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Fermilab Engineering Analysis Report
THERMAL DESIGN OF PIP-II COMMISSIONING ABSORBER, ED0013689, Rev. -

Rev.	Date	Description	Originated By	Checked By	Approved By
-	12 May 2021	Initial Release	*N. Dhanaraj*	*Yun He*	*Kris E Anderson*

1. Introduction

The PIP-II straight ahead dump/absorber will be located at the end of the LINAC and its purpose is to stop the beam used for LINAC tuning. During the commissioning process, the absorber will be used at an intermediate location 177 MeV (a.k.a. 400 W location) before being moved to its final 1 GeV location (a.k.a. 2 kW location) at the end of the tunnel. This document describes the thermal and thermal-structural analysis of the absorber for these two cases: 400 W and 2 kW average beam power. It should be noted that the locations will be identified by the average beam power, i.e. 400 W and 2 kW locations, hereafter in this document.

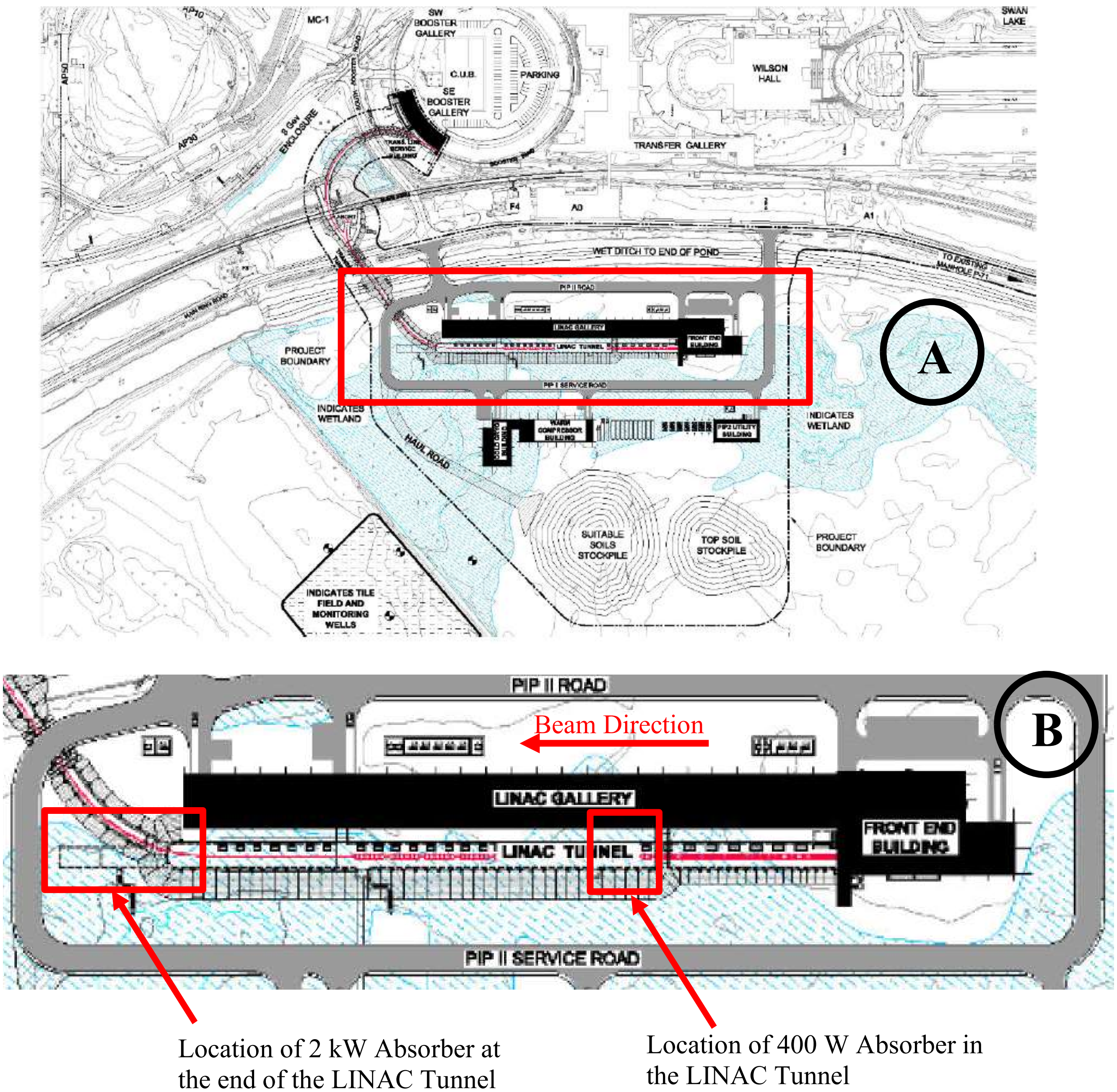


Figure 1. Site Layout of PIP-II, A: Overall Layout and B: Enlarged View.

2. Beam Parameters and Physics Requirements

Table 1 lists the beam parameters for the absorbers. All the beam parameters are applicable to both the 1 GeV and 177 MeV cases.

Particle Species	H-	
LINAC Pulse Duration	0.55 msec	
Repetition Rate	1 Hz	
Maximum Duty Factor	0.055%	
Beam Spot Size	Beam sigma of 2.5 mm	
Beam Kinetic Energy	1 GeV	177 MeV
Average Beam Power	2 kW*	400 W*

Table 1. Beam Parameters for the Absorbers.

(* Indicates that the actual Beam Power at 1 GeV is 1.13 kW and at 177 MeV is 190 W, but all analyses for 1 GeV was performed at 2 kW and 177 MeV was performed at 400 W, as per guidance received from project [1] and a naming convention of 2 kW and 400 W will be used in this document referring to the 1.13 kW and 190 W cases, respectively).

The design requirements [1] and assumptions for the absorber are listed below:

- The absorber shall be designed to abort the LINAC beam for 4 hours at an assumed LINAC energy of 1.0 GeV
- The absorber shall be designed for a total exposure of 4.2E18 H-/year assuming 4 hours of LINAC beam per week and 42 weeks of beam running per year
- The design lifetime shall be 10 years with a total number of aborted pulses per year of 604,800

3. Design Concept and Material Selection

The absorber must meet the requirements of absorbing the beam, removing efficiently the heat load from the beam energy deposited in the absorber materials and provide adequate shielding for limiting the residual radiation levels to acceptable values. Figure 2 shows the full assembly of the absorber core with the concrete shielding surrounding it for both the 400 W and 2 kW cases and Figure 3 shows the MARS model of the 2 kW case.

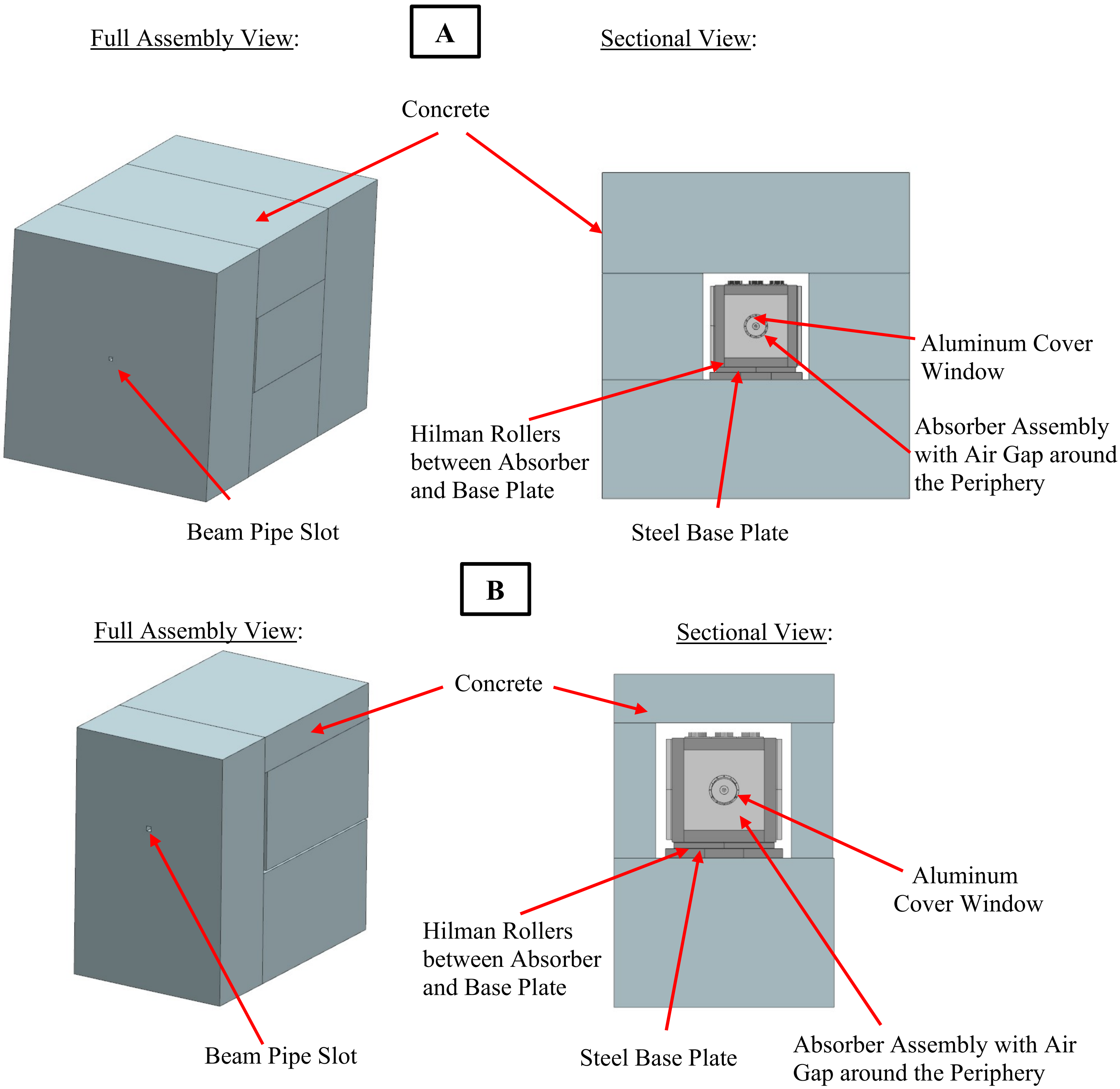


Figure 2. The Absorbers with Concrete Shielding: A: 2 kW case, B: 400 W case, which has no End Concrete

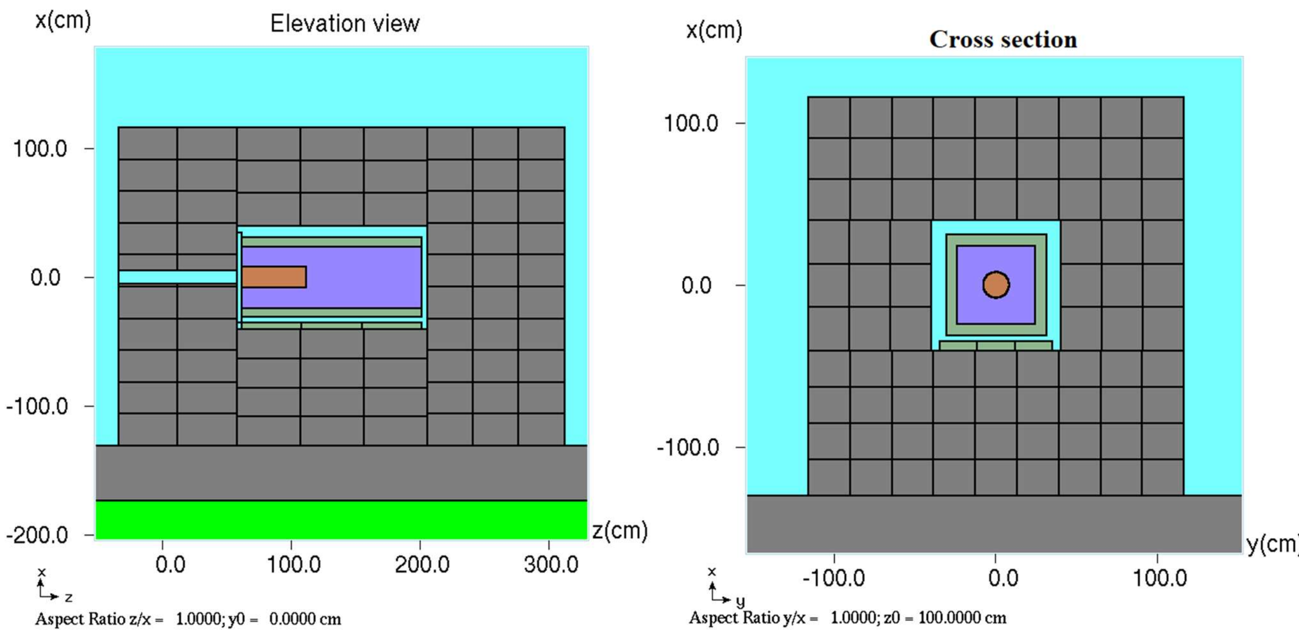


Figure 3. MARS Model for the 2 kW Absorber including the Concrete Shielding.

The absorber was designed iteratively by performing MARS and ANSYS simulations. The absorber core assembly shown in Figure 4 consists of the components summarized in the Table 2. The assembly is made by shrink fitting the Graphite core and the Aluminum block and fastening the rest of the parts by bolts (the bolts are not shown in the figures).

Component/Part	**Nominal Dimensions**
Graphite Core (2 segments) *	OD 152.4 mm X 254 mm L
Aluminum Block	Center Bore Dia. 152.4 mm X 480 mm Sides X 1400 L
Steel Plates Top and Bottom (2 Nos.)	480 mm W X 1400 L X 70 mm Thick
Steel Plates Sides (2 Nos.)	620 mm W X 1400 L X 70 mm Thick
Aluminum Finned Plates (18 Nos.)	152.4 mm W X 300 mm L X 40 mm Thick

Table 2. Parts List for the Absorbers.
(* indicates that the actual Graphite core will be in two segments due to limitations on size availability and to facilitate shrink fit).

The Graphite core was chosen due to its following properties:

- Low atomic number (Z =6) and low mass density (~1820 Kg/m^3) to absorb the beam and reduce the interactions and limit the residual radiation.
- High melting point (~ 3000 C) to withstand the thermal load from the beam
- High oxidation temperature (~450 C)
- Good Thermal Shock Resistance

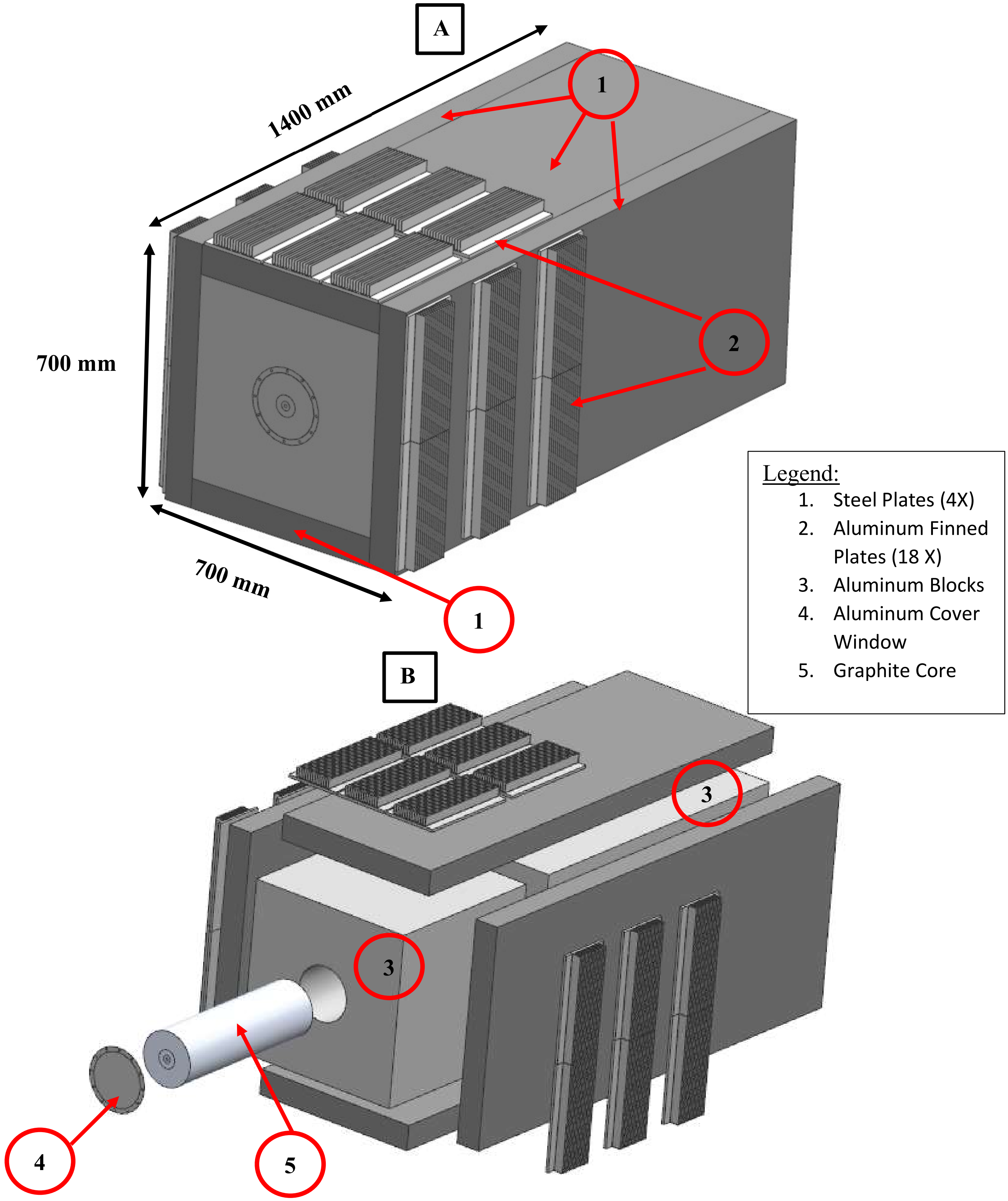


Figure 4. Model used for the Finite Element Analyses: A: Absorber Assembly, B: Exploded View.

