Calculation No:NSTXU-CALC-11-26-00 **Revision No:0**

Title: Parametric Study of Thermocouples in OBD Row 1-2 tiles

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

The shape and depth of holes for thermocouuples in the OBD12 tiles must be close enough to the plasma surface to provide adequate thermal response, and far enough below the surface to keep thermal stresses below allowable values.

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

ANSYS v19.0

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

Drawing E-ED1408

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

Heat loads are from Rev. 0 of the PFC SRD – a conservative case.

Calculation (Calculation is either documented here or attached)

A submodel of the OBD12 tile assembly was analyzed using an ANSYS finite element model. Sigrafine R6510 was the material used. Numerous hole diameters, end configurations and depths were analyzed. A detailed report follows this page.

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

A 5/32” diameter hole drilled from the base of the tile and extending up to 1.0” from the plasma surface of the tile, with a 1/32” fillet at the bottom, results in acceptable stresses (15.6 MPa maximum principal stress, below the allowable 19.0 MPa) and allows a thermal response that can be correlated with the surface temperature of the tile. The size is adequate for the electrically isolated thermocouples that are to be used.

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

R. Ellis Robert Ellis Digitally signed by Robert Ellis Date: 2018.09.24 11:23:09 -04'00'

Preparer’s printed name, signature and date

R. Ellis Robert Ellis Digitally signed by Robert Ellis Date: 2018.09.24 11:23:32 -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

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Parametric Study of Thermocouples in OBD Row 1-2 Tiles

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1.0 INTRODUCTION

A parametric study of thermocouples in OBD row 1-2 tiles has been analyzed. Simplified models of a portion of the ODB12 graphite tiles were analyzed. The thermocouple was not modeled, but three different hole depths were analyzed with a hole diameter of 1/8 inch. The tile was analyzed with the top of the hole at 0.375 in, 0.75 in, and 1.125 in from the plasma surface. *Figure 1* shows a tile, and the section of the tile analyzed. The model consists of a portion of an SGL R6510 graphite tile. The model includes a 3 toroidal by 3 poloidal array.

Additional calculations were done that included a fillet at the top of the thermocouple hole. These cases included one case with a 5/32 inch diameter hole, with the top of the hole 0.375 in from the plasma surface, and a fillet radius of 1/64 inch. The last case was a 5/32 inch diameter hole, with a with the top of the hole 1 inch from the plasma surface, and a 1/32 inch fillet radius.

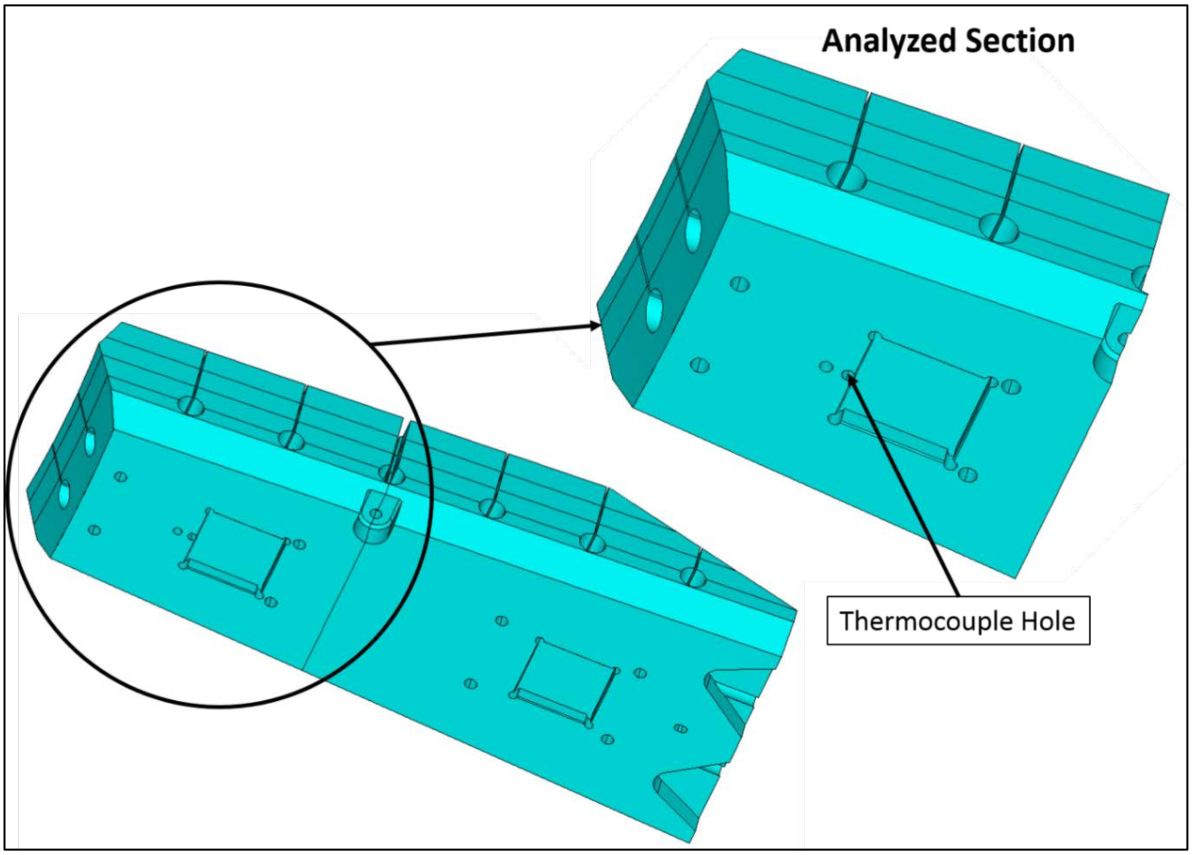

Figure 1. OBD12 Tile Section

2.0 ELEMENT INFORMATION

A portion of the OBD12 tile was meshed as shown in *Figure 2*. The model is refined in the region of the hole for the thermocouple. The figure shows the refinement on the surface above the hole. Hex elements were used in the regions where large temperature gradients are expected. The thermal model with the top of hole located 0.375 inches from the plasma surface contains 241,059 Solid90 elements and 7,199 Surf152 elements, for a total of 248,258 elements. The surface elements were included to allow radiation from the surfaces. The surface elements are shown in green in *Figure 3*. The model has 592,865 nodes. For the structural model, the Solid90 elements were converted to Solid186 elements and the Surf152 elements were eliminated, for a total of 241,059 elements. The model with the top of the hole located 0.75 inches from the plasma surface contains an additional 504 solid elements and an additional 1716 nodes, for a total of 241,563 solid elements and 594,581 nodes. The model with the top of the hole located 1.125 inches from the surface contains 420 more elements and 1430 more nodes, for a total of 241,983 solid elements and 596,011 nodes.

The last two cases include the fillet in the hole. For the case 0.375 inch from the plasma surface the thermal model from the plasma surface contains 301,632 Solid90 elements and 8,241 Surf152 elements, for a total of 309,873 elements. The model has 679,298 nodes. For the structural model, the Solid90 elements were converted to Solid186 elements and the Surf152 elements were eliminated, for a total of 301,632 elements.

For the case 1.0 inch from the plasma surface the thermal model from the plasma surface contains 324,461 Solid90 elements and 7,795 Surf152 elements, for a total of 332,256 elements. The model has 734,552 nodes. For the structural model, the Solid90 elements were converted to Solid186 elements and the Surf152 elements were eliminated, for a total of 324,461 elements.

The mesh for the 1.0 inch case is shown in Figure 4. The top surface of this mesh is the same for Case 4. The element mesh on the tile with the thermocouple ranges from about 0.0004 m to 0.0010 m. The mesh on the other tile sections was set to 0.002 m.

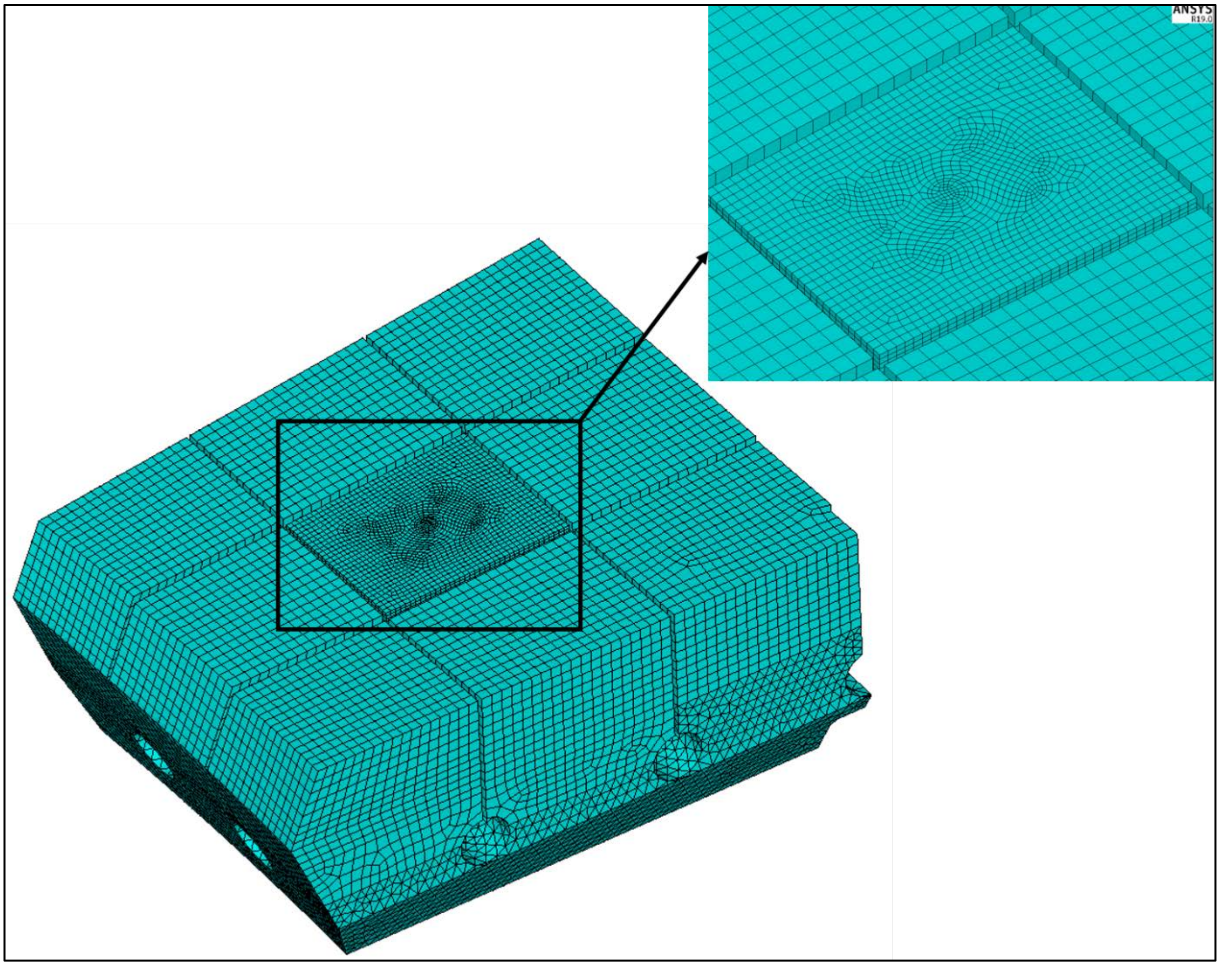

Figure 2. Model of OBD12 Tile – First 3 Cases

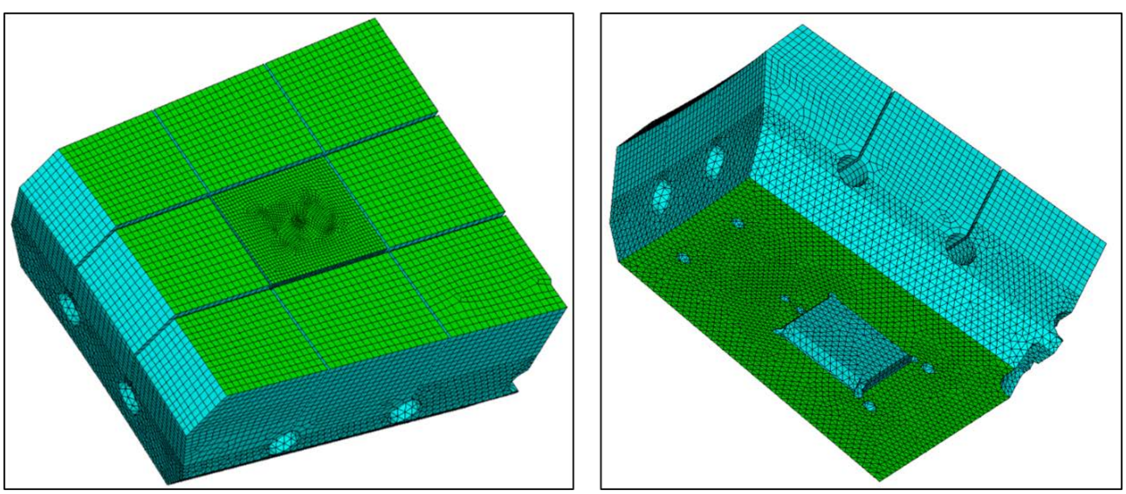

Figure 3. Radiative Surfaces shown in Green

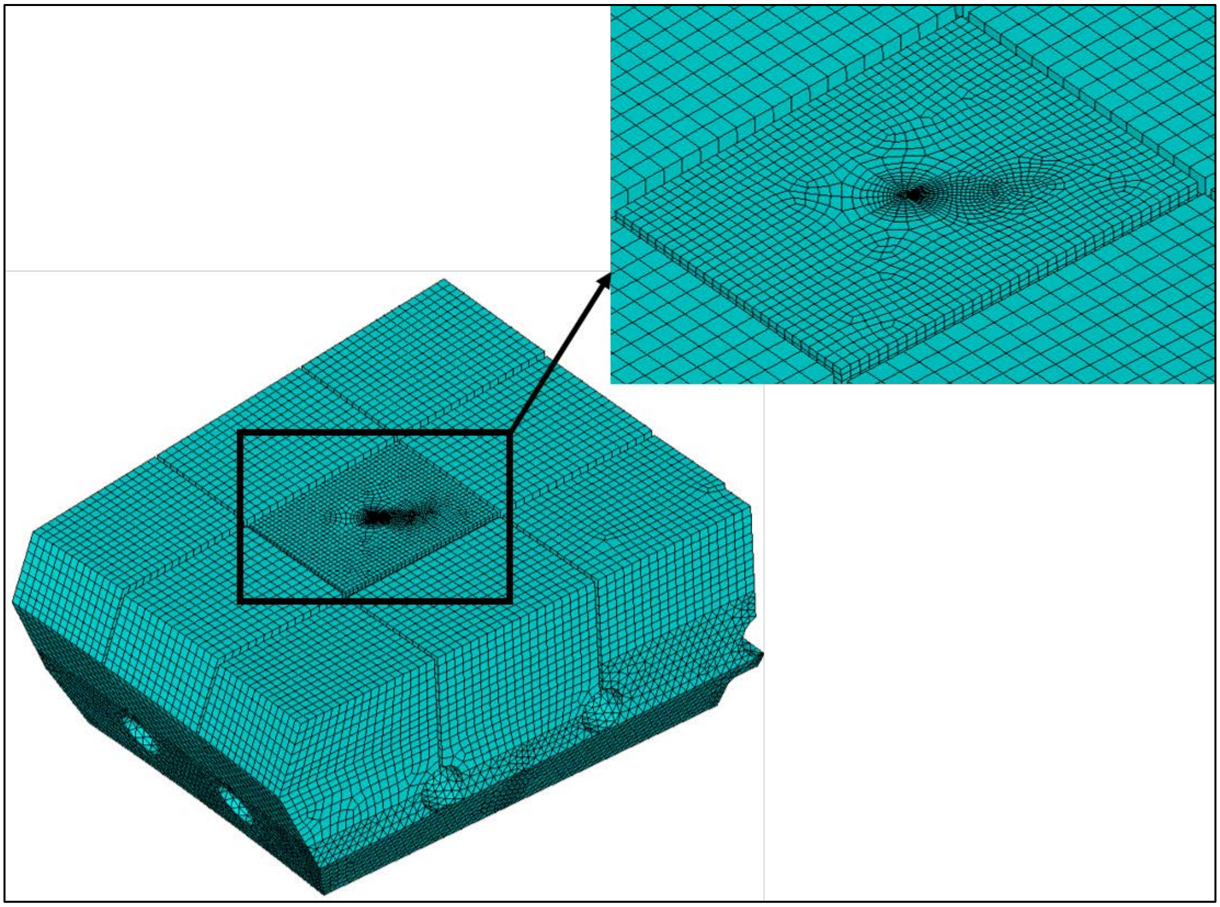

Figure 4. Model of OBD12 Tile – Last 2 Cases

3.0 MATERIALS

The material in the model consists of SGL R6510 for the OBD12 tile. The SGL R6510 material is from the PPPL workbench material file. The none temperature dependent material properties used in the analysis are shown in *Table 1*. The temperature dependent properties are shown in the figures below. Figure 5 shows the Thermal Conductivity of the SGL R6510. Figure 6 shows the Specific Heat of the SGL R6510. Figure 7 shows the temperature dependent coefficient of thermal expansion for both the SGL R6510.

