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A portable shield for a neutron howitzer used for instructional and research purposes

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HIGHLIGHTS

- MCNP5 was used to characterize the neutron dose and the gamma flux from a 1 Ci ^{239}PuBe neutron howitzer.
- A portable neutron and gamma shield with a removable port was designed and built.
- Measured neutron rates for both unshielded and shielded howitzer were compared with simulated rates.

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ABSTRACT

Neutron howitzers are routinely used in universities to activate samples for instructional laboratory experiments on radioactivity. They are also a convenient source of neutrons and gammas for research purposes, but they must be used with caution. This paper describes the modeling, design, construction, and testing of a portable, economical shield for a 1.0 Curie neutron howitzer. The Monte Carlo N Particle Transport Code (MCNP5) has been used to model the ^{239}PuBe source and the howitzer and to design the external neutron and gamma shield.

1. Introduction

Neutron howitzers are versatile resources for university physics departments (Xu et al., 2015). Typically they were manufactured in the 1960s when radiation exposure limits were higher than those currently in effect. A standard design for a howitzer is shown in Fig. 1: a PuBe neutron source in a small stainless steel capsule is located in a cavity at the center of a cylinder of paraffin cast into a large steel container. Four radial access ports have plastic plugs that can be removed so that metal foils can be inserted close to the source where they are activated by the high neutron flux. A vertical access port is also available so that the source can be removed and inspected. Neutron and gamma radiation levels are significant in the immediate vicinity of a howitzer when the radial ports are open and above the vertical port even when it is closed. In a typical pedagogical setting these howitzers are used mainly for teaching laboratory courses in radiation and for activating samples for research (DuBard and Gambhir, 1994) or other instructional purposes. As a result, students and instructors or researchers usually do not come in contact with the howitzer with its port(s) open for an extended period of time. However, when used as a neutron source over an extended period in a laboratory setting, additional shielding is required. The neutron howitzer at San Francisco State University (SFSU) is being used for preliminary characterization of a compact, robust neutron detector being developed for seaport security applications. As such, it was necessary to build a shield to protect experimenters and ancillary detectors from neutrons and gammas while the prototype neutron detector is being exposed to neutrons. The shield had to be portable, and it had to have an access port in which various moderators and absorbers could be placed to modify the energy spectrum and intensity of the neutrons emerging from the howitzer.

2. Neutron and gamma spectra from the howitzer

2.1. The PuBe source

The first step in designing the shield was to model the neutron and gamma spectra produced by the howitzer by using the Monte Carlo N Particle Transport Code (MCNP version 5) (X-5 Monte Carlo Team, 2003). The howitzer in question is a Cenco Model # 71864-001. The neutron source is a mixture of plutonium (^{239}Pu)

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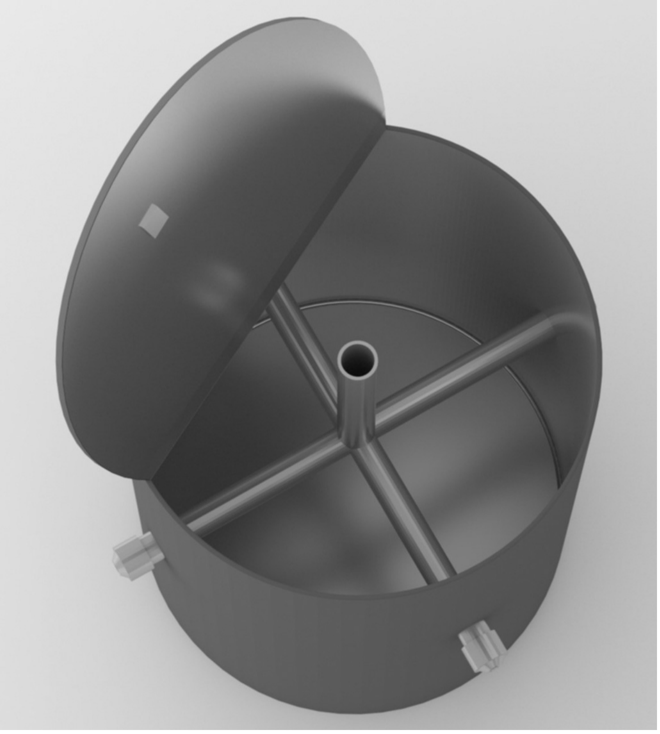

