MSG-EAR-01285
April 24, 2001

Thermal Stress Analysis of Side-installed NuMi Absorber

Bob Wands

Introduction

A proposed NuMI hadron beam absorber core, intended for side installation, consists of nine water-cooled aluminum modules, 1.32 x 1.32 x 0.31 meters in size. This design was analyzed by IHEP (Abramov, A., et. al., "Advanced Conceptual Design of the NuMI Hadron Beam Absorber Core", NuMi-B-652, June 30, 2000). In that analysis operation of the absorber under the fault condition was limited to sixteen pulses. Current design criteria require that the absorber operate for one hour (approximately 1800 pulses) under the fault condition.

A MARS analysis performed by A. Wehmann shows that the fourth module absorbs the greatest energy, dissipating 58.5 kW. The detailed distribution was tabulated and made available to an ANSYS model, which was then used for the thermal and structural analysis.

Summary

The maximum temperature reached by the absorber after 1800 pulses is 370 deg C. The maximum stress intensity is 210 Mpa (30.5 ksi). This stress occurs in the 25 deg C region near the cooling pipe, where the full room-temperature yield strength of 241 Mpa is available.

A volume of 0.021 m^3 (0.75 ft^3) yields plastically in excess of 0.2%. The maximum plastic strain is 0.7%. There is no evidence of thermal ratcheting.

The maximum displacement due to thermal expansion is vertical (core is assumed to be sitting on its lower surface), and is 3 mm.

Material Properties for the Analysis

The properties of 6061-T6 aluminum were taken from the Metals Handbook, Volume 2, "Properties and Selection: Nonferrous Alloys and Pure Metals". Two of these properties, specific heat and thermal conductivity, are substantially lower than those used in the previous FEA of the aluminum baffle.

