Fermilab
PPD/MD/Engineering Analysis Group

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Thermal Stress Analysis of Gun-drilled Numi Absorber Core

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Introduction and Summary

The Numi absorber cores have been re-designed to take into account the restricted lateral space in the experiment hall. The new core is assembled by moving modules along the beam axis, rather than perpendicular to it.

Two cooling circuits, gun-drilled in a solid aluminum core, are used. The circuits are independent; the failure of one does not affect the operation of the other.

The thermal stress analysis shows that the maximum absorber temperature after 1800 pulses (3420 seconds) at the maximum energy deposition of 58.5 kW is 313 ^{o}C with both cooling circuits circulating 25 ^{0}C water. This temperature rises to 340 ^{o}C when the down stream circuit is disabled.

High temperature gradients, and the accompanying self-constraint, produce plastic strain in the center of the core. For two operational cooling circuits, the maximum plastic strain is 0.95%, and the total volume of plastic material is 0.024 m^3; for one operational cooling circuit, the maximum plastic strain is 0.86%, and the total volume of plastic material is 0.03 m^3. The volume of plasticity is small, and the large surrounding volume of cooler, stronger material prevents any gross distortion.

Dynamic stresses were calculated, and found to be well below the threshold of concern.

A piping analysis of the cooling circuits shows that, to maintain the maximum temperatures stated above, a water flow rate of approximately 50 gpm is necessary through each circuit. This requires a pressure drop of about 30 psi, which is approximately ¼ of the total pressure drop available.

Material Properties for the Analysis

The absorber will be made from 6061-T6 aluminum. The physical and mechanical properties for this material were presented in the previous report on the IHEP absorber design (MSG-EAR-01285), and are included here for completeness.

The properties of 6061-T6 aluminum were taken from the Metals Handbook, Volume 2, “Properties and Selection: Nonferrous Alloys and Pure Metals”.

The physical properties are given in Table I. The mechanical properties are given in Table II. The stress-strain curve of Table II is plotted in Fig. 1.

Table I. Physical Properties of 6061-T6 Aluminum

Property	**Value**
Thermal Conductivity	**167 W/m-C**
Specific Heat	**896 J/kg -C**
Density	**2700 kg/m^3**
Thermal Expansion	**2.36e-5 m/m-C**

Table II. Mechanical Properties of 6061-T6 Aluminum

Temperature (°C)	Yield Stress (Mpa)	Young's Modulus (Gpa)
38	241	70.4
66	238	70.0
93	232	69.2
121	223	68.1
149	189	66.7
177	138	65.0
204	92	63.0
260	34	58.0
316	19	51.8
371	12	44.4

Figure 1. Yield Stress as Function of Temperature - 6061 T-6

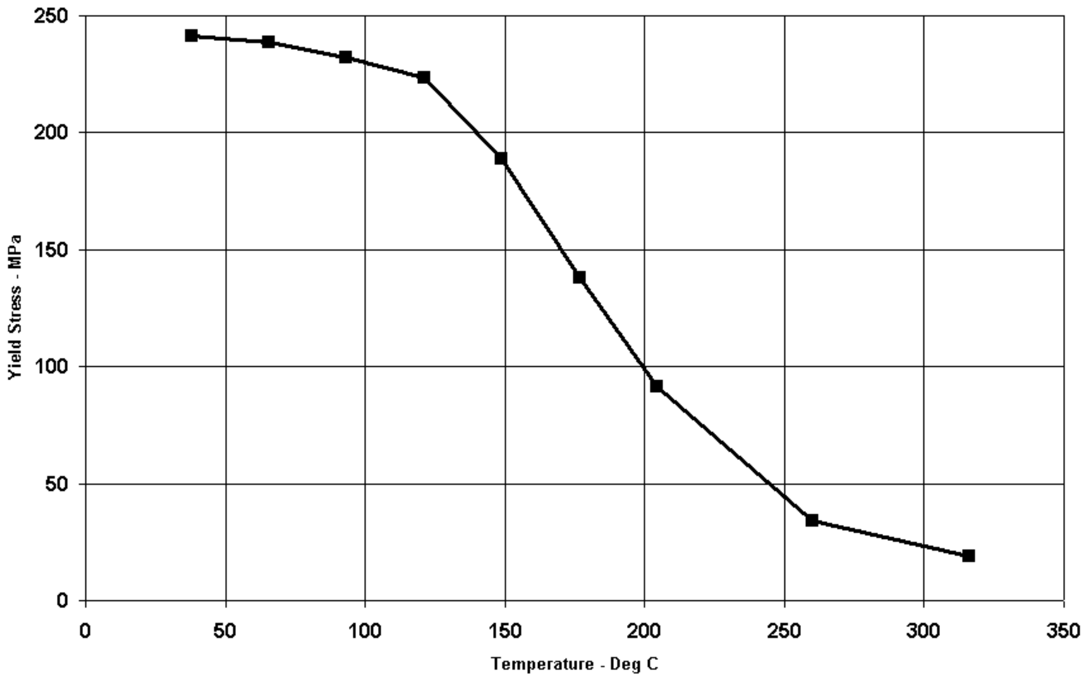
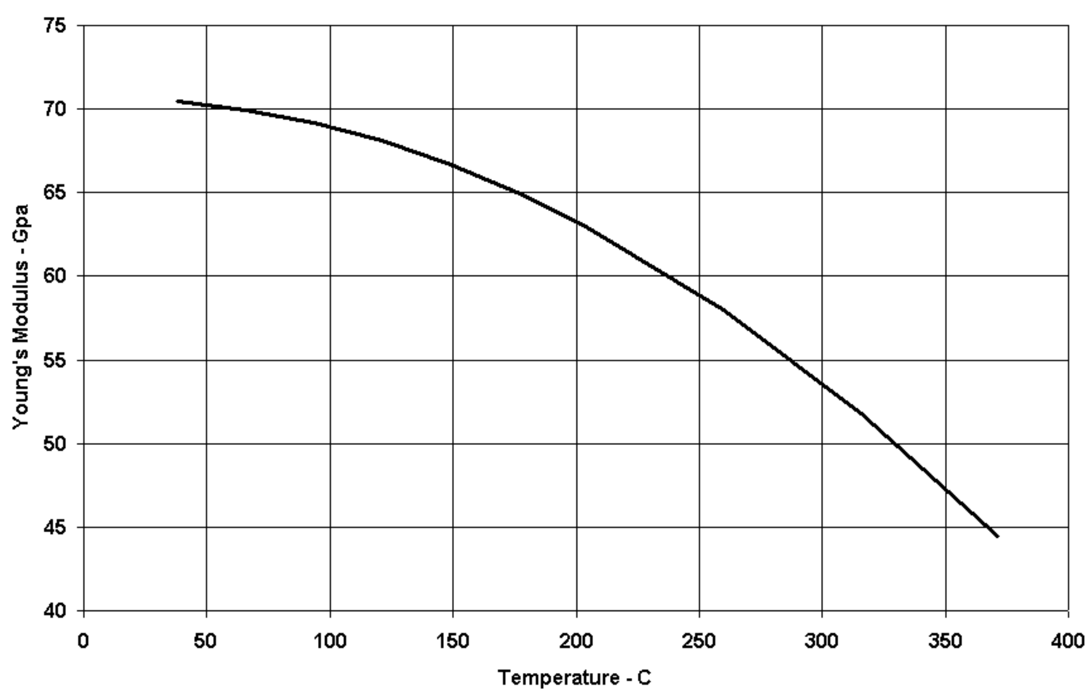


Figure 2. Young's Modulus as Function of Temperature for 6061-T6



Absorber Core Geometry

The new absorber core geometry is shown in Fig. 3. The two cooling circuits are shown in Fig. 4. These circuits are placed 7.5 cm from the front and back face.

