A Study of Neutron Fluence in the NuMI Absorber Core

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Introduction

One of the reviewers during the November, 2000 NuMI DOE Review asked about possible structural damage due to neutron fluence in the aluminum core of the NuMI Absorber. Figure 1 shows the effect[1] on structural properties of Aluminum 6061-T6 of neutrons with energies greater than 0.1 MeV. Figure 2 is the same, for neutrons with energies less than 1 eV. In this study I take neutron fluxes from a MARS simulation of the Absorber, where there was a threshold of 47 MeV in effect, and I estimate the number of neutrons between 0.1 MeV and 47 MeV and below 1 eV by making use of neutron spectra given in Reference 1.

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[1] Both figures were obtained from Jim Hylen. He said that he had gotten them from Nikolai Mokhov.

<u>Effect of Neutrons on Aluminum (6061-T6)</u>

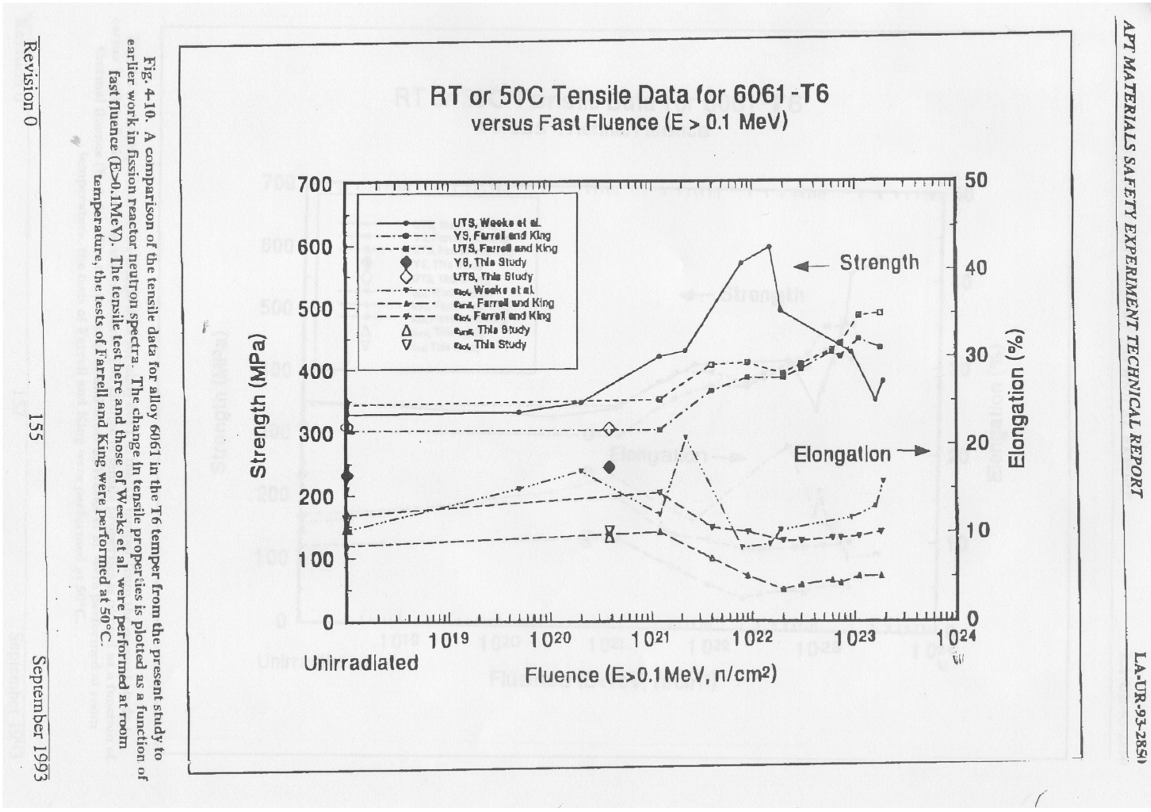

Figure 1

Effect of fast neutrons (E>0.1 MeV) on aluminum 6061-T6.

