**Calculation No: NSTXU-CALC-11-27-00 Revision No: 00**

# *Thermal, Halo, and Structural Analysis of OBD Row 1&2 Tiles*

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

Qualify OBD Row 1&2 tiles on final design review of Plasma Facing Components for the NSTX-U recovery project.

Codes and versions: (List all codes, if any, used)

ANSYS 19.0

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.
7. Global Heat Balance Calculations, NSTXU-CALC-10-6-00, Han Zhang, July 2018.
8. NSTXU-CALC-11-06-00, Analysis of OBD Row 2 High-Z Tiles, Art Brooks, March 4, 2016.
9. NSTXU-CALC-11-09-00, Field Errors and Heat Flux Enhancement, Art Brooks, January 12, 2018.
10. High Heat Flux PFC OBD12 PDR, Robert Ellis, November 15, 2017.
11. NSTX-U 2D global heat balance model and some preliminary results, Han Zhang, 2017.
12. NSTXU-CALC-11-24-00, The fashscaling factors, Bob Ellis, September, 2018.
13. NSTXU-CALC-11-29-00, Tile Hold Down Rod Submodel, Bob Ellis, September, 2018.
14. NSTXU-CALC-11-23-00, OBD12 Halo Restraints, Bob Ellis, September, 2018.
15. Drawings 0EED1408, NSTX PFC OBD Row 1&2 Assembly and Part Details.
16. Drawings, RE-Test Block Rod, Part Details.

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

Assume that all the OBD12 tiles without cooling underneath should have the repetition period of 40 minutes.

Calculation (Calculation is either documented here or attached)

The transient thermal with faceted fishscaling factors and structural models with halo and eddy loads have been analyzed to check the design qualification of OBD12 tiles. See the attached report for details.

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

The final design of OBD Row 1&2 tiles can meet the system requirements on the Plasma Facing Components.

Robert Ellis Digitally signed by Robert Ellis Date: 2018.10.01 08:31:35 -04'00'

Cognizant Individual (or designee) name: Robert Ellis________________________(sign and date)

Jiarong Fang Digitally signed by Jiarong Fang Date: 2018.09.27 10:26:12 -04'00'

Preparer's name: Jiarong Fang________________________(sign and date)

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

Han Zhang Digitally signed by Han Zhang Date: 2018.09.27 10:57:25 -04'00'

Checker's name: Han Zhang________________________(sign and date)

# National Spherical Torus eXperiment - Upgrade

# NSTX-U

## Thermal, Halo, and Structural Analysis of OBD Row 1&2 Tiles

NSTXU-CALC-11-27-00

September 17, 2018

Jiarong Fang Digitally signed by Jiarong Fang Date: 2018.09.27 10:26:44 -04'00'

Prepared By
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Reviewed By
Han Zhang, Senior Analyst, Engineering Analysis Division

Robert Ellis Digitally signed by Robert Ellis Date: 2018.10.01 08:31:59 -04'00'

Reviewed By
Robert Ellis, Responsible Engineer, Diagnostics

Michael Jaworski Digitally signed by Michael Jaworski Date: 2018.09.28 23:51:32 -04'00'

Approved By – Responsible Engineer
Michael Jaworski, RE, Plasma Facing Components

# NSTX-U CALCULATION

## Record of Changes

| Rev. | Date | Description of Changes | Revised by |
|---|---|---|---|
| 0 | 9/17/18 | Initial Release | |
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# Calculation of OBD12 Tiles

## NSTX-U Calculation Form

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

The original OBD Row 1&2 tiles could not meet the higher thermal requirements of NSTX-U project. The purpose of this calculation is to provide qualification of OBD Row 1&2 tiles on final design review of Plasma Facing Components for the NSTX-U recovery project.

### References:


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.
7. Global Heat Balance Calculations, NSTXU-CALC-10-6-00, Han Zhang, July 2018.
8. NSTXU-CALC-11-06-00, Analysis of OBD Row 2 High-Z Tiles, Art Brooks, March 4, 2016.
9. NSTXU-CALC-11-09-00, Field Errors and Heat Flux Enhancement, Art Brooks, January 12, 2018.
10. High Heat Flux PFC OBD12 PDR, Robert Ellis, 11/15/2017.
11. NSTX-U 2D global heat balance model and some preliminary results, Han Zhang, 2017.
12. NSTXU-CALC-11-24-00, The fashscaling factors, Bob Ellis, September, 2018.
13. NSTXU-CALC-11-29-00, Tile Hold Down Rod Submodel, Bob Ellis, September, 2018.
14. NSTXU-CALC-11-23-00, OBD12 Halo Restraints, Bob Ellis, September, 2018.
15. Drawings 0EED1408, NSTX PFC OBD Row 1&2 Assembly and Part Details.
16. Drawings, RE-Test Block Rod, Part Details.


### Assumptions:

These are discussed throughout the attached report.

### Calculation:

See attached Report.

### Conclusion:

The OBD Row 1&2 tiles have been analyzed. The halo and disruption eddy-current loads are included in the analysis model. The rod and key submodels are used to further verify the detailed design features to survive with the high heat flux pulse of plasma. The final design of OBD Row 1&2 tiles can meet the system requirements on the Plasma Facing Components.

# Table of Contents

## 4.0 Executive Summary

This report is intended to provide transient thermal and structural analyses of OBD Row 1&2 tiles to designers of the plasma facing components for the NSTX-U recovery project.

The OBD Row 1&2 tiles with the 40minutes repetition rate of halo and disruption eddy-current loads have been analyzed. The simplified rod and key submodels can verify and resolve the over-stress issues with the rod contact area and the halo restraints on the keys, respectively. The final design of OBD Row 1&2 tiles can meet both thermal and structural requirements on the Plasma Facing Components.

## 5.0 Introduction

The original OBD Row 1&2 tiles could not meet the higher thermal requirements of NSTX-U project. Therefore, the OBD12 tiles need to be redesigned.

## 5.1 OBD12 Tiles

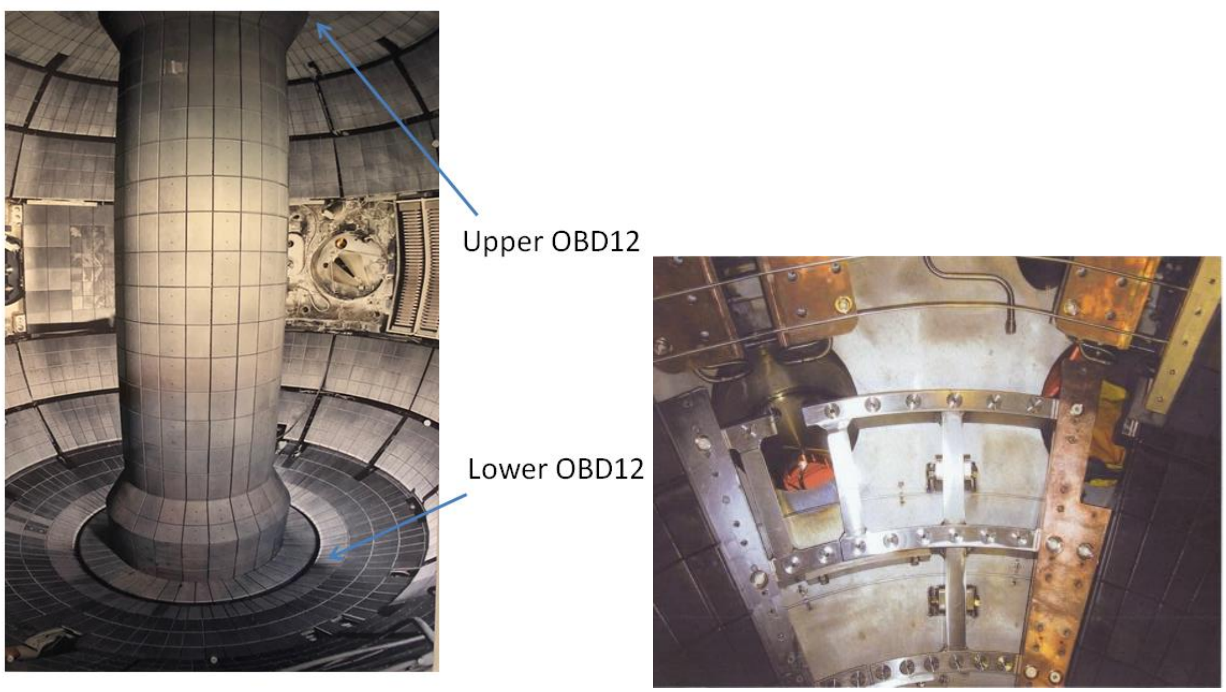



Figure 5.0-1 The original OBD Row 1&2 Tiles and underneath mounting BBQ rails without cooling.

Figure 5.0-1 shows the original OBD12 tile locations on both upper and lower portions of NSTX-U tokomak and underneath mounting structure without cooling. As described in the PFC GRD file [1-2], the OBD tiles are used to protect the outboard divertors from the plasma, and also protect the plasma from impurities generated by that surface. The OBD 1 &2 tiles are primary high-heat flux handling surface for H-mode plasmas.

## 5.2 Halo and Eddy

| Tile | | Geometry | | | Currents | | | Fields | | | Forces at Strike Point | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ` Geometry, m | | | Current, amps | | | Field, T | | | Force, N | | | |
| Row | | Width | Thick | Length | Itf | Inorm | Ipara | Btf | Bnorm | Bpara | Ftf | Fn, Pusł | Fn, Pull | Fpara |
| IBDhs | 1 | 0.065 | 0.038 | 0.166 | 1202 | 24208 | 284 | 1.87 | 0.84 | 0.62 | 570 | 0 | 0 | 1719 |
| IBDvs | 2 | 0.105 | 0.023 | 0.115 | 879 | 9583 | 600 | 2.34 | 0.53 | 1.11 | 246 | 0 | 0 | 515 |
| IBDvs | 3 | 0.105 | 0.023 | 0.102 | 779 | 8500 | 600 | 2.34 | 0.55 | 1.30 | 253 | 0 | 0 | 457 |
| OBD | 1 | 0.088 | 0.025 | 0.150 | 125 | 21875 | 44 | 1.39 | 0.74 | 0.94 | 514 | 0 | 0 | 763 |
| OBD | 2 | 0.104 | 0.025 | 0.120 | 100 | 17529 | 44 | 1.17 | 0.64 | 1.12 | 492 | 0 | 0 | 513 |
| OBD | 3 | 0.120 | 0.025 | 0.126 | 105 | 18360 | 44 | 1.02 | 0.89 | 1.23 | 566 | 0 | 0 | 469 |

Table 5.0-1 The estimation of halo forces from Art Brooks

Table 5.0-1 list the estimation of halo forces from Art Brooks [3]. The halo current is assumed to flow normal to tile, and the currents resistively share with mounting local structure. The PF fields are calculated through scanning 96 scenarios. Note that halo loads on the table are based on the tile thickness per inch, so the real input data should multiply the thickness of tiles. Table 5.0-2 shows the calculated eddy current moments of the worst case of 5 GRD disruptions. All the eddy current loads are calculated using the real size of tile.

| | | ` | Geometry (m) | | | Eddy Current Loop (amps) | | | | Field (T) | | Torque (N-m) | | | Equivalent Edge Load (N)+/- | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Row | Width | Thick | Length | Angle | Normal | Parallel | | Btf | Bnorm | Bpara | Ttf | Tnorm | Tpara | TF | PF |
| IBDhs | 1 | 0.0654 | 0.076 | 0.166 | 0 | 1597 | 740 | 0 | 1.87 | 0.84 | 0.62 | 13.83 | 6.88 | 32.42 | 83 | 495 |
| CSFW | 14 | 0.0798 | 0.019 | 0.142 | 90 | 91 | 398 | 0 | 3.06 | 0.11 | 2.10 | 2.23 | 1.85 | 3.16 | 16 | 40 |
| OBD | 1 | 0.0877 | 0.0485 | 0.15 | 21.5 | 1430 | 1400 | 0 | 1.39 | 0.74 | 0.94 | 22.10 | 8.31 | 26.24 | 147 | 299 |
| OBD | 2 | 0.1045 | 0.0485 | 0.1202 | 21.5 | 1373 | 1543 | 0 | 1.17 | 0.64 | 1.12 | 24.39 | 9.16 | 20.18 | 203 | 193 |
| OBD | 3 | 0.1196 | 0.025 | 0.1259 | 21.5 | 803 | 1018 | 0 | 1.02 | 0.89 | 1.23 | 17.63 | 3.11 | 12.37 | 140 | 103 |

Table 5.0-2 The calculation of eddy loads based on the data from Art

# 6.0 Design Input

## 6.1 Criteria

The NSTX Structural Design Criteria Document [4] defines the stress criteria for different structural materials. For the graphite materials, the allowable design stress shall be limited to 1/2 of ultimate tensile and 1/2 of the ultimate compressive stress. For the metal support structure materials, the basic stress limits should not exceed the design Tresca stress value, which is lesser of 2/3 of the minimum specified yield or 1/2 of the minimum tensile strength. Also for bolting materials, the local peak stress shall not exceed 1.5 of the design Tresca stress.

