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TITLE: SHIELDING CONCERNS AT A SPALLATION SOURCE

AUTHOR(S): Gary J. Russell, Harold Robinson, Gail L. Legate, and Richard Woods, LANSCE

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

# Shielding concerns at a spallation source

*G. J. Russell, H. Robinson, G. L. Legate, and R. Woods*
Los Alamos Neutron Scattering Center
Los Alamos, New Mexico 87545 U.S.A.

ABSTRACT: Neutrons produced by 800-MeV proton reactions at the Los Alamos Neutron Scattering Center spallation neutron source cause a variety of challenging shielding problems. We identify several characteristics distinctly different from reactor shielding and compute the dose attenuation through an infinite slab/shield composed of iron (100 cm) and borated polyethylene (15 cm). Our calculations show that (for an incident spallation spectrum characteristic of neutrons leaking from a tungsten target at 90°) the dose through the shield is a complex mixture of neutrons and gamma rays. High-energy (> 20 MeV) neutron production from the target is ≅5% of the total, yet causes ≅68% of the dose at the shield surface. Primary low-energy (< 20 MeV) neutrons from the target contribute negligibly (≅0.5%) to the dose at the shield surface yet cause gamma rays, which contribute ≅31% to the total dose at the shield surface. Low-energy neutrons from spallation reactions behave similarly to neutrons with a fission spectrum distribution.

## 1. Introduction

The Los Alamos Neutron Scattering Center (LANSCE)[1] uses 800-MeV protons from the Clinton P. Anderson Meson Physics Facility (LAMPF)[2] to produce neutrons for basic materials science and nuclear physics research.[3] Because it is a spallation source, LANSCE produces neutrons covering about 14 decades in energy (sub-meV to 800 MeV) and experiences shielding problems common to all such sources, but different from those of fission sources. We discuss the principles of spallation source shielding through a detailed calculation of a geometrically simple shield, and, using the same example, contrast spallation source spectrum problems with a fission spectrum neutron source.

At Los Alamos, we have a powerful Monte Carlo computational capability applicable to spallation neutron source design.[4] We have used this computational tool for various LANSCE shield designs including: a) proton beam line; b) target, and c) neutron beam line and beam stop

## 2. Spallation Neutron Source Shielding Issues

### 2.1 High-Energy Neutrons

For spallation reactions, we divide energy into two regions: low-energy (< 20 MeV) and high-energy (> 20 MeV). Low-energy neutrons are basically produced in three ways: a) directly from intranuclear cascade processes; b) by evaporation; and c) from fission. These low-energy neutrons are emitted "more-or-less" isotropically and cause shielding problems like those for fission reactors. High-energy neutrons, resulting from nucleon-nucleon reactions, have a strong angular dependence and cause unique shielding problems. At 0° to the proton beam, high-energy neutrons can have energies up to the incident proton energy. As the angle with respect to the proton beam increases, the high-energy neutron spectrum softens considerably. ***The presence of these high-energy neutrons and their strong angle-dependence are two reasons why shielding a spallation source is quite different than shielding a reactor source.***

### 2.2 Thin and Thick Targets

On its way to LANSCE, the LAMPF proton beam can strike a variety of objects (targets), ranging from proton beam transport pipe and magnets to the LANSCE target itself. Each of these "sources" presents different neutron spectrum and intensity to an adjacent shield, causing the effectiveness of the shield to be significantly dependent on the spill point.

For 800-MeV protons incident on stainless steel (one atom thick), the calculated double differential (energy and angle) neutron production spectra are illustrated in Fig. 1. One can see the strong angular dependence of the high-energy neutrons, but the low-energy neutrons are nearly isotropic.

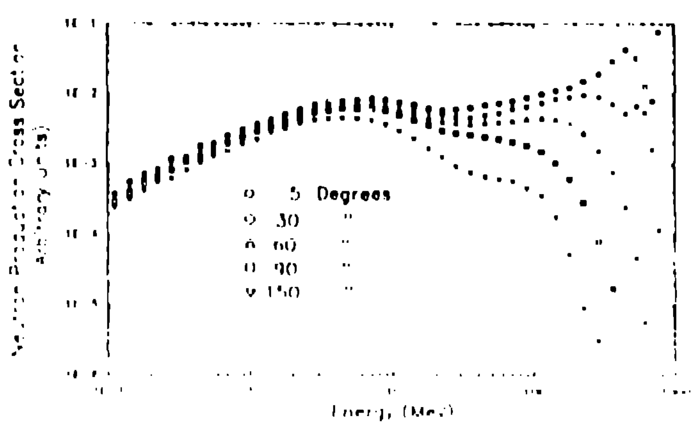


Fig. 1 Calculated neutron production spectra for 800 MeV protons on stainless steel