4. Beam Energy Deposition from MARS

The energy deposited in the absorber from the beam is obtained from MARS simulations in the form of Joules/cm^3-pulse and this data is used as input for the thermal analysis after conversion to W/cm^3 based on the repetition rate. Figures 5, 6, 7 and 8 represent the heat deposition for the 2 kW and 400 W absorbers graphite core graphically.

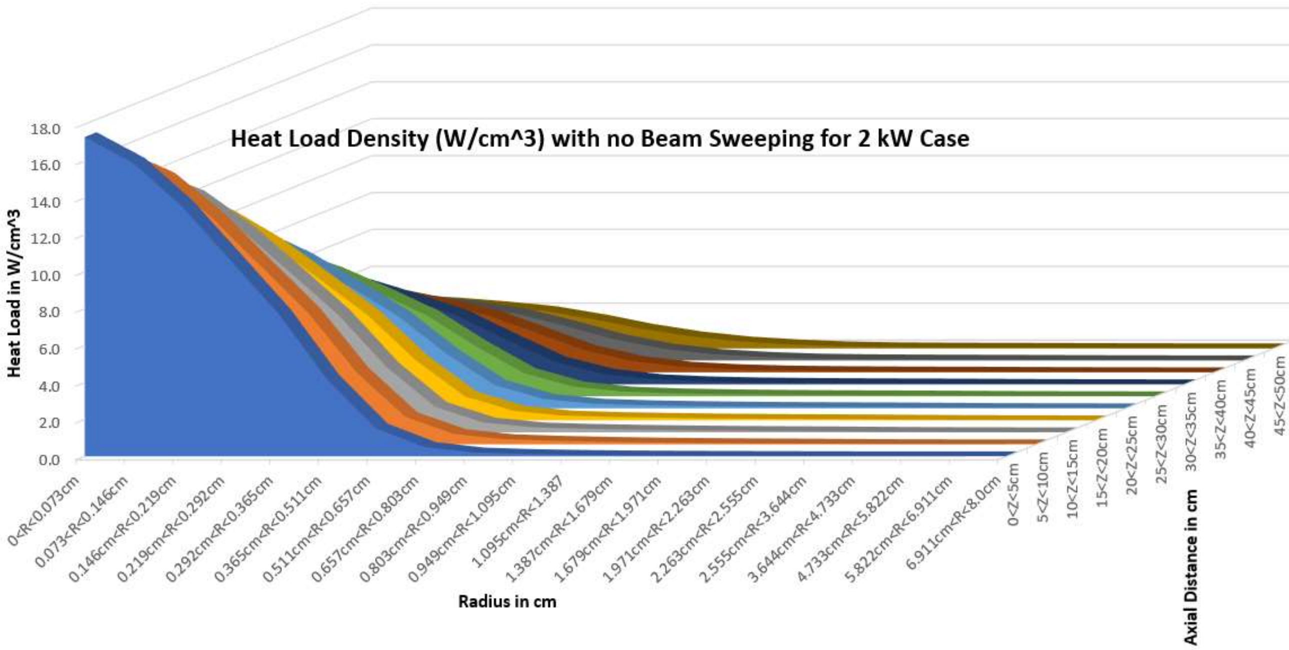


Figure 5. Heat Load Density for 2 kW Graphite Core in W/cm^3 from MARS Data.

Figures 5 and 7, represent the heat deposition data from MARS simulations for the Graphite core. The heat load is plotted as a function of the radial and axial distances/MARS bins of the Graphite core. Figures 6 and 8 represent the same data as in Figures 5 and 7, numerically.

	0<Z<5cm	5<Z<10cm	10<Z<15cm	15<Z<20cm	20<Z<25cm	25<Z<30cm	30<Z<35cm	35<Z<40cm	40<Z<45cm	45<Z<50cm
0<R<0.073cm	1.7306E+01	1.5632E+01	1.3862E+01	1.1986E+01	1.0020E+01	8.0760E+00	6.3340E+00	4.8380E+00	3.6220E+00	2.6940E+00
0.073<R<0.146cm	1.5900E+01	1.4464E+01	1.2842E+01	1.1128E+01	9.3940E+00	7.6360E+00	6.0300E+00	4.6580E+00	3.5240E+00	2.6420E+00
0.146cm<R<0.219cm	1.3548E+01	1.2300E+01	1.0972E+01	9.5740E+00	8.1560E+00	6.7600E+00	5.4320E+00	4.2660E+00	3.2800E+00	2.4920E+00
0.219cm<R<0.292cm	1.0636E+01	9.7060E+00	8.6960E+00	7.6620E+00	6.6240E+00	5.6120E+00	4.6280E+00	3.7220E+00	2.9360E+00	2.2820E+00
0.292cm<R<0.365cm	7.7080E+00	7.1020E+00	6.3780E+00	5.6940E+00	5.0320E+00	4.3800E+00	3.7400E+00	3.1120E+00	2.5340E+00	2.0220E+00
0.365cm<R<0.511cm	4.1500E+00	3.8780E+00	3.5340E+00	3.2360E+00	2.9740E+00	2.7240E+00	2.4640E+00	2.1820E+00	1.8810E+00	1.5806E+00
0.511cm<R<0.657cm	1.5046E+00	1.4774E+00	1.3752E+00	1.3024E+00	1.2688E+00	1.2596E+00	1.2512E+00	1.2230E+00	1.1588E+00	1.0598E+00
0.657cm<R<0.803cm	5.0100E-01	5.5860E-01	5.3280E-01	5.1500E-01	5.1760E-01	5.4140E-01	5.8040E-01	6.2180E-01	6.4980E-01	6.5300E-01
0.803cm<R<0.949cm	2.1000E-01	2.8200E-01	2.7620E-01	2.6420E-01	2.5900E-01	2.6460E-01	2.8420E-01	3.1500E-01	3.5140E-01	3.8200E-01
0.949cm<R<1.095cm	1.2704E-01	1.9646E-01	1.9692E-01	1.8626E-01	1.7550E-01	1.6928E-01	1.7022E-01	1.8034E-01	1.9952E-01	2.2440E-01
1.095cm<R<1.387	8.2760E-02	1.4270E-01	1.4878E-01	1.4146E-01	1.3130E-01	1.2166E-01	1.1436E-01	1.1060E-01	1.1142E-01	1.1888E-01
1.387cm<R<1.679cm	5.3720E-02	1.0186E-01	1.1206E-01	1.0832E-01	1.0162E-01	9.3520E-02	8.5980E-02	7.9120E-02	7.3940E-02	7.1040E-02
1.679cm<R<1.971cm	3.7260E-02	7.6120E-02	8.7980E-02	8.7280E-02	8.2340E-02	7.6400E-02	7.0120E-02	6.4400E-02	5.8900E-02	5.4740E-02
1.971cm<R<2.263cm	2.7240E-02	5.8700E-02	7.1120E-02	7.2420E-02	6.9100E-02	6.4520E-02	5.9320E-02	5.4300E-02	4.9640E-02	4.5800E-02
2.263cm<R<2.555cm	2.0520E-02	4.6440E-02	5.8240E-02	6.0820E-02	5.8980E-02	5.5420E-02	5.1340E-02	4.7000E-02	4.3080E-02	3.9640E-02
2.555cm<R<3.644cm	1.1808E-02	2.8520E-02	3.8440E-02	4.2420E-02	4.2680E-02	4.0980E-02	3.8380E-02	3.5540E-02	3.2660E-02	3.0060E-02
3.644cm<R<4.733cm	5.8380E-03	1.4960E-02	2.2000E-02	2.6020E-02	2.7640E-02	2.7600E-02	2.6600E-02	2.5040E-02	2.3280E-02	2.1620E-02
4.733cm<R<5.822cm	3.3260E-03	8.7520E-03	1.3652E-02	1.7002E-02	1.8880E-02	1.9560E-02	1.9414E-02	1.8698E-02	1.7666E-02	1.6582E-02
5.822cm<R<6.911cm	2.0840E-03	5.5260E-03	8.9340E-03	1.1656E-02	1.3402E-02	1.4332E-02	1.4606E-02	1.4380E-02	1.3854E-02	1.3172E-02
6.911cm<R<8.0cm	1.4106E-03	3.7040E-03	6.1020E-03	8.2820E-03	9.8140E-03	1.0778E-02	1.1252E-02	1.1320E-02	1.1088E-02	1.0694E-02

Figure 6. Energy Deposition for Graphite Core from MARS Simulations for 2 kW Location.

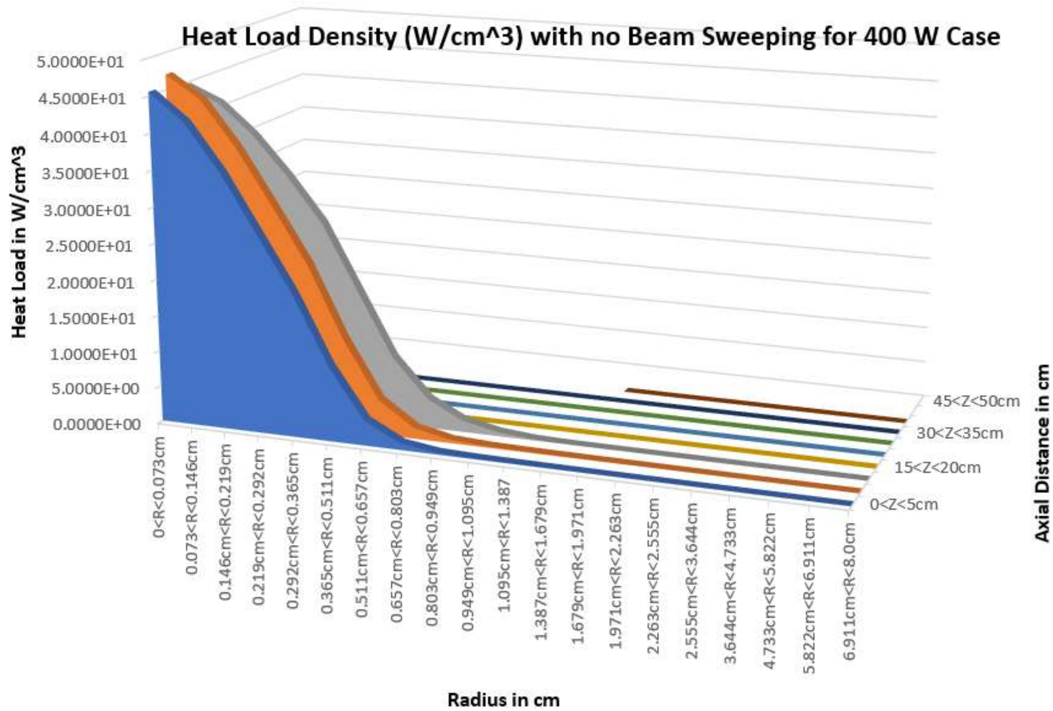


Figure 7. Heat Load Density for 400 W Graphite Core in W/cm^3 from MARS Data.

	0<Z<5cm	5<Z<10cm	10<Z<15cm	15<Z<20cm	20<Z<25cm	25<Z<30cm	30<Z<35cm	35<Z<40cm	40<Z<45cm	45<Z<50cm
0<R<0.073cm	4.5558E+01	4.7072E+01	4.4790E+01	2.7480E-04	8.7070E-05	4.9376E-05	3.1908E-05	1.8157E-05	1.6741E-05	1.1652E-05
0.073<R<0.146cm	4.1852E+01	4.3954E+01	4.2778E+01	2.6892E-04	9.2764E-05	5.0756E-05	2.6576E-05	1.7570E-05	1.3439E-05	1.0813E-05
0.146cm<R<0.219cm	3.5502E+01	3.7830E+01	3.8710E+01	2.7864E-04	9.0822E-05	4.7050E-05	2.8044E-05	1.9525E-05	1.4560E-05	1.1283E-05
0.219cm<R<0.292cm	2.7682E+01	3.0350E+01	3.3354E+01	2.7118E-04	9.3058E-05	4.8518E-05	2.8948E-05	1.9242E-05	1.4903E-05	1.0904E-05
0.292cm<R<0.365cm	1.9850E+01	2.2644E+01	2.7254E+01	2.7118E-04	9.2290E-05	4.7592E-05	2.9288E-05	1.8820E-05	1.3875E-05	9.9770E-06
0.365cm<R<0.511cm	1.0397E+01	1.2736E+01	1.8313E+01	2.7614E-04	9.4098E-05	4.6710E-05	2.7298E-05	1.8535E-05	1.3075E-05	1.0099E-05
0.511cm<R<0.657cm	3.4552E+00	4.8020E+00	9.3804E+00	2.7660E-04	9.4890E-05	4.7886E-05	2.8858E-05	1.8691E-05	1.3764E-05	9.8822E-06
0.657cm<R<0.803cm	9.3036E-01	1.4996E+00	4.0858E+00	2.8248E-04	9.5770E-05	4.8314E-05	2.9152E-05	1.9457E-05	1.3900E-05	1.0485E-05
0.803cm<R<0.949cm	2.6960E-01	4.7208E-01	1.5685E+00	2.8610E-04	9.7758E-05	4.8338E-05	3.0440E-05	1.9699E-05	1.3439E-05	9.9114E-06
0.949cm<R<1.095cm	1.2528E-01	2.0962E-01	5.6518E-01	2.8970E-04	1.0097E-04	5.0732E-05	3.0236E-05	1.9685E-05	1.4171E-05	9.7600E-06
1.095cm<R<1.387	7.4098E-02	1.2244E-01	1.5233E-01	2.9310E-04	1.0250E-04	5.1342E-05	3.0914E-05	2.0384E-05	1.4094E-05	9.9566E-06
1.387cm<R<1.679cm	4.4632E-02	8.1624E-02	4.7276E-02	2.9378E-04	1.0693E-04	5.3106E-05	3.2248E-05	2.0682E-05	1.4508E-05	1.0036E-05
1.679cm<R<1.971cm	2.7772E-02	5.8122E-02	2.5942E-02	2.9332E-04	1.0971E-04	5.5388E-05	3.2676E-05	2.1228E-05	1.4474E-05	1.0461E-05
1.971cm<R<2.263cm	1.7543E-02	4.1988E-02	1.6560E-02	2.8970E-04	1.1243E-04	5.7422E-05	3.3830E-05	2.1818E-05	1.4881E-05	1.0806E-05
2.263cm<R<2.555cm	1.1017E-02	3.0372E-02	1.0956E-02	2.8248E-04	1.1475E-04	5.9004E-05	3.4440E-05	2.2526E-05	1.5193E-05	1.0901E-05
2.555cm<R<3.644cm	3.8304E-03	1.3742E-02	4.5376E-03	2.5942E-04	1.1611E-04	6.1444E-05	3.6518E-05	2.3502E-05	1.6090E-05	1.1532E-05
3.644cm<R<4.733cm	6.6212E-04	3.3378E-03	1.1552E-03	2.1848E-04	1.1360E-04	6.3478E-05	3.8688E-05	2.5084E-05	1.7141E-05	1.2348E-05
4.733cm<R<5.822cm	1.5954E-04	7.7420E-04	3.7762E-04	1.7715E-04	1.0535E-04	6.2890E-05	3.9524E-05	2.6032E-05	1.7941E-05	1.2901E-05
5.822cm<R<6.911cm	7.2562E-05	2.2374E-04	1.8451E-04	1.4309E-04	9.4528E-05	6.0178E-05	3.9344E-05	2.6576E-05	1.8411E-05	1.3276E-05
6.911cm<R<8.0cm	4.9806E-05	1.0467E-04	1.2442E-04	1.1572E-04	8.3702E-05	5.6924E-05	3.8598E-05	2.6644E-05	1.8820E-05	1.3631E-05

Figure 8. Energy Deposition for Graphite Core from MARS Simulations for 400 W Location.

The power deposited in each of the absorber component including the concrete is shown in the Table 3 below, along with the peak heat load density in the Graphite core.