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

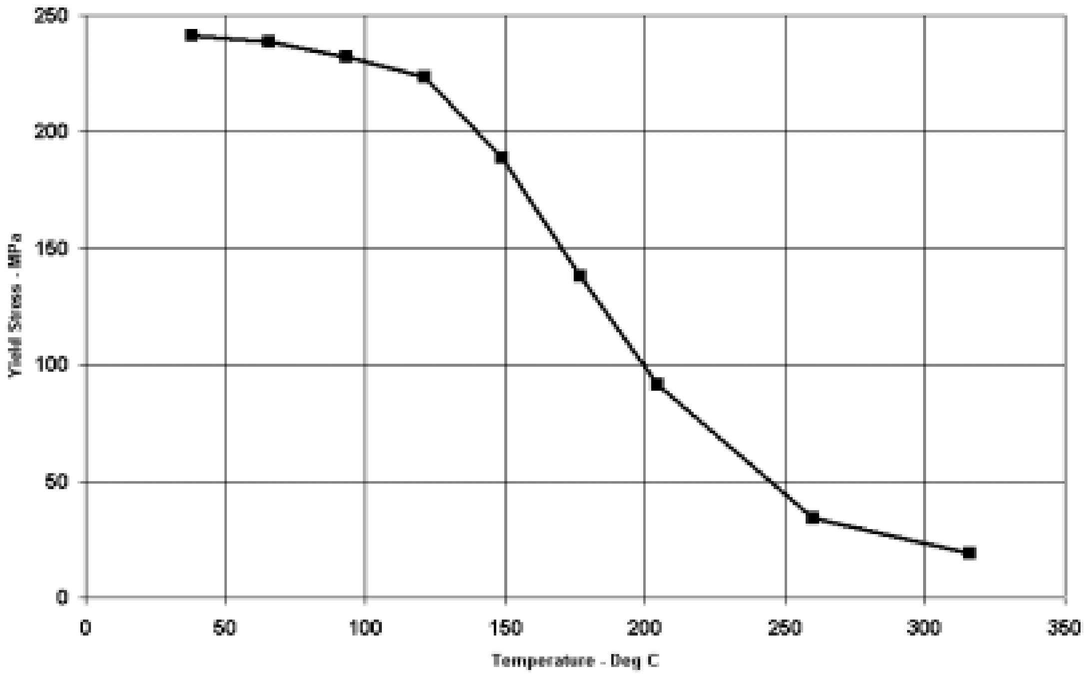
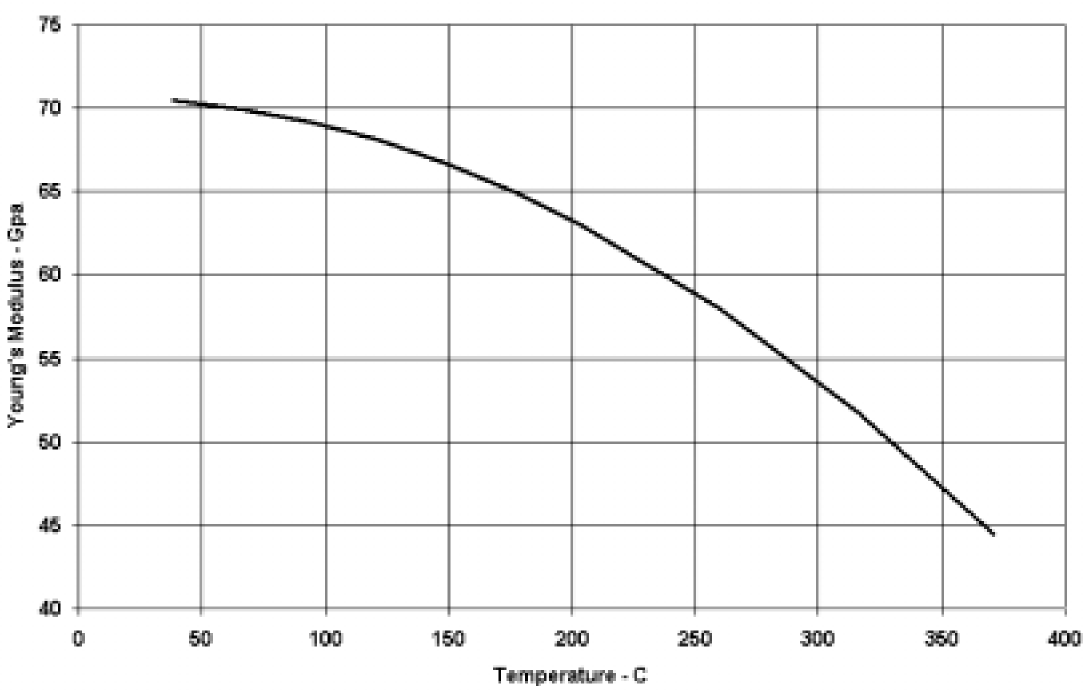


Figure 2. Young's Modulus as Function of Temperature for 6061-T6



Absorber Core Geometry

The absorber core geometry was taken from the technical paper “Advanced Conceptual Design of the NuMI Hadron Beam Absorber Core”, NuMI-B-652, June 30, 2000.

The geometry is shown in Fig. 3.

