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

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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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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($\alpha$,$\beta$) 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,$\gamma$)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,$\gamma$)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.

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.

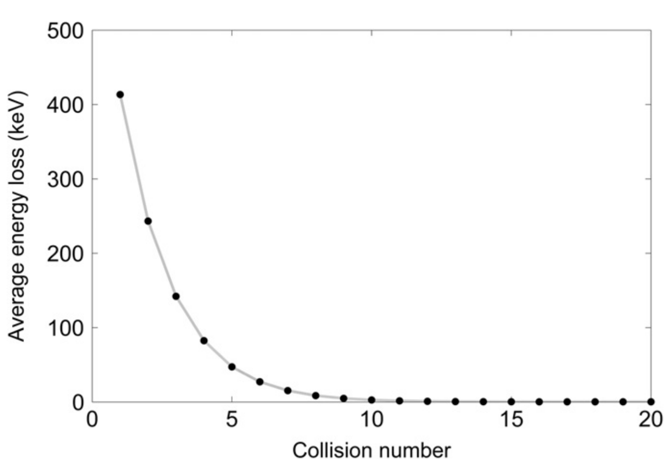


**Fig. 1.** Average energy loss of 1 MeV neutrons normally incident on a thick slab of polyethylene as a function of the neutron collision number.

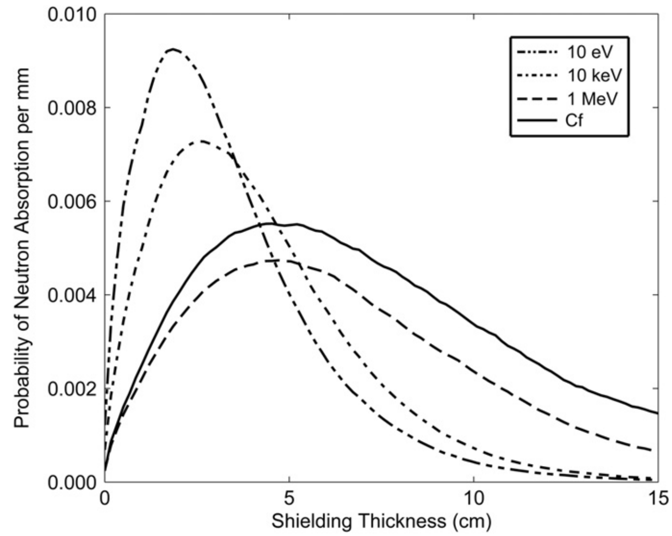


**Fig. 2.** The depth distribution of neutron capture events for 1 MeV, 10 kev, and 10 eV neutrons as well as $^{252}$Cf neutrons normally incident on a polyethylene slab.

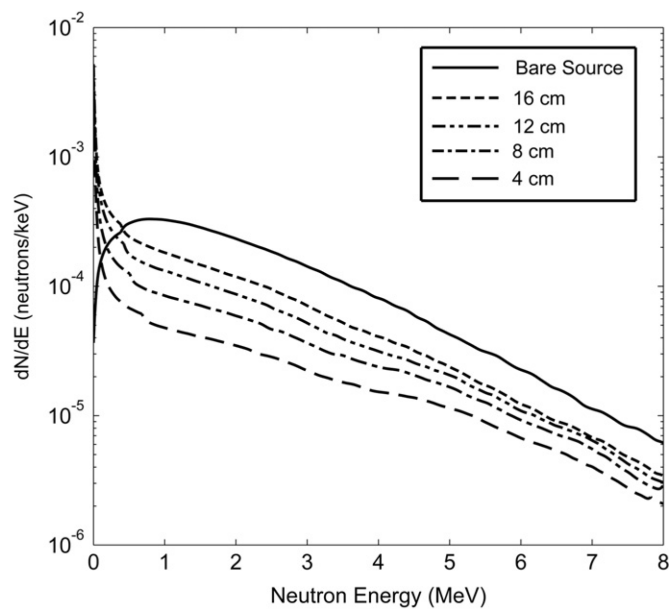


**Fig. 3.** Energy spectrum of $^{252}$ Cf neutrons emerging from spherical PE shielding of various thicknesses in comparison to the spectrum from a bare source.

## 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.

*Detector response*: This is the number of neutrons detected (those reacting with $^3$He in the detector) divided by the number of neutrons emitted by the source. The response is therefore a function of shielding, moderation, and source location. For a fixed source–detector configuration, detector response provides the best indicator the detector's count rate.

*Intrinsic efficiency*: This is the number of neutrons detected divided by the number striking the front face of the detector. It is independent of source–detector geometry and shielding considerations. Intrinsic efficiency is the best indicator of the detector's ability to detect neutrons of a given energy or energy distribution.

*Practical intrinsic efficiency*: This is the intrinsic efficiency multiplied by the fraction of neutrons that escape from the shielding. This provides a measurement of the combined shielding-detection system, but it is independent of the solid angle of the detector.

### *3.2. Dependence of detector response on front and back moderator thicknesses*

Kouzes et al. [1] describe the response of a "standard" one-tube $^3$He detector to a bare $^{252}$Cf source as a function of the thickness of moderator in front and behind. This detector consists of a $^3$He tube enclosed in a polyethylene box as shown in Fig. 4. The $^3$He tube has an internal diameter of 4.99 cm, an active length of 183 cm, and a gas pressure of 3 atm. The box has a width of 62 cm and height of 201 cm. The distance from the center of the tube to the inside front and back walls is fixed at 5.0 cm. The source is located directly in front of the center of the $^3$He tube at a distance of 200 cm from the tube center.

Kouzes et al. indicate that the response of the detector to a bare Cf source gently rises as a function of either the thickness of the front moderator or the thickness of the back moderator. It is instructive to extend the calculations to larger values of both of these quantities. Our results are illustrated in Fig. 5.