Component	Heat Load Deposited for 2 kW Location (W)	Heat Load Deposited for 400 W Location (W)
Graphite Core	467.1	377.5
Aluminum Block	892.1	2.8
Steel Casing	176.8	1.7
Steel Plate at the Bottom	13.4	0.25
All Concrete	191.2	2.1
Total	**1741 W**	**384.4 W**
Peak Heat Load Density for Graphite Core	**17.31 W/cm^3**	**47.1 W/cm^3**

Table 3. Heat Load Deposited in the Absorber Assembly

It is of significance here to observe that the heat load density for the graphite core is higher in the 400 W case. This is attributed to the fact that at lower energies, the peak local energy deposition is usually higher at the beginning, but loses energy at a faster rate, whereas in the case of higher energies, the particles can travel longer distances without losing much energy [2]. This phenomenon can be observed in the thermal analysis results.

5. Finite Element Analyses using ANSYS

The following is the list of Finite Element Analyses performed.

- Transient Thermal with Average Power
- Steady State Thermal with Average Power
- Thermal-Stress Analyses
- Transient Dynamic

5.1. Transient Thermal Analysis with Average Power

A transient thermal analysis was performed using the average beam power (shown in Figure 6 and Figure 8) to estimate the time required for the Absorber to attain steady state temperatures. The analyses were performed for two cases: 4 hours and 100 hours of average beam power. The following sub-sections describe the details of the analyses.

Material Properties

Table 4 outlines the material properties used for the thermal analysis along with the references to the source. The temperature dependent material properties used for the Transient Thermal and Thermal-Stress analyses are listed in Appendix A.

Material	Thermal Conductivity (W/m-K)	Density (Kg/m^3)	Yield/Ultimate/Compressive Strength (MPa)	Used on
Graphite – TM Grade [Appendix G]	60	1820	Negligible / 41 / 110	Absorber Core
Aluminum 6061-T6 [3]	167	2700	280 / 310 / 280	Aluminum Block encasing the Graphite core and Fin Assembly
Structural Steel [4]	60	7850	250 / 460/ 250	Steel Casing around Aluminum Block and Base Plate
Stainless Steel [4]	15.1	7750	207 / 586 / 207	Hilman Rollers
Concrete [4]	0.72	2300	Negligible / 5 / 41	Shielding around Absorber
Air [4], [5]	0.026	1.2	Not Applicable	Air Gaps

Table 4. Material Properties of the Components used in the Absorber Assembly.

Contact Conditions

The contact conditions assumed between the various components are listed in Table 5 along with the Thermal Contact Conductance (TCC) values for known contact pressure conditions, while an air gap conductance was assumed for contacts with unknown contact pressures.

Contact Source	Contact Target	Type of Joint	Contact Condition	TCC estimated using formulas (W/m^2-K	TCC used in the Analyses (W/m^2-K)
Graphite Core outer surface	Aluminum Block inner surface	Interference fit of .01 inch	Bonded	1.7e5	1000 [Appendix B], [6], [7]
Aluminum Block	Structural Steel Plates on all sides (4 plates in total)	Bolted with .75 inch bolt	Bonded	>1000	1000 [Appendix B], [6]
Structural Steel Plates	Structural Steel Plates	Bolted with .75 inch bolt	Bonded	>1000	1000 [Appendix B], [6]
Structural Steel Base Plate	Concrete Bottom	Self-Weight	Bonded	N/A	10 (corresponds to an air gap

					of .10 inch or 2.6 mm)
Aluminum Window	Aluminum Block	Bolted	Bonded	N/A	50 (corresponds to an air gap of .02 inch or 0.52 mm)
Aluminum Fins	Structural Steel Plates	Bolted	Bonded	N/A	50 (corresponds to an air gap of .02 inch or 0.52 mm)
Graphite Core	Aluminum Cover Window	Contact	Bonded	N/A	10 (corresponds to an air gap of .10 inch or 2.6 mm)

Table 5. Contact Conditions and TCCs.

Meshed Model

Figure 9 shows the finite element meshed model used for the analysis. The mesh generated was iteratively verified with the MARS model to ensure the correct import of the energy deposition as external data in ANSYS [Appendix C].

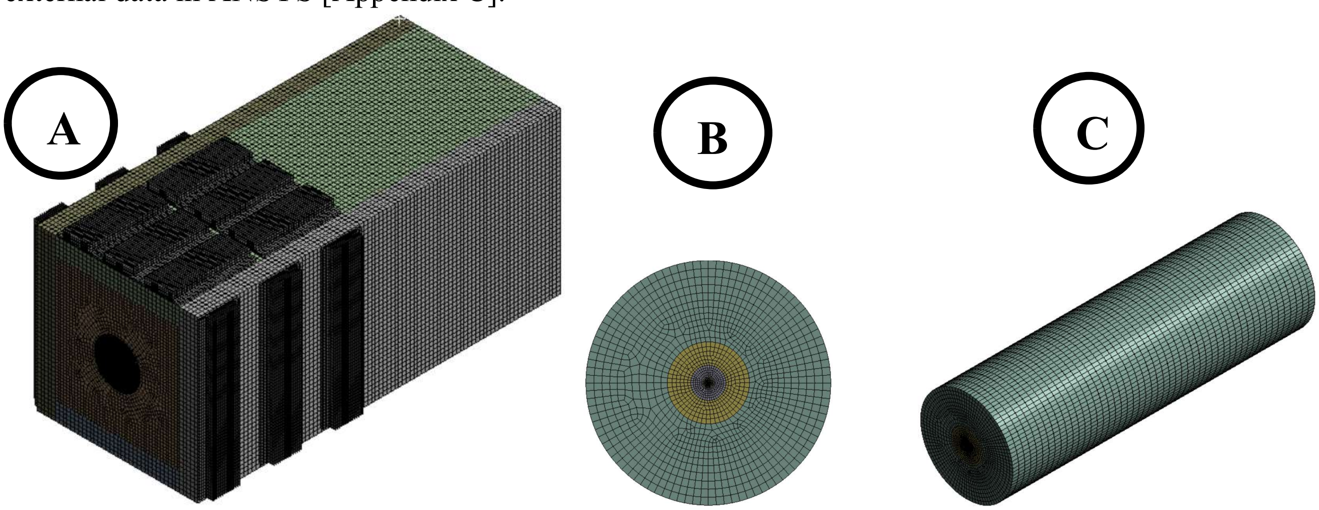


Figure 9. Meshed Models: A: Absorber Assembly, B: Graphite Core Face, C: Graphite Core Iso View

Boundary Conditions

The cooling scheme for the absorbers has been selected to be natural air convection with a typical heat transfer coefficient of 5 W/m^2-K. Nevertheless, the actual values could be different, i.e. lower, as experienced in measurements conducted for NuMI systems [8]. Thus, the analysis has assumed 2 categories: Optimistic and Nominal. Table 6 shows the heat transfer coefficients used for the 2 categories at different locations and Figure 10 shows the boundary conditions as well.

Location	Optimistic Heat Transfer Coefficient (W/m^2-K)	Nominal Heat Transfer Coefficient (W/m^2-K)
Outer surfaces/perimeter of Absorber not including the Fins	5	3
Concrete inner walls around Absorber	5	3
Concrete outer walls	5	3
Fin gaps	3	2 (0.5 – 1.5*)
Outer surface of beam window	5	3
Beampipe Slot	3	2
Base Plate Steel	5	3

Table 6. Heat Transfer Coefficient assumed in the Analysis.

(* As a reference, NuMI Stripline measurements used 2 W/m^2-K for an air gap of 3/8 inch. Also, the fin spacing was optimized [9], so using 2 W/m^2-K would be nominal/close to practical. Appendix F describes the fin optimization and sensitivity checks).

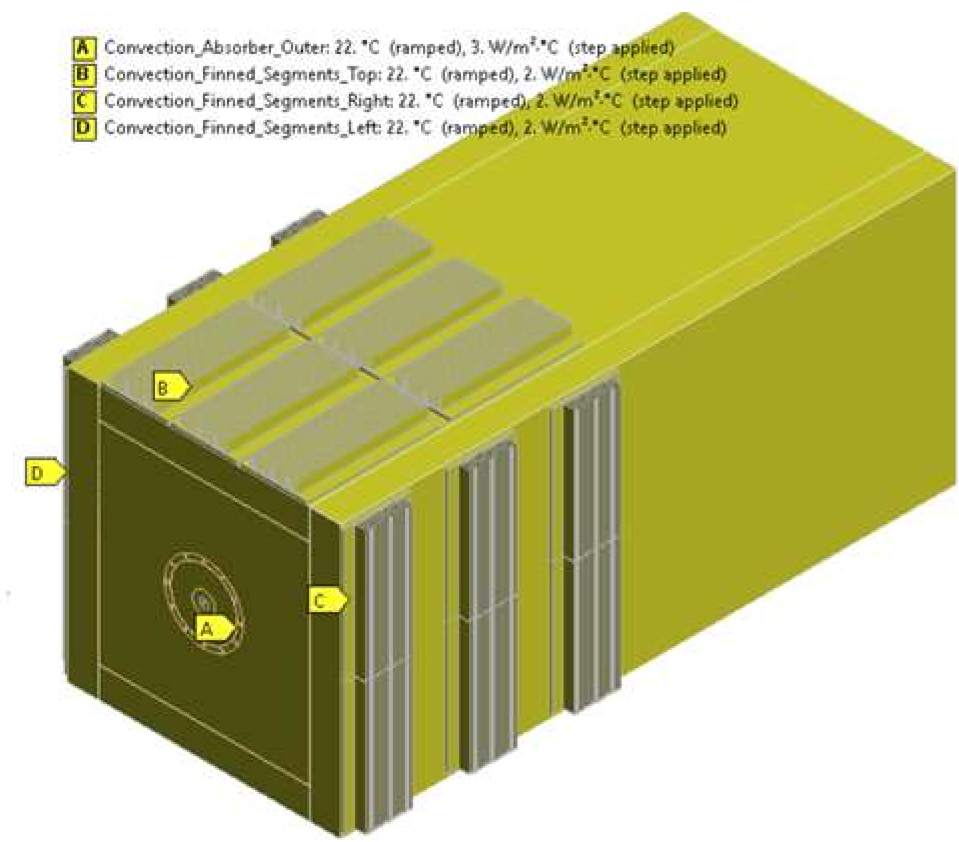


Figure 10. Convective Boundary Conditions Applied on the Absorber Assembly.

Heat Load

As described in the previous sections the energy deposited into the absorber in the form of heat generation is the only heat load. Figure 11 shows the Graphite core unto which the energy deposition is mapped (shown in black dots). The data points were generated using a MATLAB code [Appendix D] to read the MARS data and convert it into .csv files, which ANSYS can read.

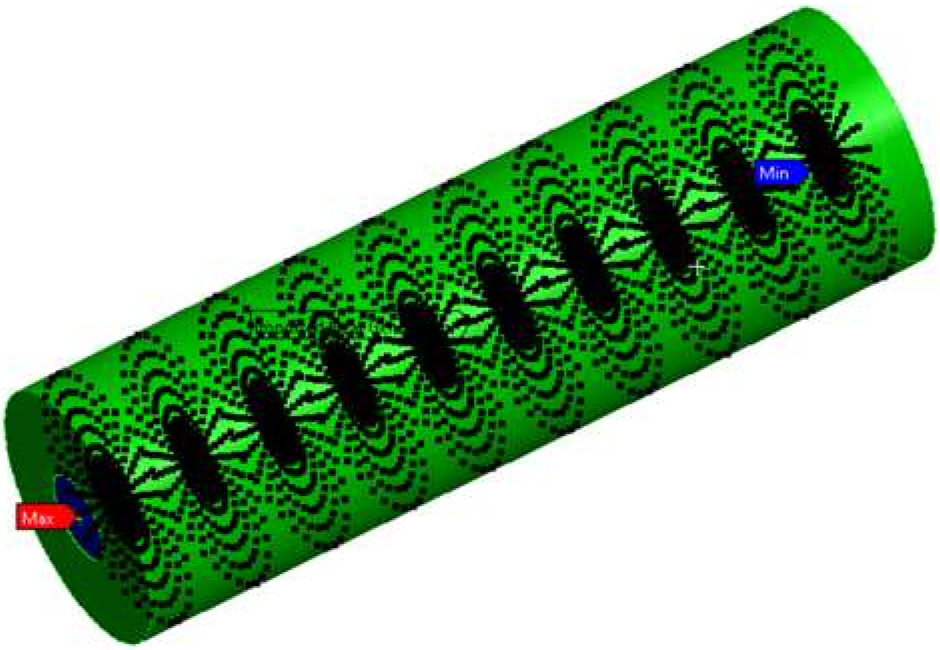
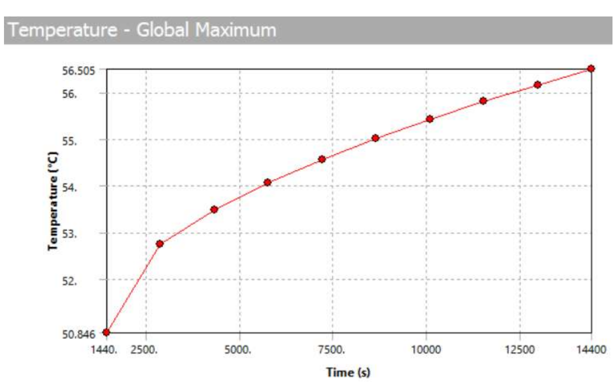
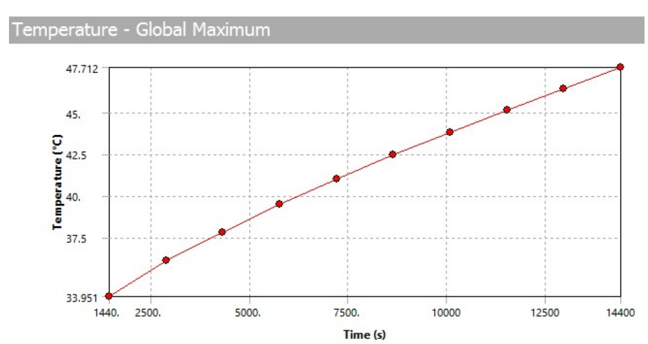


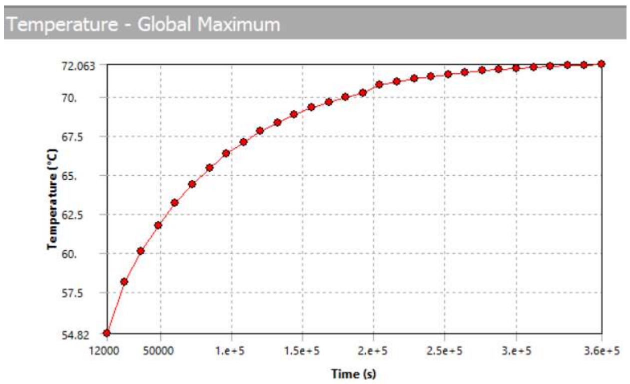
Figure 11. MARS data Mapped to the Graphite Core.

Results

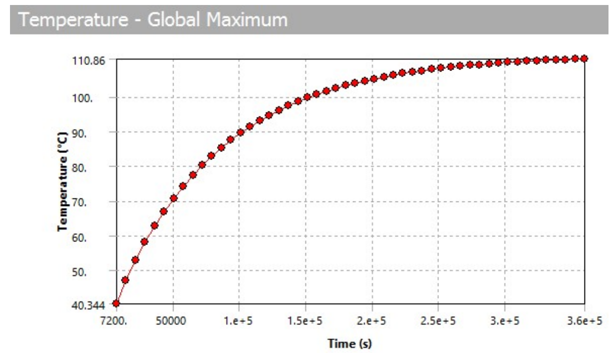
The results of the transient thermal analyses with average power are presented for the two cases: 400 W and 2 kW and for two sets of time steps, 4 hours and 100 hours.

