Calculation No:<u>**NSTXU-CALC-11-25-00**</u> **Revision No:**<u>**0**</u>

Title: OBD12 Simplified Model Langmuir Probe

<u>Purpose of Calculation: (Define why the calculation is being performed.)</u>

Langmuir probes will be installed between selected castellations of the OBD12 tiles. A simplified model encompassing a fraction of the tile assembly was used to investigate the behavior of the probe and its effect on the tile performance.

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

ANSYS version 19

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

Drawing E-ED1408, Row 1 and 2 Outboard Divertor Tiles Assembly and Details

NSTXU-RQMT-SRD-003-00, System Requirements Document, Plasma Facing Components, Rev. 0

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

An analysis of the portion of the tile assembly near a Langmuir probe is valid, because the probe will only affect the local solution.

Calculation (Calculation is either documented here or attached)

Heat loads from the PFC SRD Rev. 0 (conservative) were applied. The preload of the probe at its base, due to the spring washer on the mounting assembly, was applied. Contact conductance at the base of the probe was applied. A detailed report is on the following pages.

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

The probe temperatures track the tile temperatures, as expected. The maximum principal stress in the probe are below the Sigrafine allowable values (14.4 MPa vs. 19.0 MPa). Maximum principal stress in the Macor insulator is 8.05MPa. The flexural strength for this material is 93 MPa. Corning, the manufacturer of Macor, does not quote an ultimate tensile strength in their literature; they only quote flexural strength, which is 93 MPa. The maximum principal stress in the Macor is 8.1 MPa, which is a factor of almost 12 below the flexural strength. I looked at a lot of suppliers' websites, and couldn't find ultimate tensile stress quoted anywhere. A relevant comparison might be to look at Alumina, another engineered ceramic, where the ratio of UTS to flexural strength is 350 MPa to 260. So if we were to guess that the UTS of Macor was half of the flex modulus, or 47 MPa, there is still a safety factor of about 6.

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

Robert Ellis Robert Ellis Digitally signed by Robert Ellis Date: 2018.09.28 07:35:47 -04'00'

Preparer's printed name, signature and date

Robert Ellis Robert Ellis Digitally signed by Robert Ellis Date: 2018.09.28 07:36:07 -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

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Analysis of Langmuir Probe in OBD Row 1-2 Tiles

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1.0 INTRODUCTION

A simplified model of a portion of the ODB12 graphite, including the Langmuir Probe has been analyzed. *Figure 1* shows the tile, and the section of the tile analyzed. The model consists of a portion of an SGL R6510 graphite tile, including an SGL R6510 graphite Langmuir probe with a Macor support between the tile and the probe. The tile is shown in cyan, the probe is shown in magenta, and the base support is shown in red. The model includes a 3 toroidal by 3 poloidal array.

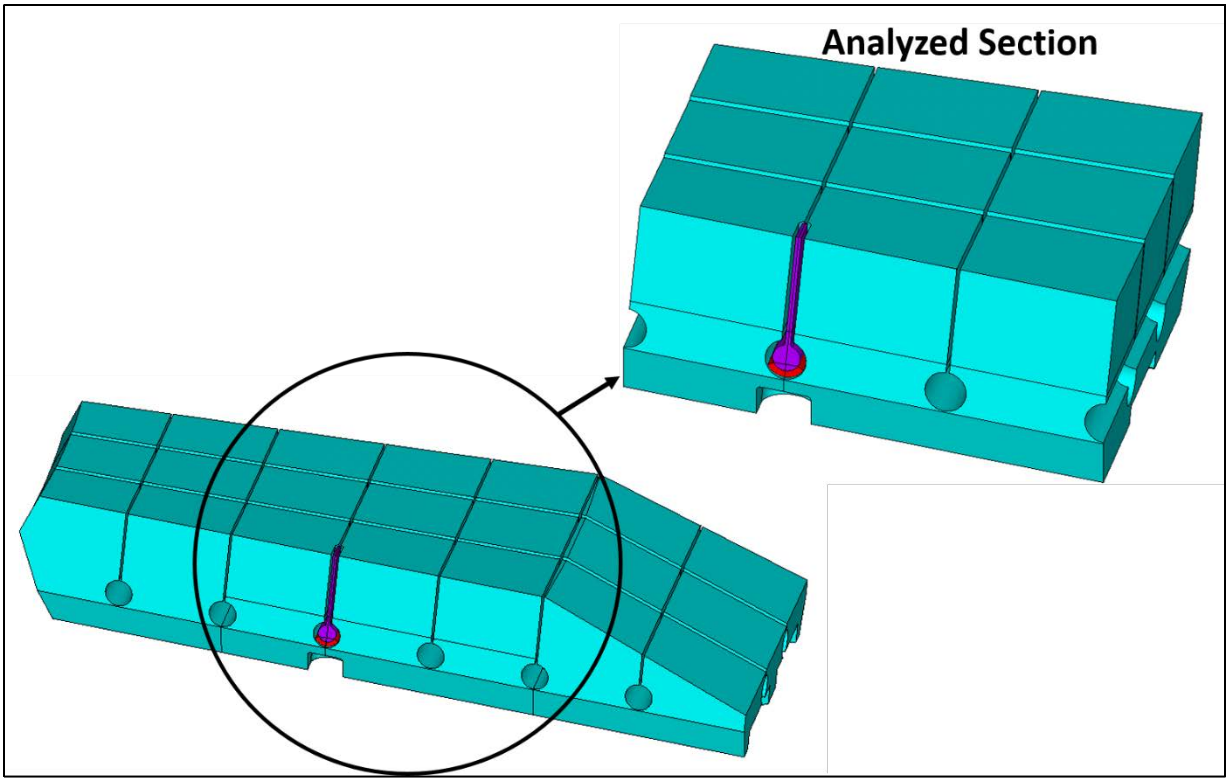

Figure 1. OBD12 Tile Section

2.0 ELEMENT INFORMATION

A portion of the OBD12 tile, the Langmuir Probe, and the base support was meshed as shown in *Figure 2* and *Figure 3*. The model is refined in the region of the probe. Hex elements were used in the regions where large temperature gradients are expected. Contact elements were included between the probe and base support, and between the base support and tile. For the thermal model the contact was bonded and included a contact conductance of 500 W/m^2K. For the structural model the contact behavior was set to standard with a friction coefficient of 0.3. The thermal model contains 279,889 Solid90 elements, 3242 Targe170 elements, 2828 Conta174, and 2670 Surf152 elements, for a total of 288,629 elements. The surface elements were included to allow radiation from the surfaces. The surface elements are shown in green in *Figure 4*. The model has 490,042 nodes. For the structural model, the Solid90 elements were converted to Solid186 elements and the Surf152 elements were eliminated, for a total of 285,959 elements.

The element mesh on the tile near the Langmuir Probe ranges from about 0.0004 m to 0.0015 m. The mesh of on the tile away from the probe was set to 0.0045 m. The mesh in the Langmuir Probe and base support was set to 0.00035 m.

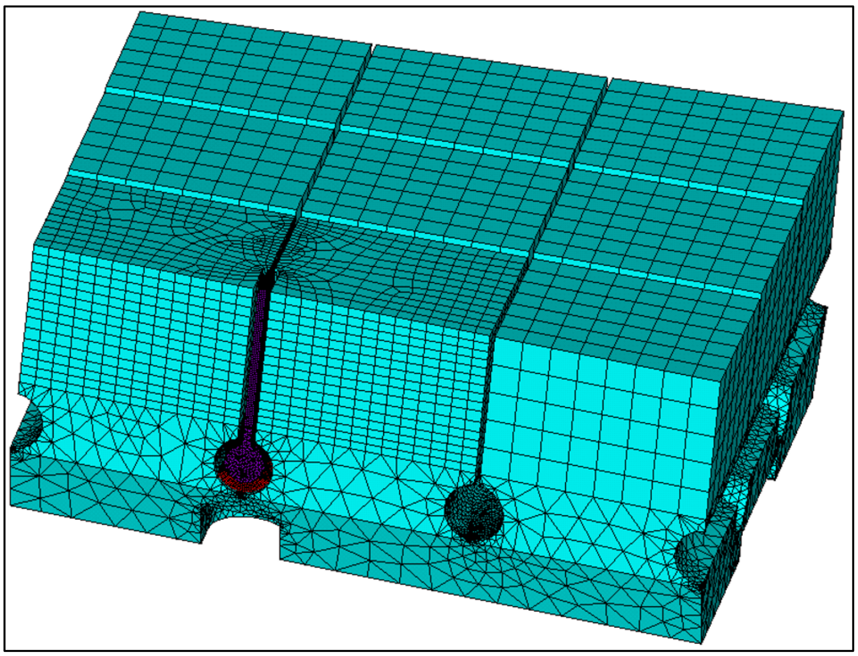

Figure 2. Model of OBD12 Tile and Langmuir Probe

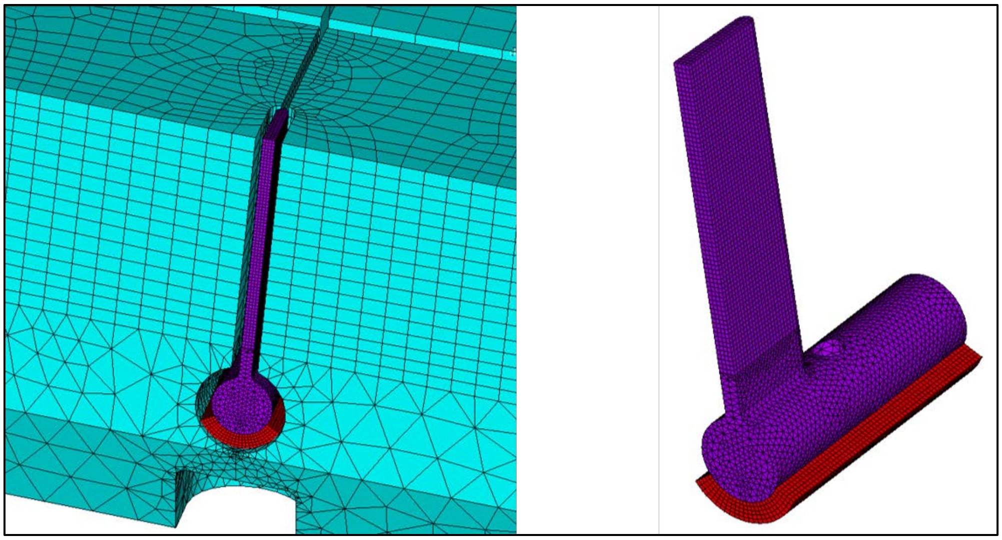

Figure 3. Langmuir Probe

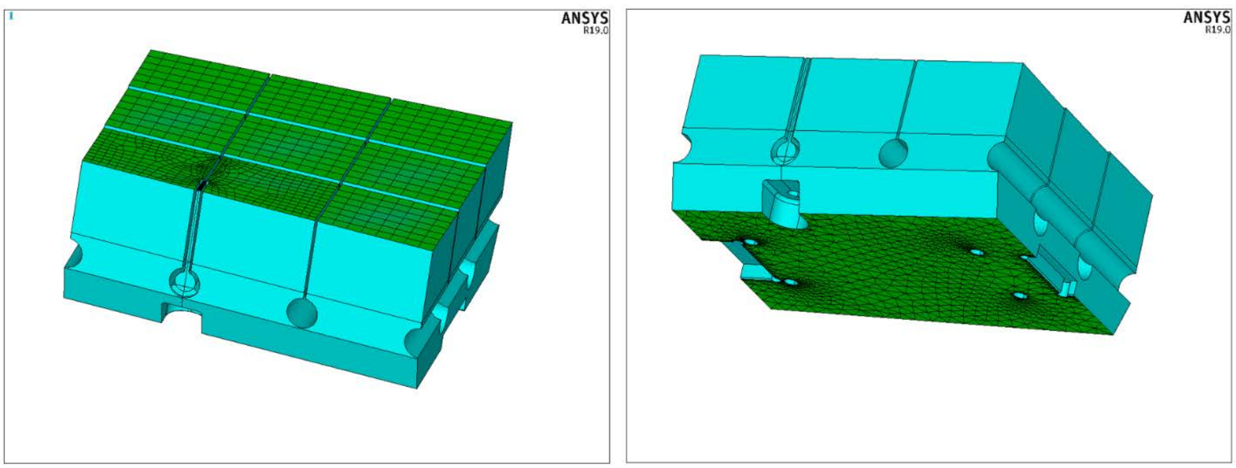

Figure 4. Radiative Surfaces

3.0 Materials

The materials in the model consists of SGL R6510 for the OBD12 tile and the Langmuir Probe. The base support is Macor. The SGL R6510 material is from the PPPL workbench material file and the properties for the Macor are from the MatWeb online materials database. The properties used in the analysis are shown in *Table 1*.

