Nuclear Instruments and Methods in Physics Research A 691 (2012) 72–80

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Optimizing moderation of He-3 neutron detectors for shielded fission sources

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ARTICLE INFO

Article history:
Received 16 December 2011
Received in revised form
27 June 2012
Accepted 4 July 2012
Available online 10 July 2012

Keywords:
Neutron detection
Portal monitor
Radiation detection
Homeland security
Detection of illicit materials
Monte Carlo modeling

ABSTRACT

The response of a ^{3}He neutron detector is highly dependent on the amount of moderator incorporated into the detector system. If there is too little moderation, neutrons will not react with the ^{3}He. If there is too much moderation, neutrons will not reach the ^{3}He. In applications for portal or border monitors where ^{3}He detectors are used to interdict illicit importation of plutonium, the fission source is always shielded to some extent. Since the energy distribution of neutrons emitted from the source depends on the amount and type of shielding present, the optimum placement of moderating material around ^{3}He tubes is a function of shielding. In this paper, we use Monte Carlo techniques to model the response of ^{3}He tubes placed in polyethylene boxes for moderation. To model the shielded fission neutron source, we use a point ^{252}Cf source placed in the center of polyethylene spheres of varying radius. Detector efficiency as a function of box geometry and shielding is explored. We find that increasing the amount of moderator behind and to the sides of the detector generally improves the detector response, but that incremental benefits are minimal if the thickness of the polyethylene moderator is greater than about 5–7 cm. The thickness of the moderator in front of the ^{3}He tubes, however, is very important. For bare sources, about 4–5 cm of moderator is optimum, but as the shielding increases, the optimum thickness of this moderator decreases to 0.5–1 cm. Similar conclusions can be applied to polyethylene boxes employing two ^{3}He tubes. Two-tube boxes with front moderators of non-uniform thickness may be useful for detecting neutrons over a wide energy range.

1. Introduction

In recent years the use of neutron detectors in radiation portal monitoring (RPM) systems has gained increasing attention. Passive interrogation is a good way to interdict importation of plutonium, but is probably not effective for detecting highly enriched uranium. Kouzes et al. [1] wrote a review article that thoroughly explores the need for RPM systems and describes the characteristics of these systems. Kouzes' paper focused on pressurized ^{3}He gas-tube detectors. As the authors noted, any plutonium illicitly entering ports via shipping containers will be shielded, either intentionally or not. It is therefore very important for a neutron detection system to be sensitive not only to bare fission sources, but also to shielded sources. Kouzes' paper included a discussion of various types of shielding and concluded with a Monte Carlo analysis of several moderating schemes and parameters.

The present paper is largely an extension of the work of Kouzes et al. [1]; however, there are several other recent papers that treat related topics. Chandra et al. [2] have argued that the fast-neutron component of emissions from shielded sources is important and should not be ignored. Lintereur et al. [3] and Kouzes et al. [4] have demonstrated that ^{3}He-tube efficiency depends logarithmically on tube pressure. Kouzes et al. [5] have published a survey of alternatives to ^{3}He detectors for homeland security applications. Runckle has recently written two surveys about the use of neutron detection in nonproliferation applications [6,7]. A good source for general information about neutron detection is given by Knoll [8].

For this analysis we use the computer code MCNP [9] to calculate the overall response and efficiency of ^{3}He detectors in various configurations and MCNP-PoliMi [10] to give information on the interaction of individual neutrons within shielding and moderating materials. We go beyond the work of Kouzes et al. to calculate the response of various configurations of ^{3}He tubes to ^{252}Cf fission neutrons, both from bare and shielded sources. We show how the standard configuration described by Kouzes et al. can be improved for neutron detection in a wide range of shielding scenarios.

2. Moderation and shielding

In this paper we use the term "shielding" to describe the interaction of neutrons with material associated with the source. For RPMs, shielding includes the shipping container and its

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http://dx.doi.org/10.1016/j.nima.2012.07.004

contents. Kouzes et al. [1] describe the effects of shielding from a number of different types of materials. In this paper, we limit our shielding to spheres of polyethylene (PE) surrounding a point ^{252}Cf source. Polyethylene was chosen as it is typical of hydrogenous shielding materials. Although the specific choice of hydrogenous shielding affects details of the calculations, the results are primarily dependent on the total number of hydrogen atoms encountered by each neutron along its path through the shielding. In our calculations we use ENDF/B-VI Release 3 thermal S(α,β) tables for the hydrogen [11] in polyethylene.

We use the term “moderation” to describe the effects of material surrounding the ^{3}He tube. Moderating material can be placed in front, to the sides, and to back of the tubes. We call any of this, “moderator,” in distinction to Kouzes who uses the term “reflector” when referring to moderator placed behind the tube. Our moderators will all be in the form of polyethylene boxes surrounding the ^{3}He tubes.

First, we consider some general effects of moderation with polyethylene. Using MCNP-PoliMi, we can calculate how neutrons interact with the moderating material. When neutrons enter polyethylene, they collide with both C and H, losing most of their energy in H collisions. Fig. 1 shows the average energy loss as a function of collision number for 1 MeV neutrons normally incident upon a thick slab of polyethylene. Note that a large fraction of the energy is lost in the first few collisions in the moderator. In this process, the direction the neutrons travel also becomes randomized fairly quickly (Fig. 1). As the low-energy neutrons bounce around more or less randomly in the polyethylene, they form what we could describe as a “neutron cloud” within the material. We can get a good idea of the location of this cloud by noting where neutrons are captured (primarily by the n(p,γ)d reaction) within the polyethylene. This distribution is seen in Fig. 2 for neutrons of three energies as well as for ^{252}Cf neutrons. As in Fig. 1, the neutrons are normally incident on the polyethylene slab. Note that in terms of neutron depth, the ^{252}Cf neutrons resemble 1 MeV neutrons fairly closely. This demonstrates that moderator placed in front of the ^{3}He tubes needs to be large enough to slow the neutrons so they can be captured in the ^{3}He, but small enough that they do not shield the ^{3}He from the source. (In Figs. 2 and 3 the data are generated by MCNP-PoliMi and the output data have been smoothed to better represent the underlying distributions and facilitate comparisons.)