## 6.2 Assumptions

The document of GRD Systems (NSTX-U-RQMT-GRD-001-02) [1] requires following assumptions for the pulse duty cycle. At the full rated pulse length, the repetition period shall be 40 minutes, but upgradeable to 20 minutes via modification and upgrades to components outside the tokamak core. Plasma pulses with shorter duration may be performed at a more rapid rate, consistent with the cooling of the coils and in-vessel components. Since OBD12 do not have the cooling system underneath, all the OBD12 tiles inside the tokamak chamber shall be designed for the duty cycle of 40 minutes.

| Near OBD (aka R1,R2) | Case # -> | 1 | 2 | 3 |
|---|---|---|---|---|
| Range of Application | m | R < 0.7 | R < 0.7 | 0.70 < R < 0.81 |
| Extent | cm | 13 | 10 | full |
| Max Angle | degrees | 1.0 | 5.0 | 4.4 |
| Min Angle | degrees | 1.0 | 5.0 | 2.6 |
| Heat Flux | $MW/m^2$ | 5.4 | 5.4 | 3.3 |
| Duration | sec | 1.5 | 5 | 5 |
| Reference Scenario | --- | 'Spillover' for stationary large poloidal flux expansion | 'Spillover' for High Ip/Bt Long Pulse Swept Case | Swept Case on OBD |

Table 6.0-1: Heat fluxes on the OBD Row 1 & 2 tiles (from ***Table 4.4-1 in SRD [5]***)

As listed on Table 6.0-1, the PFC SRD [5] defines the heat fluxes with Cases 1, 2, and 3 on the OBD Row 1 & 2 tiles. Considering the fishscaling factors and chamfering, the OBD12 tiles will be calculated and verified with each case under the worst conditions. The tile temperature at the end of the pulse (EOP) should not exceed 1600 deg C on the surface and 2000 deg C at the edge.

## 6.3 Materials and Allowable

### Graphite Mechanical Properties

After the material down selection, we choose the Sigrafine 6510 as the first priority with POCO TM as a backup. Table 6.0-2 shows the allowable data of two potential graphites and mounting rods.

| Material | Modulus (GPa) | Poisson's Ratio | Allowable S1 (MPa) | Allowable S3 (MPa) |
|---|---|---|---|---|
| Sigrafine 6510 | 11.5 | 0.3 | 19 | -65.0 |
| POCO TM | 10.5 | 0.3 | 20.5 | -55.0 |
| 316 Stainless Steel | 193 | 0.3 | 289 | |

Table 6.0-2. The material properties with allowable.

# 7.0 Modelling

## 7.1 Fishscaling Thermal Models

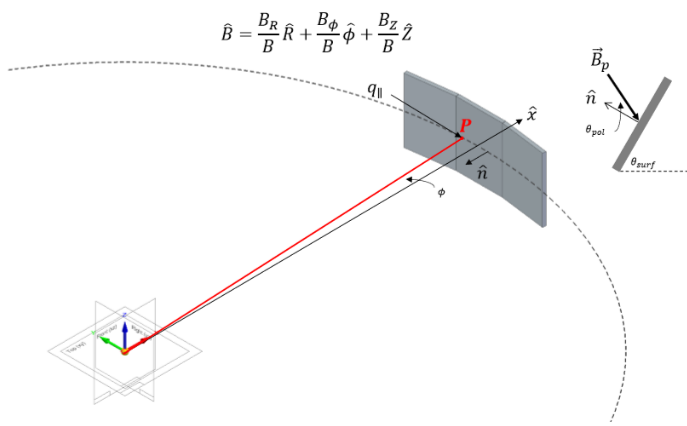



Figure 7.0-1 The scheme for a vertical plate, faceted divertor (from Reinke [6])

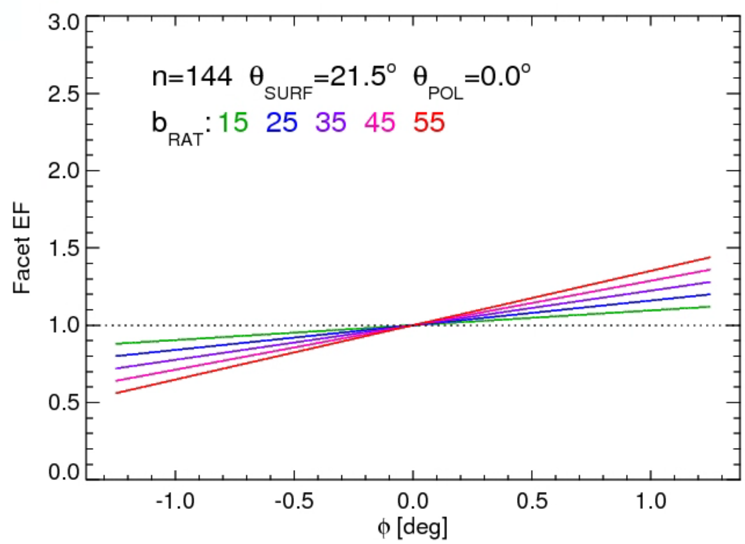
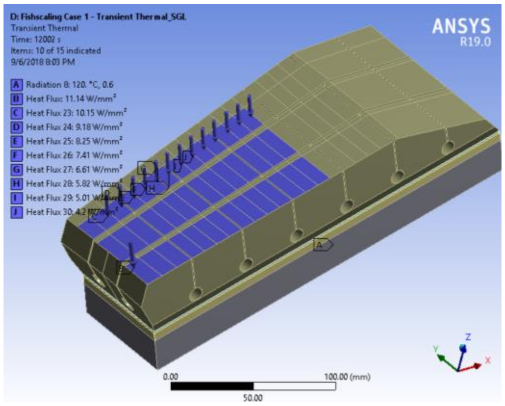



Figure 7.0-2 Faceting Enhancement Factors for OBD12 with angles of incidence from Reinke

As shown in Figure 7.0-1, Reinke Memo [6] describes the faceting issue with the OBD12 tiles due to the b_hat dot n_hat from the axisymmetric plasma and the non-axisymmetric surface. Figure 7.0-2 shows the faceting analysis run for the each faceted constellation. Roughly the angle is atan(1/(b_rat))*180/pi, and at the shallow field line angles the enhancement is increased by 0.3-0.4. The OBD12 tiles also need the fishscaling angle to avoid edge over-heated by the heat flux at the max shallow toroidal angle, so at the worst min impingement angle, the shadowing of the tile constellation by its neighbor will increase the enhancement factors.

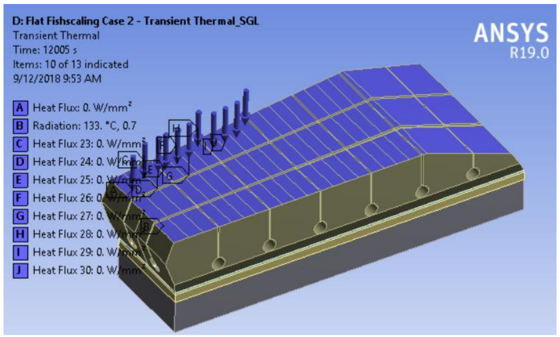
# Calculation of OBD12 Tiles

Figures 7.0-3, 4 and 5 show the thermal models with the fishscaling enhancement factors of OBD12 for Case 1, 2, and 3, respectively. As a quick check, we assume the enhancement factor will be linearly increased by 0.4 as described in the faceting enhancement factors tables for each case.



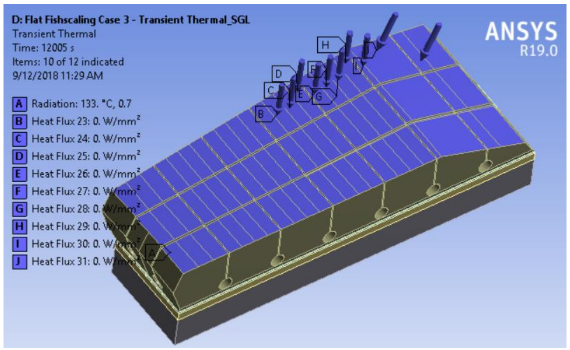

| Flat Fishscaling OBD12 Flux | | | | | | |
|---|---|---|---|---|---|---|
| Case 1 | | | | | | |
| R_edges | | R_mp | Length | Theoretical Heat Flux | Enhancement Factor | Heat Flux Inputs |
| 0.58792 | | 0.5931 | 0.0104 | 5.1815 | 2.55 | 13.21 |
| 0.59832 | | 0.6034 | 0.01023 | 4.7481 | 2.54 | 12.04 |
| 0.60855 | | 0.6137 | 0.01023 | 4.3182 | 2.52 | 10.89 |
| 0.61878 | | 0.6235 | 0.0094 | 3.9058 | 2.51 | 9.79 |
| 0.62818 | | 0.6325 | 0.00869 | 3.5257 | 2.49 | 8.79 |
| 0.63687 | | 0.6412 | 0.00868 | 3.1608 | 2.48 | 7.84 |
| 0.64555 | | 0.6499 | 0.00867 | 2.7962 | 2.47 | 6.90 |
| 0.65422 | | 0.6589 | 0.0094 | 2.4166 | 2.46 | 5.94 |
| 0.66362 | | 0.6680 | 0.00869 | 2.0365 | 2.44 | 4.98 |
| 0.67231 | | 0.6767 | 0.00868 | 1.6716 | 2.43 | 4.06 |
| 0.68099 | | 0.6853 | 0.00867 | 1.3070 | 2.42 | 3.16 |
| 0.68966 | | 0.6944 | 0.0094 | 0.9274 | 2.41 | 2.23 |
| 0.69906 | | 0.7034 | 0.00868 | 0.5475 | 2.39 | 1.31 |
| 0.70774 | | 0.7121 | 0.00869 | 0.1826 | 2.38 | 0.43 |
| 0.71643 | | | | | | |

Figure 7.0-3 The Thermal Model with the Fishscaling Factors of OBD12 Case 1




| Flat Fishscaling OBD12 Flux | | | | | | |
|---|---|---|---|---|---|---|
| Case 2 | | | | | | |
| R_edges | | R_mp | Length | Theoretical Heat Flux | Enhancement Factor | Heat Flux Inputs |
| 0.58792 | | 0.5931 | 0.0104 | 5.1240 | 1.63 | 8.35 |
| 0.59832 | | 0.6034 | 0.01023 | 4.5765 | 1.63 | 7.44 |
| 0.60855 | | 0.6137 | 0.01023 | 4.0335 | 1.62 | 6.55 |
| 0.61878 | | 0.6235 | 0.0094 | 3.5126 | 1.62 | 5.69 |
| 0.62818 | | 0.6325 | 0.00869 | 3.0325 | 1.62 | 4.90 |
| 0.63687 | | 0.6412 | 0.00868 | 2.5716 | 1.61 | 4.15 |
| 0.64555 | | 0.6499 | 0.00867 | 2.1111 | 1.61 | 3.40 |
| 0.65422 | | 0.6589 | 0.0094 | 1.6316 | 1.61 | 2.62 |
| 0.66362 | | 0.6680 | 0.00869 | 1.1515 | 1.61 | 1.85 |
| 0.67231 | | 0.6767 | 0.00868 | 0.6905 | 1.60 | 1.11 |
| 0.68099 | | 0.6853 | 0.00867 | 0.2301 | 1.60 | 0.37 |
| 0.68966 | | 0.6944 | 0.0094 | | | |
| 0.69906 | | | | | | |
| 0.70774 | | | | | | |
| 0.71643 | | | | | | |

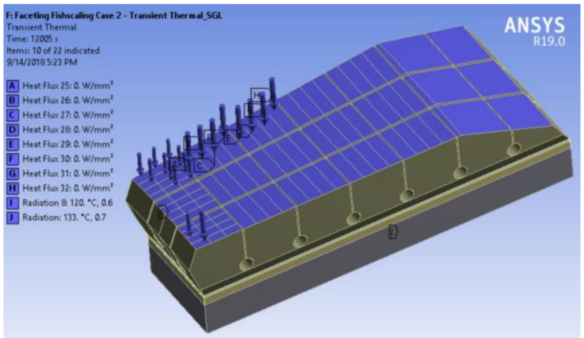
Figure 7.0-4 The Thermal Model with the Fishscaling Factors of OBD12 Case 2




| Flat Fishscaling OBD12 Flux | | | | | | |
|---|---|---|---|---|---|---|
| Case 3 | | | | | | |
| R_edges | | R_mp | Length | Theoretical Heat Flux | Enhancement Factor | Heat Flux Inputs |
| 0.69906 | | 0.7034 | 0.00868 | 3.3000 | 1.66 | 5.48 |
| 0.70774 | | 0.7121 | 0.00869 | 3.3000 | 1.66 | 5.47 |
| 0.71643 | | 0.7208 | 0.00867 | 3.3000 | 1.65 | 5.46 |
| 0.7251 | | 0.7298 | 0.00939 | 3.3000 | 1.65 | 5.44 |
| 0.73449 | | 0.7388 | 0.00869 | 3.3000 | 1.65 | 5.43 |
| 0.74318 | | 0.7475 | 0.00868 | 3.3000 | 1.64 | 5.42 |
| 0.75186 | | 0.7562 | 0.00867 | 3.3000 | 1.64 | 5.41 |
| 0.76053 | | 0.7630 | 0.005 | 3.3000 | 1.64 | 5.40 |
| 0.76553 | | 0.7828 | 0.03457 | 3.3000 | 1.63 | 5.39 |
| 0.8001 | | 0.8051 | 0.0099 | 3.3000 | 1.62 | 5.35 |
| 0.81 | | | | | | |

