RADIATION SOURCE TERMS FOR SHIELDING DESIGN AT SYNCHROTRON LIGHT SOURCES

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ABSTRACT

Shielding design at Argonne's Advanced Photon Source was originally performed using empirical equations for dose due to both bremsstrahlung photons and photoneutrons. These equations provide a conservative estimate of dose and also provide a convenient way to account for the effects of shielding materials through simple exponential attenuation. Modern radiation transport codes provide a way to calculate source terms more accurately and also allow for more convenient and accurate calculation of doses outside inhomogeneous shielding. MCNP6 was used to calculate the photon and neutron source terms for 6 GeV electrons incident on materials commonly found at light sources. The resulting source terms are compared with the empirical equations.

KEYWORDS
MCNP, synchrotron light source

1. INTRODUCTION

Argonne's Advanced Photon Source is planning a major upgrade which will significantly increase the brightness of hard x-rays and incorporate advanced beamlines, optics, and detectors. The upgraded facility will feature high charge-per-bunch swap-out injection into the storage ring and an increase in storage ring current from the present 100 mA to 200 mA. Because of the different injection method, higher stored current, and shorter beam lifetimes, there is a potential for higher losses and thus higher doses around the facility. An assessment of shielding requirements must necessarily start with an assessment of the radiation source terms, which is the subject of the present study.

2. SOURCE TERMS

2.1. Photon Source Terms

The original APS shielding was designed using an equation of Swanson [1]

$$H(\theta) = 167E_0\left(2^{-\theta/(100/E_0)}\right) + 8330\left(10^{-\theta/21}\right) + 250\left(10^{-\theta/110}\right) \qquad \mu\text{Sv/J} \qquad (1)$$

for the photon source term. The equation is meant to represent the dose due to electrons incident on thick targets of high-Z materials. The effects of shielding were accounted for using exponential attenuation. The first term is this equation is meant to represent the dose at small angles due to forward-directed bremsstrahlung at high energies, while the second and third terms represent the dose at larger angles. There are no factors to correct for varying target size or composition.

Another equation by Nelson and Jenkins [2] is a fit to experimental data obtained for 10 GeV electrons incident on a 30.48 cm long x 10.16 cm diameter iron target (which they refer to as the “standard target”).

$$H(\theta) = 52.55E_0\left(e^{-0.959\sqrt{\theta}}\right) + 12.97\left(e^{-\theta/72.2}\right) \qquad \mu Sv/J \qquad (2)$$

The first term was used to fit a set of measurements from 0-5 degrees, and the second term fit data over the range 30-180 degrees. The region in between is covered by the sum of the two terms extrapolated into this region. This equation (and the underlying experimental data) does not contain the sharp spike at forward angles found in Swanson’s equation, but does include an energy-dependent term for the dose at somewhat larger angles. Scaling factors for different target size and composition are given in [2].

2.2. Neutron Source Terms

For the APS shielding design, Moe [3] used the equation

$$H_N(\theta) = A + \frac{B}{1-0.75cos\theta} + \frac{C}{(1-0.72cos\theta)^2} \qquad (\mu Sv/J) \qquad (3)$$

where the first term corresponds to neutrons produced through the giant resonance interaction, and the second and third terms represent neutrons produced with higher energies. The coefficients are functions of the target element, as shown in Table I. Nelson and Jenkins [2] use an equation of a similar form

$$H_N(\theta) = 0.0308Z^{0.662} + \frac{0.274A^{-0.37}}{1-0.75cos\theta} + \frac{0.0855A^{-0.65}}{(1-0.72cos\theta)^2} \qquad (\mu Sv/J). \qquad (4)$$

The giant resonance and high-energy components are smaller, and the medium-energy component larger, than in the equation used by Moe (see Table I). Neither model for neutron dose includes corrections for target size. The equations were based on estimates of neutron production in large targets, and do not account for neutrons that are absorbed inside the target before escape.

Table I. Coefficients for neutron source terms [2,3].