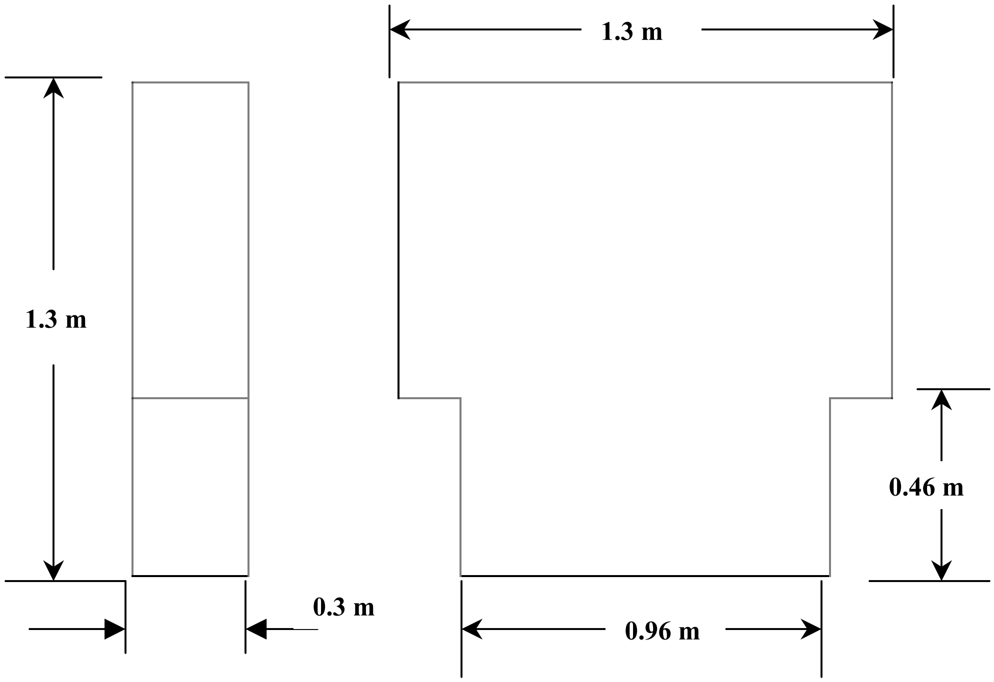


Figure 3. Absorber Core Geometry

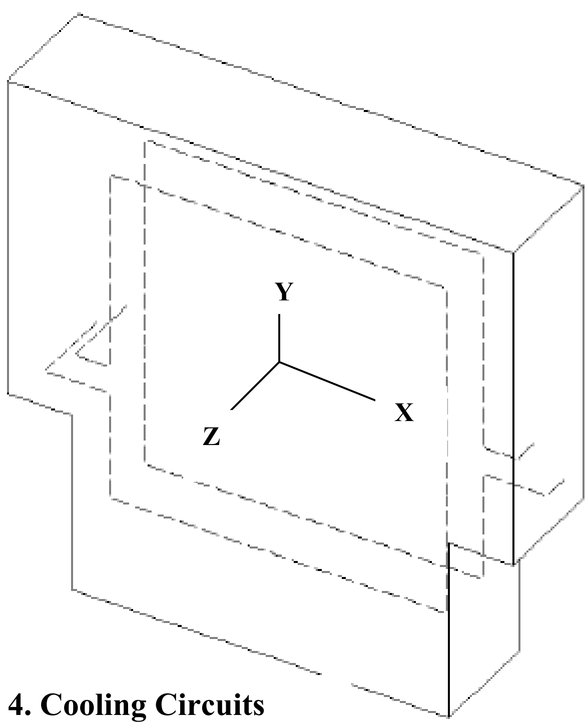


Figure 4. Cooling Circuits

Finite Element Model

The absorber core was modeled with 20-node brick elements. For the multi-cycle thermal analysis, the nodes corresponding to the cooling pipe elements were constrained to a temperature of 25 C . No convective surface cooling was assumed. For the structural analysis, support was provided in the vertical direction over the entire bottom surface. Gravity was applied to account for core dead weight.

The pressure drop and exit temperature of the cooling water were determined from a similar finite element model, in which the absorber elements were converted to 8-node bricks, and the cooling passages were modeled with thermal-fluid pipe elements. These pipe elements accept pressures and flow rates, and use the Dittus-Boelter correlation for heat transfer.

The finite element model is shown in Fig. 5.