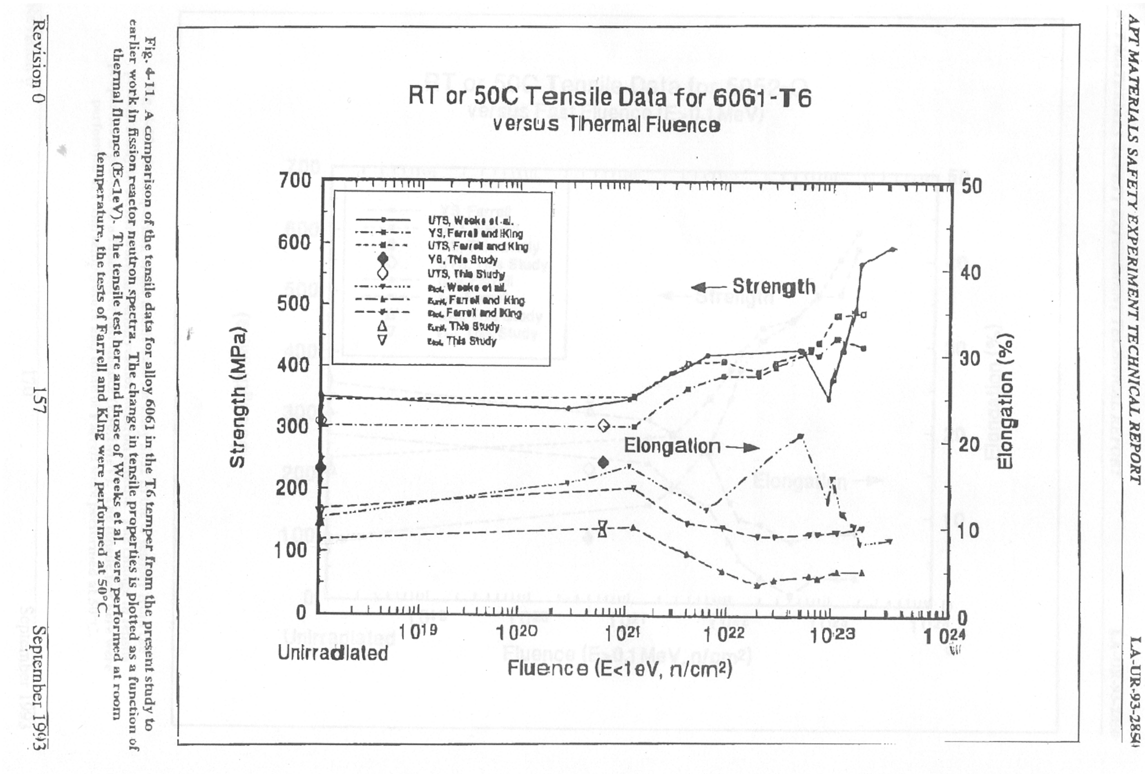

Figure 2

Effect of thermal neutrons (E<1 eV) on aluminum 60601-T6.

<u>MARS results</u>

From the MARS run done for the update of the Absorber conceptual design described in the report at URL http://www-numi:8875/monthly_reports/secure/abs_update.pdf, I have extracted the information presented in the following plot