Table 1. Material Properties

Material	Modulus of Elasticity	Poisson's Ratio	Density	Thermal Conductivity	Specific Heat	Ultimate Tensile Strength	Ultimate Compressive Strength
	(GPa)		(kg/m^3)	(W/m-°C)	(J/kg-°C)	(MPa)	(MPa)
SGL R6510	11.5	0.30	1830	Figure 4	Figure 5	38	130

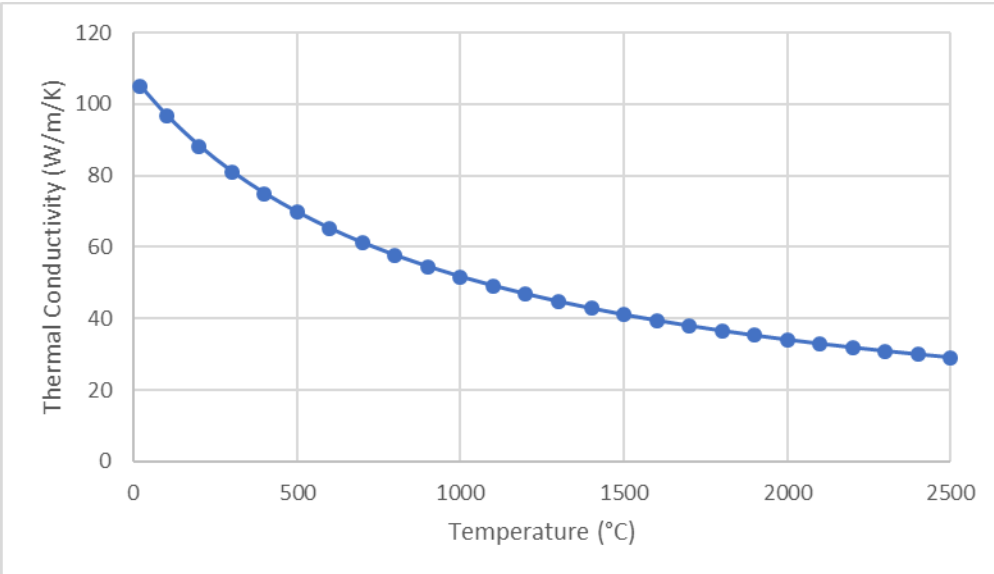

Figure 5. SGL R6510 Thermal Conductivity

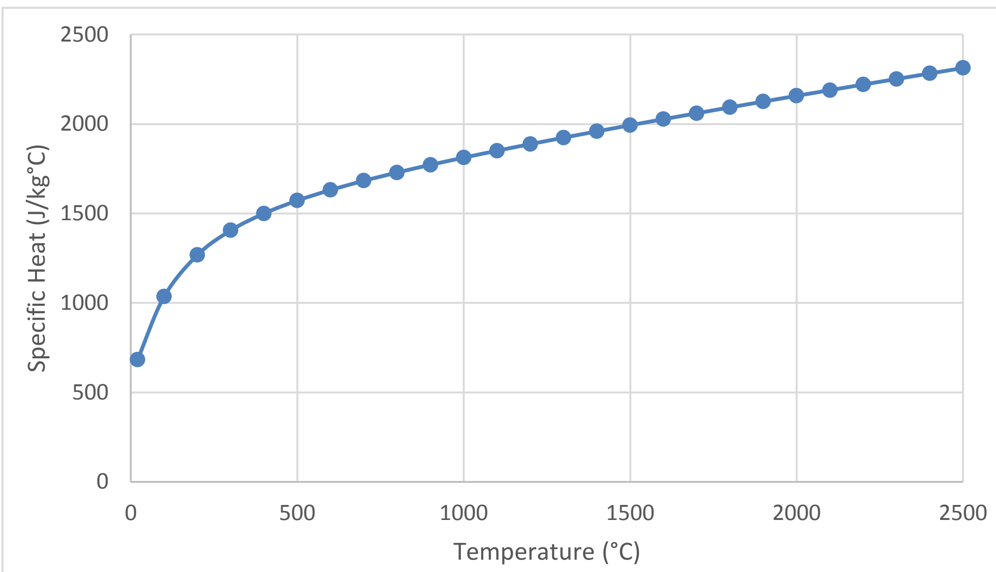

Figure 6. SGL R6510 Specific Heat

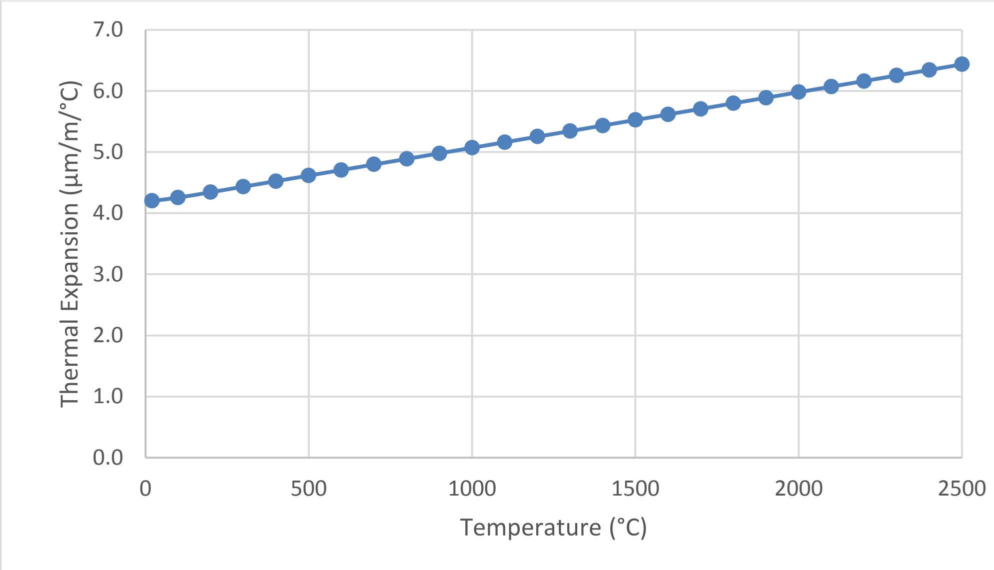

Figure 7. SGL R6510 Coefficient of Thermal Expansion

4.0 LOADS AND BOUNDARY CONDITIONS

Five different models were used for the parameter study of the thermocouple. The first three cases had different hole depths for the thermocouple (0.375 in, 0.75 in, and 1.125 in from the plasma surface). The last two cases included a fillet at the top of the thermocouple hole. Case 4 was a hole that started 0.375 from the plasma surface with a 1/64 inch fillet. Case 5 was a hole that started 1 inch from the plasma surface with a 1/32 inch fillet.

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 edge of the tile with the thermocouple hole as shown in *Figure 8*. This load was applied to all five models.

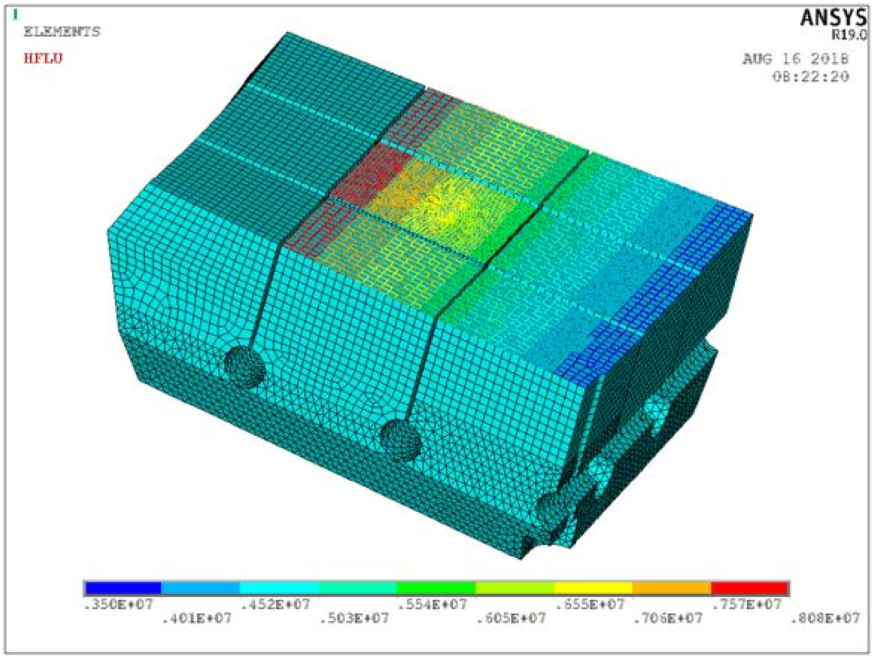

Figure 8. Heat Flux Load (W/m^2)

A uniform initial temperature of 400°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 3*. All other surfaces were assumed to be adiabatic.

4.2 Structural Model

For the structural model, the temperature profile from each of the five thermal models was applied to the corresponding structural model. The temperature profiles at 5 seconds and 15 seconds were analyzed.

The bottom of the tile was constrained to have no displacement normal to the surface (UY=0) as shown in *Figure 9.* Additional X and Z constraints were added to eliminate rigid body motion as shown in the figure.

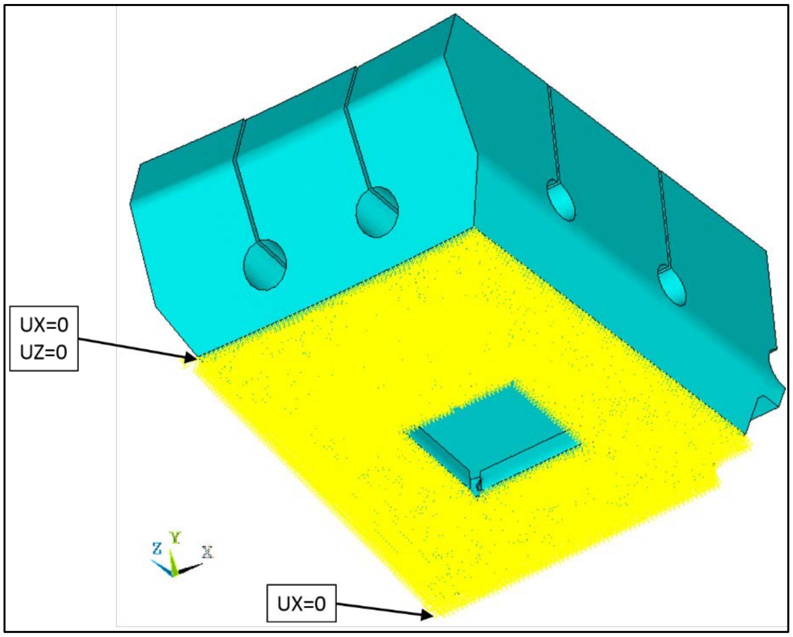

Figure 9. Displacement Constraints with UY Shown in Yellow

5.0 RESULTS

Five different cases were analyzed. The models included cases with four different hole depths for the thermocouple. The last two cases included a fillet at the top of the hole.

5.1 Thermal Results

The Thermal results for the five cases are shown below.

5.1.1 Case 1 - Top of Hole 0.375 inches from Plasma Surface

The results the transient analysis of temperature vs time for the first case, with the top of the hole 0.375 inches from the plasma surface, are shown in *Figure 10*. The figure shows the peak temperature on the surface of the tile and at the top of the hole. The figure shows that the peak temperature at the top of the hole is 1112.6°C and the peak temperature on the surface of the tile is 2171.5°C. The temperature profile at 5 seconds is shown in *Figure 11*. At 5 seconds the temperature ranges from 399.8°C to 1938.0°C. The temperature profile at 15 seconds is shown in Figure 12. At 15 seconds the temperature ranges from 400.6°C to 844.9°C. *Figure 13* shows a peak temperature of about 2,171.3°C after 12,055 seconds. The minimum temperature is about 635.8°C.

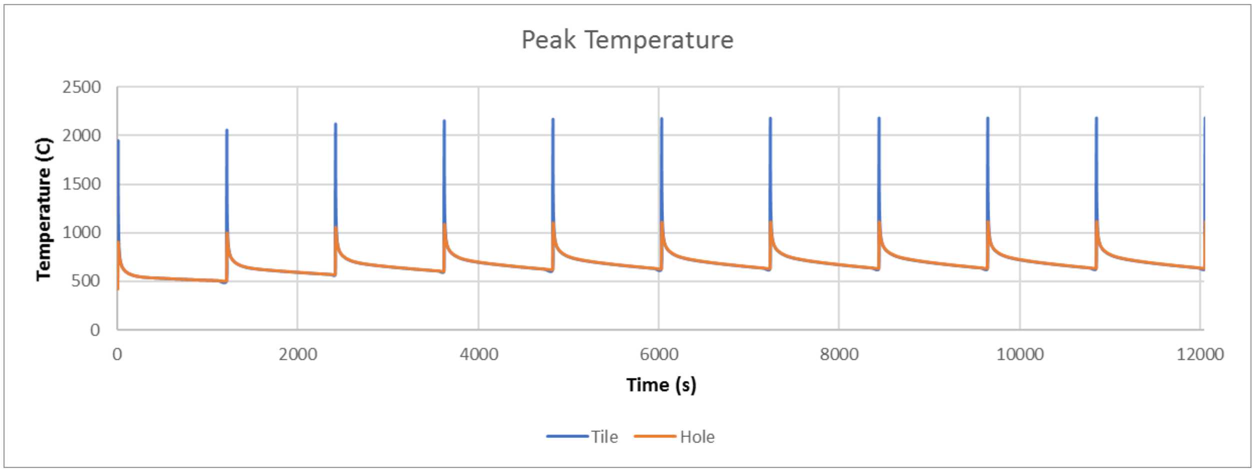

Figure 10. Case 1 - Temperature vs Time for Case with Top of Hole 0.375 inches from Plasma Surface

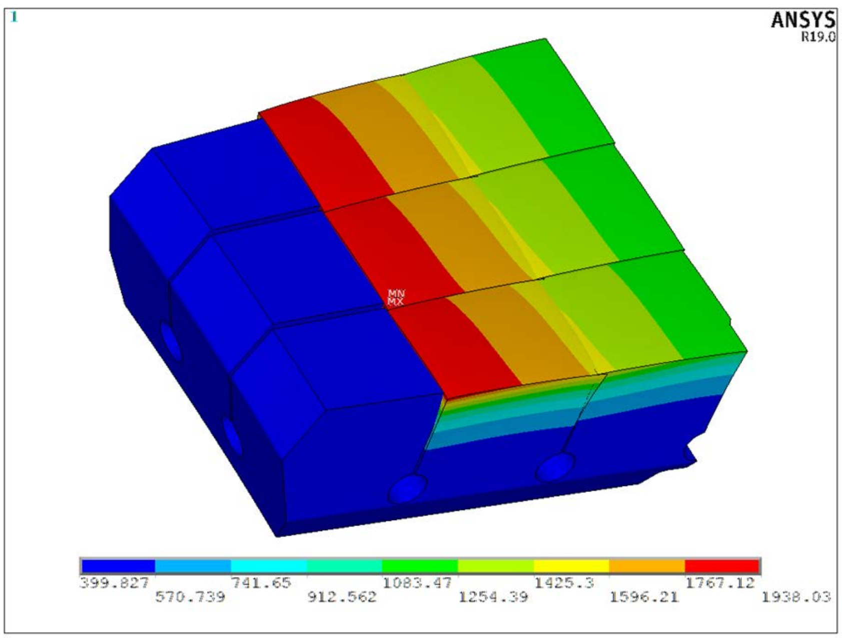

Figure 11. Case 1 - Temperature Profile at 5 seconds (°C)

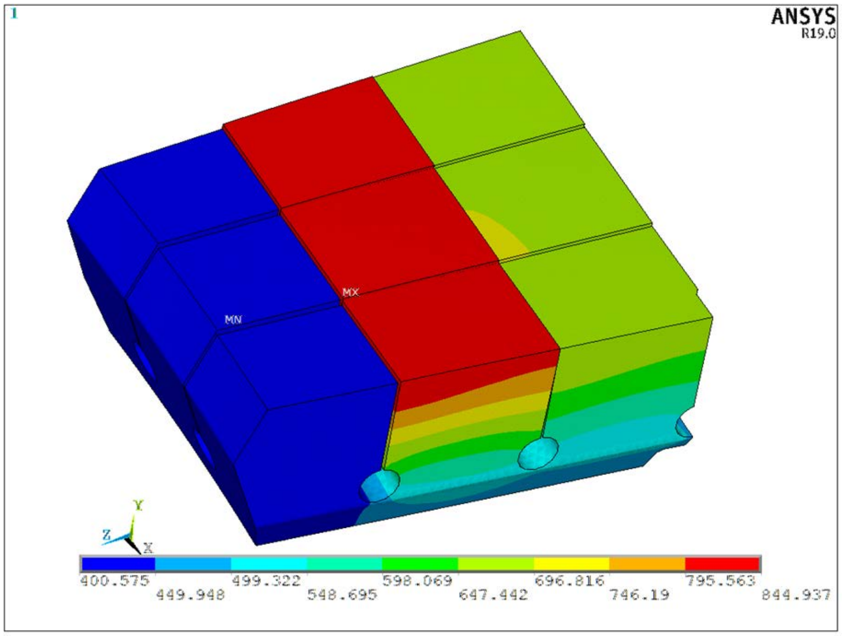

Figure 12. Case 1 - Temperature Profile at 15 seconds (°C)

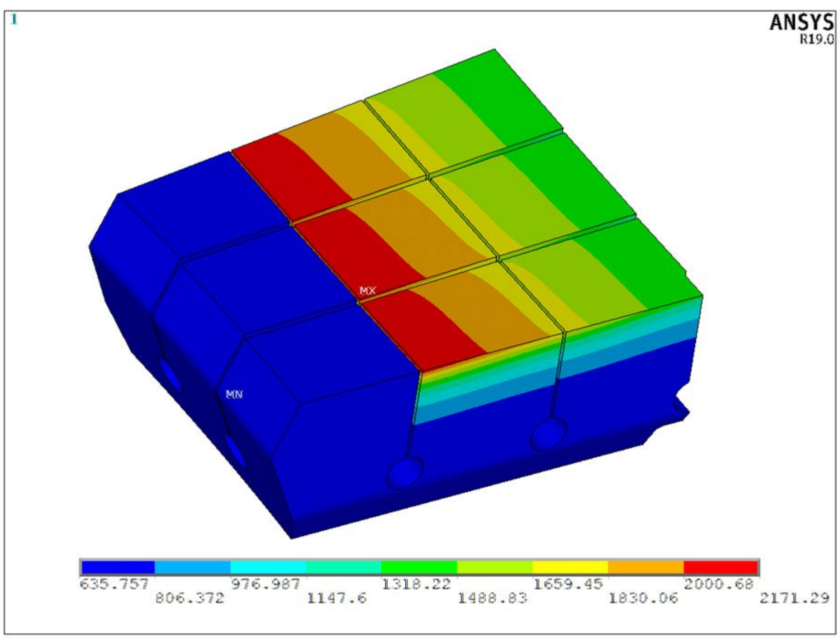

Figure 13. Case 1 - Temperature Profile at 12,055 seconds (°C)

5.1.2 Case 2 - Top of Hole 0.75 inches from Plasma Surface

The results of temperature vs time for the second case, with the top of the hole 0.75 inches from the plasma surface, are shown in *Figure 14*. The figure shows the peak temperature on the surface of the tile and at the top of the hole. The figure shows that the peak temperature at the top of the hole is 1081.6°C and the peak temperature on the surface of the tile is 2171.1°C. The temperature profile at 5 seconds is shown in *Figure 15*. At 5 seconds the temperature ranges from 399.8°C to 1937.7°C. The temperature profile at 15 seconds is shown in Figure 16. At 15 seconds the temperature ranges from 400.6°C to 843.7°C. *Figure 17* shows a peak temperature of about 2,171.1°C after 12,055 seconds. The minimum temperature is about 635.8°C.