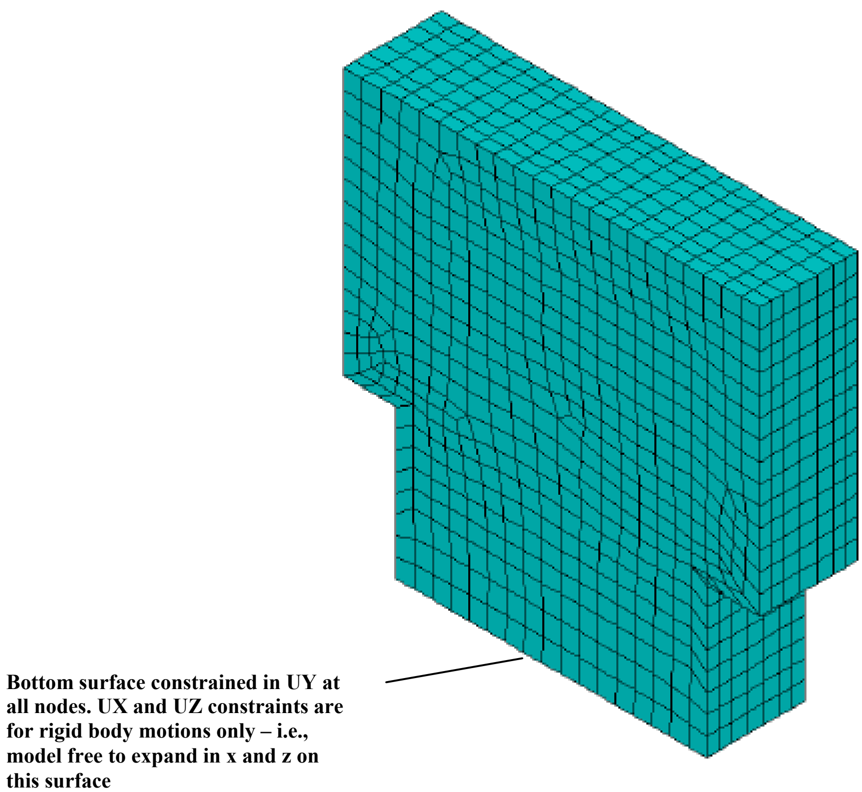
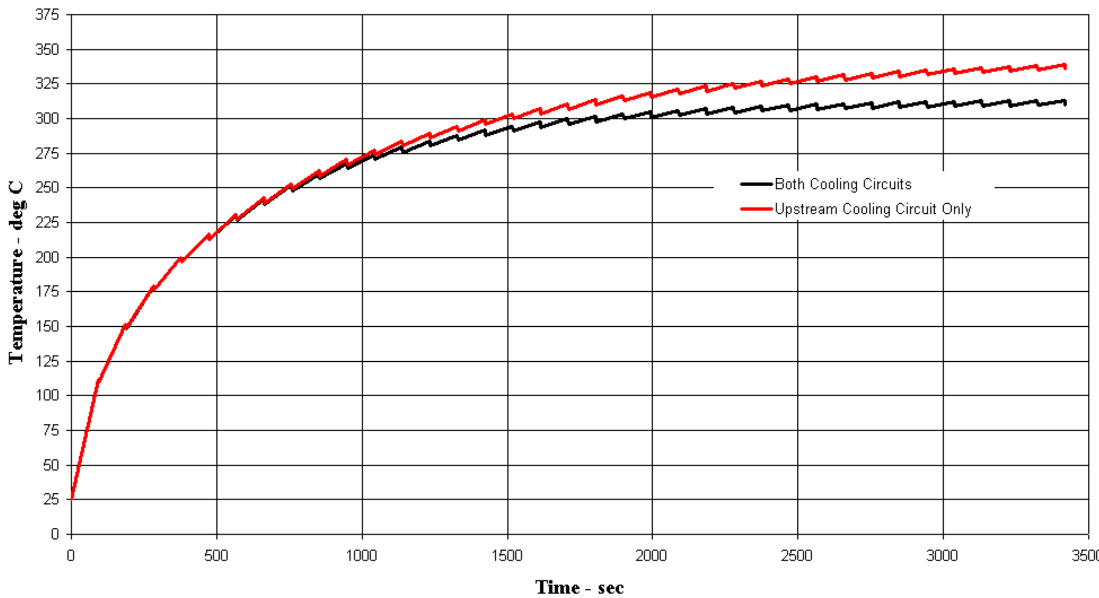


Figure 5. Finite Element Model of Gun-drilled Absorber

Thermal Analysis Results – 1800 pulses

Fig. 6 shows the maximum temperature in the absorber up to 1800 pulses, for normal (two cooling circuits) and fault (one cooling circuit) operation. The maximum temperature with two cooling circuits is about 313 ^{0}C. With the downstream circuit disabled, the maximum temperature rises to about 340 ^{0}C.

Figure 6. Gun-drilled Absorber Maximum Temperature - 1800 pulses



Stress Analysis Results – 1800 pulses

Two Active Cooling Circuits

With both cooling circuits active, the maximum absorber temperature is 313 ^{o}C. The resulting plastic strains are shown in Fig. 7. The maximum plastic strain is 0.95 %.

The maximum stress intensity in the absorber is 138 Mpa (20 ksi), as shown in the cross section of Fig. 8, and occurs in the cool regions where the full room temperature yield of 240 Mpa (35 ksi) is available.

Figs. 9-11 show the various components stresses in the absorber (refer to coordinate system in Fig. 4 for stress directions.)

For the case of two cooling circuits, no progressive thermal distortions were observed.

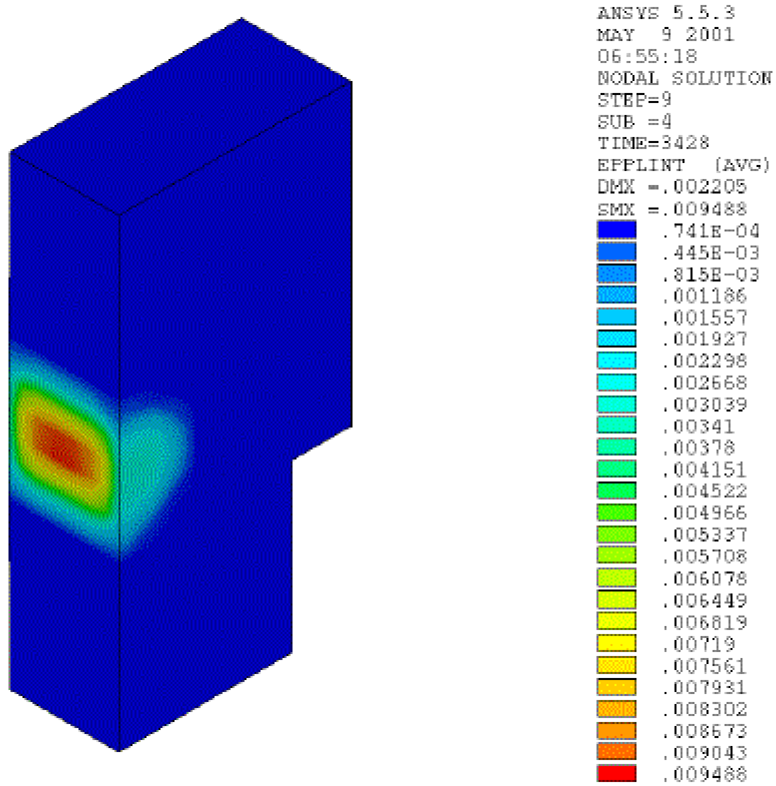


Figure 7. Plastic Strain in Absorber after 1800 pulses – Two cooling circuits active

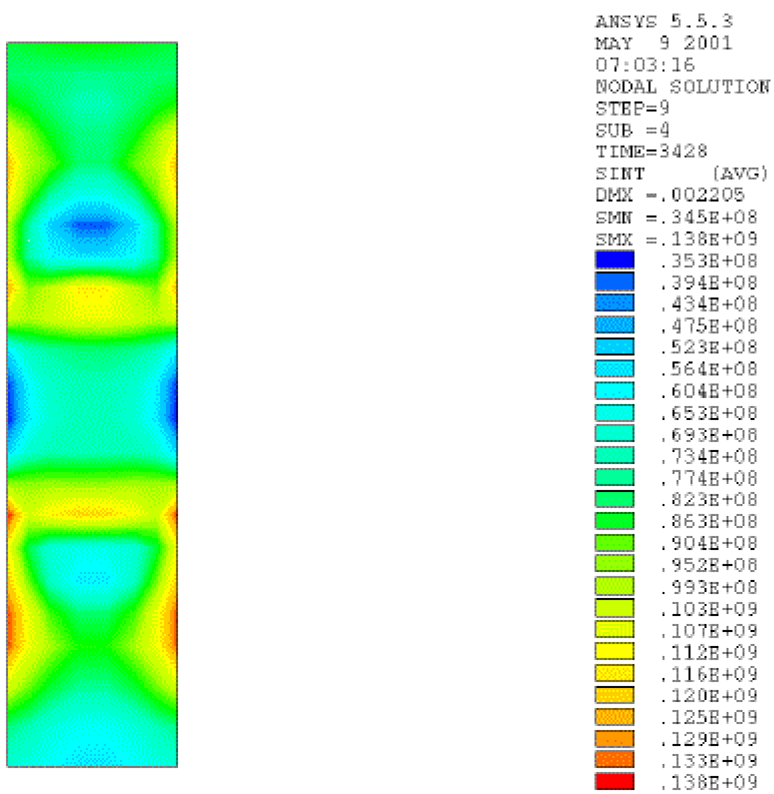


Figure 8. Stress intensity in Absorber after 1800 pulses – cross section through center