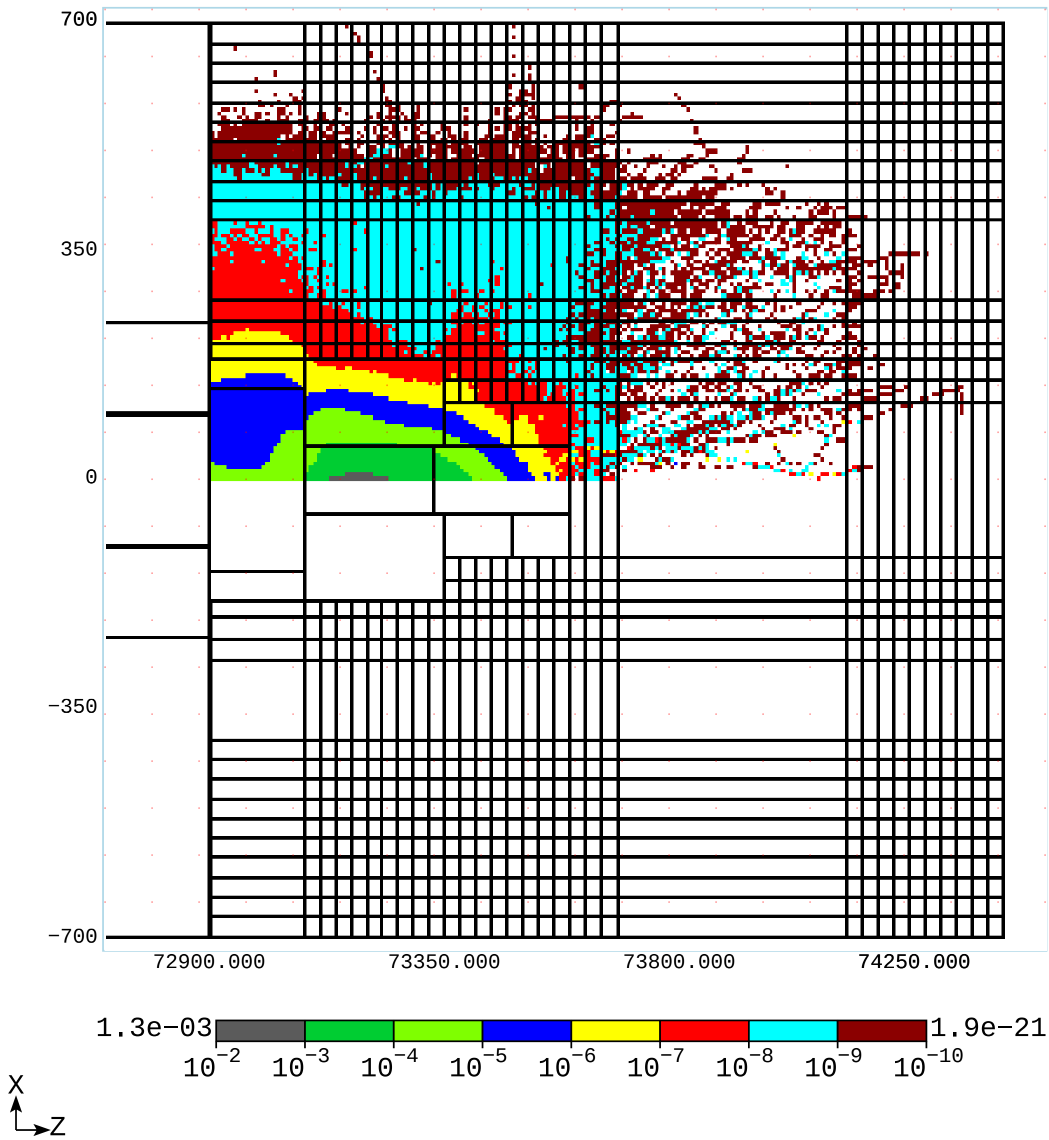

Figure 3
This figure is a superimposition of a neutral hadron fluence plot (E>47 MeV) and an Absorber Geometry plot. It starts at 72700 cm, which is 200 cm ahead of the end of the decay pipe. The fluence units are particles/cm^2/proton (the fluences are best viewed in color). The absorber core begins at z=73083 cm.

<u>Neutron Spectrum at lower energies</u>

In order to understand the neutron flux below the 47 MeV threshold that was in effect during the MARS calculations I use the following figure.