Fig. 1. Diagram of an empty howitzer with four horizontal beam ports and the vertical source port.

and beryllium (Be) powder encased in a stainless steel capsule. It has a nominal strength of 1 Curie (Ci) (Manual, 1964). The source was made by Magna Research, and the capsule is stamped with the serial number MRC PuBe73. Neutrons are produced when alpha particles emitted by ^{239}Pu react with ^{9}Be to produce ^{13}C* nuclei, which decay predominantly through the following reaction: $^{13}C^{*} \rightarrow {}^{12}C^{*} + n$ (Leo, 1994). The neutrons produced in (α,n) reactions have energies up to about 10 MeV. The high energy neutron flux for a ^{239}PuBe source diminishes with age as more and more carbon atoms are generated by the (α,n) reaction (Martoff et al., 1996). On the other hand, activity of the source can increase if some of the daughter products of decay are also alpha emitters. Since we do not know the exact composition and age of the ^{239}PuBe source in our howitzer, we ran our simulations using a neutron spectrum for a typical ^{239}PuBe source (Cember, 1996) as shown in Fig. 2. The average neutron energy for such a source is 4.5 MeV, and the neutron flux for a 1 Ci source is 1.7×10^{6} neutrons/cm^{2} s (Shores, 2000).

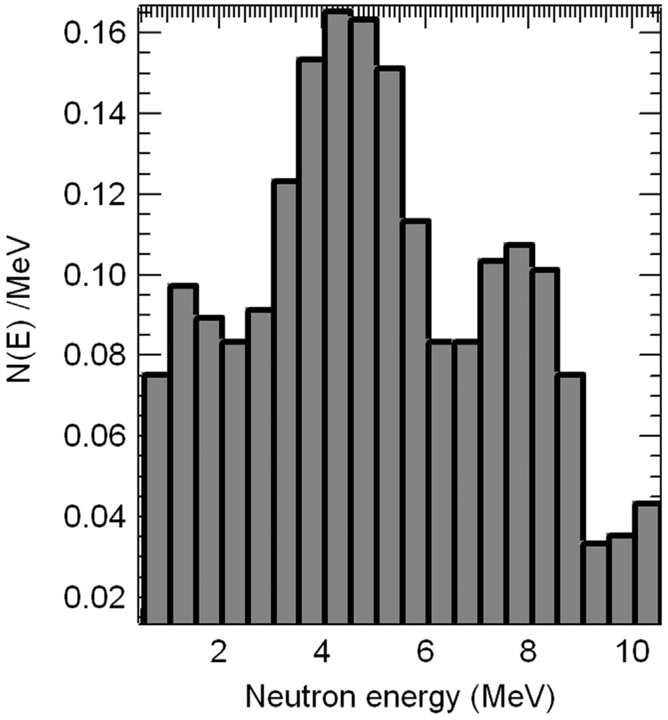

Fig. 2. Normalized number density N(E)/MeV of neutrons in a typical spectrum of ^{239}PuBe.

The howitzer is also a significant source of gamma radiation, which is often not taken into consideration. Gammas are produced by two different processes in the howitzer. The ^{239}PuBe source emits a flux of 4.4 MeV gammas created when the excited ^{12}C* nuclei decay. This flux is roughly one-third of the total neutron flux (Cember, 1996; Cooper, 1986) and for our source is estimated to be about 0.6×10^{6} gammas/cm^{2} s. Moreover, many of the high energy neutrons are moderated to the “thermal” energy range (0.025 eV) through elastic scattering with the hydrogen in the paraffin. Because hydrogen has an appreciable cross section (0.33b) for absorbing thermal neutrons and turning into deuterium, the howitzer body glows with 2.224 MeV gammas emitted during the capture reactions (Rinard, 1991).