Figure 7.0-5 The Thermal Model with the Fishscaling Factors of OBD12 Case 3

Figures 7.0-6 show the thermal models with the modified faceted fishscaling factors of OBD12 for Case 2 according to fishscaling factor distribution toroidally as shown in Figure 7.0-2.




| R_mp | Faceting Enhancement | | | |
|---|---|---|---|---|
| Four Ranges | Low2 | Low1 | High1 | High2 |
| Factor | 0.93 | 1.13 | 1.33 | 1.53 |
| 0.5951 | 4.765322 | 5.790123 | 6.814923 | 7.839724 |
| 0.6034 | 4.256162 | 5.171466 | 6.08677 | 7.002073 |
| 0.6137 | 3.751198 | 4.557907 | 5.364617 | 6.171326 |

Figure 7.0-6 The Thermal Model with the modified Faceted Fishscaling Factors of OBD12 Case 2

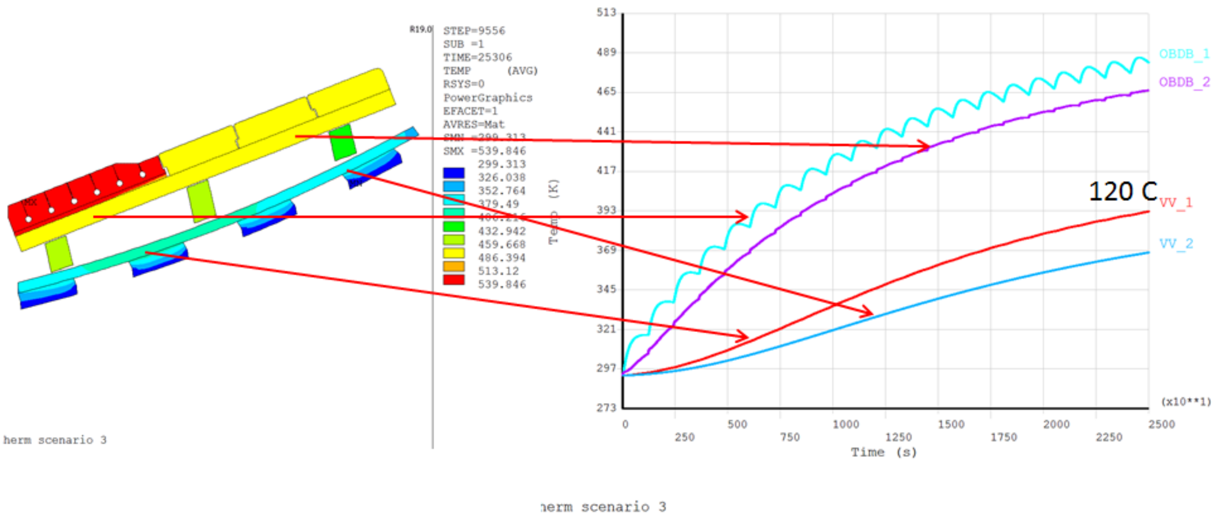



Figure 7.0-7 The temperature ratcheting of global model for OBD12 from Han Zang

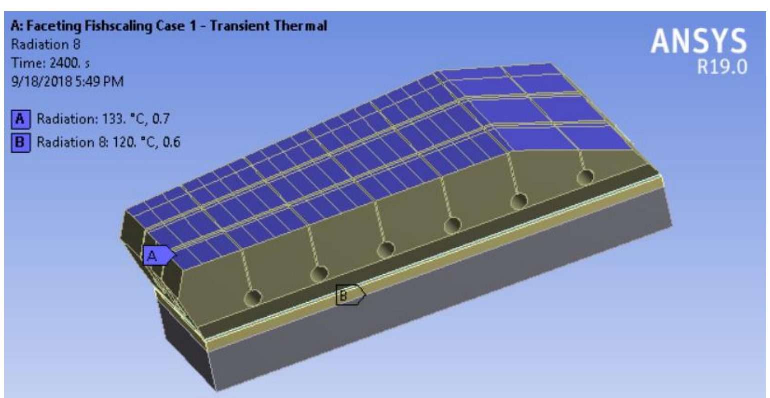



Figure 7.0-8 The radiation settings of the thermal model for OBD12

Based on the temperature ratcheting of global model for OBD12 from Han Zang [7], the ambient temperatures for the top and bottom surfaces of tiles will choose the average of transient temperature. The radiation settings are shown in Figure 7.0-8.

## 7.2 Combined Structural

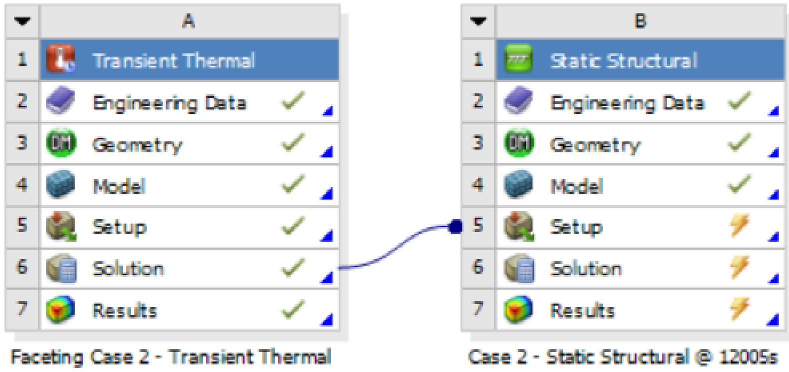



Figure 7.0-9 The combined structural model with the imported thermal loads

We need to analyze thermal and structural stresses of OBD12. As shown in Figure 7.0-9, before the structural analysis, we need to do the transient thermal analysis, and then choose the peak temperature distribution at the end of pulse (EOP) on the whole structure to map into the structural model as an imported load.

## 7.3 Rod and Key Submodels

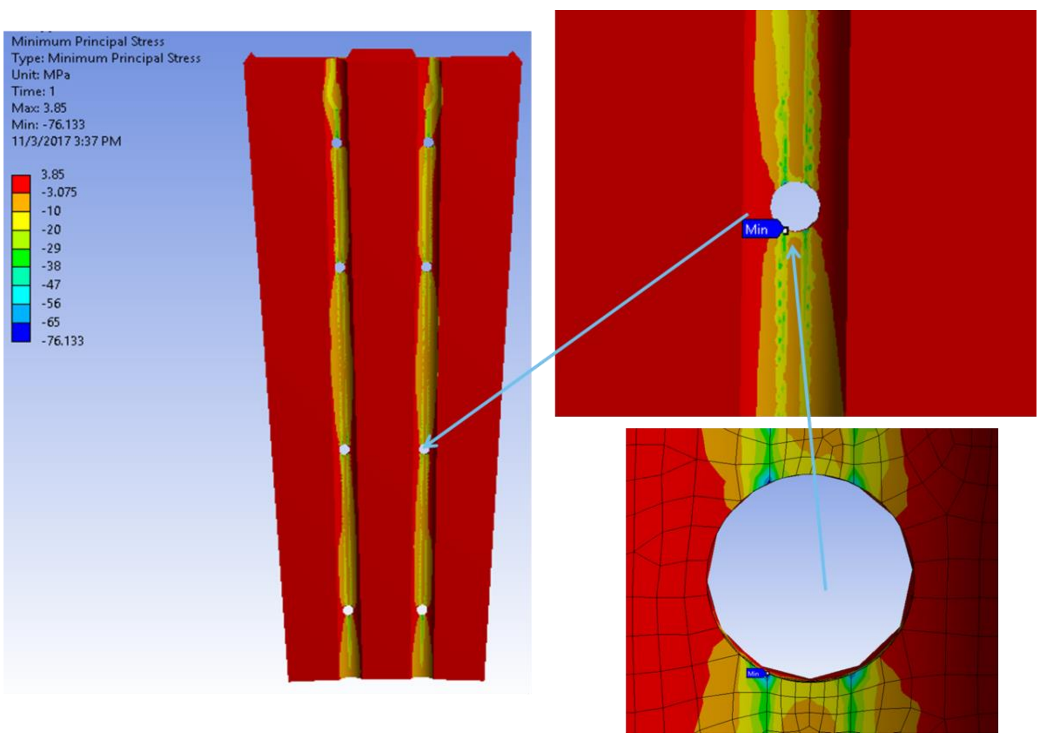



Figure 7.0-10. Minimum Principal Stress of Sigrafine R6510 from PDR analysis.

# Calculation of OBD12 Tiles

As shown in Figure 7.0-10, Stress analyses of the OBD Row 1-2 tiles presented at the November 2017 Preliminary Design Review [10] have high contact stresses where the hold-down rods cross the holes for their #8-32 screws. These stresses can be reduced by thinning the rods where they cross over the screw holes, thus shifting the contact area away from the edge of the hole.

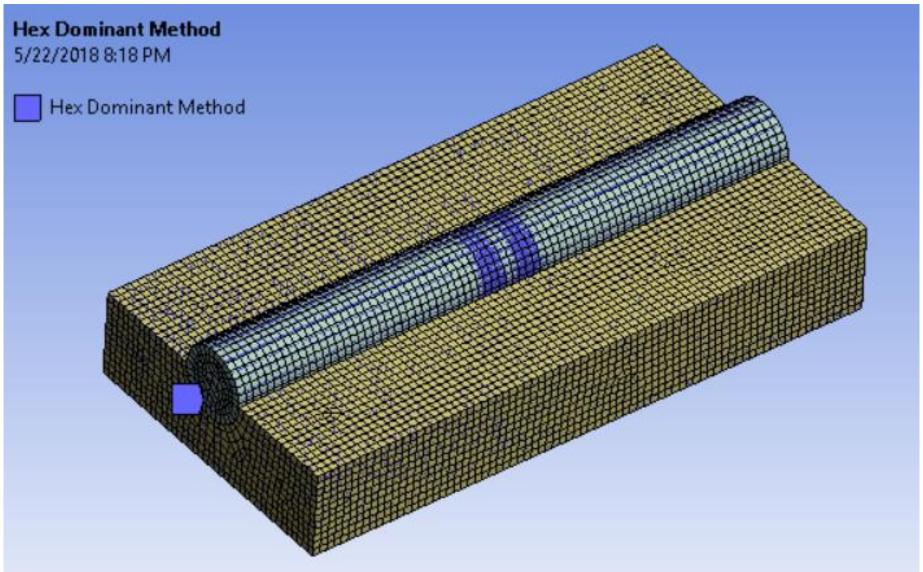



Figure 7.0-11. Workbench model of rod and graphite block

Figure 7.0-11 shows a tapered rod with a simple tile block to simulate a hold-down rod submodel. See attached Appendix B for detailed structure of rod submodel and see another calculation report [11].

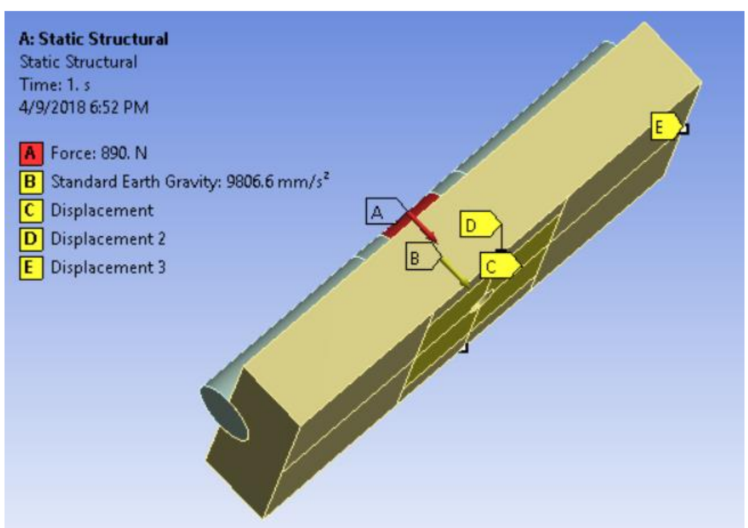



Figure 7.0-12. Boundary Conditions

As shown in Figure 7.0-12, the bottom surface of the graphite was constrained vertically ($u_y$=0) and lateral constraints were applied at two nodes to eliminate rigid body motion. A downward force of 890N (200 lbf) was applied at the top midpoint of the rod.

Table 7.0-1. Comparison of two submodels with different locations of rod contact points.