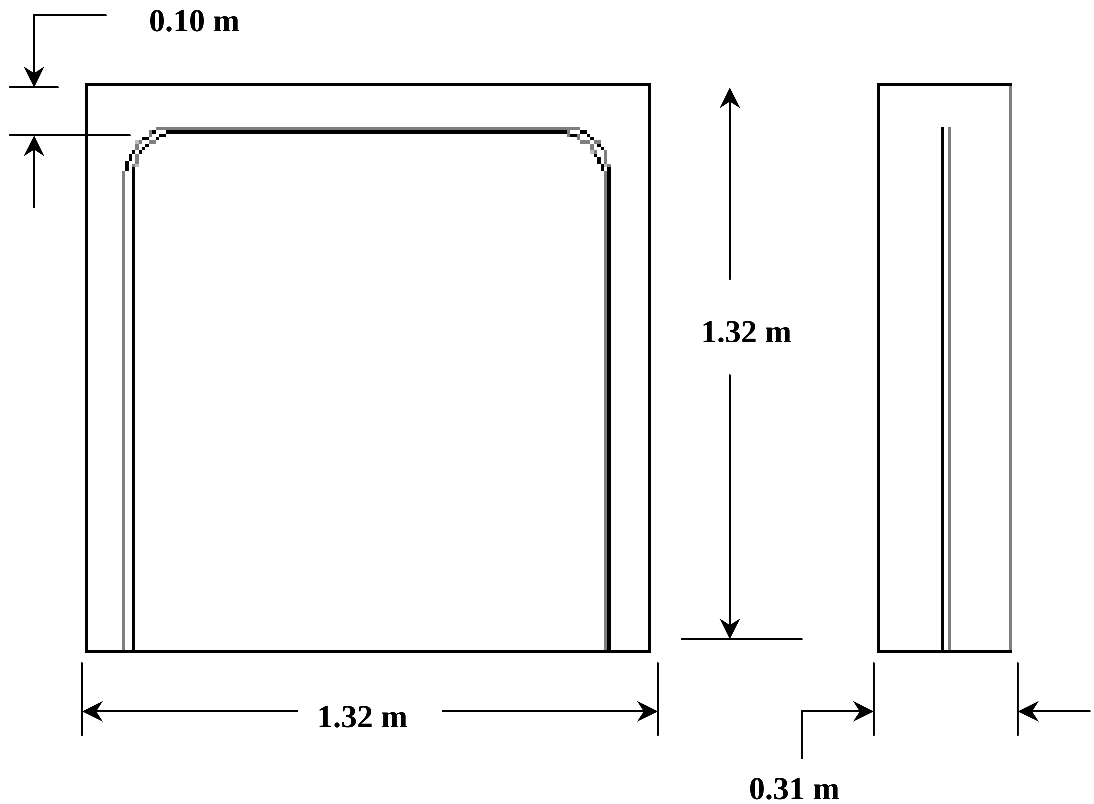


Figure 3. Absorber Core Geometry

Finite Element Model

One-half of the absorber core was modeled with 20-node brick elements. For the 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, symmetry constraints were applied at the vertical cut, and support was provided in the vertical direction over the entire bottom surface. Gravity was applied to account for core dead weight.

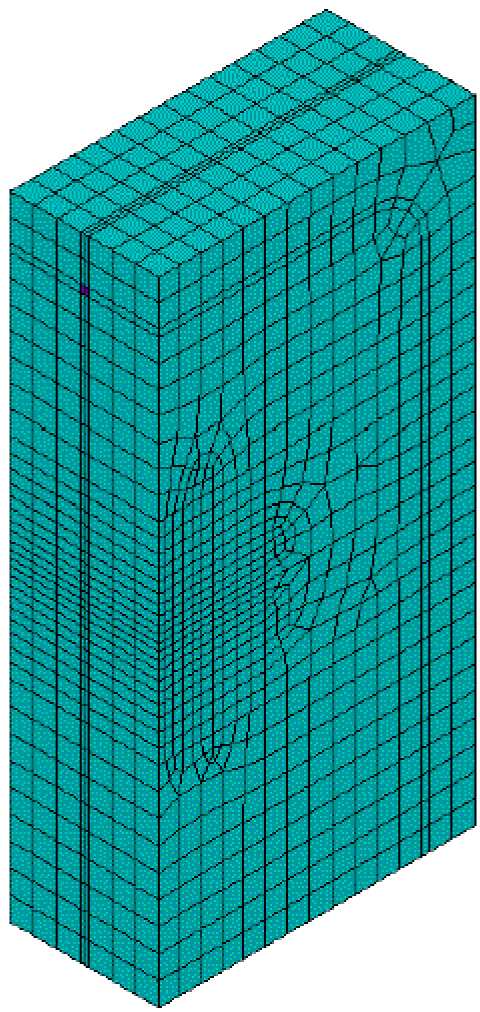


Figure 4. Finite Element Model

Heat generations were input from a table generated by A. Wehmann. The input was checked against internal energy calculations, where the total energy E was defined as the sum of the individual finite element energies, based on an initial temperature of 25 C:

$$E = \sum_{i=1}^{i=n} \rho c_p v_i \Delta T_i$$

where ρ = mass density
c_p = specific heat
v_i = volume of element i
ΔT_i = temperature rise of element i
n = number of elements in model

This summation was made after the 10 μsec pulse. A different method was also used, in which the model was run at a steady-state heat generation, and the heat flow into the constrained nodes was summed.