As can be seen in Fig. 5, the detector response continues to increase slightly as the thickness of the back moderator increases from 5 to 7 cm. More importantly, the response drops as the thickness of the front moderator increases to 7 cm. This is consistent with Fig. 2, where the neutron cloud in a slab of polyethylene is seen to become less dense as the polyethylene depth increases beyond 5 cm.

**Table 1**
Percentage of neutrons emitted from a $^{252}$Cf source that are absorbed in spherical polyethylene shielding.

| Shielding radius (cm) | Percentage of neutrons absorbed (%) |
|---|---|
| 4 | 2.7 |
| 8 | 29.2 |
| 12 | 61.2 |
| 16 | 80.9 |
| 20 | 90.8 |
| 24 | 95.5 |
| 28 | 97.7 |

### *3.3. Dependence of detector response on shielding*

Similar plots are shown in Figs. 6–9 for neutrons from sources shielded with 4 cm, 8 cm, 12 cm, and 16 cm of polyethylene. Note that as the shielding increases, the optimum thickness of the front moderator drops from about 4.5 cm for a bare source to about 1 cm as the thickness of the shielding increases to 16 cm. Moderator on all sides of the $^3$He tube tends to reflect neutrons captured within the box, and so some moderation in front of the tube is beneficial even when the source is shielded with 16 cm of polyethylene.

Also note that the overall response of the detector drops considerably as the shielding increases. This is due in large measure to the absorption of neutrons in the shielding.

Perhaps the most important conclusion that we can draw from these figures is that the detector response is highly dependent on the front moderator thickness. This is better illustrated by plotting

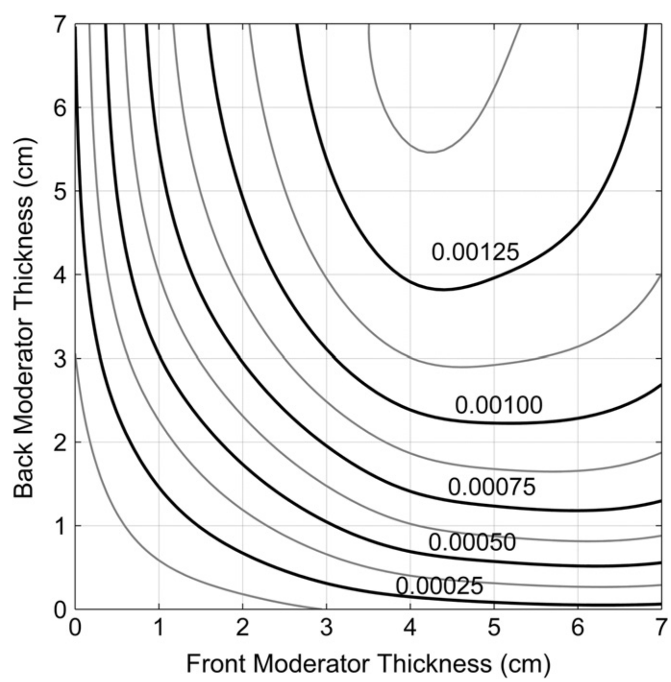


**Fig. 5.** Detector response (counts per emitted neutron) of a bare $^{252}$Cf source as a function of front and back moderator thicknesses for a single-tube detector in the geometry of Fig. 4.

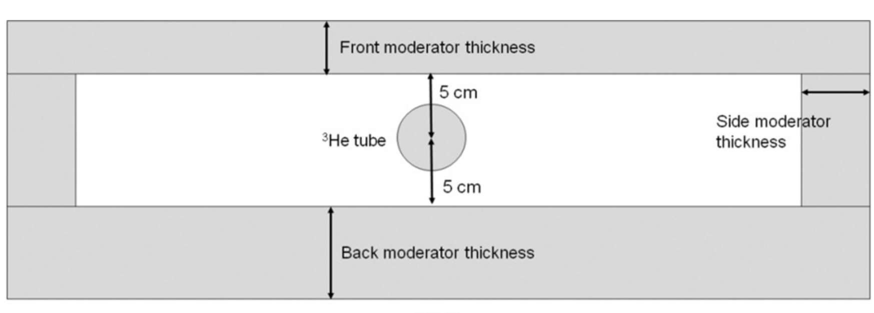


**Fig. 4.** Basic geometry of the one-tube detector consisting of a $^3$He tube inside of a polyethylene box.

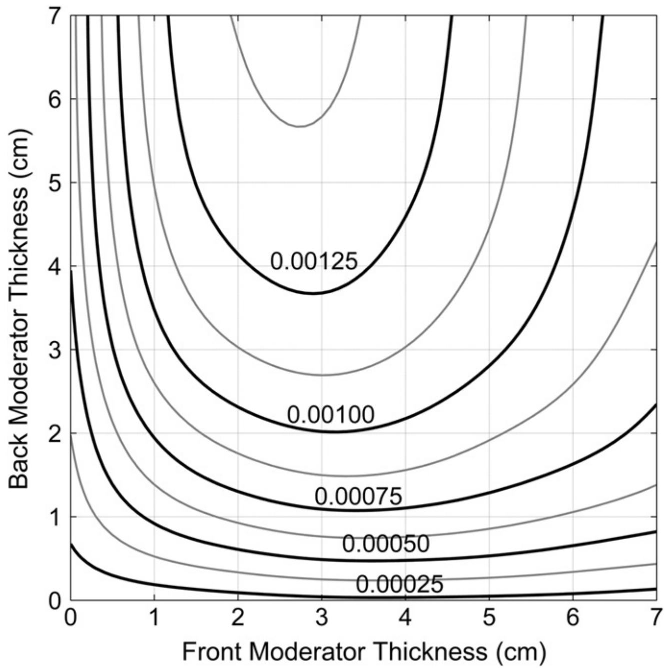


**Fig. 6.** Contour plot of detector response of a $^{252}$Cf shielded with 4 cm of PE as a function of front and back moderator thicknesses.

