Title: PHOTONEUTRON PRODUCTION IN ELECTRON BEAM STOP FOR DUAL-AXIS RADIOGRAPHIC HYDROTEST FACILITY (DARHT)

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Photoneutron Production in Electron Beam Stop for Dual-Axis Radiographic Hydrotect Facility (DARHT)

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Abstract

A beam stop design for an electron linear accelerator was analyzed from the perspective of photoneutron production and subsequent dose. Sophisticated nuclear data modeling codes were used to generate the photoneutron production cross sections and spectra that were then used in MCNP transport calculations. The resulting neutron dose exceeded limits for workers present in the experimental area while the accelerators are producing electron beam pulses. Therefore, the beam stop was redesigned to limit doses to acceptable values, consistent with the ALARA philosophy.

1. INTRODUCTION

DARHT is a pulsed-electron linear accelerator facility being built at Los Alamos National Laboratory. Its final configuration, depicted in Fig. 1, will be two 20-MeV accelerators with perpendicularly intersecting beamlines to provide dual-axis radiography of weapon-related high-energy hydrodynamic experiments. Each accelerator will have a beam stop located downstream of the last accelerating stage (see Fig. 1). When engaged, the beam stops will allow the accelerators to be maintained in a pulsing mode when workers perform experimental setup and adjustment in the region in front of the bullnoses and steel cones.

A preliminary shielding design of the DARHT beam stops was published in Ref. [1]. Subsequently, more accurate transport calculations including photoneutron production and transport have been performed. Those calculations, described here, have necessitated a redesign of the DARHT beam stops.

Section 2 of this paper describes our calculational methodology. The theoretical basis for the photonuclear data used is found in Sec. 3. The remainder of the paper provides calculational results and discussion.

2. CALCULATIONAL METHODOLOGY

The calculational methodology used in the preliminary shielding design is described in detail in Ref. [1]. Basically, two series of MCNP [2] calculations were performed. The first was a coupled electron-photon calculation with the 20-MeV electron source impinging on the graphite region of the beam stop. From this study, the required thickness of graphite was determined. Additionally, an electron-induced photon source was generated for use in the second series of calculations.

This second series employed MCNP in a photon-only mode. Calculations were made to various locations and the resulting photon doses were determined. From these calculations, the dimensions of the tungsten in the beam stop were fixed.

Therefore, the preliminary shielding design was based only on calculated photon doses. Subsequently, we desired to calculate neutron doses resulting from photon-induced neutrons. Although there has been a demonstration of the capability to adapt MCNP to do such calculations, [3] the production version of MCNP does not model photonuclear reactions.

We used MCNP to estimate the photon-induced neutron doses at DARHT by modifying the second series of calculations described above and by adding a third series of calculations.

The second series of calculations were still photon transport only, however, we modified them to obtain the magnitude of the photon-induced neutron source. This was accomplished by multiplying the calculated photon fluence in subdivided regions of the tungsten by the photoneutron production cross section for
tungsten (using the DE/DF feature of MCNP). Scaling this result by tungsten atom density, cell volume, and photon source strength gives a spatial-dependent neutron production rate in the beam stop. This photon multiplier procedure is conservative due to the photon fluence not being depleted by photoneutron production; however depletion is small due to the magnitude of the production cross sections. A description of the tungsten photoneutron production cross sections used is given in the following section.

The third (new) series of calculations uses the spatial-dependent neutron production rate so determined as a source for coupled neutron-photon MCNP problems. These simulations, however, require knowledge of not only the neutron production rate, but also the energy and angular spectra of the photoneutrons. Once again, Sec. 3 describes how these neutron spectra were obtained. This series of calculations allows us to determine neutron doses (as well as neutron-induced photon doses). Bremsstrahlung photon doses are still determined, as before, from the second series of calculations.

3. MODEL CALCULATIONS OF PHOTONUCLEAR DATA

Radiation transport calculations typically make use of evaluated nuclear reaction cross sections in the Evaluated Nuclear Data File (ENDF-6) format. However, such evaluated data files do not yet exist for photonuclear reactions, nor is MCNP currently able to utilize them. Therefore we have generated a photoneutron source using nuclear model calculations, as described below. A weakness of the approach we have implemented is that correlations are lost between the energy of the photon inducing the photonuclear reaction and the emitted photoneutron energy spectrum. Thus, no account is taken of the fact that the energy spectrum of neutrons produced in photonuclear reactions would become softer, as a function of depth in tungsten, as the photon energy is degraded by the tungsten. Errors introduced by using this method are expected to be small. However, a more sophisticated analysis will require the development of evaluated photonuclear data files and MCNP enhancements.