For a thick target, both the shape and magnitude of the leakage neutron spectrum and the ratio of high-energy to low-energy neutrons can change dramatically from one target to another. The target itself "moderates", "self-shields", and "amplifies" the neutrons produced. The neutron spectrum (integrated over all angles) from a mild steel thick-target (50-cm-thick and 20-cm-diam) is shown in Fig. 2. In contrast, the equivalent spectrum from a thin-target (0.3-cm-thick and 20-cm-diam) of the same material is also shown in Fig.2. The dramatic difference (both in intensity and energy) between the two leakage spectra is evident. Figure 2 also gives the neutron spectrum from a 30-cm-thick and 10-cm-diam tungsten target (a typical LANSCE target). For this target, low-energy neutrons account for 95.3% of the total neutron production, and high-energy neutrons 4.7%.

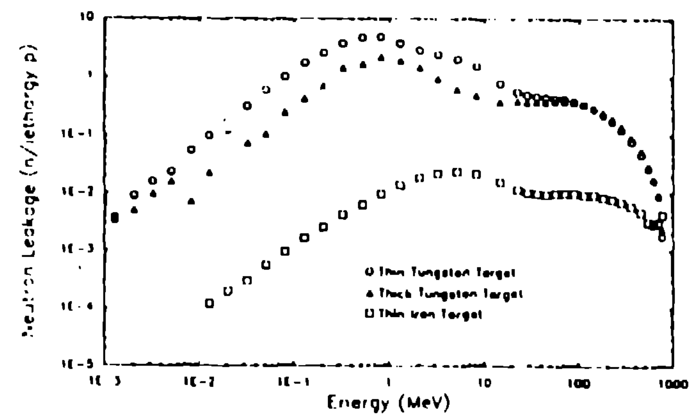


Fig. 2. Calculated neutron yields from thin and thick targets for 800-MeV protons.

***This is another reason why shielding a spallation source is more complex than shielding a reactor source: different leakage neutron spectra are produced depending upon whether the proton beam strikes a thin or thick target; neutron production is also material dependent.***

## 2.3 Thin and Thick Shields

In a particular shielding application, the distinction between "thin" and "thick" shields can be important and may affect the applicability of simplistic formalisms for estimating the neutron doses at the shield surface. If primary low energy neutrons contribute significantly (either directly or by producing gamma-rays) to the total dose at the outer shield surface, we define the shield to be thin. Two other components contributing to the neutron dose are: a) high energy neutrons, and b) secondary low energy (evaporation) neutrons produced by high energy neutron interactions in the shield itself. These secondary low energy neutrons are distributed throughout the shield, and arise from the disappearance (attenuation) of high energy neutrons as they "penetrate" the shield. Both the high-energy and secondary low-energy neutrons produce gamma-rays, which also contribute to the total dose at the shield surface.

***This is another complexity arising in shielding a spallation source relative to a reactor source: when a shield attenuates high-energy neutrons, low-energy neutrons are produced, i.e., the shield itself becomes a neutron source. Depending on the application, the high-energy neutrons plus progeny may dominate the dose at a shield surface.***

## 2.4 Flux-to-Dose Conversion Factors

***Another shielding complication has to do with flux-to-dose conversion factors for neutrons and gamma-rays.*** The flux required to produce one mrem per hour of dose is energy dependent as shown in Fig. 3.[5] It takes a flux of ≅5.5 n/cm$^2$-s of 100 MeV neutrons to produce 1 mrem/hr of dose, compared to a flux of ≅220 n/cm$^2$-s of 1 eV neutrons. At 1 MeV, it takes ≅60 times more gamma-ray flux than neutron flux to produce 1 mrem/hr. Thus, the energies of neutrons and gamma rays leaking through a shield can have profound effects on the total dose at the shield surface. The rapid change of the flux-to-dose conversion factors can cause significant errors in dose estimation, if the spectra are not well known.