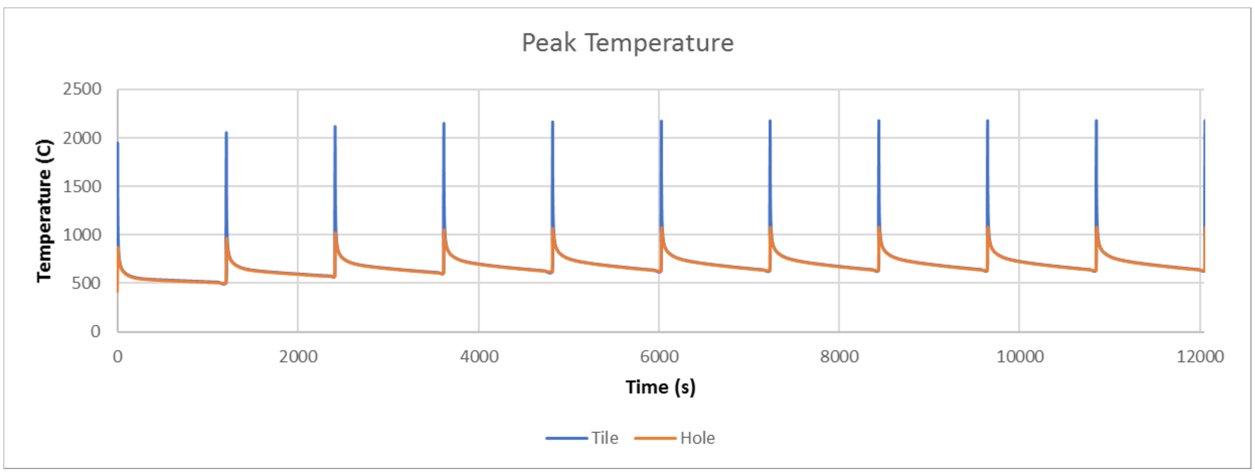

Figure 14. Case 2 - Temperature vs Time for Case with Top of Hole 0.75 inches from Plasma Surface

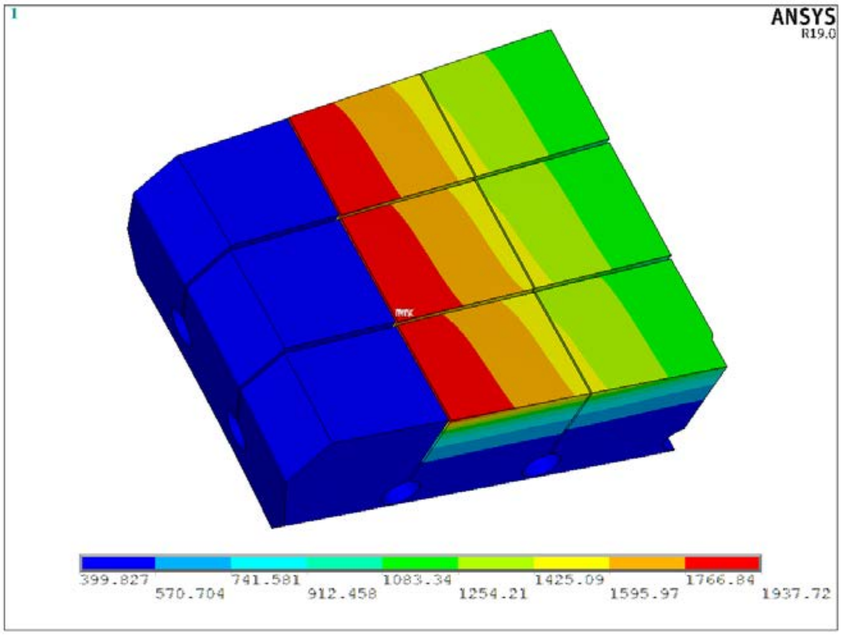

Figure 15. Case 2 - Temperature Profile at 5 seconds (°C)

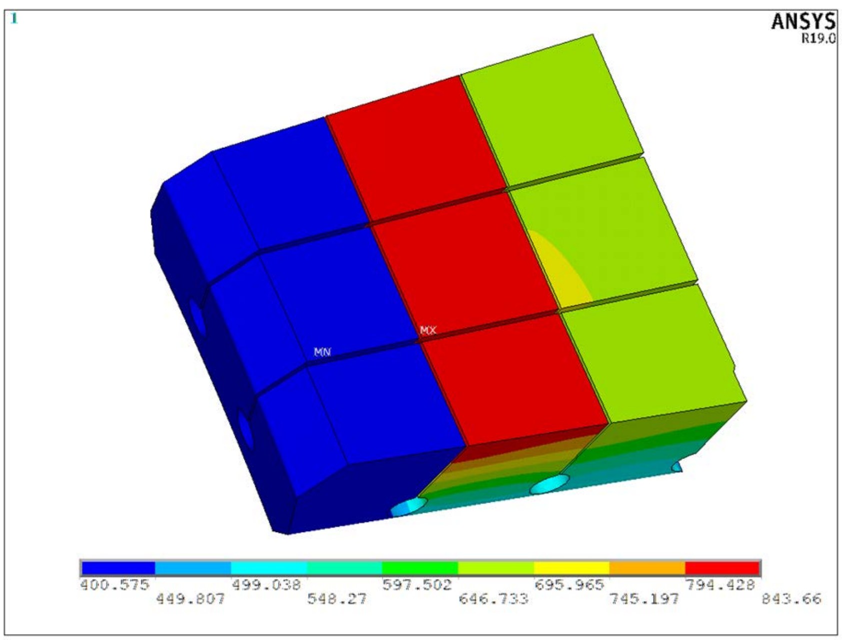

Figure 16. Case 2 - Temperature Profile at 15 seconds (°C)

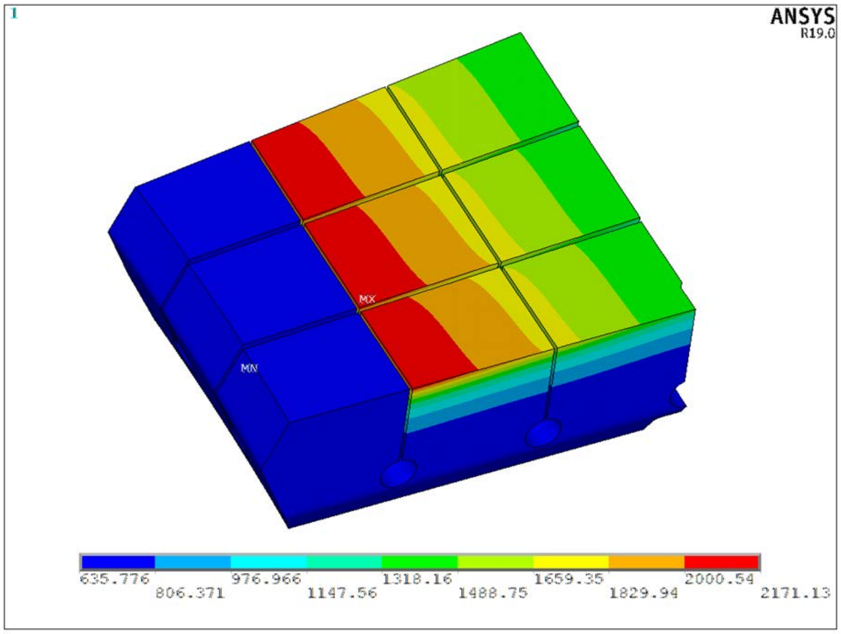

Figure 17. Case 2 - Temperature Profile at 12,055 seconds (°C)

5.1.3 Case 3 - Top of Hole 1.125 inches from Plasma Surface

The results of temperature vs time for the third case, with the top of the hole 1.125 inches from the plasma surface, are shown in Figure 18. The figure shows the peak temperature on the surface of the tile and at the top of the hole. The figure shows that the peak temperature at the top of the hole is 835.4°C and the peak temperature on the surface of the tile is 2171.1°C. The temperature profile at 5 seconds is shown in Figure 19. At 5 seconds the temperature ranges from 399.8°C to 1937.7°C. The temperature profile at 15 seconds is shown Figure 20. At 15 seconds the temperature ranges from 400.6°C to 843.1°C. Figure 21 shows a peak temperature of about 2,171.1°C after 12,055 seconds. The minimum temperature is about 635.8°C.

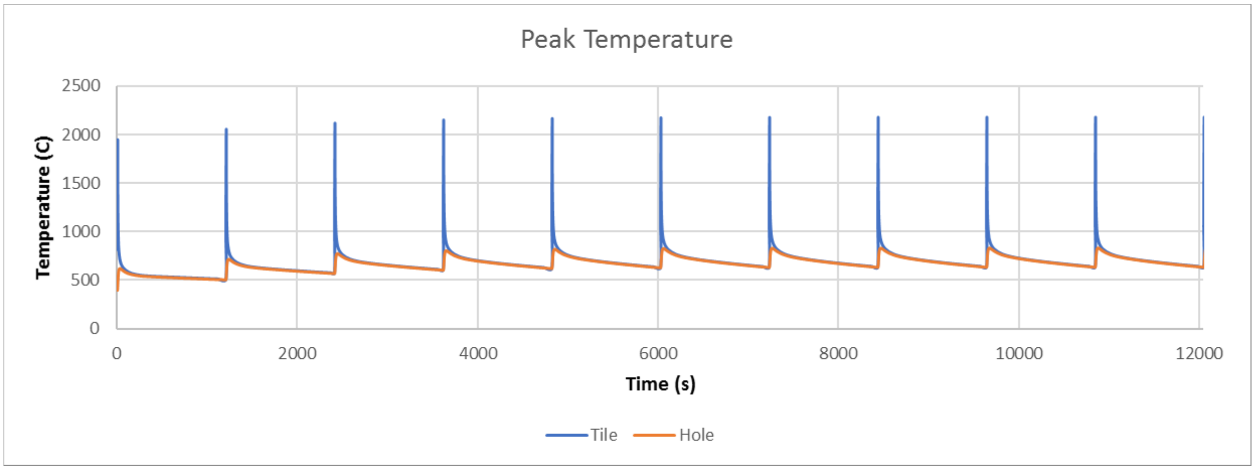

Figure 18. Case 3 - Temperature vs Time for Case with Top of Hole 1.125 inches from Plasma Surface

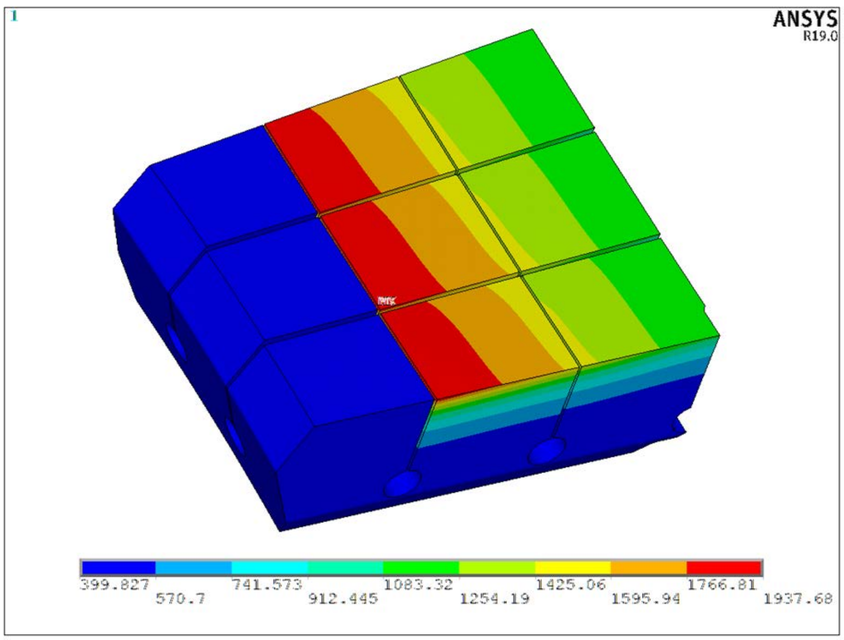

Figure 19. Case 3 - Temperature Profile at 5 seconds (°C)

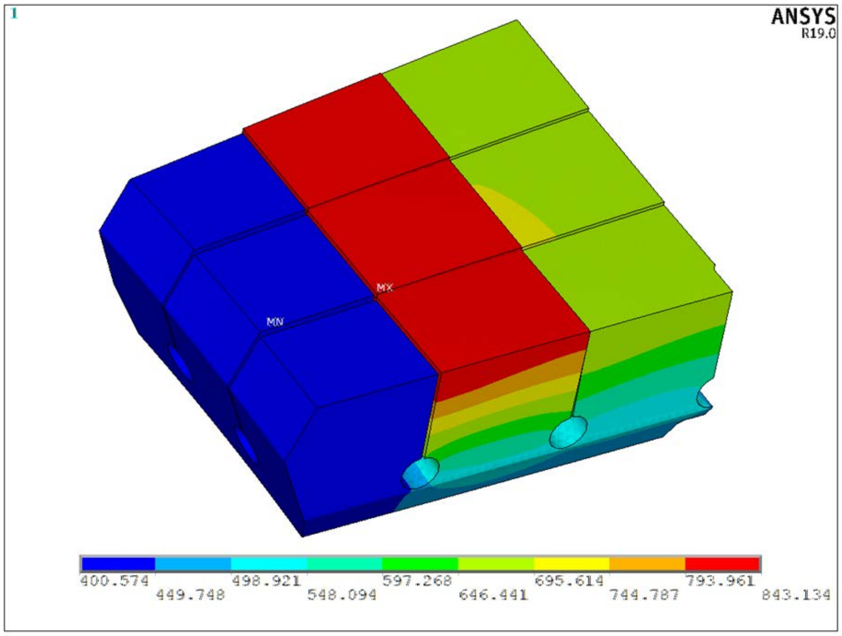

Figure 20. Case 3 - Temperature Profile at 15 seconds (°C)

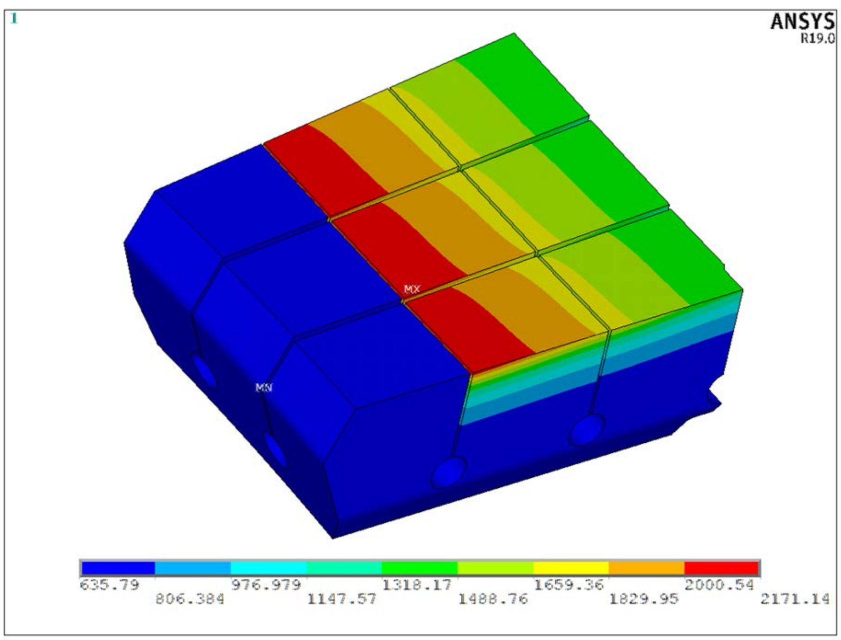

Figure 21. Case 3 - Temperature Profile at 12,055 seconds (°C)

5.1.4 Case 4 – Top of Hole 0.375 inches from Plasma Surface with 1/64 inch fillet

This case was done to determine if the addition of a fillet around the top of the hole would reduce the stresses at the top of the hole. It was only run to 5 seconds to evaluate the peak stress at this point. The temperature profile at 5 seconds is shown in Figure 22. At 5 seconds the temperature ranges from 399.8°C to 1938.3°C.

