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Tailoring the Neutron Spectrum from a 14-MeV Neutron Generator to Approximate a Spontaneous-Fission Spectrum

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Abstract. Many applications of neutrons for non-invasive measurements began with isotopic sources such as AmBe or Cf-252. Political factors have rendered AmBe undesirable in the United States and other countries, and the supply of Cf-252 is limited and significantly increasing in price every few years. Compact and low-power deuterium-tritium (DT) electronic neutron generators can often provide sufficient flux, but the 14-MeV neutron spectrum is much more energetic (harder) than an isotopic neutron source. A series of MCNP simulations was run to examine the extent to which the 14-MeV DT neutron spectrum could be softened through the use of high-Z and low-Z materials. Some potential concepts of operation require a portable neutron generator system, so the additional weight of extra materials is also a trade-off parameter. Using a reference distance of 30 cm from the source, the average neutron energy can be lowered to be less than that of either AmBe or Cf-252, while obtaining an increase in flux at the reference distance compared to a bare neutron generator. This paper discusses the types and amounts of materials used, the resulting neutron spectra, neutron flux levels, and associated photon production.

Keywords: Neutron Spectrum, Neutron Generator, Spontaneous Fission Source, AmBe, PuBe
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INTRODUCTION

The goal of this modeling exercise was to estimate to what degree it would be practical to alter the neutron spectrum from a 14-MeV neutron generator, lowering the mean neutron energy to approximate radioisotope neutron sources. The flux-weighted average energy of an AmBe or PuBe source is about 4.2 MeV [1] and for a spontaneous fission source it is about 2 MeV [2], so the model was used to evaluate effectiveness of various sequences and amounts of high-Z (HZ) and low-Z (LZ) materials to approximate the softer neutron spectrum from isotopic sources. Internal structures of the generator itself would influence these results somewhat, more in terms of spatial distribution than in spectral modification. It is important to include some of the construction features of the neutron generator, such as the accelerator housing wall to achieve reasonable fidelity with a real-world measurement.

Acknowledging this, the modeling effort described here is roughly based on the Thermo Fisher Scientific MP 320 neutron generator [3]. This generator has limited space on its interior to host an internal neutron moderating material [4] but is readily adaptable with predrilled mounting holes to support external neutron breeding, reflecting, and moderating materials.

The MCNP [5] model for this problem as illustrated in Fig. 1 is a cylinder of air 80 cm in diameter and 60 cm tall. At the center of this volume there is a 14 MeV neutron source. The energy distribution of the neutron source is that of the Gaussian distribution for DT fusion built into MCNP. For the low-Z materials, the S(α,β) thermal treatment was included via the MT card, although variance reduction techniques were not used. The neutron generator model was very simple: a point source on axis and at the midpoint, of a 10.4-cm diameter by 60-cm long cylindrical aluminum housing. Aluminum is a common material for the housing of a neutron generator, and the wall thickness was also typical at 0.5 cm.

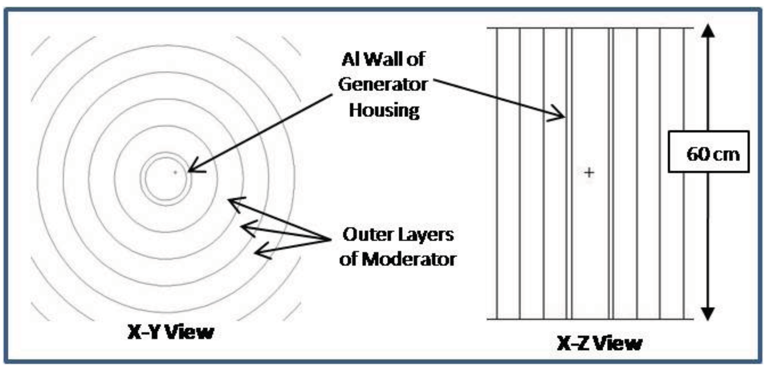

FIGURE 1. Cylindrical geometry of MCNP model: 14 MeV neutron source centered in an aluminum cylinder, with outer layers of moderator material.