Table 1. Material Properties

Material	Modulus of Elasticity	Poisson's Ration	Ultimate Tensile Strength	Ultimate Compressive Strength
SGL R6510	11.5 GPa	0.3	38 MPa	130 MPa
Macor	6.69 GPa	0.29		345 MPa

4.0 Loads and Boundary Conditions

4.1 Thermal Model

The peak heat flux applied to the tile was 8.08 MW/m^2, with an extent of 13 cm. It was applied as a 5 second pulse, followed by a 1200 second cooldown. The peak value was applied at the location of the Langmuir probe as shown in *Figure 5*. Two cases were considered. For the 1st case, the heat flux was applied across 3 blocks toroidally and with the gradient based on a 13 cm extent in the poloidal direction as shown in the left side of the figure. For the 2nd case, the heat flux was applied across 2 blocks toroidally and with the gradient based on a 13 cm extent in the poloidal direction as shown in the right side of the figure. The peak load was applied as a 5 second pulse, followed by a 1200 second cool down.

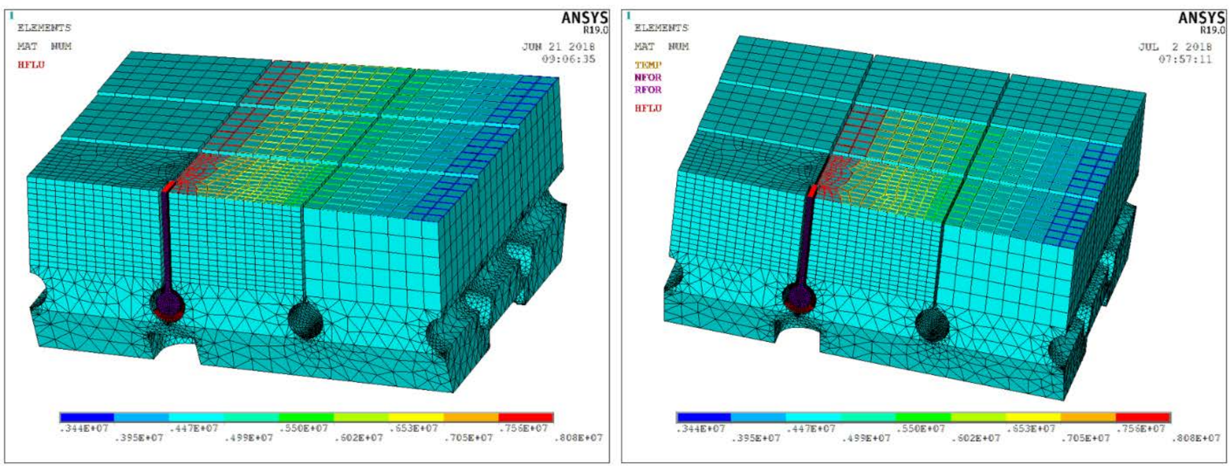

Figure 5. Heat Flux Load

A contact conductance of 500 W/m^2K was used for the contact elements. A uniform initial temperature of 450°C was applied to the model. Radiative thermal boundary conditions, with a sink temperature of 100°C and an emissivity of 0.7, were applied to the surface elements shown in *Figure 4*. All other surfaces were assumed to be adiabatic.

4.2 Structural Model

For the structural model, temperature profiles from the thermal model were applied to the model. Four structural analyses were run. The temperature profiles from both Cases 1 and 2 discussed above, at 5 seconds and 15 seconds, were analyzed.

To account for the preload applied to the probe from the stud, a 44.48 N (10 lbf) downward force was applied to the inside surface of the hole through the probe as shown *Figure 6*. The force was distributed between the nodes along the inside surface. The figure shows only half the probe for clarity.

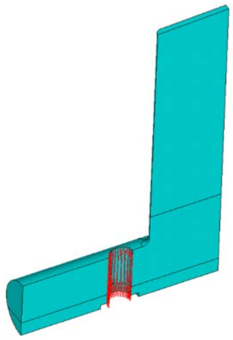

Figure 6. Half of Probe, showing Force Applied to Hole in Probe

The bottom of the tile was constrained to have not displacement normal to the surface (UY=0) as shown in *Figure 7.* Additional X and Z constraints were added to eliminate rigid body motion as shown in the figure.

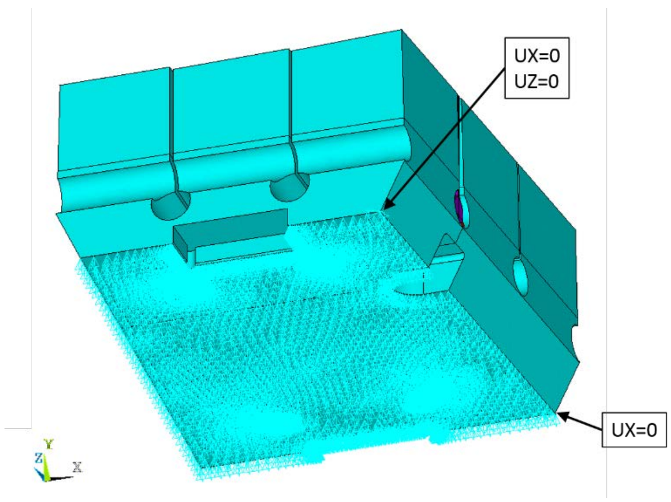

Figure 7. Displacement Constraints

5.0 Results

5.1 Thermal Results

As was discussed in Section 4.1, two different heat flux load cases were analyzed. The results of temperature vs time for the first case, with the heat flux applied across 3 blocks toroidally, are shown in *Figure 8*. The temperature profile at 5 seconds is shown in *Figure 9*. At 5 seconds the temperature ranges from 449.7°C to 2036.6°C. The temperature profile at 15 seconds is shown in Figure 10. At 15 seconds the temperature ranges from 449.9°C to 897.6°C. *Figure 11* shows a peak temperature of about 2,100°C after 12,030 seconds. The minimum temperature is about 507°C.

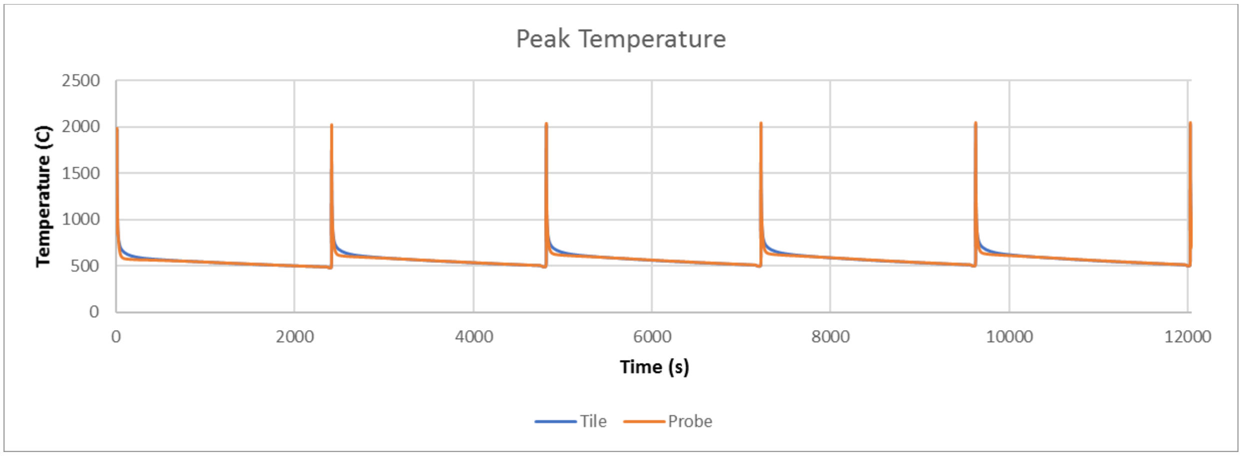

Figure 8. Case 1 - Temperature vs Time for Case with Heat Flux across 3 Blocks Toroidally