2.2. *Structure of the howitzer*

In order to simulate the neutron and gamma spectra from our howitzer we need to take into account not only the characteristics of the PuBe source but also the physical details of the housing. In the SFSU howitzer the ^{239}PuBe neutron source is contained in a 24 in tall by 24 in diameter cylinder made of 18-gauge steel that is filled with paraffin to within 1.5 in of the top. The source is introduced into the howitzer through a central 14 in long by 1.7 in diameter vertical steel tube. The four radial beam ports consist of 12 in long by 1.5 in diameter tubes located 90° apart. The vertical tube has a polyethylene (PE) plug, and the four beam ports have Lucite plugs that fit snugly inside of the beam tubes. The paraffin and the PE and Lucite plugs moderate and absorb most of the neutrons emitted by the source, but they do little to shield users from gamma rays that are produced by the source and by absorption of neutrons in the paraffin.

2.3. *Preliminary measurements*

A preliminary on-axis survey of our neutron source at a distance of 17 cm from the open beam port showed the neutron and gamma doses to be 3 mrem/h and 1.3 mrem/h, respectively. With the Lucite plug in place, both neutron and gamma doses were reduced to 0.7 mrem/h. Although we could not directly measure the angular dependence of the neutron flux of our source we could measure the angular dependence of the neutron dose rate using a Thermo Scientific BF$_{3}$ neutron detector (see Fig. 3).

2.4. *Modeling neutron and gamma fluxes using MCNP5*

We used Monte Carlo calculations by applying the MCNP5 code to estimate the neutron and gamma energy distribution fluxes outside of the howitzer. The analog F2 tally was used to simulate both neutron and gamma fluxes. The neutron source and the howitzer were modeled as a spherical ^{239}PuBe capsule of 1 cm radius at the center of a set of six 4-cm and one 2-cm thick concentric spherical shells of paraffin enclosed in an 18 gauge spherical steel shell. As noted earlier, the ^{239}PuBe source was modeled by the idealized spectrum shown in Fig. 2. For simplicity only one beam port was included in the idealized model. The approximation of

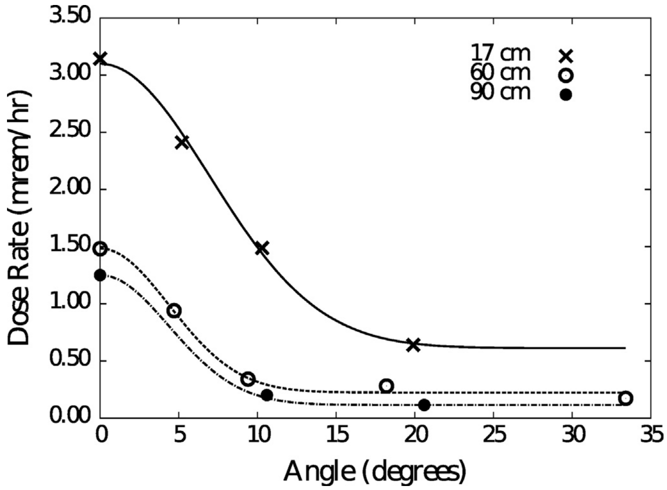

Fig. 3. Angular dependence of neutron dose rate relative to port axis.

using spherical geometry greatly reduced the computation time in these calculations.

2.5. Validation of the model

The neutron and gamma fluxes and neutron dose rates were simulated at several distances from the beam port with and without the Lucite port plug in place. MCNP5 calculations for different configurations of the howitzer (with and without the Lucite plug in the port) were run with 5.0×10^7 histories resulting in statistical uncertainties below 1% for simulated flux values. Standard variance reduction methods including geometry splitting, source biasing and varying importances were used to reduce computation time and reduce error (Shultis and Faw, 2004).

The simulated unshielded neutron dose values reported in Table 1 at 17 cm with and without the Lucite beam port plug, 0.75 mrem/h and 3.02 mrem/h, respectively, are very close to the measured neutron doses of 0.715 mrem/h and 3.140 mrem/h reported in Table 2; those results validated our simulation and gave us confidence to use the model to design the external shield.