On the interior of the generator was a concentric cylindrical cell, with a thickness of 2 cm. The material choice for this cell is to be either sulfur hexafluoride gas, the normal dielectric gas inside the generator, or some other material with the goal of altering the neutron spectrum. On the exterior of the housing, there was a series of concentric cylinders, each 2.5 cm thick. These cells of concentric cylinders were initially all filled with air. To reflect the addition of HZ or LZ material in subsequent runs, the cells were changed, starting at the interior and working out, from air to the LZ or HZ material.

The problem included a variety of neutron and photon ring detectors, as well as multiple segmented surface tallies for neutrons and photons. The main tally of interest for this paper is a surface flux tally 30 cm from the neutron origination point (where the DT ion beam hits the target). The tally was segmented to look only at flux between $\pm$7.5 cm of the target plane. Various amounts and combinations of materials would fit within 30 cm of the sources, allowing comparisons at a reference distance for flux levels and spectrum.

MODELING APPROACH

The general flow of the analysis was to look first at HZ materials (tungsten, bismuth, and iron) in several thicknesses. Figure 2 shows how the (n,2n) and (n,3n) cross sections [6] decline rapidly below 10 MeV. In order to benefit from neutron multiplication, it was logical to put these materials closest to where the neutrons have their highest energy. The other benefits were at least some gamma shielding by outer layers of material, and in terms of weight, it is much more efficient to add 1 cm of dense material near the generator than to add it farther from the generator. The various thicknesses of HZ materials are each evaluated for their ability to incrementally increase flux.

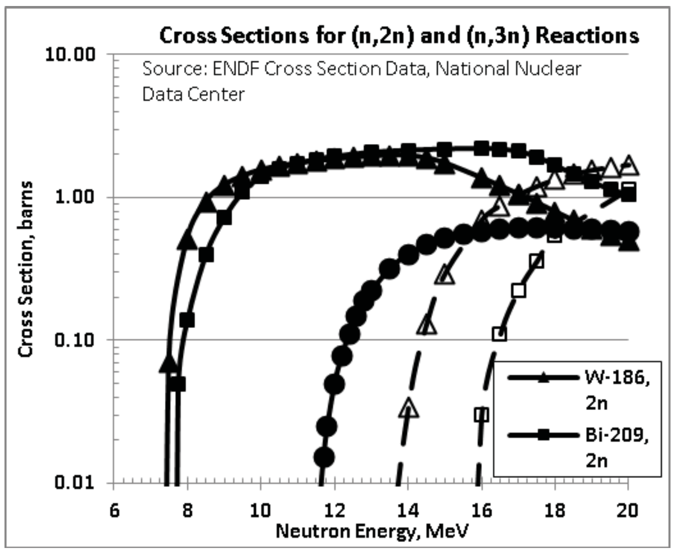

FIGURE 2. Cross section for (n,2n) and (n,3n) reactions in tungsten, bismuth, and iron.

After determining a more or less optimal thickness of HZ material, then LZ materials (polyethylene, Teflon, water, a 50-50 mix of light- and heavy-water, and heavy water) were put into the next available layers. As a minor perturbation, the first 2 cm of HZ material was relocated to the interior of the housing, as a possible configuration on some neutron generators. The remaining HZ material was on the exterior of the housing. The thicknesses of LZ material were evaluated in terms of lowering the average energy of the neutron spectrum without imposing undue penalties on lowering the total neutron flux.

NEUTRON SPECTRUM & INTENSITY

Table 1 provides a summary of the cases run to initially evaluate HZ materials. The fluxes reported are per-particle, normalized fluxes. To change normalized flux into a real flux, it would be multiplied by the output of the generator; a value of

1E+08 n/s is a commonly used benchmark for the yield of portable DT neutron generator.

TABLE 1. Materials in moderator layers for HZ runs and results for use of high-Z materials only, external to neutron generator.