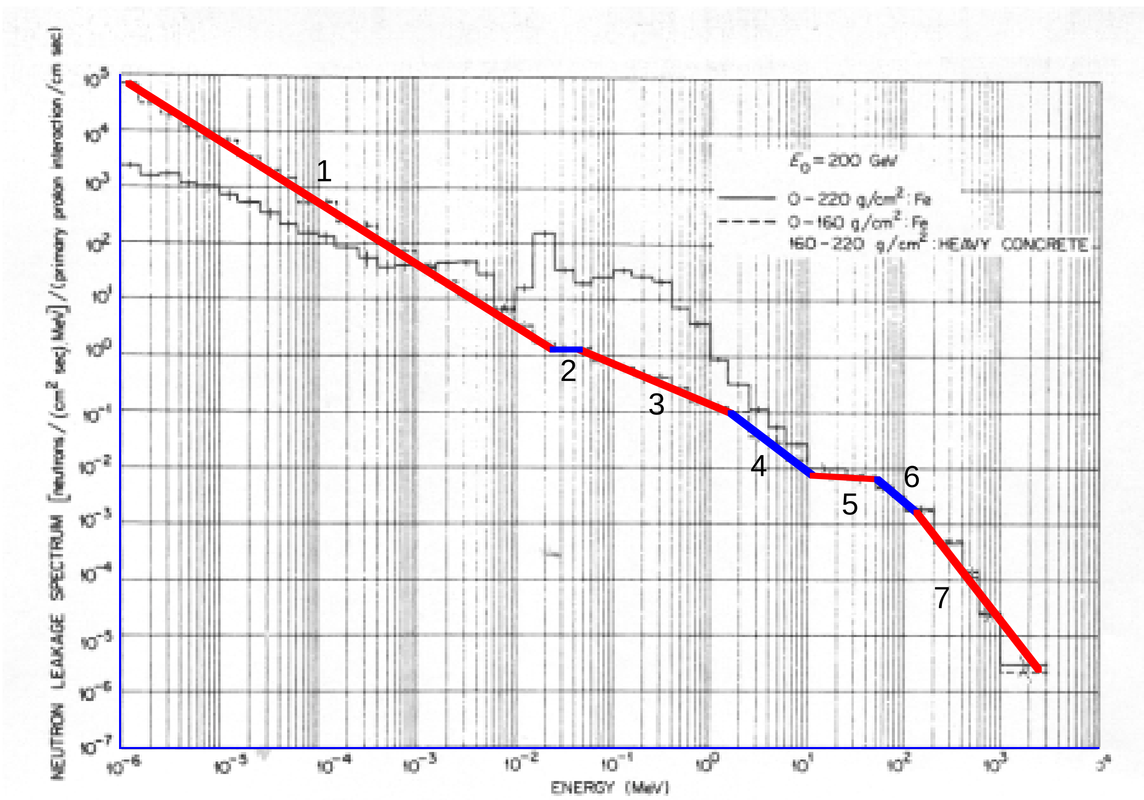

Fig. 14. Neutron leakage spectra at a radius of 220 g/cm^2 for iron and iron followed by heavy concrete.

Figure 4

This figure is adapted from Fig. 14 of reference 1. It shows neutron leakage spectra at a radius of 220 g/cm^2 for iron and iron followed by heavy concrete. The heavy concrete spectrum is approximated by a series of straight lines.

	E (MeV)	Flux (ϕ)	α	integral
Line 1	1.00E-06	8.79E+04	1.095	5.74E-01
	2.66E-02	1.26E+00		
Line 2	2.66E-02	1.26E+00	0.000	2.94E-02
	4.99E-02	1.26E+00		
Line 3a	4.99E-02	1.26E+00	-0.733	4.80E-02
	1.00E-01	7.57E-01		
Line 3b	1.00E-01	7.57E-01	-0.733	3.24E-01
	1.74E+00	9.32E-02		
Line 4	1.74E+00	9.32E-02	1.333	2.31E-01
	1.20E+01	7.08E-03		
Line 5a	1.45E+01	7.08E-03	-0.107	2.14E-01
	4.70E+01	6.24E-03		
Line 5b	4.70E+01	6.24E-03	-0.107	4.88E-02
	5.49E+01	6.14E-03		
Line 6	5.49E+01	6.14E-03	1.481	2.51E-01
	1.38E+02	1.57E-03		
Line 7	2.45E+03	2.45E-06	2.245	1.69E-01
	1.38E+02	1.57E-03		

Table 1

This table gives information for the lines shown in Figure 4. Column five contains the result of performing the integral $\int_{E_1}^{E_2} \phi_1 \left(\frac{E_1}{E}\right)^{\alpha} dE$. The shaded boxes show the 47 MeV threshold that was present in MARS, and the 0.1 MeV threshold that was present in the reactor studies.