3. Shield design

3.1. Basic structure

We also used the MCNP5 code to determine the best way to construct a shield that would reduce radiation from the howitzer to an acceptable level. For the shield to be effective it must moderate and absorb neutrons and also absorb high energy gamma rays. We simulated the neutron shield as concentric layers of spherical shells of a neutron moderator/absorber material. The gamma shield was similarly modeled as a concentric lead shell surrounding the howitzer and neutron shield. Our idealized spherical representation of the howitzer and shield materials is shown in Fig. 4.

Table 1
MCNP simulated neutron dose rates (on-axis) for spherical geometry.

Distance from port (cm)	Closed port unshielded (mrem/h)	Open port unshielded (mrem/h)	Open port shielded (mrem/h)
17	0.754	3.015	3.443
61	0.171	1.418	0.063
90	0.109	1.287	0.025
180	0.049	0.523	0.010

Table 2
Measured neutron dose rates (on-axis).

Distance from port (cm)	Closed port unshielded (mrem/h)	Open port unshielded (mrem/h)	Open port shielded (mrem/h)
17	0.715	3.140	n/a[a]
61	0.253	1.482	0.023
90	0.138	1.108	0.017
180	0.040	0.438	0.012

[a] Positions that are not physically accessible when the shield is in place.

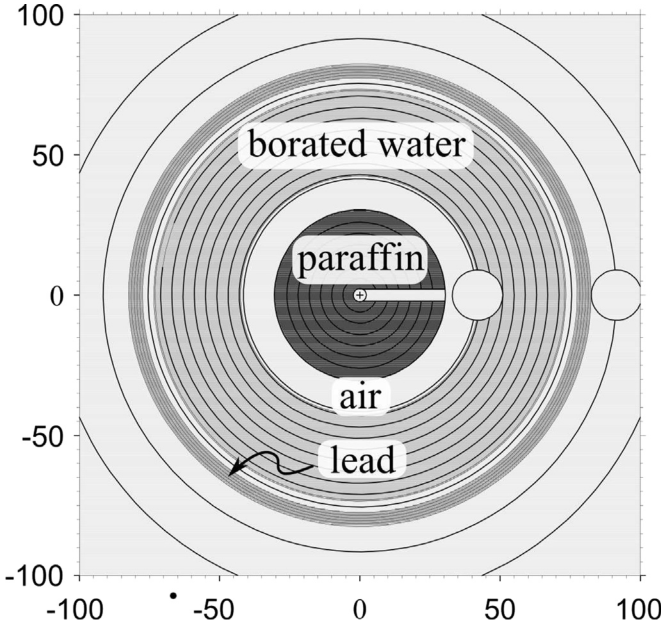

Fig. 4. The spherical model of the PuBe source in a paraffin howitzer with a neutron moderator/absorber shield and a lead gamma shield. The small spheres represent the neutron detectors.The horizontal and vertical axes are in cm.

3.2. Design criteria for neutron shield

In our studies of neutron moderation/absorption we used MCNP5 to simulate the effectiveness of light water, heavy water, 10% by weight of boric acid solution in water, and boron carbide. For design purposes the thickness of the neutron absorber/moderator was increased in 4 cm increments until the average transmitted neutron flux was reduced to less than 5% of the average incident value when the howitzer port was open. To determine the effectiveness of shield materials, the MCNP5 F2 tally (average neutron or photon flux) was taken over 4.5 cm radius spheres (used to simulate the REM Ball neutron detectors) at distances of 17 cm, 61 cm, 90 cm, and 180 cm from the howitzer port. The neutron dose rate was determined from the F2 tally by multiplying the normalized neutron flux by the appropriate flux-to-dose conversion factor (ICRP, 1987). The simulated neutron dose rates at 61 cm (this is the closest working distance for our howitzer and shield configuration) for various trial thicknesses of the moderator/absorber layer are shown in Fig. 5. The ^{10}B isotope has the largest neutron absorption cross section of the materials considered. Unfortunately, only 20% of naturally occurring boron is the ^{10}B isotope (NIST, 2009) and the number of ^{10}B nuclei in a typical 10% boric acid solution is therefor very low. As can be seen from the plot, our simulations found the efficiency of water to be almost identical to 10% boric acid water solution as a neutron shield and moderator.