Equation	constant	mechanism	Al	Fe	Cu	W	Pb
Moe	A	giant resonance	0.208	0.328	0.353	0.654	0.700
	B	medium energy	0.0614	0.033	0.033	0.020	0.020
	C	high energy	0.0154	0.0083	0.0083	0.012	0.012
SHIELD11	A	giant resonance	0.168	0.266	0.286	0.532	0.569
	B	medium energy	0.0810	0.0619	0.0590	0.0398	0.0381
	C	high energy	0.0100	0.0063	0.0058	0.0029	0.0027

3. CALCULATION METHODS AND RESULTS

MCNP6 [4] calculations were performed for copper and iron targets using condensed-history physics. In the results shown, fractional standard deviations are generally a few percent or less, but as high as 10% for small angular bins around 0°. Figure 1 shows the photon dose as a function of angle for several sizes of a copper target, with the dose normalized to energy content of the incident electrons. The results for the 1 cm long x 1 cm diameter target shows that the high doses that occur in the forward direction come from electron interactions in the front of the target, before the electrons have lost much energy. The resulting photons have energies near that of the incident electrons, and suffer little attenuation within the target. High doses to the side do not occur until the target diameter is increased enough so that the transverse shower can develop. A typical “large” target would be at least ten radiation lengths long and three Moliere radii in radius (14.4 cm and 3.7 cm in copper, respectively). For the three larger target sizes considered, there is little difference in the photon dose for angles larger than a few degrees.

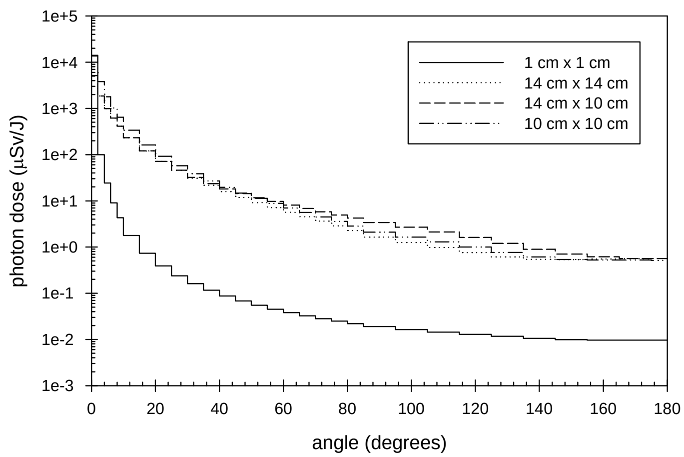

Figure 1. Photon dose for selected cylinder sizes.

Figure 2 compares the photon dose for the 14 cm long x 10 cm diameter cylinder to the equations of Nelson and Jenkins and of Swanson. Equation 2 was scaled by factors described in [2] to account for differences in target material and dimensions from the iron target used in the measurements. The MCNP6 results are somewhat lower than those of Nelson and Jenkins (Figure 2a). The equation of Swanson gives doses that are about ten times higher for angles larger than a few degrees. At very small angles (Figure 2b), the MCNP6 calculations diverge from the measured data, which will be discussed below.