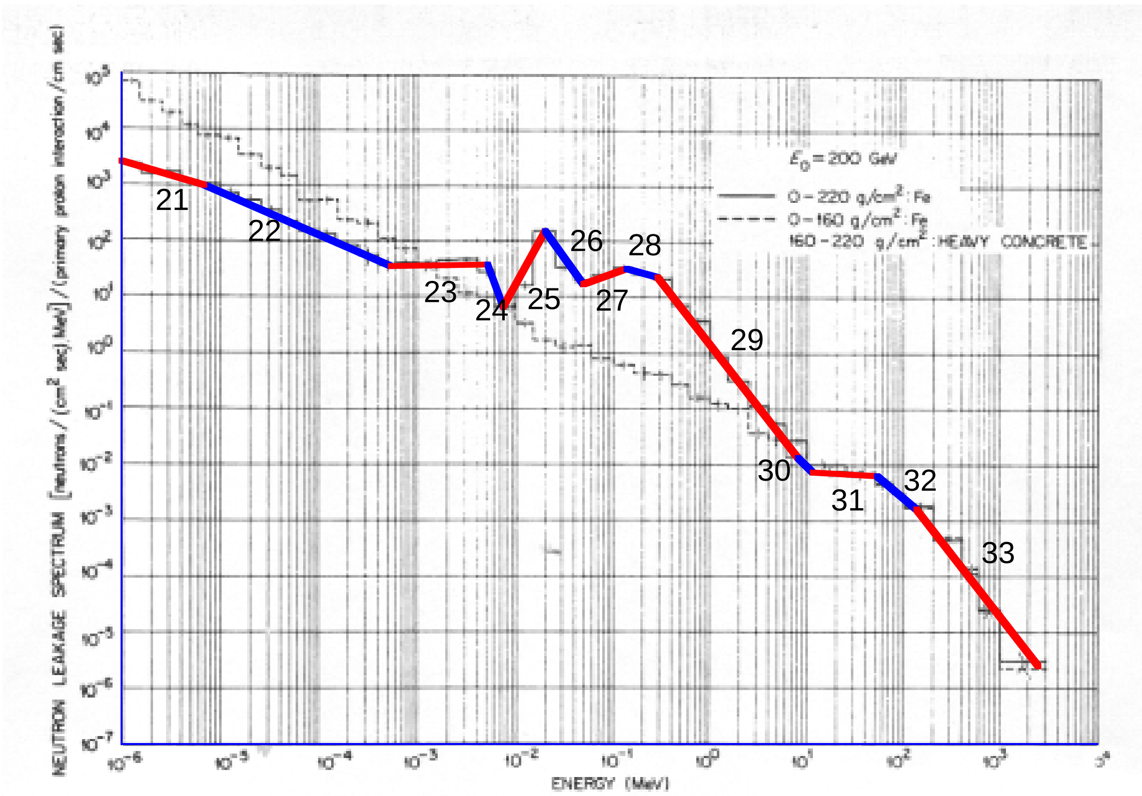

Fig. 14. Neutron leakage spectra at a radius of 220 g/cm^2 for iron and iron followed by heavy concrete.

Figure 5

This figure is adapted from Fig. 14 of reference 1. It shows neutron leakage spectra at a radius of 220 g/cm^2 for iron and for iron followed by heavy concrete. The iron spectrum is approximated by a series of straight lines.

	E (MeV)	Flux (ϕ)	α	integral
Line 21	1.00E-06	2.69E+03	-0.511	8.80E-03
	7.04E-06	9.93E+02		
Line 22	7.04E-06	9.93E+02	-0.760	5.46E-02
	5.74E-04	3.50E+01		
Line 23	5.74E-04	3.50E+01	0.025	1.84E-01
	5.63E-03	3.71E+01		
Line 24	5.63E-03	3.71E+01	-4.756	4.14E-02
	8.11E-03	6.56E+00		
Line 25	8.11E-03	6.56E+00	3.138	7.69E-01
	2.19E-02	1.48E+02		
Line 26	2.19E-02	1.48E+02	-2.455	1.62E+00
	5.34E-02	1.65E+01		
Line 27a	5.34E-02	1.65E+01	0.619	9.58E-01
	1.00E-01	2.43E+01		
Line 27a	1.00E-01	2.43E+01	0.619	1.37E+00
	1.49E-01	3.12E+01		
Line 28	1.49E-01	3.12E+01	-0.475	4.12E+00
	3.09E-01	2.20E+01		
Line 29	3.09E-01	2.20E+01	-2.249	5.36E+00
	8.45E+00	1.29E-02		
Line 30	8.45E+00	1.29E-02	-1.703	3.41E-02
	1.20E+01	7.08E-03		
Line 31a	1.20E+01	7.08E-03	-0.094	2.29E-01
	4.70E+01	6.23E-03		
Line 31b	4.70E+01	6.23E-03	-0.094	4.87E-02
	5.49E+01	6.14E-03		
Line 32	5.49E+01	6.14E-03	-1.481	2.51E-01
	1.38E+02	1.57E-03		
Line 33	1.38E+02	1.57E-03	-2.245	1.69E-01
	2.45E+03	2.45E-06		

Table 2

This table gives information for the lines shown in Figure 5. Column five contains the result of performing the integral $\int_{E_1}^{E_2} \phi_1 \left(\frac{E_1}{E} \right)^{\alpha} dE$. The shaded boxes show the 47 MeV threshold that was present in MARS, and the 0.1 MeV threshold that was present in the reactor studies.