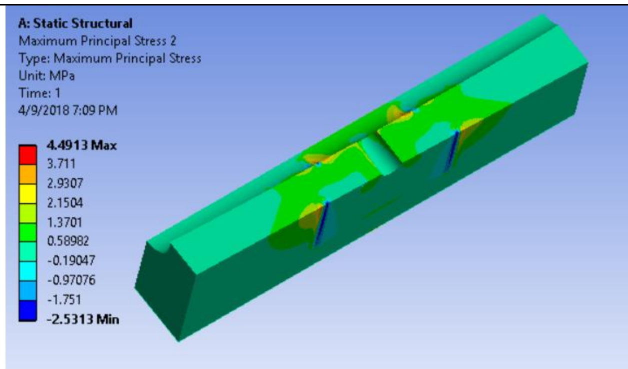
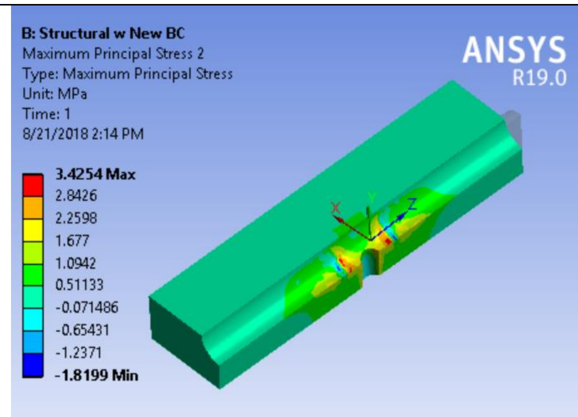
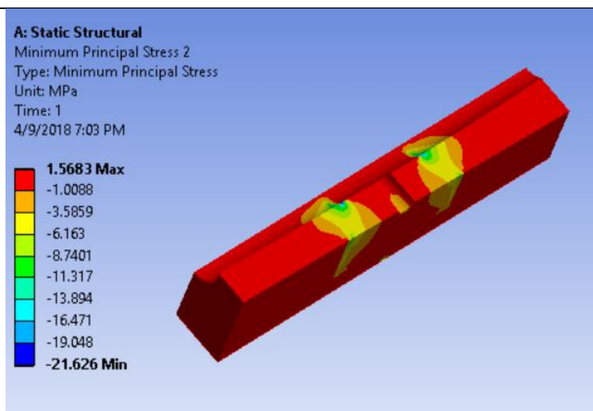
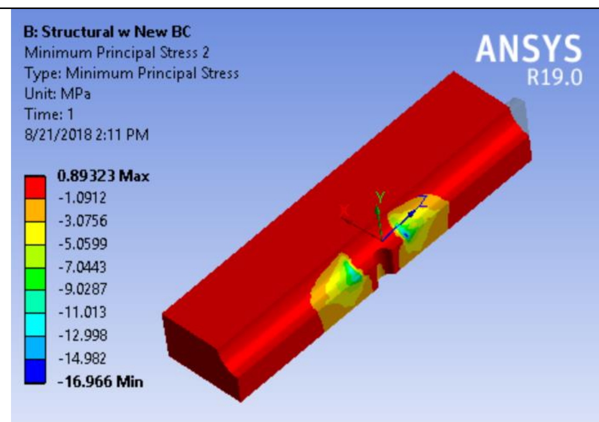
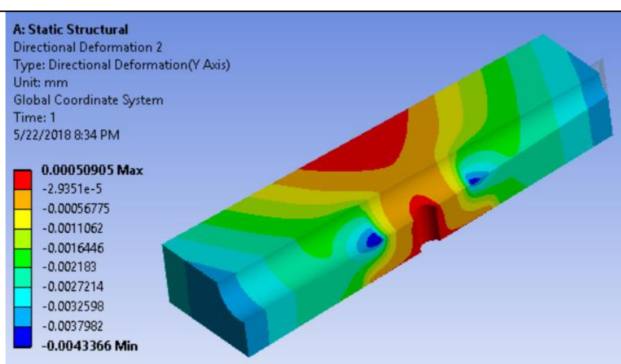
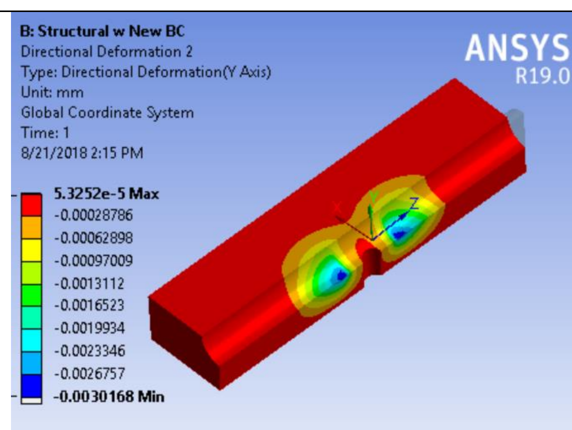
<table>
<tr><td></td><td>Rod 1 (contact 0.375” from the hole centerline)</td><td>Rod 2 (0.250” from the hole centerline)</td></tr>
<tr><td>S1</td><td>
</td><td>
</td></tr>
<tr><td>S3</td><td>
</td><td>
</td></tr>
<tr><td>Vert. Deform.</td><td>
</td><td>
</td></tr>
</table>

Table 7.0-1 compares the max (S1) and min (S3) principal stresses and also vertical deformation of tile with different rod contact points. They are all within their allowable ranges. Those analysis results indicate that the contact point of rod can be moved closer to the screw hole, from 0.375 inches to 0.250 inches to further reduce the stress by ~25%.

The results of Rod 1 case with the 0.375" away contact point are comparable with those of independent calculation form [13]. Figure 7.0-13 shows the vertical displacement of tile along the contact path, which is matching the similar tour plot plus 25% reduction in the calculation report [13].

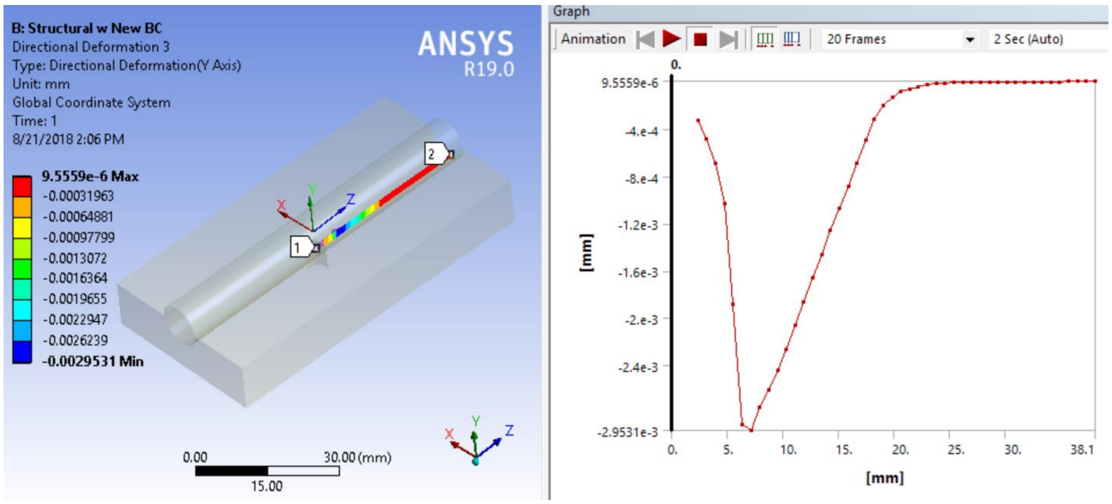



Figure 7.0-13. Vertical Displacement of tile along the contact path.

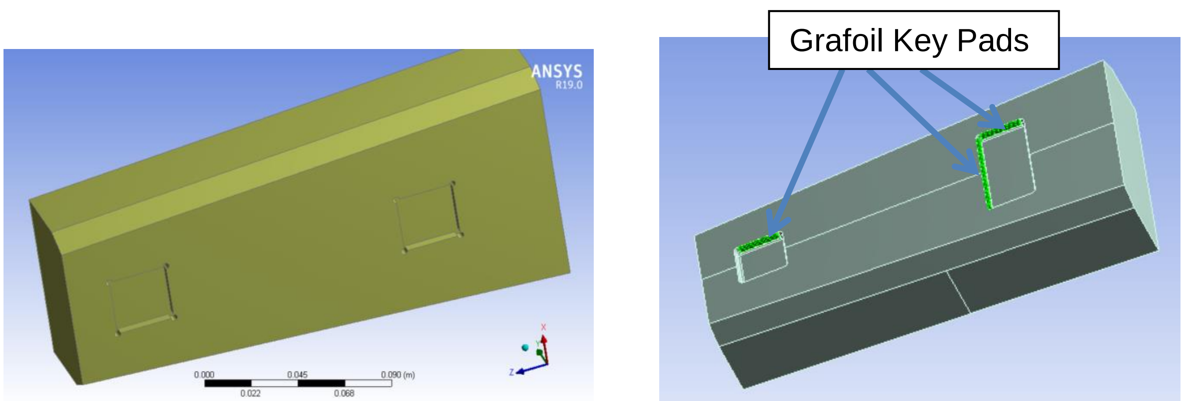



Figure 7.0-14. Original vs new simplified key model (halo restraints)

Seen from Figure 7.0-14, the original identical keys are modified into two different shapes of key concave with round-edged ceilings. The new simplified key submodel for halo restraints will be reported in another calculation form [14] with detailed design and results.

## 8.0 Results of OBD12 Tiles

### 8.1 Thermal Results

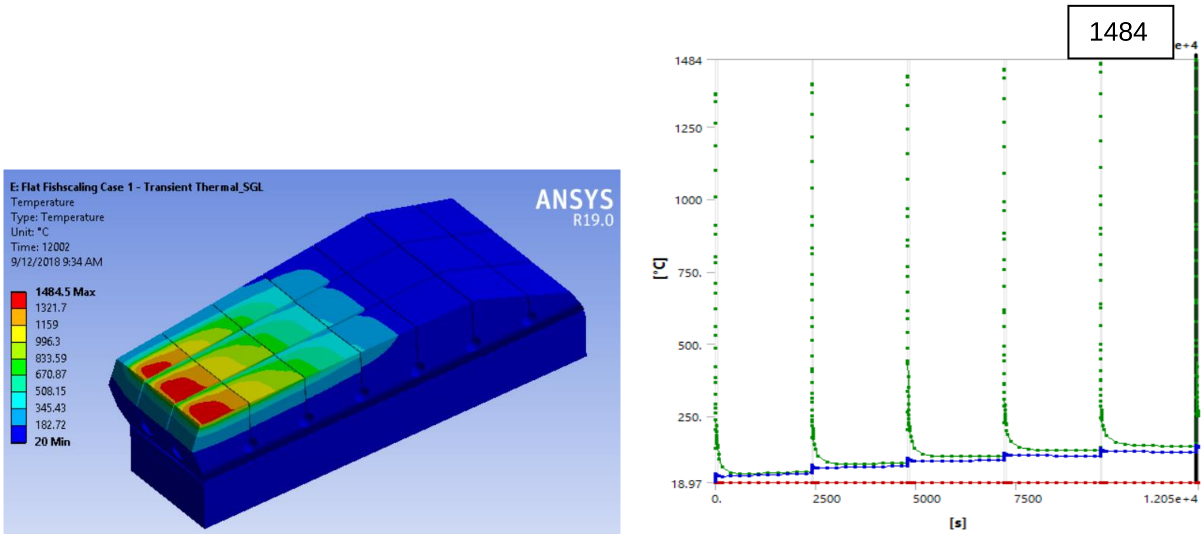



Figure 8.0-1 The temperature ratcheting and peak temperature at 12001.5s with OBD12 Case 1

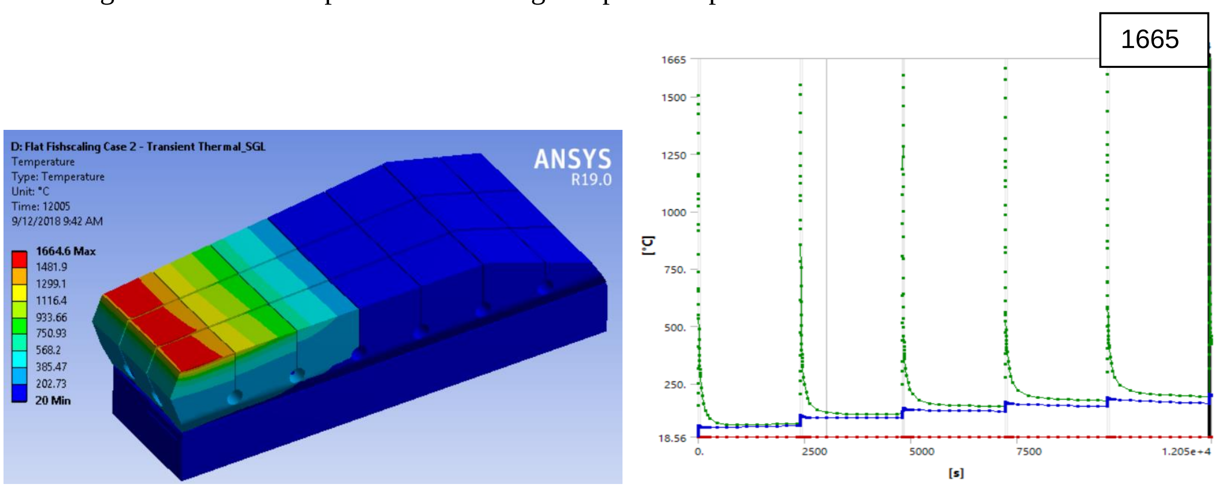



Figure 8.0-2 The temperature ratcheting and peak temperature at 12005s with OBD12 Case 2

According to the first three thermal models with Case 1-3 heat fluxes on OBD12 tiles, Figure 8.0-1-3 show the respective transient temperature ratcheting results and peak temperature at the end of 6$^{th}$ pulse with the repetition rate of 40 minutes. Except Case 2, other two cases can meet the required thermal limit of 1,600 degree C as described in PFC SRD[5]. Considering the ramped faceting factor along the toroidal direction for each surface of OBD12 tile constellations (see Figure 7.0-6), the peak temperature of tile on Case 2 could be reduced from 1,664 to 1,476 degree C as shown in Figure 8.0-4.