Both methods agreed with the input to within 2.5%, verifying correct implementation of the heat load.

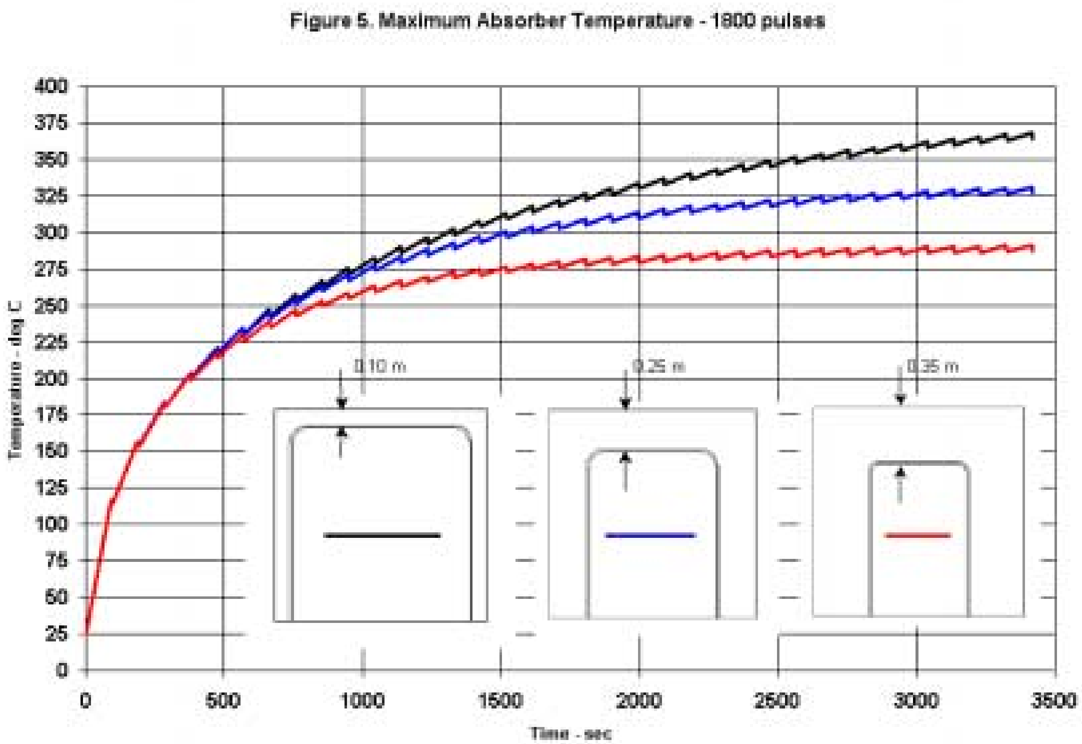
Thermal Analysis Results - 1800 Pulses

The maximum core temperature as a function of time is shown in Fig. 5. After 1800 pulses (3420 sec) the core temperature is 368 deg C.

Fig. 6 shows the distribution of temperature at the end of 1800 pulses.

Included in the figure are two alternate cooling pipe geometries, in which the pipe is moved closer to the center of the absorber. While such close proximity is possible, the demands put on the heat transfer to the cooling fluid are greater due to the shorter cooling pipe length and higher temperature gradient.

The following stress and displacement results are based on the original 0.1 m cooling pipe geometry.