<u>Use of Heavy Concrete Spectrum</u>

Using the integrated flux values in column 5 of Table 1, I can determine the neutron flux in the energy interval 0.1 to 47 MeV relative to the neutron flux for energies above 47

MeV; the former value is 0.77 and the latter value is 0.47. The ratio $\frac{0.77}{0.47}$ is 1.64. Using the peak value of 1.3 10^{-3} neutrons/cm^2/proton from Figure 3, I can then obtain a value for the integrated flux (E>0.1 MeV) as $2.64 \times 1.3 \cdot 10^{-3} = 3.4 \cdot 10^{-3}$ neutrons/cm^2/proton. NuMI expects[2] to target 3.7 10^{20} protons per year for eight years in its first decade of operation; using this value the integrated neutron flux is 1.0 10^{19} neutrons/cm^2.

It is also of interest to estimate the thermal neutron fluxes (E < 1 eV). The flux values in Figure 4 go as low as 1 eV. I take the thermal neutron energy region to be between 1 eV and kT (0.026 eV for T = 300° K). I make the observation that $\int_{E_1}^{E_2} \phi_1 \left(\frac{E_1}{E}\right) dE$ is

$\phi_1 E_1 \ln(\frac{E_2}{E_1})$ (the case where flux per MeV is falling as 1/E). This means that for a 1/E energy dependence of the flux, the integrated flux for each factor of 10 in energy is the same. The slope of line #1 on Figure 4 is quite close to –1 & I can assume it to be –1 for making an estimate of the thermal neutron flux. From Table 1 the value of φ_1 at E=1 MeV is 8.79E+04. The integral for a factor of 10 in energy would then be[3] 0.2 neutrons/(cm^2 sec)/(primary proton interaction/cm sec). For the range of 0.026 eV to 1 eV the integral would be 0.32 neutrons/(cm^2 sec)/(primary proton interaction/cm sec). The ratio 0.32/0.47 is 0.68. The peak integrated flux (E<1eV) for the first decade of NuMI operation would be $0.68 \times 1.3 \cdot 10^{-3} \times 3.7 \cdot 10^{20} \times 8 = 2.6 \cdot 10^{18}$ neutrons/cm^2.

Neither of the peak fluence values calculated would be a problem--according to Figures 1 & 2.

<u>Use of Iron Spectrum</u>

It is of interest to use instead the iron spectrum from Figure 5 to make the same estimates. It can be noted in Figure 14 of Reference 1 that there is an excess of neutrons in the iron spectrum in the energy range 0.01 MeV to 10 MeV, when compared to the heavy concrete spectrum. This is explained as due to the large variation of the iron cross section in the energy region around 0.01 MeV. I don't have readily available a spectrum for aluminum, so I'll assume it can be no worse than it is for iron[4].

Using the integrated flux values in column 5 of Table 2 I can determine the neutron flux in the energy interval 0.1 to 47 MeV relative to the neutron flux for energies above 47

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[2] This is the same as 4 10^{13} protons per spill, a spill every 1.9 seconds, 100 hours of operation in a 168 hour week, 9 months out of 12 in a year, over a total period of 10 years. These are the assumptions used in Fermilab TM-2009 (NuMI-B-279).

[3] This is assuming a 1/E spectrum.

[4] The AIP Handbook lists the K Level for iron as 7112 eV and that for aluminum as 1559.6 eV. Since the spectrum irregularity for iron is often mentioned as due to the value of its K level, for aluminum I would expect such an effect to be lower in energy by a factor of 4.5.

MeV; the former value is 11.1and the latter is 0.47. The ratio $\frac{11.1}{0.47}$ is 23.6. Using the peak value of 1.3 10^{-3} neutrons/cm^2/proton from Figure 3, I can then obtain an integrated flux (E>0.1 MeV) to be $24.6 \times 1.3 \cdot 10^{-3} = 3.2 \cdot 10^{-2}$ neutrons/cm^2/proton. As noted earlier, NuMI expects to target 3.7 10^{20} protons per year for eight years in its first decade of operation; using this value the integrated neutron flux is 9.4 10^{19} neutrons/cm^2. This value is also not of concern, when one examines Figures 1 and 2.

Since the iron spectrum doesn't show the moderating effect of the light elements in the heary concrete, the flux of neutrons in the region below 1 eV is less than what was considered for the heavy concrete spectrum.

Conclusion

An estimate made of the neutron fluence in the NuMI Absorber core does not produce values that indicate worrisome changes in the mechanical properties of aluminum.

References:

1. T.W. Armstrong and R.G. Alsmiller, Jr.,
Calculation of the Residual Photon Dose Rate Around High-Energy Proton Accelerators, Nuclear Science and Engineering: 38, pages 53-62 (1969)