

Boron-10 Lined Proportional Counter Model Validation

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Abstract—The decreasing supply of ^3He is stimulating a search for alternative neutron detectors; one potential ^3He replacement is ^{10}B -lined proportional counters. Simulations are being performed to predict the performance of systems designed with ^{10}B -lined tubes. Boron-10-lined tubes are challenging to model accurately because the neutron capture material is not the same as the signal generating material. Thus, to simulate the efficiency, the neutron capture reaction products that escape the lining and enter the signal generating fill gas must be tracked. The tube lining thickness and composition are typically proprietary vendor information, and therefore add additional variables to the system simulation. The modeling methodologies used to predict the neutron detection efficiency of ^{10}B -lined proportional counters were validated by comparing simulated to measured results. The measurements were made with a ^{252}Cf source positioned at several distances from a moderated 2.54-cm diameter ^{10}B -lined tube. Models were constructed of the experimental configurations using the Monte Carlo transport code MCNPX, which is capable of tracking the reaction products from the $(n, ^{10}\text{B})$ reaction. Several different lining thicknesses and compositions were simulated for comparison with the measured data. This paper presents the results of the evaluation of the experimental and simulated data, and a summary of how the different linings affect the performance of a coincidence counter configuration designed with ^{10}B -lined proportional counters.

I. INTRODUCTION

The shortage of ^3He has prompted a search for alternative neutron detectors for various applications [1]. Neutron coincidence counters are currently designed with ^3He filled proportional counters, and are one of the systems for which a ^3He -free configuration needs to be identified. Neutron coincidence counters are complex, high performance systems that are used in safeguards applications to quantify the mass of plutonium or uranium in a sample [2]. Coincidence

counters require a high neutron detection efficiency and short die-away time to minimize the required measurement time and the number of accidental coincidences that are counted. A potential neutron coincidence counter configuration with ^{10}B -lined proportional counters has been modeled [3]. Boron-10-lined proportional counters are not a direct replacement for ^3He filled proportional counters because ^{10}B has a lower thermal neutron cross section than ^3He [4] (Table I), and the neutron capture material in ^{10}B -lined proportional counters is limited to a thin coating on the tube surface (approximately five ^{10}B -lined tubes, with a 1 μm lining, are required to achieve the same number of neutron capture sites as one 4-atm ^3He tube). Moreover, not all the capture-reaction products emerge into the proportional gas, causing ^{10}B -lined proportional counters to have an intrinsic loss of counting efficiency. Therefore, systems designed with ^{10}B -lined proportional counters instead of ^3He filled proportional counters can be complicated to design in a practical configuration.

Building different systems is not a realistic method of testing multiple designs; instead, simulations present an alternative technique for studying different configurations. There are various codes available for performing the simulations to predict neutron detector performance. The Monte Carlo radiation transport code, Monte Carlo N-Particle (MCNP), developed by Los Alamos National Laboratory, is a well established code for modeling detectors and detector response. For situations that require the simulation of radiation quanta other than electrons, photons and neutrons the extended version, MCNPX, was developed [5]. MCNPX was used to model the detectors and the coincidence counter configurations for this study.

Simulations are convenient for comparing multiple configurations and optimizing designs. However, before the simulation results can be used to predict the performance of physical systems the modeling methodology must be validated with measurements. Presented here are simulation methods and validation measurements for ^{10}B -lined proportional counters, and model predictions for coincidence counter configurations designed with these tubes.

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TABLE I. THERMAL NEUTRON CAPTURE REACTIONS, CROSS-SECTIONS, AND REACTION PRODUCT ENERGY FOR ^3He AND ^{10}B .