<table>
<tr><th>400 W Results</th><th>2 kW Results</th></tr>
<tr><td>Maximum Temperature Plot for 4 hours of Average Power in the Graphite core: 56.505 C
</td><td>Maximum Temperature Plot for 4 hours of Average Power in the Graphite core: 47.712 C
</td></tr>
</table>

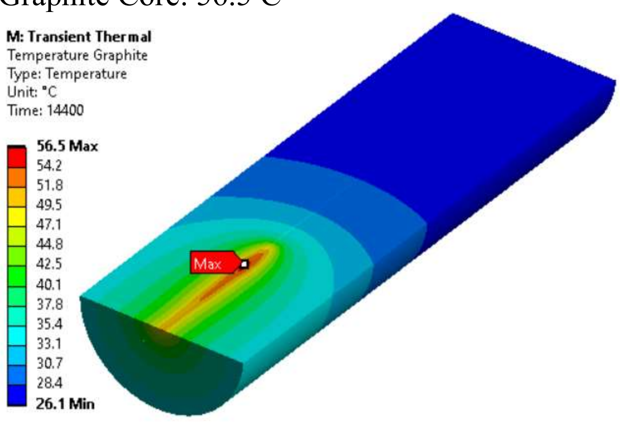
<table>
<tr><td></td><td></td></tr>
<tr><td>Maximum Temperature Plot for 100 hours of Average Power in the Graphite core: 72.063 C



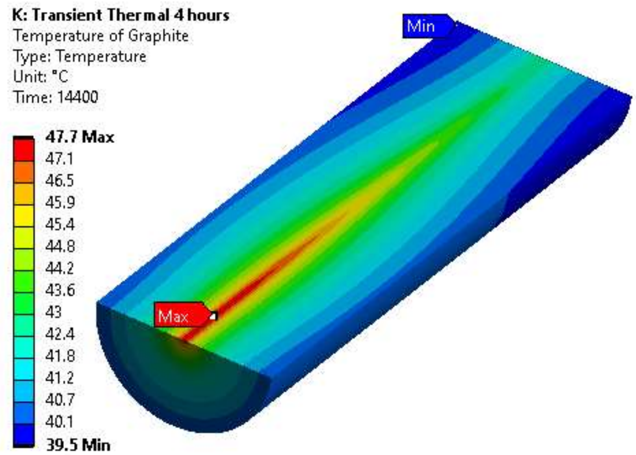
</td><td>Maximum Temperature Plot for 100 hours of Average Power in the Graphite core: 110.9 C



</td></tr>
<tr><td>Maximum Temperature at end of 4 hours in Graphite Core: 56.5 C



</td><td>Maximum Temperature at end of 4 hours in Graphite Core: 47.7 C



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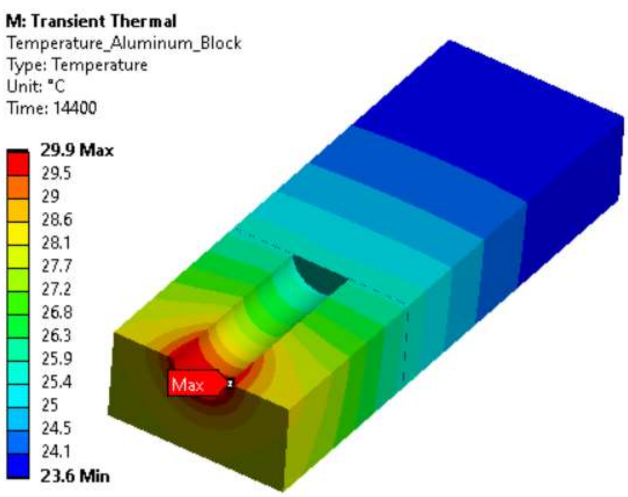
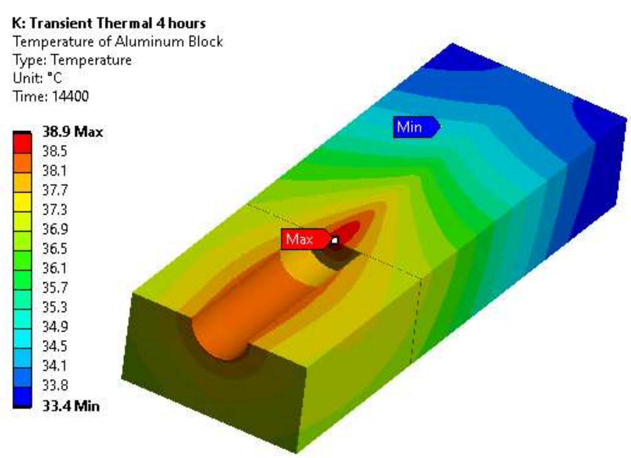
<tr><td>Maximum Temperature at end of 4 hours in the Aluminum Block: 29.9 C



</td><td>Maximum Temperature at end of 4 hours in the Aluminum Block: 38.9 C



</td></tr>
</table>

Summary and Conclusions

The results from the transient thermal analyses show that at 4 hours of continuous operation (as per requirements) at the average beam power, the absorber does not reach steady state temperatures. The steady state temperatures are attained around 100 hours of continuous operation at average beam power as shown in Figure 12.

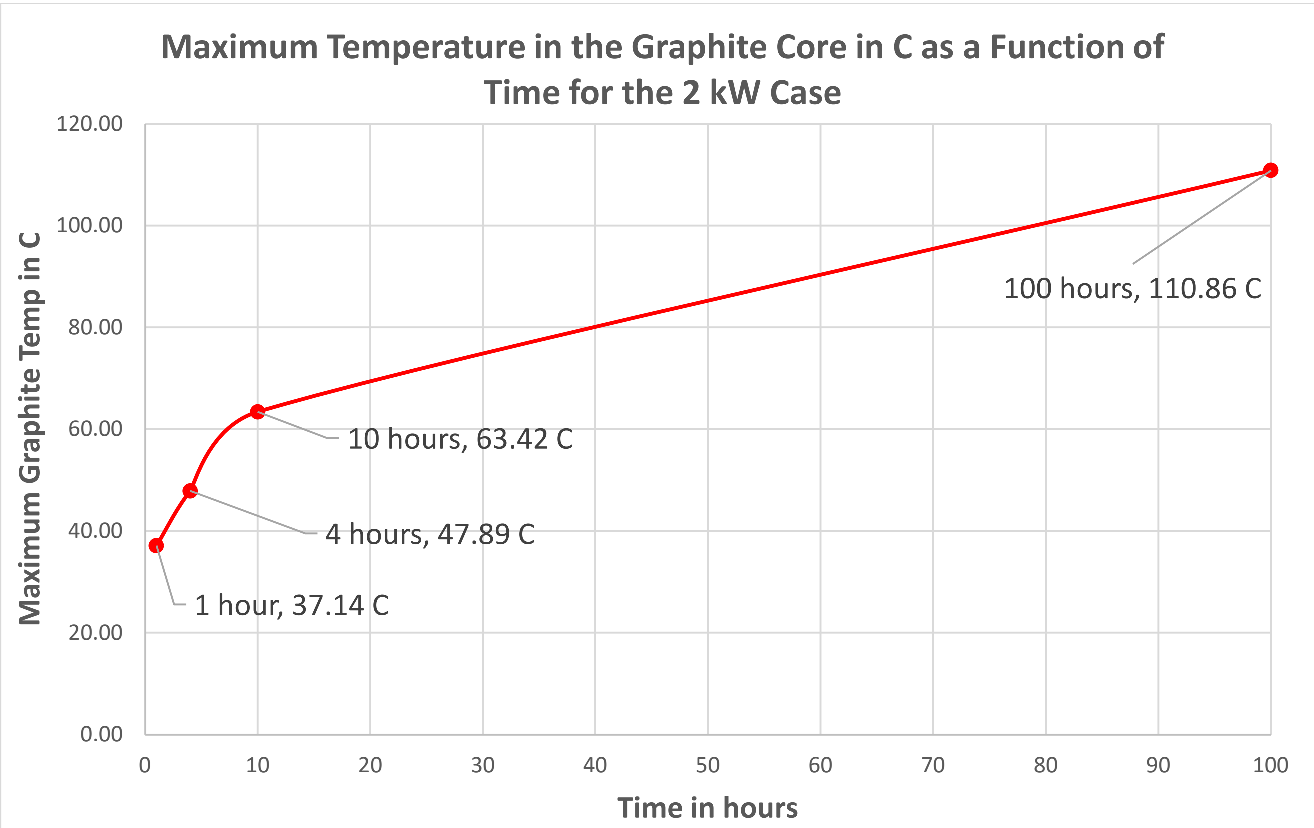


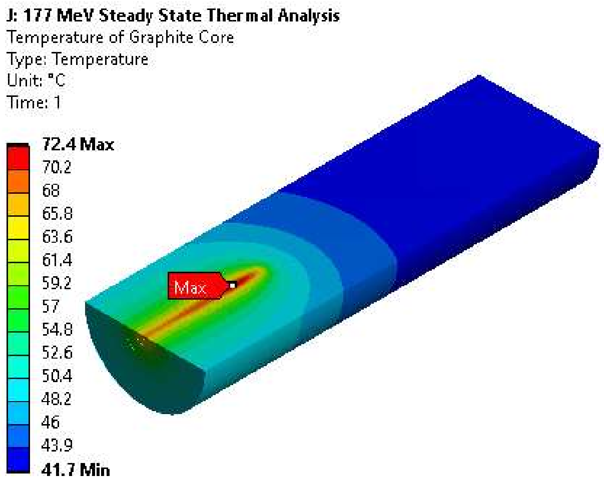
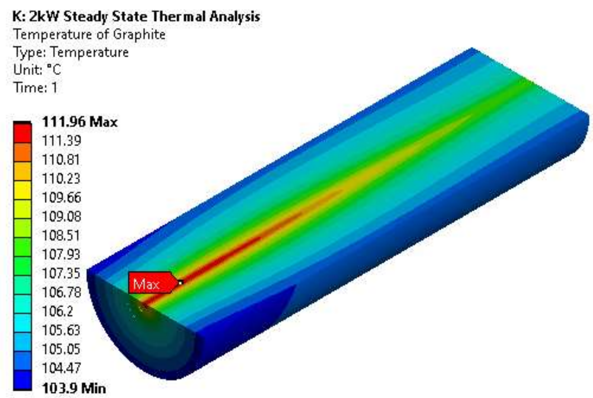
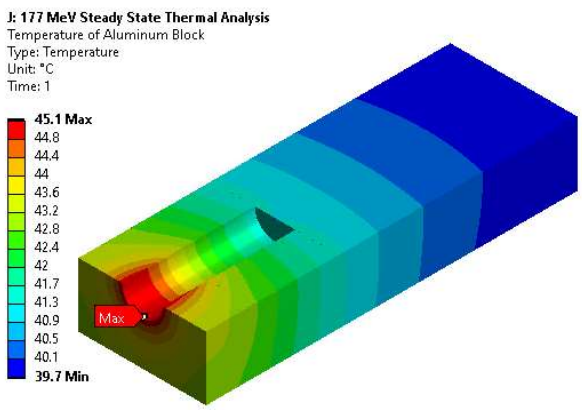
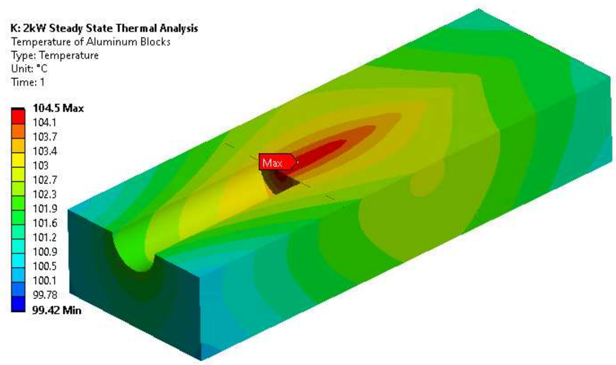
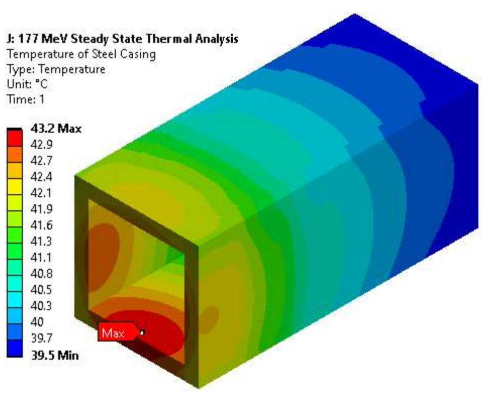
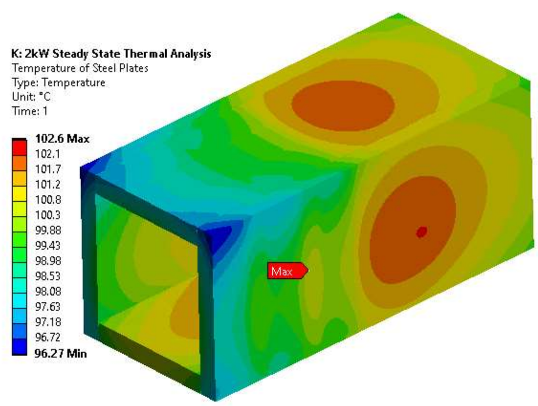
Figure 12. Maximum Temperature of Graphite Core as a Function of Time for the 2 kW Case.

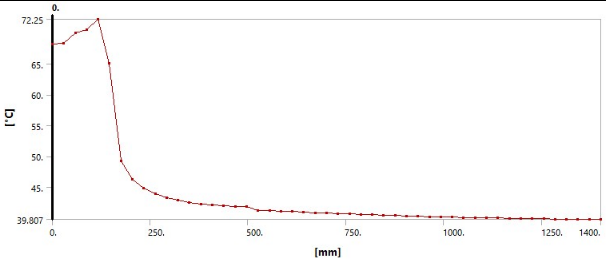
Thus, this provides a good safety margin in terms of temperatures in the components of the assembly, especially in the Aluminum block, where the material properties begin to degrade above 100 C.

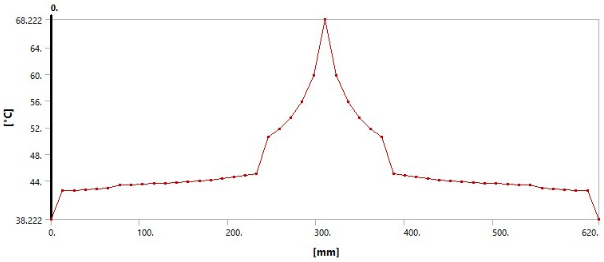
5.2. Steady State Thermal Analysis with Average Power

A steady state (equivalent to 100 hours average beam power) thermal analysis was performed to estimate the maximum temperatures in the absorber components. The same boundary conditions as in the transient thermal analyses were used. The results of the steady-state thermal analyses are presented for both the 400 W and 2 kW cases.

Results

<table>
<tr><th>400 W Absorber Results</th><th>2 kW Absorber Results</th></tr>
<tr><td>Graphite Core Max. Temperature 72.4 C

</td><td>Graphite Core Max. Temperature 112 C

</td></tr>
<tr><td>Aluminum Block Max. Temperature 45.1 C

</td><td>Aluminum Block Max. Temperature 104.5 C

</td></tr>
<tr><td>Steel Casing Max. Temperature 43.2 C

</td><td>Steel Casing Max. Temperature 102.6 C

</td></tr>
<tr><td>Temperature Profile of Axial Path:</td><td>Temperature Profile of Axial Path:</td></tr>
</table>

<table>
<tr>
<td>


Temperature Profile of Radial Path:


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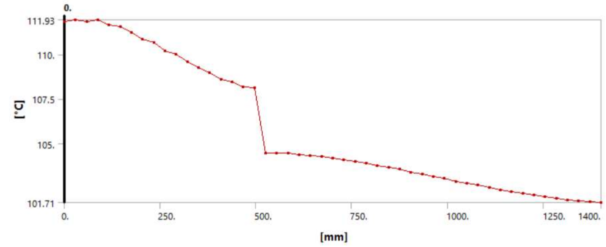
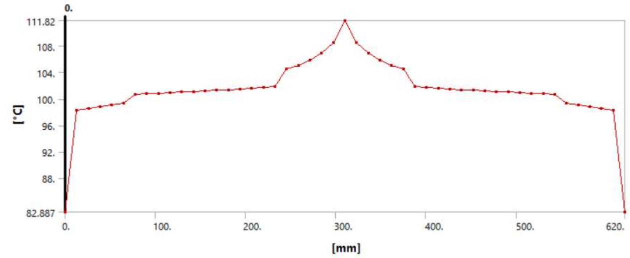


Temperature Profile of Radial Path:


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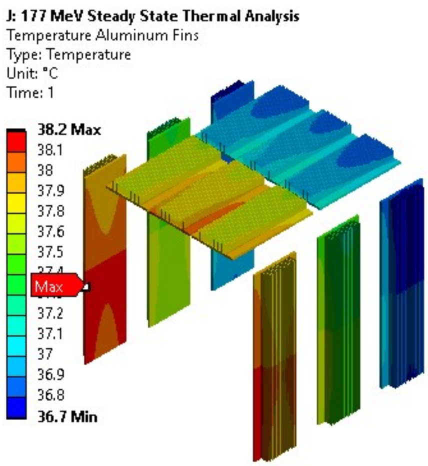
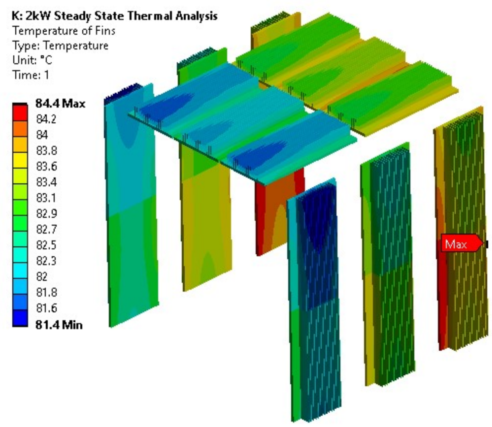
<tr>
<td>
Aluminum Fins Max. Temperature 38.2 C