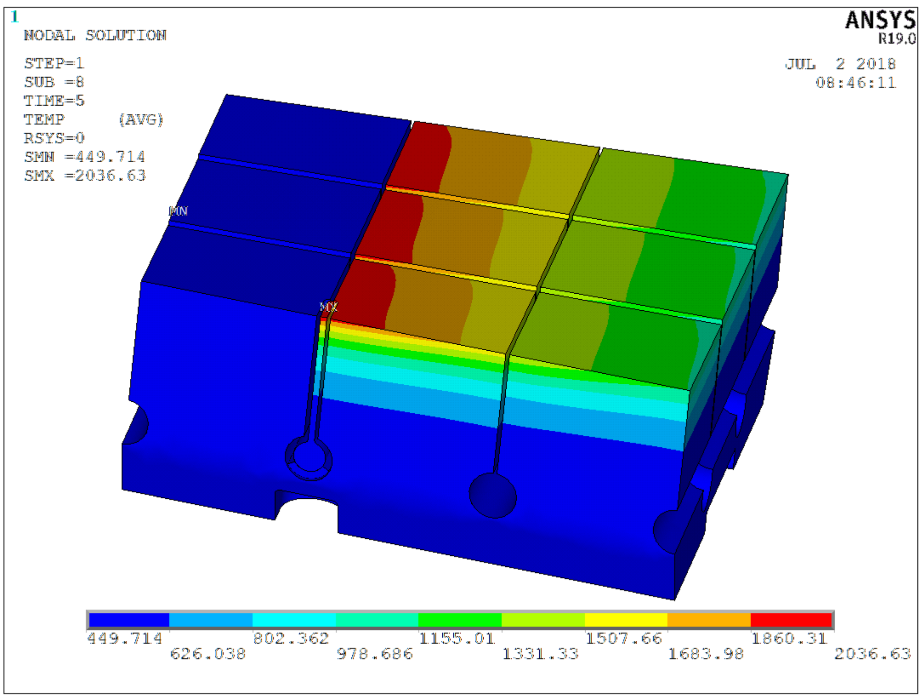

Figure 9. Case 1 - Temperature Profile at 5 seconds

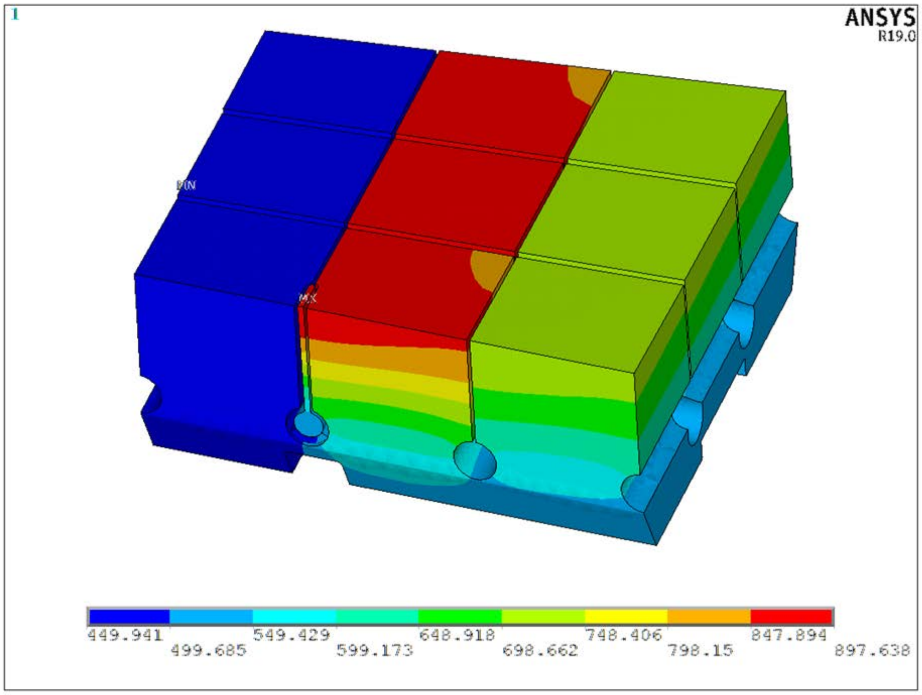

Figure 10. Case 1 - Temperature Profile at 15 seconds

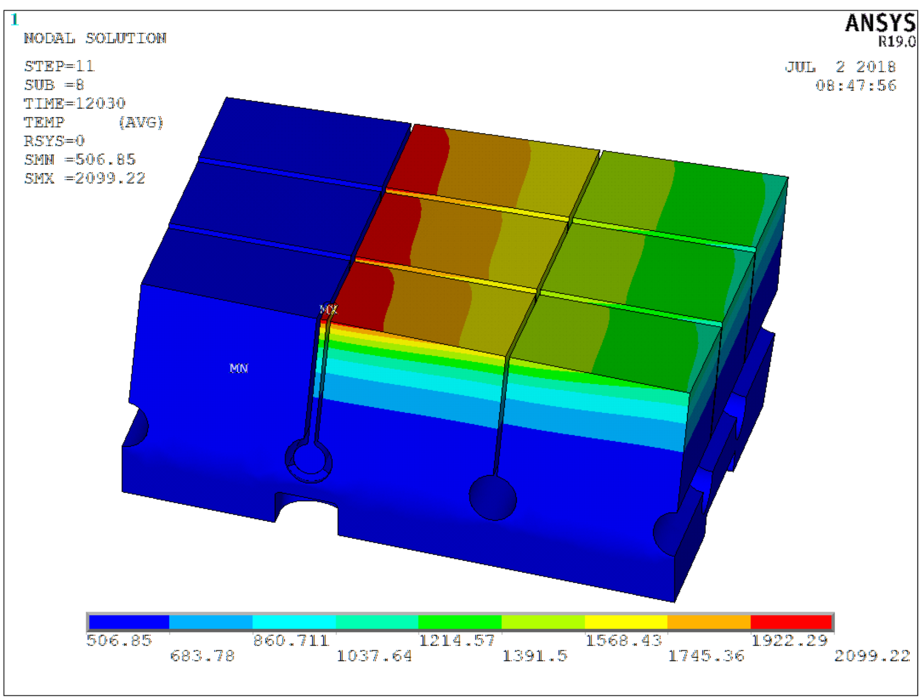

Figure 11. Case 1 - Temperature Profile at 12,030 seconds

The results of temperature vs time for the second case, with the heat flux applied across 2 blocks toroidally, are shown in *Figure 12*. The temperature profile at 5 seconds is shown in *Figure 13*. At 5 seconds the temperature ranges from 449.7°C to 2037.2°C. The temperature profile at 15 seconds is shown in Figure 14. At 15 seconds the temperature ranges from 449.5°C to 897.7°C. *Figure 15* shows a peak temperature of about 2,063°C after 12,030 seconds. The minimum temperature is about 471°C.

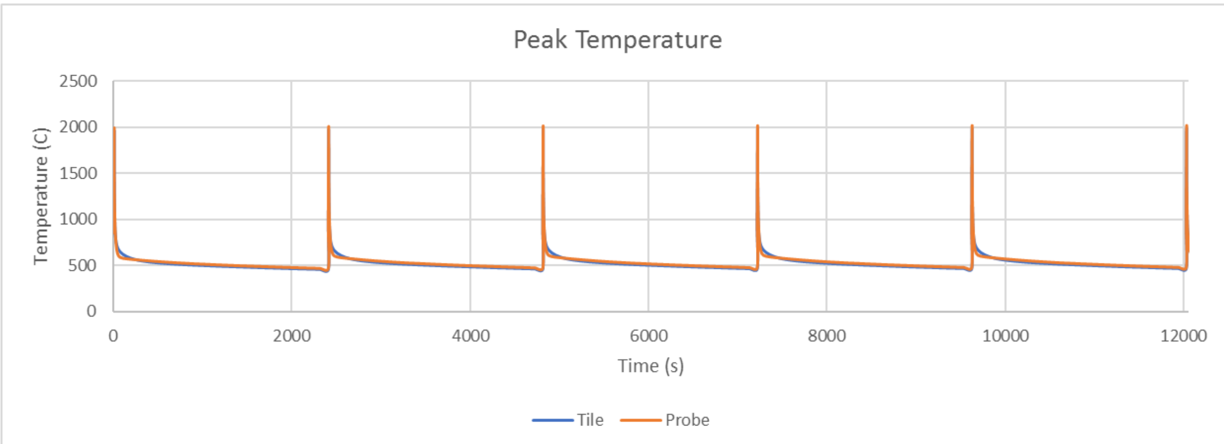

Figure 12. Case 2 - Temperature vs Time for Case with Heat Flux across 2 Blocks Toroidally

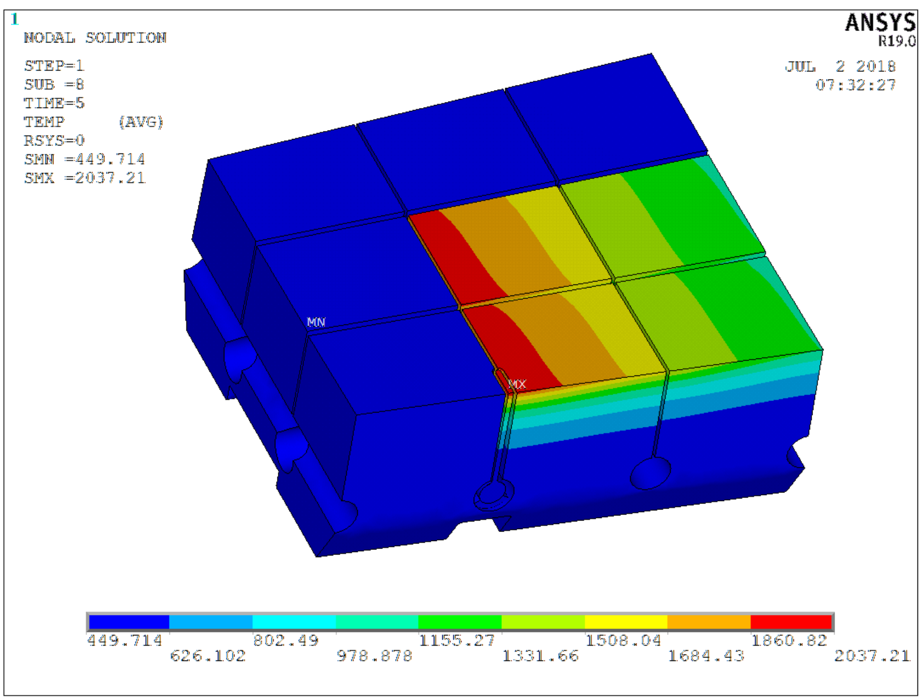

Figure 13. Case 2 - Temperature Profile at 5 seconds

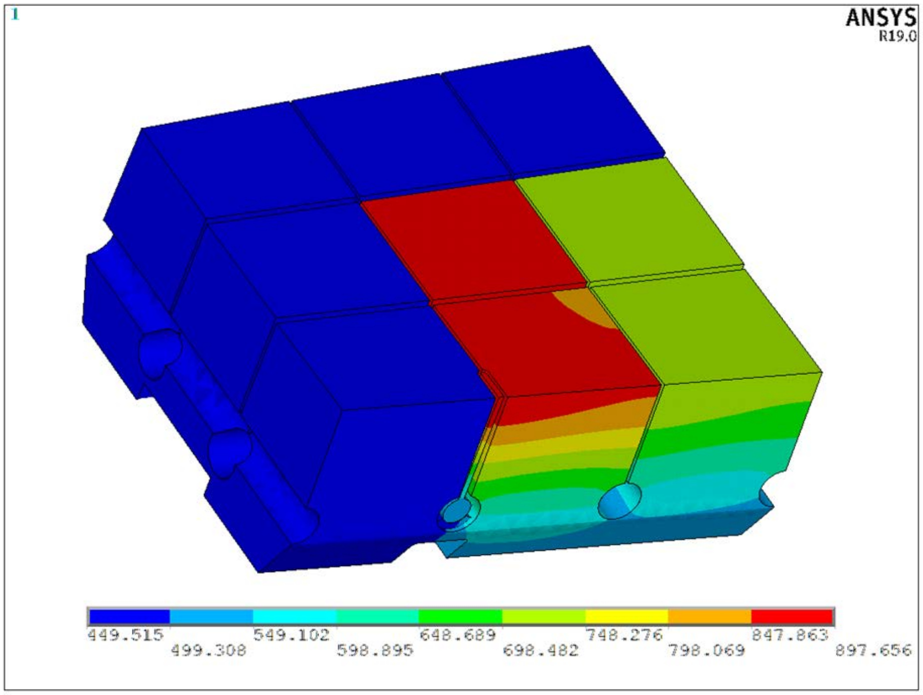

Figure 14. Case 2 - Temperature Profile at 15 seconds

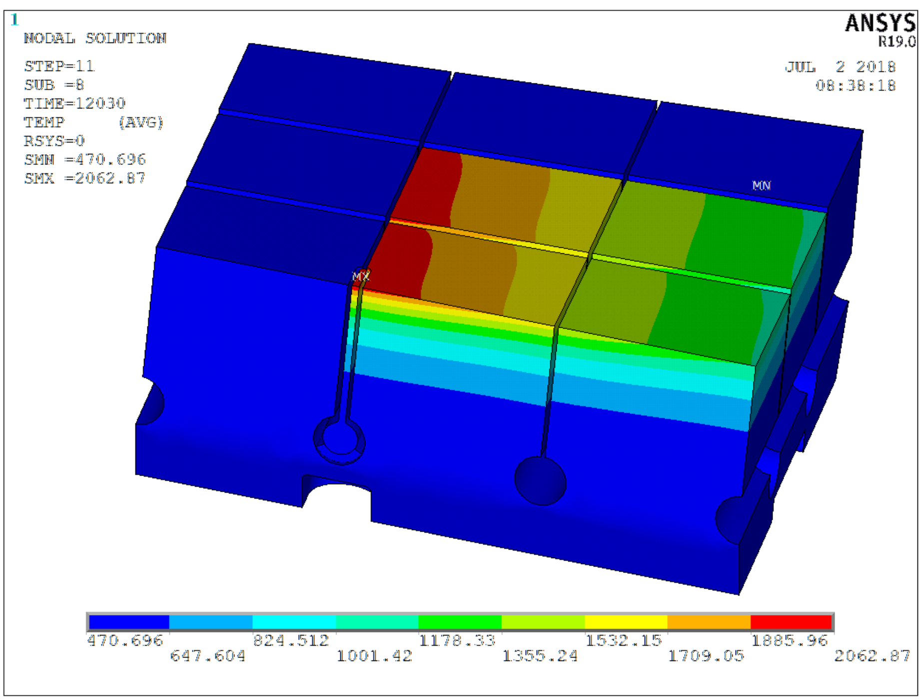

Figure 15. Case 2 - Temperature Profile at 12,030 seconds

5.2 Structural Results

The structural results for the two loading conditions are shown below at 5 seconds and 15 seconds. The loading conditions include cases with the heat flux applied across 3 blocks toroidally and across 2 blocks toroidally.

5.2.1 Case 1 - Heat Flux Applied across 3 Blocks Toroidally

The results show that all the stresses are well below the strength of the materials. Figure 16 and Figure 17 show the results of the maximum and minimum principal stresses in the Langmuir probe after the first 5 second pulse. Figure 18 shows the von Mises stress in the probe after heating for 5 seconds. The left side figures show the stresses in the whole probe, which includes local stresses around the hole. The right side of the figures show the stresses in the top section of the probe. The results show that even considering the local stresses, the probe stresses are all below the strength of the graphite. The maximum tensile stress of 13.8 MPa is well below the ultimate tensile strength of 38 MPa and the compressive stress of 14.7 MPa is well below the ultimate compressive strength of 130 MPa.