# Calculation of OBD12 Tiles

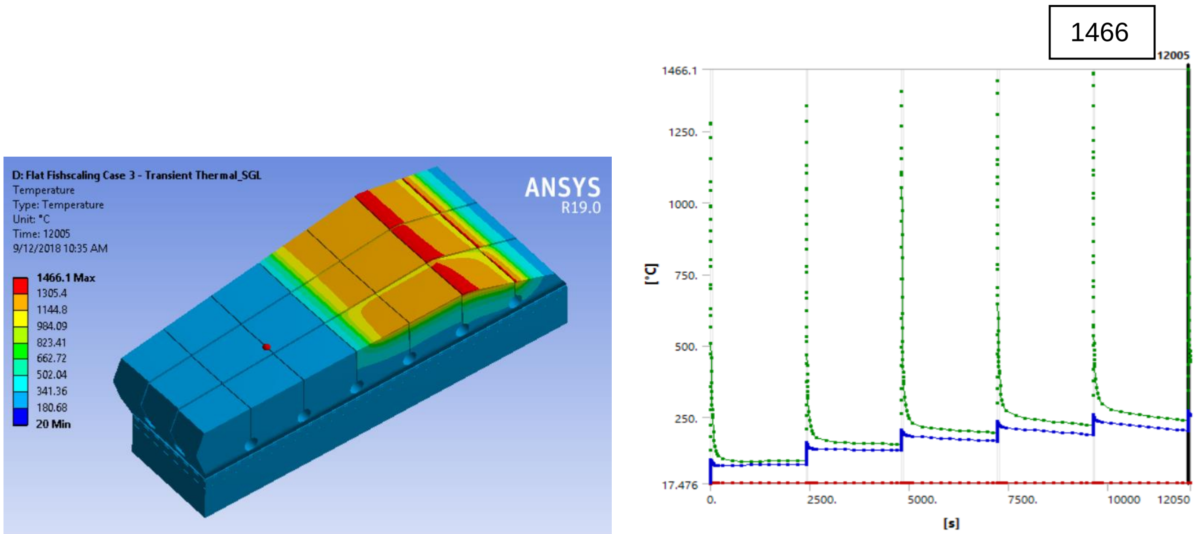



Figure 8.0-3 The temperature ratcheting and peak temperature at 12005s with OBD12 Case 3

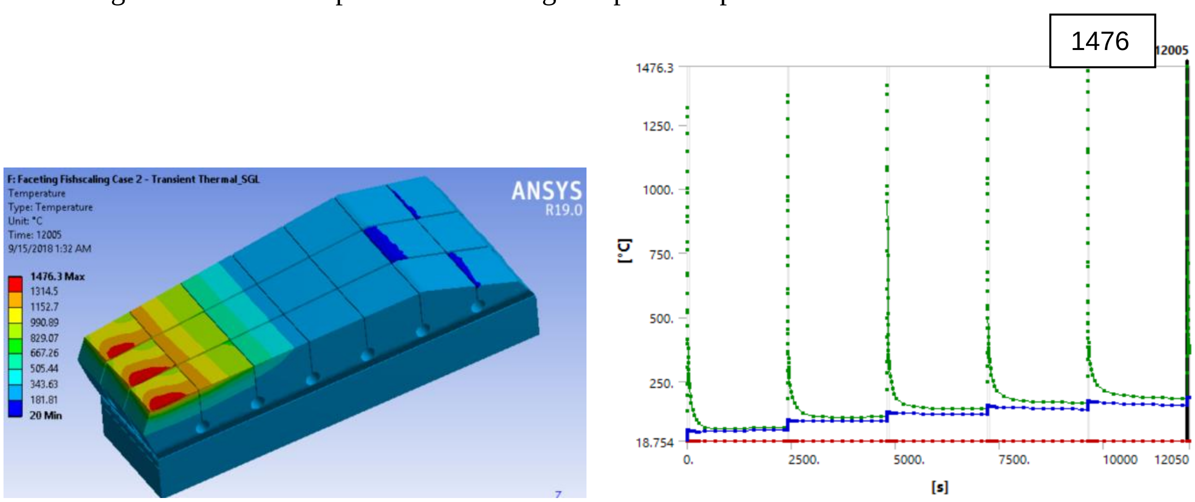



Figure 8.0-4 The temperature ratcheting and peak temperature at 12005s with modified faceting OBD12 Case 2.

## 8.2 Tile Material Selection

| Tile Material | Density@ 20°C (kg/m³) | Thermal Conductivity @20°C (W/m-°C) | Specific Heat @20°C ( J/kg-°C) | Peak Temperature ( °C) | Peak Compressive | | Peak Tensile | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Simu (MPa) | Percent /limit | Simu (MPa) | Percent /limit |
| *SGL R6510 | 1830 | 105 | 682 | 1485 | -48 | 74% | 15 | 50% |
| *POCO TM | 1820 | 105 | 682 | 1500 | -55 | 100% | 12 | 57% |
| T953 | 1800 | 108 | 682 | 1765 | -49 | 98% | 33 | 110% |
| G347 | 1850 | 116 | 682 | 1684 | -42 | 93% | 31 | 112% |
| ET10 | 1750 | 104.4 | 682 | 1806 | -39 | 80% | 33 | 114% |
| SEMCO 15388 | 1780 | 90 | 682 | 1933 | -59 | 107% | 32 | 100% |

* SGL and POCO TM tiles were recalculated based on new case heat flux

Table 8.0-1. Thermal and structural results of OBD12 tile with high heat flux

Some thermal and structural results of OBD12 tile with high heat flux inputs are listed in Table 8.0-1. **In summary, the best potential material is Sigrafine R6510, otherwise POCO TM is the second choice.**

### 8.3 Sigrafine Combined thermal, halo and preload

All the following results are based on the tile material of Sigrafine R6510. Since the peak temperature and heat flux of Case 3 are lower than others. Here we only present the structural results with the combined EOP thermal, halo and preloads for Cases 1 and 2.

***Case 1***

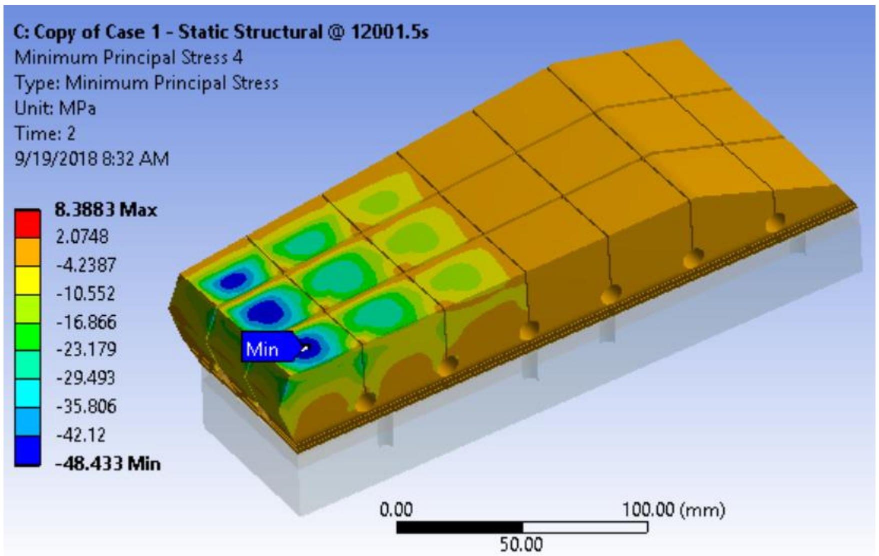



Figure 8.0-5 The minimum principal stress of tile at 12001.5s with OBD12 **Sigrafine** Case 1

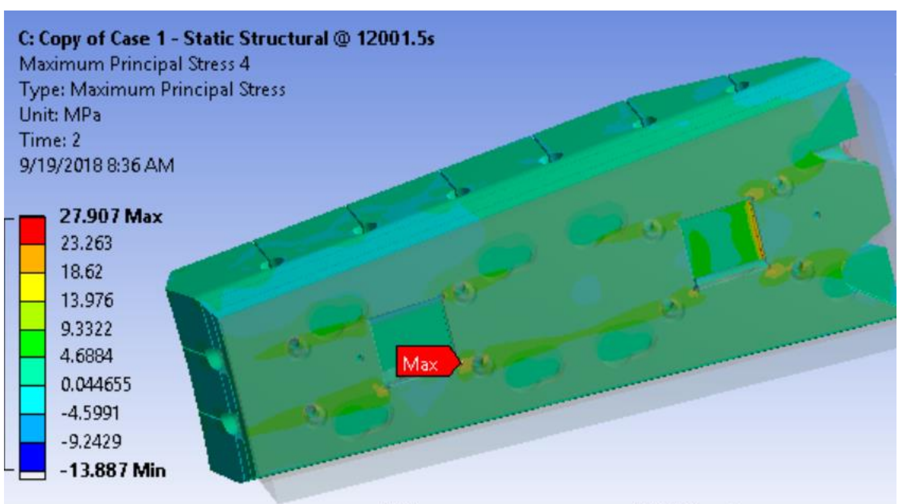



Figure 8.0-6 The max principal stress of tile at 12001.5s with OBD12 **Sigrafine** Case 1

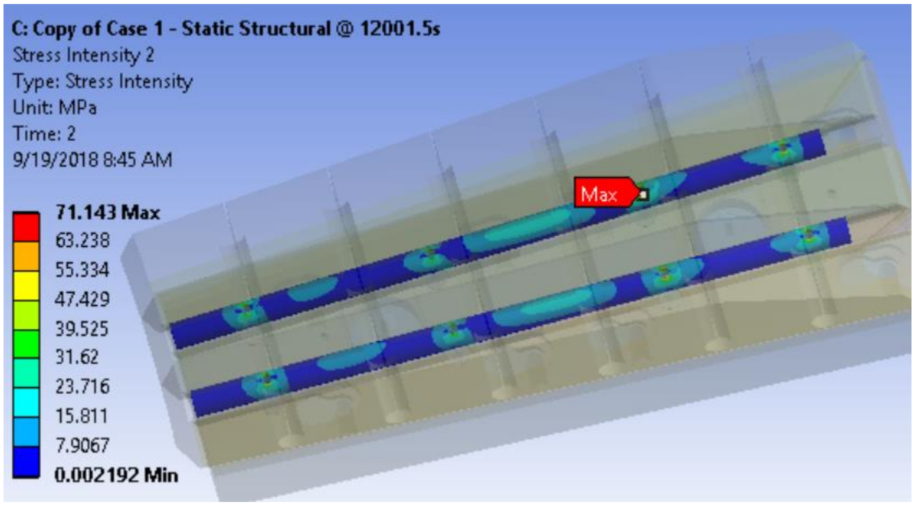



Figure 8.0-7 The stress of rods at 12001.5s with OBD12 **Sigrafine** Case 1

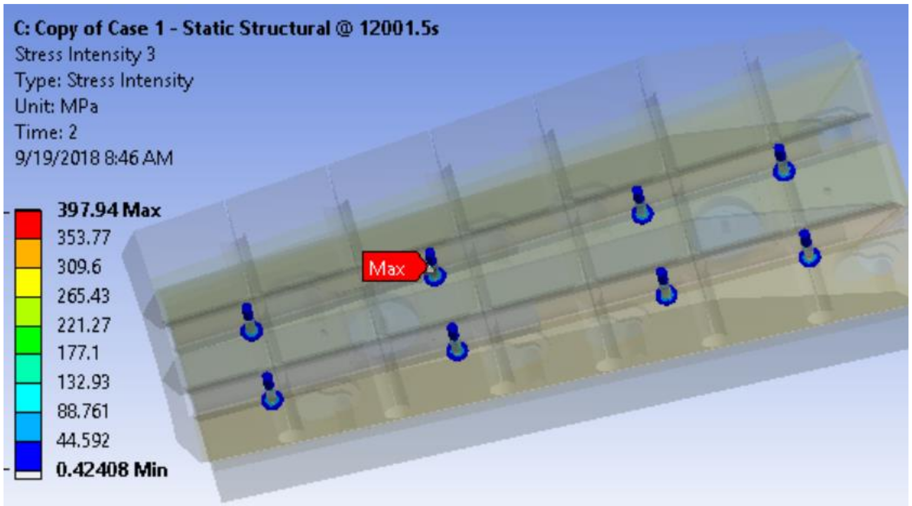



Figure 8.0-8 The stress of bolts at 12001.5s with OBD12 **Sigrafine** Case 1

***Case2***

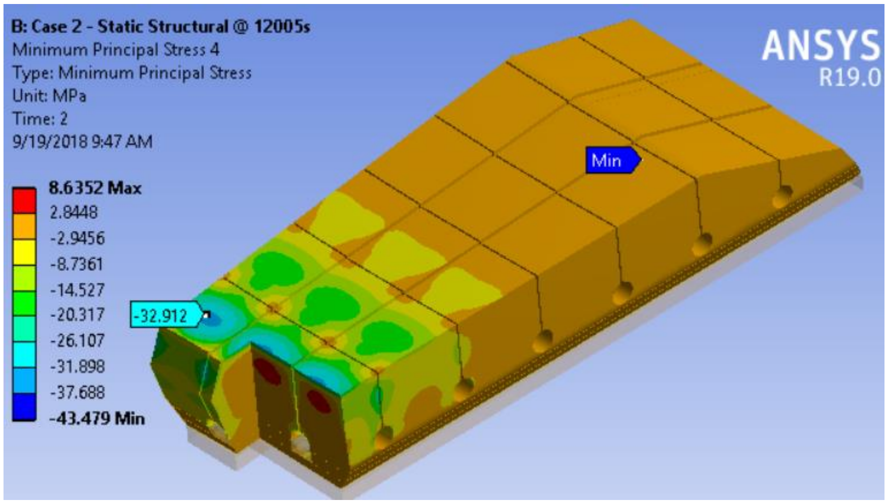



Figure 8.0-9 The minimum principal stress of tile at 12005s with OBD12 **Sigrafine** Case 2