	Bare Neutron Generator	Tungsten				Bismuth				Iron			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Interior	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
Al housing	Al	Al	Al	Al	Al	Al	Al	Al	Al	Al	Al	Al	Al
Layer 1	Air	W	W	W	W	Bi	Bi	Bi	Bi	Fe	Fe	Fe	Fe
Layer 2	Air	Air	W	W	W	Air	Bi	Bi	Bi	Air	Fe	Fe	Fe
Layer 3	Air	Air	Air	W	W	Air	Air	Bi	Bi	Air	Air	Fe	Fe
Layer 4	Air	Air	Air	W	W	Air	Air	Bi	Bi	Air	Air	Fe	Fe
Layer 5	Air	Air	Air	Air	W	Air	Air	Air	Bi	Air	Air	Air	Fe
Layer 6	Air	Air	Air	Air	W	Air	Air	Air	Bi	Air	Air	Air	Fe
Layer 7	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
Layer 8	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air	Air
$\Phi_{total,}$ [1]	8.7E-05	1.3E-04	1.6E-04	1.6E-04	1.3E-04	1.1E-04	1.3E-04	1.6E-04	1.8E-04	1.0E-04	1.1E-04	1.2E-04	1.3E-04
Φ < 3 MeV [1]	1.6E-06	6.9E-05	1.1E-04	1.4E-04	1.2E-04	3.1E-05	5.8E-05	1.0E-04	1.4E-04	3.3E-05	5.7E-05	9.0E-05	1.1E-04
Ratio Φ<3 MeV to ΦTotal	2%	52 %	71 %	86 %	92 %	28 %	45 %	65 %	76 %	32 %	51 %	74 %	86 %
Avg. Energy, MeV	14.1	7.0	4.4	2.3	1.5	9.9	7.6	5.0	3.6	9.5	6.9	3.9	2.4

[1]Units are n/cm^2 per source particle

Referring to Fig. 3, Column 1 illustrates the flux and spectrum at 30 cm, for a bare DT neutron generator, 8.7E-04 n/cm^2, with an average energy of 14 MeV and a spectrum that is essentially all above 12 MeV. If the generator were operating at 1E+08 n/s, the physical flux would be 8.7E+04 n/cm^2/s.

Columns 2-5 in Fig. 3 depict the flux and spectrum for increasing layers of tungsten. Column 2 is the case with 2.5 cm of tungsten, providing a drop in flux-weighted average energy by 50%. Adding another 2.5 cm, for a total of 5 cm of tungsten (Column 3) drops the average energy further and increases the flux in lower energy bins. Going to 10 cm and 15 cm of tungsten (Columns 4 and 5) continues to lower the average energy and soften the spectrum, although going to 15 cm of tungsten lowers the flux at 30 cm.

The same sequence is repeated for bismuth in Columns 6 through 9. There are two main differences with bismuth. The ability to lower average energy per cm of moderator thickness is less than tungsten, and the multiplication from bismuth increases all the way up to 15 cm. Columns 10-13 for iron show that the per-unitthickness ability to lower average energy is somewhere between bismuth and tungsten, although gain in flux at 30 cm is much less than one obtains with the other two materials.