Capture Medium	Reaction	Cross-Section (b)	Q-Value (MeV)	Reaction Product Energy (MeV)	Reaction Product Energy (MeV)
^{10}B (~96%)	$^{10}_5\text{B} + {}^1_0\text{n} \rightarrow {}^7_3\text{Li}^* + {}^4_2\alpha$	3840	2.310	${}^7\text{Li}^* - 0.840$	$\alpha - 1.470$
^{10}B (~4%)	$^{10}_5\text{B} + {}^1_0\text{n} \rightarrow {}^7_3\text{Li} + {}^4_2\alpha$		2.792	${}^7\text{Li} - 1.015$	$\alpha - 1.777$
^3He	$^3_2\text{He} + {}^1_0\text{n} \rightarrow {}^3_1\text{H} + {}^1_1\text{p}$	5330	0.764	$\text{p} - 0.573$	${}^3\text{H} - 0.191$

II. BACKGROUND

The information produced with MCNPX simulations is dependent upon user specified tallies. Different tallies are available to address various situations, although not all tallies are applicable for every scenario. Counting the number of neutrons that are captured with the use of modified cell flux tallies (F4 type with cross-section multipliers) is a well proven method for determining the neutron detection efficiency when the neutron capture material is the same as the signal generating material (such as ^3He filled proportional counters [6]). However, this method is not applicable for neutron detectors where the neutron capture material and the signal generating material are separate (such as ^{10}B -lined proportional counters). An efficiency estimate based on the number of neutron captures in the detector when the signal is generated in a different material will result in an over prediction of the efficiency. Because of their sub-micron mean free paths, not all of the neutron capture reaction products escape the capture material and enter the signal generating material. To produce an accurate performance prediction for detectors with different neutron capture and signal generating materials the reaction products from the neutron capture must be tracked and then tallied in the signal generating media [7].

Simple counting tallies (F1-type surface current tallies) can be used to determine the total number of reaction products escaping the neutron capture media and entering the signal generating media. However, surface current tallies assume that every particle entering the signal generating media produces a recordable signal, and furthermore don't account for situations in which the particle escapes without depositing all of its energy. A more accurate prediction of the signal produced can be generated with pulse height tallies (F8). The F8 tallies are only applicable for situations where the particle generating the pulse does not originate in the cell where the tally is being applied (i.e., this cannot be used for ^3He filled proportional counters). A more general tally, the pulse height light (PHL) tally was introduced to overcome this limitation by combining an energy deposition tally (F6) with the F8 tally [5].

The performance of ^{10}B -lined proportional counters is strongly influenced by the lining thickness and composition. Specific information about the tube linings is traditionally proprietary to the vendors, so simulations have to address the lining as an unknown variable. Because the lining has a significant impact on the predicted performance of a detector it is beneficial to determine the lining parameters that produce the closest simulated response to what is measured. Three different linings (pure ^{10}B , B_4C , and BN), spanning a range of possible ^{10}B concentrations (from 96% to 50% ^{10}B), and a

variety of thicknesses, were simulated for this study. The thicker the lining the more neutrons get captured; however, if the lining is thicker than the range of the reaction products they will not all escape the lining and contribute to the signal (Fig. 1). As the lining thickness increases the efficiency will reach a maximum, and then begin to decrease as more of the reaction products are stopped before entering the fill gas (Fig. 2). The reaction products do not travel a fixed distance through the lining; instead they will traverse a range of distances, before they enter the fill gas. This is due to the fact that the neutron capture depth is not constant, rather the neutrons are captured throughout the tube lining, as can be seen by simulating a beam of thermal neutrons and counting the neutron captures in concentric rings of ^{10}B (Fig. 3).