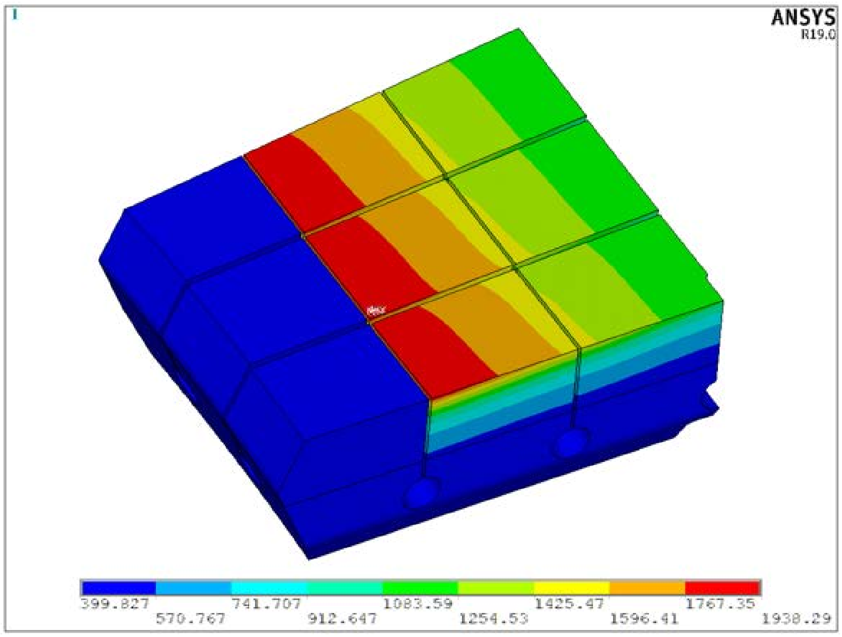

Figure 22. Case 4 - Temperature Profile at 5 seconds (°C)

5.1.5 Case 5 – Top of Hole 1.0 inches from Plasma Surface with 1/32 inch fillet

Case 5 was run based on the results of the previous four cases. It was determined that the only case that kept the hole stresses below ½ the ultimate was the 1.125 inch case (Case 3). The results of temperature vs time for the fifth case, with the top of the hole 1.0 inch from the plasma surface, are shown in Figure 23. The figure shows the peak temperature on the surface of the tile and at the top of the hole. The figure shows that the peak temperature at the top of the hole is 858.1°C and the peak temperature on the surface of the tile is 2171.1°C. The temperature profile at 5 seconds is shown in Figure 24. At 5 seconds the temperature ranges from 399.8°C to 1937.7°C. The temperature profile at 15 seconds is shown Figure 25. At 15 seconds the temperature ranges from 400.6°C to 843.5°C. Figure 26 shows a peak temperature of about 2,171.2°C after 12,055 seconds. The minimum temperature is about 635.8°C.

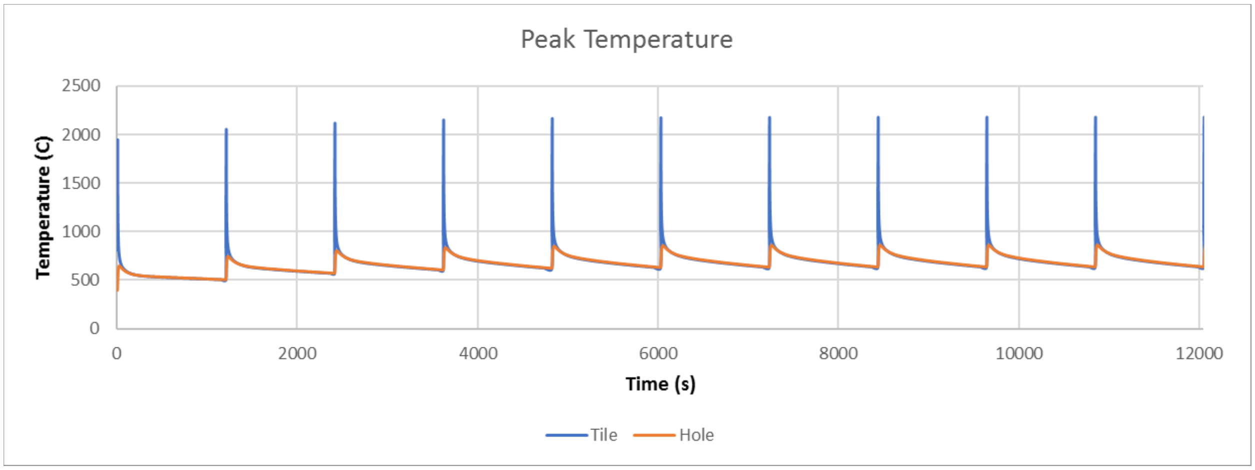

Figure 23. Case 5 - Temperature vs Time for Case with Top of Hole 1.0 inch from Plasma Surface

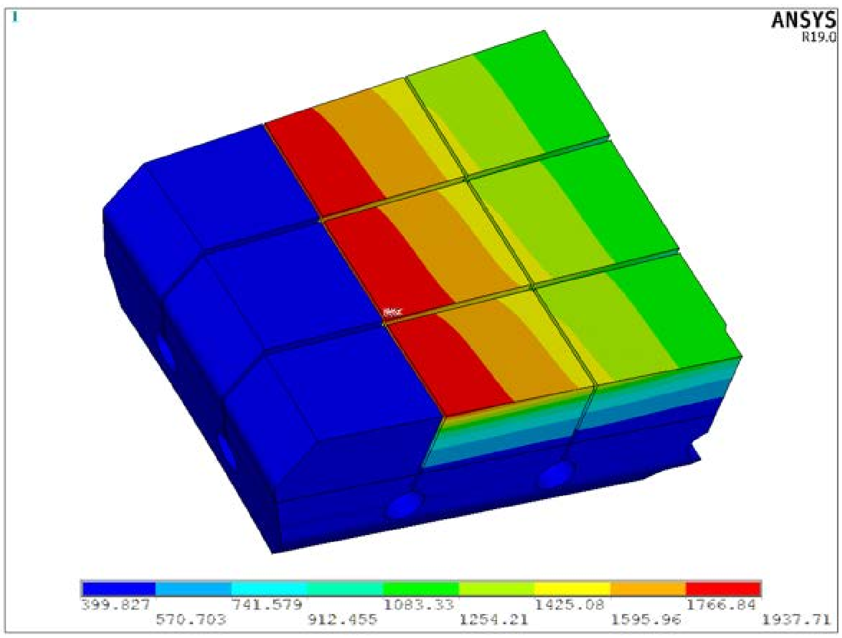

Figure 24. Case 5 - Temperature Profile at 5 seconds (°C)

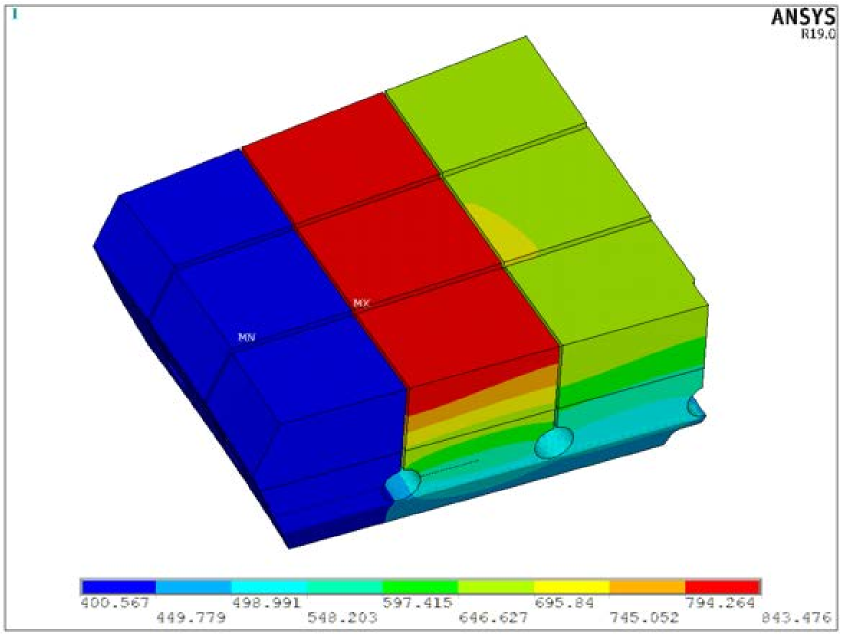

Figure 25. Case 5 - Temperature Profile at 15 seconds (°C)

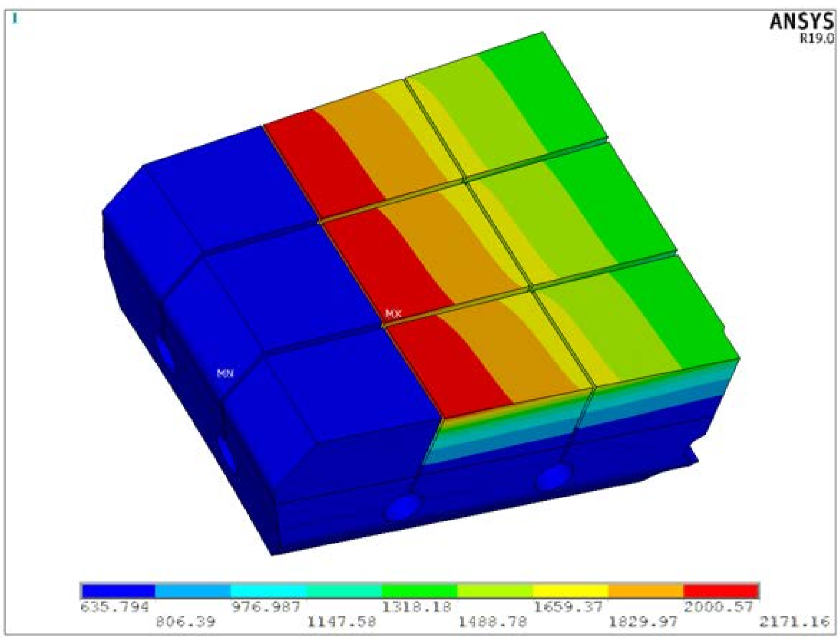

Figure 26. Case 5 - Temperature Profile at 12,055 seconds (°C)

5.2 Structural Results

The structural results for the five cases are shown below. The results are shown for all the cases, except Case 4, at 5 seconds and 15 seconds. Case 4 is only shown at 5 seconds.

5.2.1 Case 1 - Top of Hole 0.375 inches from Plasma Surface

The results show that all the stresses are below the strength of the materials. Figure 27 and Figure 28 show the results of the minimum and maximum principal stresses in the tile after the first 5 second pulse. The maximum principal stress is highly localized, so the figure is zoomed in on the hole. Figure 29 shows the von Mises stress in the tile after heating for 5 seconds. The results show that even considering the local stresses, the tile stresses are all below the strength of the graphite. The maximum tensile stress of 28.5 MPa is below the ultimate tensile strength of 38 MPa and is localized as shown in Figure 28. The compressive stress of 43.4 MPa is well below the ultimate compressive strength of 130 MPa. The maximum von Mises stress is 41.1 MPa located on the top of the tile. The maximum von Mises stress in the hole is 20.7 MPa.

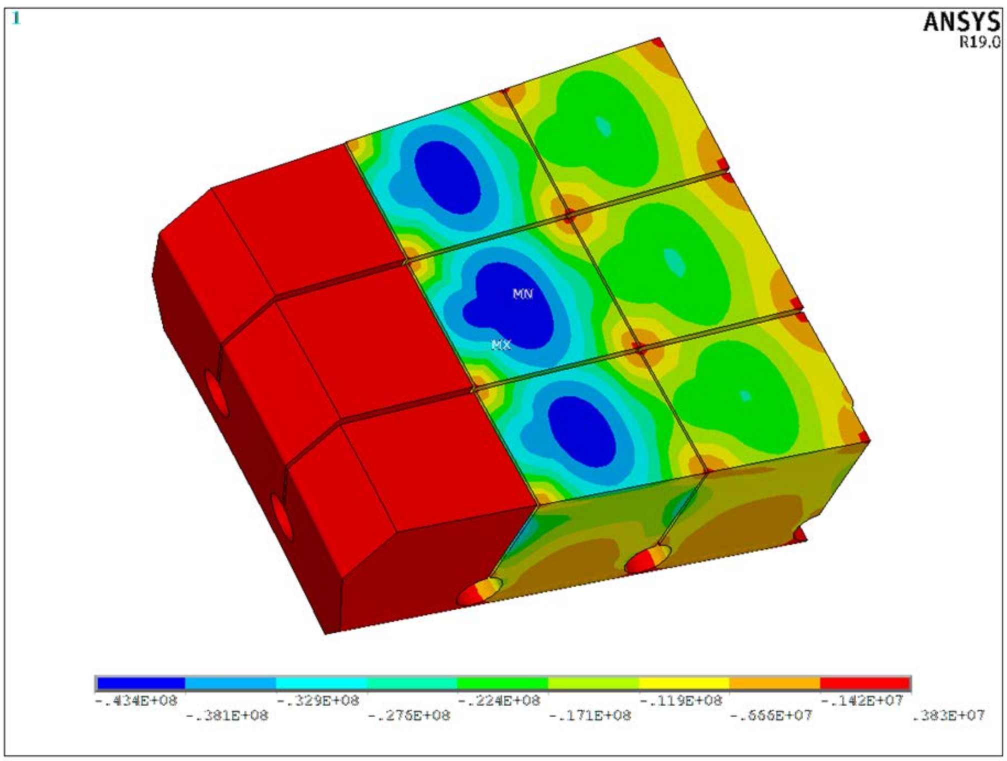

Figure 27. Case 1 - Min Principal Stress at 5 seconds (Pa)

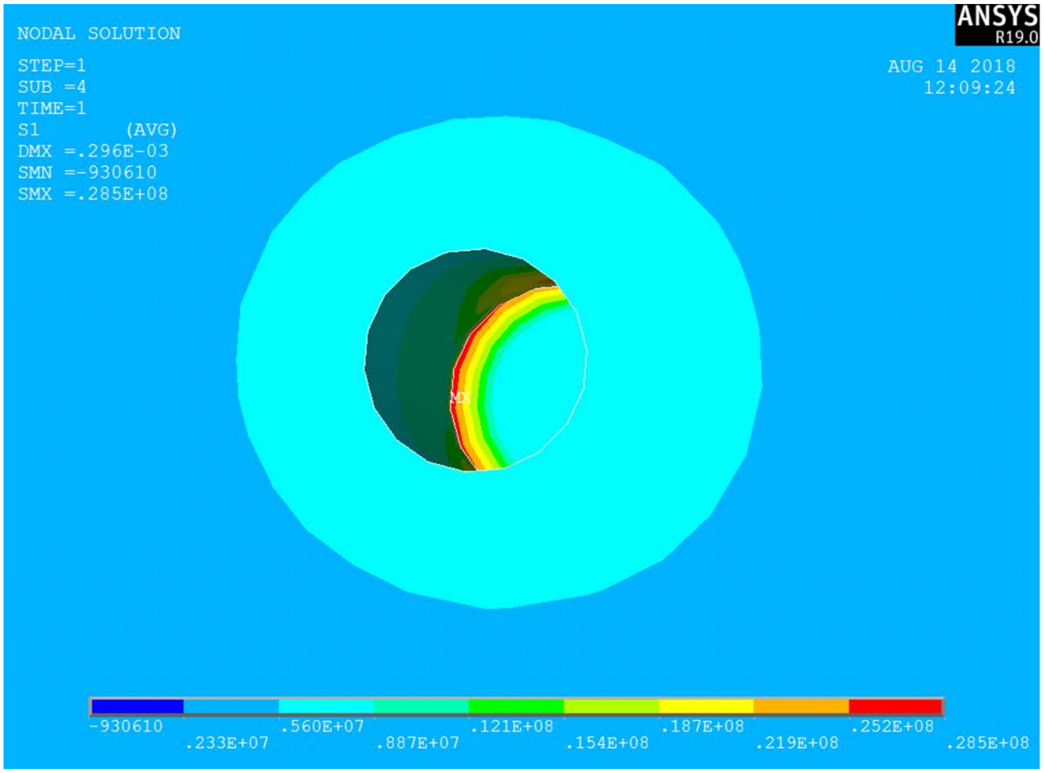

Figure 28. Case 1 - Max Principal Stress in Hole at 5 seconds (Pa)

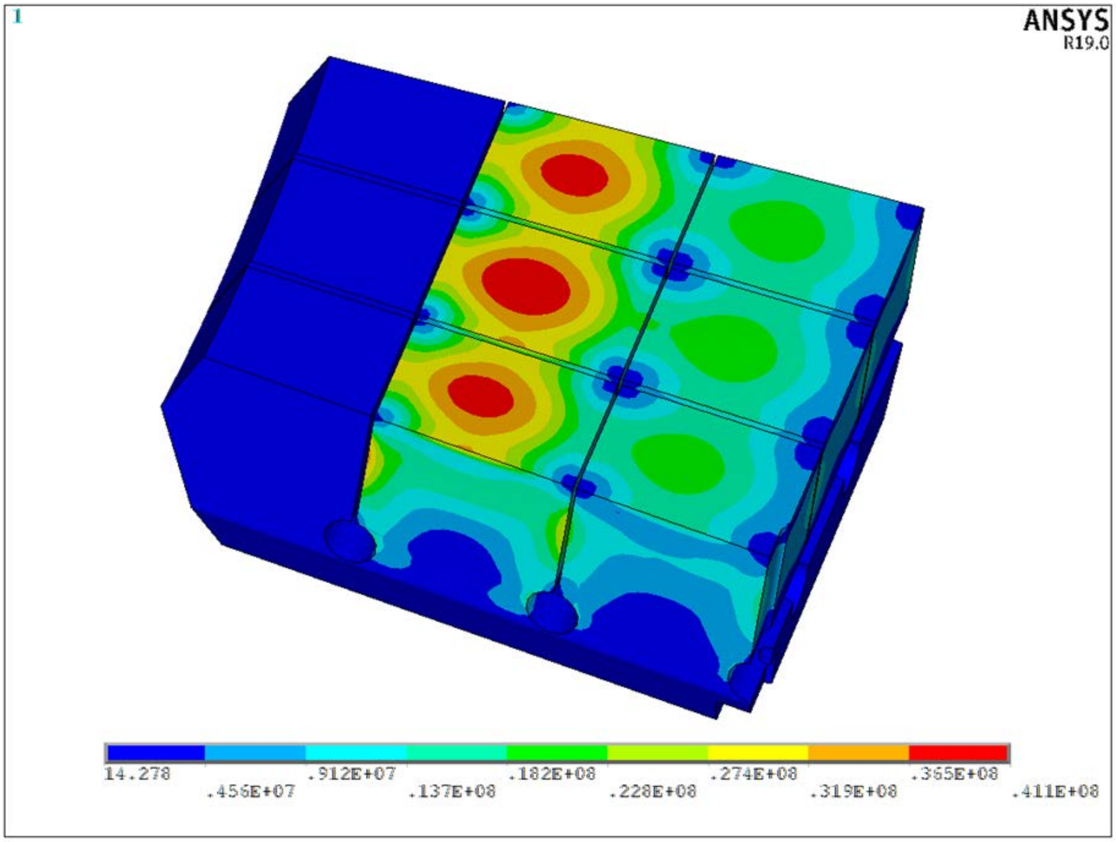

Figure 29. Case 1 - Von Mises Stress at 5 seconds (Pa)

Figure 30 and Figure 31 show the results of the minimum and maximum principal stresses in the tile after 15 seconds. The stresses are lower at 15 seconds. Figure 32 shows the von Mises stress in the tile after 15 seconds. The results show that even considering the local stresses, the tile stresses are all below the strength of the graphite. The maximum tensile stress of 5.7 MPa is well below the ultimate tensile strength of 38 MPa and is located around the cut outs in the bottom of the tile. The compressive stress of 8.7 MPa is well below the ultimate compressive strength of 130 MPa. The maximum von Mises stress is 8.4 MPa.