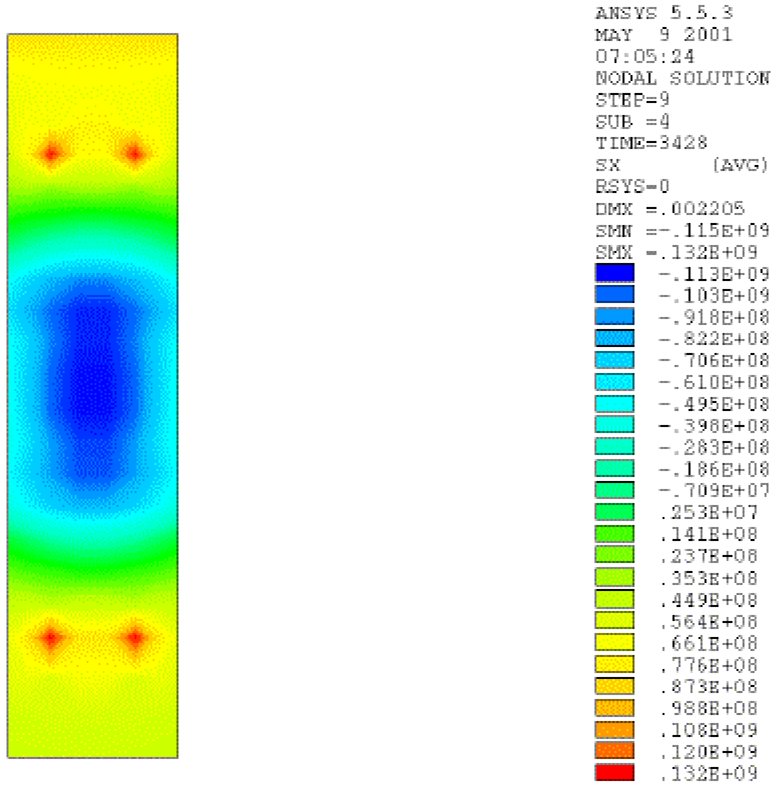


Figure 9. X-direction Stress in Absorber after 1800 pulses – two cooling circuits

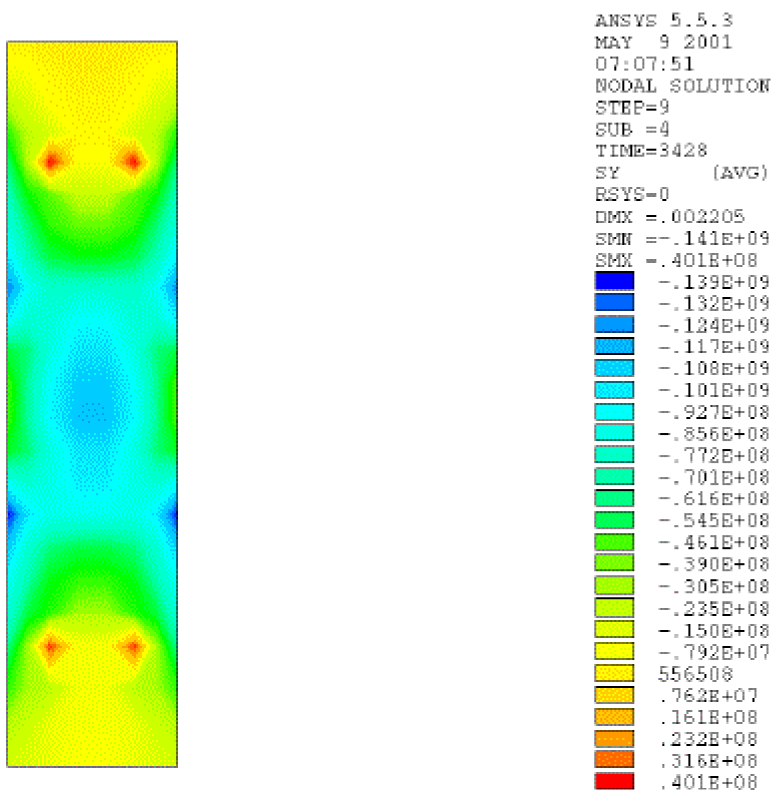


Figure 10. Y-direction Stress in Absorber after 1800 pulses – two cooling circuits

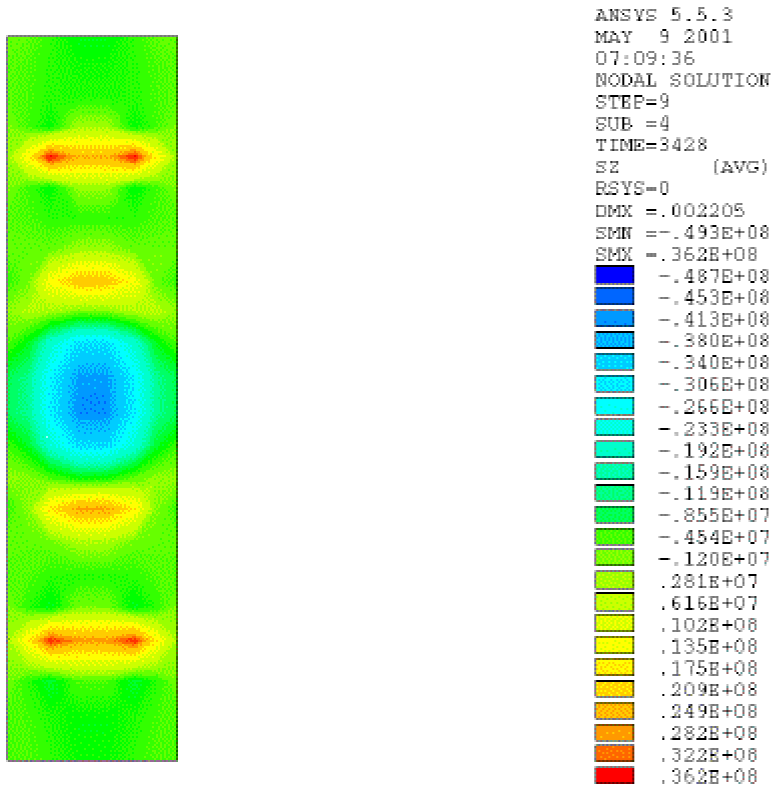


Figure 11. Z-direction Stress in Absorber after 1800 pulses – two cooling circuits