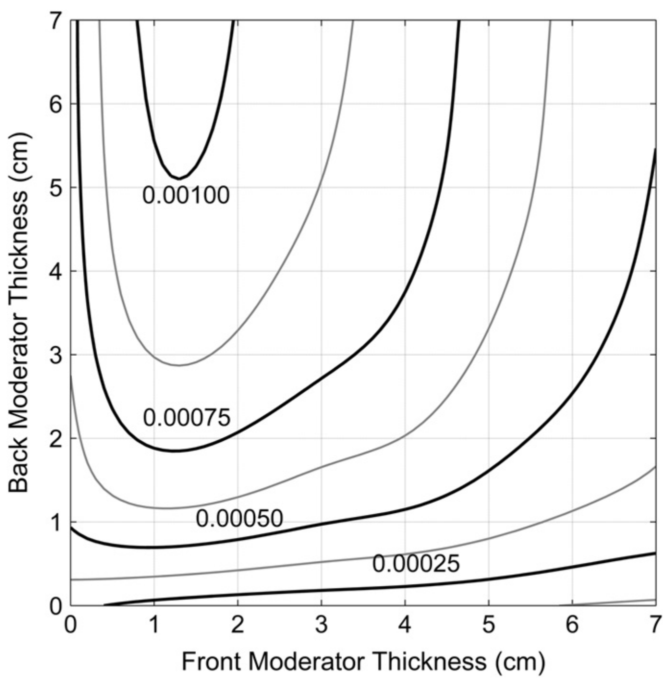


**Fig. 7.** Contour plot of detector response of a $^{252}$Cf shielded with 8 cm of PE as a function of front and back moderator thicknesses.

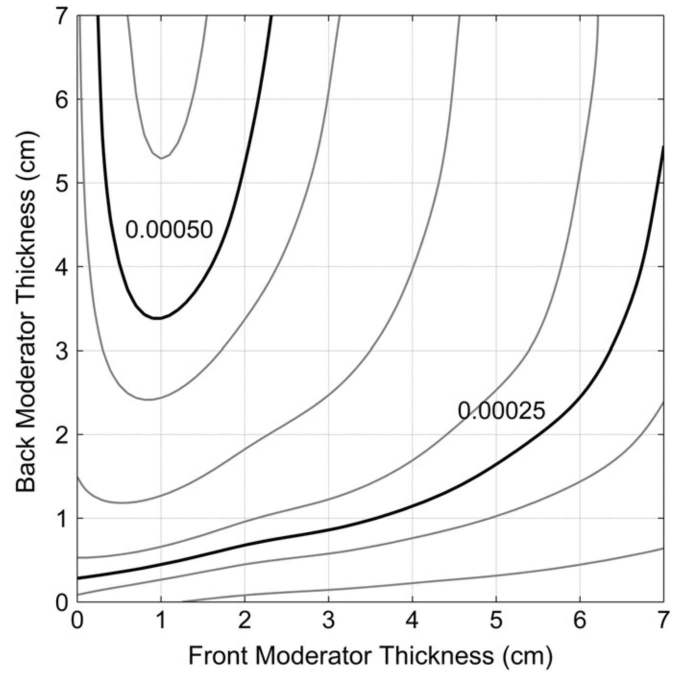


**Fig. 8.** Contour plot of detector response of a $^{252}$Cf shielded with 12 cm of PE as a function of front and back moderator thicknesses.

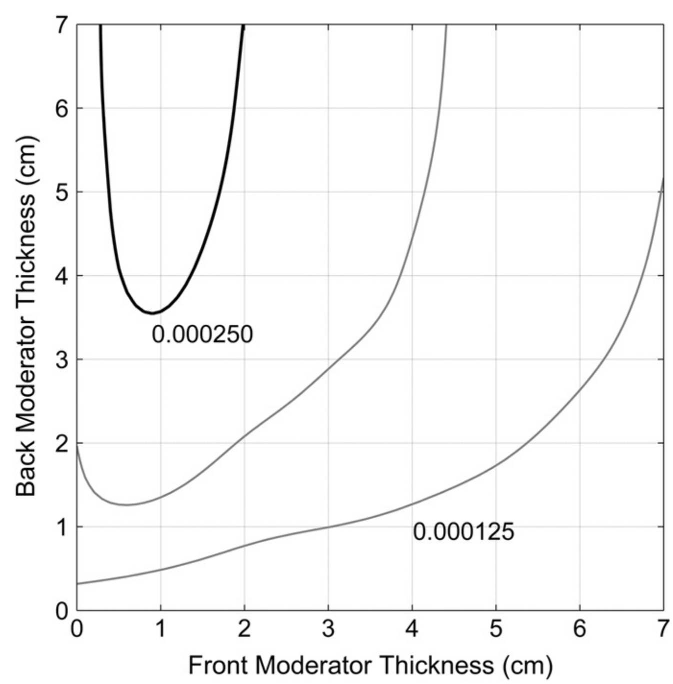


**Fig. 9.** Contour plot of detector response of a $^{252}$Cf shielded with 16 cm of PE as a function of front and back moderator thicknesses.

the detector response as a function of front moderator thickness with the back moderator thickness fixed at 7 cm, as shown in Fig. 10. For large amounts of shielding, the front moderator has two competing effects. It not only absorbs lower-energy neutrons from the source to reduce the response but also reflects neutrons from the cloud inside the box to increase the response. With the large box and thin front moderator, reflection is the dominant process even for 16 cm shielding. Hence, some front moderator is better than none at all.