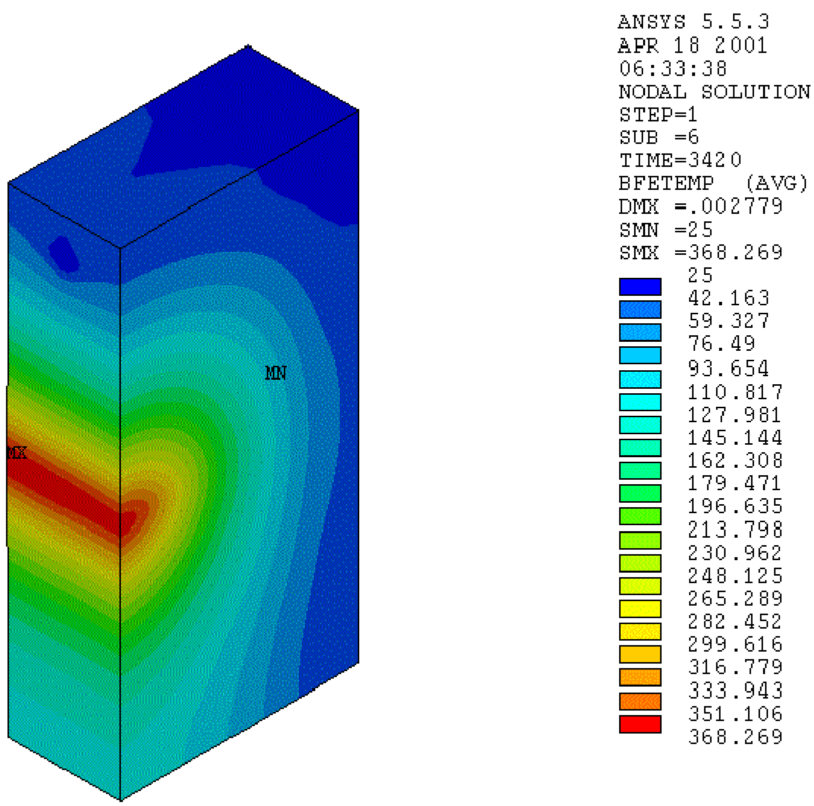


Figure 6. Temperature Distribution after 1800 Pulses

Stress Analysis Results

The stress analysis was performed for five temperature excursions between the maximum temperatures obtained at the end of the 1800th pulse, and the 1800th rest period. These distributions differ by only a few degrees, and for this reason, there appears to be no discernible thermal ratcheting. Unlike the baffle, which produced large drops in temperature between pulses, the absorber core's much smaller temperature drop doesn't give the necessary conflict of compressive and tensile stresses necessary to cause any systematic growth due to thermal distortion.

The high temperatures of the core, and the attendant loss of yield strength produce a large volume of plastically strained material. The red elements in Fig. 7 show the region in which plastic strains exceed 0.2% (the standard permanent offset used to define the yield strength of a material.)

The maximum plastic strain is slightly over 1%.

Figs 8-11 show the stresses in the absorber. For these figures, the core was sectioned in the plane of the water cooling pipe.