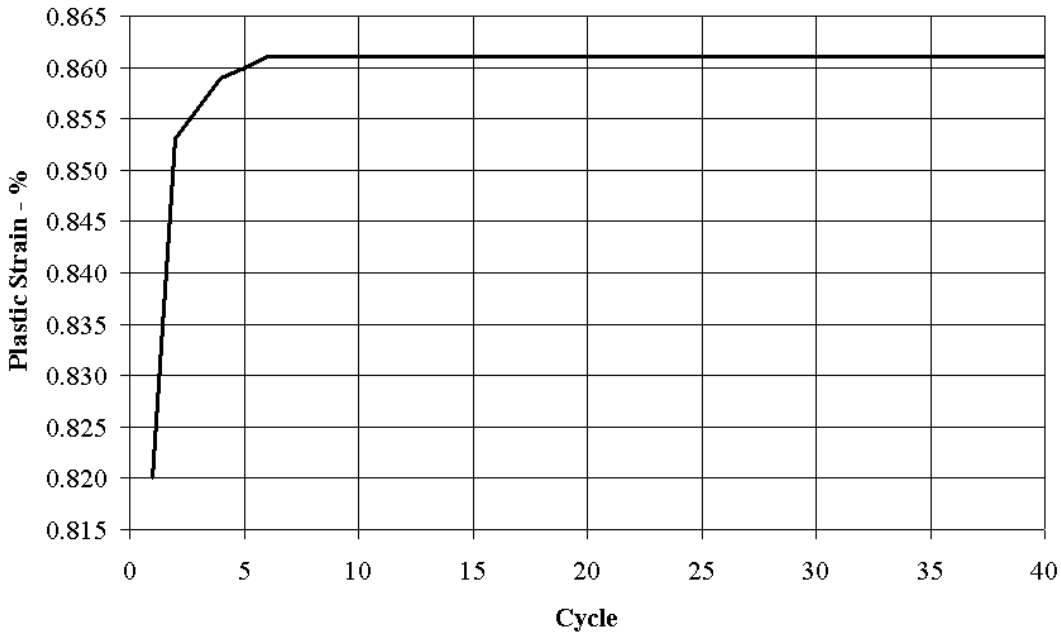
Upstream Cooling Circuit Only

The downstream cooling circuit was disabled, leaving one cooling circuit active. Although no progressive thermal distortions were noted for the case of two active circuits, some small amount was detected for this single circuit case. Fig. 12 shows the maximum plastic strain as a function of thermal cycle for the first forty cycles at maximum temperature. Although the plastic strain changes slightly during the first ten cycles, it settles down to a constant value quickly, and there is no reason to expect gross thermal distortions for repeated high-temperature cycles.

Maximum plastic strain (0.86%) is slightly lower than that calculated for two cooling circuits. This is probably due to the smaller thermal gradients (and hence displacement gradients) produced by the reduced cooling.

Maximum stress intensities are approximately 10 Mpa (1400 psi) higher for this case.

Figure 12. Plastic Strain in Absorber with One Cooling Loop
(all cycles are at Maximum Temperature)



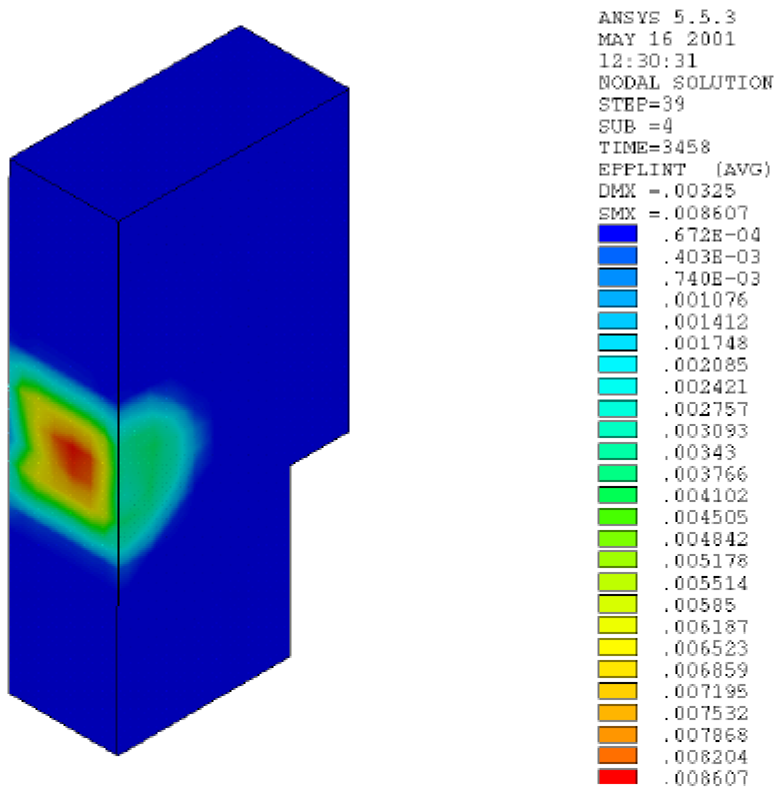


Figure 13. Plastic Strain in Absorber after
1800 pulses – one cooling circuit

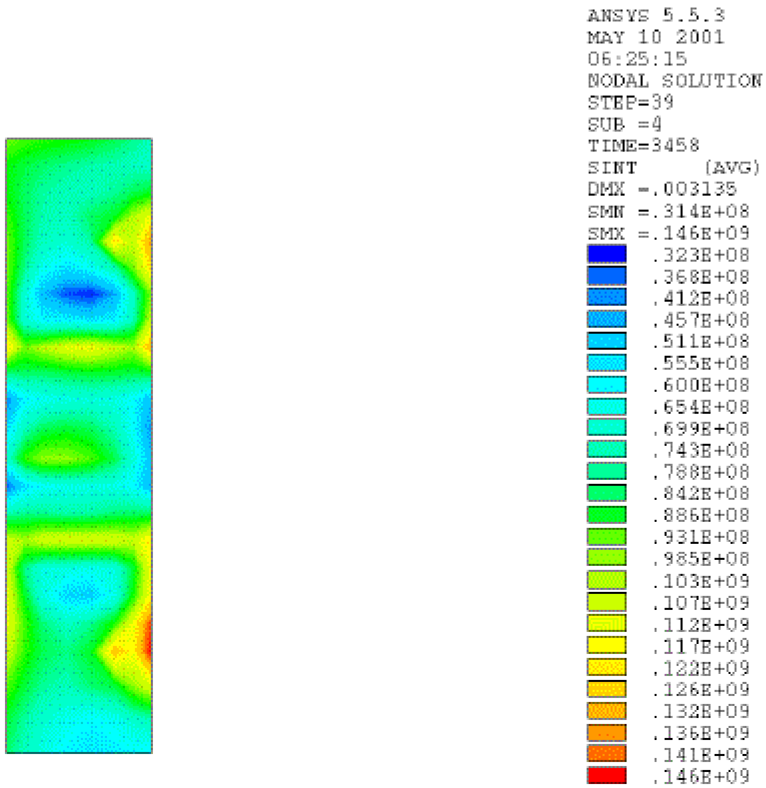


Figure 14. Stress intensity in absorber after 1800 pulses - section through center, one cooling circuit