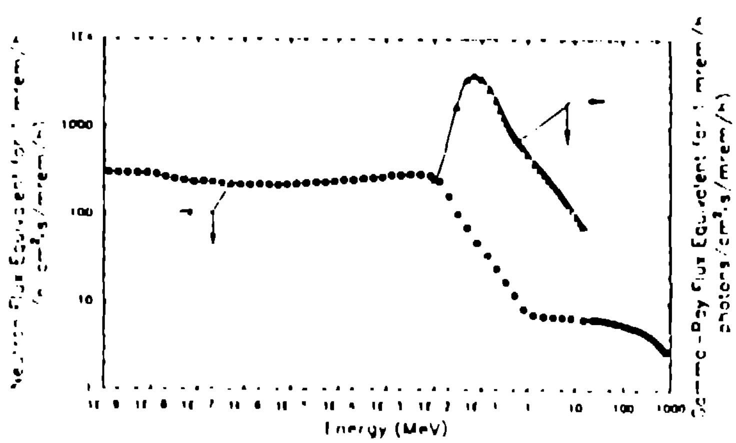


Fig. 3. Neutron and gamma ray flux to dose conversions.

## 2.5 Flux and Dose

Neutron and gamma-ray fluxes are related to the physical number of neutrons and photons, respectively. Detectors used in LANSCE scientific instruments respond to flux; unwanted neutrons and gamma rays can cause background problems. However, these detectors are inside instrument shielding and their response includes the effects of the instrument shield on the incident neutrons and gamma rays. Dose, on the other hand, is also relevant because it is related to human biological response to radiation.

Because flux-to-dose conversion factors are energy dependent, flux and dose are attenuated differently by a shield. When a shield "attenuates" low-energy neutrons, it moderates (slows down) the neutrons within the shield (decreasing the neutron dose) and captures neutrons and produces gamma rays. Whether attenuation of flux or dose dominates the criteria for a shield design depends on the particular shield application. Flux is important when shielding detectors; dose is important when shielding people.

## 2.6 Gamma Rays

Biologically, we need to concern ourselves with the total dose (neutron plus gamma rays) at the shield surface. Detectors also respond to both neutrons and gamma-rays, therefore, gamma rays must be accounted for when designing detector shielding. All low-energy neutrons that do not undergo particle reactions, such as (n,xn), (n,p), etc., with nuclei are eventually captured in the shield or leak from it. In addition to capture and inelastic scattering gamma rays from low-energy neutron interactions, additional gamma rays are produced from the spallation process itself. These latter gamma rays may or may not be important in a particular shield application.

***We have identified another difference between spallation and fission source shielding to be an additional gamma-ray source from the spallation process itself.*** Depending on the application, one may need to account for all three neutron components (primary low-energy, primary high-energy, and secondary low-energy) plus gamma rays when designing a shield for a spallation neutron source.

## 2.7 The Calculated High-Energy Neutron Source

A complication in using calculated high-energy neutron specra in shield design is the potential that the computed angle-dependent spectra are incorrect both in magnitude and shape compared to measured results. There have been both excellent agreement and major disagreement between measured and calculated double-differential high energy neutron production. In general, calculations underpredict measured cross section values. Until these problems are resolved, one may (in some shield calculations) multiply the calculated high energy neutron production by some factor to account for these uncertainties. Such a bias may be consequential when deciding the relative importance between primary and secondary low energy neutrons in a particular shield design.

## 3. LANSCE Shielding Concerns

LANSCE shielding issues can be broadly summarized as follows: a) adequate definition of the neutron source; b) proton beam line; c) service cell; d) target/moderator/reflector; e) target area; f) neutron collimator; g) longitudinal neutron beam line; h) transverse neutron beam line; i) neutron instrument; and j) neutron beam stop. We have used our Monte Carlo code package to address many of these shielding concerns.

## 4. Calculations for an Infinite Iron/Polyethylene Slab Shield

### 4.1 Problem Definition

To help understand the complexities of spallation source shielding, we chose a geometrically simple shield model (infinite slab). The shield (see Fig. 4) was composed of 100 cm of iron (mild steel) followed by 15 cm of borated polyethylene (5 wt% natural boron) with a monodirectional point source of neutrons incident normal to the iron shield surface. The attendant neutron and gamma-ray progeny sum to give the total dose at various locations throughout the shield. By primary high-energy gamma rays, we mean those gamma rays produced by high-energy reactions. Secondary low-energy gamma rays result from secondary low-energy neutron interactions. These two gamma-ray components sum to give a segment we call spallation gamma rays. Primary low-energy neutron interactions produce primary low-energy gamma rays. No gamma rays were assmed incident on the shield.

