DESIGN OF REDUCED SIZE LONG COUNTER WITH FLAT RESPONSE FUNCTION FROM FEW keV TO 20 MeV

by

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In this study, a reduced size neutron long counter with improved response function was designed using SuperMC simulation code. The main parts of the reduced size long counter are ^{3}He proportional counter, cylindrical moderators made of polyethylene, chromium metal converter, neutron absorber material and outer aluminum cover. A 1.5 cm thick layer of chromium metal was embedded into the hydrogen-rich moderator to enhance response of the long counter at high neutron energies. The radius and length of the long counter was reduced to 15 cm and 35 cm, respectively. In this design we managed to obtain a flat response function from a few keV to 20 MeV energy range. The angular response function, determined at 0.5 MeV and 14 MeV neutron energies, confirmed that the reduced size long counter designed in this study is not significantly affected by in-scattered neutrons. The reduced size long counter is suitable for use as a standard transfer instrument for monitoring neutron fluence in mono-energetic neutron fields.

Key words: neutron detector, long counter, response function, neutron fluence, SuperMC

INTRODUCTION

A neutron detector whose counting efficiency does not depend on neutron energy and the graph of its detection efficiency versus neutron energies is almost horizontal, is called a flat-response neutron detector. Although no real detector exists with a perfectly flat response over the entire range of possible neutron energies, several designs have been proposed that come close to this ideal [1]. Long counters are the most popular flat response neutron detectors that have been designed and used for neutron fluence measurements in many neutron metrologies [2-4]. Apart from the flat response function, long counters are simple to use, insensitive to photons and are influenced only to a small extent by in-scattered neutrons [5]. However, long counters require bulky neutron moderator cylinders with about 22 cm radius or more to obtain flat-response characteristics.

The larger moderator size can be an undesirable source of scattered neutrons, which causes perturbation in the surrounding neutron field [6]. Another problem of the existing long counters is that their response function falls rapidly above 5 MeV. For instance, the response function of the long counter, first introduced by Hanson and McKibben, was only flat from 10 keV up to 3 MeV [7].

Studies to improve response function and reduce the weight and size of long counters have been conducted elsewhere [8-10]. For instance, Tanimura, *et al.*, (2014) developed a portable and light-weight *neutro*n long counter [11]. They successfully reduced the long counter weight to 15 kg but, their flat neutron response ranged from 0.4 eV to 5 MeV, which is not suitable for high energy neutron measurements such as accelerator-based high energy neutron source, fusion-driven subcritical system and various types of fast neutron reactors [12-16].

In the present study a SuperMC simulation code is applied to design a reduced size long counter with improved response function from a few keV to 20 MeV. A chromium metal target is embedded in a polyethylene moderator in order to reduce the size and to enhance the response of the long counter at higher neutron energies. The designed long counter is suitable for use as standard transfer instrument for monitoring neutron fluence in mono-energetic neutron fields.

THEORY OF NEUTRON DETECTION USING LONG COUNTER

Neutrons incident on the front face of long counter, parallel to its cylindrical axis, are slowed down through inelastic scattering with hydrogen and carbon

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atoms of polyethylene moderator. As the neutrons are slowed down by the moderator, they lose energy and become thermal neutrons. These moderated neutrons interact with ^{3}He-counter through ^{3}He (n, p) ^{3}H nuclear reaction.

$$^{3}\text{He} \quad n \quad ^{1}p \quad ^{3}\text{H} \quad 0.764\ \text{MeV} \qquad (1)$$

The ^{3}He (n, p) ^{3}H reaction produces proton (p) with 0.573 MeV of kinetic energy and tritium (^{3}H) with 0.191 MeV of kinetic energy [17]. These charged particles dissipate their energy by ionizing the ^{3}He gas and create electron-ion pairs. The electrons drift toward the anode and positive ions drift toward the cathode, allowing neutron-events to be detected, processed and counted. Those neutrons incident from other directions tend to be captured in the boron and beryllium layers without raising the counts.

MATERIALS AND METHODS

Super Monte Carlo (SuperMC) code

SuperMC code for neutronics and radiation transport simulation is a general, intelligent and multi-functional program for designing radiation detectors and performing safety analyses of nuclear systems. This code has been designed, developed and distributed under license by The Institute of Nuclear Energy Safety Technology, Chinese Academy of Science (INEST, CAS) [18-20].

The latest version of SuperMC 2.3.7 professional edition is equipped with the functions of geometry and physics automatic modelling and visualization, it has different features including hybrid MC and deterministic transport method, advanced acceleration methods in transport calculation, visualization and virtual simulation [21-24].