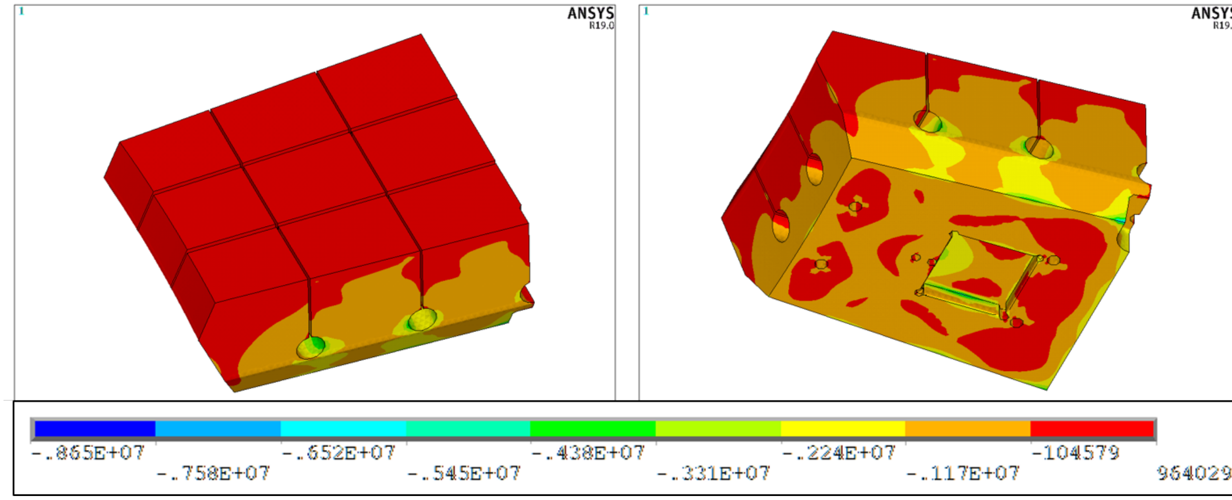

Figure 30. Case 1 - Min Principal Stress at 15 seconds (Pa)

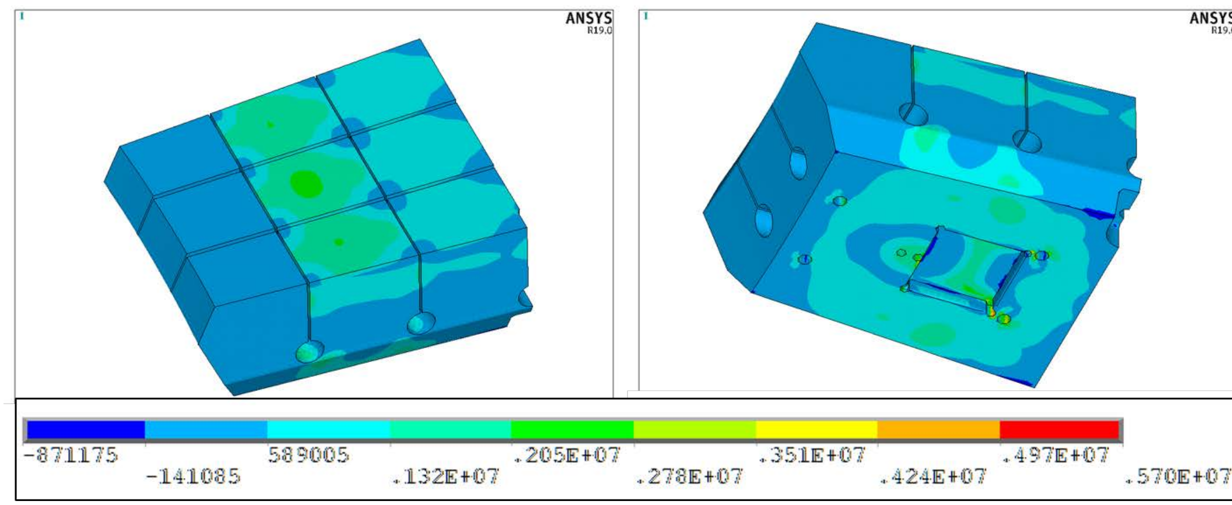

Figure 31. Case 1 - Max Principal Stress at 15 seconds (Pa)

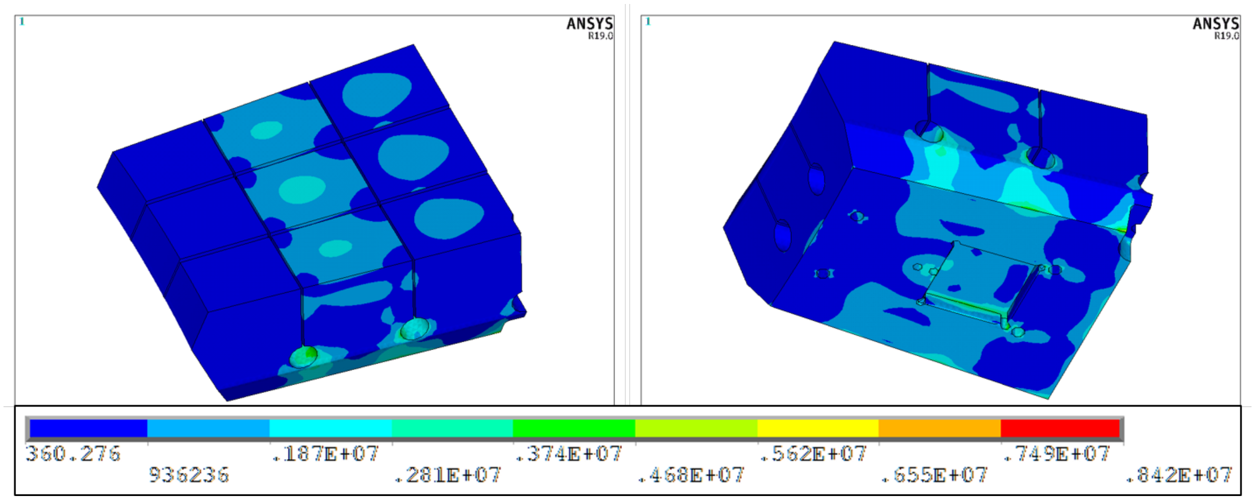

Figure 32. Case 1 - Von Mises Stress at 15 seconds (Pa)

5.2.2 Case 2 - Top of Hole 0.75 inches from Plasma Surface

The results show that all the stresses are below the strength of the materials. Figure 33 and Figure 34 show the results of the minimum and maximum principal stresses in the tile after the first 5 second pulse. The maximum principal stress is highly localized, so the figure is zoomed in on the hole. Figure 35 shows the von Mises stress in the tile after heating for 5 seconds. The results show that even considering the local stresses, the tile stresses are all below the strength of the graphite. The maximum tensile stress of 27.6 MPa is below the ultimate tensile strength of 38 MPa and is localized as shown in Figure 34. The compressive stress of 43.4 MPa is well below the ultimate compressive strength of 130 MPa. The maximum von Mises stress is 41.4 MPa located on the top of the tile. The maximum von Mises stress in the hole is 22.7 MPa.

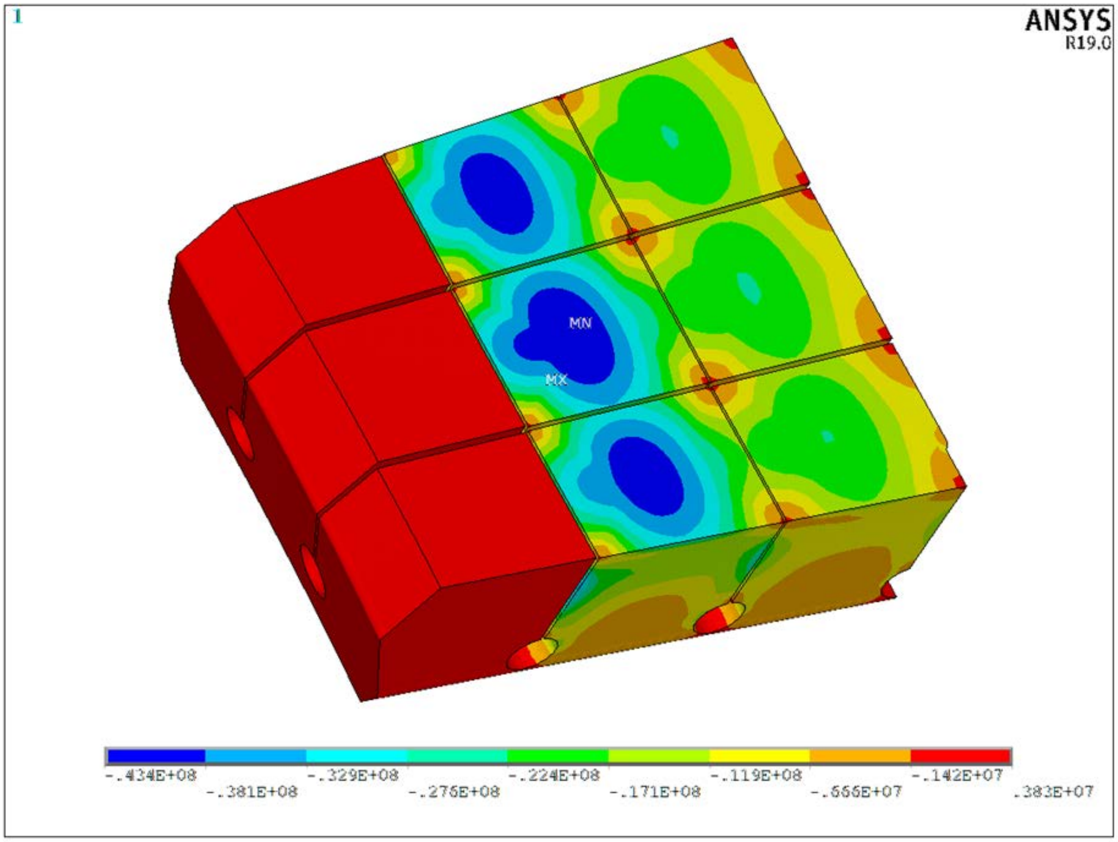

Figure 33. Case 2 - Min Principal Stress at 5 seconds (Pa)

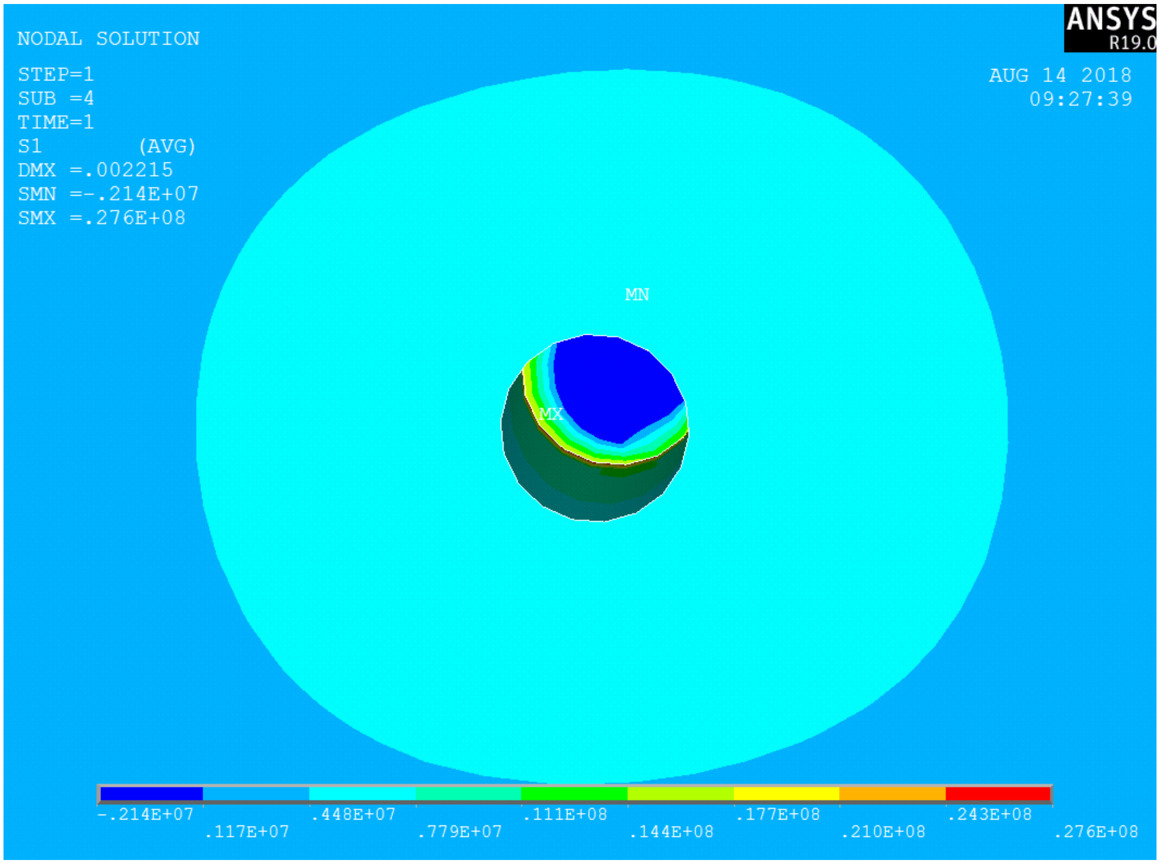

Figure 34. Case 2 - Max Principal Stress in Hole at 5 seconds (Pa)

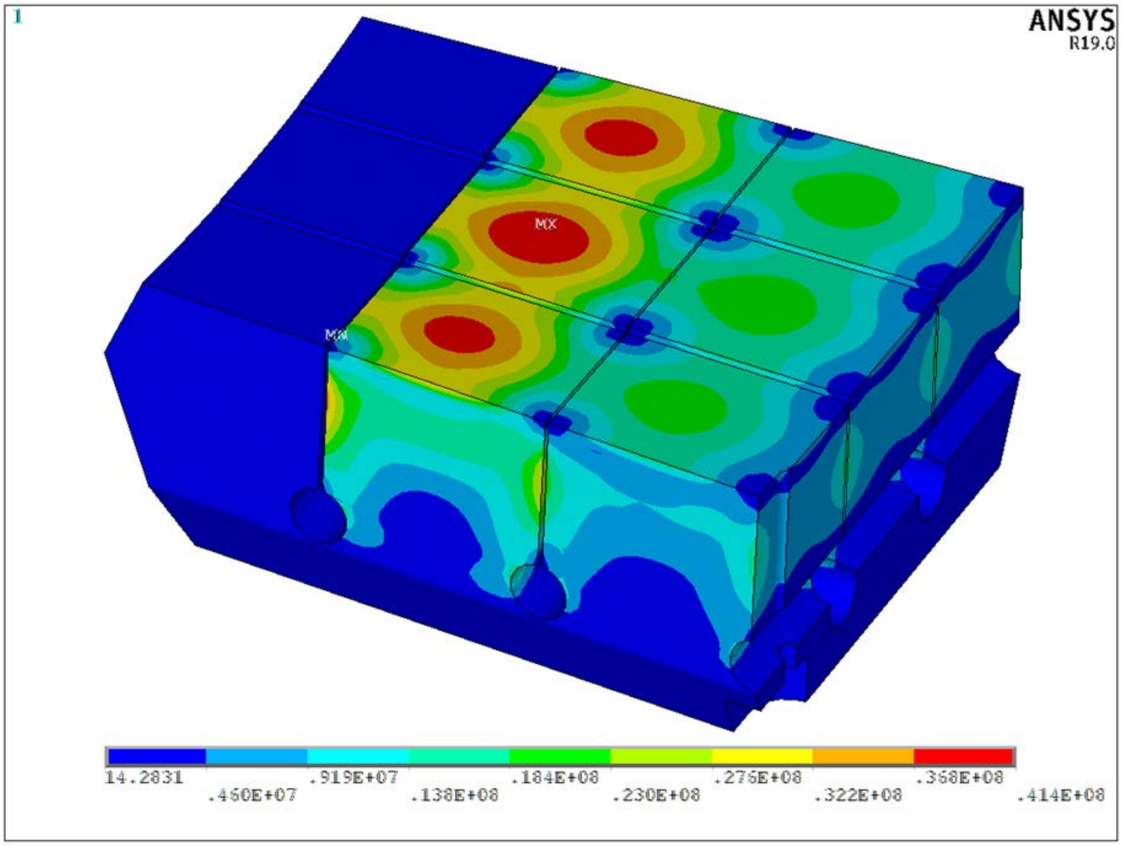

Figure 35. Case 2 - Von Mises Stress at 5 seconds (Pa)

Figure 36 and Figure 37 show the results of the minimum and maximum principal stresses in the tile after 15 seconds. The stresses are lower at 15 seconds. Figure 38 shows the von Mises stress in the tile after 15 seconds. The results show that even considering the local stresses, the tile stresses are all below the strength of the graphite. The maximum tensile stress of 5.7 MPa is well below the ultimate tensile strength of 38 MPa and is located around the cut outs in the bottom of the tile. The compressive stress of 8.6 MPa is well below the ultimate compressive strength of 130 MPa. The maximum von Mises stress is 8.4 MPa.