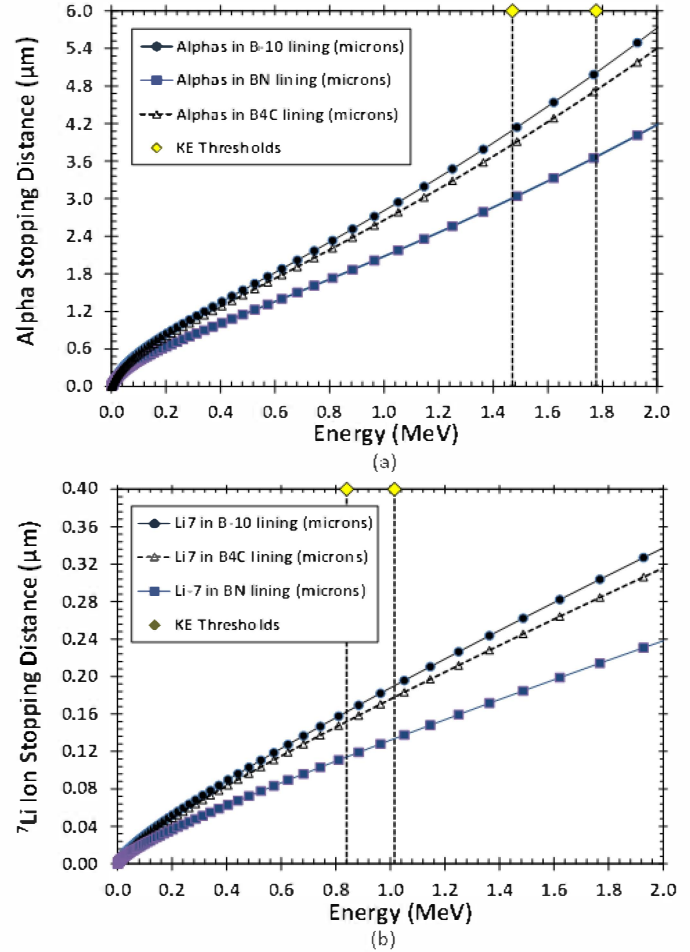


Fig. 1. Boron-10 neutron capture reaction product, alpha (a) and ${}^7\text{Li}$ (b), ranges for different tube lining materials calculated from the stopping power. The yellow diamonds indicate the location of the maximum reaction product energies for the excited state and ground state reactions.

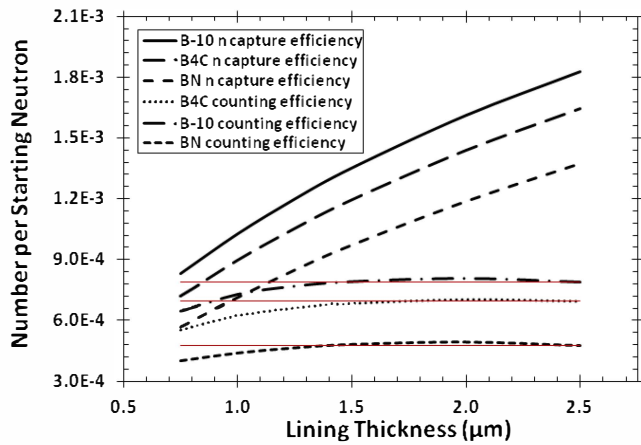


Fig. 2. Neutron capture and detection efficiency for a ^{10}B -lined tube with different tube linings (the red lines represent a constant efficiency).

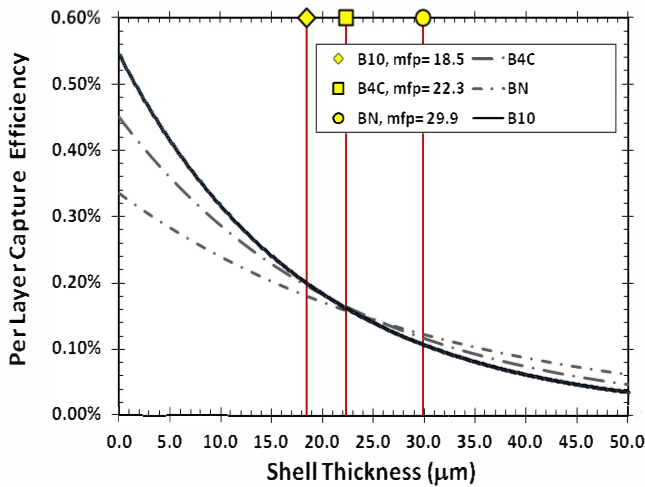


Fig. 3. Thermal neutron capture probability per 0.1- μm thick shell (inner to outer layers) for 500 layers.

The die-away time (the average lifetime of the neutron in the counter) is another important coincidence counter performance metric [2] that is affected by the tube lining thickness and composition. A thin lining leads to a longer die-away time in a full system (because it takes longer for the neutrons to be absorbed) and a thick lining leads to a shorter die-away time (because the neutrons are absorbed faster). More than one lining thickness can produce comparable detection efficiencies, thus simply simulating a lining that produces an efficiency that is in agreement with the measured efficiency may not result in accurate total system performance estimates.