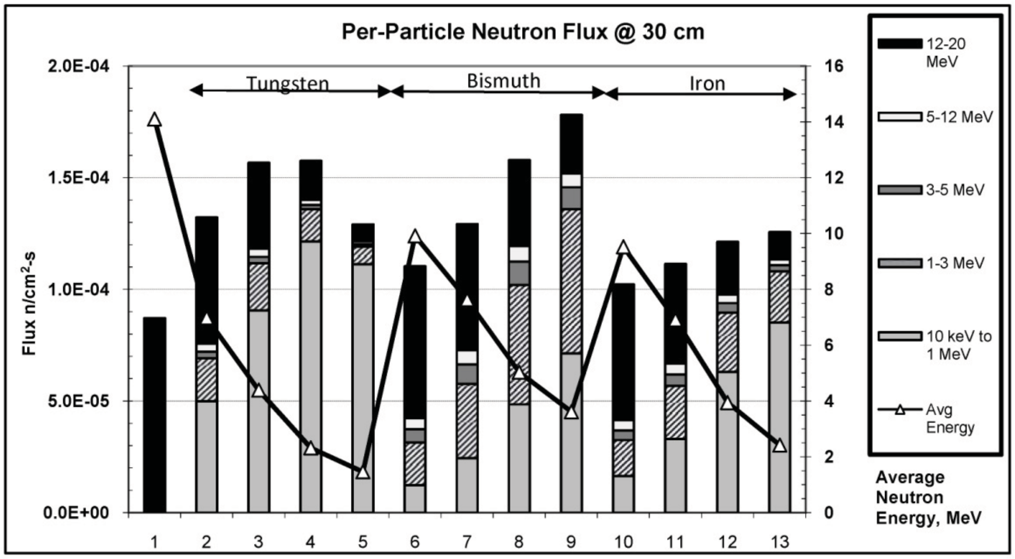

FIGURE 3. Neutron spectra and average energy from layers or tungsten, bismuth or iron, in thicknesses ranging from 2.5 to 15 cm.

Although photon creation is discussed in the next section, at this point it will be noted that the photon/gamma-ray creation from tungsten is significantly higher than from bismuth. For 5 cm of material, tungsten produces about 13 photons per source particle versus about 5 for bismuth. Putting the tungsten first allows the bismuth to shield some of the tungsten gammas. The bismuth continues to lower the average neutron energy and increase the flux at 30 cm. Using 5 cm of tungsten followed by 5 cm of bismuth results is an average energy of 3.1 MeV, closer to the average energy of a fission source.

Moving onto the use of LZ material to further soften the spectrum, 5 LZ materials were examined; the results are shown graphically in Fig. 4. Columns 1 through 5 corresponds polyethylene, Teflon, light water, 50-50 mix of light- and heavy-water, and heavy water, respectively. Figure 4 points out that polyethylene and water impose a significant penalty on total flux at 30 cm, which is due to the high hydrogen content. Teflon and heavy water are preferred for softening the spectrum to an average energy of less than 2 MeV without causing a decrease in flux. Among these two, Teflon would be preferable because it is relatively cheap, plentiful and easy to export if required. The combination of 5 cm each of tungsten and bismuth, followed by 10 cm of Teflon (W-Bi-Teflon) achieves an average energy 1.72 MeV, which is below that of a fission source. Compared to a bare neutron generator, the per-particle flux is about two times higher at 30 cm (1.84E-04), with the following coarse spectrum: 7.7% in 12-20 MeV, 12.8% in 1-12 MeV, 56.7% in 10 to 1000 keV, and 22.8% less than 10 keV.

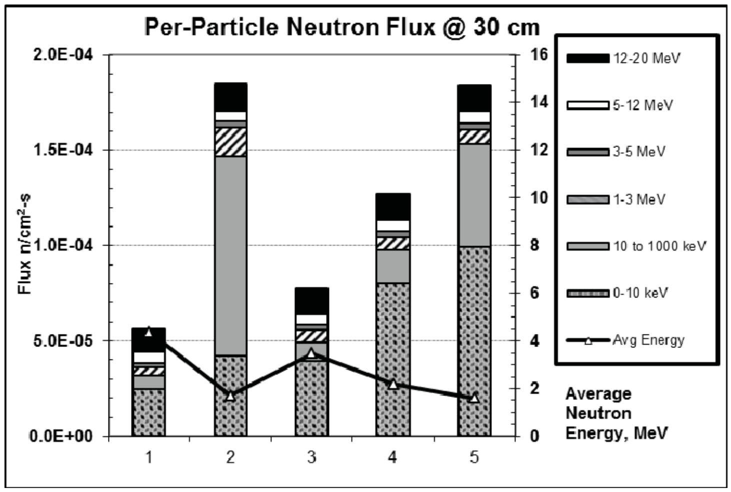

FIGURE 4. Results for Low-Z materials, exterior to 5 cm of tungsten and 5 cm of bismuth.

Up until now, the discussion has been about cases of using the moderator material along the entire 60 cm of the housing length. This makes for a moderator add-on weighing about 550 kg. Next the attention was turned to reducing the moderator weight by shortening it, to look for a minimal amount that could still achieve the desired results of a boost in flux while also lowering the average neutron energy.

Figure 5 illustrates the results of shortening the W-Bi-Teflon moderator length to 40 cm, 30 cm, and 20 cm, while keeping it centered over the source, which corresponds to weights of 367 kg, 275 kg and 184 kg respectively. The average neutron energy reaching the tally surface between $\pm$7.5 cm of the target plane remains almost the same. The significant impact is lower flux at that location. Shortening the moderator assembly to 20 cm still results in significant softening of the spectrum, but the flux decreases to 8.6E-05, which is comparable to total flux from a bare neutron generator.

