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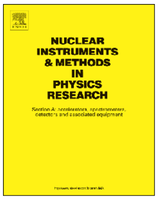

Examining the departure in response of non-point detectors due to non-uniform illumination and displacement of effective center

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ABSTRACT

A mathematical simulation approach based on the general purpose Monte Carlo N-particle transport code MCNP was developed to calculate the departure in reading of the neutron spectrometer instrument from that expected according to the inverse square law. The calculations were performed to evaluate the effects of beam divergence on the response of a 10 in. spherical device equipped with a long BF_3 counter irradiated by 11 mono-energy neutron beams. The necessary geometry correction factor, because of non-uniform illumination, for the calibration of seven polyethylene spheres with several radionuclide neutron sources, i.e. Ra–Be, ^{241}Am–Be, ^{241}Am–B and Po–Be sources was also determined. In all calculations, the displacement of effective center from the geometric center of moderating spheres, when used as an instrument for neutron fluence measurement, was quantified.

1. Introduction

Neutrons merit special attention in radiation protection because of their important quality factor, which is energy dependent. Neutron dosimetry of the personnel working in workplaces within nuclear facilities is very complex. The measurement of a neutron spectrum is neither a trivial nor a straightforward task. Suitable knowledge of the neutron spectrum is necessary to determine radiation protection quantities such as dose equivalent, ambient dose equivalent, and radiation damage [1–3].

Various neutron spectrometry systems exist; however, all have limitations [4]. Neutron spectrometers based on moderate and capture techniques are used in a variety of applications. A neutron spectrometer, Bonner Sphere Spectrometer (BSS), is used in neutron radiation protection measurement. In spite of the poor resolution of the BSS, it has played a very important role in the field of neutron spectrometry, especially in radiation protection monitoring for neutrons due to its relatively high sensitivity and wide range of the energy responses from thermal to several hundred MeV neutrons, isotropic response and easy operation [5–7]. It is based on the ability of some materials to moderate and capture the neutrons and is made up of a thermal detector, a set of polyethylene spheres and the associated electronics. This applies for an active detector like $^{10}BF_3$ or ^3He, or scintillator like $^6LiI(Eu)$ [8–10].

Evaluation of this type of spectrometer with different counters has recently been reported. Such studies [11,12] investigated the ability and suitability of a long BF_3 counter as a thermal neutron detector in BSS. The effective length of this proportional counter was 25.4 cm with the height of 28.2 cm, and also the pressure of gas filling of BF_3 was 0.92 atm at 293 K. The set of BSS used in that work consists of seven polyethylene spheres, with outer diameters of 3.5 in., 4.2 in., 5 in., 6.5 in., 8 in., 10 in. and 12 in. However, this system needed some improvements to reduce the counting of scattered neutrons. To decrease these scattered neutrons, the rear part of the BF_3 long counter that is out of sphere has been covered with boric acid. In addition in the design with smaller shadow cone, the separation distance between the neutron source and sphere was decreased.

In order to calibrate this set-up, one of the important factors is the geometry correction factor which is influenced by the source–detector distance, the source size and the detector size [13]. A geometry correction term is necessary for shorter irradiation distances to take account of the beam divergence and variation in fluence rate over the detector as a consequence of the inverse square law. It means that the measured detector response needs to be corrected so that it is representative of a plane-parallel beam irradiation.

The use of an extended BF_3 counter as the central thermal neutron detector can be challenging. When it is mounted axially with the neutron beam, rather than the problem of determination of the geometry factor, specification of the position of the effective center becomes a problem.

Axton derived a simple expression of the geometry correction for spherical device in an isotropic radiation field [14]. However, Hunt derived it from the theory presented by Axton as the following exact expression [15]:

$$F_1(d) = 1 + \delta\left\{\frac{2d^2}{R^2}\left[1-\left(1-\frac{R^2}{d^2}\right)^{1/2}\right]-1\right\} \tag{1}$$

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where R represents the radius of the detector, d is the distance between the source and the detector center, and the parameter δ attempts to account for the relative effectiveness of extra neutrons in producing a response in the detector.

In fact, $F_1(d)$ is a correction factor by multiplying which in the device reading, the effect of beam divergence on the response is resolved; however, in order to calibrate the detector response from an instrument reading, several factors characterized by a number of parameters and corrections need to be taken into consideration. The result is a value for the detector response that is independent of the experimental conditions.

Axton reasoned that δ is probably energy dependent, but independent of R/d [14] (confirmed by the Monte Carlo calculations [16,17]), and must be a value between 0 and 1. Indeed, this range for δ is when the center of thermal counter is near the center of polyethylene sphere or towards the neutron source.

The work presented here complements the mentioned studies [11,12], and uses the similar configuration with them to investigate geometry effects for source–detector combinations. In the first step, the geometry factor of a 10 in. polyethylene sphere equipped with a long BF_3 counter was evaluated for 11 different energies based on the Monte Carlo calculation by the MCNP4C code [18]. Then in continuation, MCNP calculations have been performed to investigate the effects of beam divergence on the response of 3.5 in., 4.2 in., 5 in., 6.5 in., 8 in., 10 in. and 12 in. spheres irradiated by four radionuclide neutron sources having different energy spectra.