Modelling design

A reduced size long counter employs a ^{3}He-tube, as a thermal neutron counter, with a gas pressure of 70 kPa, an active length of 25 cm and diameter of 5 cm. Inner polyethylene moderator of radius 9.5 cm, and length 30 cm surrounds the counter. Outer polyethylene moderator of 15.0 cm radius and 35 cm length follows the inner moderator. Layers of absorber materials, boron oxide and beryllium oxide of 2 cm thickness each, are inserted between the inner and outer moderators in order to prevent the counter from unwanted scattered neutrons. Figure 1 shows the model of the reduced size long counter.

Small polyethylene cylinder of 2.5 cm radius and 5 cm length is inserted in front of the counter in order to improve the response function at lower neutron energies. A chromium metal target of 1.5 cm thickness is embedded inside the inner moderator to improve the response function at higher neutron energies. Aluminum sheet is used for housing the reduced size long counter.

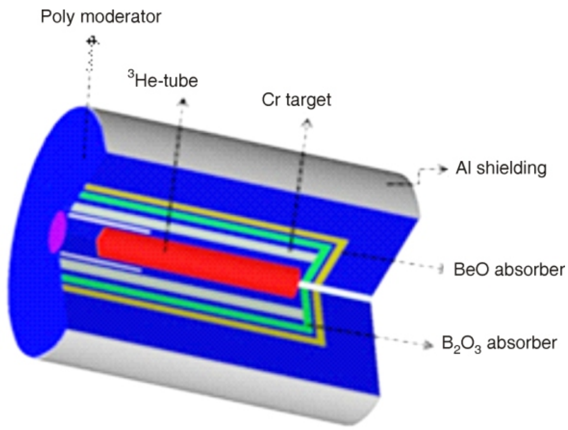

Figure 1. SuperMC model of the reduced size long counter

Adopted technique

Technique of removing a portion of polyethylene moderator and inserting a chromium metal target of small thickness, enables long counter size to be reduced and response function at higher neutron energies to be improved. This technique was first proposed by Birattari, *et al*., 1990 [25]. By inserting a 1cm thick lead metal into the moderator of rem counter, Birattari, *et al*. managed to improve the response function of rem counter above 10 MeV. However, chromium metal target is preferred and used in this study because of its small density as compared to lead.

Monte Carlo simulations

In SuperMC, the neutron source is modelled as a parallel monoenergetic beam, emitted from a plane surface situated at 100 cm away from the front face of the long counter, as shown in fig. 2. The diameter of the source is equal to 30 cm, same as the external diameter of the long counter. This arrangement ensures that all emitted neutrons strike the long counter. The response was evaluated from the ^{3}He gas density of 2.5034 10^{19} atoms/cm^{3} and 25 cm active length of the thermal neutron counter.

In all the simulations, the latest ENDF/B-VII.1 evaluated nuclear data library was used for all materials [26]. The $S(\alpha, \beta)$ treatment option was used based on MT (poly.01T) card to accurately account for thermal neutron scattering within the polyethylene moderator.

The response is defined as;

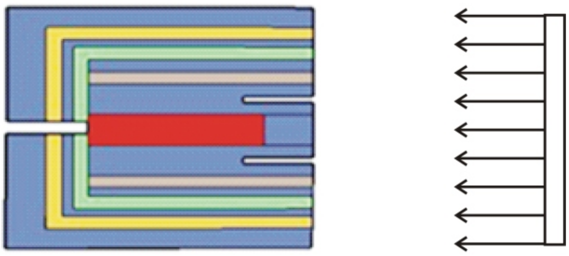

Figure 2. Simulated parallel neutron beam striking the font face of reduced size neutron long counter

$$R(E_n) \quad \frac{M}{\phi(E_n)} \qquad (2)$$

where M are the counts and ϕ E_n is the neutron fluence, with units cm^{-2}. The units of response are thus cm^2.

The fluence response, R [cm^2] of the long counter was calculated using the formula

$$R(E_n) \quad \frac{M}{\phi(E_n)} \quad T_4 \quad V \quad A \quad n \quad \sigma_{n,p}(\tilde{E}_j) \qquad (3)$$

where T_4 is the track length tally estimator for fluence with units of particles per cm^2, V – the effective volume of ^{3}He-tube, A – the source surface area, n – the atomic density in the effective volume, $\sigma_{n,p}(\tilde{E}_j)$ is the cross-section for (n, p) interaction, and $\tilde{E}_j \quad (E_{j\ 1}, E_j)$ is the energy of a slowed down neutron in the detector volume in the range j – 1 to j.