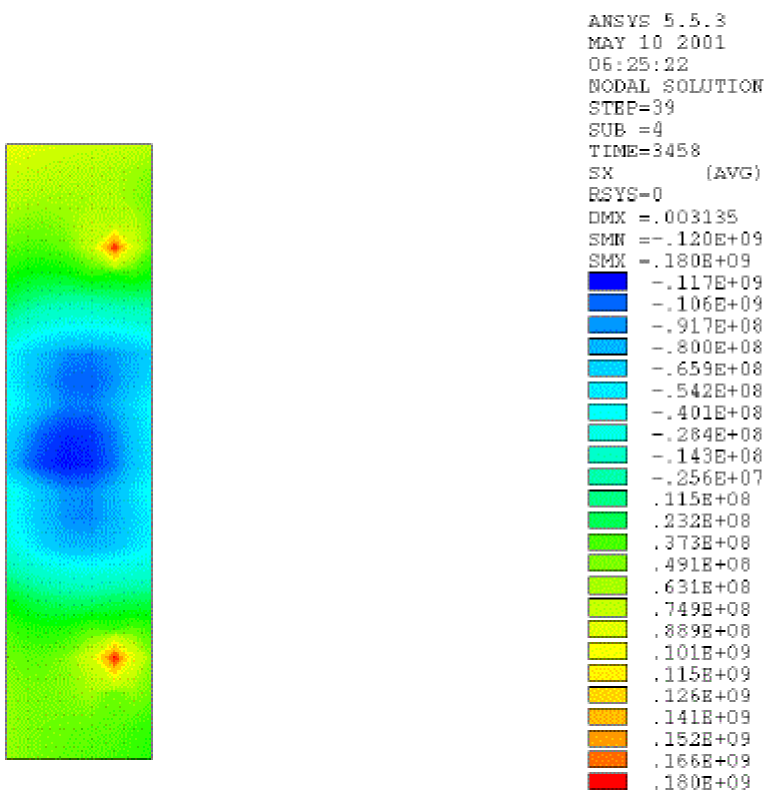


Figure 15. X-direction stress in absorber after 1800 pulses – one cooling circuit

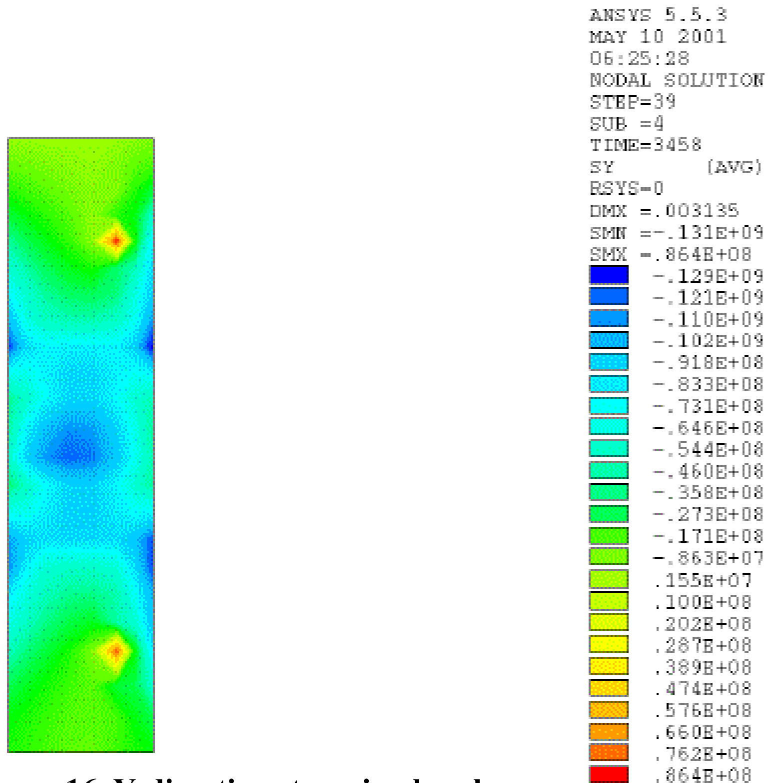


Figure 16. Y-direction stress in absorber after 1800 pulses – one cooling circuit

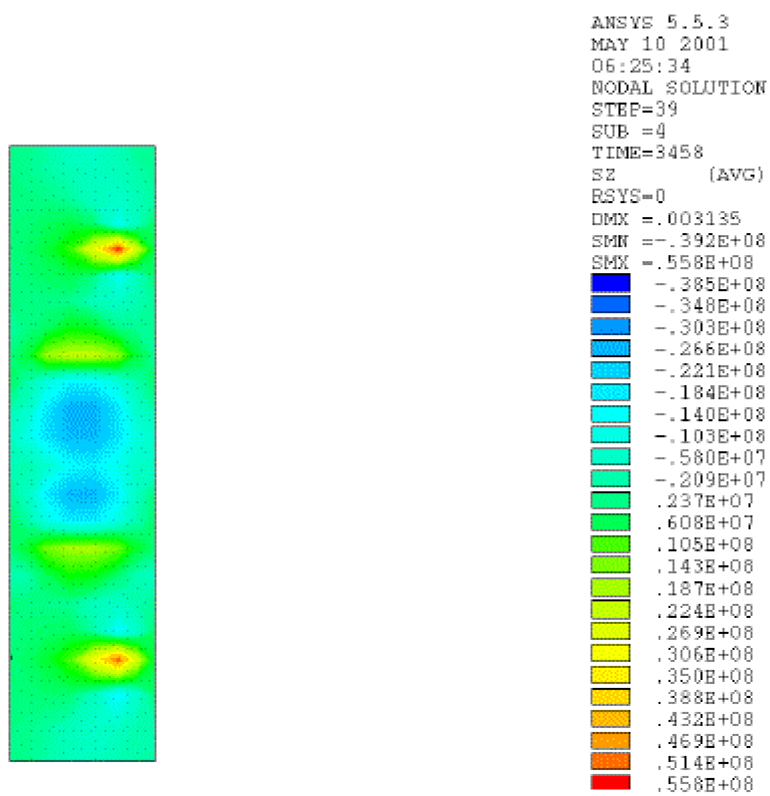


Figure 17. Z-direction stress in absorber after 1800 pulses – one cooling circuit

Dynamic Stresses

Compressive stresses at the center of the absorber, generated by rapid thermal expansion, propagate in all directions at the speed of sound in aluminum (approximately 5000 m/sec). The furthest free surface from the center is about 65 cm, and so will be reached in less than 150 microseconds; the nearest free surface, half the absorber thickness away, is reached in about 30 microseconds. The reflected waves can be tensile, and these tensile waves can cause spalling of the material at the free surface.