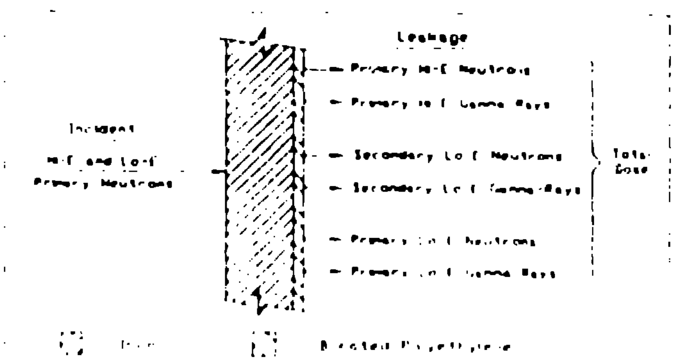


Fig. 4 Infinite slab shield mockup geometry

A unit source of spallation neutrons calculated at 90° to the axis of a 10-cm-diam by 30-cm-thick tungsten target (see Fig. 5) was used as the primary incident spallation spectrum. In addition, we used a unit Watt fission spectrum, which is also depicted in Fig. 5.

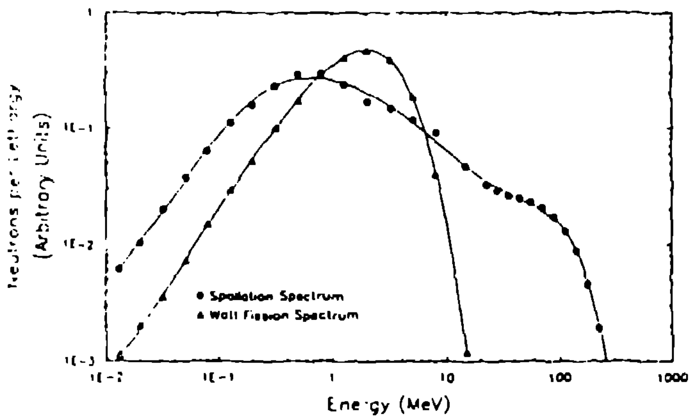


Fig. 5. Unit source spectra used in shield calculations.

## 4.2 Results

For the tungsten spallation neutron-spectrum in Fig. 5, primary low-energy neutrons account for 95.3% of the total neutron leakage from the target; primary high-energy neutrons account for 4.7%. Using this spallation neutron spectrum, we show calculated neutron and gamma-ray doses throughout the shield and at the shield surfaces in Figs. 6 and 7. Secondary low-energy neutron production is depicted in Fig. 6.

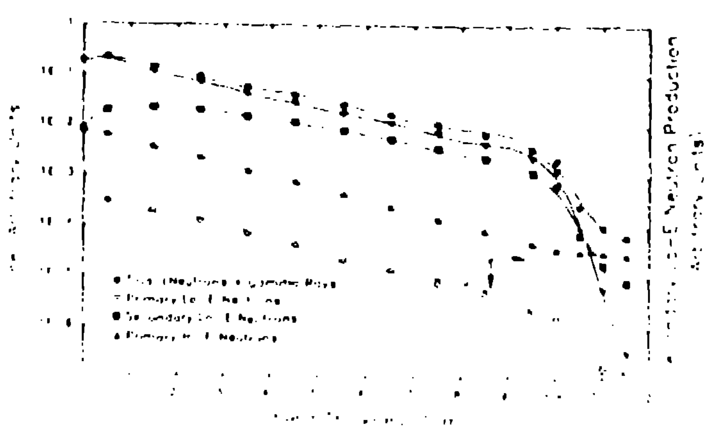

Fig. 6 Relative neutron and total dose through the iron/polyethylene shield for an incident spallation spectrum

In Fig. 6, you can see the buildup of the secondary low-energy neutron dose as the high-energy neutrons are attenuated by the shield. The high-energy neutrons are attenuated very little by the polyethylene; secondary low-energy neutron production falls as well. At the outer surfaces of the iron shield low-energy neutron doses fall rapidly, due to neutron capture, enhanced moderation, and lack of isotropic reflection. The same arguments hold for the secondary low-energy neutrons; in addition, the source of these neutrons decreases rapidly. The doses at the shield surface are detailed in Table I.