RESULTS AND DISCUSSION

Response function of the long counter

The total response function of the reduced size long counter is found to be almost flat for an energy range from 1 keV to 20 MeV (fig. 3). The mean value of the response is 3 cm^2 over the entire energy range,

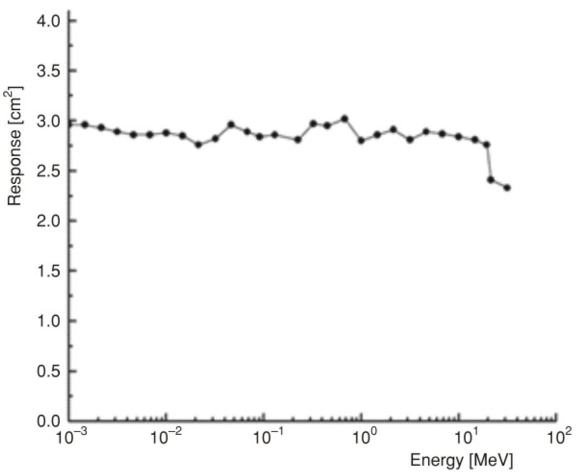

Figure 3. The response function of the designed long counter, calculated from SuperMC code

with a 5.1 % maximum relative deviation to the mean. Small polyethylene cylinder inserted in front of the thermal neutron counter plays an important role in improving the response function at lower neutron energies, by reducing the influence of thermal neutrons, which would otherwise interact with the counter and lower the response.

Chromium metal target inserted in the moderator increased the response function to neutrons with energy greater than 10 MeV via (n, $2n$) spallation reaction, which produced two lower energy neutrons, while no significant effect was observed on neutrons with energies below 10 MeV. Chromium metal was chosen as converter material because of its good neutron cross-section and low density of 8.9 g/cm^2, which makes it useful in improving response and reducing the weight and size of long counter.

Angular response function

It is essential to calculate the angular response of the reduced size long counter in order to analyze its behavior in relation to the neutron scattering effect. The angular response was calculated using SuperMC code for neutron energies at 0.5 MeV and 14 MeV. The angle of incidence was varied from 0° to 360°, at intervals of 15°, as shown in fig. 4. The angular response values obtained for each angle were normalized at 0°.

As shown in fig. 4, the reduced size long counter gives maximum response for neutrons incident at 0° parallel to front face of the counter. Incident neutrons that strike the counter on the sides or perpendicular to the front face have a poor response. This shows that the annuli of beryllium oxide and boron oxide, inserted in the moderating medium as neutron absorbing material, play an important role to suppress detection of scattered neutrons incident from the sides of the reduced size long counter.

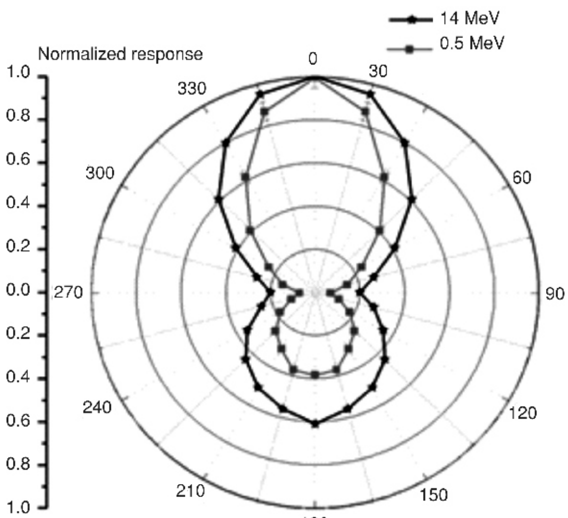

Figure 4. Normalized angular response functions of the reduced size long counter, at 0.5 MeV and 14 MeV neutron energies

Effective centre of the long counter

Effective center is the exact position at which the long counter (assumed as a point detector) measures the neutron fluence in a divergent beam. Due to their cylindrical geometry and finite depth, the exact position of effective center of long counters is not obvious. The position varies with energy, so the effective center has to be determined for particular energy spectrum in which it is used [27]. The effective center was calculated using

$$N(r_0) \quad \frac{A_s}{(r_0 \quad r)^2} \tag{4}$$

where $N(r_0)$ is the count rate of the long counter at the position of effective center, r_0. As is the long counter cross section area. Calculation of count rates was performed in vacuum using SuperMC code, in the energy range from 0.565 to 20 MeV. Long counter position was varied for 24 different source-to-detector distances, r in a step of 20 cm each, ranging from 80 cm to 540 cm. The counter rates obtained at 14 MeV neutrons energy were plotted against the source to long counter distances, as shown in fig. 5. The effective centers were then obtained using the least squares fit method with two free parameters (A_s and r_0), at each neutron energy point.