Table 1 shows the average neutron dose rates simulated for a spherical-geometry shield with a 30 cm thick neutron moderator/

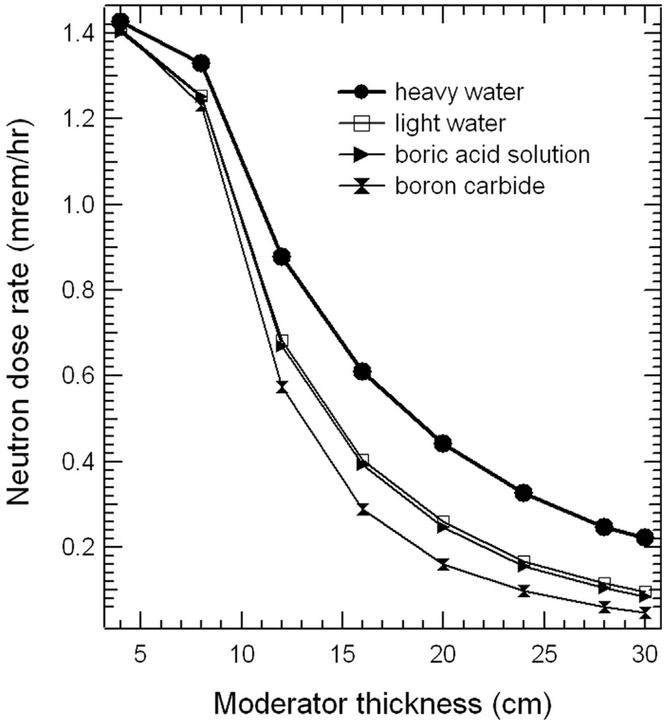

Fig. 5. Simulated neutron dose at 61 cm, closest working distance, from the open port as a function of moderator thickness. The effect of boric acid water solution is almost identical to that of plain water.

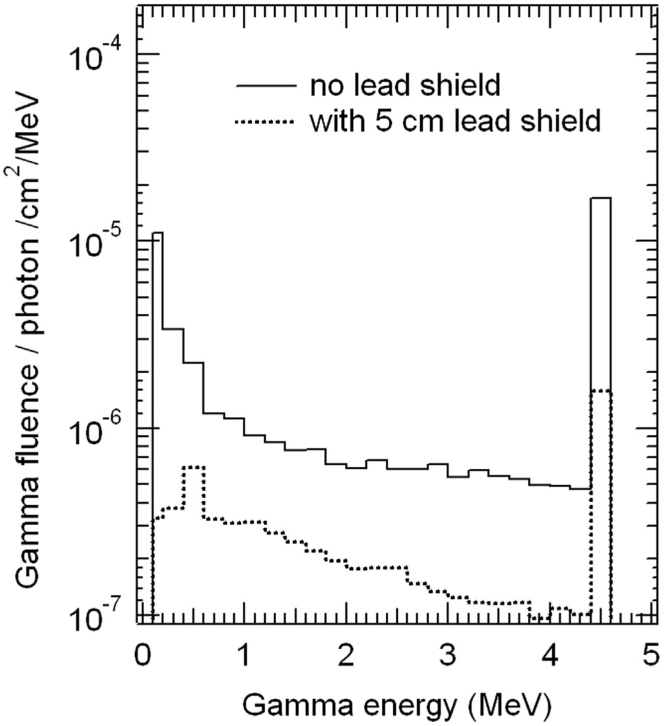

Fig. 6. The MCNP simulated fluence for 4.44 MeV gamma radiation from the PuBe source.