The ^{10}B concentration and the range of the reaction products in the tube lining both affect the system performance. The neutron detection efficiency may not scale linearly with the ^{10}B concentration in the lining because the reaction product range changes with lining composition (as was shown in Fig. 1). Therefore, the relative contribution of the ^7Li ion and alpha particle to the total signal generated is not the same for the different lining compositions. Matching the simulated and measured spectral shapes may provide a method for identifying the lining thickness and composition that should be used for ^{10}B -lined tube models.

III. MEASUREMENTS AND SIMULATIONS

The simulation methodology used to determine the neutron detection efficiency in ^{10}B -lined proportional counters was validated by comparing simulation results to measured results for a single ^{10}B -lined proportional counter [7]. The configuration used for the model validation measurements was a single 2.54-cm diameter ^{10}B -lined proportional counter with a length of 71.1 cm. The tube was located in a polyethylene sleeve with a center opening just over 2.54-cm in diameter and outer dimensions of 10.5 cm x 10.5 cm x 61 cm, as shown in Fig. 4. The detector was centered 1.5-m from the floor. The measurements were made using a ^{252}Cf neutron source (with an activity of 4.5×10^4 n/s) housed in a polyethylene moderating “pig” (with 2.6-cm thick polyethylene walls) positioned at various distances from the detector. The models included the room structures near the detector and those that would produce the largest scattering contributions, such as the floor, walls, electronics, and detector holder

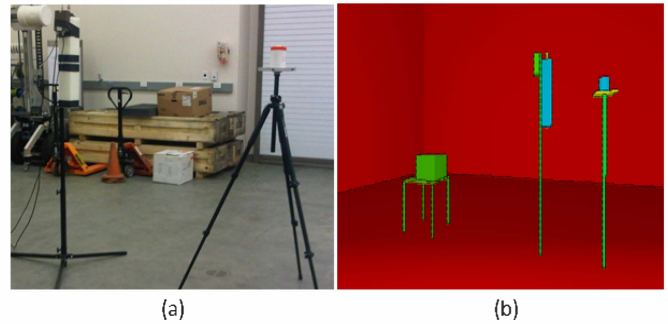


Fig. 4. Validation measurement (a) and simulation (b) setup.

Several different tallies were performed with the simulations to establish consistency between the methodologies. The most basic tally used to estimate the total neutron detection efficiency was a current tally of the ^7Li ion and alpha particle reaction products entering the proportional gas. Pulse Height Light (PHL) tallies were also applied to the reaction products in the proportional gas to provide more accurate spectral information (note that pulse height tallies would also have been appropriate in this situation). For the three simulated lining compositions both the total efficiencies and pulse height spectra were compared to the measured data.

IV. RESULTS COMPARISON

The measured pulse height spectrum (Fig. 5) clearly showed two distinct regions, as is seen when two reaction products are produced but only one is typically counted (because the reaction products are emitted in opposite directions). The first plateau is from the summation of the alpha particle and ^7Li ion energy depositions, the second plateau is the result of alpha particle energy deposition only. The estimated location of the alpha particle and ^7Li ion kinematic values (from Table I) for the excited state and ground state reactions are marked with yellow diamonds. The red triangle at 0.100 MeV marks the estimated position of the lower level discriminator (LLD) that is typically used to cutoff the gamma ray contribution to the signal. The measured and simulated spectra shown here are

for a source located 25-cm from the detector. Extending the distance between the source and the detector decreases the overall intensity of the results, but does not change the spectral shape.

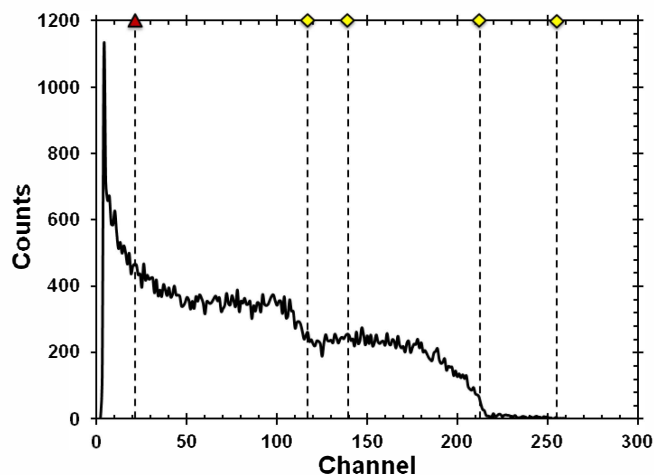


Fig. 5. Measured spectrum with a ^{10}B -lined proportional counter positioned 25-cm from a ^{252}Cf source. The yellow diamonds indicate the estimated position of the maximum energy of the reaction products for the ground state and excited state neutron capture reactions and the red triangle indicates the estimated location of a 0.100-MeV LLD.