Selected values of the detection efficiency are tabulated in Table 2. The maximum intrinsic efficiency remains fairly constant for all thicknesses of shielding, but with more shielding the maximum occurs at smaller thicknesses of the front moderator. The practical intrinsic efficiency decreases as does the detector response, due to neutron absorption in the shielding.

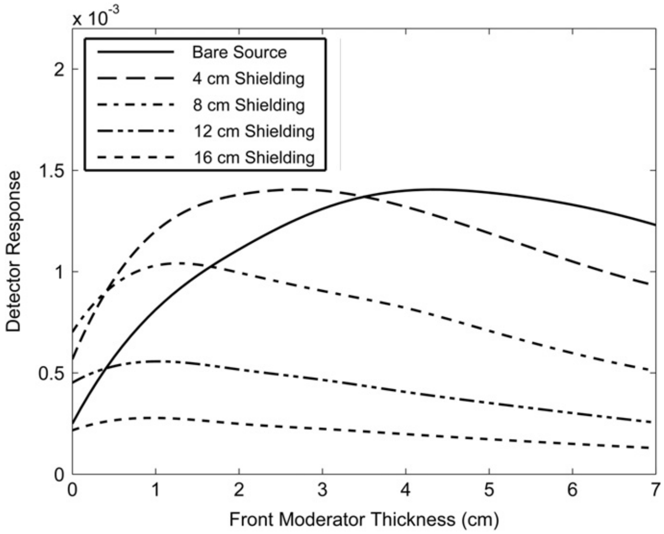


**Fig. 10.** Detector response for one-tube detectors with varying front moderator thicknesses and a 7-cm thick back moderator.

**Table 2**
Efficiency of a single "standard" $^{3}$He tube for detecting neutrons from a shielded $^{252}$Cf source. All entries are for 7 cm of polyethylene moderator behind the $^{3}$He tube. Uncertainty in the response is 1%.

| PE Shielding (cm) | Front moderator thickness (cm) | Detector response (counts per emitted neutron) | Practical Intrinsic efficiency (%) | Intrinsic efficiency (%) |
|---|---|---|---|---|
| 0 | 3 | $1.31\times10^{-3}$ | 5.4 | 5.4 |
| 0 | 4 | $1.40\times10^{-3}$ | 5.7 | 5.7 |
| 0 | 5 | $1.39\times10^{-3}$ | 5.7 | 5.7 |
| 0 | 6 | $1.33\times10^{-3}$ | 5.4 | 5.4 |
| 0 | 7 | $1.23\times10^{-3}$ | 5.0 | 5.0 |
| 4 | 1 | $1.20\times10^{-3}$ | 4.9 | 5.0 |
| 4 | 2 | $1.38\times10^{-3}$ | 5.7 | 5.8 |
| 4 | 3 | $1.40\times10^{-3}$ | 5.7 | 5.9 |
| 4 | 4 | $1.32\times10^{-3}$ | 5.4 | 5.5 |
| 4 | 5 | $1.19\times10^{-3}$ | 4.9 | 5.0 |
| 8 | 0 | $7.02\times10^{-4}$ | 2.9 | 4.1 |
| 8 | 1 | $1.03\times10^{-3}$ | 4.2 | 5.9 |
| 8 | 2 | $9.95\times10^{-4}$ | 4.1 | 5.8 |
| 8 | 3 | $9.05\times10^{-4}$ | 3.7 | 5.2 |
| 12 | 0 | $4.52\times10^{-4}$ | 1.8 | 4.8 |
| 12 | 1 | $5.57\times10^{-4}$ | 2.3 | 5.9 |
| 12 | 2 | $5.17\times10^{-4}$ | 2.1 | 5.4 |
| 12 | 3 | $4.66\times10^{-4}$ | 1.9 | 4.9 |
| 16 | 0 | $2.17\times10^{-4}$ | 0.9 | 4.7 |
| 16 | 1 | $2.78\times10^{-4}$ | 1.1 | 6.0 |
| 16 | 2 | $2.49\times10^{-4}$ | 1.0 | 5.3 |
| 16 | 3 | $2.24\times10^{-4}$ | 0.9 | 4.8 |

### 3.4. Dependence of detector response on box width

Another important question is how the width of the box affects the detector response. The standard box used by Kouzes et al. [1] is rather wide. This provides a large amount of moderating material so that more neutrons can be slowed and trapped within the box, but it is clear that the intrinsic efficiency is reduced by the large solid angle of the detector. Fig. 11 shows the detector response as a function of detector width and source shielding for the case of 1 cm of polyethylene moderator in front of the $^{3}$He tube. Fig. 12 shows similar data for the case of 4.5 cm of polyethylene moderator in front of the $^{3}$He tube. Both figures use 7 cm of moderator behind the tube. The data are summarized in