The energy distribution of neutrons from a source is highly dependent on shielding. The shielding material both moderates and absorbs neutrons. ^{3}He detectors are insensitive to gammas, and so the production of 2.2 MeV gammas in the n(p,γ)d reaction is inconsequential. The fraction of emitted neutrons that are absorbed in various thicknesses of spherical polyethylene shielding is shown in Table 1. Note that for shielding thicknesses as small as 8 cm, this can be quite large.

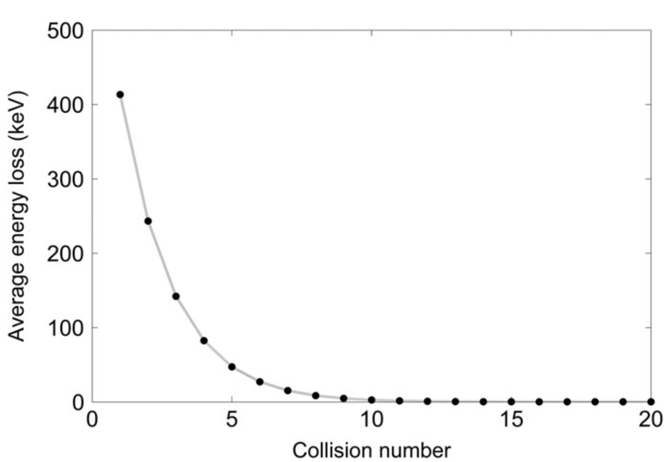

Fig. 1. Average energy loss of 1 MeV neutrons normally incident on a thick slab of polyethylene as a function of the neutron collision number.

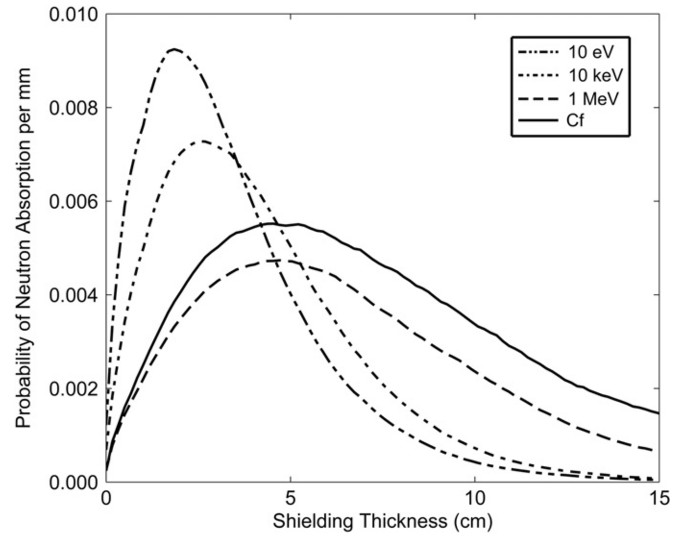

Fig. 2. The depth distribution of neutron capture events for 1 MeV, 10 kev, and 10 eV neutrons as well as ^{252}Cf neutrons normally incident on a polyethylene slab.

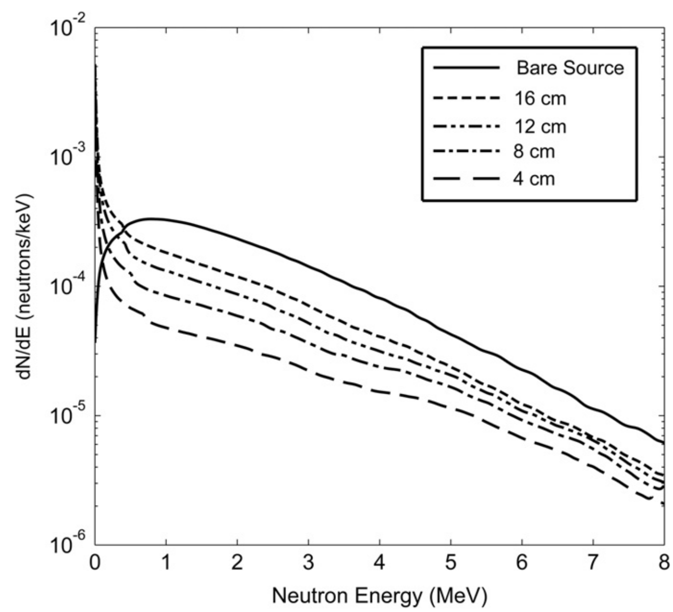

Fig. 3. Energy spectrum of ^{252} Cf neutrons emerging from spherical PE shielding of various thicknesses in comparison to the spectrum from a bare source.

The energy spectrum of neutrons leaving the shielding is depicted in Fig. 3. Even for small amounts of shielding, the number of very low energy neutrons is greatly increased and the number of higher energy neutrons is reduced as compared to the bare source. Since high-energy neutrons can penetrate fairly large amounts of shielding, the ratio of higher-energy neutrons to neutrons near 1 MeV in energy that leave the shielding becomes larger as the shielding is increased.

3. Monte Carlo results for a one-tube detector

3.1. Characterization of the detector

Before we discuss details of different detector configurations, we need to define three different ways in which we can describe the overall quality of the detector.