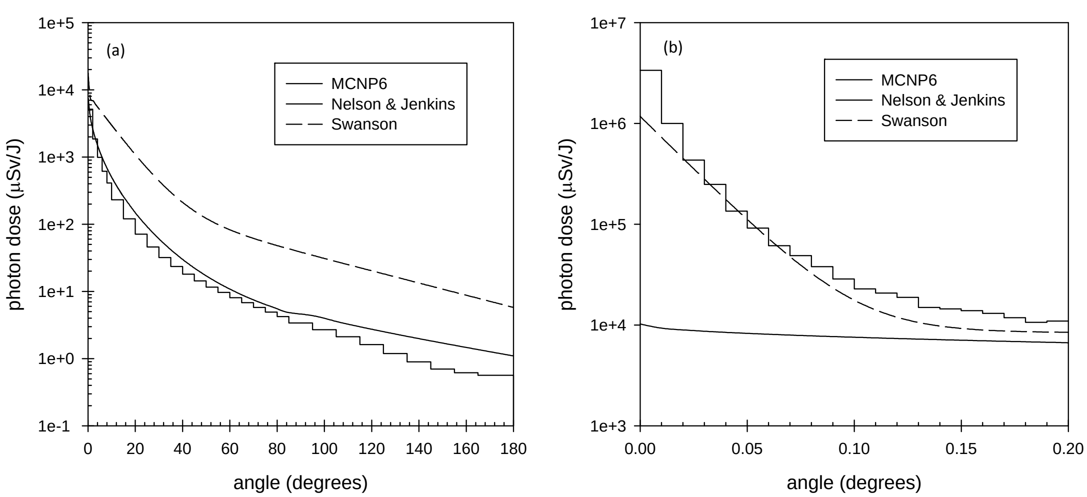

Figure 2. Photon dose for the 14 cm x 10 cm Cu cylinder.

Figure 3 shows the photon dose calculated with MCNP6 for electrons of selected energies incident on a 30.48 cm long x 10.16 cm diameter iron target. Over a broad range of angles $30 \leq \theta \leq 120°$, the dose is independent of electron energy, depending only on the beam power. At larger angles, the dose is higher for lower-incident-energy electrons, while the opposite is true at smaller angles.

Figure 4 shows doses for angles smaller than 10°. The MCNP6 results show a forward peak which is not seen in the measurements of Nelson and Jenkins [2]. If this peak represents the first term in Swanson's equation, as suggested by Figure 2, the peak should get narrower for increasing incident electron energy. However, the peak width remains constant at about 0.1 degrees, close to the angle (1.4 mrad = 0.08 deg) at which the MCNP6 treatment of electron scattering changes from table-based (at larger angles) to equation-based. Although the distribution is continuous at that point, the slope may not be, and this could lead to some unphysical effects in the scattering. Figure 4 suggests that this peak may be due to the numerics of the scattering calculation rather than being a physical phenomenon. The peak in Swanson's equation appears to be based on data for the angular dependence of dose for electron incident energies ≤ 20 MeV (see Figure 18 in Ref. [5]), which may not extrapolate well to GeV energies. Figure 5 shows that if the first angular bin covers 0-1° the angular distribution is closer to the measured results.

Neutron doses for electrons incident on cylindrical copper targets are shown in Figures 6 and 7. Figure 6 shows that the neutron dose calculated using MCNP6 depends much more on target size than the photon dose. The dose at side angles increases for longer targets since there is more area from which neutrons can be emitted, and decreases for angles around 90° as the target diameter increases above a few cm since there is a greater chance for neutrons to be absorbed inside the target. Figure 7 shows that the equations of both Nelson & Jenkins and of Moe offer reasonable approximations to the MCNP6 results. Since the doses for most locations outside the shielding at synchrotron light sources will be dominated by neutrons, dose calculations using the empirical and computational approaches will differ by factors of only a few.

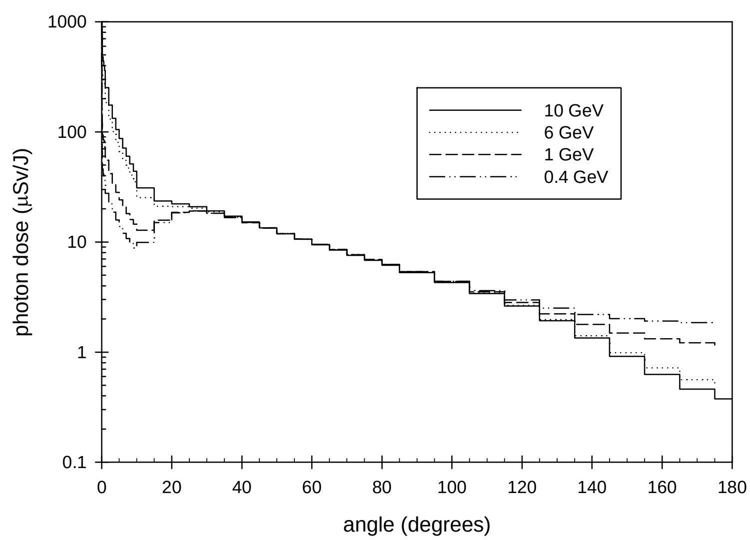

Figure 3. Photon dose for electrons incident on the standard Fe target calculated with MCNP6.