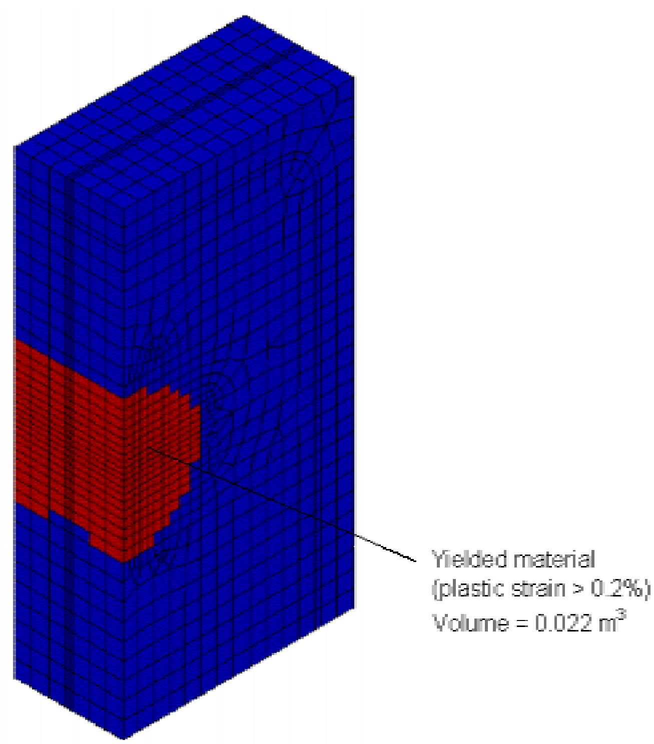


Figure 7. Plasticity in Absorber after 1800 pulses

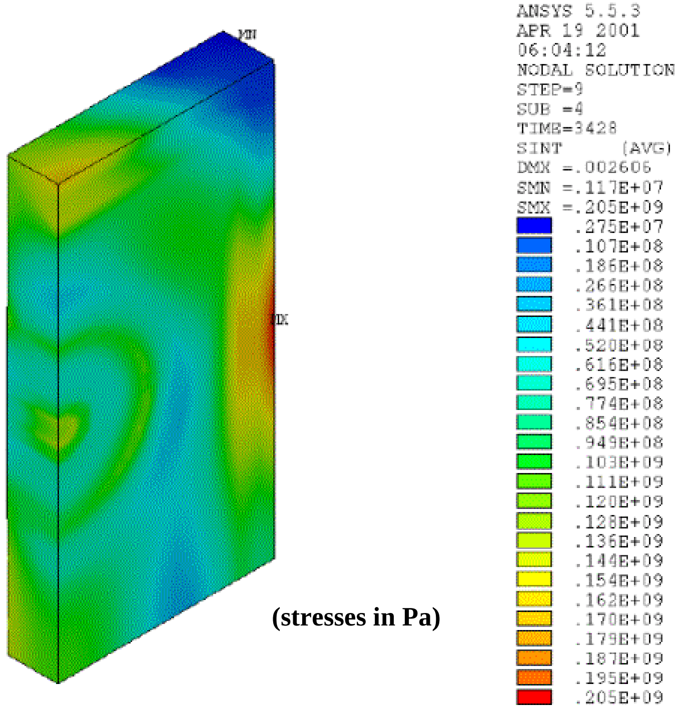


Figure 8. Stress Intensity – 1800 pulses

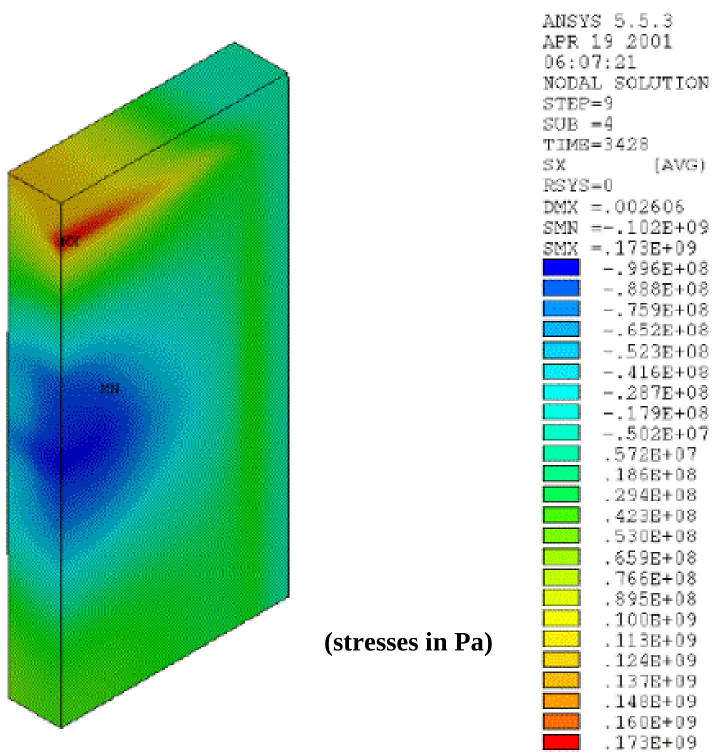


Figure 9. Horizontal (x) Stress – 1800 pulses