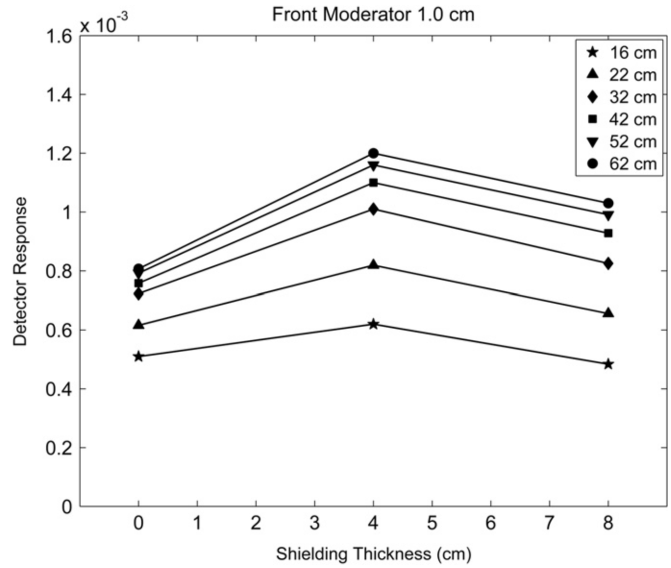


**Fig. 11.** Detector response as a function of box width for front moderator of thickness 1 cm.

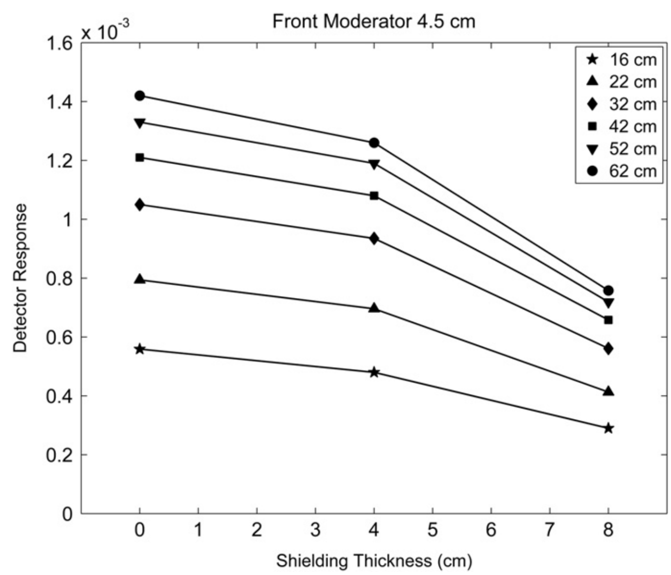


**Fig. 12.** Detector response as a function of box width for front moderator of thickness 4.5 cm.

Table 3. As anticipated, the detector response decreases as the box becomes narrower, but the intrinsic efficiency increases.

### 3.5. Dependence of the response of a narrow box detector to front moderator thickness

Another interesting piece of information is obtained when we vary the front moderator thickness in a detector where the sides are narrow. This configuration more closely resembles the physics of scintillator-based detectors where the scintillator also functions as a moderator. We take a box that has 5 cm of moderator on each side of the $^{3}$He tube with the total box width of 16 cm. This configuration has the side walls almost touching the $^{3}$He tube. The polyethylene moderator behind the tube is fixed at 7 cm and the moderator in front of the tube is allowed to vary. The results for several shielding thicknesses are shown in Fig. 13. Note that in this case, the optimum front moderator thickness drops to zero for shielding thickness above about 8 cm. Here the sides

**Table 3**
Efficiency of single $^3$He tubes in boxes of varying width. Data are for a shielded $^{252}$Cf source. All entries are for 7 cm of polyethylene moderator behind the $^3$He tube. Uncertainty in the response is 1%.

| Front moderator thickness (cm) | PE shielding (cm) | Box width (cm) | Detector response | Practical intrinsic efficiency (%) | Intrinsic efficiency (%) |
|---|---|---|---|---|---|
| 1.0 | 0 | 16 | $5.10 \times 10^{-4}$ | 9.2 | 9.2 |
| 1.0 | 0 | 32 | $7.23 \times 10^{-4}$ | 6.5 | 6.5 |
| 1.0 | 0 | 62 | $8.07 \times 10^{-4}$ | 3.8 | 3.8 |
| 1.0 | 4 | 16 | $6.20 \times 10^{-4}$ | 11.1 | 11.4 |
| 1.0 | 4 | 32 | $1.01 \times 10^{-3}$ | 9.1 | 9.4 |
| 1.0 | 4 | 62 | $1.20 \times 10^{-3}$ | 5.7 | 5.8 |
| 1.0 | 8 | 16 | $4.84 \times 10^{-4}$ | 8.7 | 12.3 |
| 1.0 | 8 | 32 | $8.25 \times 10^{-4}$ | 7.4 | 10.5 |
| 1.0 | 8 | 62 | $1.03 \times 10^{-3}$ | 4.9 | 6.9 |
| 4.5 | 0 | 16 | $5.59 \times 10^{-4}$ | 9.8 | 9.8 |
| 4.5 | 0 | 32 | $1.05 \times 10^{-3}$ | 9.2 | 9.2 |
| 4.5 | 0 | 62 | $1.42 \times 10^{-3}$ | 6.5 | 6.5 |
| 4.5 | 4 | 16 | $4.80 \times 10^{-4}$ | 8.4 | 8.6 |
| 4.5 | 4 | 32 | $9.35 \times 10^{-4}$ | 8.2 | 8.4 |
| 4.5 | 4 | 62 | $1.26 \times 10^{-3}$ | 5.8 | 5.9 |
| 4.5 | 8 | 16 | $2.90 \times 10^{-4}$ | 5.1 | 7.2 |
| 4.5 | 8 | 32 | $5.61 \times 10^{-4}$ | 4.9 | 6.9 |
| 4.5 | 8 | 62 | $7.58 \times 10^{-4}$ | 3.5 | 4.9 |