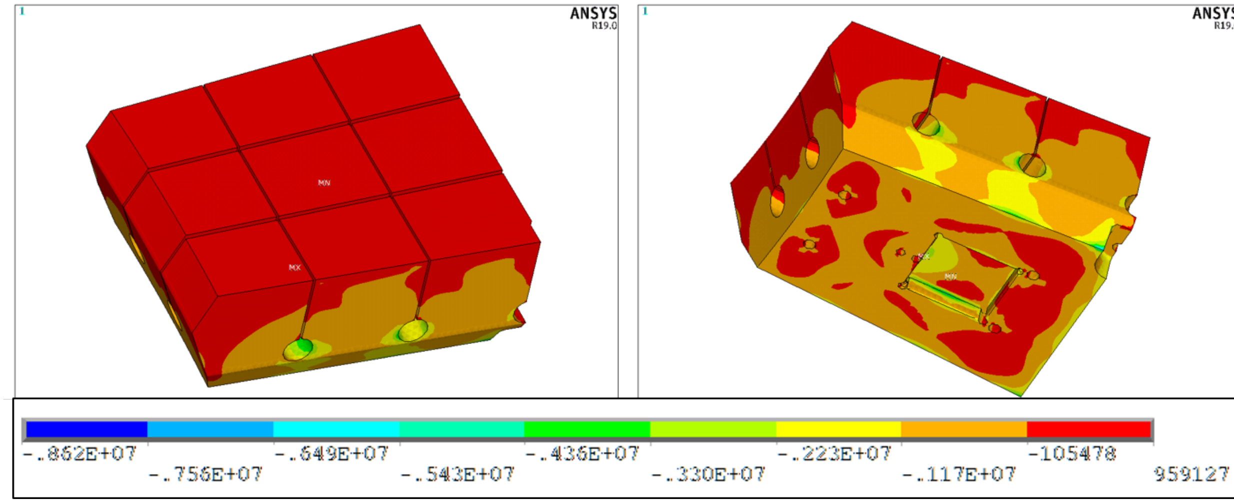

Figure 36. Case 2 - Min Principal Stress at 15 seconds (Pa)

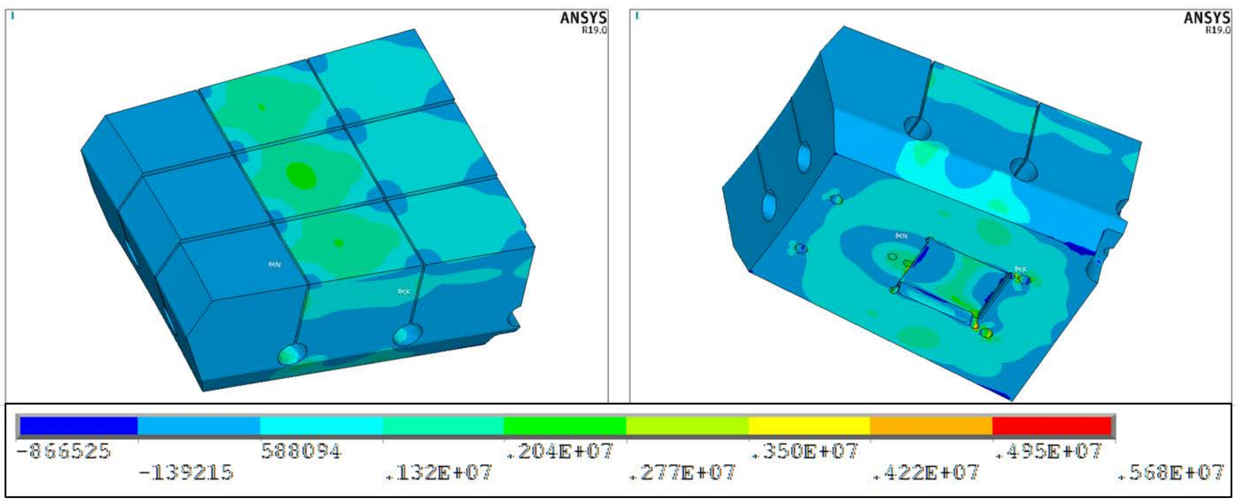

Figure 37. Case 2 - Max Principal Stress at 15 seconds (Pa)

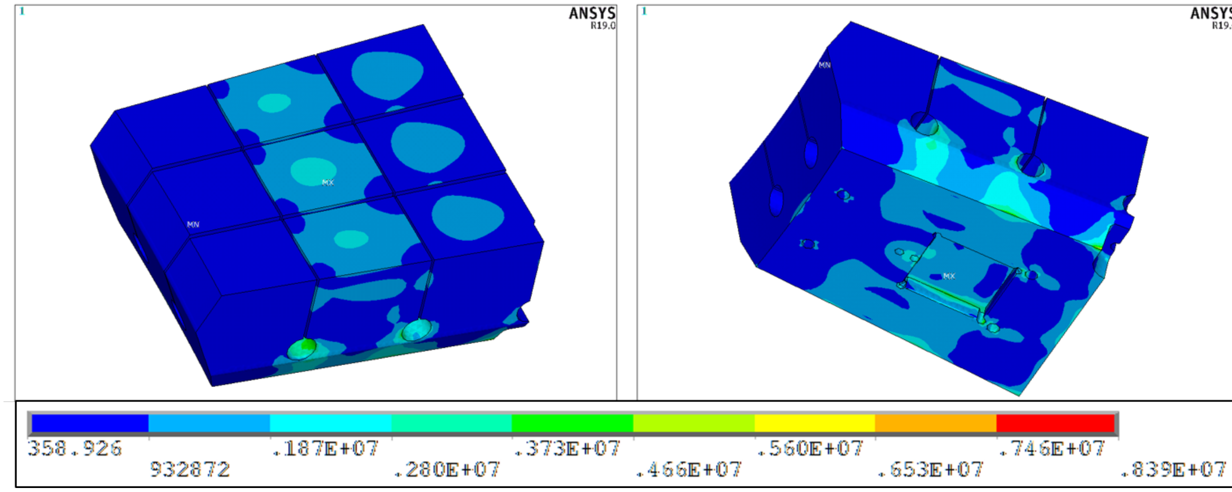

Figure 38. Case 2 - Von Mises Stress at 15 seconds (Pa)

5.2.3 Case 3 - Top of Hole 1.125 inches from Plasma Surface

The results show that all the stresses are below the strength of the materials. Figure 39 and Figure 40 show the results of the minimum and maximum principal stresses in the tile after the first 5 second pulse. The maximum principal stress is highly localized, so the figure is zoomed in on the hole. Figure 41 shows the von Mises stress in the tile after heating for 5 seconds. The results show that even considering the local stresses, the tile stresses are all below the strength of the graphite. The maximum tensile stress of 17.6 MPa is below the ultimate tensile strength of 38 MPa and is localized as shown in Figure 40. The compressive stress of 43.4 MPa is well below the ultimate compressive strength of 130 MPa. The maximum von Mises stress is 41.4 MPa located on the top of the tile. The maximum von Mises stress in the hole is 14.3 MPa.

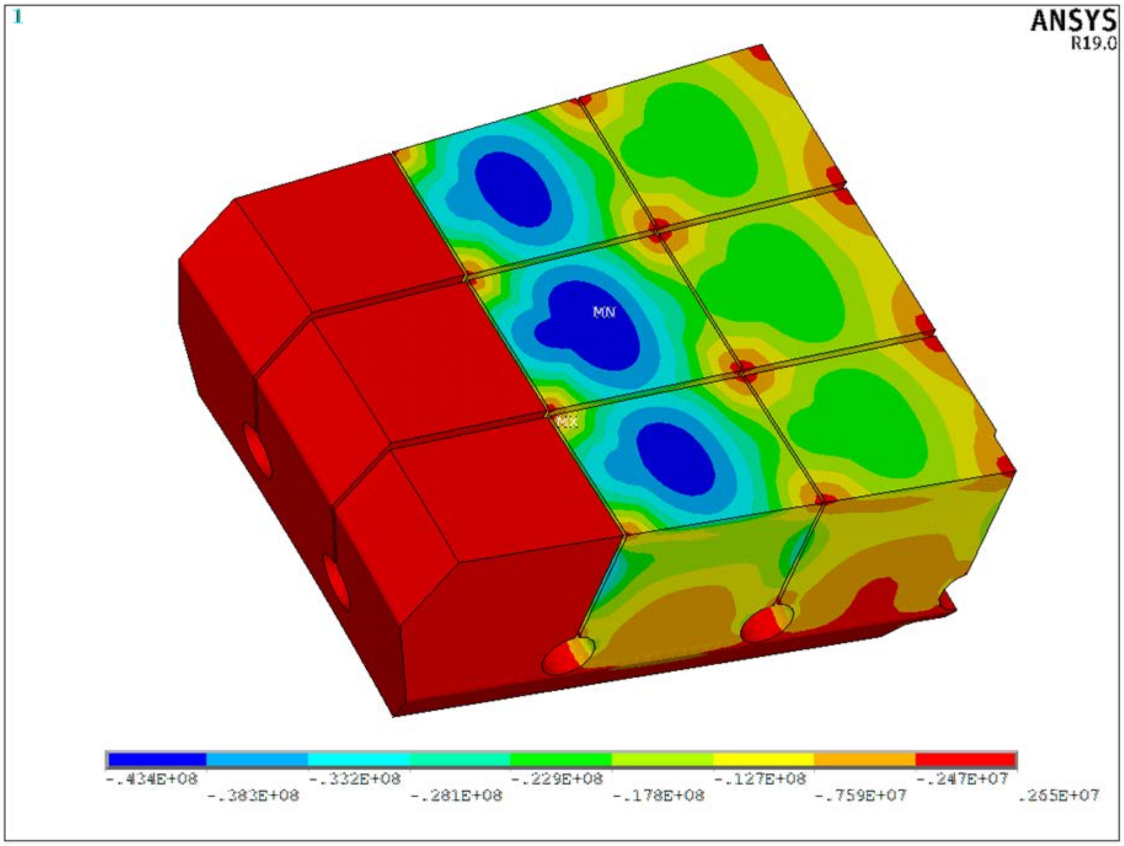

Figure 39. Case 3 - Min Principal Stress at 5 seconds (Pa)

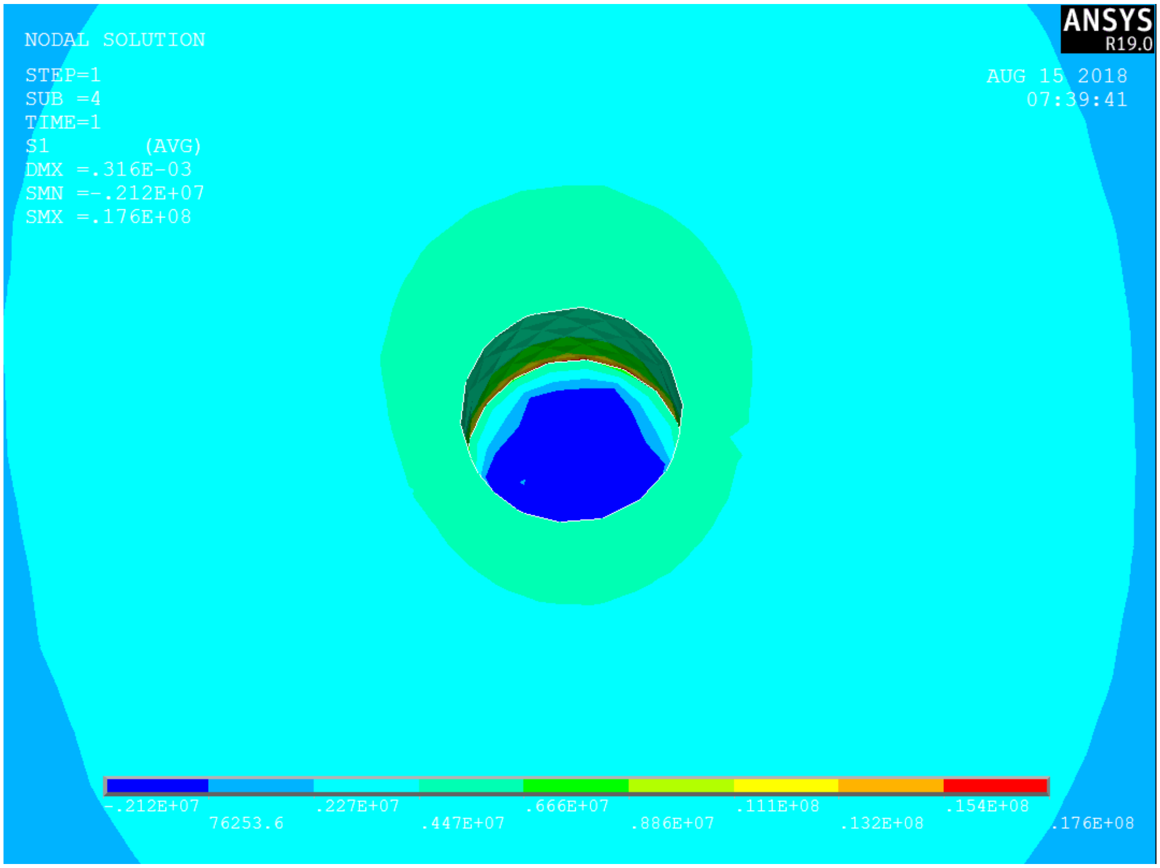

Figure 40. Case 3 - Max Principal Stress in Hole at 5 seconds (Pa)

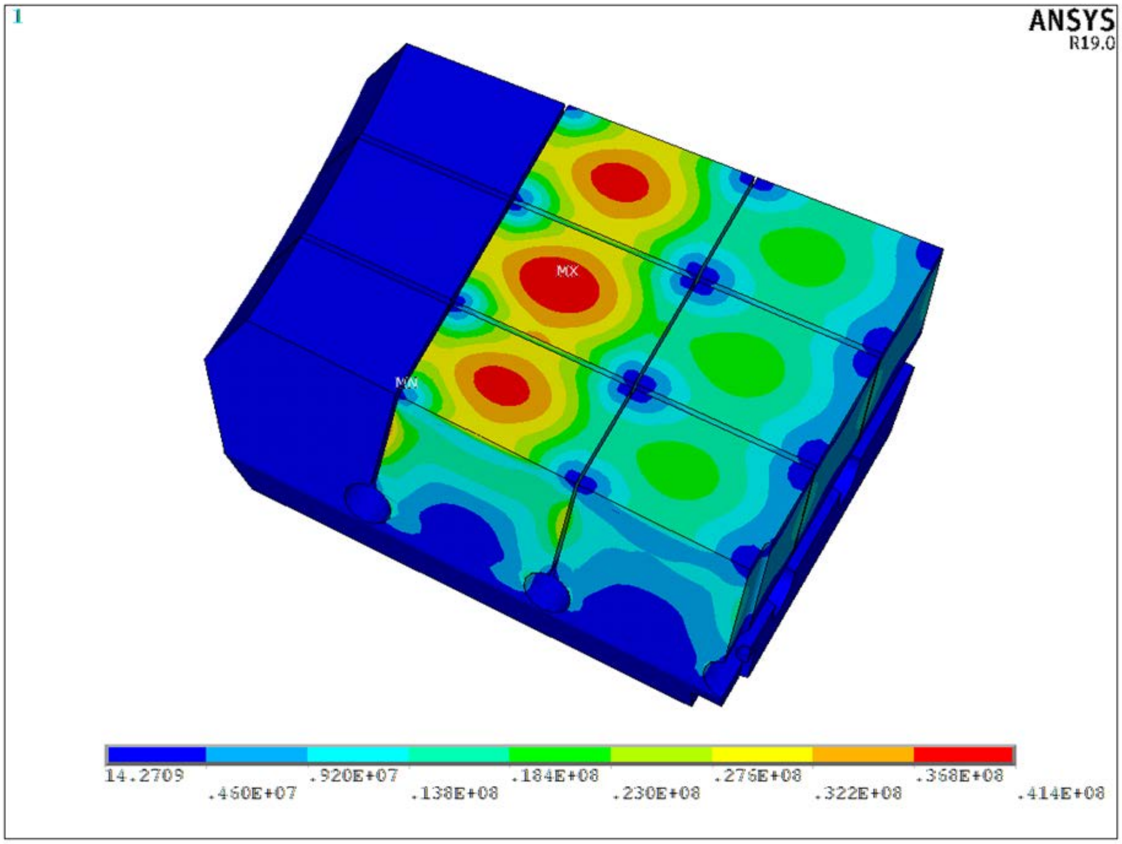

Figure 41. Case 3 - Von Mises Stress at 5 seconds (Pa)

Figure 42 and Figure 43 show the results of the minimum and maximum principal stresses in the tile after 15 seconds. The stresses are lower at 15 seconds. Figure 44 shows the von Mises stress in the tile after 15 seconds. The results show that even considering the local stresses, the tile stresses are all below the strength of the graphite. The maximum tensile stress of 5.7 MPa is well below the ultimate tensile strength of 38 MPa and is located around the cut outs in the bottom of the tile. The compressive stress of 8.6 MPa is well below the ultimate compressive strength of 130 MPa. The maximum von Mises stress is 8.4 MPa.