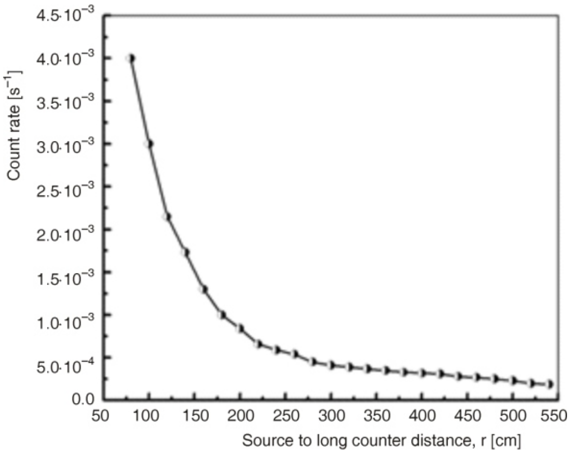

Figure 5. Count rate $N(r_0)$ *vs.* distance r from neutron point source to the long counter front face, for neutron energy at 14 MeV

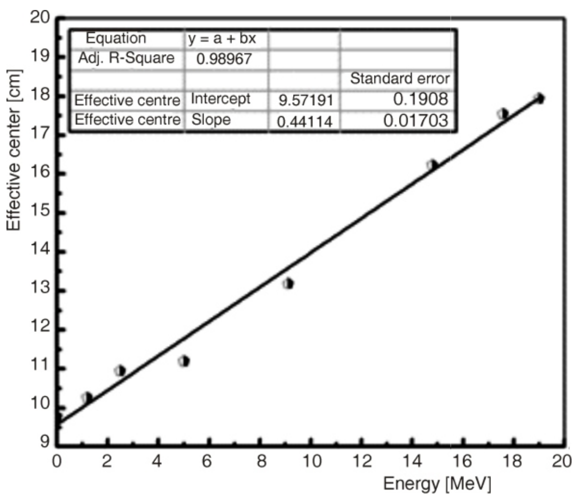

Figure 6. The relationship between effective center and neutron energies

The effective center of the reduced size long counter is 9.57 cm from the front face of the counter, as shown in fig. 6. The positions of the effective center increase with increasing neutron energy. This is due to the fact that high-energy neutrons penetrate deep into moderator, as compared to low-energy neutrons.

CONCLUSION

In this study, we reduced the size of the long counter to 15 cm in radius and 35 cm in length, which is smaller than the standard long counter of about 22 cm in radius and 46 cm in length. The dimensions, materials and geometry of the body of the long counter were all optimized in many trials through SuperMC calculations until the flat response function, for an energy range from a few keV to 20 MeV, was obtained. Through SuperMC code the angular response and the effective center of reduced size long counter were determined. The designed reduced size long counter can easily be used as a transfer standard instrument for fluence measurements in mono-energetic neutron fields.

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AUTHORS' CONTRIBUTIONS

Manuscript is equally contributed by the all four authors.

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ДИЗАЈН ДУГОГ БРОЈАЧА НЕУТРОНА СМАЊЕНИХ ДИМЕНЗИЈА СА РАВНОМ ФУНКЦИЈОМ ОДЗИВА ОД НЕКОЛИКО keV ДО 20 MeV

Применом SuperMC симулационог програмског пакета, дизајниран је дуги бројач неутрона са смањеним димензијама. Главни делови овог бројача су ^{3}He пропорционални бројач, цилиндрични модератори израђени од полиетилена, хромни метални конвертор, апсорбујући материјал за неутроне и спољашње алуминијумско кућиште. Слој хромног метала дебљине 1.5 cm додат је модератору богатом водоником како би се унапредио одзив дугог бројача при високим енергијама неутрона. Полупречник и дужина бројача смањени су на 15 cm и 35 cm, респективно. Овим дизајном успели смо да добијемо равну функцију одзива за енергије од неколико keV до 20 MeV. Функција угаоног одзива, одређена при енергијама од 0.5 MeV и 14 MeV, потврдила је да расејани неутрони немају значајног утицаја на овако дизајниран бројач. Дуги бројач са смањеним димензијама може се користити као стандардни преносни уређај за мониторинг флуенса неутрона у моноенергетским неутронским пољима.

Кључне речи: неуӣронски дешекшор, дуӣи бројач, функција одзива, флуенс неуӣрона, SuperMC