2. Materials and method

Modeling of the BSS was carried out using MCNP4C, a general-purpose, continuous energy, generalized geometry, time dependent, and coupled neutron–photon–electron Monte Carlo transport code system. These Monte Carlo results represent an average of the contributions from many histories sampled during the course of the problem. An important quantity equal in stature to the Monte Carlo result (or tally) is the statistical error or uncertainty associated with the result. For a well-behaved tally, the estimated relative error ($\varDelta$) defined to be one estimated standard deviation of the mean divided by the estimated mean. The $\varDelta$ is also proportional to $1/\sqrt{N}$ where N is the number of histories [18].

Geometrical models were designed from detailed construction drawings. A BF_3 cylindrical proportional counter with a height of 28.2 cm (having 25.4 cm effective length) and diameter of 2.54 cm (LND2210 type) was located at the center of a polyethylene $(C_2H_4)_n$ sphere with diameter of 10 in. (Fig. 1). Details of the BF_3 tube used in the BSS were obtained from the manufacturers of that tube, LND Inc.

The response characteristics of the instrument were calculated for 11 mono-energetic neutron fields. The latest ENDF/B-VI cross-sections were used for the various materials that make up the device. In this problem, the $S(\alpha, \beta)$ thermal neutron scattering treatment is included in all the simulations to account for the chemical-binding effects of hydrogen in polyethylene in the calculations. The response of the system was calculated for both plane-parallel and divergent beam conditions. The geometry correction factor can be achieved by determining the ratio of the response of divergent beam to response of plane-parallel beam [19,20].

The modeling of the plane-parallel beam was performed in the following way: the positions of the starting particles were sampled uniformly on the surface of a disk source which is centered on and perpendicular to an axis of the sphere. All neutron tracks were parallel with the source–detector axis, and fully included the whole surface of the moderating sphere. For simulation of divergent beam, an isotropic point-like source was also inserted in distance of d from the center of sphere. To decrease the statistical error in the Monte Carlo calculation, this distance was considered equal to the radius of sphere (R); this means that the point source was placed in contact with the sphere. In this status, the geometry factor is maximum in value, and can be determined according to the following relation:

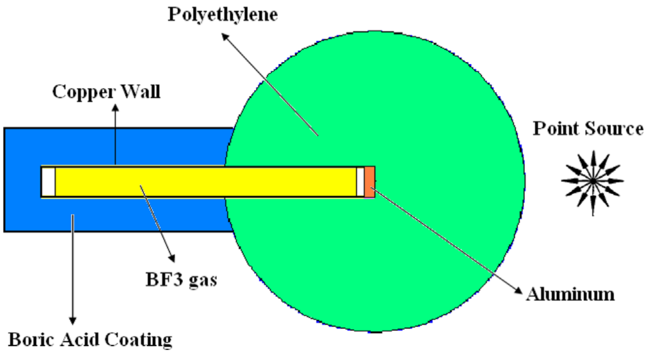

Fig. 1. View of MCNP geometry model for the 10-in. BSS with a long BF_3 counter exposed to a point neutron source.

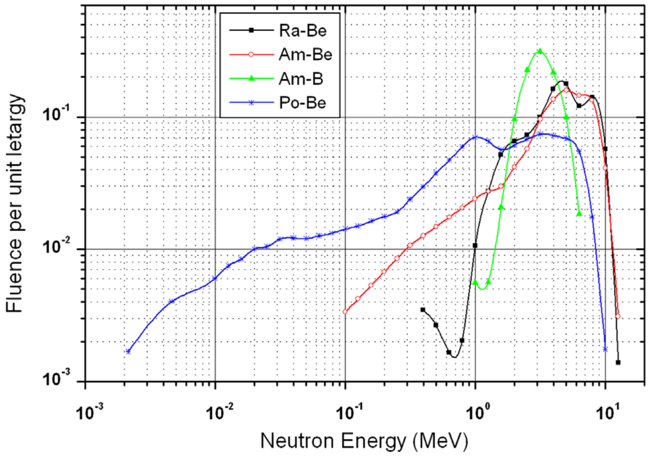

Fig. 2. The Monte Carlo simulated spectra of Ra–Be (α, n), ^{241}Am–Be, ^{241}Am–B and Po–Be neutron sources [21].

$$F_1(d)_{\max} = 1 + \delta \tag{2}$$

Obtaining the left-hand side of Eq. (2) from the Monte Carlo calculation can quantify the effectiveness parameter δ.

Usually for calibration of BSS, radionuclide neutron sources are used. In this study, for four neutron sources, e.g. Ra–Be (α, n), ^{241}Am–Be, ^{241}Am–B and Po–Be sources, the geometry factor and effectiveness parameter were evaluated for 3.5 in., 4.2 in., 5 in., 6.5 in., 8 in., 10 in. and 12 in. polyethylene spheres with the long BF_3 counter. The mean energy values of these sources were 4.78, 4.46, 3.27 and 2.04 MeV, respectively. The energy spectra of these sources shown in Fig. 2 have been used in MCNP simulation [21].

In these models, the responses of BSS exposed to the divergent and plane-parallel beams were also calculated. To achieve the response of divergent beam, the radionuclide source was considered as a point-like source in contact with the related spheres.

The second term in Eq. (1) is the additional fractional number of neutrons entering the thermal counter. This analysis assumes that the reference point is located at the geometric center of the instrument (BSS), and placed at the point of the test. For such a device, whose sensitivity is spherically symmetric, with its reference point at the geometric center, by considering the geometry