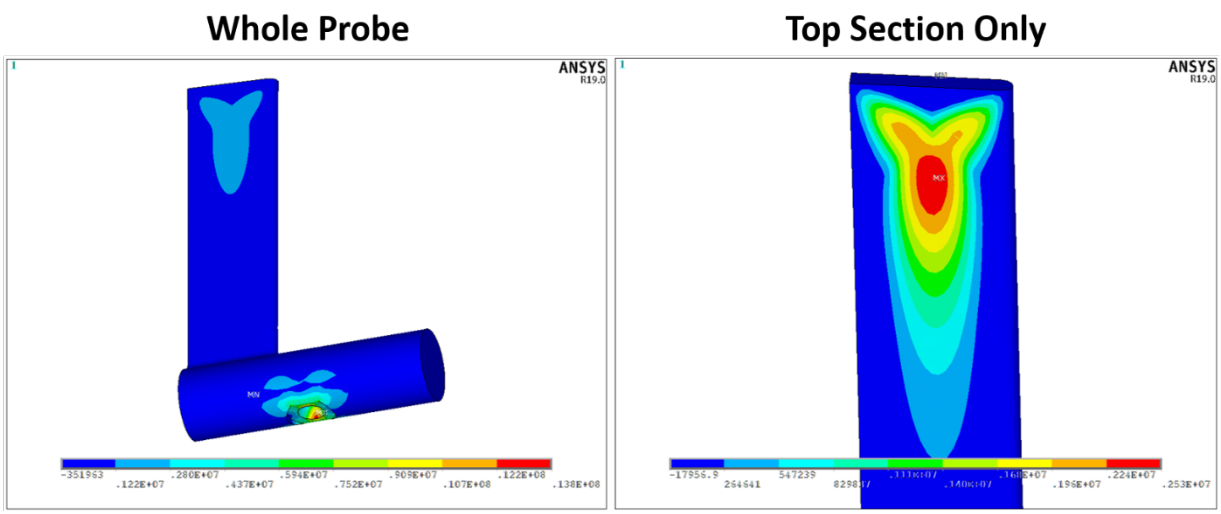

Figure 16. Case 1 - Max Principal Stress in Probe at 5 seconds

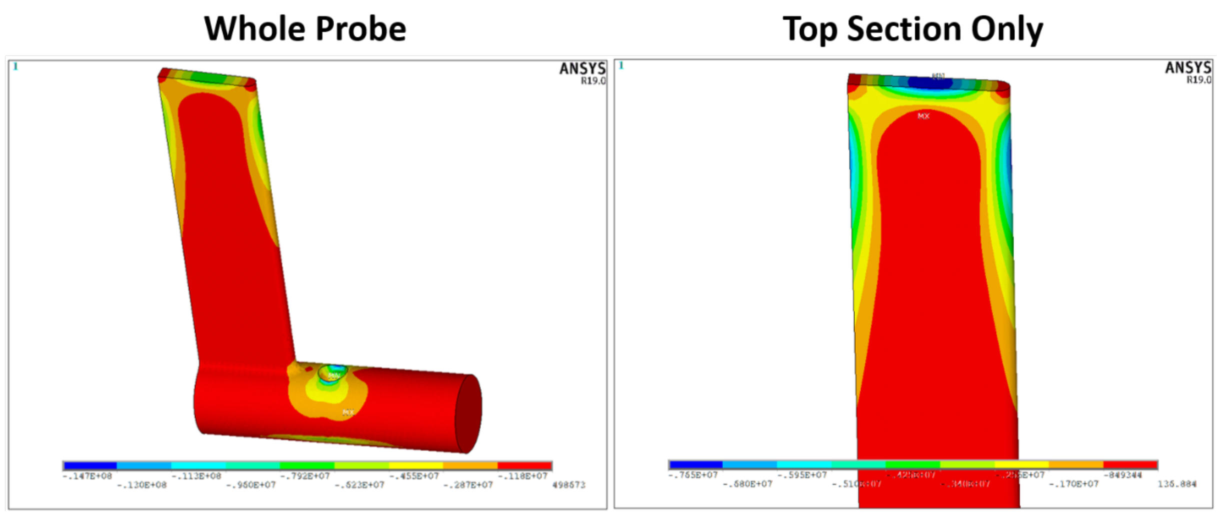

Figure 17. Case 1 - Min Principal Stress in Probe at 5 seconds

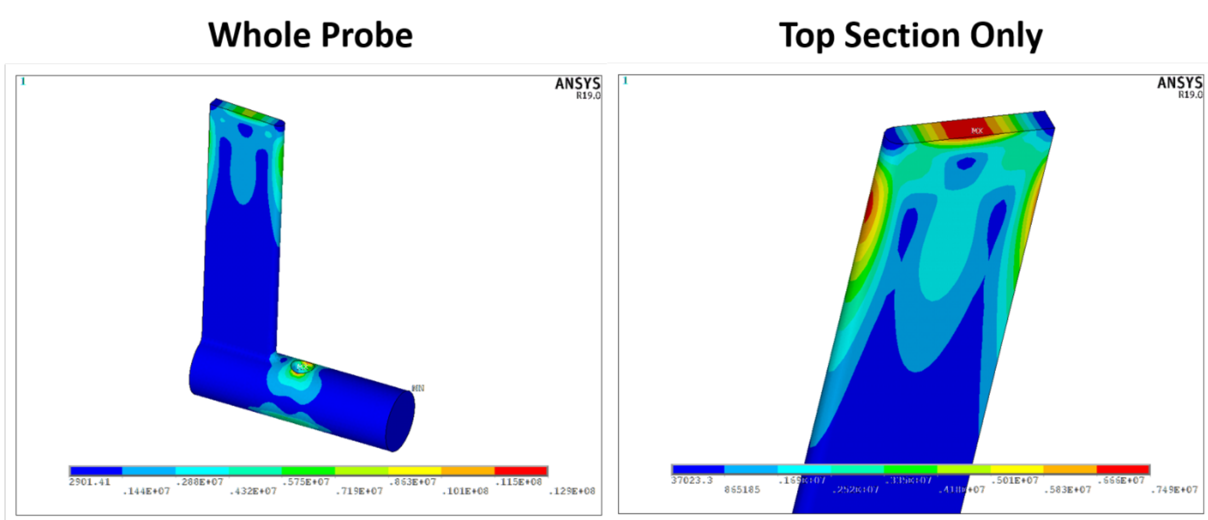

Figure 18. Case 1 - Von Mises Stress in Probe at 5 seconds

Figure 19 and Figure 20 show the results of the maximum and minimum principal stresses in the tile after the first 5 second pulse. Figure 21 shows the von Mises stresses in the tile. The results show that the tile stresses are all below the strength of the graphite. The maximum tensile stress of 5.76 MPa is well below the ultimate tensile strength of 38 MPa and the compressive stress of 43.8 MPa is well below the ultimate compressive strength of 130 MPa.

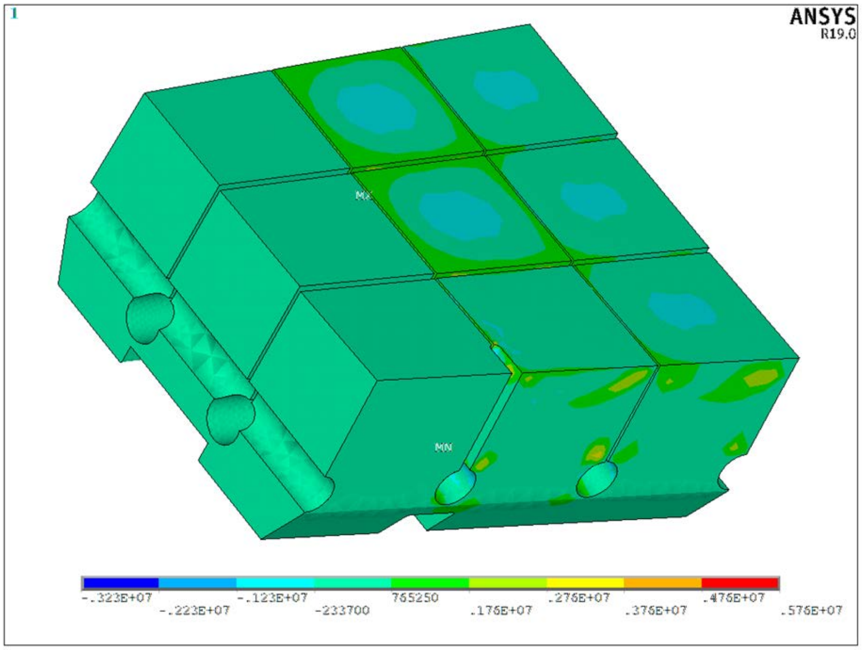

Figure 19. Case 1 - Tile Max Principal Stress at 5 seconds

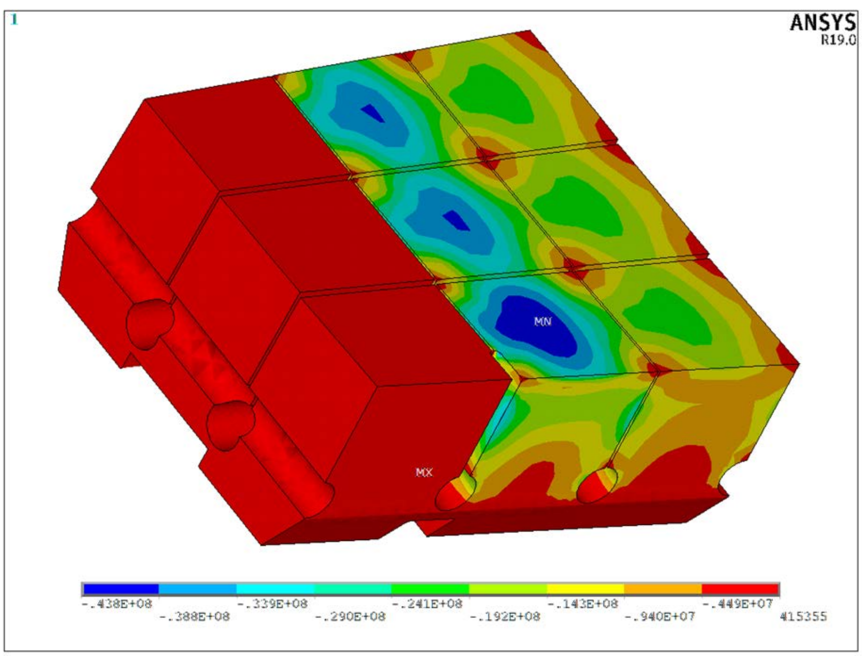

Figure 20. Case 1 - Tile Min Principal Stress at 5 seconds

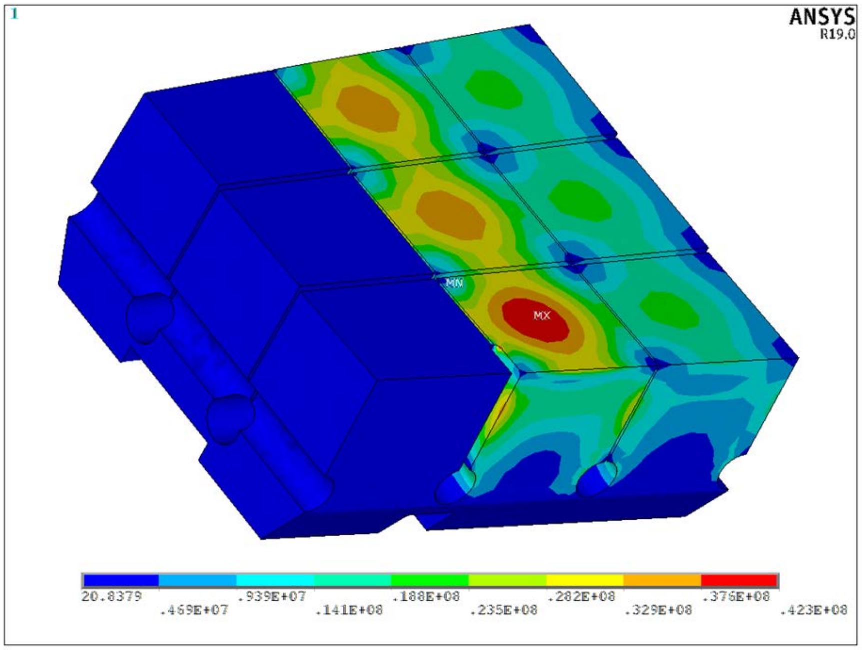

Figure 21. Case 1 - Tile Von Mises Stress at 5 seconds

Figure 22 shows the results of the maximum and minimum principal stresses in the Macor base support after the first 5 second pulse. The results show that the support stresses are all below the strength of the Macor. The maximum tensile stress of 7.34 MPa is well below the ultimate tensile strength (I am not sure what value to use for the ultimate tensile strength) and the compressive stress of 17.9 MPa is well below the ultimate compressive strength of 345 MPa.