4. CONCLUSIONS

MCNP6 results for photons emitted from electron interactions with an iron target agree well with measurements. Neutron emission calculated using MCNP6 is consistent with empirical equations used for accelerator shielding. While condensed-history physics has generally been restricted to electron energies below 1 GeV, the present results indicate that the radiation source terms arising from MCNP6 calculations could be used for shielding design at high-energy electron accelerators. These results may be improved through the use of new single-event physics in MCNP6, which will be the subject of future studies.

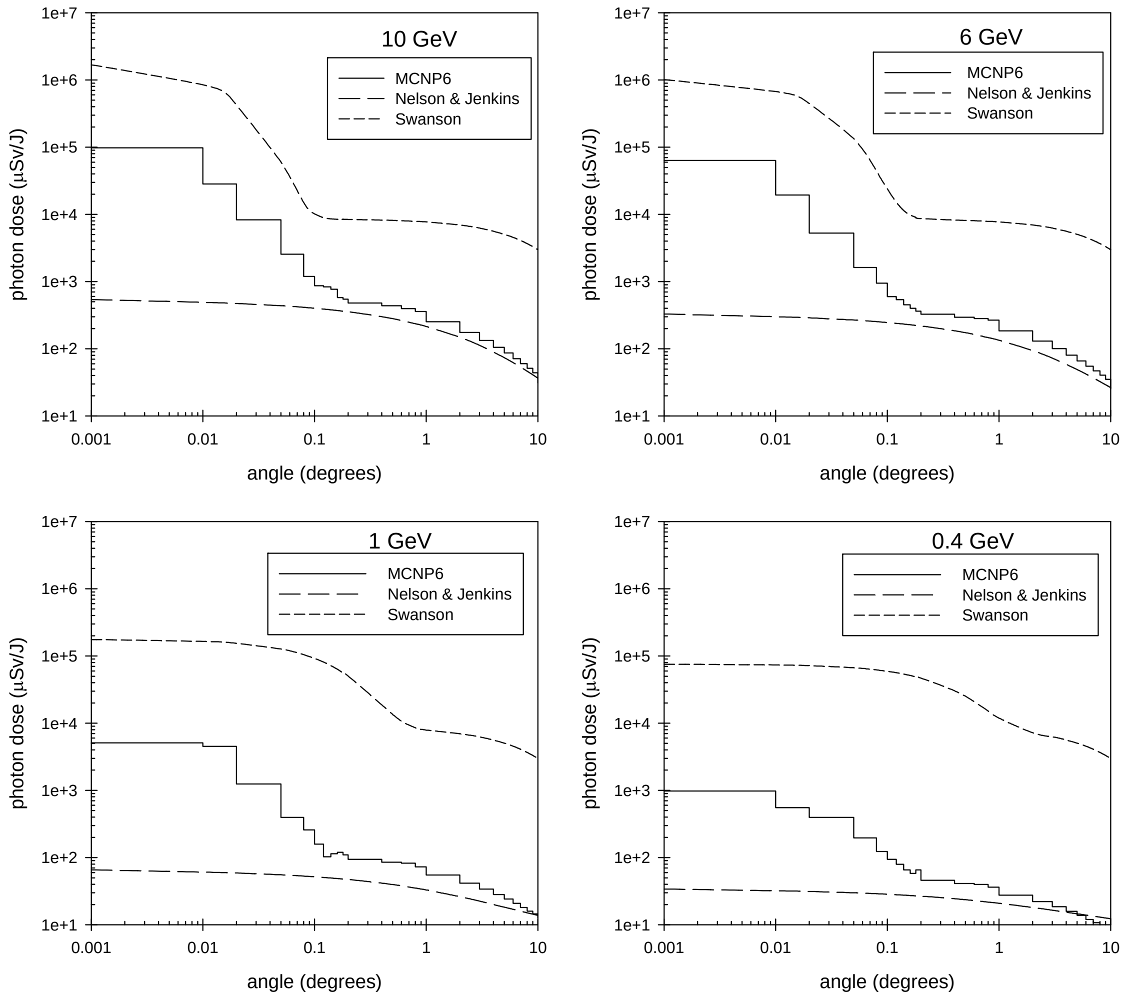

Figure 4. Photon dose for electrons of selected energies incident on the standard Fe target.