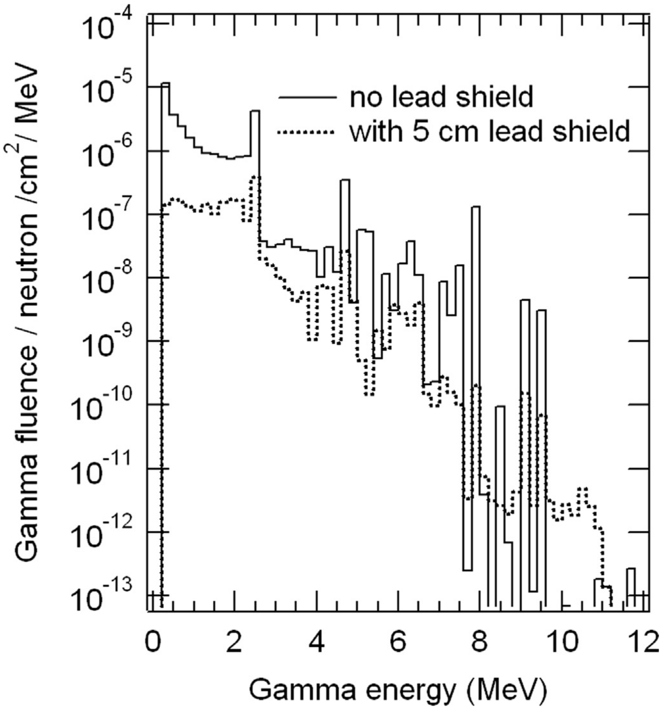

Fig. 7. The MCNP simulated fluence for gamma radiation created by the interaction of neutrons with other materials.

absorber layer made of borated water and a 5 cm thick gamma shield made of lead. These are the materials and thicknesses of planar layers used to construct the actual shield described in the next section. The simulated data in Table 1 and the measured data in Table 2 are in very good agreement. Note that the simulated data for 17 cm is higher for the shielded configuration than for the unshielded case, because the calculation takes into account the reflected neutron flux from the shield. There is no measured data at this point because we cannot place a neutron detector at that distance with the shield in place.

3.3. *Design criteria for gamma shield*

The thickness of the lead shield in the simulation was also increased until the transmitted gamma flux was reduced to less than 10% of its incident value. The gamma fluxes were not converted to dose rates. The PuBe source produces 4.44 MeV gamma radiation from de-excitation of ^{12}C. Other gamma radiation originates from bremsstrahlung of secondary electrons and various (n,xγ) interaction of neutrons with the storage container, shielding paraffin, the boric acid tank, the external shields and the storage room. The 4.44 MeV gamma flux and the neutron-induced gamma fluxes were simulated separately using MCNP5. Figs. 6 and 7 show the simulated reduction of gamma flux at 61 cm from the howitzer due to the external gamma shield. It is important to note that neutron interactions can produce gamma rays with energy as high as 12 MeV.

4. Shield construction

The external shield was designed to have two parts: (i) a neutron moderator/absorber and (ii) a gamma absorber. For the neutron absorber we decided to use a boron mixture rather than paraffin or water because gammas emitted after neutron capture by boron have energy of only 478 keV, whereas gammas emitted after neutron capture by hydrogen have energy of 2.224 MeV. We initially attempted to make a homogeneous mixture of borax and paraffin, but we were unsuccessful. We ultimately decided to make the shield using borated water because it is easy to prepare a saturated solution of 10% by weight of boric acid in water at room temperature. For safety purposes, we decided to use a large plastic tank as a secondary containment for smaller plastic containers