</td>
<td>
Aluminum Fins Max. Temperatrue 84.4 C


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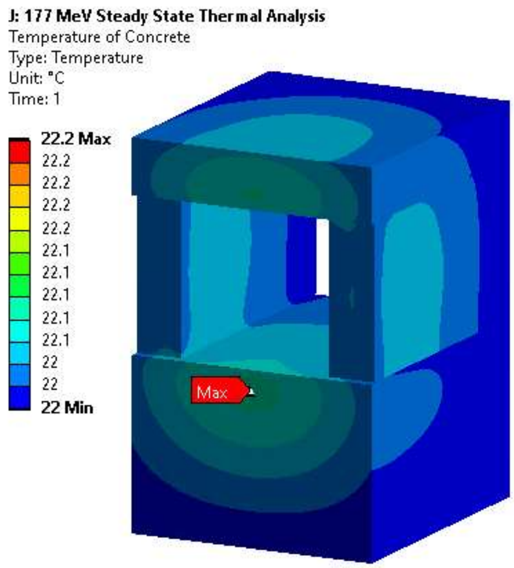
<tr>
<td>Concrete Shielding Max. Temperature 22.2 C (except front)

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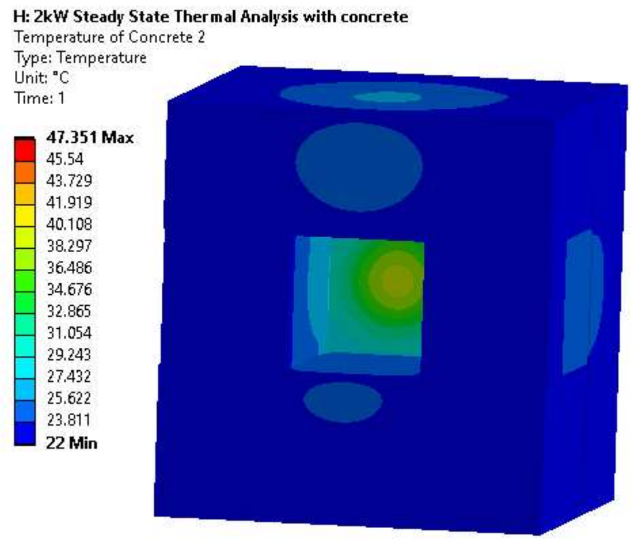
<td>Concrete Shielding Max. Temperature 47.35 C (except front)

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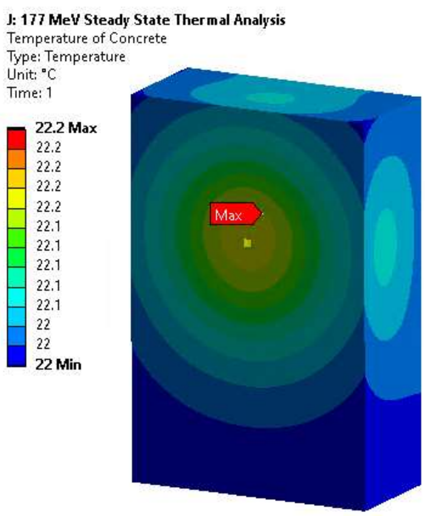
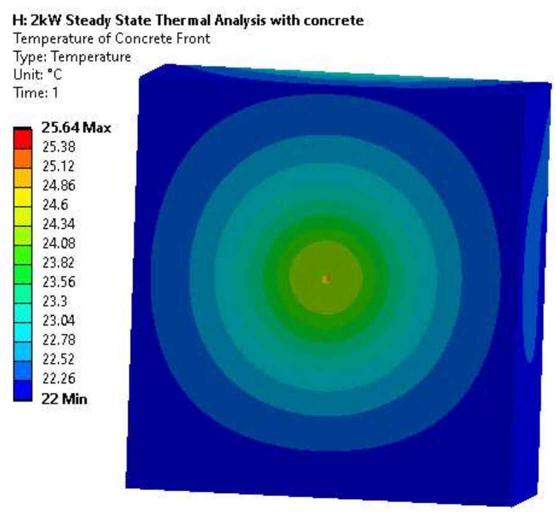
<tr>
<td>Concrete Shielding Front Max. Temperature 22.2 C

</td>
<td>Concrete Shielding Front Max. Temperature 25.64 C

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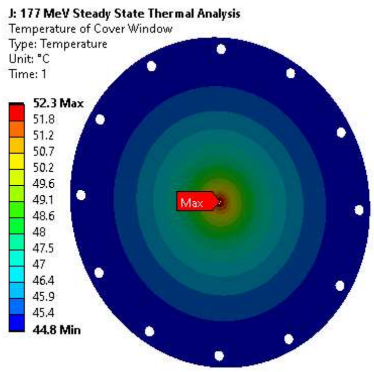
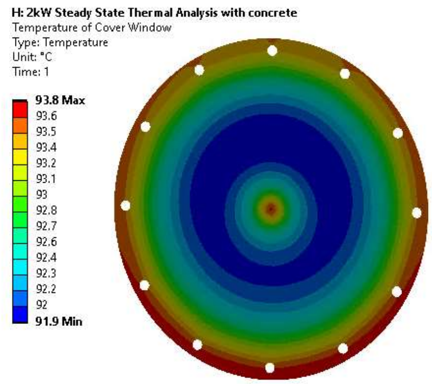
Aluminum Cover Window Max. Temperature 52.3 C



Aluminum Cover Window Max. Temperature 93.8 C



Reaction Load Comparison:

Component	FEA Results	MARS Data
Absorber	240.3 W	**382 W**
Top Fins	54.7 W	
Right Fins	54.8 W	
Left Fins	54.8 W	
Total	**404.6 W**	
Concrete Outer	2.2 W	**2.1 W**
Concrete around Absorber	0.5 W	
Beam Pipe Slot	0.033 W	
Concrete Base	0.12 W	
Total	**2.85 W**	
Base Plate	0.18 W	0.25 W
Grand Total	**407.63 W**	**384.4 W**

Reaction Load Comparison:

Component	FEA Results	MARS Data
Absorber	998.44 W	**1536 W**
Top Fins	216.01 W	
Right Fins	216.74 W	
Left Fins	216.73 W	
Total	**1647.92 W**	
Concrete Outer	100.47 W	**191.2 W**
Concrete around Absorber	82.02 W	
Beam Pipe Slot	0.74 W	
Concrete Base	20.98 W	
Total	**204.21 W**	
Base Plate	10.83 W	13.4 W
Grand Total	**1862.96 W**	**1740.6 W**

Summary and Conclusions

The steady state thermal results show that the peak temperatures of the absorber match very well with the equilibrium temperatures attained in the transient thermal analysis at the end of 100 hours. The peak temperatures are much less than the melting point of any of the components of the absorber core (Table 7). The natural convection cooling scheme is adequate.

Material	Maximum Temperatures in C				Melting Point in C
	400 W Case		2 kW Case		
	4 hours	100 hours	4 hours	100 hours	
Graphite TM Grade	56.5	72.4	47.7	112	3500
Aluminum 6061-T6	29.9	45.1	38.9	104.5	585
Structural Steel	27.93	43.2	37	102.6	1425

Table 7. Results Comparison between Steady State Conditions (100 hours) and Transient at Average Power of 4 hours.

The temperature profile of the Graphite core also highlights a point of discussion mentioned earlier in this document in section 4 and Table 3. The high temperature zone in the Graphite core of the 400 W case dies down faster when compared to the 2 kW case. This confirms the fact that the particles in the lower energy case lose energy more quickly and thus travel less distance, although they may have high initial energies.

The reaction probe results from the FEA also agree well with the MARS data, although the FEA overpredicts the heat load deposited this is deemed as a conservative approach. Appendix C discusses this aspect in greater detail. The deformation plots in the axial and radial directions capture accurately the expected behavior of the assembly.

It can also be observed that the temperatures at the junctions/interfaces of the different components do not match and have a few degrees jump and this is due to the fact that the contact conditions had a thermal resistance or Thermal Contact Conductance (TCC) specified in the analysis.

Also, it must also be noted that the absorber will not reach the steady state peak temperatures of 112 C for the 2 kW case and 72.4 for the 400 W case during operation as the number of hours of continuous exposure as per the requirements are only 4 hours, while the steady state is attained around 100 hours.

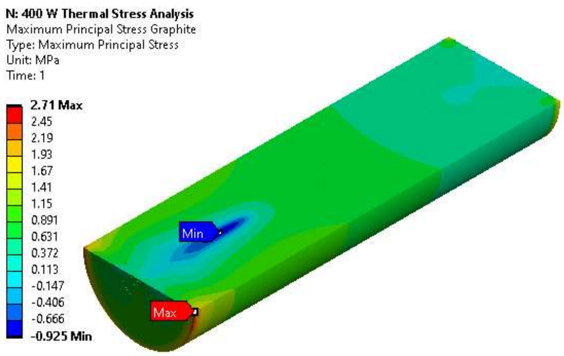
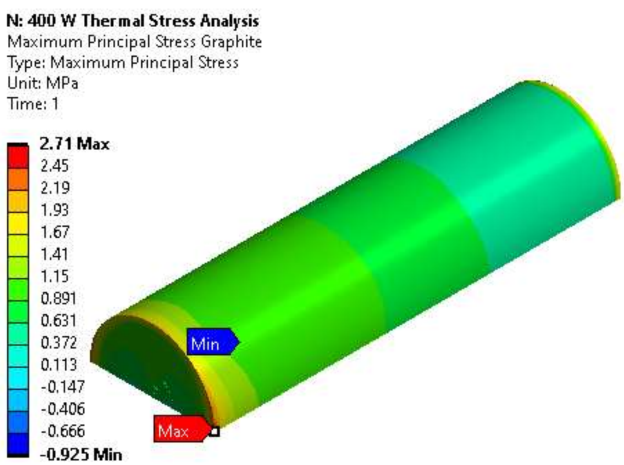
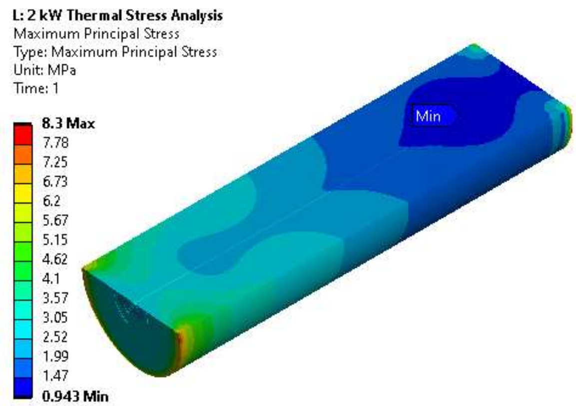
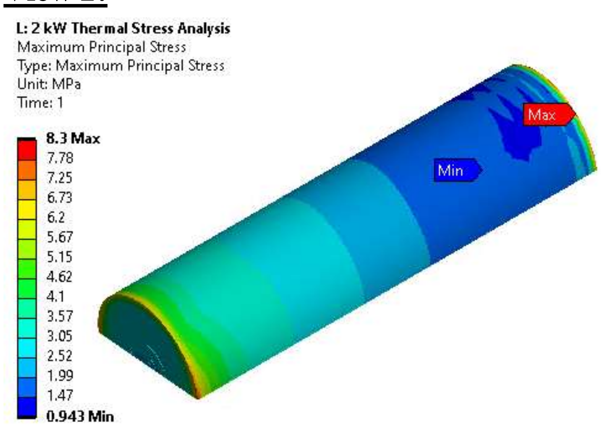
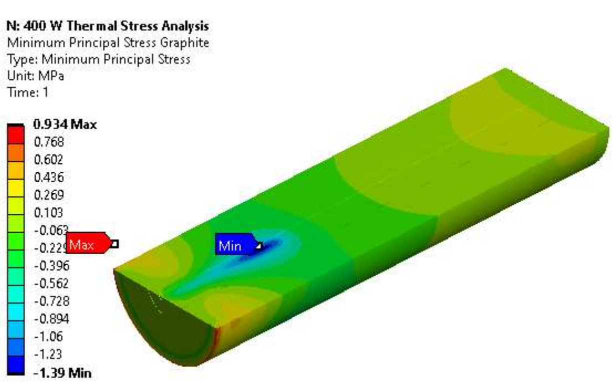
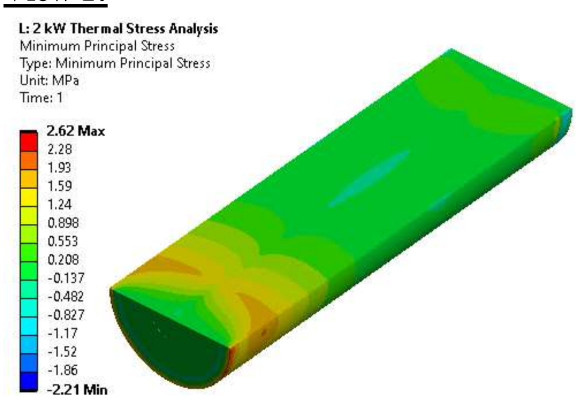
5.3. Steady State Thermal-Stress Analysis

Thermal-stress analysis were also performed for the 400 W and 2 kW cases to study the effect of the differential Coefficient of Thermal Expansion (CTE) between different materials as they are subjected to the heat load from the beam. The analyses were performed in two steps: Initial transient thermal for 4 hours at average beam power followed by steady state structural to estimate the stresses.

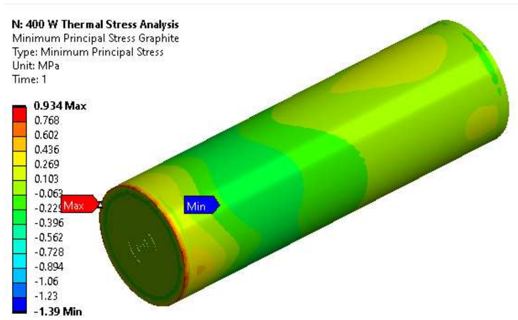
Boundary Conditions

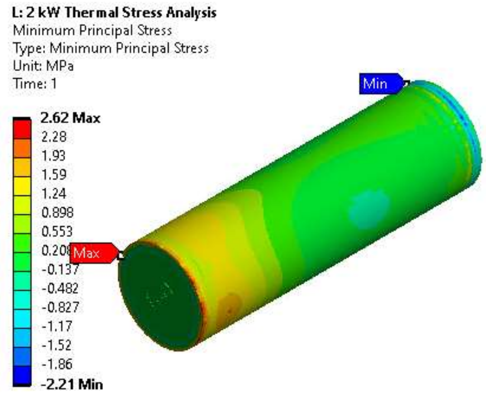
The thermal-stress analysis was performed using the nominal boundary conditions for the thermal part as described in the earlier section. For the structural part of the analysis, the bottom of the absorber displacement was held in the vertical direction and the standard gravity load applied. The pre-stress due to the shrink fit of the Graphite core and the Aluminum block was not included in the analyses.