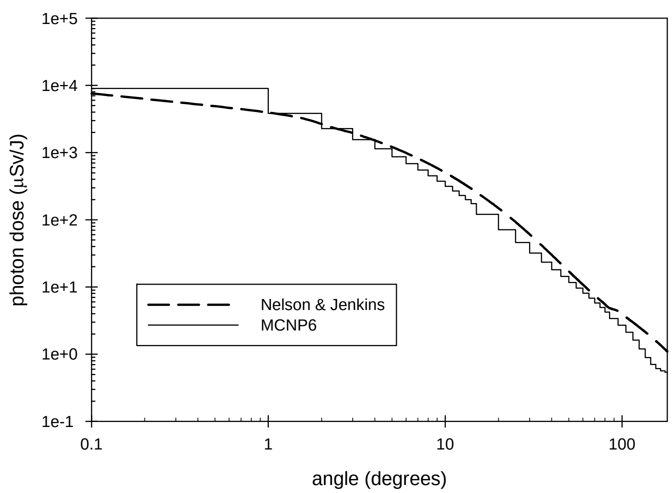

Figure 5. Photon dose for 7 GeV electrons incident on a 14cm x 10cm copper target.

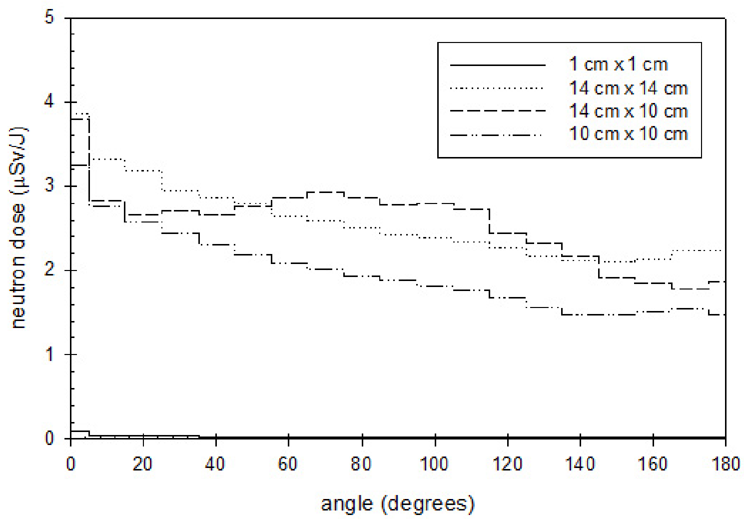

Figure 6. Neutron dose for selected sizes of a Cu cylinder calculated with MCNP6.

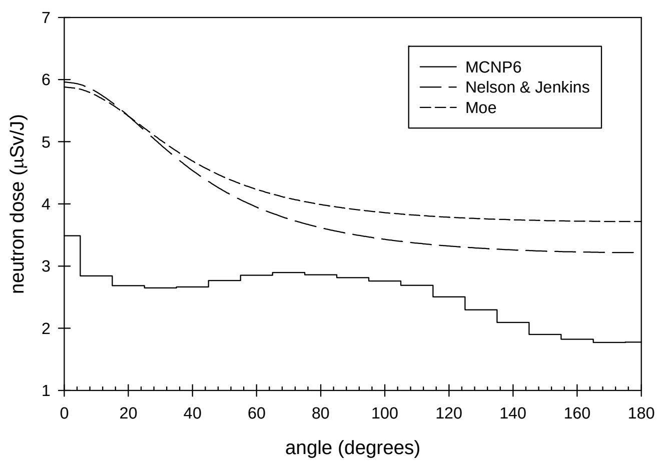

Figure 7. Neutron dose for the 14 cm x 10 cm Cu cylinder.

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