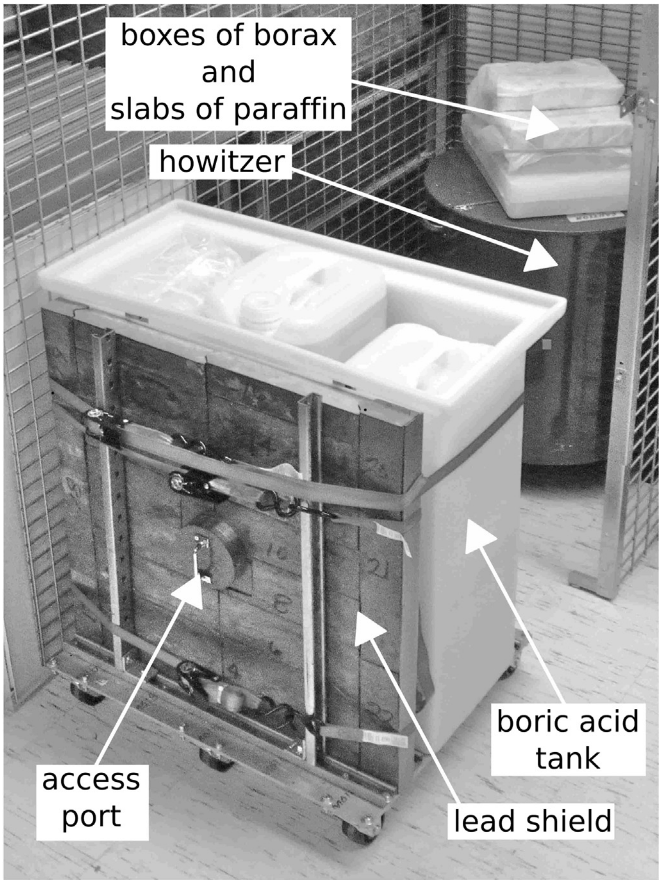

Fig. 8. Photograph of the neutron howitzer with the movable neutron and gamma shield.

that were filled with boric acid and sealed tightly; the remainder of the tank was filled with water. The estimated effective volume of boric acid in the tank is 80%. The boric acid in the smaller containers was dyed blue so that leaks into the tank can be immediately detected. The pH of the water in the tank surrounding the boric acid containers is monitored regularly. The polyethylene tank is 33 in wide by 30 in high by 12 in thick. The gamma shield is made from a wall of fifty interlocking lead bricks of size 2 in × 4 in × 8 in.

Both the water tank and the lead wall have 6 in diameter plugs that can be removed to gain access to a port in which various types of moderators and absorbers can be placed as needed to characterize the response of the detector. The shield assembly is set on a reinforced wheeled platform so that it can be moved. Fig. 8 is a photograph of the shield in front of the neutron howitzer.

As can be seen from Fig. 8 this external shield can only be used with one active port. The top port of the howitzer is not as well shielded by the polyethylene plug and paraffin as the side ports so we use blocks of paraffin and boxes of borax to moderate and absorb the neutron flux from this port. We plan to build a shelf to support a layer of 2 in thick lead bricks to attenuate gamma radiation from the top of the howitzer.

5. Measurements

The shield was tested in a concrete-walled storage room that is 25 feet wide by 25 ft long by 8 ft high. The neutron dose was measured with a Thermo ASP-2e/NRD neutron survey meter and a Ludlum model 12-4 Ratemeter with a 42-31H REM Ball type neutron detector. Table 2 shows the neutron doses measured at various distances from the howitzer. The shield as constructed reduces the neutron dose by a factor of ≈ 60 at a distance of 60 cm from the open port. The gamma spectrum of the howitzer with the Lucite plug in place was measured with a Bicron 2 in × 2 in NaI detector with and without the shield as shown in the logarithmic plot in Fig. 9. The unshielded ^{239}PuBe gamma spectrum is consistent with previous measurements reported (Vega-Carrillo et al., 2002). Notice that there is an additional 2.224 MeV peak resulting from the neutron interaction in the paraffin howitzer. The shield reduces the gamma flux to less than 10% of the unshielded value. The residual peak at 1461 keV is due to potassium-40 background radiation.

6. Conclusions

The neutron dose rate at a distance of 1 m from our howitzer is about 1.1 mrem/h when it is being used with one port open. Our shield reduces the dose rate to a few percent of the unshielded value, so it protects students and researchers who use the howitzer for instructional and research purposes. However it is also necessary to consider exposure received when the howitzer is stored with all ports closed. In that case the neutron dose rate at a distance of 1 m is about 0.1 mrem/h. The occupational radiation dose limit for adults is 5 rems per calendar year or 0.57 mrem/h. Thus the potential annual neutron dose received from the howitzer in storage with all its ports closed is not large, but it is not negligible. In accordance with the practice of reducing radiation to a level As Low As Reasonably Achievable (ALARA), all unnecessary radiation exposures are undesirable and should be kept to a minimum. With that in mind, we have adopted the practice of storing the howitzer behind the shield.