Results

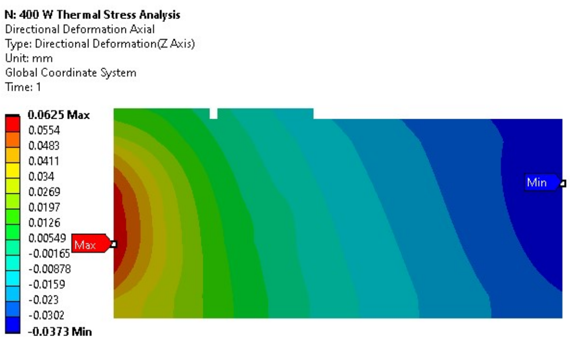
400 W Absorber Results	**2 kW Absorber Results**
Maximum Principal Stress in Graphite 2.71 MPa **<u>View 1:</u>**  **<u>View 2:</u>**  	Maximum Principal Stress in Graphite 8.3 MPa **<u>View 1:</u>**  **<u>View 2:</u>** 
Minimum Principal Stress in Graphite: -1.39 MPa **<u>View 1:</u>**  	Minimum Principal Stress in Graphite 2.62 MPa **<u>View 1:</u>**  **<u>View 2:</u>**

<u>View 2:</u>

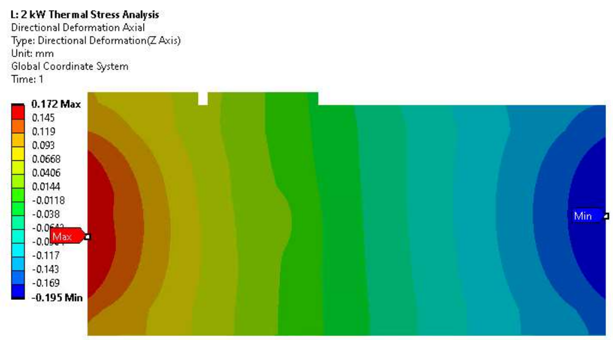




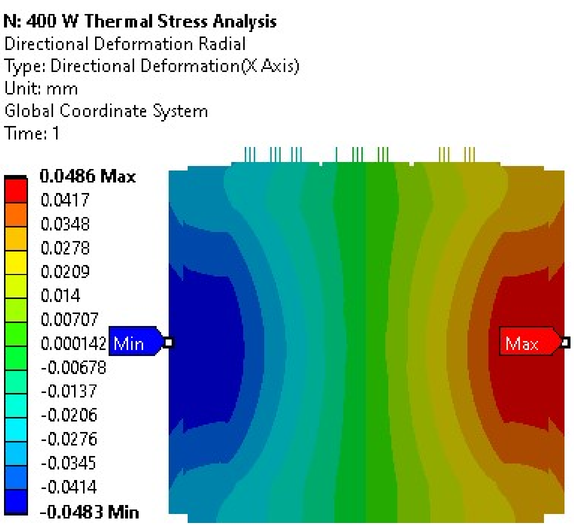
Axial Deformation of Absorber Assembly: +0.0625 mm to -0.034 mm



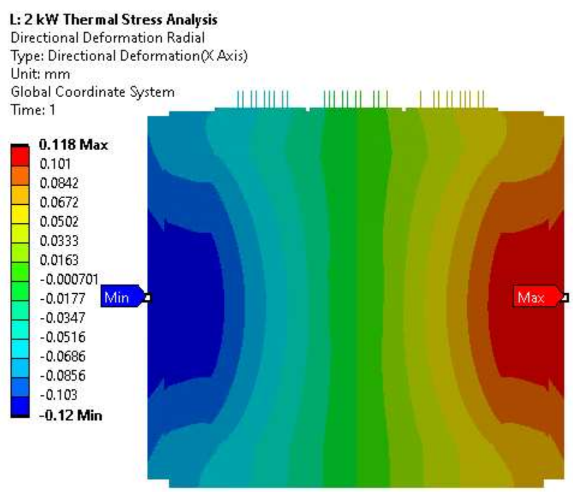
Axial Deformation of Absorber Assembly: +0.172 mm to -0.195 mm

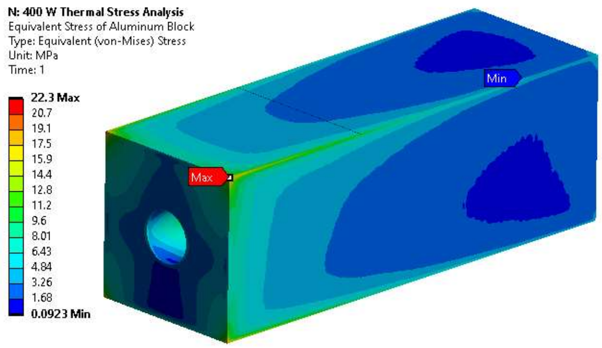
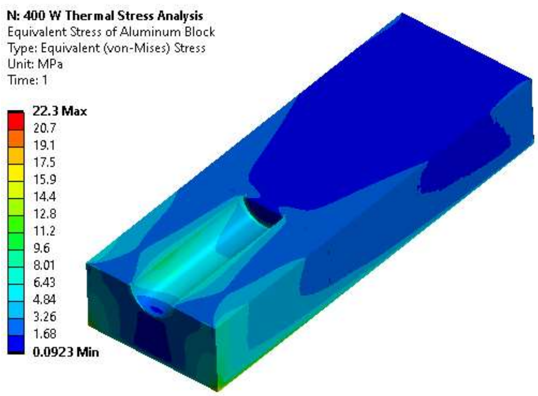
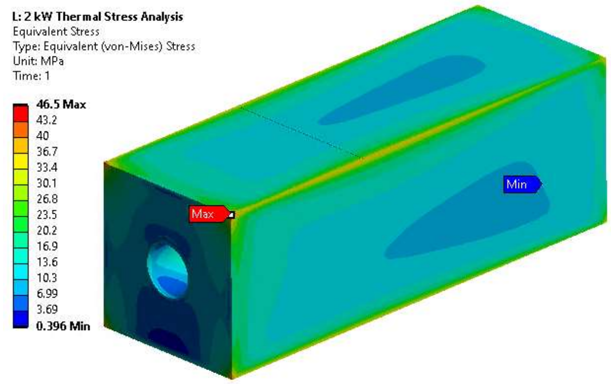
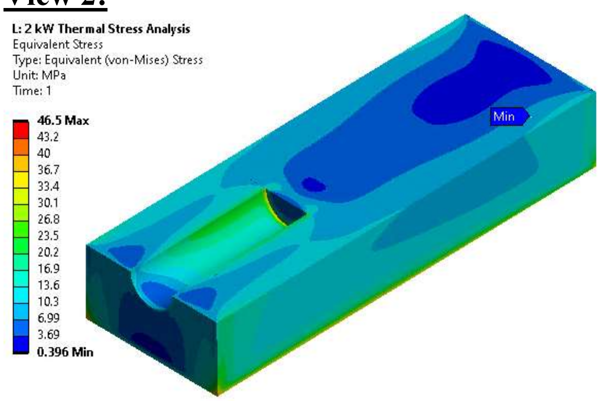
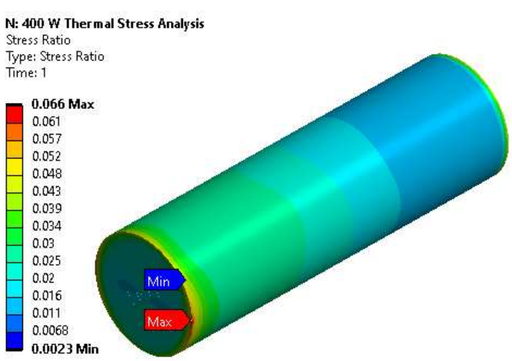
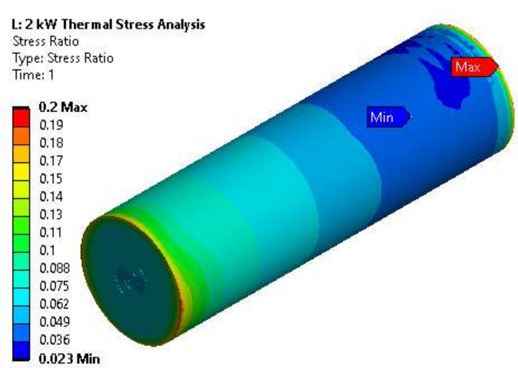


Radial (X-Axis) Deformation of Absorber Assembly: +0.049 mm to -0.048 mm



Radial (X-Axis) Deformation of Absorber Assembly: +0.118 mm to -0.12 mm



Von Mises Stress in Aluminum Block: 22.3 MPa	Von Mises Stress in Aluminum Block: 46.5 MPa
View 1:  **View 2:**  	**View 1:**  **View 2:** 
Mohr-Coulomb Criteria for Graphite Core: Max. of 0.066 **Stress Ratio:**  	Mohr-Coulomb Criteria for Graphite Core: Max. of 0.2 **Stress Ratio:** 

Comparison of 4 hours and 100 hours stresses

Component		400 W case		2 kW case		Allowables
		4 hours of continuous operation	100 hours of continuous operation	4 hours of continuous operation	100 hours of continuous operation	
Graphite	Maximum Principal Stress in MPa	2.71	15.4	8.3	**69.3**	Graphite Ultimate: 41 MPa
	Safety Factor	15	2.7	5	**0.6**	
Graphite	Mohr-Coulomb Stress Ratio	0.066	0.2	0.2	0.88	Stress Ratio <1
	Safety Factor	15	5	5	1.14	
Aluminum 6061-T6	Von Mises Stress in MPa	22.3	76.1	46.5	253	Aluminum Yield: 280 MPa
	Safety Factor	12.6	3.7	6	1.1	

Table 8. Results Comparison for the 4 hours and 100 hours thermal-stresses.

Effect of Pre-stress due to Shrink Fit

As mentioned earlier, the pre-stress from the shrink fit of the Graphite core and the Aluminum block was not included in the analyses, but the interfacial pressure was estimated from hand calculations using the equation shown below [10] to be 20 MPa for an interference of 0.005 inch radial.

$$p = \frac{\delta}{R\left[\frac{1}{E_o}\left(\frac{r_o^2 + R^2}{r_o^2 - R^2} + \nu_o\right) + \frac{1}{E_i}\left(\frac{R^2 + r_i^2}{R^2 - r_i^2} - \nu_i\right)\right]}$$

The pre-stress of 20 MPa acts as a compressive stress on the Graphite outer surface. It was estimated that the Aluminum block will have to be heated to a deltaT of 130 C or more to achieve the shrink fit, while the actual maximum temperature in the Aluminum block for the 4 hours of operation is ~ 40 C absolute. Thus, it is deemed that the pre-stress will not undergo stress relaxation from the temperature rise from the energy deposition.

Summary and Conclusions

The thermal-stress analysis results for the critical components have been shown in the above plots and the Table 8 shows the comparisons between all the cases. The critical components of the assemblies are the Graphite core and the Aluminum block. Since Aluminum is a ductile material the Von Mises stress criterion was used to check for any failure (yielding), and it can be observed from the results the stresses are well within the allowable (as quantified in Table 8) in the case of the 4 hours of operation and still within the allowable for the 100 hours operations.

The Graphite core on the other hand is a brittle material and the maximum principal stress plot shows that in all cases the stresses are within the allowable (Table 8) except for the 100 hours case, where the stress exceeds the allowable. It should be noted that the 100 hours exposure is not the actual operational time and the actual operational time is 4 hours. The Mohr-Coulomb criterion [11] was also applied to check for any failures. The stress ratio is given by the equation below and the stress tool plot shows that the stress ratio is much less than 1 (Table 8) and does not compromise the design function.

$$\frac{\sigma_1}{S_{tensile\ limit}} + \frac{\sigma_3}{S_{compressive\ limit}} < 1$$

Thus, the thermal stresses induced in the assembly due to the difference in the coefficient of thermal expansion between the different materials are within safe limits for the operation of the absorber. Also, the pre-stress is high enough to still hold the Graphite core in compression during operation. So, no relaxation of the pre-stress is anticipated.

5.4. Transient Dynamic Analysis

A transient thermal-structural analysis was performed to study the behavior of the 2 kW Graphite core as it is subjected to thermal stress by the impinging beam. The analysis was performed on a 2D axisymmetric model of the just the Graphite core.

Boundary conditions

The outer boundary of the Graphite was assumed to be at 22 C, which is the ambient temperature. This is a conservative condition as this assumption would produce the highest differential between the heated and unheated parts of the core. The face of the Graphite was held at a convective coefficient of 3 W/m^2-K and the far end face was insulated.

For the structural part, displacement boundary conditions were applied on the outer surface, x-zero and for the far end of the core y displacement was zero.

Mesh and Loads and Analysis Settings

For the dynamic analysis, where one wants to study the stress waves there are two important parameters that need to be considered. One is the element size and the other is the timesteps [12]. In this analysis the mesh discretization was in the order of microns in the vicinity of the impinging beam. The load setting for the thermal part of the analysis was applied in 5 load steps, starting from zero to 550 microseconds during which the beam is on and then turned off for the next 1 sec.

For the structural part the load was applied in 2 steps. The first step was ramped during the beam on and the second step beam off. The timesteps for the second load step was applied in the order of nanoseconds from the moment the beam is off to 1 msec.

Results

The plot of the normal stress for the Graphite in x direction is shown in Figure 13. The magnitude of the stress waves is very small, only about 0.7% of the ultimate strength (41 MPa) and dampens out quickly.

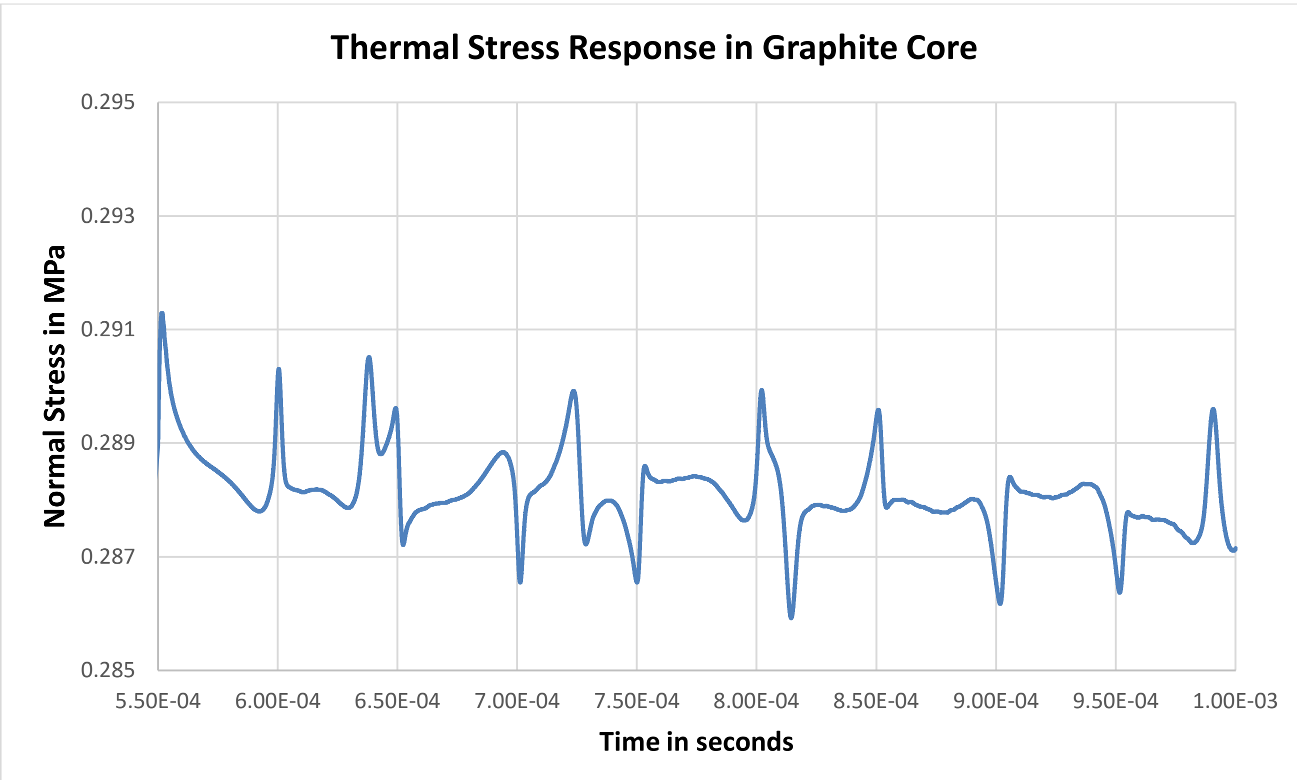


Figure 13. Normal Stress Plot for the Center Node of the Graphite Core for 2 kW.

Fatigue Considerations

In order to estimate the stresses contributing to the fatigue life of the Graphite core, the deltaT rise due to a single beam pulse was calculated from the ANSYS analysis and was found to be 14 C. Figure 14 shows the plot of the temperature rise due to a single beam pulse.

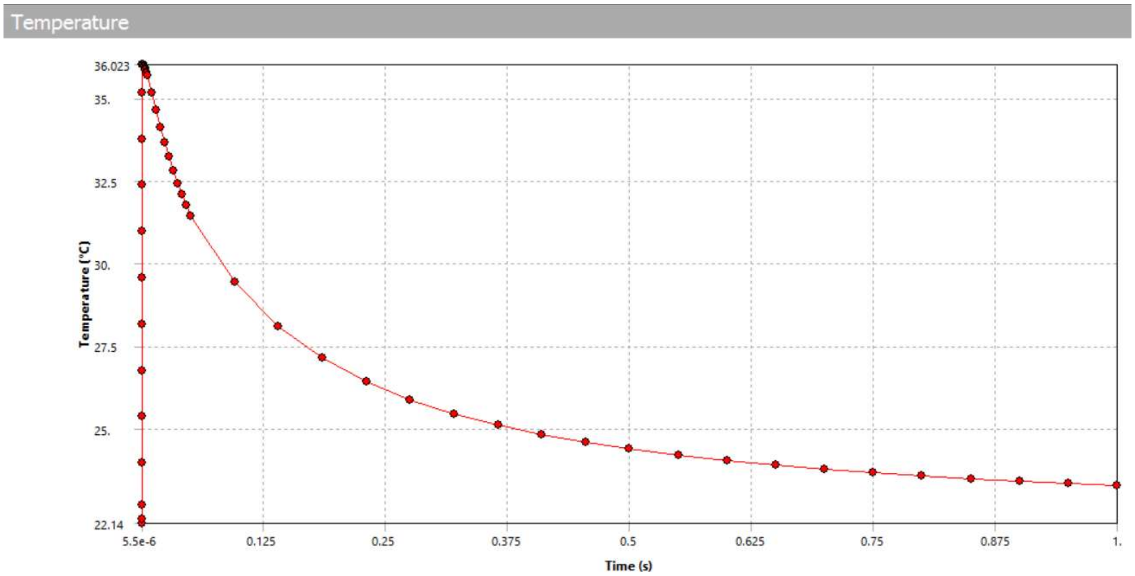


Figure 14. Temperature Rise in the Graphite Core from a Single Beam Pulse.

Since the maximum temperature in the absorber assembly occurs between the end of the 4 hour operation and the subsequent pulse, the stress contribution from this temperature rise (~ 48 C after 4 hours) was also deduced and added to the single pulse deltaT. Thus, the total deltaT is estimated to be 40 C (i.e. 48 -22 + 14 = 40 C, where 22 C is the ambient temperature).