The photoneutron production cross sections and emission energy spectra in tungsten were determined using the GNASH nuclear model code [4]. This code has recently been extended to calculate photonuclear reactions for incident energies up to 150 MeV [5]. The importance of using nuclear theory to determine photoneutron emission lies in the fact that theory can be used to predict emission spectra in addition to the total photoneutron production. Experimental data are often available for the photoneutron production cross sections [6], but rarely do measurements exist for the emission spectra of the secondary ejectiles.
The GNASH code models the photonuclear reaction as proceeding through the Giant Dipole Resonance, for incident energies below approximately 30 MeV, and through the Quasi-Deuteron mechanism for higher incident energies. The initial interaction excites particle-hole states in the nucleus, from which preequilibrium emission of high-energy ejectiles may occur. The particle-hole excitation may also undergo further nucleon-nucleon interactions until equilibrium is reached, after which particle decay is calculated using Hauser-Feshbach theory. Full details of the models used in the GNASH calculations are provided in Ref. [5].

The calculated photoneutron production cross section is shown in Fig. 2a as a function of the incident photon energy, compared to experimental data for elemental tungsten [6, 7]. The agreement with the experimental data is seen to be good, which is important for two reasons: firstly, it is important to accurately describe the magnitude of photoneutron production and its dependence on incident energy; secondly, an accurate description of the photoneutron production cross section provides indirect support for the accuracy of the calculated photoneutron energy spectra. This is because the shape of the energy spectrum of the first photoneutron ejectile, by energy balance, effects the energy available for subsequent neutron emission — and if the multiplicity for photoneutron emission is correctly calculated, one can have some confidence in the calculated emission spectra shapes.

In order to calculate an energy-dependent neutron source due to photonuclear reactions in tungsten, we compute a photoneutron source spectrum by folding calculated photoneutron spectra over the bremsstrahlung photon spectrum within the tungsten. Figure 2b shows typical calculated photoneutron emission (angle-integrated) spectra for incident photon energies of 10, 12, 14, 16, and 18 MeV. (The integral of each of these spectra over emission energies equals the corresponding photoneutron production cross section shown in Fig. 2a.) It is evident that the magnitude of these spectra is greatest for incident energies of 14-16 MeV, which is the energy regime of the maximum of the Giant Dipole Resonance (GDR). Their shape comes from the Hauser-Feshbach and preequilibrium calculations: at the lower emission energies the shape is that of a typical evaporation spectrum, and the high-energy tail is due to preequilibrium ejectiles. The individual photoneutron emission spectra shown in Fig. 2b are then weighted by the bremsstrahlung spectrum shape (Fig. 3) to produce the thick solid line in Fig. 2b. While the bremsstrahlung spectrum weights the lower photon energies more strongly, the photonuclear reaction mechanism weights higher photon energies in the GDR regime, as seen in the production cross section in Fig. 2a. This averaged neutron spectrum is then renormalized to unity to give a probability energy distribution, and is used, along with the calculated photoneutron production cross section, to provide a neutron source for the subsequent MCNP transport calculations.

The photoneutron source is assumed to be isotropic. For lighter target nuclei, a dipole-shaped angular
distribution (peaked at 90\(^\circ\)) often occurs, and at higher incident energies (photons above approximately 30 MeV) a forward-peaked angular distribution is observed [5, 8]. However, at the energies studied in this work, isotropy is a good approximation for the photoneutrons produced in tungsten.

4. RESULTS

4.1 PHOTONEUTRON DOSE FOR ORIGINAL BEAM-STOP DESIGN

Applying the enhanced calculational methodology described in Sec. 2 to the original beam stop design [1], the annual neutron+(n,\(\gamma\)) dose from transport through the tungsten was calculated to be 412 mrem on the beamline at minimum worker distance from the beam stop (on the beamline just outside the steel cone). This value is a factor of nine greater than the annual bremsstrahlung photon dose of 46 mrem calculated for the original design. This unexpected high photoneutron dose prompted reevaluation of the shielding design.
4.2 DOSE CALCULATIONS FOR MODIFYING BEAM STOP TO ATTENUATE PHOTONEUTRONS