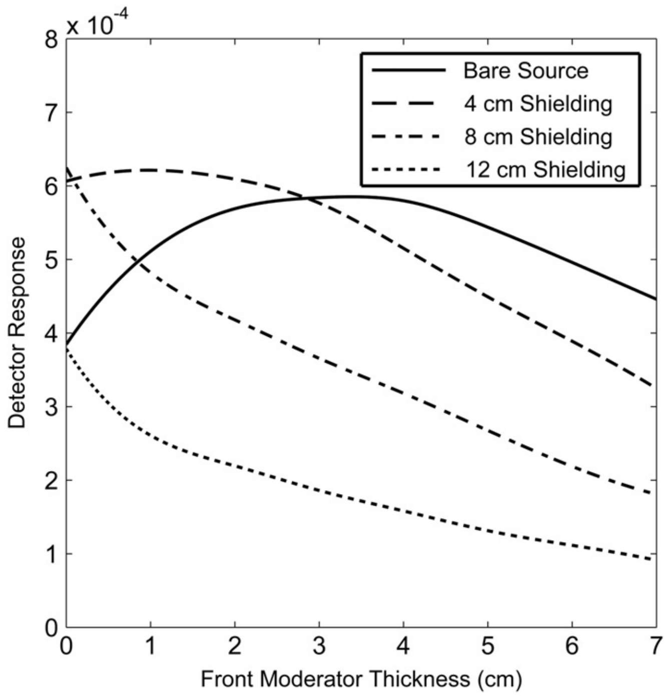


**Fig. 13.** Detector response of a 16 cm-wide box with variable front moderator thickness and a fixed back moderator thickness of 7 cm.

provide enough moderation and reflection to keep a cloud of low-energy neutrons in the vicinity of the $^3$He tube. The front moderator becomes not only unnecessary, but it actually reduces the detector efficiency by shielding neutrons from the tube.

### 3.6. Dependence of detector response on side-moderator thickness

One other parameter we can vary is the thickness of the side moderators. We present results for those calculations in Fig. 14 for overall box widths of 62 cm and 22 cm. For the wider box, we let the side thickness vary from 1 cm to 9 cm. For the narrower box, the maximum side thickness is 8 cm, as the 8 cm sides almost touch the $^3$He tube. The plot also shows results for three different shielding thicknesses: 0 cm, 4 cm, and 8 cm. The front

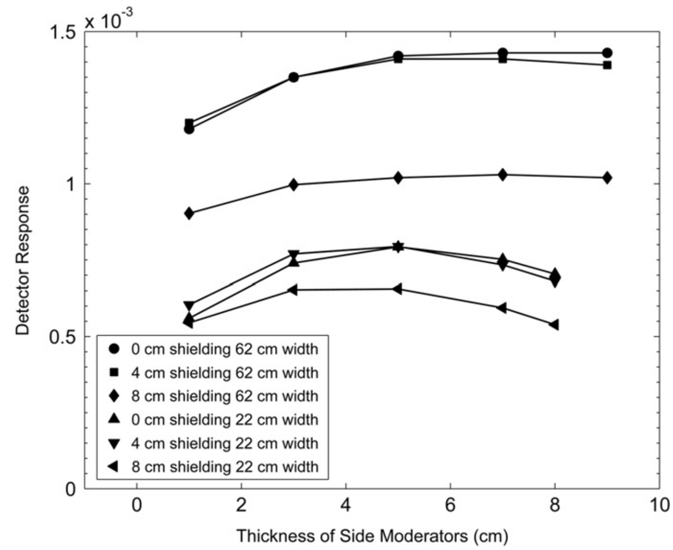


**Fig. 14.** Detector response as a function of side moderator thickness for boxes of 22 cm and 62 cm-widths.

moderator thicknesses were chosen to be 5 cm, 3.5 cm, and 1.5 cm. These were chosen so as to maximize the detector response for each shielding thickness.

We see that there are slight increases in response for wider side moderators in the case of the wide box, but the response actually decreases in the narrow box. This is likely due to the absorption of neutrons in the polyethylene near the $^3$He tube. The polyethylene acts as a sink of neutrons from the neutron cloud in the region of the tube and thereby reduces the number detected in the tube.

## 4. Monte Carlo results for a two-tube detector

In practical applications, two $^3$He tubes can be placed inside one of the standard 62 cm-wide boxes that Kouzes et al. describe. They find that the placement of the tubes within the box is a slowly varying function of position with the optimum spacing between the centers of the two tubes being about 30 cm. Placing the tubes near each other is problematic because each serves as a

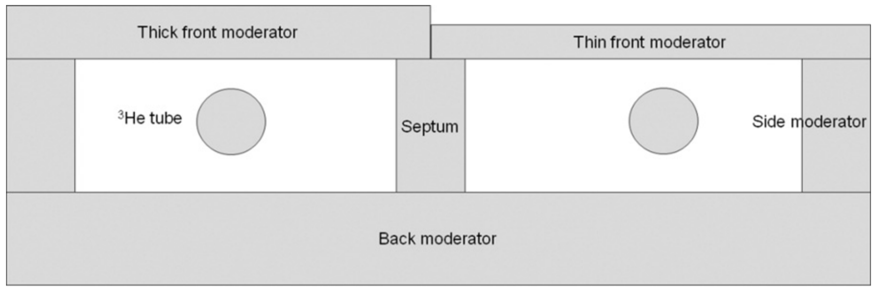


**Fig. 15.** Geometry of the two-tube box.

sink in the neutron density distribution of the other tube. Based on these ideas, we calculated the response of several variants of the two-tube box. Our variants differ from the Kouzes two-tube box in two ways. Firstly, each variant has a polyethylene septum 5 cm thick separating the two $^3$He tubes. This septum serves to provide some additional moderation while also providing structural stability. One additional benefit of the septum is that it helps isolate each tube from the other. There is hardly any variation at all in the detector response with the location of each tube within the box. A simple and suitable choice is to place each $^3$He tube in the center of its side of the box. Secondly, the front shielding of the detector is allowed to have variable thickness. For most cases, we employ shielding of a different thickness in front of each tube in the box. This geometry is depicted in Fig. 15. We also tried a "wedge" where the front shielding thickness varies linearly from 5 cm to 0 cm along the length of the box.