The simulated alpha and ^7Li ion current entering the gas, shown in Fig. 6 for a $1.5\text{ }\mu\text{m}$ ^{10}B metal lining, demonstrates the same two part response as the measured spectra. However, the simulated currents show clear kinematic thresholds, without the blurring from the wall effect (and noise from the electronics) evident in the measured response. This is because the current tallies simply count the number of particles entering the gas within a specific energy bin, and do not record the actual energy deposited.

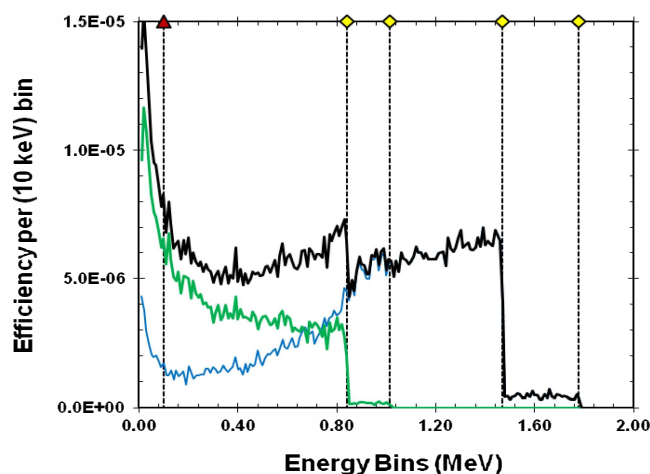


Fig. 6. Simulated ($^{10}\text{B},n$) reaction product current distributions entering the detector fill gas for a $1.5\text{-}\mu\text{m}$ ^{10}B lining with the source positioned 25-cm from the detector.

The spectra generated with the results of the PHL tallies, which estimate the amount of energy deposited in the fill gas, are a better representation of what is physically measured. The addition of the Gaussian Energy Broadening parameter, to represent the electronic noise of the circuitry, produces a simulated pulse height spectrum that is more appropriate for comparison to the measured spectrum than the current simulations. A comparison of three lining thicknesses for each of the three lining compositions simulated illustrates the differences in the pulse height spectra (Fig. 7).

While the simulated efficiency for the pure ^{10}B $0.75\text{-}\mu\text{m}$ lining produced the closest efficiency to what was measured (2% agreement at a source to detector distance of 25 cm [7]) the corresponding pulse height spectrum indicates that the actual lining was thicker than $0.75\text{-}\mu\text{m}$. The thinner linings allow more of the reaction particles to enter the fill gas with most of their energy, which results in a more distinct peak for each of the two regions. The plateaus aren't observed (especially for the alpha only region) until the lining is greater than $\sim 1.0\text{-}\mu\text{m}$ thick and the reaction products enter the fill gas with a more even energy distribution (due to energy loss in the lining). The average energy deposited by the reaction products decreases as the lining thickness increases because more of the particles have to travel further (losing energy) before entering the fill gas. The shapes of the pulse height spectra show that the $1.5\text{-}\mu\text{m}$ B_4C lining simulation is more consistent to the measured data. The simulated efficiency with a $1.5\text{-}\mu\text{m}$ lining doesn't agree as well to the measured efficiency as the efficiency simulated with a $0.75\text{-}\mu\text{m}$ thick pure ^{10}B lining [7]. However, over-estimates of the efficiency are to be expected, due to the limitation of the simulations (no signal generation or electronics simulated).