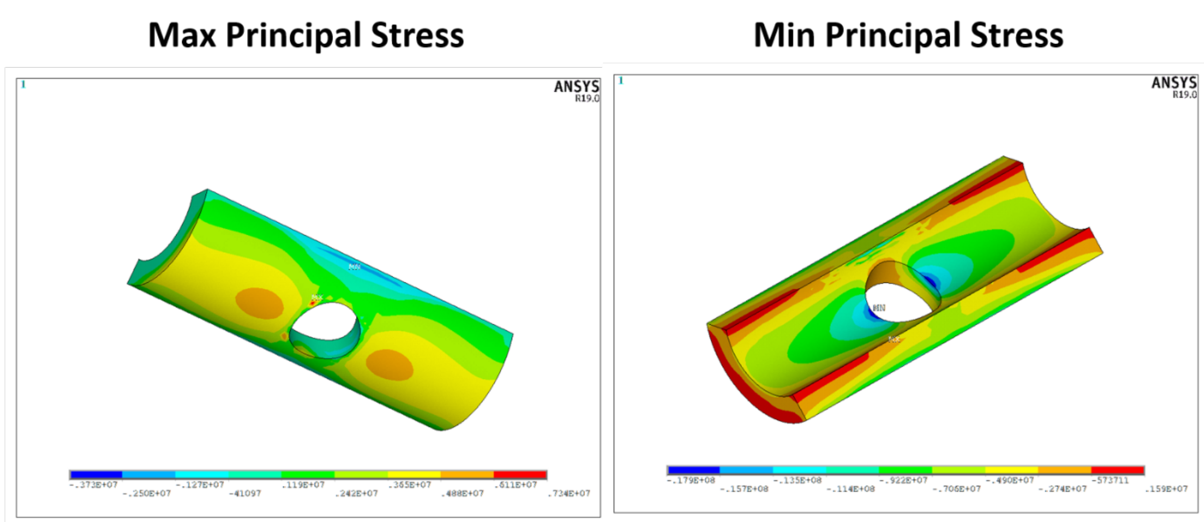

Figure 22. Case 1 - Macor Base Support Principal Stresses at 5 seconds

Figure 23 and Figure 24 show the results of the maximum and minimum principal stresses in the Langmuir probe after 15 seconds. Figure 25 shows the von Mises stress in the probe after 15 seconds. The left side figures show the stresses in the whole probe, which includes local stresses around the hole. The right side of the figures show the stresses in the top section of the probe. The results show that even considering the local stresses, the probe stresses are all below the strength of the graphite. The maximum tensile stress of 14.4 MPa is well below the ultimate tensile strength of 38 MPa and the compressive stress of 15.3 MPa is well below the ultimate compressive strength of 130 MPa.

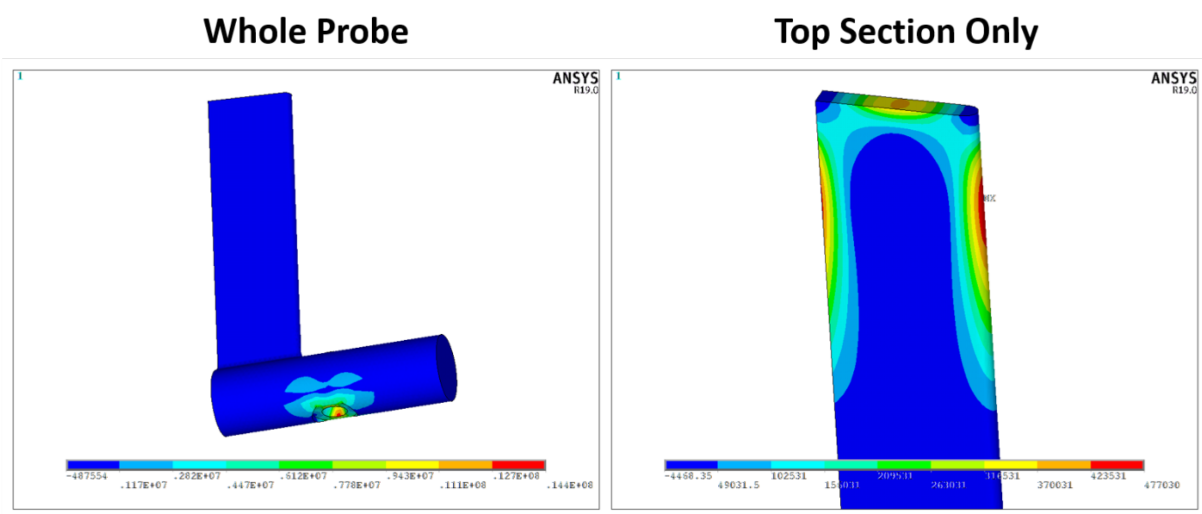

Figure 23. Case 1 - Max Principal Stress in Probe at 15 seconds

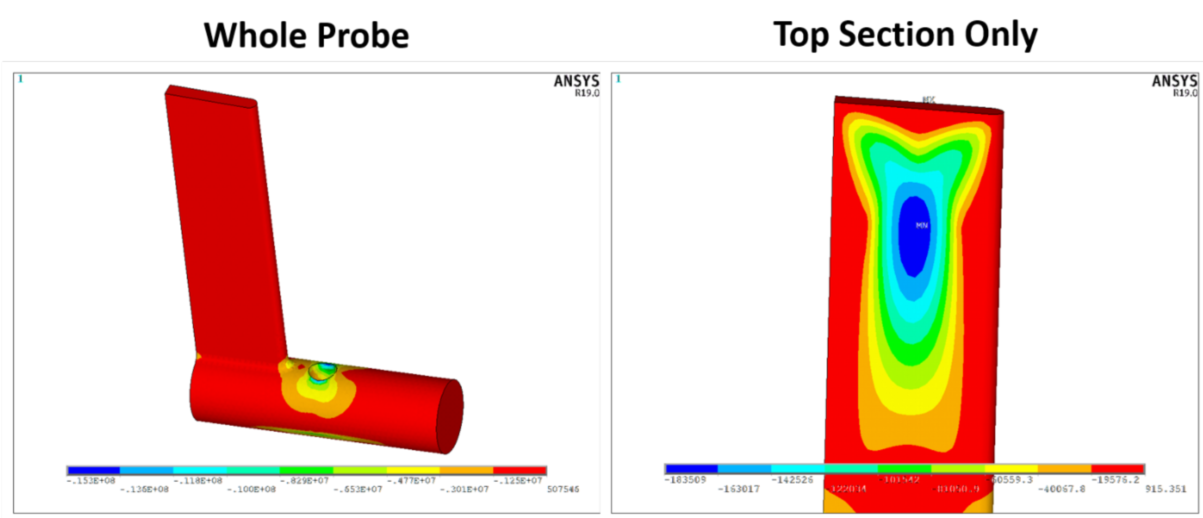

Figure 24. Case 1 - Min Principal Stress in Probe at 15 seconds

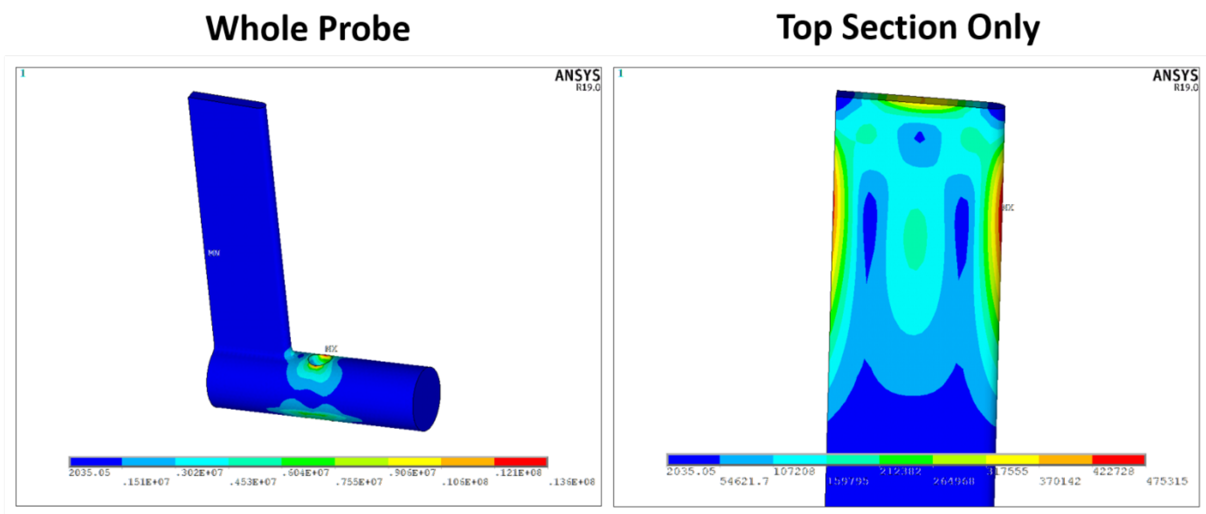

Figure 25. Case 1 - Von Mises Stress in Probe at 15 seconds

Figure 26 and Figure 27 show the results of the maximum and minimum principal stresses in the tile after 15 seconds. Figure 28 shows the von Mises stresses in the tile. The results show that the tile stresses are all below the strength of the graphite. The maximum tensile stress of 5.23 MPa is well below the ultimate tensile strength of 38 MPa and the compressive stress of 9.84 MPa is well below the ultimate compressive strength of 130 MPa.