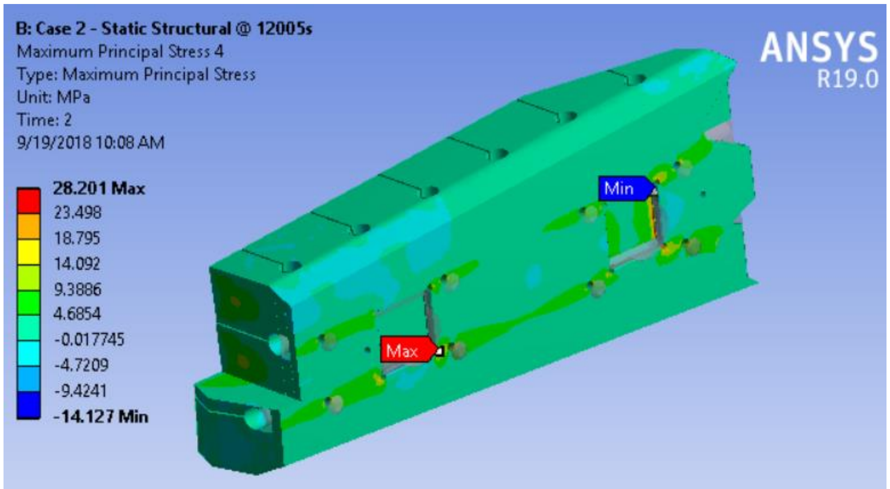



Figure 8.0-10 The max principal stress of tile at 12005s with OBD12 **Sigrafine** Case 2

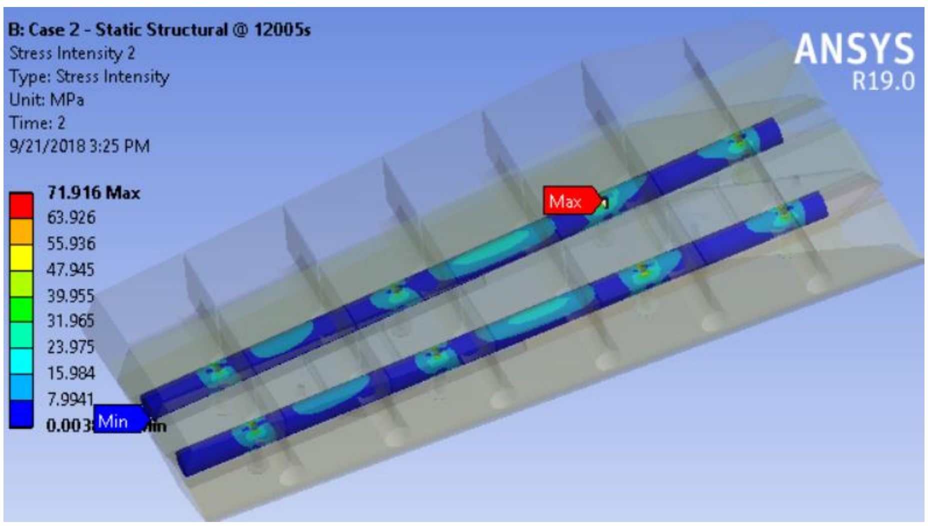



Figure 8.0-11 The stress of rods at 12005s with OBD12 **Sigrafine** Case 2

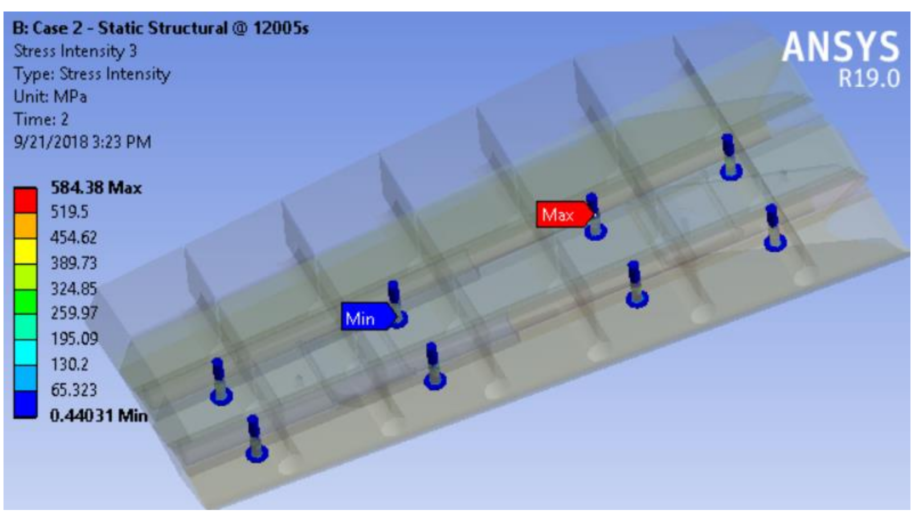



Figure 8.0-12 The stress of bolts at 12005s with OBD12 **Sigrafine** Case 2

Figures 8.0-5~8 and Figure8.0-5.9~12 show the stress of tile, rods and bolts for OBD12 **Sigrafine** tiles Cases 1 and 2, respectively. All the stress data are within the allowable range except some local contact areas which can be resolved by the taped rods and round key concave ceiling as described in other two submodeling reports.

## 9.0 Results of POCO Tiles

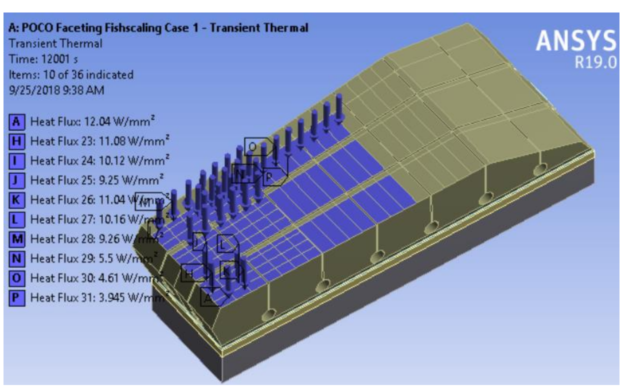
### 9.1 New Case 1

| OBD12 | Case | 1 | 2 | 3 |
|---|---|---|---|---|
| Range of Application | m | R<0.7 | R<0.7 | 0.70<R<0.81 |
| Extent | cm | 13 | 10 | full |
| Max Angle | degrees | 1 | 5 | 4.4 |
| Min Angle | degrees | 1 | 5 | 2.6 |
| Heat Flux | $MW/m^1$ | 5 | 5.4 | 3.3 |
| Duration | sec | 1 | 5 | 5 |

Table 9.0-1: Heat fluxes on the OBD Row 1 & 2 tiles

Since the tile material is changed from Sigrafine R6510 to the POCO TM, the required heat flux for Case 1 on orange color was also modified from 5.4 $MW/m^2$, 1.5s to 5$MW/m^2$, 1s as shown in Table 9.0-1.

### 9.2 Thermal Results




| R_mp | Faceting Enhancement | | | |
|---|---|---|---|---|
| Four Ranges | Low2 | Low1 | High1 | High2 |
| Factor | 1.91 | 2.11 | 2.31 | 2.51 |
| 0.5931 | 9.896657 | 10.93296 | 11.96925 | 13.00555 |
| 0.6034 | 9.068792 | 10.0184 | 10.96802 | 11.91763 |
| 0.6137 | 8.247749 | 9.111388 | 9.975026 | 10.83866 |
| 0.6235 | 7.460013 | 8.241166 | 9.02232 | 9.803473 |
| 0.6325 | 6.734076 | 7.439215 | 8.144354 | 8.849493 |
| 0.6412 | 6.037033 | 6.669183 | 7.301333 | 7.933483 |
| 0.6499 | 5.340792 | 5.900037 | 6.459282 | 7.018527 |

Figure 9.0-1 The Thermal Model with the modified Fishscaling Factors of OBD12 Case 1

In comparison with the Case 1 thermal model as shown in Figure 7.0-3, the right table in Figure 9.0-1, modifies the faceting enhancement factors and heat fluxes for first six constellations according to fishscaling factor distribution toroidally as shown in Figure 7.0-2. Figure 9.0-2 shows the corresponding temperature ratcheting and peak temperature at the end of sixth pulse (12005s). In comparison with the results of previous sigrafine Case 1, with the pulse during time changing from 1.5s to 1s, the peak temperature of POCO is dropped by 25% to 1100 degree C.

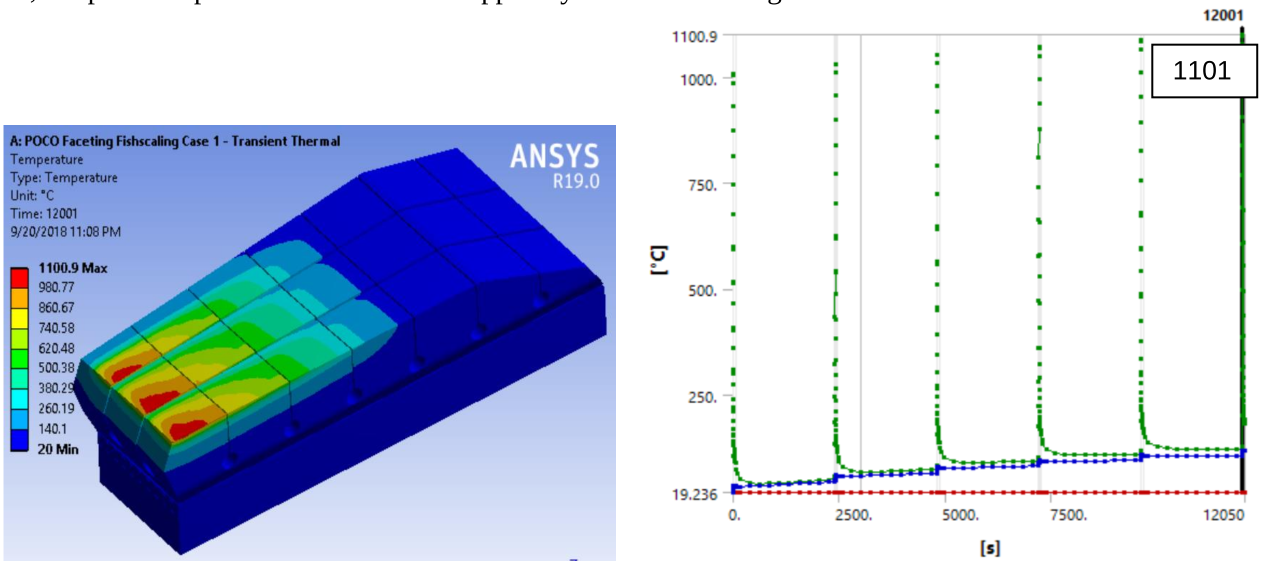



Figure 9.0-2 The temperature ratcheting and peak temperature at 12001s with OBD12 POCO Case 1

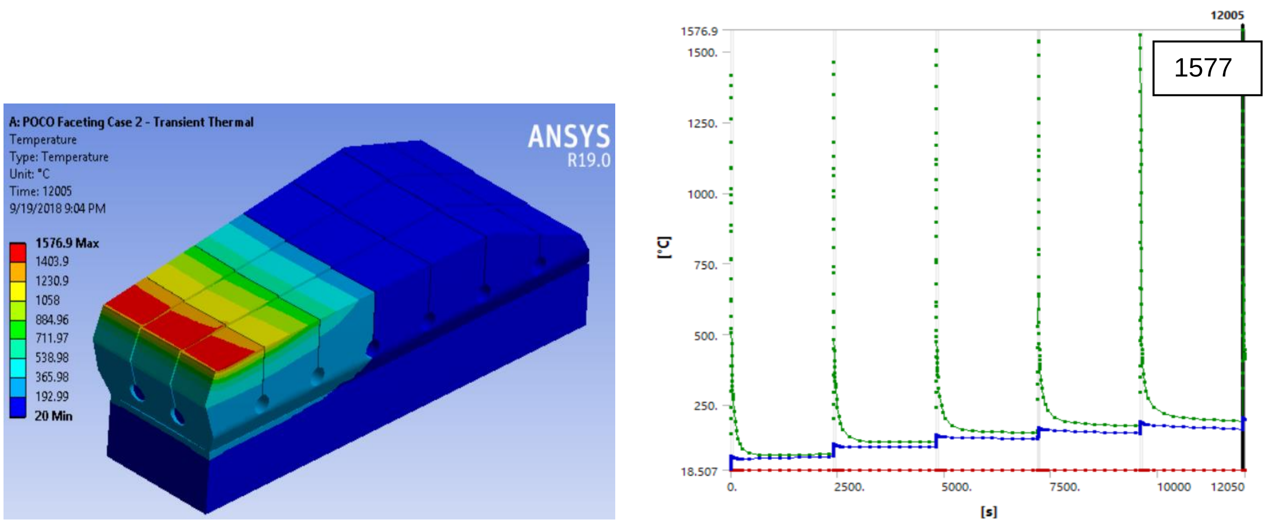



Figure 9.0-3 The temperature ratcheting and peak temperature at 12005s with OBD12 POCO Case 2

The peak temperature of POCO at 12005s is 1577 degree C as shown in Figure 9.0-3 with OBD12 POCO Case 2, which is less than 2% margin to the temperature limit for PFC tiles.