The static stresses due to the thermal conditions was estimated using the relationship for thermal stresses as follows:

$$Sigma = E * alpha * delatT$$

Where E is the Young's Modulus = 10500 MPa for TM Graphite,
alpha, Coefficient of Thermal Expansion = 7.2E-6 microns/m/C
deltaT = 40 C

This results in a sigma = 3.024 MPa, which is the maximum stress. To estimate the minimum stress, considerations were given to the fact that the temperature in the absorber would cool back down to the 48 C before the next pulse. This results in a minimum deltaT of 26 C (48 C - 22 C) and the corresponding minimum stress would be 1.97 MPa, based on the calculations using the above equation. Table 9 provides a summary of the stresses considered for the estimation of fatigue life of the Graphite.

Parameter	Result
Maximum Stress σmax, MPa	3.024
Minimum Stress σmin, MPa	1.97
Stress Amplitude σa, MPa	0.527
Mean Stress σm, MPa	2.497
Stress Ratio (σmin/σmax) R	1.54
Amplitude Ratio (σa/σm) A	0.211

Table 9. Fatigue Parameters.

Due to the unavailability of test data for the Graphite TM grade, fatigue properties of a comparable grade of IG-110 was used from available literature [13]. Table 10 provides a comparison of the material properties for the two different grades.

Parameters	Graphite TM Grade	Graphite IG-110
Density, kg/m^3	1820	1770
Tensile Strength, MPa	41	24.4

Table 10. Properties Comparison for Graphite TM and IG-110 Grades.

Figure 15 shows the plot [13] used to deduce the fatigue safety factor. It should be noted that the plot is for IG-110 grade and it is assumed that for the Graphite grade TM will have higher allowable due to its higher Tensile Strength.

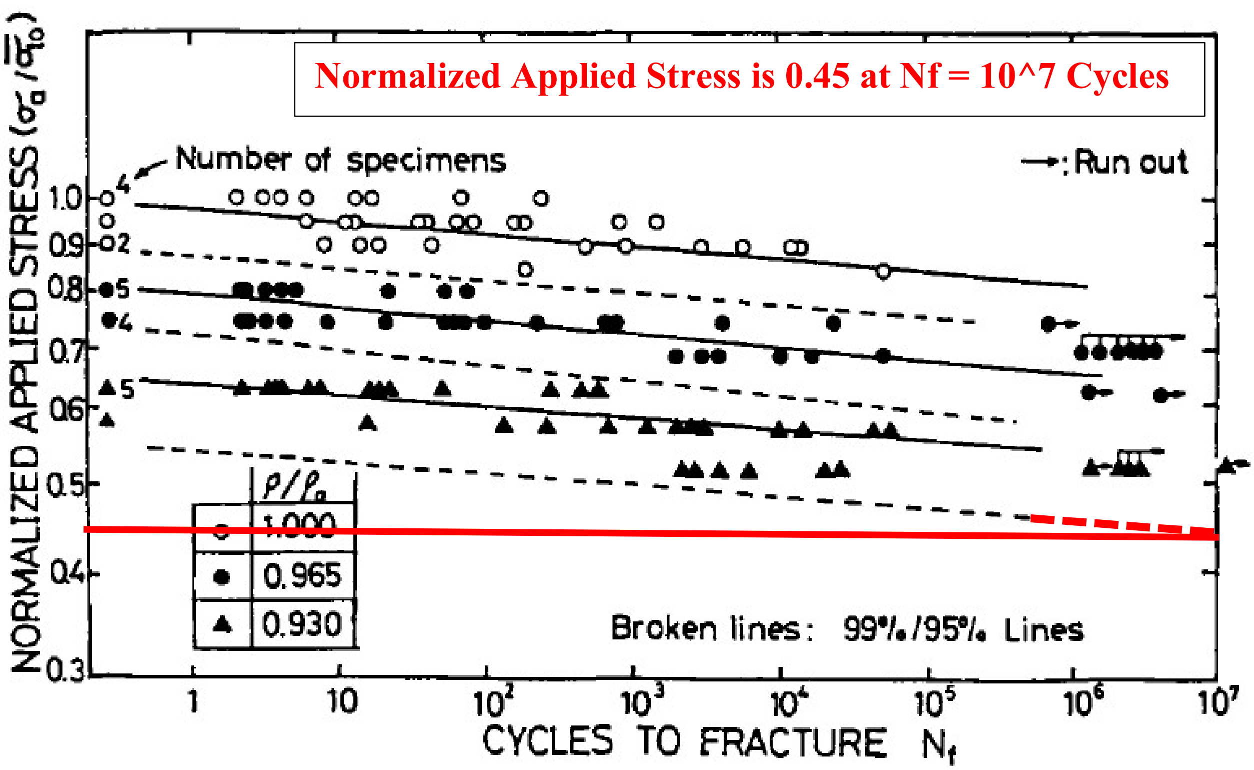


Figure 15. Test Results for IG-110 [12] for Maximum Applied Stress/Mean Tensile Strength.

The above plot shows that at 10^7 cycles the 'Normalized Applied Stress' (ratio of maximum applied stress to the mean strength of specimen) for IG-110 would be 0.45 and if the maximum stress from Table 9 is used then the 'Normalized Applied Stress' (Sigma_max/Tensile Strength of IG-110) would be 0.124, which is not available in this plot, so the results are very conservative. It should also be noted that the project requirements are for 604,800 pulses of beam per year, over a period of 10 years and we have a better than 10 million cycles to failure. So, fatigue is not an issue for this absorber.

Summary and Conclusions

It is concluded that the thermal stress waves will not be detrimental. Figure 15 shows that the IG-110 grade Graphite with lower strength has a fatigue life of 1E7 cycles for a normalized applied stress of 0.45. In our case, if we consider using the same grade of Graphite the normalized applied stress is much less than 0.45 and is only 0.124, so a better than 1E7 cycles of fatigue life is expected for both static and dynamic stress states.

6. Overall Summary

The thermal design of the 400 W and the 2 kW commissioning absorber has been described in this document and 4 types of analyses have been performed (transient thermal, steady state thermal, thermal-stress and the dynamic analysis). The Table below summarizes all the analyses.

Analysis	Conclusions
Transient Thermal with Average Power	The Transient Thermal Analysis provided an estimation of the time required to attain steady state temperatures for the absorbers and it was found to be around 100 hours of continuous operation at average beam power for both the 2 kW and 400 W cases. Thus, no issue is anticipated at the nominal 4 hour operations requirements. The shrink fit also will not undergo any stress relaxation at the operating conditions and the temper of the Aluminum block also will not be compromised.
Steady State Thermal Analyses	The steady state peak temperatures in the absorber core for the 400 W case is 72.4 C and that for the 2 kW case is 112 C. These numbers agree very well with the Transient Thermal Analyses at average powers at 100 hours. Nevertheless, it is not anticipated that the absorbers will reach these temperatures during its 4 hour operational requirements. Also, many conservative factors have been built into the design, such as the Thermal Contact Conductance, Conservative Heat Transfer Coefficients.
Thermal-Stress Analyses	Thermal stresses are not an issue at the 4 hour operating limits, the stresses are detrimental only for long operating times of 100 hours, which is not anticipated during the 10 year lifetime of the absorbers.
Transient Dynamic Analysis	The transient dynamic analysis has shown that the effect of the thermal shock is not significant and also the stress amplitudes are very small (0.3 MPa) for any fatigue loading effects. A fatigue life of at least 1E7 cycles is anticipated for the operational pulses of 608,400 pulses per year over the 10 year lifetime of the absorber.

Finally, to summarize, the absorber has good thermal and structural margins as indicated by the FEA. Furthermore, to ensure that the ambient temperatures assumed in the analyses are reasonable, it was decided to incorporate a fan and the details of the fan design are beyond the scope of this document. Overall, the design is deemed sound.

7. References

[1] Technical Requirements Specification, Teamcenter #: ED0011432

[2] I. Rakhno, Private Communication (email 30 DEC 2020).

[3] http://www.matweb.com/search/datasheet_print.aspx?matguid=1b8c06d0ca7c456694c7777d9e10be5b

[4] ANSYS Materials Database

[5] https://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html

[6] V.W. Antonetti et al., “An Approximate Thermal Contact Conductance Correlation”, Journal of Electronic Packaging, 115(1993) 131-134.

[7] http://mhtlab.uwaterloo.ca/courses_old/ece309/notes/conduction/cont.pdf

[8]https://fermipoint.fnal.gov/project/focusing_horns/Shared%20Documents/H1_Stripline_Boundary_Conditions.htm

[9] Bar-Cohen, et al., “Design of Optimum Plate-Fin Natural Convective Heat Sinks”, Journal of Electronic Packaging”, June 2003, 125(2): 208-216.

[10] Richard Budynas and J. Keith Nisbett, “Shigley's Mechancial Engineering Design”, 11th edition.

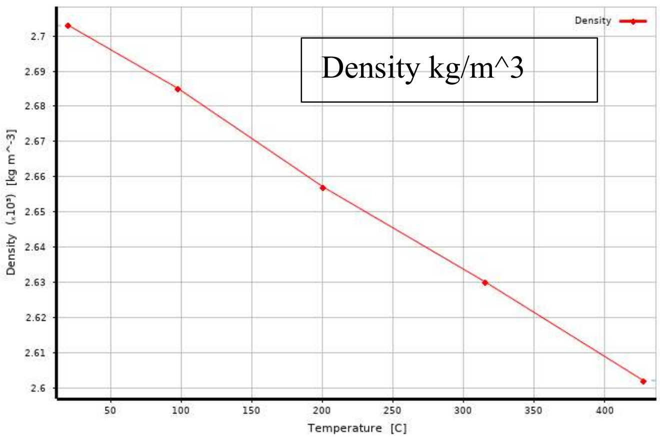
[11] ANSYS Manual

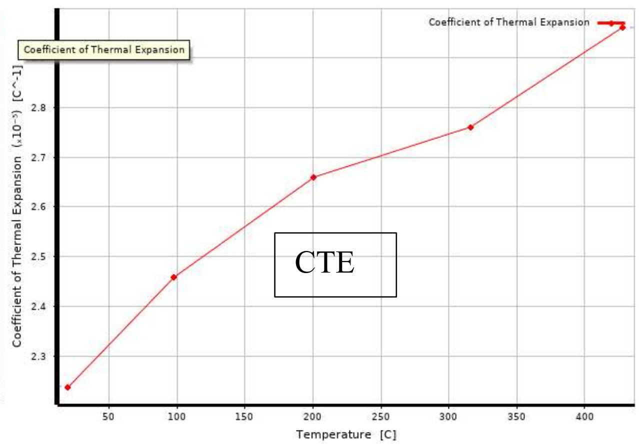
[12] J. Zheng et al., “Criteria for Determining Element Size and Time Step for Thermal Shock Simulation”, Journal of Neutron Research, 9(1): 21-38.

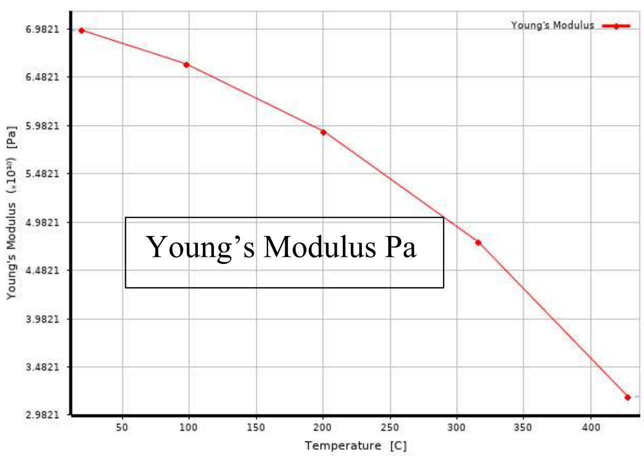
[13] S. Ishiyama et al., “Fatigue Failure and Fracture Mechanics of Graphites for High Temperature Engineering Testing Reactor”, Journal of Nuclear Science and Technology, 28:5, 472-483, May 1991.

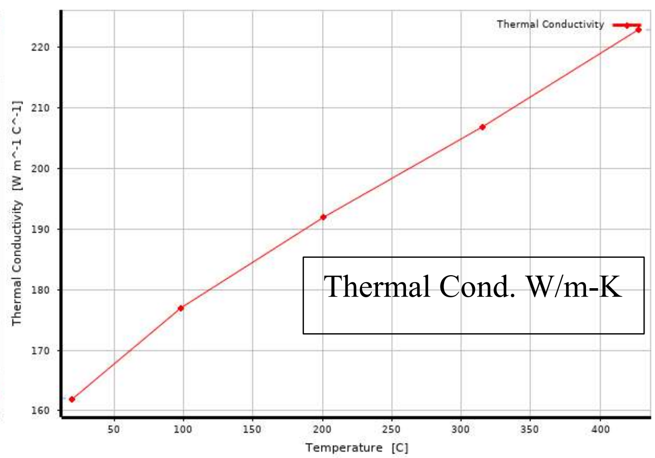
Appendix A: Temperature Dependent Material Properties

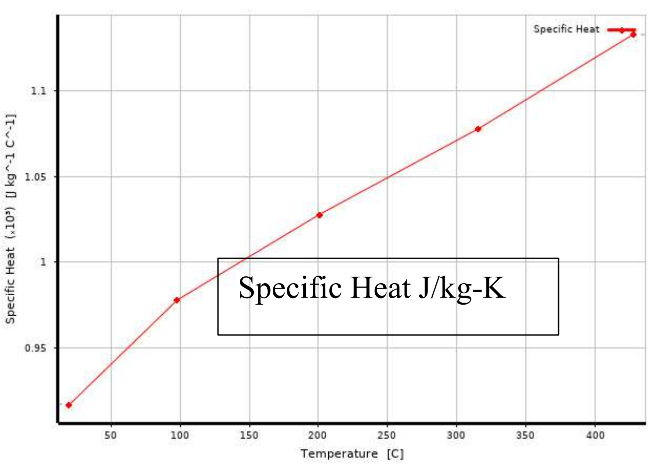
1. Aluminum 6061-T6:



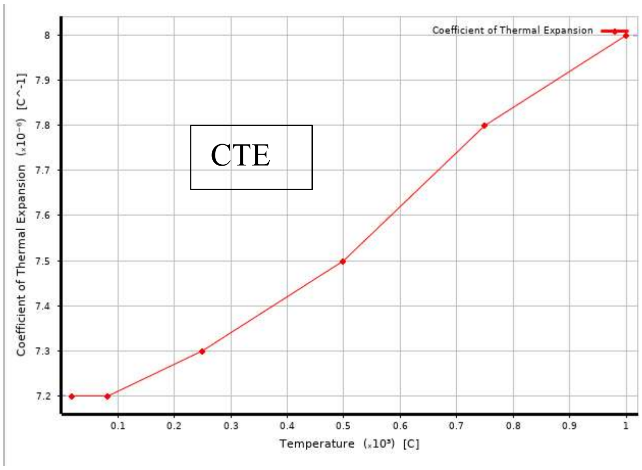


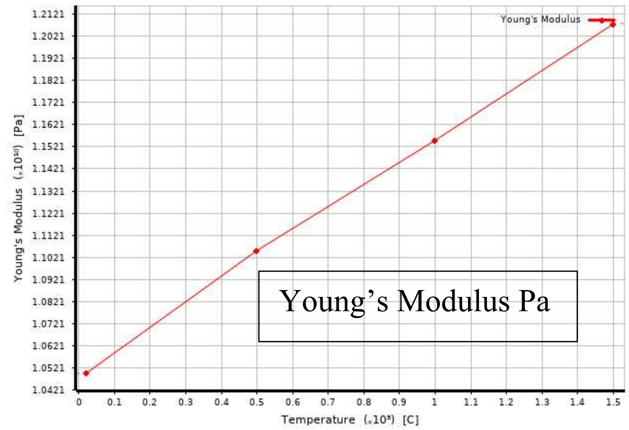


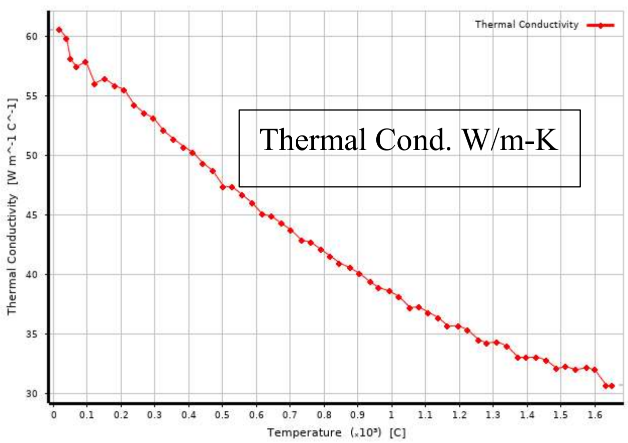


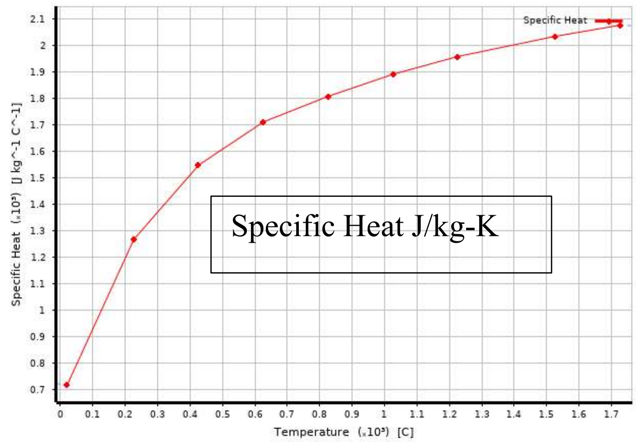


2. **Graphite TM:**









Appendix B: Thermal Contact Conductance Calculations and Assumptions

As mentioned in this document earlier, the contact conditions between the various components of the absorber assembly for the thermal analyses were defined to have a thermal contact conductance limitation. The TCC values which are typically given in W/m^2-K were estimated for some of the contact regions as mentioned in Table 5 earlier.