We will first consider the case where the thickness of the front moderator is the same for both tubes. Detector responses for front moderator thicknesses of 0 cm, 0.5 cm, 2 cm, 4 cm, and 6 cm are given in Fig. 16. For each case, polyethylene shielding thicknesses of 0 cm, 4 cm, 8 cm, and 12 cm are given. In each case the back moderator is 7 cm. The general results are similar to those for single-tube detectors. For shielding of 8 cm or larger, the optimum front moderation is about 0.5 cm. For a bare source, however, the optimum is about 4 cm. These thicknesses are slightly smaller than those for a single-tube detector because of the additional moderation offered by the septum. For a bare source, adding the septum increases the detector response by 1.6% when the front moderator thickness is 5 cm and 15% when the front moderator thickness is 0.5 cm. If the source is shielded by 8 cm of polyethylene, the effect is much smaller. The detector response actually drops by 0.9% when there is 5 cm of front moderator, but increases the response by 1.8% when the front moderator has a thickness of 0.5 cm. Therefore, the septum is helpful mostly for thin front moderators and sources with little or no shielding.

An important question is how to optimize the moderation for a given application. These results suggest that for a bare source, the optimum front shielding is around 4 cm when a 5 cm septum is present. The response is only about 1.2% better than that when using a 4.5 cm front moderator with no septum; however, as the shielding increases, the optimum front moderation drops and the additional moderation afforded by the septum becomes significant. Therefore the question of how to optimize the moderation is highly dependent on shielding. If, as is usually the case, the details of the shielding are not known *a priori*, there are two types of detectors that are most important: (1) a detector that is optimized for special nuclear materials being clandestinely transported in shipping containers and (2) a general purpose detector that is sensitive to neutrons with a wide range of energies.

In the first case, it is important to detect fission sources that will most likely be heavily shielded. If the source has little shielding, the neutron flux would be large and the source could

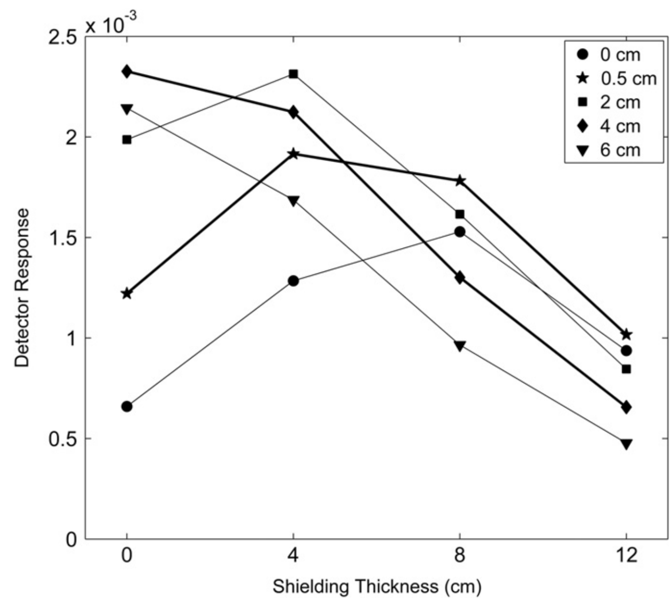


**Fig. 16.** Response of two-tube detectors with 7 cm back moderators, 5 cm-wide septa, and uniform front moderators as a function of shielding thickness.

be detected relatively easily. So for these applications, we would optimize the detector for heavily shielding. Hence, the best moderating scheme would be to have about 7 cm of polyethylene at the back of the box, 5 cm sides, a 5 cm septum, and 0.5 cm front moderators.

For the second case, the best moderation strategy would probably be to use variable front moderator thickness so that part of the detector would be optimized for bare sources and part for more highly shielded sources. Fig. 17 shows the detector response as a function of shielding thickness for several such detectors. In each case, we use 7 cm rear moderation and employ a 5 cm-wide septum. For most of the cases, we have divided the front moderator into halves, one half over each tube. We have shown results for moderators with thicknesses of 0 and 5 cm, 0.5 and 4 cm, and 1 and 5 cm. Other combinations were also tried with very similar results. We also modeled the "wedge" detector described above. For comparison, we included in Fig. 17 responses of detectors with single-width front moderation of 0.5 cm and 5 cm.

In the paper of Kouzes et al. [1], the two-tube detector is compared to a standard one-tube detector with 5 cm of polyethylene moderation both in front and behind the tube. Fig. 18 shows a similar comparison for the same moderation schemes shown in Fig. 17. As before, each of the two-tube detectors has a 5 cm-wide polyethylene septum between the two tubes and 7 cm of polyethylene behind the tubes. This figure bears out the fact that 0.5 cm moderation in front of both tubes significantly improves the detector for moderately to highly shielded sources.

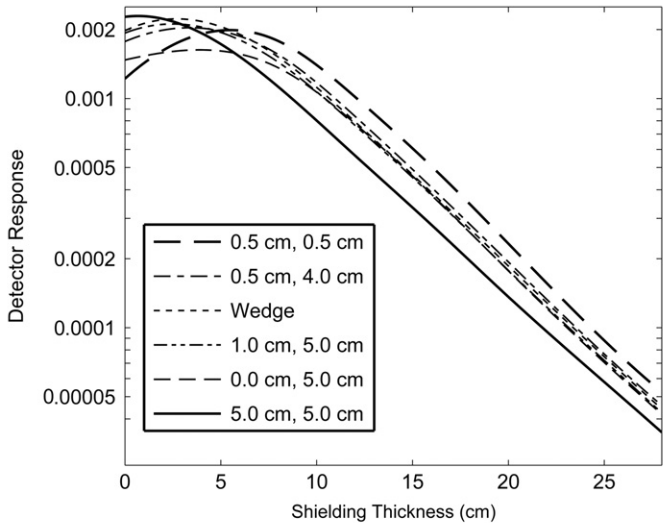


**Fig. 17.** Semilog plot of the response of several two-tube detectors with 7 cm back moderators, 5 cm-wide septa, and various front moderation schemes.