Keeping the moderator material to a size of $\pm$10 cm of the target plane significantly reduces the weight and keeps the total flux at about the same level as a bare generator. One other possibility to further reduce the weight is to use moderator around half of the generator, although this was not evaluated for the impact on average neutron energy and flux level.

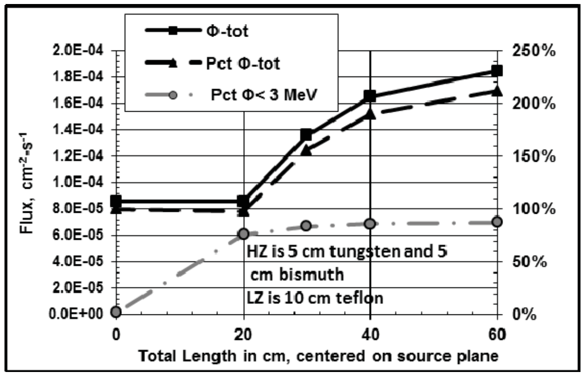

Figure 5. Effect on flux, and flux less than 3 MeV by reducing the length of moderator material, relative to that of a bare neutron generator.

GAMMA SPECTRUM & INTENSITY

The gain in neutron flux and softening of the spectrum come from inelastic neutron interactions with the HZ materials; these reactions lead to photon production. Isotopic sources also produce photons: ^{252}Cf produces ~10 γ/n [7] and AmBe produces ~0.6 γ/n from fission [8]. An AmBe source also produces many lower energy photons from the natural decay of Am; these photons are not associated with neutron production. With HZ material alone (5 cm each of W and Bi), the photon production is 17 γ/n; the additional 10 cm of Teflon brings the total to 22 γ/n. Figure 6 compares the AmBe and PuBe photon spectra above 200 keV from Ref. [1] to the photon spectra calculated for the moderated neutron generator. The data were normalized for equivalent source strength of $1x10^8$ n/s and a detector separation from the sources of 100 cm. The photon production for the generator is higher than for the isotopic sources and extends out to 11 MeV.

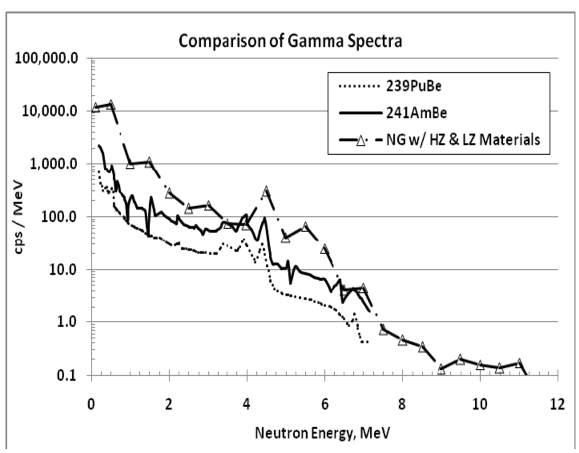

FIGURE 6. Measured ^{241}AmBe and ^{239}PuBe photon spectra from [1] and calculated photon spectra for the neutron generator with 5 cm each of tungsten and bismuth surrounded by 10 cm of Teflon.

SUMMARY

The 14-MeV neutron spectrum from a portable neutron generator can be significantly softened with the addition of modest thicknesses of HZ and LZ materials along the entire generator, with the benefit of a gain in flux by a factor of 2 relative to a bare neutron generator at a reference distance of 30 cm. Shortening the moderator reduces the moderator weight, keeps the average neutron energy about the same, and gradually decreases the flux gain. The density of the HZ materials also means that the portable generator is no longer practical as a portable device with the additional weight of the moderating materials. Since neutron generators are often operable as pulsed devices, further work may be of interest to understand the timing behavior or neutron generator/moderator assemblies such as the one considered here. Additional studies to examine the short-term and long-term activation products associated with the use of these materials may also be warranted.

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