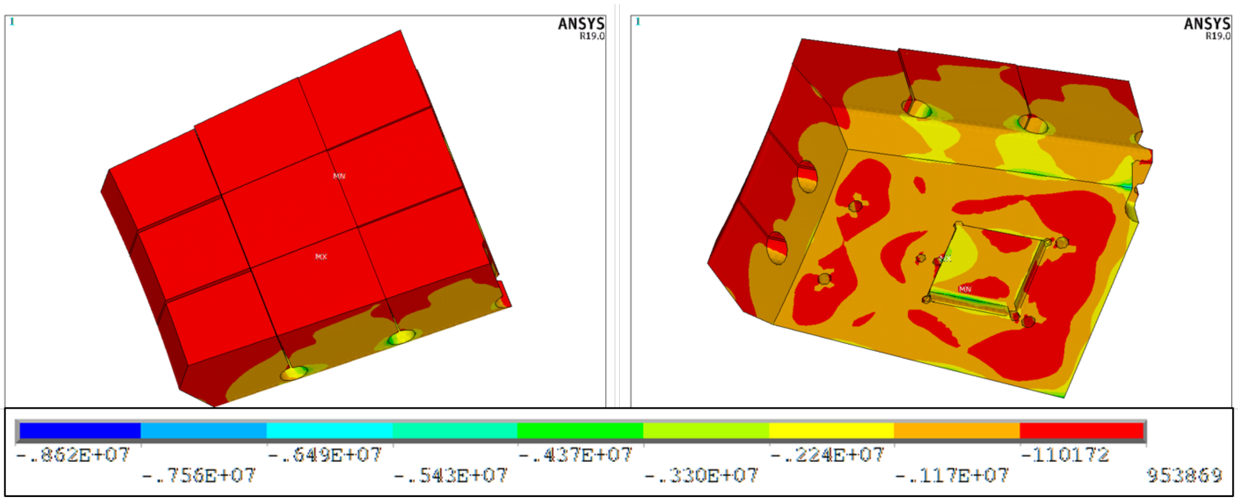

Figure 42. Case 3 - Min Principal Stress at 15 seconds (Pa)

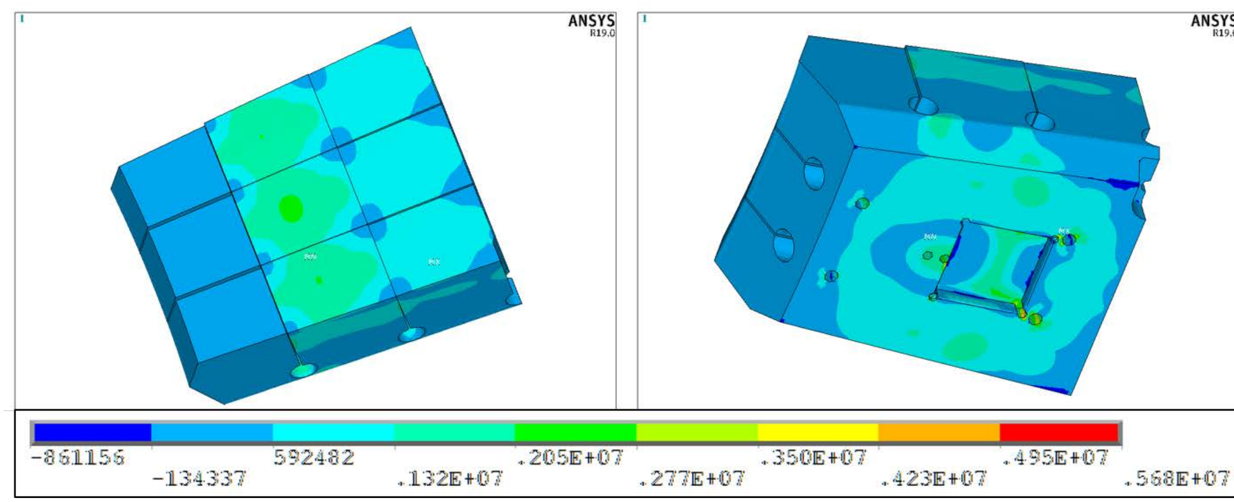

Figure 43. Case 3 - Max Principal Stress at 15 seconds (Pa)

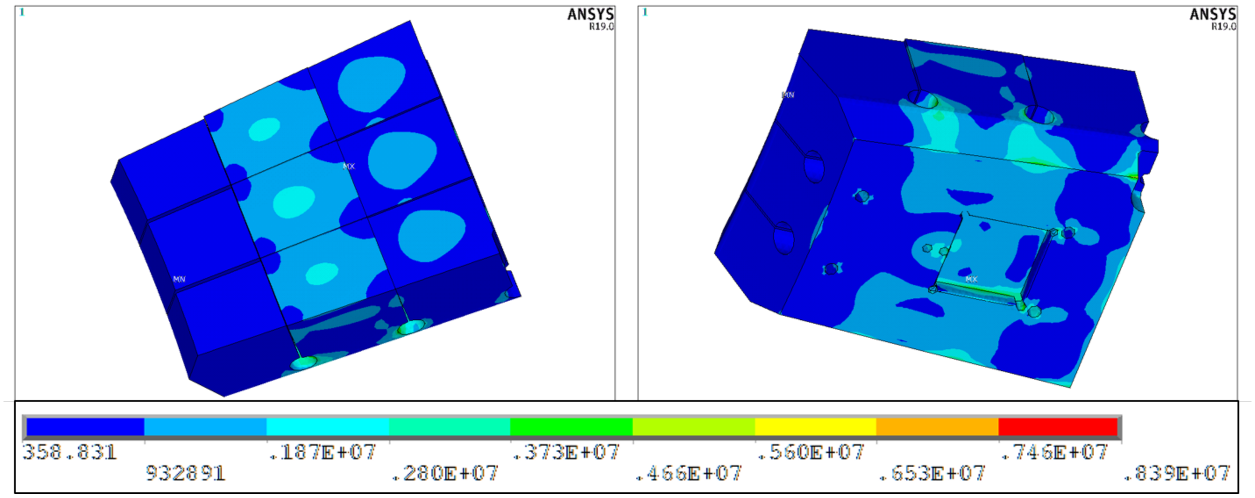

Figure 44. Case 3 - Von Mises Stress at 15 seconds (Pa)

5.2.4 Case 4 - Top of Hole 0.375 inches from Plasma Surface with 1/64 inch Fillet

The results show that all the stresses are below the strength of the materials. Figure 45 and Figure 46 show the results of the minimum and maximum principal stresses in the tile after the first 5 second pulse. The maximum principal stress is highly localized, so the figure is zoomed in on the hole. Figure 47 shows the von Mises stress in the tile after heating for 5 seconds. The results show that even considering the local stresses, the tile stresses are all below the strength of the graphite. The maximum tensile stress of 25.4 MPa is below the value to 28.5 MPa for Case 1 without the 1/64 inch radius. The compressive stress of 43.0 MPa is well below the ultimate compressive strength of 130 MPa. The maximum von Mises stress is 41.0 MPa located on the top of the tile. The maximum von Mises stress in the hole is 20.7 MPa.

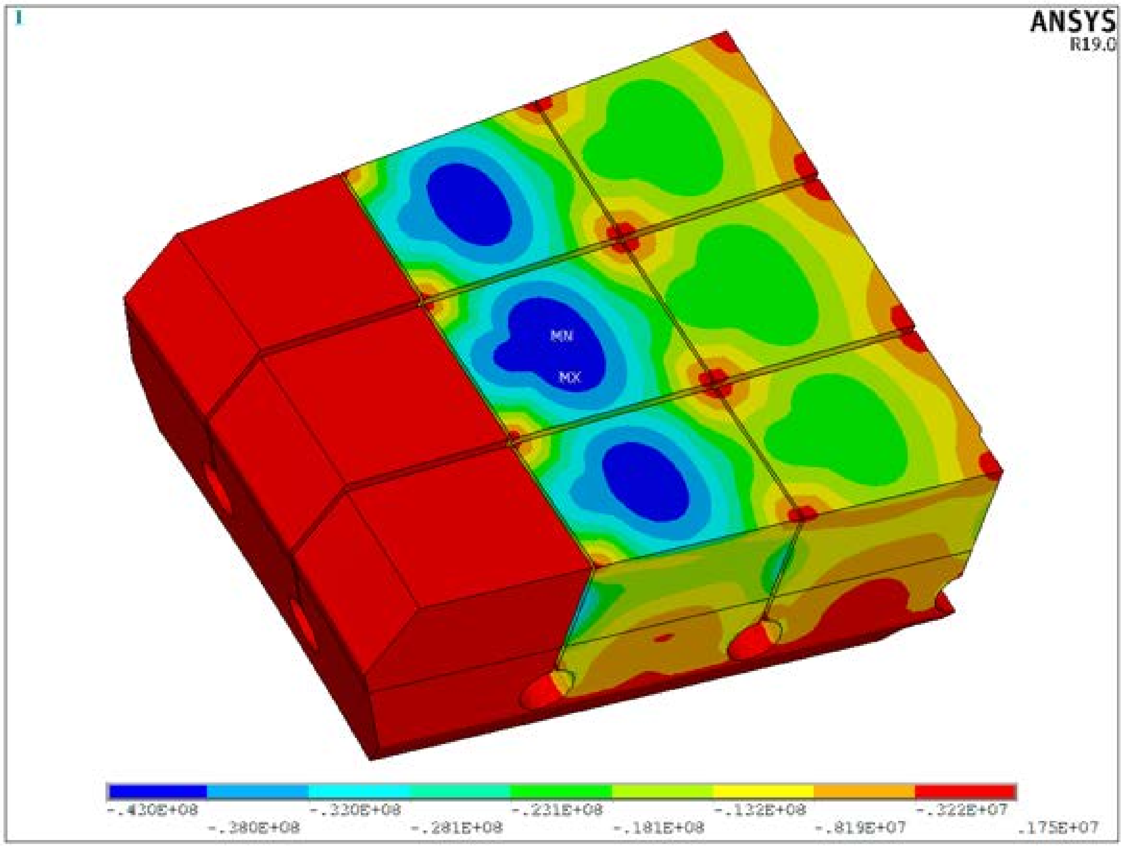

Figure 45. Case 4 - Min Principal Stress at 5 seconds (Pa)

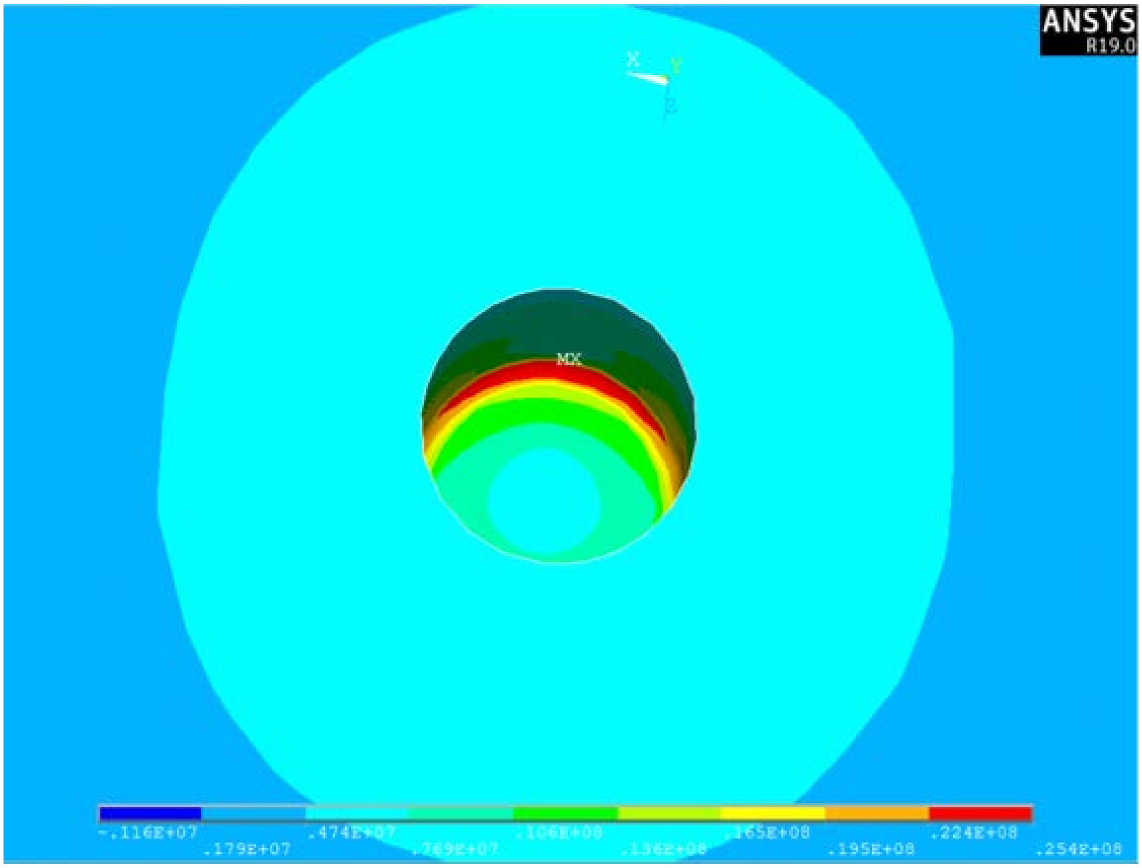

Figure 46. Case 4 - Max Principal Stress in Hole at 5 seconds (Pa)

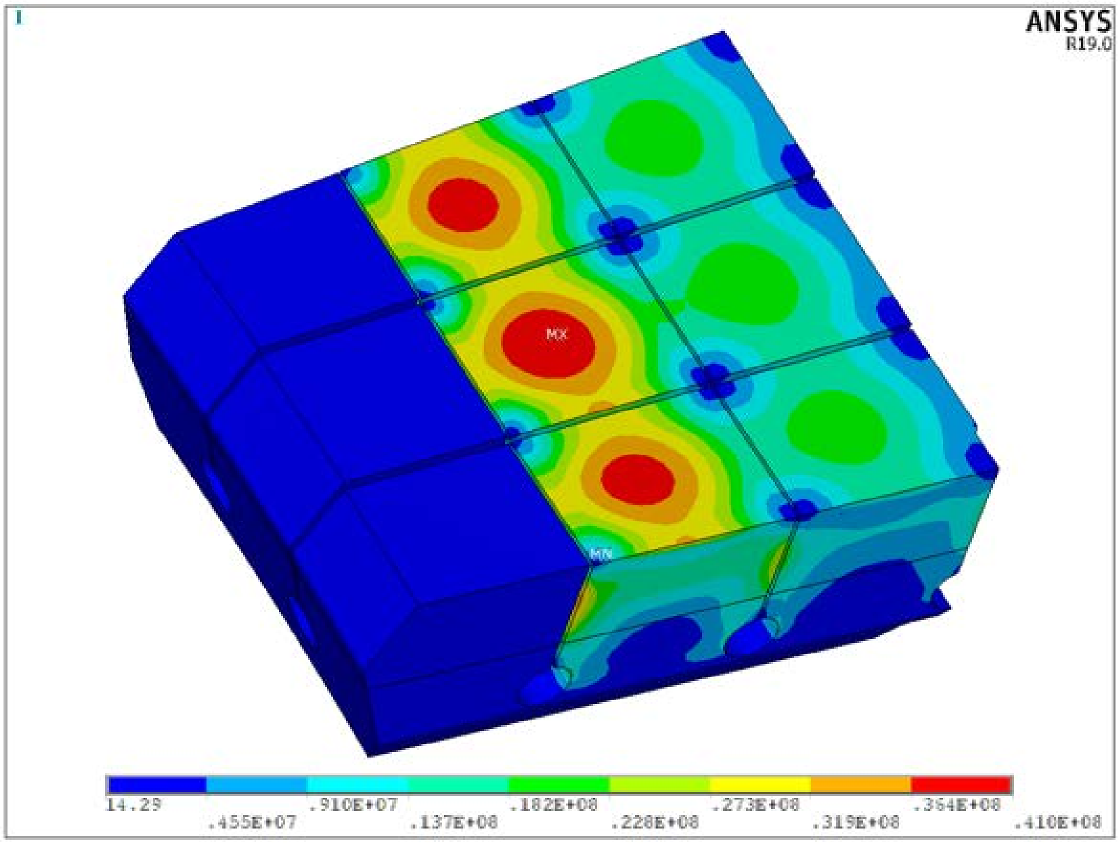

Figure 47. Case 4 - Von Mises Stress at 5 seconds (Pa)

5.2.5 Case 5 - Top of Hole 1.0 inch from Plasma Surface with 1/32 inch Fillet

The results show that all the stresses are below the strength of the materials. Figure 48 and Figure 49 show the results of the minimum and maximum principal stresses in the tile after the first 5 second pulse. The maximum principal stress is highly localized, so the figure is zoomed in on the hole. Figure 50 shows the von Mises stress in the tile after heating for 5 seconds. The results show that even considering the local stresses, the tile stresses are all below the strength of the graphite. The maximum tensile stress of 15.6 MPa is below the ultimate tensile strength of 38 MPa and is localized as shown in Figure 49. The compressive stress of 43.5 MPa is well below the ultimate compressive strength of 130 MPa. The maximum von Mises stress is 41.5 MPa located on the top of the tile. The maximum von Mises stress in the hole is 12.7 MPa.