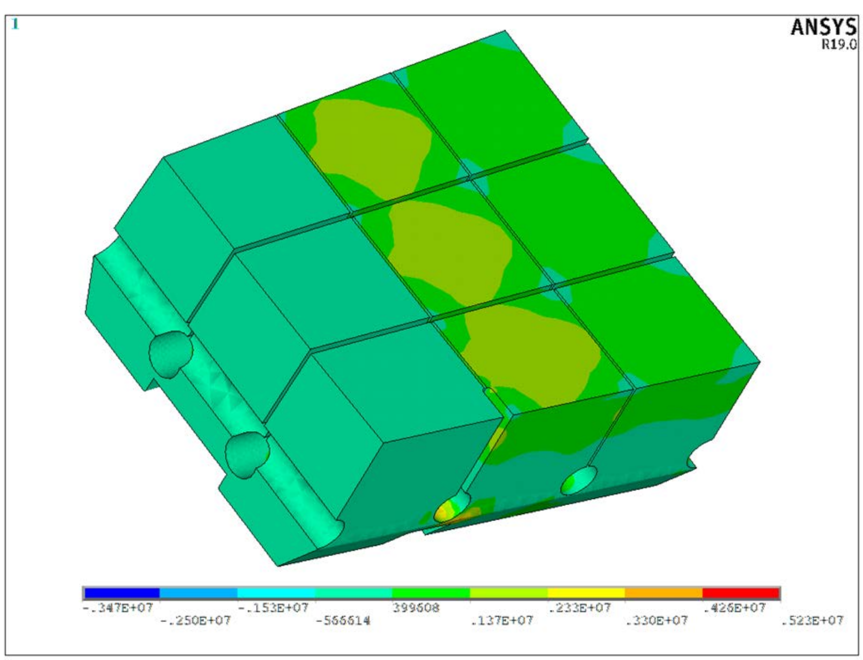

Figure 26. Case 1 - Tile Max Principal Stress at 15 seconds

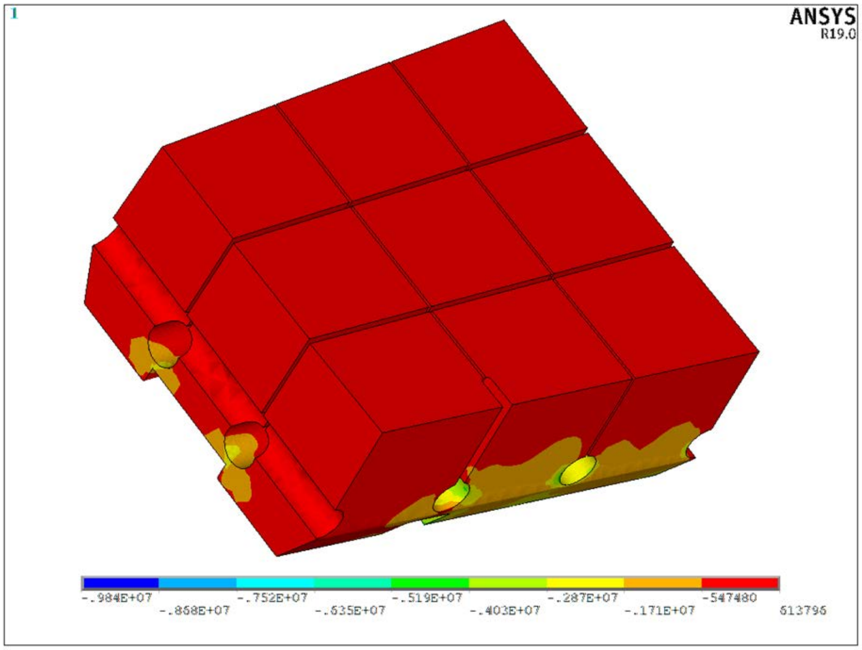

Figure 27. Case 1 - Tile Min Principal Stress at 15 seconds

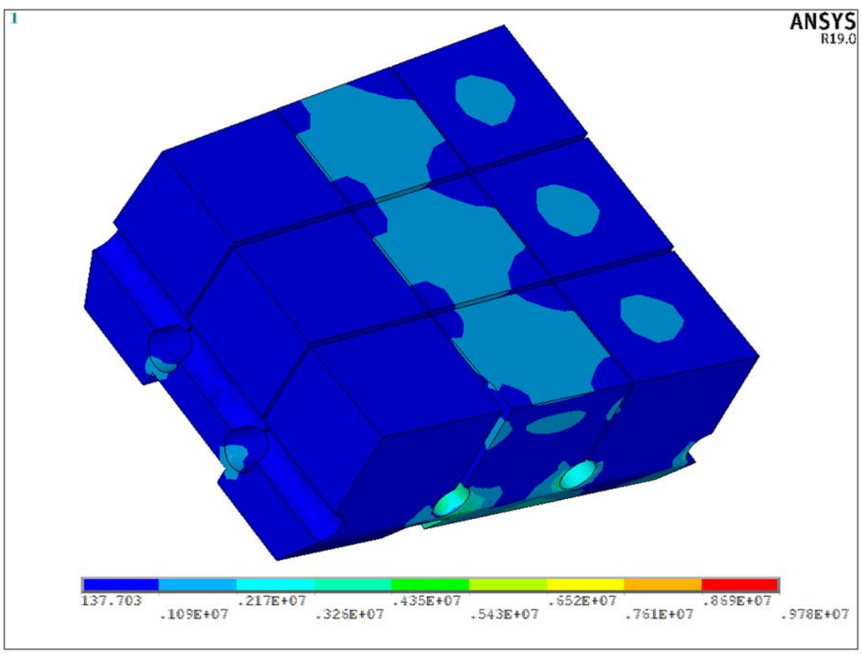

Figure 28. Case 1 - Tile Von Mises Stress at 15 seconds

Figure 29 shows the results of the maximum and minimum principal stresses in the Macor base support after 15 seconds. The results show that the support stresses are all below the strength of the Macor. The maximum tensile stress of 8.05 MPa is well below the ultimate tensile strength (I am not sure what value to use for the ultimate tensile strength) and the compressive stress of 20.2 MPa is well below the ultimate compressive strength of 345 MPa.

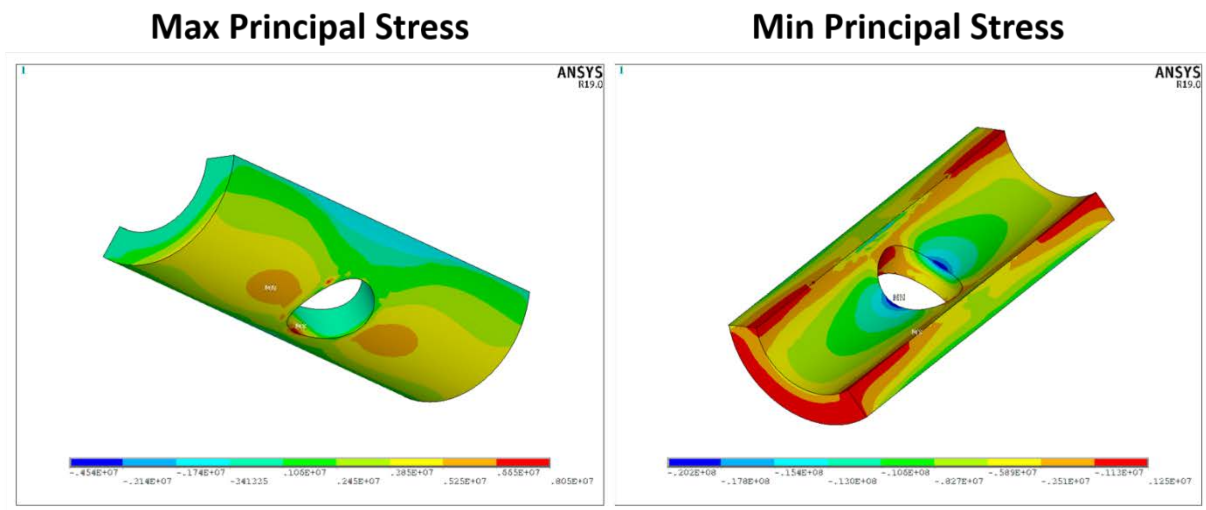

Figure 29. Case 1 - Macor Base Support Principal Stresses at 15 seconds

5.2.2 Case 2 - Heat Flux Applied across 2 Blocks Toroidally

The results show that all the stresses are well below the strength of the materials. Figure 30 and Figure 31 show the results of the maximum and minimum principal stresses in the Langmuir probe after the first 5 second pulse. Figure 32 shows the von Mises stress in the probe after heating for 5 seconds. The left side figures show the stresses in the whole probe, which includes local stresses around the hole. The right side of the figures show the stresses in the top section of the probe. The results show that even considering the local stresses, the probe stresses are all below the strength of the graphite. The maximum tensile stress of 13.8 MPa is well below the ultimate tensile strength of 38 MPa and the compressive stress of 14.6 MPa is well below the ultimate compressive strength of 130 MPa.

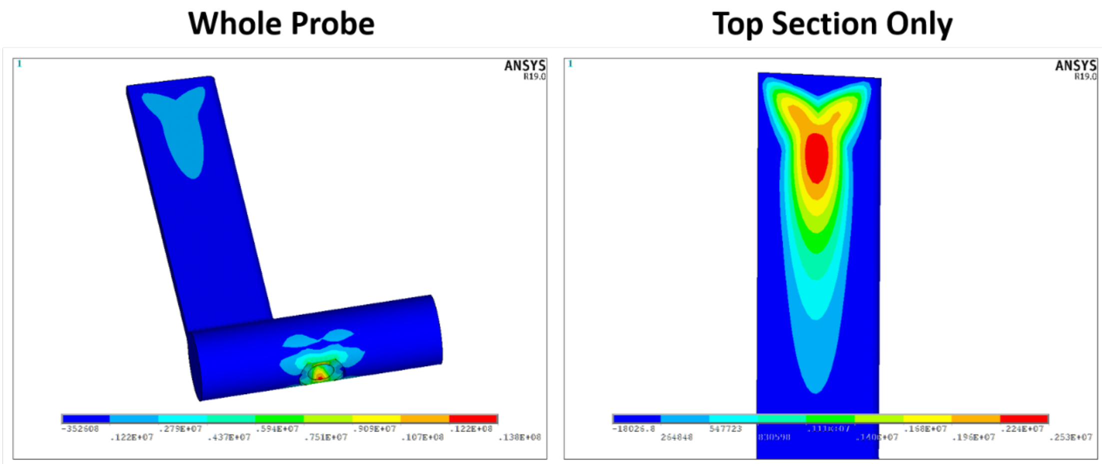

Figure 30. Case 2 - Max Principal Stress in Probe at 5 seconds

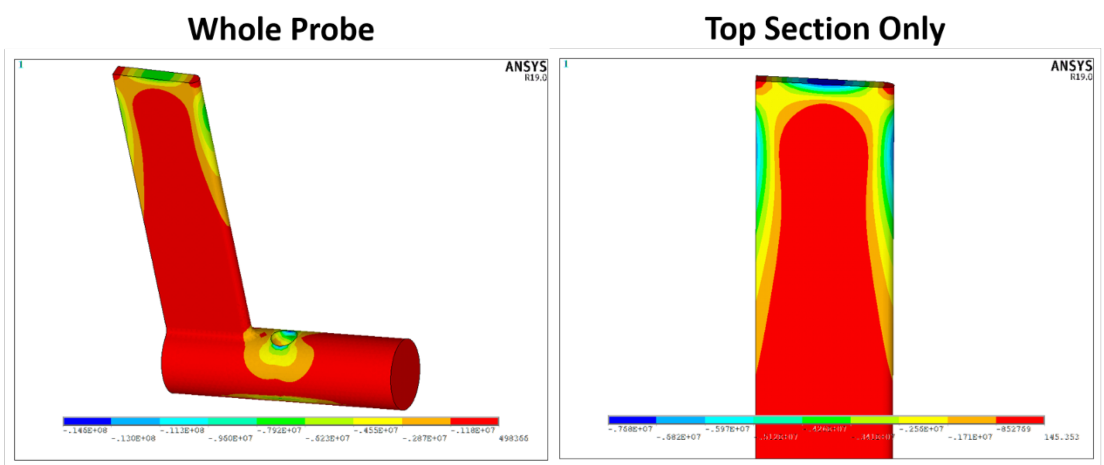

Figure 31. Case 2 - Min Principal Stress in Probe at 5 seconds

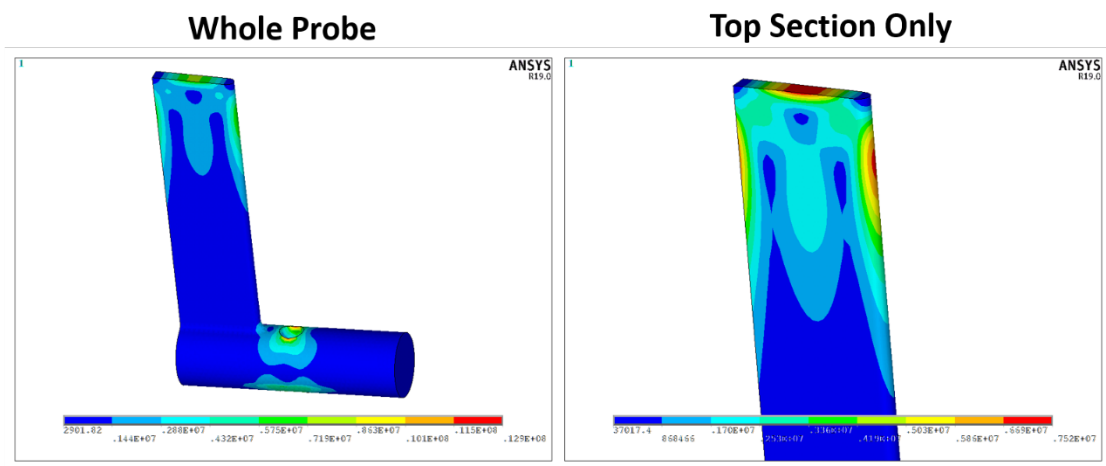

Figure 32. Case 2 - Von Mises Stress in Probe at 5 seconds

Figure 33 and Figure 34 show the results of the maximum and minimum principal stresses in the tile after the first 5 second pulse. Figure 35 shows the von Mises stresses in the tile. The results show that the tile stresses are all below the strength of the graphite. The maximum tensile stress of 5.76 MPa is well below the ultimate tensile strength of 38 MPa and the compressive stress of 43.8 MPa is well below the ultimate compressive strength of 130 MPa.