Table I. Doses at the Surface of a $Fe/CH_2$ (5% B) 100/15 cm Shield

| Dose Type | | % of Total Dose | % of Incident Neutrons (W @ 90°) |
|---|---|---|---|
| Primary Hi-E Neutrons | | 43.0 | 4.7 |
| Secondary Lo-E Neutrons | | 12.8 | |
| Gamma-Rays from Primary Hi-E and Secondary Lo-E Neutrons | | 11.4 | |
| | Subtotal | 68.1 | |
| Primary Lo-E Neutrons | | 0.5 | 95.3 |
| Gamma-Rays from Primary Lo-E Neutrons | | 31.4 | |
| | Subtotal | 31.9 | |
| | Total | 100.0 | |

The gamma-ray dose is further illustrated in Fig. 7. Gamma-ray production starts to increase at the iron/polyethylene interface and continues into the first part of the polyethylene. This increase is caused by the removal of neutrons via neutron capture and inelastic processes showing why, for some materials, it is important to account for gamma rays as well as neutrons in shield designs.

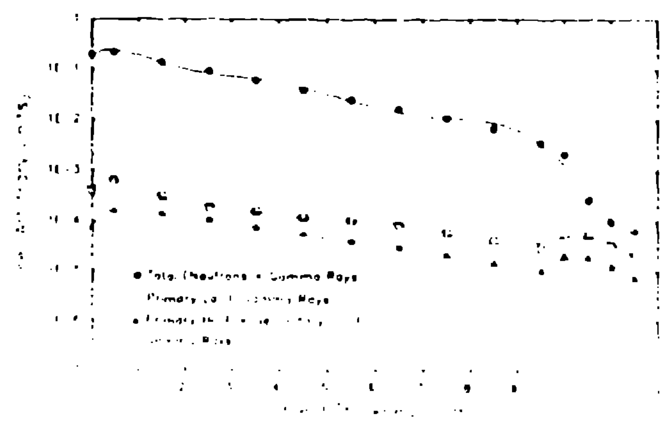

Fig. 7 Relative gamma ray and total dose through the iron/polyethylene shield for an incident spallation spectrum

The effects of a unit Watt fission spectrum on neutron and gamma-ray doses for the same shield are shown in Fig. 8. A similar dose attenuation is observed here as for the primary low-energy neutrons in Fig. 6. At the shield surface in Fig. 8, the dose is essentially all caused by gamma rays. The complexity of spallation neutron source shielding compared to fission source shielding is seen in comparing Figs. 6 and 8.

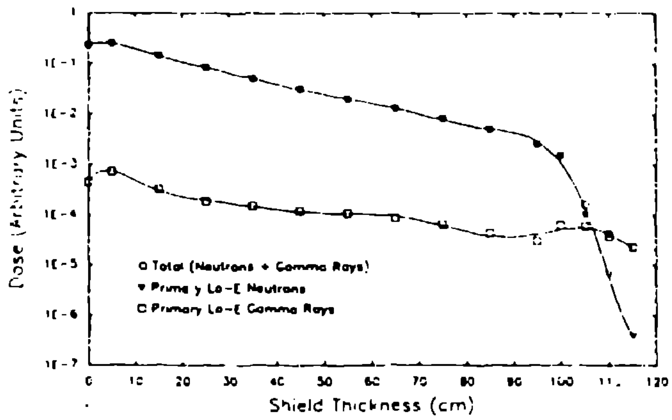


Fig. 8. Relative neutron and gamma-ray dose through the iron/polyethylene shield for an incident Watt fission spectrum.

Shielding calculations for spherical shields are underway.[6] One might expect spherical shields to behave neutronically different than infinite slab shields. One reason is that, for the infinite slab shield discussed here, ≅79% of the primary low-energy neutrons incident on the inner shield surface are removed by back scattering and do not contribute to the dose at the outer shield surface. For a spherical shield, these "albedo" neutrons are incident on the opposite side of the shield, and, consequently, have repeated opportunities to contribute to the dose at the outer shield surface. Thus, depending on shield particulars, primary low-energy neutrons can contribute significantly to the dose at the outer surface of a spherical shield.

## 5. Conclusions

A spallation neutron source presents more difficult shielding problems than those posed by a reactor source. We demonstrated the basic differences between the two and showed the increased complexity of spallation-source shielding through a calculation for an iron/polyethylene shield. This example illustrates basic shielding principles for a spallation source; the particulars depend on the specific shielding problem. Shielding a fission source is similar to shielding the primary low energy neutrons at a spallation source. The incident neutron spectrum and the shield geometry, composition, and thickness determine whether high-energy or low-energy neutrons dominate the neutron dose at the shield surface, and the relative importance of gamma rays.

## 6. Acknowledgements

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