Two primary parameter changes have been made to the original beam-stop design basis: (1) increase in beam current from 3.0 kA to 4.0 kA, and (2) replacement of tungsten powder with higher density tungsten alloy (90 wt% W, 6 wt% Ni, and 4 wt% Cu). The first change by itself raised the total annual dose from 458 mrem to 612 mrem. The second change was prompted by fabrication of tungsten alloy being easier than encapsulating tungsten powder. These two changes along with the original design basis gave the present design basis of (1) electron pulse parameters of 20-MeV energy, 4.0-kA current, and 60-ns period, (2) 5000 annual pulses per accelerator with beam stop engaged, (3) nearly all beam electrons and their progeny electrons to be stopped in graphite, (4) tungsten alloy to be used for attenuation of bremsstrahlung photons, (4) workers present at highest dose locations in occupied areas during accelerator pulsing with beam stop engaged, and (5) doses to individual workers in occupied areas to be less than 500 mrem per year and as low as reasonably achievable (ALARA) [9].

Two beam stop modification options, (1) adding borated hydrogenous material to the downstream end of the tungsten alloy or (2) lengthening the tungsten alloy, were evaluated for attenuating the additional dose due to direct photoneutron transmission down the beamline. The selected hydrogenous material was a boro-silicone product manufactured by Reactor Experiments, Inc. This product was selected for its higher temperature limit (400°F) because the accelerator may occasionally be pulsed with sufficient frequency and duration to cause high beam-stop temperatures. However, the higher temperature limit comes at the expense of lower hydrogen density (two thirds of that of water) than exists in materials with lower temperature limits.

Both bremsstrahlung photon and coupled neutron-photon transport calculations were performed with MCNP to compare the two options for attenuating the additional dose, using the calculational model shown in Fig. 4. Photoneutron production was considered only from tungsten, whose photoneutron cross section is significantly larger than that for the other elements in the beam stop. All doses were calculated as effective dose equivalent, incorporating the ANSI/ANS-1991 fluence-to-dose conversion factors [10]. Dose at the indicated tally location is maximum in the area occupied during accelerator pulsing. The energy spectra of the photon source used in the calculations, shown in Fig. 3, were generated in the original beam-stop design by tallying photons emerging from the whole outside surface of the graphite. The spectra tallied in this manner were collapsed into a point source, preserving the angle and energy dependence, for photon transport calculations in the tungsten to determine photon dose and photoneutron production. Point representation of the photon source at the indicated location in Fig. 4 is conservative because it maximizes neutron production and collided photon and neutron dose contributions while not significantly changing uncollided contributions. The major non-conservative feature of the calculational model is neglect of scattering from the wall of the beamline penetration in the bullnose. The judgment was made that the beam stop is far enough away from the penetration for the wall-scattered dose contribution to be small relative to the non-scattered contribution.

The spatial distribution of photoneutron production in tungsten alloy, depicted in Fig. 5, was calculated in the manner prescribed in Sec. 2. Production falls off rapidly axially due to attenuation of the photons' energy to below its 7.5-MeV tungsten photonuclear threshold. It occurs mostly in the innermost radial interval, which at smaller axial distances is largely an artifact of the point spatial representation of the photon source. The production spatial distribution, along with the energy spectrum in Fig. 2b and isotropic emission, defines the source for the neutron transport calculations.

The calculated annual doses, listed in Table 1, indicate that varying boro-silicone length for constant total length of tungsten alloy plus boro-silicone length has little effect on total dose. Thus, both beam-stop modification options, tungsten-alloy lengthening and boro-silicone addition, give approximately the same reduction in total dose. This conclusion is surprising in view of the large ratio of neutron+(n,γ) dose to bremsstrahlung photon dose for tungsten alloy only and of the ratio increasing rapidly with tungsten-alloy length. Similarity in total dose reduction is a consequence of the relative magnitudes of photon and neutron attenuations for the two materials: photon attenuation being high for tungsten and small for boro-silicone and neutron attenuation being high for the hydrogenous boro-silicone and moderate for tungsten alloy due to inelastic scattering by tungsten. The gain in neutron attenuation from an increase in boro-silicone length is offset by the losses in photon and neutron attenuations from the consequent decrease in tungsten-alloy length. Because of the total-dose reduction similarity of the two modification options, the choice of options was based on other considerations. The tungsten-alloy lengthening option was selected because it permits
Figure 4: Model for calculating photon and neutron dose transmission down the beamline.