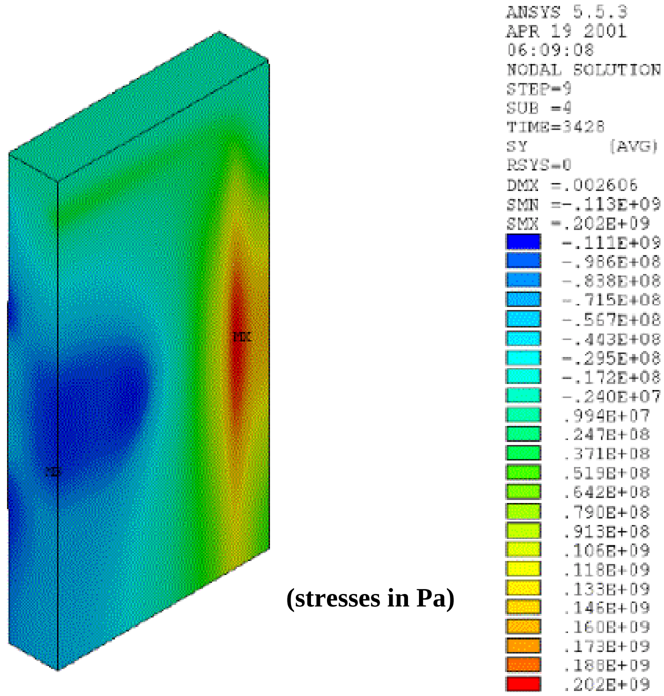


Figure 10. Vertical (y) Stress – 1800 pulses

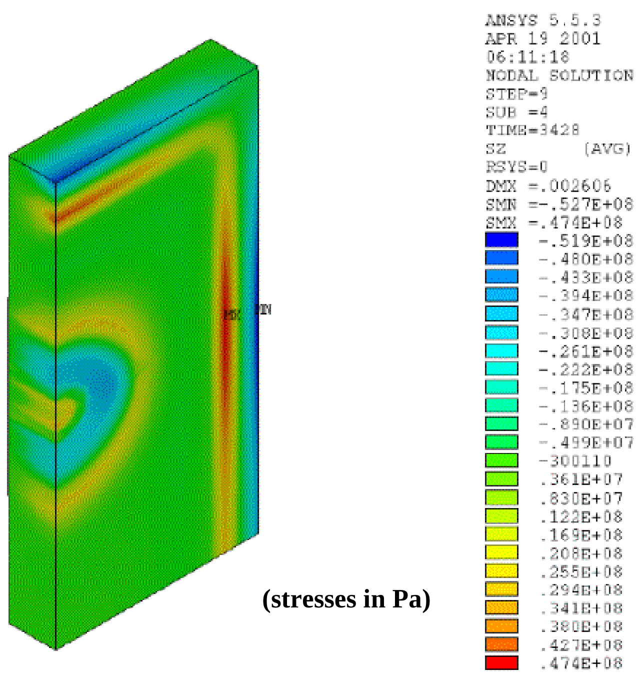


Figure 11. Axial (z) Stress – 1800 pulses

The displacements of the core are shown in Figs 12-14.