Fig. 18 shows the normal stresses in the absorber during and after one pulse. The temperature rise in the absorber is linear during the 10 microsecond beam pulse, and all stresses in the absorber center become increasingly compressive. When the heat generation ceases at t = 10 microseconds, the compression decreases, and stresses reach their peak tensile (or least compressive) values at 40 microseconds.

Fig. 19 shows the stress intensity at the absorber center. Because the center is compressed nearly hydrostatically, the stress intensity is not as large as the largest component stresses, being a maximum of about 8 Mpa.

Fig. 20 shows the axial stress, Sz, at the upstream face of the absorber. Tensile stresses, the result of wave reflection, peak at 4 Mpa at t = 54 microseconds. This compares to a compressive peak at 10 microseconds of –6 Mpa.

In any case, all dynamic stresses are small compared with the strength of the material (approximately 240 Mpa yield strength) and no failure from dynamic stresses should be anticipated.

Figure 18. Dynamic Normal Stresses at Center of Absorber

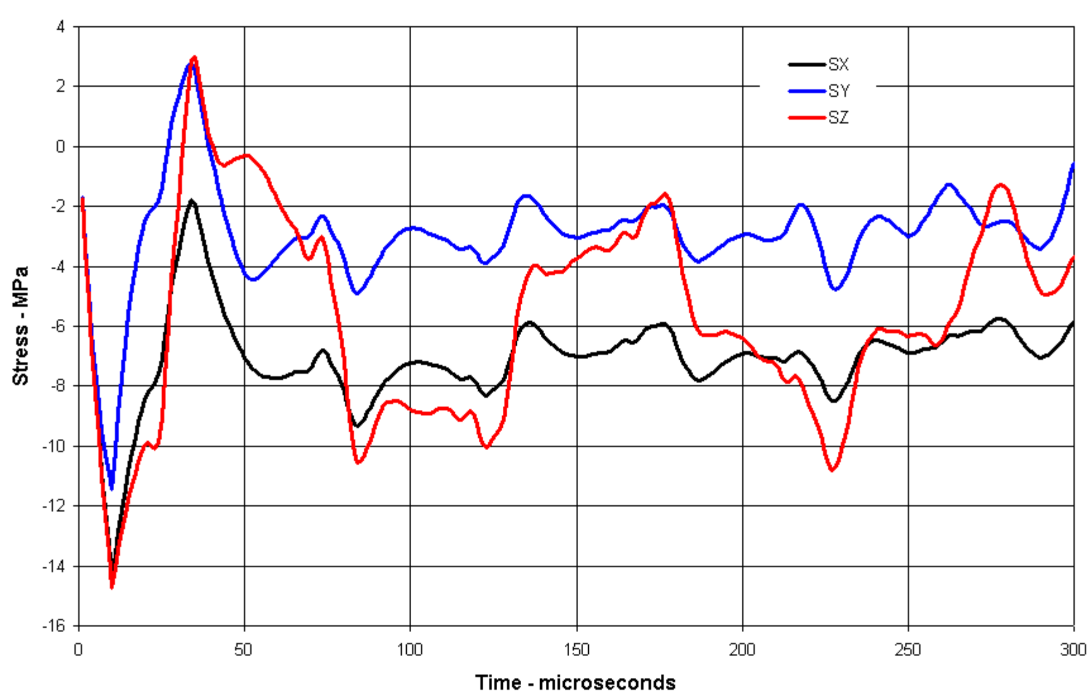


Figure 19. Dynamic Stress Intensity at Center of Absorber

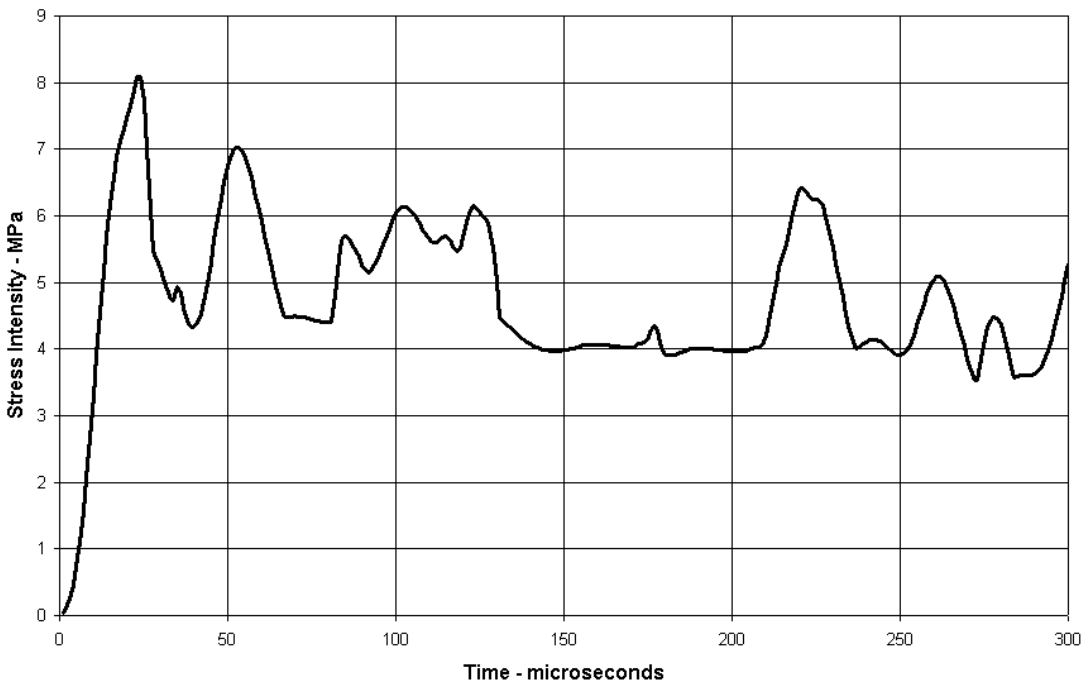
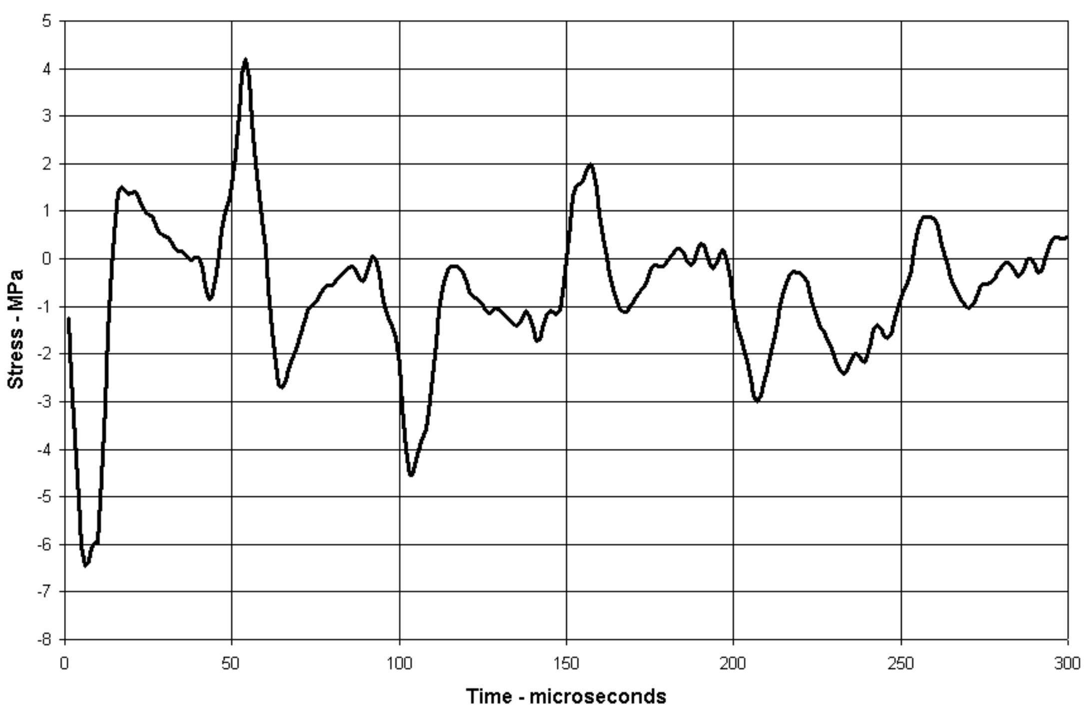


