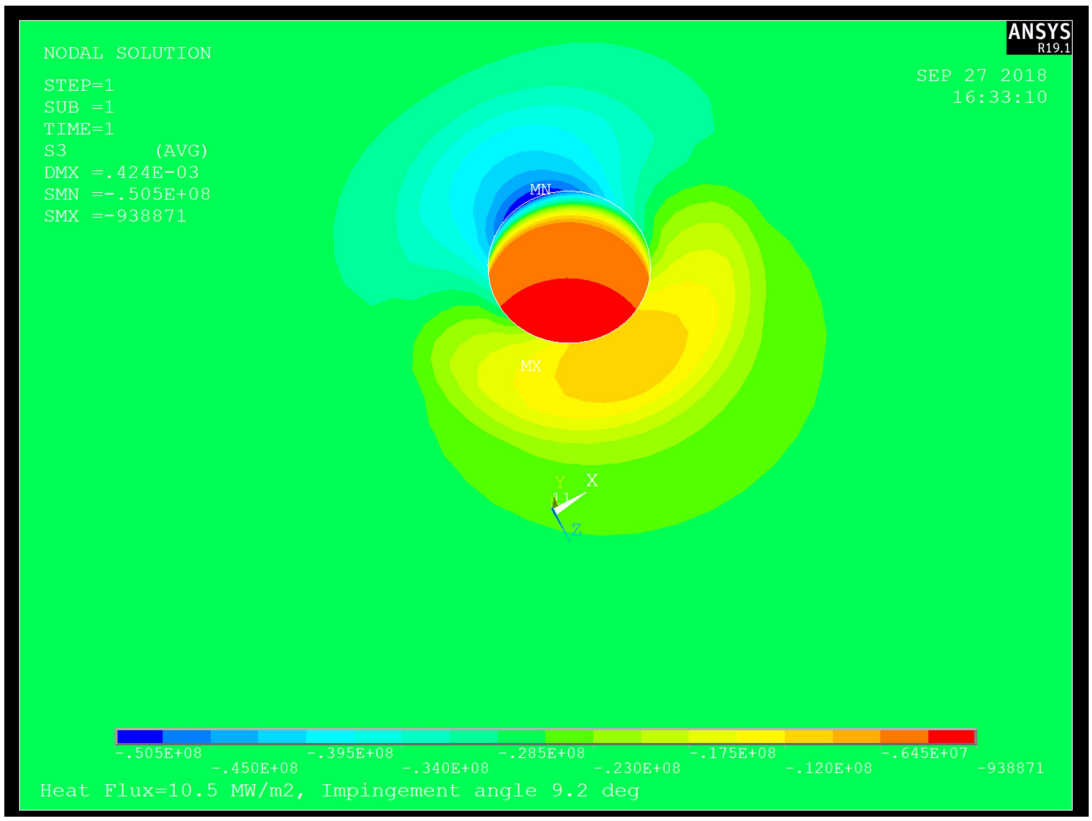
The analysis contained within this report did not include any chamfers on the edges around the row 3 bolt access holes. Subsequent to these analyses, a 4.96 degree chamfer having length 0.11 inch was incorporated onto the surface around the bolt access holes of all row 3 tiles. This chamfer is reflected on the drawings for row 3 tiles E-ED1402 and E-ED1403. A picture of the finalized design of row 3 tiles is given below where the chamfers incorporated can clearly be seen.



The chamfer was validated by running a 2D APDL script. The results are shown below.

The maximum temperature on the chamfer is 1205C and the minimum principle stress is -50.5 MPa as shown below.


NODAL SOLUTION
STEP=1
SUB =1
TIME=1
BFETEMP (AVG)
RSYS=0
DMX =.424E-03
SMN =78.1446
SMX =1025.45
ANSYS
R19.1
SEP 27 2018
16:34:27
MX
MN
78.1446
183.4
288.656
393.912
499.168
604.424
709.68
814.936
920.192
1025.45
Heat Flux=10.5 MW/m2, Impingement angle 9.2 deg


NODAL SOLUTION
STEP=1
SUB =1
TIME=1
S3 (AVG)
DMX =.424E-03
SMN =-.505E+08
SMX =-938871
ANSYS
R19.1
SEP 27 2018
16:33:10
MN
MX
-.505E+08
-.450E+08
-.395E+08
-.340E+08
-.285E+08
-.230E+08
-.175E+08
-.120E+08
-.645E+07
-938871
Heat Flux=10.5 MW/m2, Impingement angle 9.2 deg