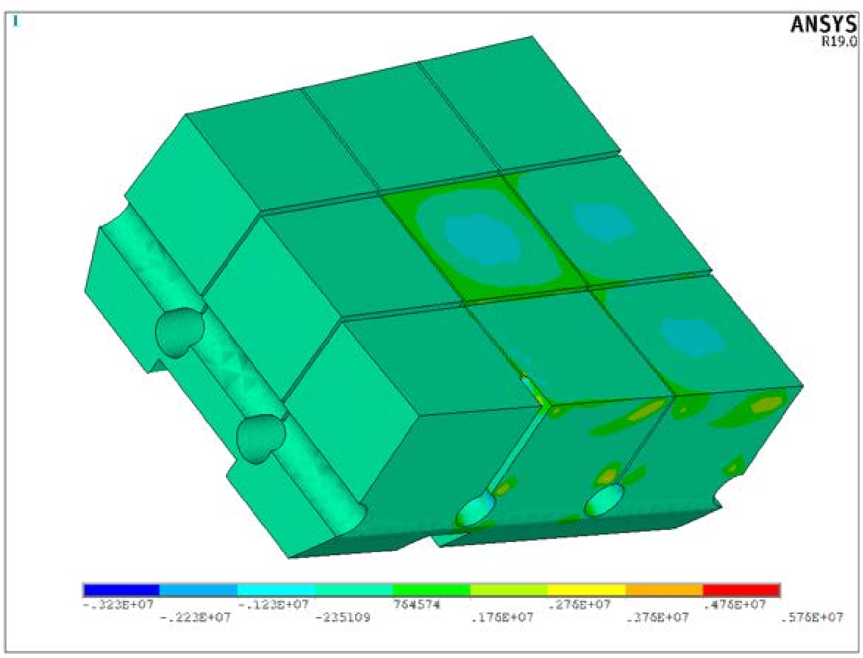

Figure 33. Case 2 - Tile Max Principal Stress at 5 seconds

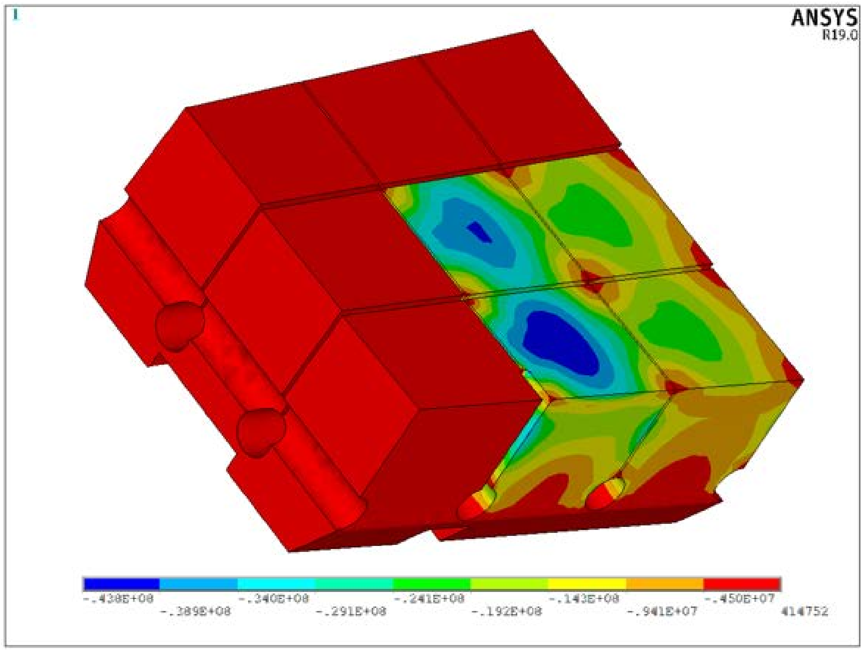

Figure 34. Case 2 - Tile Min Principal Stress at 5 seconds

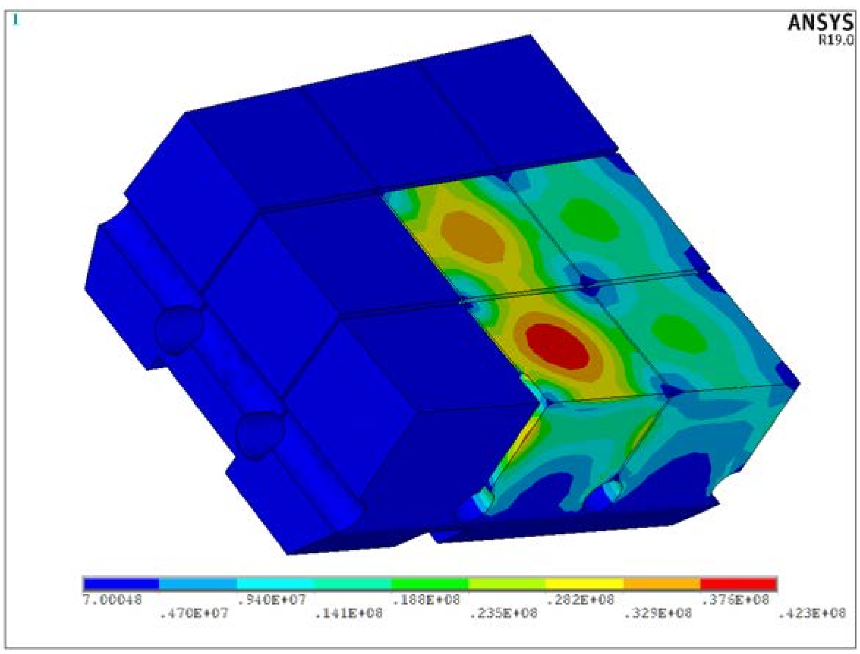

Figure 35. Case 2 - Tile Von Mises Stress at 5 seconds

Figure 36 shows the results of the maximum and minimum principal stresses in the Macor base support after the first 5 second pulse. The results show that the support stresses are all below the strength of the Macor. The maximum tensile stress of 7.34 MPa is well below the ultimate tensile strength (I am not sure what value to use for the ultimate tensile strength) and the compressive stress of 17.8 MPa is well below the ultimate compressive strength of 345 MPa.

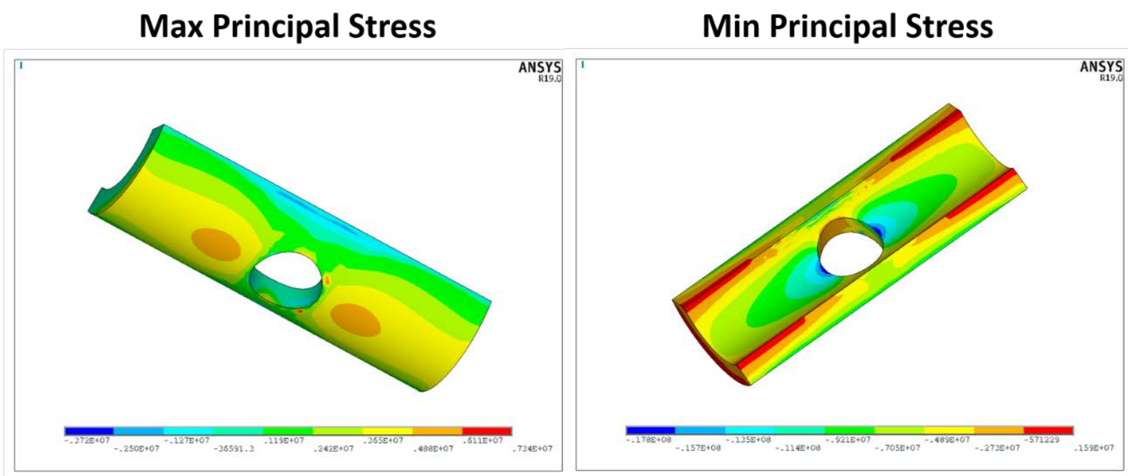

Figure 36. Case 2 - Macor Base Support Principal Stresses at 5 seconds

Figure 37 and Figure 38 show the results of the maximum and minimum principal stresses in the Langmuir probe after 15 seconds. Figure 39 shows the von Mises stress in the probe after 15 seconds. The left side figures show the stresses in the whole probe, which includes local stresses around the hole. The right side of the figures show the stresses in the top section of the probe. The results show that even considering the local stresses, the probe stresses are all below the strength of the graphite. The maximum tensile stress of 14.3 MPa is well below the ultimate tensile strength of 38 MPa and the compressive stress of 15.3 MPa is well below the ultimate compressive strength of 130 MPa.