### 9.3 Combined thermal, halo and preload

All the following results are based on the tile material of POCO TM.

# Calculation of OBD12 Tiles

***Case 1***

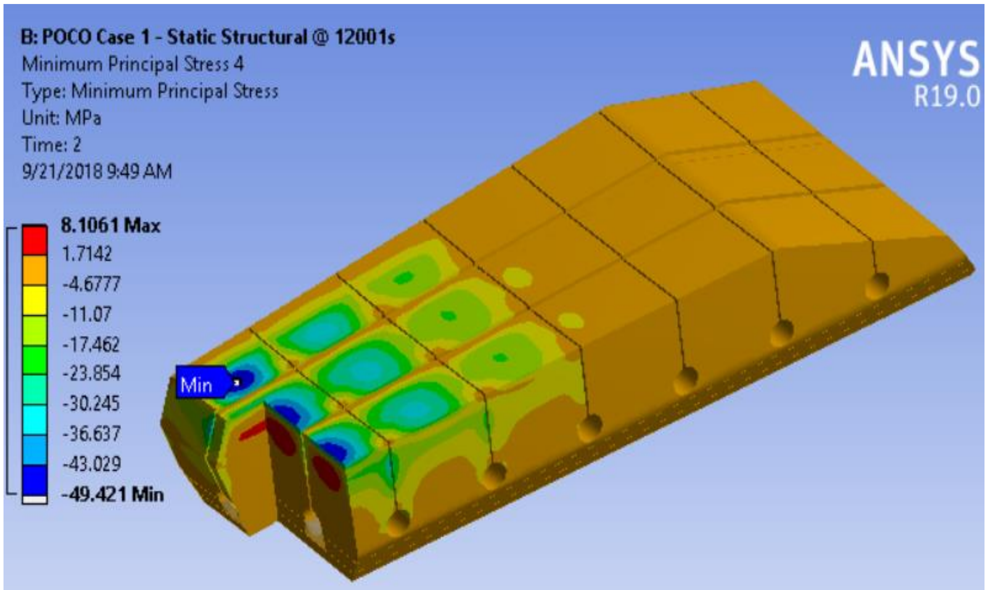



Figure 9.0-4 The minimum principal stress of tile at 12001s with OBD12 POCO Case 1

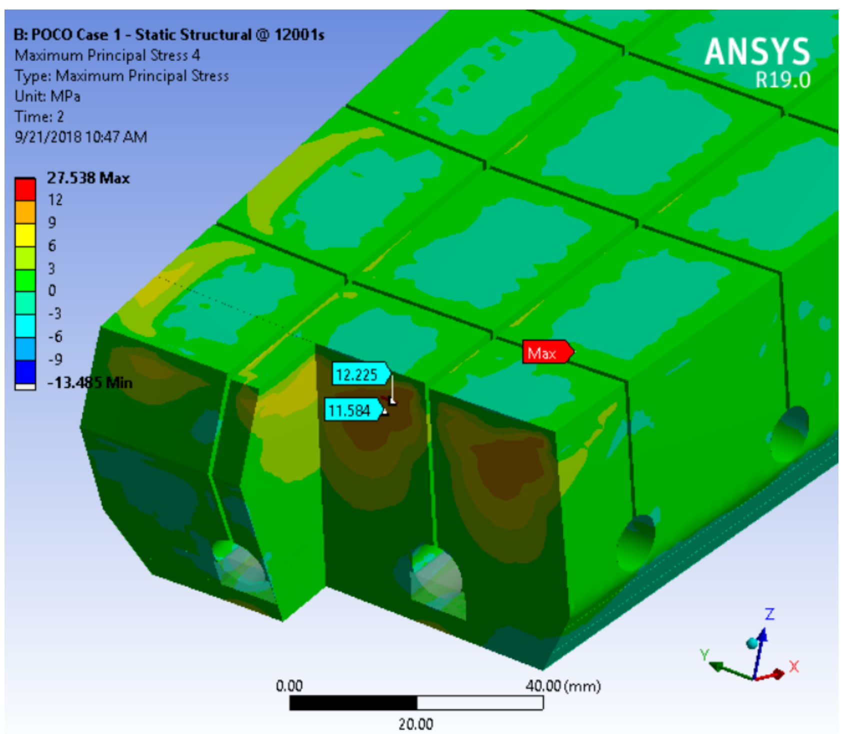



Figure 9.0-5 The max principal stress of tile at 12001s with OBD12 POCO Case 1

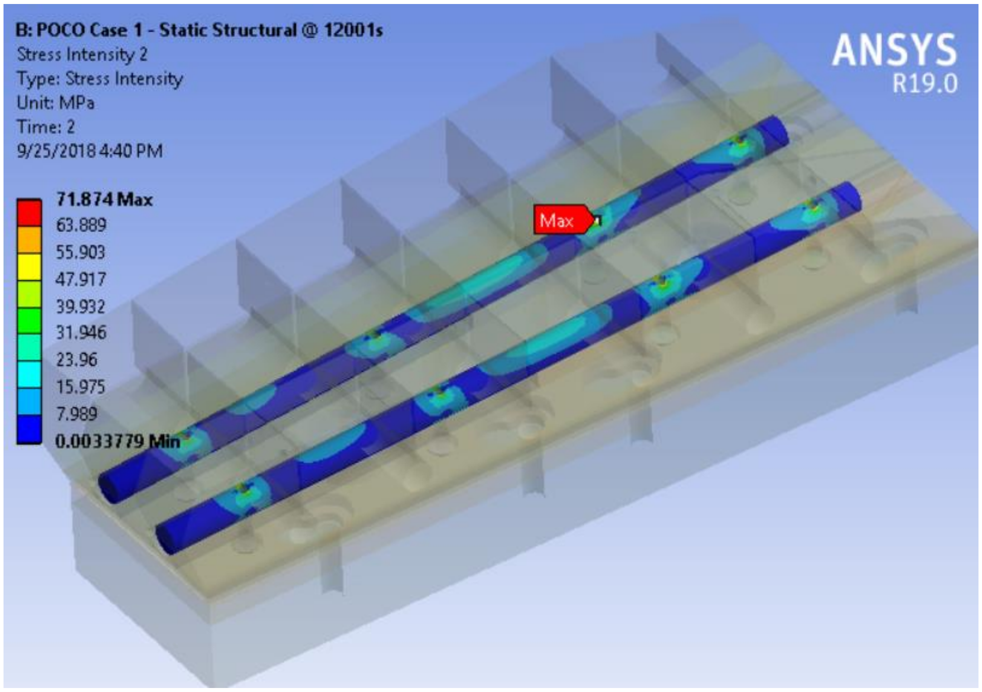


Figure 9.0-6 The stress of rods at 12001s with OBD12 POCO Case 1

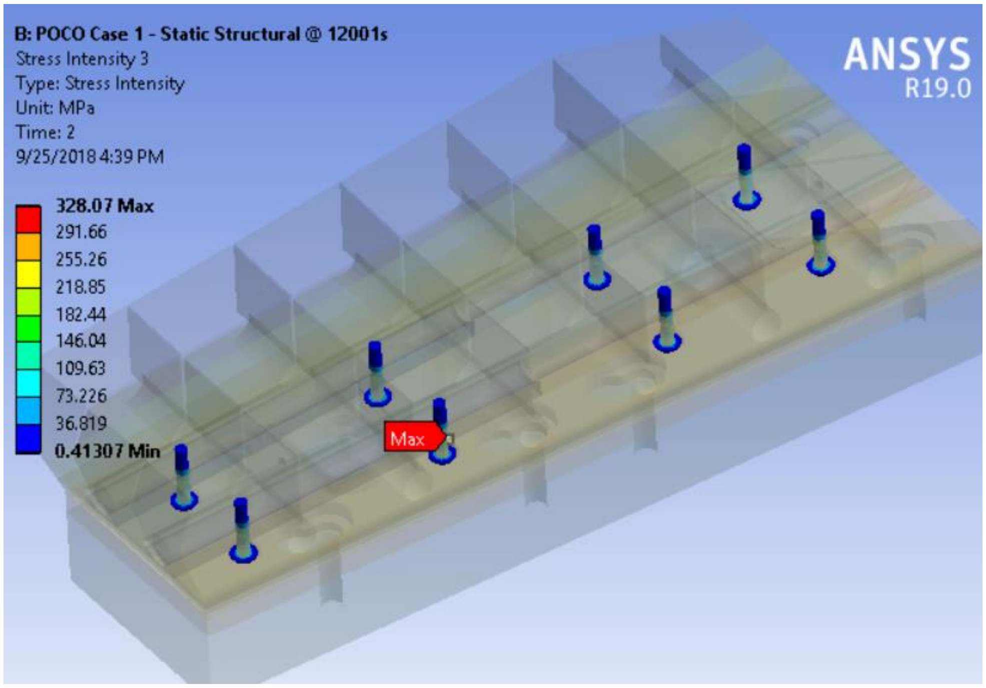


Figure 9.0-7 The stress of bolts at 12001s with OBD12 POCO Case 1

***Case2***

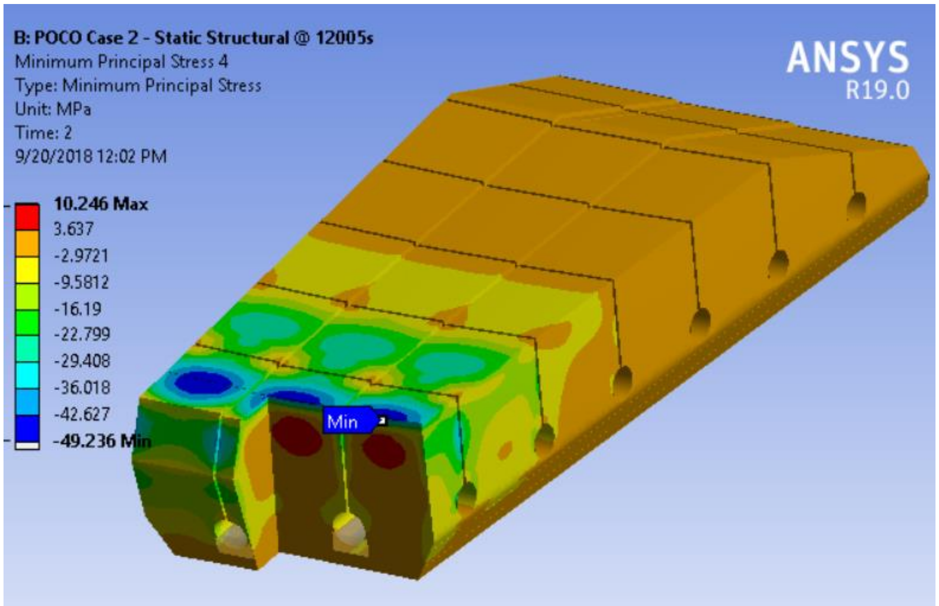



Figure 9.0-8 The minimum principal stress of tile at 12005s with OBD12 POCO Case 2