Figure 20. Axial Stress, SZ, at Upstream Face at Absorber Center



Piping Analysis

The ANSYS fluid66 element was used to calculate the pressure drop and temperature rise in the cooling circuits. The ANSYS results for pressure drop were checked by using smooth pipe friction factor correlations, and found to agree to within a percent.

The right angles in the gun-drilled channels add additional pressure drop to the circuit. This was accounted for by adding 20 cm of length to the circuit for each elbow, for a total additional length of 1.6 m. Total circuit length is 5.75 m.

Pressure drop was calculated from the Darcey-Weisbach equation:

$$h_f = f\,(L/D)(V^2/2g)$$

where h_f = head loss, m
L = length of circuit = 5.75m
V = fluid velocity, m/sec
D = hydraulic diameter = 1.9 cm
g = gravitational constant = 9.8 m/sec^2
f = friction factor = $0.316/Re^{0.25}$, where Re = Reynolds number

The convective heat transfer from the pipe wall to the fluid is solved for by ANSYS, using the Dittus-Boelter correlation for fully developed turbulent flow in smooth tubes:

$$Nu = 0.023Re^{0.8}Pr^{0.4}$$

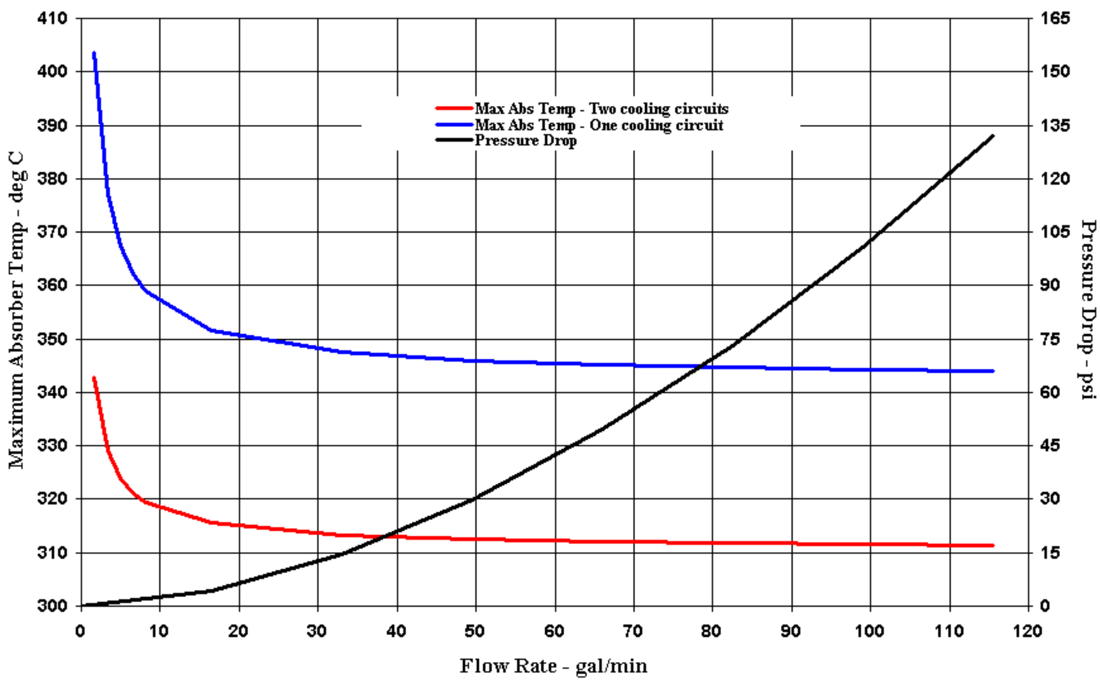
where Nu = Nusselt number
Re = Reynolds number
Pr = Prandtl number

The results of the pressure drop/heat transfer analysis are shown in Fig. 18. With two cooling circuits, the flow rate of coolant should be greater than about 50 gpm. Higher flow rates don't have an appreciable effect on the maximum temperature.

The same flow rate applied to a single cooling circuit is adequate to keep the maximum temperature below 350 ^oC.

The pressure drop for 50 gpm is a little less than 30 psi. The total pressure drop available to each circuit is 125 psi, giving a comfortable margin for increasing flow rates if actual cooling performance does not match calculated performance.

Figure 21. Pressure Drop and Maximum Absorber Temperature as Function of Cooling Flow Rate (two cooling circuits, inlet water temperature = 25 C)



Conclusion

The maximum temperatures reached after 1800 pulses (3420 secs) at a deposition of 58.2 kW are high enough to significantly reduce the strength of a small volume of material at the absorber center. However, this analysis, which takes into account this loss of yield strength and onset of plasticity, shows that the surrounding volumes of cooler, stronger material are sufficient to keep the absorber from undergoing any large plastic deformations.

Dynamic stresses were investigated, and found to be well within the capacity of the absorber aluminum.

Pressure drop and heat transfer calculations verify that the cooling system is comfortably sized, with a substantial margin available above the recommended minimum flow rate of 50 gpm to compensate for any unforeseen cooling difficulties.

It should be noted that the thermal analysis assumes 25 ^{0}C water. The temperature of the actual cooling water may be higher, which will lead to a corresponding increase in the absorber temperature.