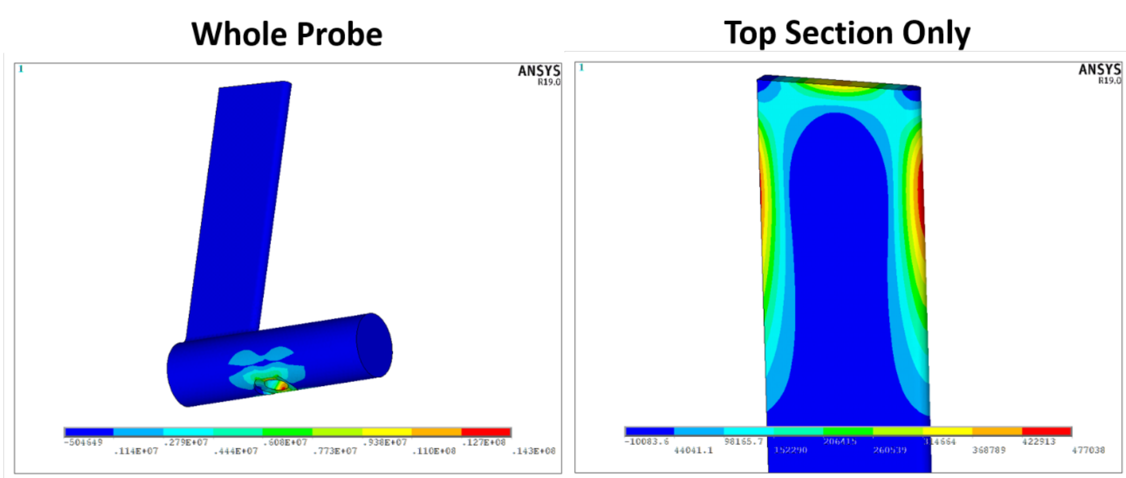

Figure 37. Case 2 - Max Principal Stress in Probe at 15 seconds

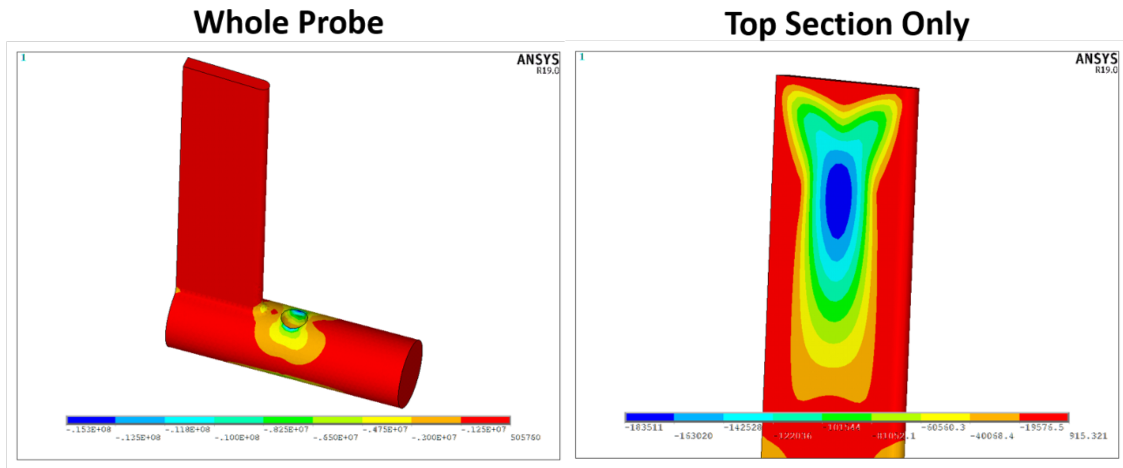

Figure 38. Case 2 - Min Principal Stress in Probe at 15 seconds

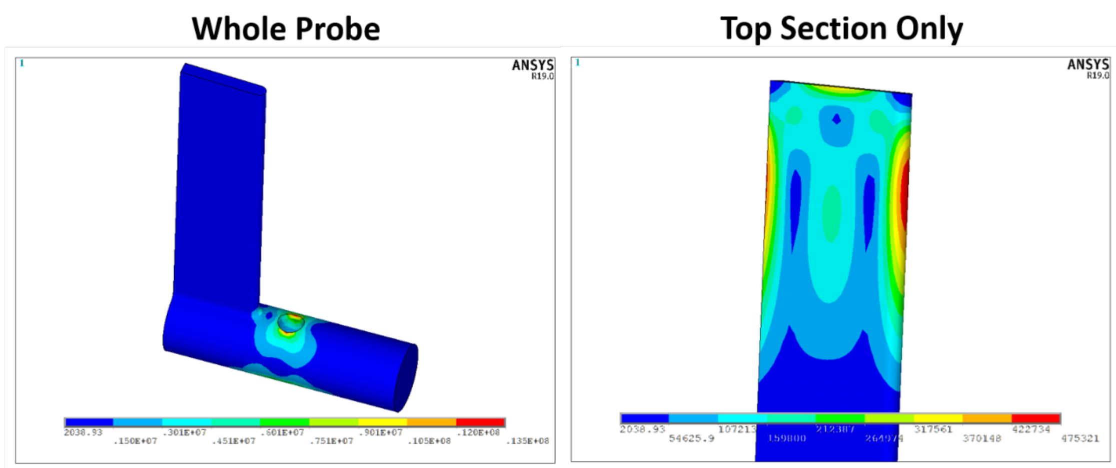

Figure 39. Case 2 - Von Mises Stress in Probe at 15 seconds

Figure 40 and Figure 41 show the results of the maximum and minimum principal stresses in the tile after 15 seconds. Figure 42 shows the von Mises stresses in the tile. The results show that the tile stresses are all below the strength of the graphite. The maximum tensile stress of 7.06 MPa is well below the ultimate tensile strength of 38 MPa and the compressive stress of 13.0 MPa is well below the ultimate compressive strength of 130 MPa.

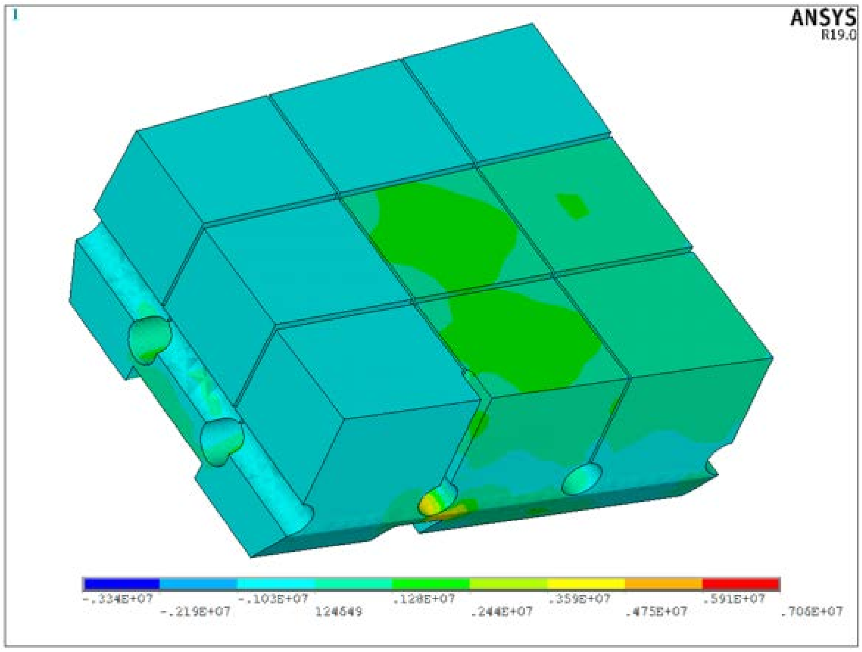

Figure 40. Case 2 - Tile Max Principal Stress at 15 seconds

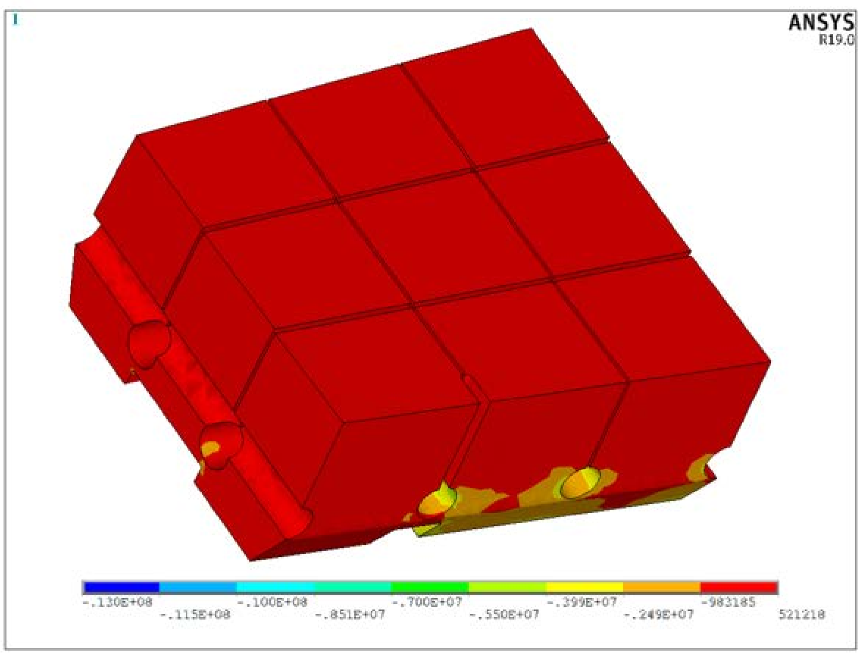

Figure 41. Case 2 - Tile Min Principal Stress at 15 seconds

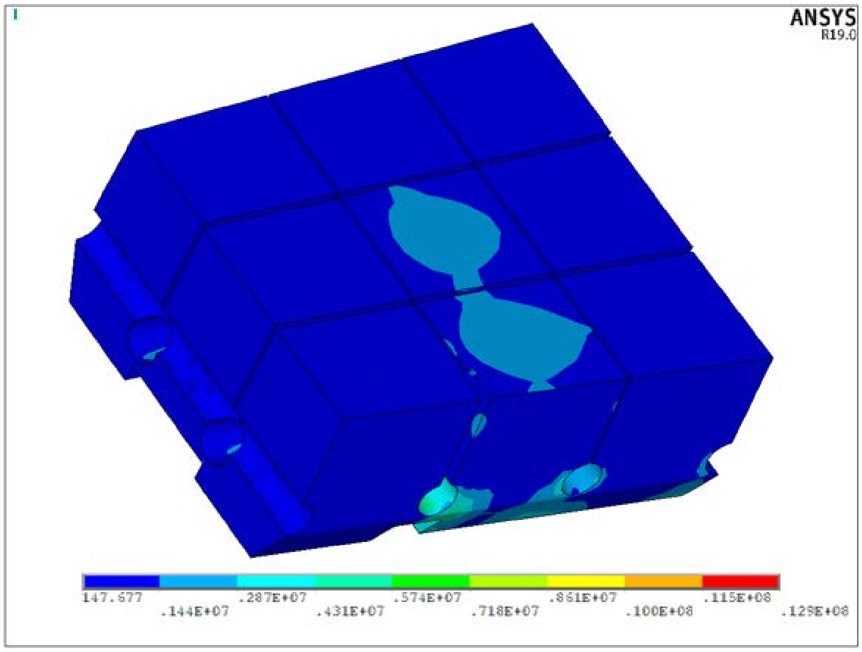

Figure 42. Case 2 - Tile Von Mises Stress at 15 seconds

Figure 43 shows the results of the maximum and minimum principal stresses in the Macor base support after 15 seconds. The results show that the support stresses are all below the strength of the Macor. The maximum tensile stress of 7.76 MPa is well below the ultimate tensile strength (I am not sure what value to use for the ultimate tensile strength) and the compressive stress of 19.5 MPa is well below the ultimate compressive strength of 345 MPa.

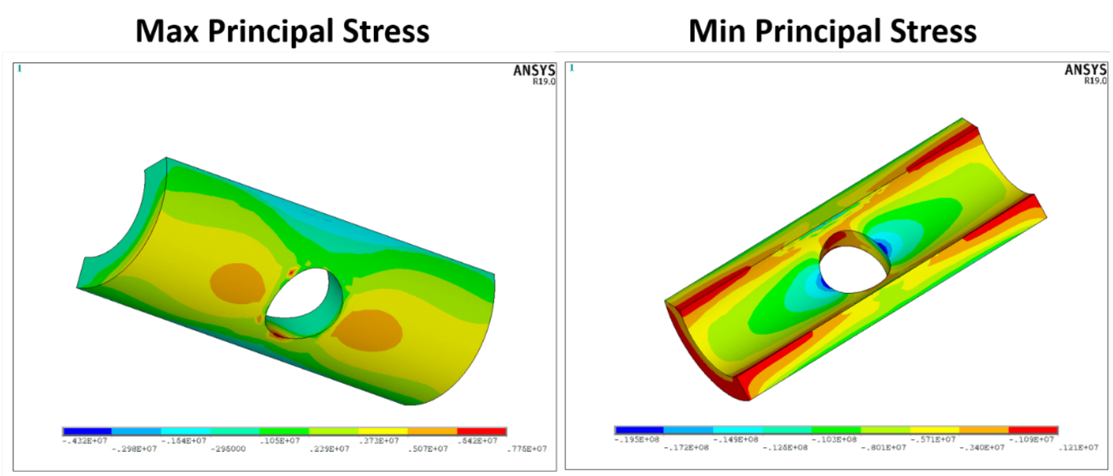

Figure 43. Case 2 - Macor Base Support Principal Stresses at 15 seconds

6.0 Summary

A summary of the peak maximum and minimum principal stresses are shown in Table 2 for Cases 1 and 2, at 5 seconds and at 15 seconds. The results show that all the stresses are well below the ultimate strength of the materials. The material assumed for the probe and the tile is SGL R6510, with an ultimate tensile strength of 38 MPa and an ultimate compressive strength of 130 MPa. The material assumed for the base support is Macor with an ultimate compressive strength of 345 MPa.

Table 2. Summary of Maximum and Minimum Principal Stresses (MPa)

	Case 1 at 5 s	**Case 1 at 15 s**	**Case 2 at 5 s**	**Case 2 at 15 s**
Probe Max Principal Stress (All) (MPa)	13.8	14.4	13.8	14.3
Probe Max Principal Stress (Top) (MPa)	2.53	0.48	2.53	0.48
Probe Min Principal Stress (All) (MPa)	-14.7	-15.3	-14.6	-15.3
Probe Min Principal Stress (Top) (MPa)	-7.65	-0.18	-7.68	-0.18
Tile Max Principal Stress (MPa)	5.76	5.23	5.76	7.06
Tile Min Principal Stress (MPa)	-43.8	-9.84	-43.8	-13.0
Base Support Max Principal Stress (MPa)	7.34	8.05	7.34	7.76
Base Support Min Principal Stress (MPa)	-17.9	-20.2	-17.8	-19.5