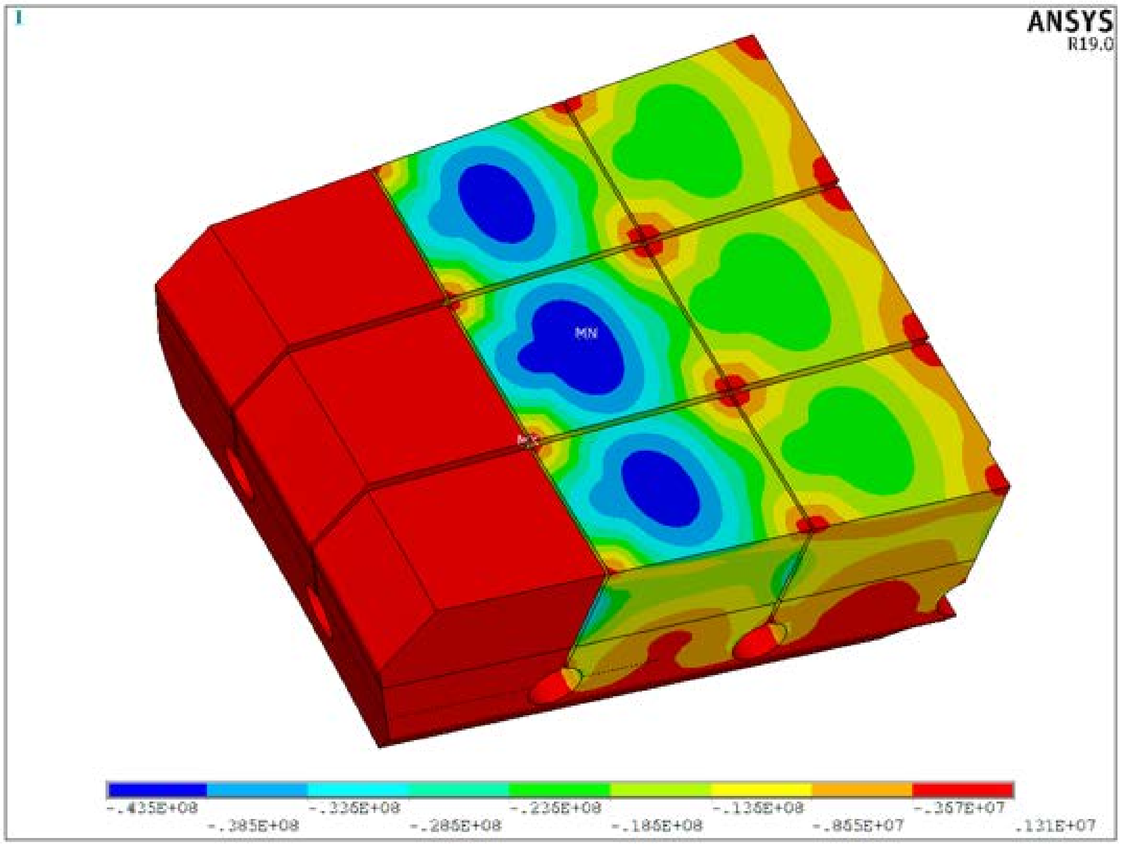

Figure 48. Case 5 - Min Principal Stress at 5 seconds (Pa)

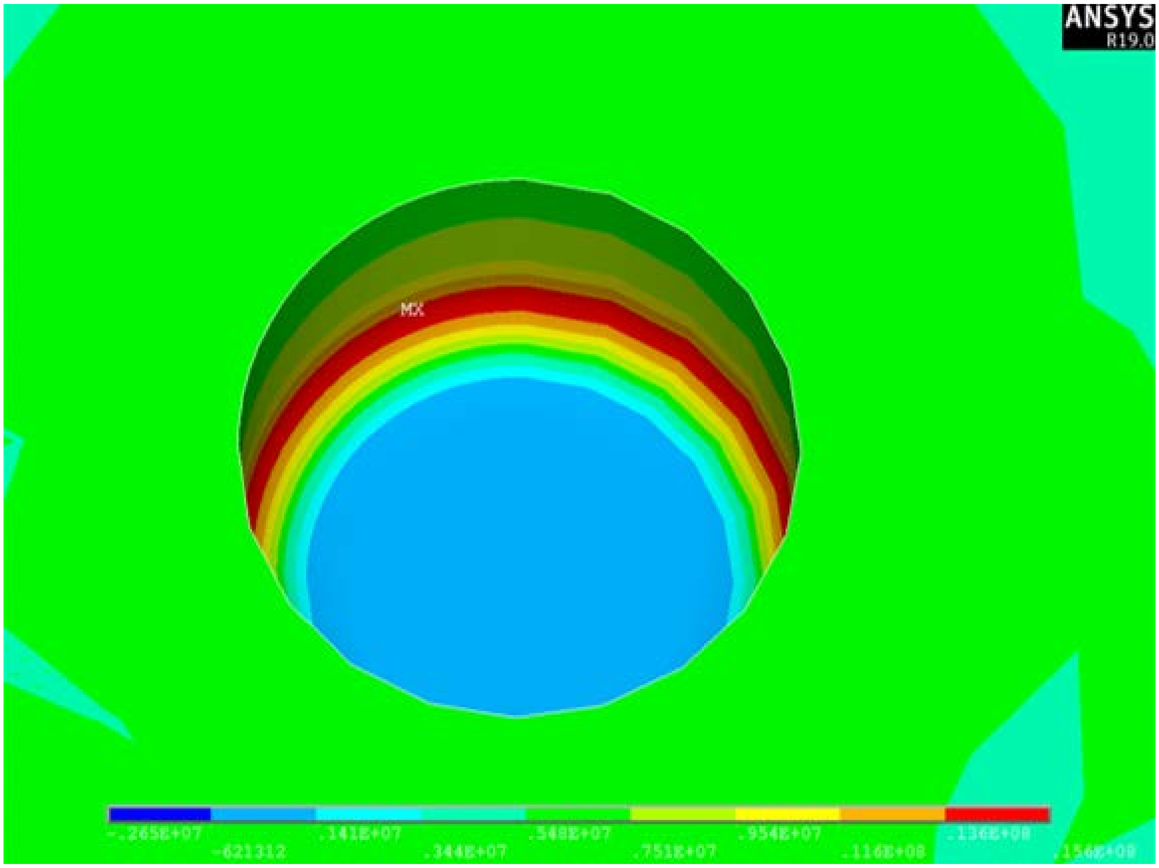

Figure 49. Case 5 - Max Principal Stress in Hole at 5 seconds (Pa)

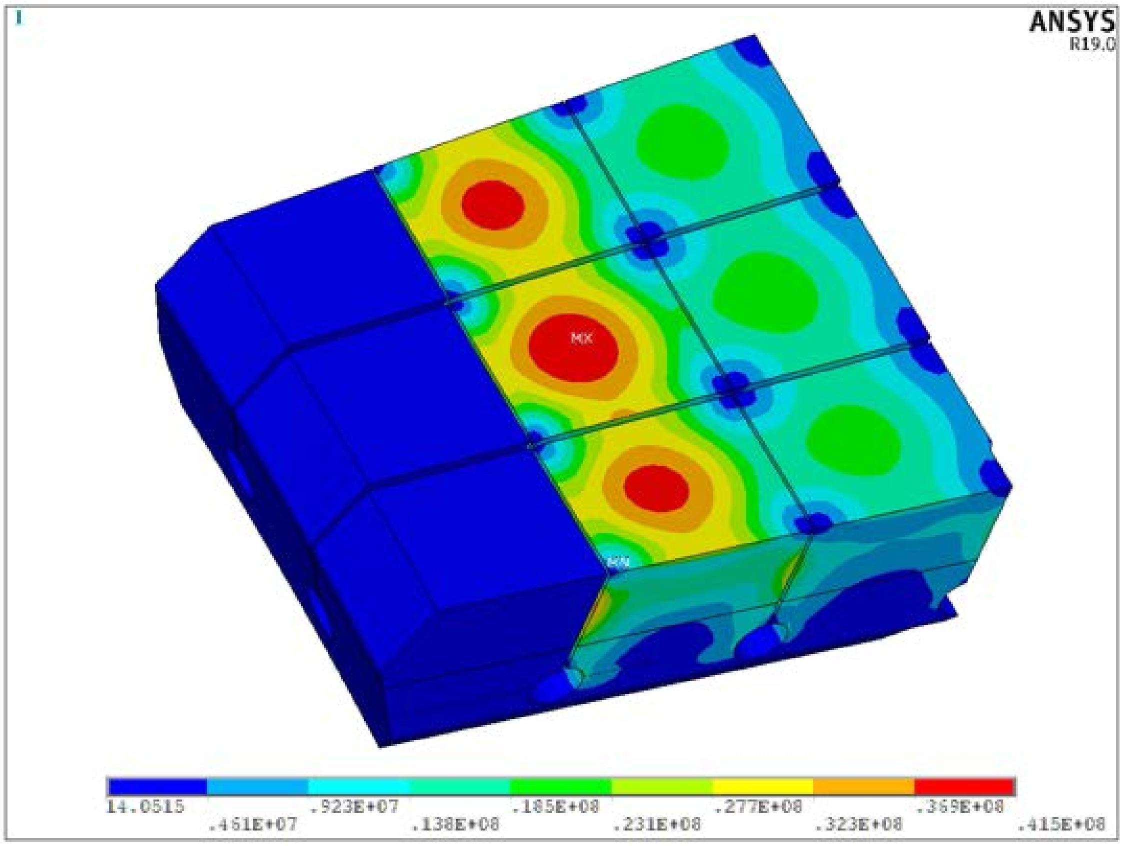

Figure 50. Case 5 - Von Mises Stress at 5 seconds (Pa)

Figure 51 and Figure 52 show the results of the minimum and maximum principal stresses in the tile after 15 seconds. The stresses are lower at 15 seconds. Figure 53 shows the von Mises stress in the tile after 15 seconds. The results show that even considering the local stresses, the tile stresses are all below the strength of the graphite. The maximum tensile stress of 6.3 MPa is well below the ultimate tensile strength of 38 MPa and is located around the cut outs in the bottom of the tile. The compressive stress of 9.0 MPa is well below the ultimate compressive strength of 130 MPa. The maximum von Mises stress is 8.9 MPa.

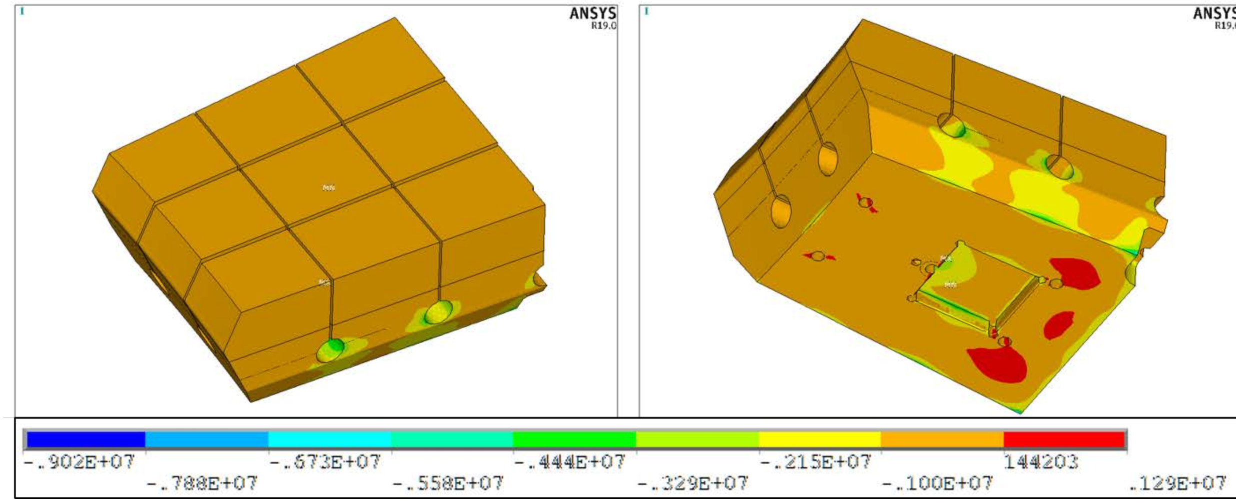

Figure 51. Case 5 - Min Principal Stress at 15 seconds (Pa)

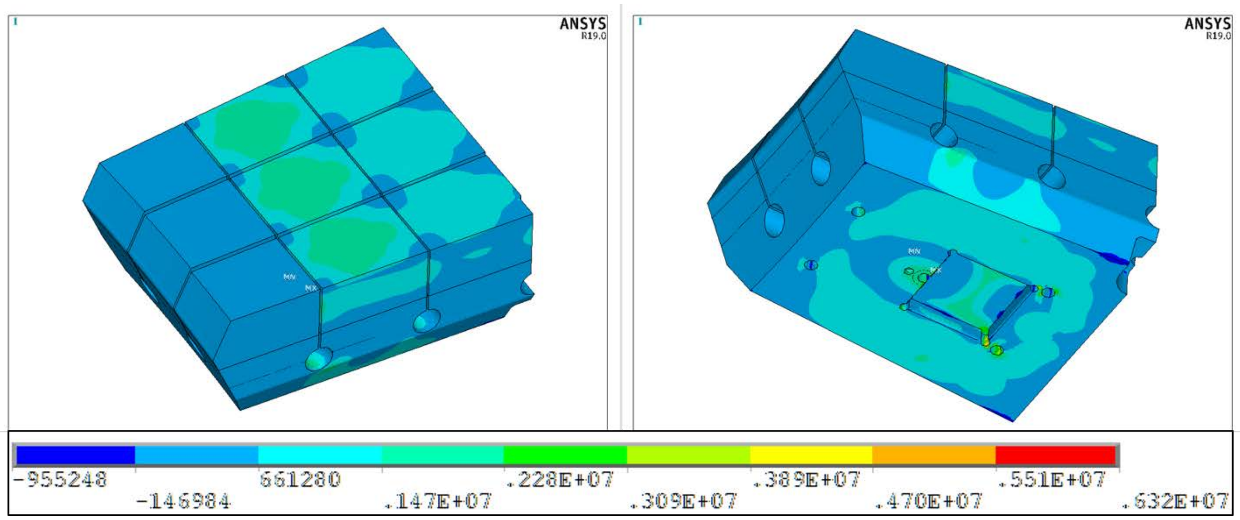

Figure 52. Case 5 - Max Principal Stress at 15 seconds (Pa)

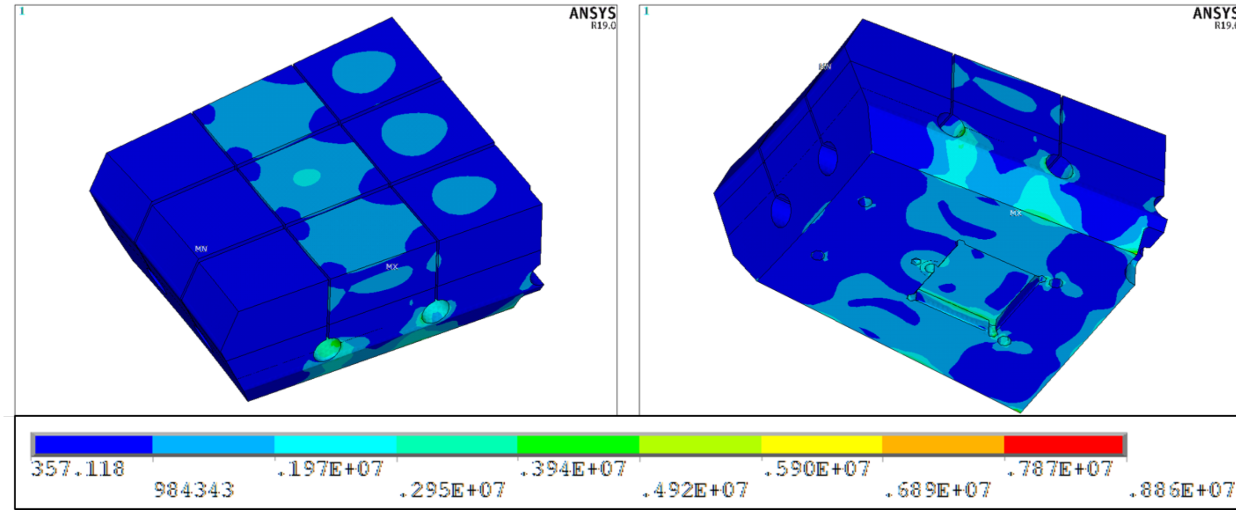

Figure 53. Case 5 - Von Mises Stress at 15 seconds (Pa)

6.0 SUMMARY

A summary of the peak maximum and minimum principal stresses are shown in Table 2 for Cases 1, 2, 3, and 5 at 5 seconds and 15 seconds. Results at only 5 seconds are shown for Case 4. The results show that all the stresses are well below the ultimate strength of the materials. The material assumed for the tile is SGL R6510, with an ultimate tensile strength of 38 MPa and an ultimate compressive strength of 130 MPa.

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

	Case 1	Case 2	Case 3	Case 4	Case 5
Max Principal Stress @ 5s (MPa)	28.5	27.6	17.6	25.4	15.6
Max Principal Stress @ 15s (MPa)	5.7	5.7	5.7	--------	6.3
Min Principal Stress @ 5s (MPa)	-43.4	-43.4	-43.4	-43.0	43.5
Min Principal Stress @ 15s (MPa)	-8.7	-8.6	-8.6	--------	-9.0