Figure 5: Normalized spatial distribution of photoneutron production in tungsten alloy.
<table>
<thead>
<tr>
<th>Length of shield regions (cm)</th>
<th>Annual Dose (mrem)</th>
<th>Photon</th>
<th>Neutron (n,γ)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Tungsten Alloy Boro-silicone</td>
<td>23 23 0</td>
<td>42.0 ±0.20%</td>
<td>437±0.22%</td>
<td>1.53±1.05%</td>
</tr>
<tr>
<td>23 20 3</td>
<td>251.0±0.06%</td>
<td>371±0.10%</td>
<td>5.43±0.23%</td>
<td>627±0.06%</td>
</tr>
<tr>
<td>27 27 0</td>
<td>3.18±0.28%</td>
<td>164±0.32%</td>
<td>0.671±1.16%</td>
<td>168±0.31%</td>
</tr>
<tr>
<td>27 23 4</td>
<td>34.1±0.06%</td>
<td>130±0.47%</td>
<td>3.13±0.79%</td>
<td>167±0.37%</td>
</tr>
<tr>
<td>30 30 0</td>
<td>0.463±0.14%</td>
<td>77.8±0.56%</td>
<td>0.370±2.00%</td>
<td>78.6±0.55%</td>
</tr>
<tr>
<td>30 27 3</td>
<td>2.72±0.15%</td>
<td>63.8±0.38%</td>
<td>1.29±0.71%</td>
<td>67.8±0.36%</td>
</tr>
<tr>
<td>30 23 7</td>
<td>29.2±0.12%</td>
<td>53.3±0.69%</td>
<td>3.19±0.69%</td>
<td>85.7±0.43%</td>
</tr>
</tbody>
</table>

Table 1: Dose versus length of tungsten alloy and boro-silicone regions of beam stop, for 1 accelerator. Annual dose values listed as sample mean ± relative error, where the relative error is one standard deviation of the mean divided by the sample mean. The heading "(n,γ)" stands for the neutron-induced photon dose.

accelerator pulsing with beam stop temperatures above 400°F and avoids fabrication costs and difficulties associated with attaching boro-silicone to the tungsten alloy.

A length of 30 cm was selected for the tungsten-alloy. As observed from Table 1, this length corresponds to an annual total dose of 78.6 mrem from a single accelerator. Since this dose is the maximum value in the occupancy area during accelerator pulsing, twice its value exceeds the dose from both accelerators at any location in the occupancy area. Hence, 157 mrem is an upper bound on the annual dose from both accelerators. The following argument is offered for the latter dose being in the neighborhood of ALARA. As observed from Table 1, the single-accelerator total doses for lengths of 23 and 27 cm are 481 mrem and 168 mrem, respectively, and therefore the upper-bound two-accelerator doses are 962 mrem and 336 mrem, respectively. Minimum length is set by making the upper-bound two-accelerator dose equal to the 500-mrem annual design dose. Interpolating at 500 mrem gives an approximate minimum length of 26 cm. Lengthening tungsten alloy from 26 cm to 30 cm reduces the single-accelerator dose by 171 mrem and therefore the upper-bound two-accelerator dose by 343 mrem. This reduction is considered justified because the material cost of the 4-cm increment of tungsten alloy is a very small fraction of the overall design and fabrication cost of the beam stop.

The tungsten alloy provides little attenuation of neutrons emitted laterally relative to the beamline, but the 5-ft thick bullnose concrete wall provides considerable attenuation. To verify attenuation sufficiency of the bullnose wall, an upper bound on the neutron+(n,γ) dose transmitted through the bullnose wall was calculated with a simple model consisting of a 5-ft thick concrete spherical shell with a 100-cm inside radius and photoneutron emission located at the origin as a point source. The annual neutron+(n,γ) dose was calculated to be less than 5 mrem, which is considered negligible.

There was no attempt to calculate the scattered dose contribution from neutrons being scattered from the walls of the Accelerator Hall to the beamline penetration in the bullnose and then down the penetration to the dose location just outside the cone. It is suspected that this dose contribution is small relative to direct transmission through the beam stop, but this suspicion should be verified by transport calculations.

5. SUMMARY

In summary, an enhanced calculational method has been applied to the shielding design and analysis of beam stops at the DARHT electron linear accelerator facility. Sophisticated nuclear data models have been used to generate photoneutron production cross sections and spectra for tungsten. These data have been incorporated into a sequence of MCNP calculations to determine photon and neutron doses. Results using a preliminary beam stop design indicated neutron doses that were a factor of 9 greater than the bremsstrahlung photon dose. Since these doses were unacceptably high, a redesign of the beam stop ensued. Calculations using this model predict acceptable worker doses, consistent with the ALARA philosophy.

Future shielding analyses dependent upon accurate modeling of photonuclear processes could be improved further through the use of evaluated photonuclear data libraries and the capability to utilize them directly in MCNP.
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References


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