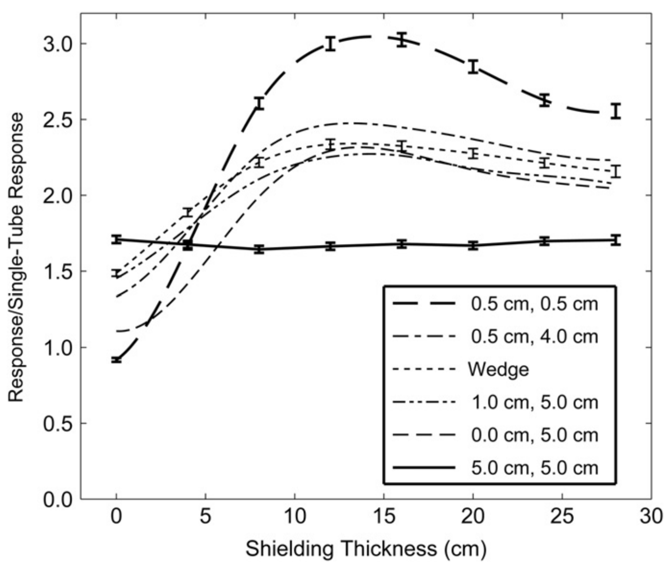


**Fig. 18.** Ratio of the response of several two-tube detectors to the response of a one-tube detector with 5 cm of PE moderator front and back as a function of source shielding.

Also note that when no shielding is used over one tube (the 0 cm, 5 cm case), the response is relatively poor for small amounts of shielding. Otherwise, there is little distinction between the other moderation schemes. In each of these cases, there is an improvement of roughly 20% in response over the detector with 5 cm of moderation over both tubes. When the thickness of the shielding is under 4 cm, the variable-thickness front moderators have slightly poorer response than when the front moderator is 5 cm in thickness. Data for the detectors with 5 cm front moderation over both sides and 0.5 cm and 4 cm front moderation are given in Table 4.

## 5. Conclusions

The moderating material placed around a $^3$He tube is an essential component of a $^3$He neutron detector. The optimum amount and placement of the shielding are highly dependent on

**Table 4**
Efficiency of two $^3$He tubes in boxes with front moderator thicknesses of (a) 0.5 cm and 4 cm and (b) 5 cm in front of both tubes. Data are for a shielded $^{252}$Cf source. All entries are for 7 cm of polyethylene moderator behind the $^3$He tubes. Uncertainty in the response is 1%.

| Front moderator thicknesses (cm) | PE shielding (cm) | Detector response | Practical intrinsic efficiency (%) | Intrinsic efficiency (%) |
|---|---|---|---|---|
| 5/5 | 0 | $2.27\times10^{-3}$ | 10.4 | 10.4 |
| 5/5 | 4 | $1.93\times10^{-3}$ | 8.8 | 9.0 |
| 5/5 | 8 | $1.12\times10^{-3}$ | 5.1 | 7.2 |
| 5/5 | 12 | $5.64\times10^{-4}$ | 2.6 | 6.6 |
| 5/5 | 16 | $2.80\times10^{-4}$ | 1.3 | 6.7 |
| 5/5 | 20 | $1.36\times10^{-4}$ | 0.62 | 6.7 |
| 5/5 | 24 | $6.85\times10^{-5}$ | 0.31 | 6.9 |
| 5/5 | 28 | $3.49\times10^{-5}$ | 0.16 | 6.9 |
| 0.5/4 | 0 | $1.77\times10^{-3}$ | 8.2 | 8.2 |
| 0.5/4 | 4 | $2.03\times10^{-3}$ | 9.3 | 9.6 |
| 0.5/4 | 8 | $1.56\times10^{-3}$ | 7.1 | 10.1 |
| 0.5/4 | 12 | $8.36\times10^{-4}$ | 3.8 | 9.9 |
| 0.5/4 | 16 | $4.09\times10^{-4}$ | 1.9 | 9.8 |
| 0.5/4 | 20 | $1.94\times10^{-4}$ | 0.89 | 9.7 |
| 0.5/4 | 24 | $9.19\times10^{-5}$ | 0.42 | 9.3 |
| 0.5/4 | 28 | $4.57\times10^{-5}$ | 0.21 | 9.2 |

shielding of a source. When placing one or two $^3$He tubes in a polyethylene box, we can draw several conclusions:

(1) Increasing box widths improves detector response, but may decrease intrinsic efficiency due to the larger solid angle. However box widths larger than the "standard" 62 cm width improve the response minimally.
(2) Increasing shielding to the sides and behind the box usually increases response as more neutrons are reflected into the $^3$He tube. Thicknesses larger than about 7 cm provide little increased response.
(3) Shielding in front of the $^3$He tube is helpful for more energetic neutrons, but substantial shielding can be detrimental for detecting neutrons from more highly shielded sources. For a bare $^{252}$Cf source, about 4.5 cm of front moderation is optimum for a one-tube box, and for a two-tube box with a 5 cm-wide septum about 4 cm is optimum. For polyethylene shielding of 8 cm or more around the source, 1 cm of front moderation is optimum for a one-tube box and 0.5 cm for a two-tube box.
(4) For portal monitors, it is best to use moderation optimized for highly shielded sources.
(5) For general-purpose neutron detectors, variable front-moderator thickness can be useful. Various schemes yield similar results for the response of a two-tube box with a septum. One option that is good is to cover one tube with 4 cm of front moderator and the other with 0.5 cm of moderator.

Although the data presented in this paper pertain directly to $^3$He tubes, some of the conclusions can be applied to other detectors as well. Any detector with a tube-like geometry will have similar characteristics to a $^3$He tube.


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