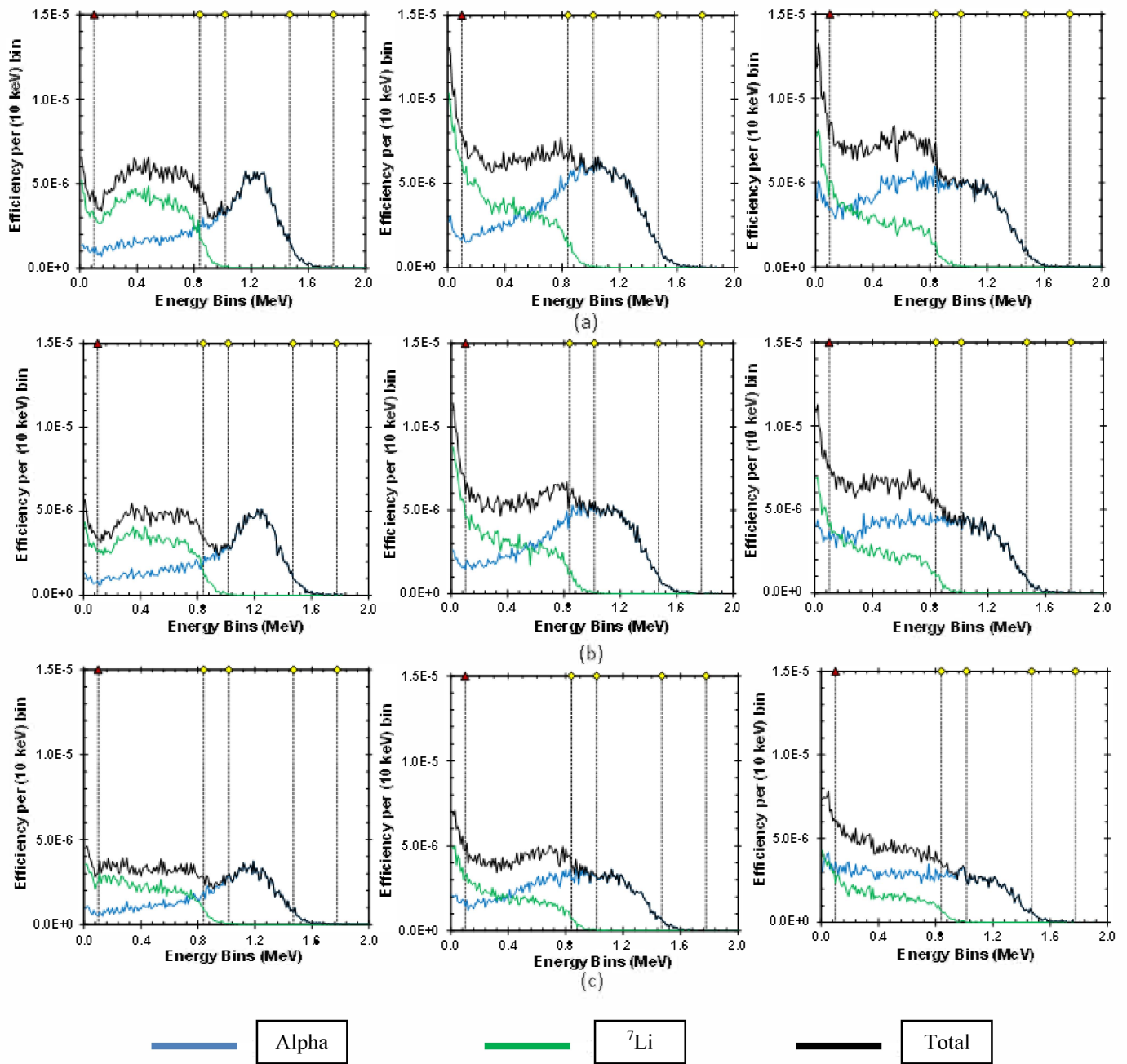


Fig. 7. Pulse height spectra, simulated with the PHL tally, for three different tube lining thicknesses: 96% enriched ^{10}B metal (a), B_4C (b) and BN (c). The lining thicknesses shown, from left to right, for each of the compositions, are 0.75- μm , 1.5- μm and 2.5- μm .

