

Design and Monte Carlo Optimization of an Extended-Range Long Counter for Neutron-Yield Verification

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1. Introduction

The increasing use of accelerator-based neutron facilities has created a growing need for reliable neutron-yield measurements, particularly at energies above 50 MeV. Neutron yield is commonly estimated from the incident proton current using a predetermined conversion factor [1]. However, this indirect method depends on the proton energy, target properties, and operating conditions and may therefore require independent verification [2]. Time-of-flight measurements require pulsed beams and fast timing systems, whereas activation methods require foil irradiation, gamma-ray spectrometry, and spectrum unfolding [3].

A long counter provides a practical alternative for neutron-yield verification because of its broad and nearly energy-independent response, low gamma-ray sensitivity, directional characteristics, and relatively simple operation [4]. It can directly measure neutron fluence, independently verifying proton-current-based neutron yields.

The first long counter was developed by Hanson and McKibben in 1947, and the Precision Long Counter was subsequently introduced by De Pangher and Nichols in 1966 [5, 6]. Although conventional long counters have been extensively studied at energies below approximately 20 MeV, their response generally deteriorates at higher energies [7]. Extended-range long counters incorporating neutron-multiplying materials, such as lead and chromium, have been investigated using Monte Carlo simulations. Although these studies predict flattened responses extending beyond 100 MeV, experimental validation at comparable energies has not been widely reported. In this study, a long counter was designed and optimized to achieve a flattened response in the high-energy neutron region up to 200 MeV and to evaluate its applicability to neutron-yield verification. The upper energy limit was selected to cover the range of established high-energy quasi-monoenergetic neutron reference fields, which extend to approximately 200 MeV and are used for detector characterization and calibration.

2. Methods and Results

2.1 Reference Model and Response Calculation

The extended-range long counter proposed by Li et al. was selected as the benchmark model because its response was conceptually designed and optimized over

neutron energies extending to 1 GeV. The reported performance of this detector was adopted as a reference for the present design, and its geometry-optimization procedure was adapted to develop the proposed long counter. In the benchmark study, neutron transport below 150 MeV was calculated using SuperMC with the ENDF/B-VII.1 evaluated nuclear data library. At higher energies, FLUKA was employed with the intranuclear-cascade and pre-equilibrium models implemented in the PEANUT event generator [7].

The fluence response of the long counter to monoenergetic neutrons of energy E_n was defined as equation 1.

$$R_d(E_n) = \frac{M_d}{\phi(E_n)} = T_4 \times V \times A \times n \times \sigma_{n,a}(\bar{E}_j) \quad (1)$$

where M_d is the count recorded by BF₃, $\phi(E_n)$ is the neutron fluence rate at E_n , V is the effective volume of BF₃, A is the surface area of the source, n is the atomic density of effective volume, $\sigma_{n,a}(\bar{E}_j)$ is the microscopic cross section of (n, a) reaction, and T_4 is the track length estimate tally [7].

The incident neutron energies ranged from the thermal region to 1 GeV and were logarithmically distributed using ten energy points per decade, resulting in a total of 121 incident energy points.

2.2 MCNP6 Modeling and Detector Modification

Monte Carlo simulations were performed using MCNP6 based on the response definition and energy points described in Section 2.1. The initial detector configuration was modeled as shown in Figure 1. A monoenergetic circular planar neutron source with a radius of 25 cm was positioned at $z = 100$ [7].

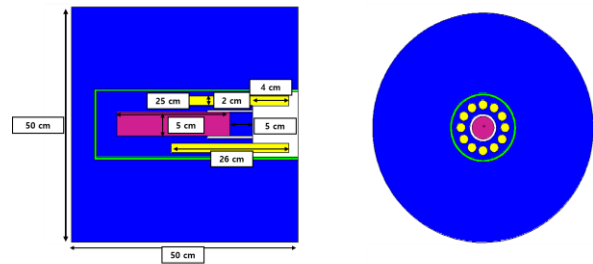


Fig 1. Benchmarked long counter model [7]

Neutrons were sampled uniformly over the source area and emitted parallel to the detector axis in the -z direction. The source energy was varied for each calculation according to the predefined incident-energy points. The resulting fluence response of the initial model is presented in Figure 3.

Subsequently, the extended-range long-counter geometry reported in the benchmark study was modified in MCNP6, as shown in Figure 2.

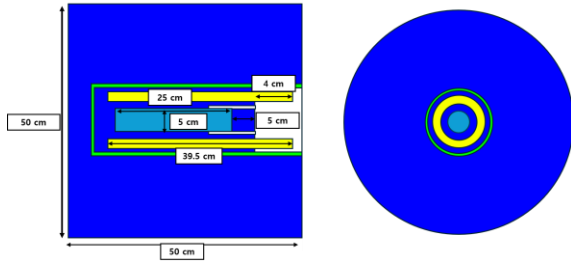


Fig 2. Modified long counter model

The benchmark long-counter geometry was reproduced and modified in MCNP6 by replacing the BF_3 counter and chromium rods with a ^3He counter and cylindrical copper component, respectively as in Figure 2. Identical source and energy conditions were applied to both models, and their calculated responses are compared in Figure 3.

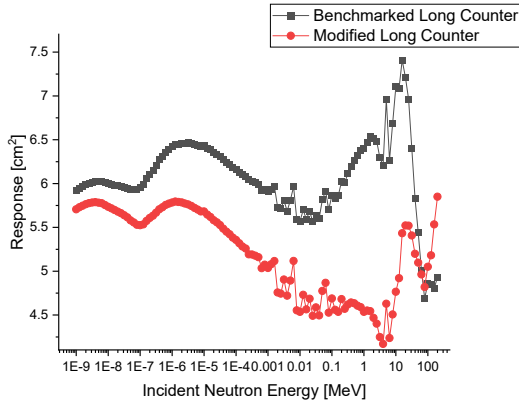


Fig 3. Responses of long counter models

2.3 Response Comparison and Performance Evaluation

Table I: Comparison of the mean response and response uniformity of the benchmark and modified long-counter models.

Model	Mean response	Stand. response	Rel. stand. Deviation [%]
Benchmark model	5.95	0.63	10.63
Modified model	4.79	0.36	7.47
Response change [%]	19.5	-	-
Uniformity improvement [%]	-	42.9	29.7

As shown in Table 1, the benchmark BF_3 -chromium model exhibited a mean response of 5.95 and a relative standard deviation of 10.63%, whereas the modified ^3He -copper model yielded 4.79 and 7.47%, respectively. Although the mean response was 19.5% lower, the response variation decreased by 42.9%, corresponding to a 29.7% improvement in response uniformity.

This improvement resulted from the different neutron-detection and secondary-neutron-production characteristics of ^3He and copper. Their combination altered neutron multiplication, moderation, and absorption within the detector, producing a flatter energy response. Because the detector gas, multiplier material, and geometry were changed simultaneously, their individual contributions could not be separately quantified.

3. Conclusions

A ^3He -copper long counter was designed using MCNP6 for neutron energies up to 200 MeV. Compared with the benchmark model, response uniformity improved by 29.7%, although the mean response decreased by 19.5%. These results demonstrate its potential for high-energy neutron-yield verification, subject to experimental validation.

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