The following snapshot shows the TCC calculations for the Graphite Core and Aluminum Block which are shrink fit to one another. The interfacial pressure of the shrink fit provides the pressure load for the TCC calculations.

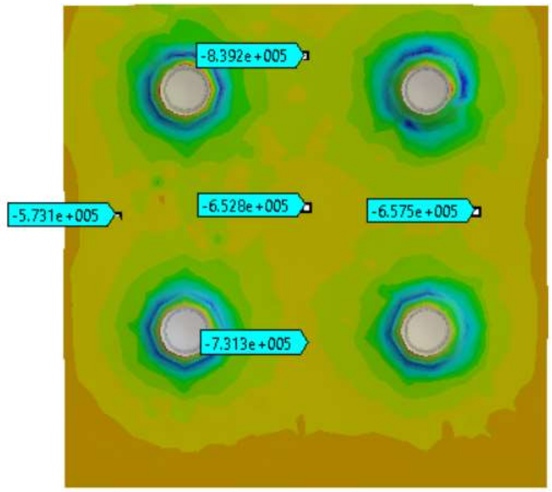
10-Mar-21 Calculation of Thermal Contact Conductance (TCC) between Shrink Fit Graphite Core and Alumium Block

Reference Paper: [1] An Approximate Thermal Contact Conductance Correlation, V.W. Antonetti, T.D. Whittle and R.E. Simons
[2] http://www.thermalengineer.com/library/calculating_interface_resistance.htm

Formula used from Reference [1]	$h_c = 4200 k_s R_a^{-0.257} \left(\frac{P}{H}\right)^{0.95}$			where, hc is the TCC
The First step is to select a roughness value that is expected on the two mating parts which is given by Ra. We assume same Ra values for the 2 mating components.				
	Ra	**3.2**	**micrometer**	This number corresponds to roughness of 125 microinches
The next step is to estimate the sigma for the two mating parts, which is the effective RMS surface roughness of the contacting asperities				
	sigma1	**4.00E+00**	**micrometer**	Sigma values estimated from formulas used in the reference paper [1]
	sigma2	**4.00E+00**	**micrometer**	
The slopes of the asperities are calculated using formulas in reference [2]				
slope	**m1**	**5.64E+01**		
slope	**m2**	**5.64E+01**		
mean	**ms**	**7.97E+01**		
		1.39E+00		
Thermal Conductivity of Aluminum	**k1**	**167**	**W/m-K**	
Thermal Conductivity of Graphite	**k2**	**60**	**W/m-K**	
Harmonic Mean Thermal Conductivity	**ks**	**88.28193833**	**W/m-K**	
Interface pressure	**P**	**4.00E+01**	**Mpa**	
vicker's hardness of aluminum	**H**	**107**		
vicker's hardness of graphite		**500**		
Aluminum hardness in MPa		**1049**	**MPa**	Choose the hardness of the softer material
ratio	**P/H**	**3.81E-02**		
Average roughness of Material 1	**Ra1**	**1.60E-06**	**meters**	
Average roughness of Material 2	**Ra2**	**1.60E-06**	**meters**	
sqrt of Ra1^2 + Ra2^2	**Ra total**	**2.26274E-06**	**meters**	
Thermal Contact Conductance from Reference [1]	**hc**	**4.70E+05**	**W/m^2-K**	antonetti paper approximation, upper limit for Ra = 1.6 micrometer
corrected error of 23%	**hc, corrected**	**3.62E+05**	**W/m^2-K**	A 23% correction factor was applied as per reference [1]

The calculations shown above predicts a very high contact conductance (~30000 W/m^2-K) between the Graphite and the Aluminum block for an interfacial pressure of 40 MPa. Nevertheless, the values of TCC assumed in the FEA was 1000 W/m^2-K only. Thus, there is a very high safety margin.

In cases where the components were held together by bolts, the contact pressures were estimated by calculating the clamping force and by simulating the clamped joint as shown below (this image is specific to the joint between the aluminum block and the steel plates). The units of the contact pressure shown below are in MPa.



Appendix C: Lessons Learned

There are a number of lessons learned from designing the absorbers outlined in this document. We will discuss one such aspect in this section.

Appendix C: Conversion of MARS Energy Deposition Data into ANSYS FEA Model:

As mentioned earlier, the only heat load in the absorbers are in the form of heat generation due to the energy deposited by the beam. The energy deposited is obtained from the MARS group typically in the form of "Joules/cm^3*pulse". This is then multiplied by number of pulses per second to obtain the heat generation in the form W/cm^3.
The MARS data are then mapped on to the absorbers using the "external data" function in ANSYS which reads the ".csv" file generated from the MARS data reduction. ANSYS works by reading in the point cloud from the .csv file and maps the source mesh to the target mesh of the components. Thus, the mapping accuracy highly depends on the ANSYS mesh or rather the relationship between the source mesh (point cloud) and target mesh and also the different settings used for the mapping.
Several iterations of this mesh mapping were performed to understand the behavior of this mapping and following are some pointers for guidance:

- The first step for a successful mapping is to mesh the FEA model to have a reasonable mesh size. This can be typically done by applying some known loads and determining the mesh size by sensitivity checks until the mesh size saturates. i.e. results do not change. Also, prior experience in meshing FEA models aids in judging a good quality mesh.
- The next step would be to generate an ANSYS input file from the MARS data by defining the point cloud, i.e. generate data points from MARS data to have the same order of magnitude of nodes (data points) as the FEA model. This is a critical step as this dictates the accuracy of final results.
- The matching of the data points between the MARS source nodes and ANSYS target nodes is typically done in several iterations while simultaneously monitoring the heat input to match the MARS data. This is somewhat of a trial and error process.

- It should be noted that obtaining an accurate result is very tedious, thus, it is better to err on the conservative side, i.e. allow the data mapping to have higher heat load in ANSYS.
- Also, care should be exercised to map the data points to from a single file to a single body, so, the data is not overwritten.

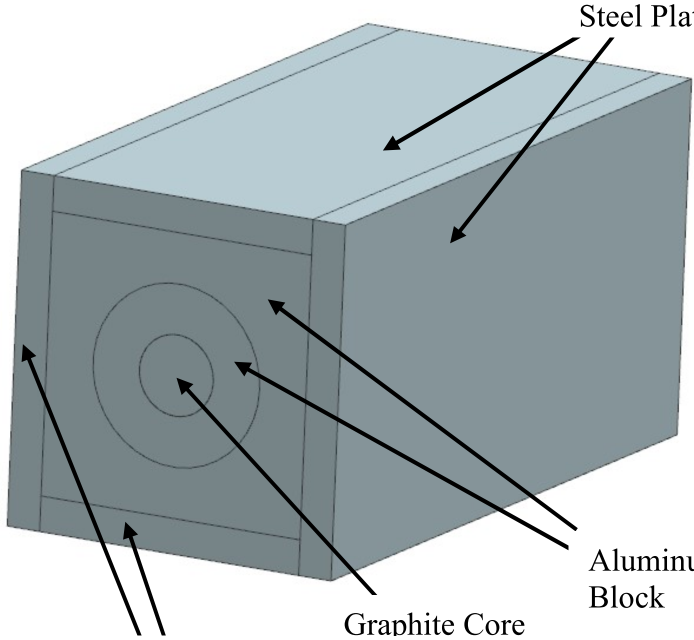
Appendix D: MATLAB Codes

The generation of the data points from the MARS data to ANSYS input file was done by both manual and by means of MATLAB codes. A sample MATLAB code is shown below. The MARS data is typically discretized in the form of bins, so, generally the mid-point of the bins are used to represent the MARS data of each bin.

```
file =‘C:\Users\dhanaraj\Documents\PIP-II_Absorbers\MATLAB_File\Graphite_core_input_2nd_run_optimized_15FEB2021.csv';

T= readmatrix(file);   % input array

R = T(:,1); %First Column of T is the Radii

theta = linspace(0,360,36)*2*pi/360; % theta is the number of angles considered

N = 20*36*10;   % 20 different R, 36 different angles, 10 different z

T2 = zeros(N,4);   % final output array

Tsize = size(T);   % input array dimension

Z=[ 2.5;7.5;12.5;17.5;22.5;27.5;32.5;37.5;42.5;47.5]; % Z locations in cm


for i = 1:7200

  AngleIdx = mod(i,36);    % angle repeat every other 36 rows, increase every row

if AngleIdx == 0

 AngleIdx = 36;

  end

  Zidx = floor(mod((i-1),360)/36)+1;     % Z repeat every other 396 rows, increase every other 36 rows

  Ridx = floor((i-1)/360) + 1;    % R increase every other 396 rows

  T2(i,1) = R(Ridx);

  T2(i,2) = theta(AngleIdx);

  T2(i,3) = Z(Zidx);

  T2(i,4) = T(Ridx,Zidx+1);

end

plot(T2(:,1),T2(:,2));

writematrix(T2,‘Graphite_core_ouput_2nd_run_optimized_15FEB2021.csv’)
```

Appendix E: Sensitivity Checks

The nominal design discussed in this document was a result of an optimization process which considered few designs initially. The path to this optimized model and a comparison of the results and some sensitivity analyses are described here.
One of the initial designs are shown below where the aluminum part was divided into a jacket and a block and no fins were considered. Also, the initial studies were performed assuming stagnant air cooling for the absorber with a heat transfer coefficient of 5 W/m^2-K. The table below summarizes the results comparison between the initial design and the optimal design.



Component	Initial Design (no fins)		Optimized Design (with fins)
	h = 5 W/m^2-K	h = 10 W/m^2-K	h = 5 W/m^2-K
Graphite Core Maximum Temperatures with no TCC	98 C	67 C	73 C
Graphite Core Maximum Temperatures with TCC of 3000 W/m^2-K at all contacts	101 C	70 C	75 C

As can be interpreted from the above table, the optimized design is more superior to the initial design in terms of its thermal performance. The addition of fins has led to results being closer to the initial design with a heat transfer coefficient of 10 W/m^-K. It should be noted that in the practical environment the heat transfer coefficients are typically smaller than the theoretical values, so the thermal designs should include some safety factors. For this reason, the nominal design used lower values of the heat transfer coefficients as was explained in the main body of this document.

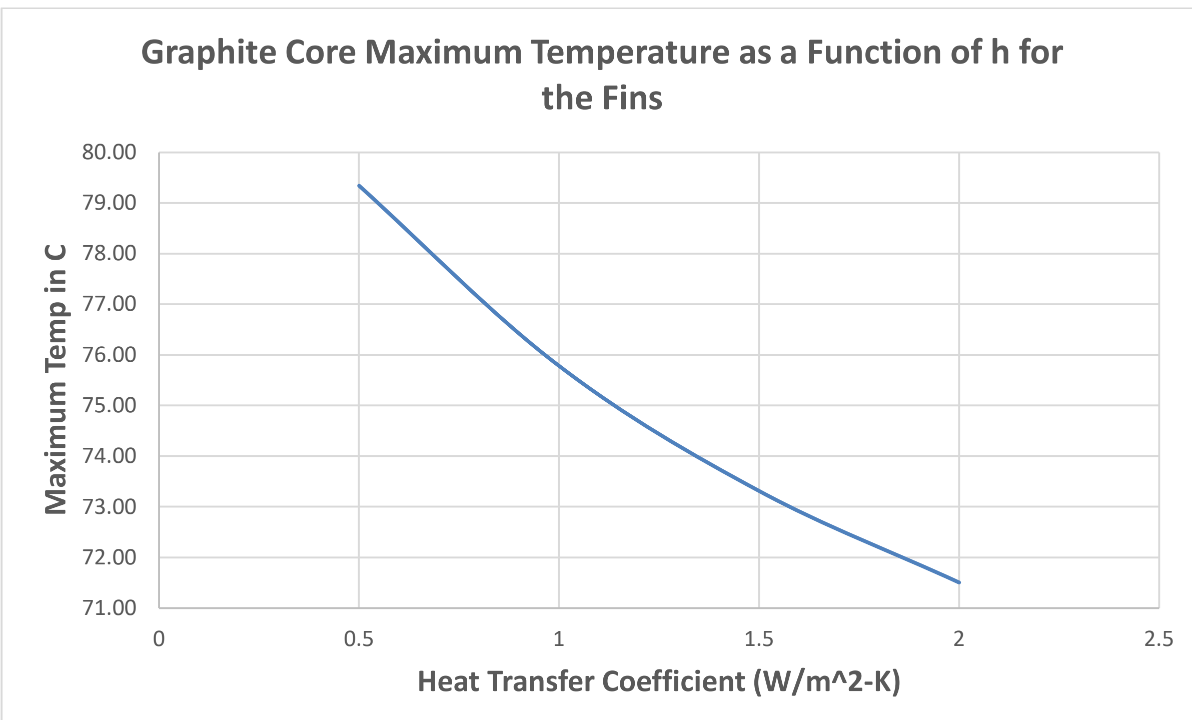
It should also be noted that the bounding box dimensions of the absorbers between the initial and optimized designs are the same. The optimized model was scaled down and the fins were added, but the physical envelope remains the same.

Appendix F: Fin Optimization

As a part of the analyses, some sensitivity and optimization studies were also performed for the fins. Firstly, the aluminum finned plates were optimized to enhance the heat transfer by designing the gaps between the adjacent fins. The equation below from literature (Bar-Cohen et al, "Design of Optimum Plate-Fin Natural Convection Heat Sinks") was used to estimate an optimal gap between the adjacent fins. The model of the optimized finned plates was used in the analyses.

$$s_{\text{opt}} = 2.66(L\nu^2/g\beta\,\eta_{\text{fin}}\theta_b \text{Pr})^{1/4}$$

Secondly, a parametric study was performed to estimate the maximum temperatures in the Graphite core as a function of the heat transfer coefficient on the fin surface for the nominal model. As shown below in the plot the maximum deltaT between the nominal and conservative case is about 10 C, which is still less than the 100 C criteria we would like to maintain. The plot shown here is for the case of 400 W heat load and it is expected that the 2kW case would predict about the same deltaT.



Appendix G: Graphite Material Properties

Industrial Grade Graphite - Typical Material Properties

Property	Units	ZXF-5Q	ACF-10Q	AXF-5Q	AXM-5Q	AXZ-5Q	TM
Particle size	Microns	1	5	5	5	5	10
	μin	40	200	200	200	200	400
Pore size	Microns	0.3	0.8	0.8	0.8	0.7	1.5
	μin	12	32	32	32	28	60
Total porosity	% volume	20	21	20	23	26	20
Open porosity	% of total	80	75	80	85	90	85
Apparent density	g/cc	1.78	1.77	1.78	1.73	1.66	1.82
	lb/in^3	0.064	0.064	0.064	0.062	0.060	0.065
Compressive strength	MPa	175	186	138	124	103	110
	PSI	25,500	27,000	20,000	18,000	15,000	16,000
Flexural strength	MPa	112	97	86	69	52	59
	PSI	16,200	14,000	12,500	10,000	7,500	8,500
Tensile strength[1]	MPa	79	69	62	48	34	41
	PSI	11,500	10,000	9,000	7,000	5,000	6,000
Modulus of elasticity	N/mm^2	14,500	11,000	11,000	10,500	9,000	10,500
	PSI x 106	2.1	1.6	1.6	1.5	1.3	1.5
Tensile strain	to Failure %	0.78	0.62	0.95	0.99	n/a	n/a
Hardness	Shore	86	95	74	72	69	65
Electrical resistivity	μohm-cm	1,950	2,460	1,470	1,650	2,030	1,220
	μohm-in	770	970	580	650	800	480
Coefficient of thermal expansion	Microns/m/°C	8.1	8.5	7.9	7.8	7.6	8.2
	μin/in/°F	4.5	4.6	4.4	4.3	4.2	4.5
Thermal conductivity	watts/m.K	70	60	95	88	70	105
	BTU-ft/hr/ft^2 °F	40	35	55	50	40	60
Oxidation threshold[2]	°C	450	470	450	460	440	460
	°F	840	880	840	860	820	860

[1] *Estimated at 70% of flexural strength.*
[2] *Temperature that results in 1% weight loss in 24 hours. Oxidation threshold increases by approximately 100°C if graphite is purified.*

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