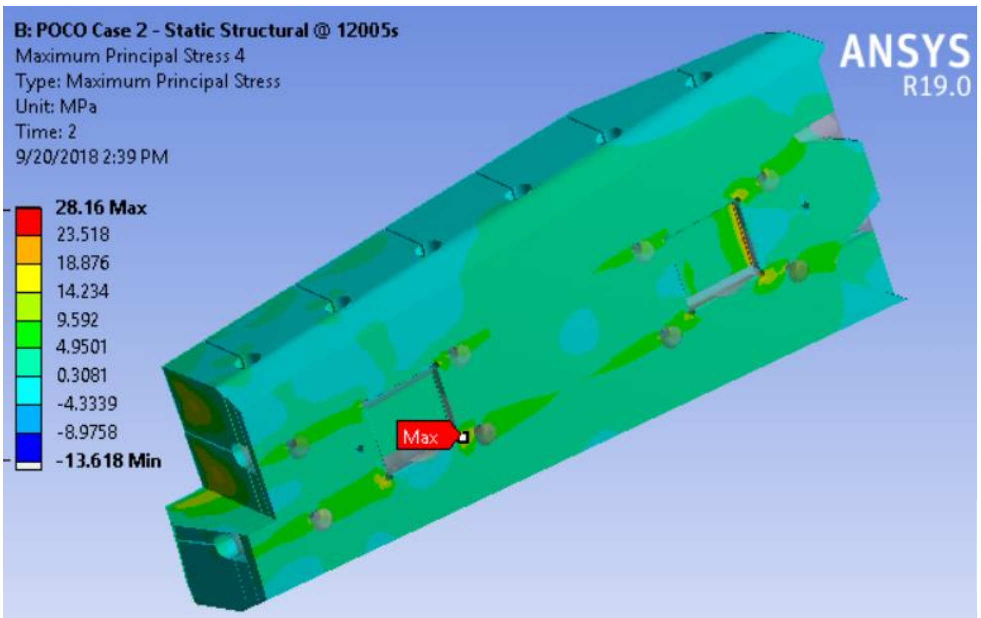



Figure 9.0-9 The max principal stress of tile at 12005s with OBD12 POCO Case 2

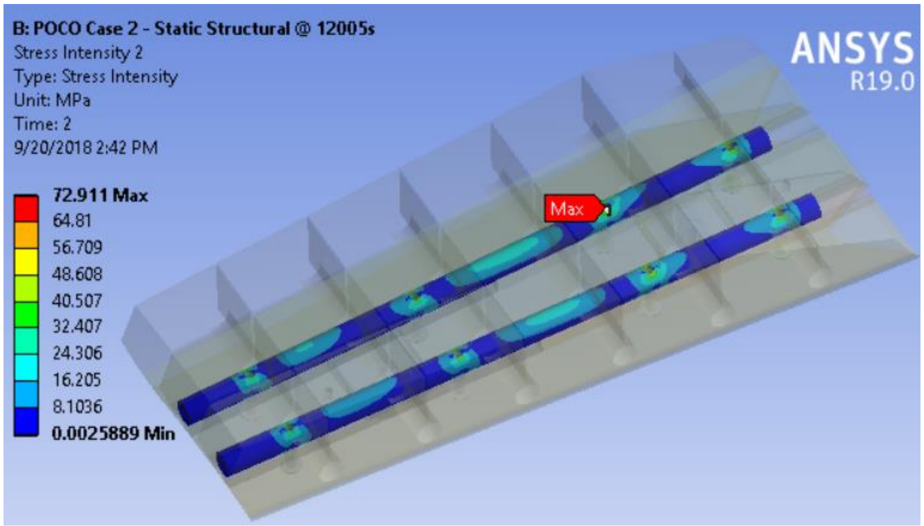



Figure 9.0-10 The stress of rods at 12005s with OBD12 POCO Case 2

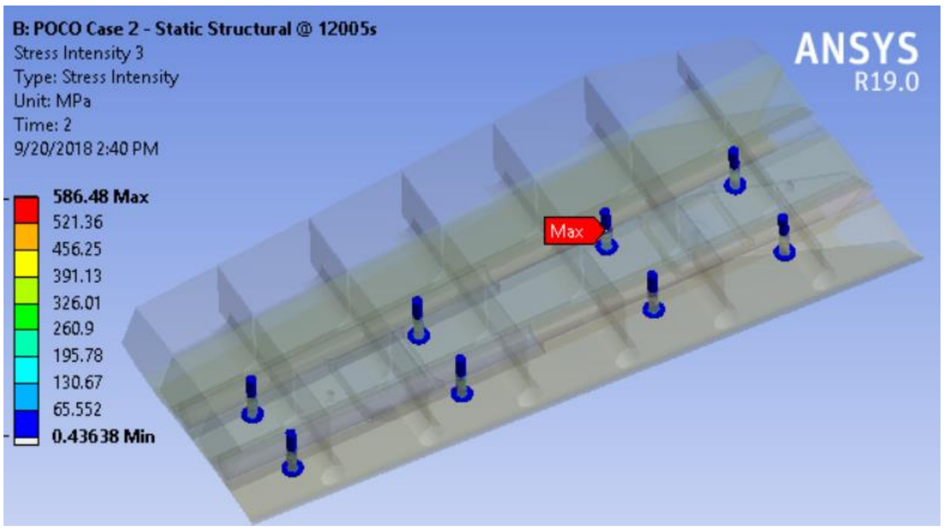
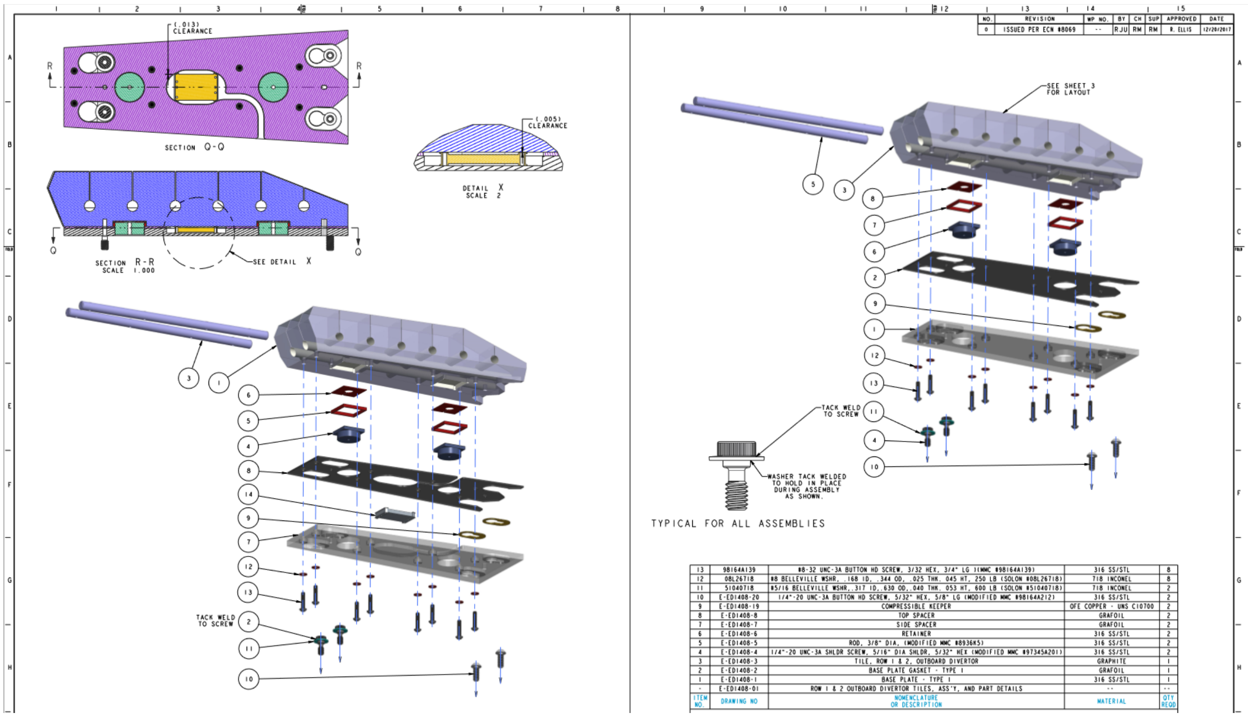



Figure 9.0-11 The stress of bolts at 12005s with OBD12 POCO Case 2

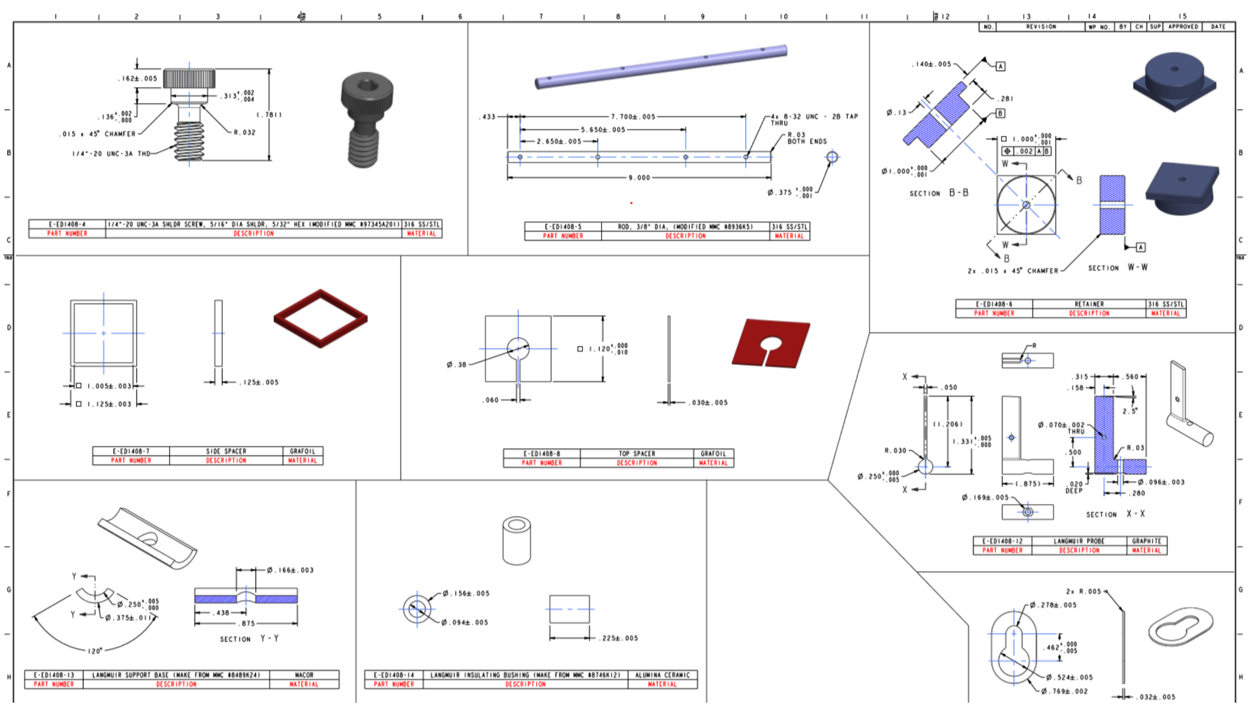
Figures 9.0-4~7 and Figure 9.0-8~11 show the stress of tile, rods and bolts for POCO tiles Cases 1 and 2, respectively. All the stress data are within the allowable range except some local contact areas which can be resolved by the taped rods and round key concave ceiling as described in other two submodeling reports.

# Calculation of OBD12 Tiles

Appendix A. Drawings of OBD Row 1&2 Tiles (0EED1408)

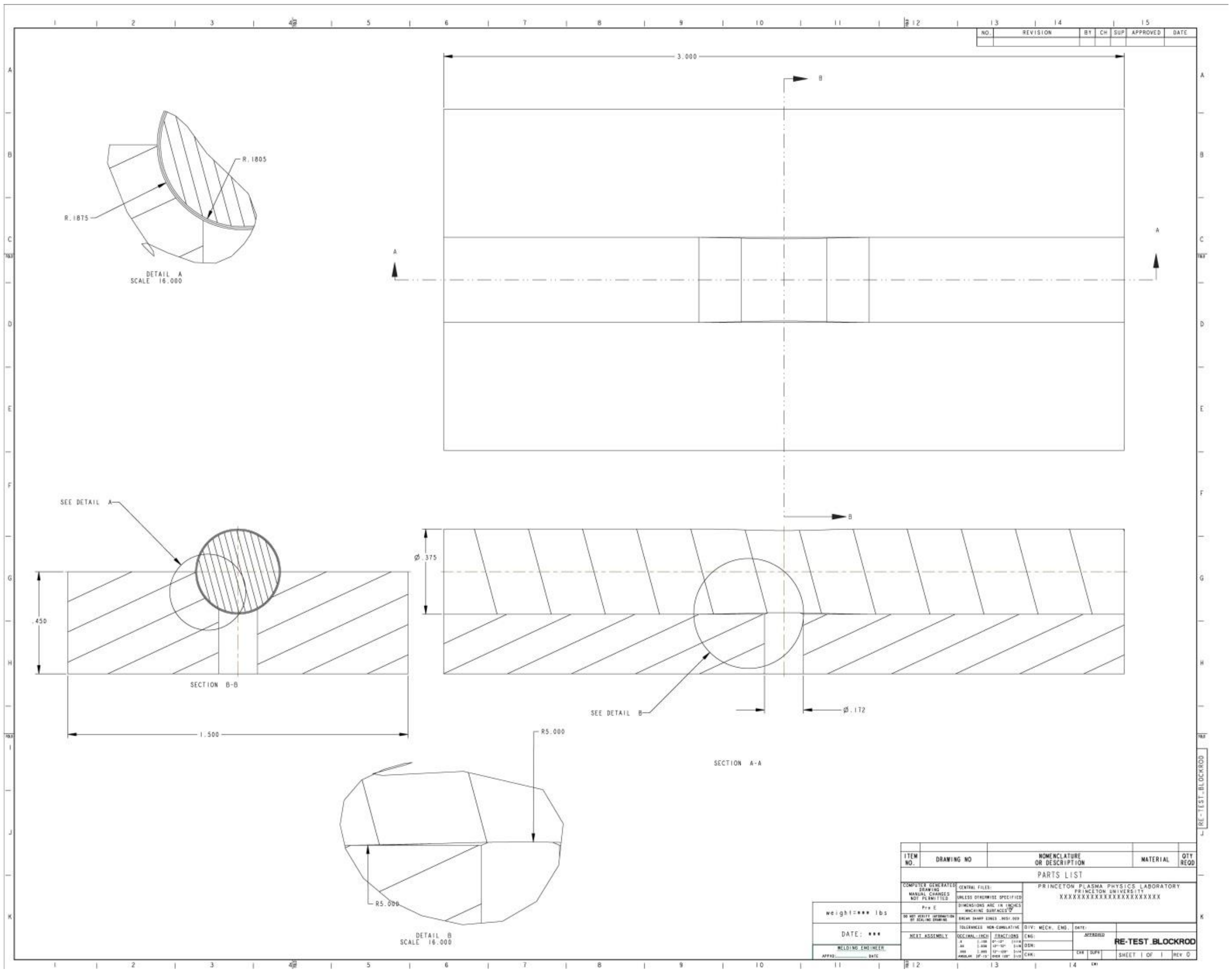


OBD12 tile overview with diagnostics.



Details of OBD12 key and rod submodels with diagnostics.

Appendix B. Drawings of RE-Test Block Rod




One tapered rod and simple graphite block