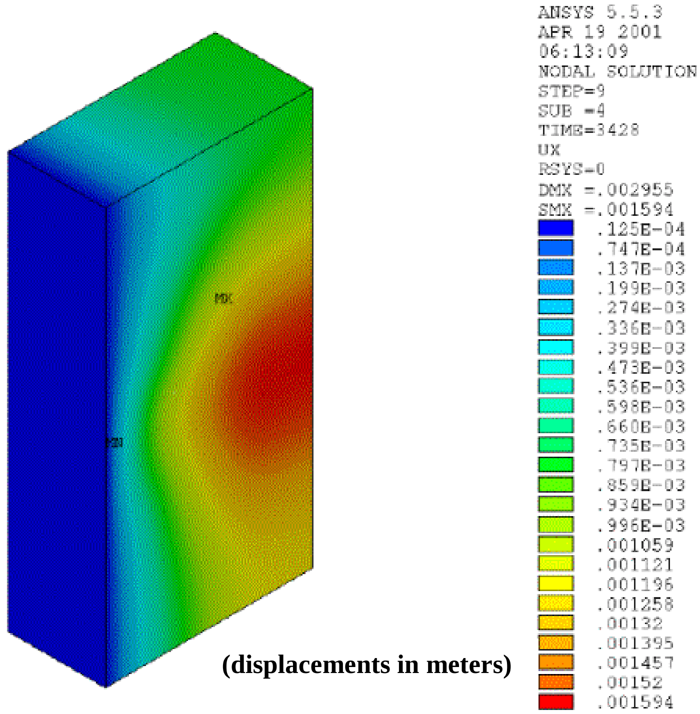


Figure 12. Horizontal (x) displacement of Core – 1800 pulses

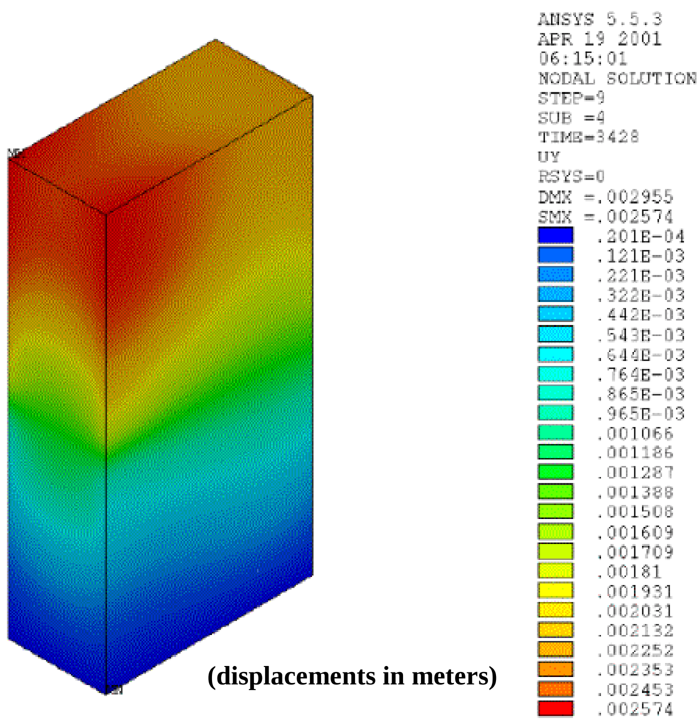


Figure 13. Vertical (y) displacement of Core – 1800 pulses

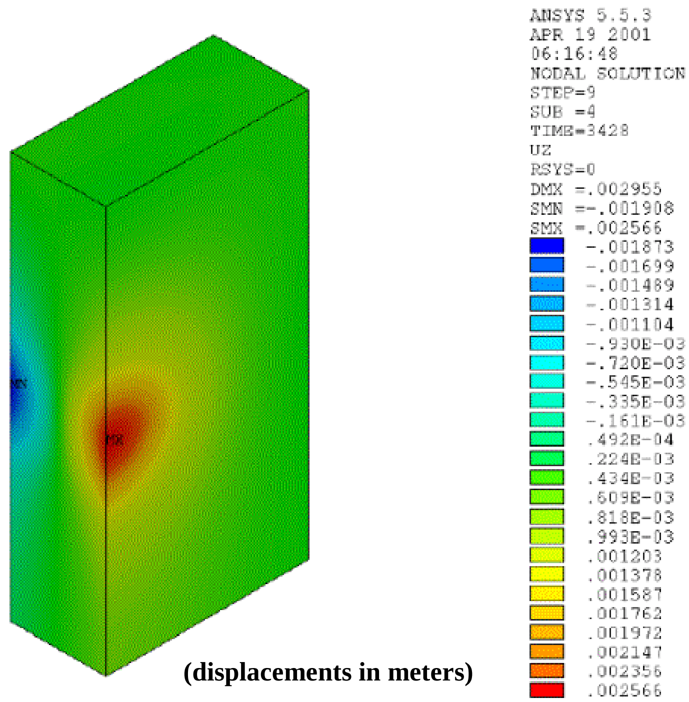


Figure 14. Axial Displacement of Core – 1800 pulses

Conclusion

The absorber as currently conceived is capable of enduring one hour of continuous operation in the fault condition. Plastic strains are moderate (a maximum of about 1%), and stresses, while highest in the low-temperature regions (a result of their resistance to the pressures produced at the center as it heats and swells), are admissible, being below the material yield stress. Thermal stress design philosophy would allow such stresses to substantially exceed the yield stress, in the absence of thermal ratcheting. No thermal ratcheting was found in this analysis.

The absorber is currently being re-designed to account for changes in the installation and replacement conditions; the experimental area has been reduced in size sufficiently to preclude the side installation for which these absorbers were intended.