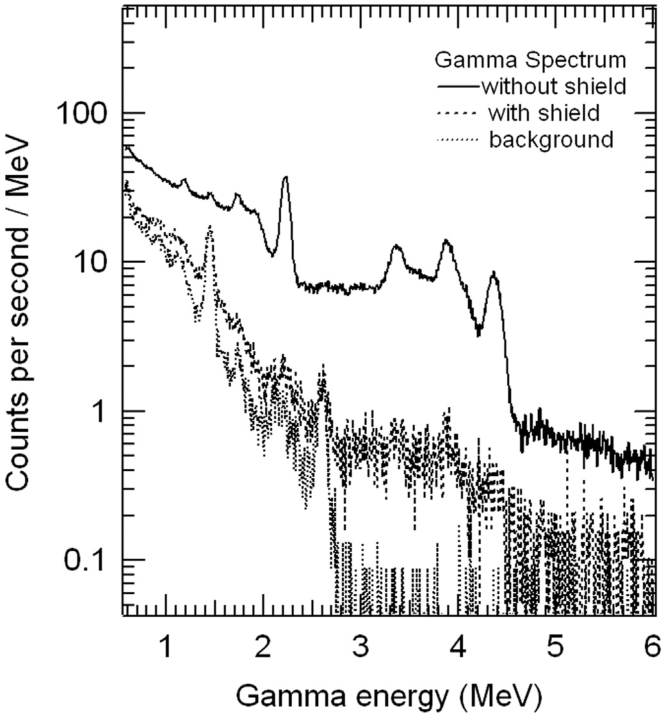

Fig. 9. Gamma spectrum from the howitzer measured with a NaI detector. The gamma shield effectively reduces the gamma flux to less than 10% of its unshielded value.

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References

Cember, H., 1996. Introduction to Health Physics, 3rd edition. McGraw-Hill Medical, New York, NY.

Cooper, P., 1986. Introduction to Nuclear Radiation Detectors. Cambridge University Press, Cambridge, MA.

DuBard, J., Gambhir, A., 1994. Dust off the neutron howitzer to teach nuclear physics. Am. J. Phys. 62, 3 http://dx.doi.org/10.1119/1.17608.

ICRP, 1987. Data for use in protection against external radiation. Publication 51, ICRP.

Leo, W., 1994. Techniques for Nuclear and Particle Physics Experiments, 2nd edition. Springer-Verlag, Berlin, Heidelberg.

Manual, 1964. Operation and Experiment Manual, Neutron Beam Irradiation Facility. Atomic Laboratories Inc., San Ramon, CA.

Martoff, C.J., Garzarella, A., Getaneh, M., Kaczanowicz, E., Neuhauser, B., Snowden-Ifft, D., Wang, X.X., Zhang, Y., 1996. Prototype direction-sensitive solid-state detector for dark matter. Phys. Rev. Lett. 76, 4882 http://dx.doi.org/10.1103/PhysRevLett.76.4882.

NIST, 2009. Atomic weights and isotopic compositions for all elements. Available online at ⟨www.nist.gov/pml/data/comp.cfm⟩.

Rinard, P., 1991. Neutron interaction with matter. In: Reilly D, Ensslin N, Smith Jr. H, Kreiner S, (Eds.), Passive Nondestructive Assay of Nuclear Materials. Nuclear Regulatory Commission.

Shores, E.F., 2000. Contact dose equivalent rates from common neutron sources. In: American Nuclear Society Topical Meeting.

Shultis, J., Faw, R., 2004. An mcnp primer. Available online at ⟨www.mne.ksu.edu/~jks/MCNPprmr.pdf⟩.

Vega-Carrillo, H., Manzanares-Acuna, E., Becerra-Ferreiro, A., Carrillo-Nunez, A., 2002. Neutron and gamma-ray spectra of ^{239}pube and ^{241}ambe. Appl. Radiat. Isot. 57, 167–170 http://dx.doi.org/10.1016/S0969-8043(02)00083-0.

X-5 Monte Carlo Team, 2003. MCNP—A General Monte Carlo N-Particle Transport Code Version 5. Los Alamos National Laboratory, Los Alamos, New Mexico, USA.

Xu, N., Kuhn, K., Gallimore, D., Martinez, M., Schappert, M., Montoya, D., Lujan, E., Garduno, K., Tandon, L., 2015. Elemental composition in sealed plutonium–beryllium neutron sources. Appl. Radiat. Isot. 95, 85–89 http://dx.doi.org/10.1016/j.apradiso.2014.10.013.