V. DISCUSSION AND FULL SYSTEM EFFECTS

The importance of simulating the tube lining accurately can be seen by varying the lining thickness and composition of the tubes in a coincidence counter configuration. A Uranium Neutron Coincidence Collar system with ^{10}B -lined tubes was previously optimized [3]. The optimized design consisted of 5 layers of ^{10}B -lined tubes (with a lining thickness of 0.75- μm); the tube length was extended to 61.0 cm to improve the system efficiency and match the standard manufactured length (Fig. 8). The optimal system is the one that produces the largest Figure of Merit (FOM); the standard FOM for

coincidence counters is the square of the efficiency divided by the die-away time [8]. Modifications to the tube lining can significantly alter the simulated system FOM, as can be seen in Table II (for the different lining compositions) and Table III (for different lining thicknesses).

It is evident in Table II that reducing the amount of ^{10}B in the system decreases the FOM (recall that the ^{10}B content of the BN lining is less than that of the B_4C lining, which in turn is less than that of the ^{10}B lining). Therefore, simulating pure ^{10}B linings may result in simulations that over-predict the physical system capabilities. The ratio of neutron detection efficiency to neutron capture efficiency (Table III, column two) decreases with increasing tube lining thickness.

However, when the entire system performance is considered (Table III, column five) the decrease in efficiency with increasing lining thickness is countered by the improvement in the die-away time. The maximum FOM for this coincidence counter configuration occurs with a lining thickness of 1.5 μm (for pure ^{10}B). Therefore, if the tube lining is thicker than the 0.75- μm lining used for the system optimization it is possible that the system performance could exceed the current predictions.

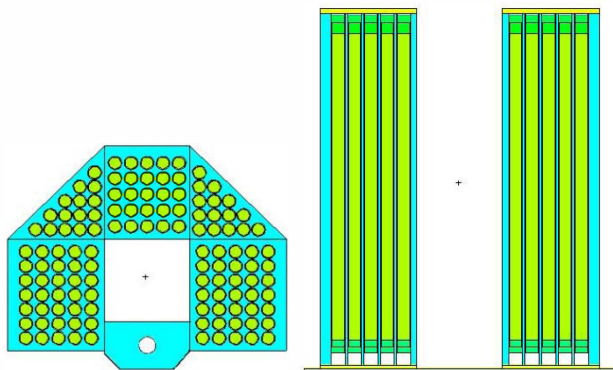


Fig. 8. Top view (left) and side view (right) of the five row ^{10}B -lined Uranium Neutron Coincidence Counter configuration with extended length tubes.

TABLE II. SIMULATED FIVE ROW ^{10}B -LINED TUBE COINCIDENCE COUNTER PERFORMANCE WITH THREE DIFFERENT TUBE LINING COMPOSITIONS.

Lining Material (1.5 μm)	ρ (g/cm ³)	$\epsilon > 0.1$ MeV (%)	τ (μs)	FOM (ϵ^2/τ)
^{10}B	2.34	17.3	77	3.9
B_4C	2.52	16.0	88	2.9
BN	3.45	12.7	107	1.5

TABLE III. SIMULATED FIVE ROW ^{10}B -LINED TUBE COINCIDENCE COUNTER PERFORMANCE WITH THREE DIFFERENT PURE ^{10}B LINING THICKNESSES.

^{10}B -Lining Thickness (μm)	ϵ /(total neutron captures)	$\epsilon > 0.1$ MeV (%)	τ (μs)	FOM (ϵ^2/τ)
0.75	0.78	18.3	124.0	2.7
1.5	0.59	17.3	77.0	3.9
2.5	0.43	14.5	55.0	3.8

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The modeled detector components should be as accurate as possible to ensure that the simulated results reflect the measured results. Simply matching the simulated and measured efficiency may not result in precise system performance predictions; multiple tube lining thicknesses will produce the same detection efficiency, but different die-away times. Simulations with a single ^{10}B lined tube demonstrated that comparing the measured to simulated pulse height spectra is a potential method for selecting the appropriate tube lining composition to model. The shape of the simulated spectra indicate that the lining in the tube used for the optimization studies was not 0.75 μm (even though that thicknesses resulted in the closest agreement between measured and simulated efficiency), so future optimization studies should consider the system performance with a thicker (> 1.0 μm) lining that has less ^{10}B (such as B_4C).