Progress in NUCLEAR SCIENCE and TECHNOLOGY, Vol. 1, p.162-165 (2011)

ARTICLE

Control of Relative Sensitivity of Track Detector-Based Neutron Dosemeter Using Radiator of Multi-Layer Structure

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The relative sensitivity of personal dosemeter composed of a detector element and a radiator, in general, has a large dependence on the neutron energy. In this report, the dosemeter characteristics have been attempted to be improved by introducing multi-layer structured radiator, where a thicker polyethylene was divided into several segments. The contribution of each radiator segment to the sensitivity was numerically calculated on a simple mathematical model in the case of normal neutron incidence, and was found to produce different energy dependence. The total sensitivity could be the sum of respective components for arbitrarily chosen thickness and position in the radiator. It was confirmed that the dependence of the sensitivity on the neutron energy could be controlled within about 15% by the specially designed multi-layer structure in the range of 0.1-20 MeV.

KEYWORDS: neutron dosemeter, radiator, sensitivity, energy dependence, degrader, multi-layer structure

I. Introduction

In recent years, accelerated protons and secondary neutrons have been utilized for various applications in material science, medical therapy, life science, and so on. A large number of particle accelerators and neutron sources have already been operated, and more are in construction or planning. Around such facilities, a considerable amount of high-energy neutrons would cause unexpected dose to radiation workers, as well as lower energy neutrons. It is very important for radiation protection to evaluate correctly the dose-equivalent of neutrons having a wide energy distribution from thermal region to near 100 MeV.

In general, neutrons are indirectly detected through interactions with a detector and radiator/converter materials. Not only the cross sections but also the factor converting neutron fluence into the personal dose-equivalent will vary largely with the neutron energy. Accordingly, any neutron dosemeter consisting of a detector element and radiator/converter has eventually the significant energy dependence. For example, the deviation in the sensitivity would amount to 300% or more for poly-allyl-diglycol carbonate (PADC) plastic track detector, commercially called as CR-39, in the neutron energy range of 0.1-15 MeV.[1)] Because an original characteristic of a detector element is very difficult to be changed drastically, an enhancement effect should be improved or controlled by designing the radiator structure.[2-4)] It is the purpose of this study to develop a systematic technique for controlling the energy dependence of dosemeter sensitivity, based on a precise analysis of the radiator effect and its mechanism.

A detailed procedure for the dosemeter design, in general, depends upon the species of detector element and the neutron energy range of interest. As an example, the goal has been set in this report that the broad width of about 300% should be reduced to 20% in the energy response characteristics of PADC-based personal dosemeter in the range between 0.1 and 20 MeV.

II. Calculation Model for Radiator Effect

PADC track detector with a polyethylene radiator can register the tracks of protons recoiled through elastic scatterings between a neutron and hydrogen atoms in polyethylene. A Monte Carlo code is often employed as a most effective tool for persuading neutron transport and energy deposition. This time-consuming calculation, however, is not suitable for optimizing several parameters such as radiator material, the number of layers, their thickness and so on. For this reason, we carried out numerical calculations in a more analytical way.

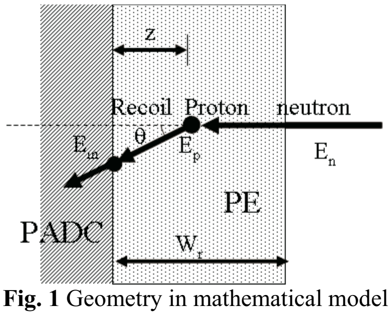

Fig. 1 Geometry in mathematical model

A geometry used in a mathematical model is shown in **Fig. 1**, where a neutron is assumed to be incident normally on the radiator with the energy of E_n. It generates a proton recoil though elastic collision of which yield per unit solid angle can be expressed by the product of the atomic density of hydrogen, N and the angular differential cross section, $d\sigma / d\Omega$. The proton is recoiled at a depth, z from the boundary between polyethylene (PE) and PADC track detector with an initial energy of $E_p = E_n \cos^2 \theta$. It

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traverses PE layer with losing its energy and reaches PADC surface with the energy, E_{in}. By using the well-known range-energy relation, $R(E_p)$, E_{in} can be obtained so that $R(E_{in}) = R(E_p) - z/\cos\theta$. The proton leaves a damage trail in PADC plastic, which is called latent track and observed as an etch-pit after chemical or electro-chemical etching process.

Two conditions should be satisfied that are ascribed to characteristics of chemically etched track detectors. One is the well-known critical angle condition, and is expressed by the equation that $\cos\theta \geq 1/V$, where V is the etch rate ratio as a function of the proton energy. The other condition is closely related with the etch-pit identification with a microscope. Usually a criterion is set for the radius of etch-pits to avoid error counts of pit-like scratch, dust and roughness on post-etched surface. Owing to these conditions, the range of the double integral of the yield is limited with respect to the solid angle and the depth. Let $h(E_n)$ be the coefficient converting the neutron fluence into the personal dose equivalent, Hp(10), then the dosemeter sensitivity, $S(E_p)$ defined as the density of counted etch-pits per unit dose equivalent, is expressed as follows:

$$S(E_n) = \frac{1}{h(E_n)} \int_0^{W_r} \int_0^{4\pi} N \frac{d\sigma}{d\Omega} d\Omega \, dz \,. \qquad (1)$$

III. Experimental Result and Comparison with Calculations

A neutron irradiation experiment was carried out in mono-energetic fields of 0.14, 0.57, 5.0 and 15 MeV neutrons, generated by a Van de Graff accelerator installed at National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan. The PADC plastic sheet of 1.6 mm thick was manufactured by Chiyoda Technol Co. Ltd., Japan.[5] The detector samples with 93 mg/cm^2 thick polyethylene (PE) were set in the reference field so as to be exposed perpendicularly to neutrons. After chemical etching in a stirred KOH solution, the surface of PADC was analyzed with a fast scanning microscopy system HSP-1000[6] consisting of an optical microscope, a line sensor, three-dimensional stage and auto-focus system. The experimental results of the relative sensitivity are shown in **Fig. 2** by four closed circles.

In order to understand its energy dependence, numerical calculations are performed by using **Eq. (1)** together with ENDF-B-IV cross section values and an estimated characteristic data for the etch rate ratio. A theoretical response curve is represented by a solid line in Fig. 2. Both measured and calculated results are found to agree with each other, especially in a lower energy region of 0.1-1 MeV. About 50% difference for neutron energies higher than 5 MeV may be attributed mainly to the error in estimating the etch rate ratio.

The theoretical response curve represented by a solid line is divided into two components according to the place where protons are recoiled, i.e. in PADC plastic and in PE radiator. The intrinsic sensitivity shown by a dotted line decreases with the neutron energy, whereas the enhancement by the radiator shown by a chain line increases up to 8 MeV and then drops rapidly.

An ideal dosemeter has no dependence on the neutron energy, namely the response curve should be a perfect straight line parallel to the abscissa. For lower energy neutrons under about 0.2 MeV, the total sensitivity is determined by the intrinsic one; which means that little effect was causes by PE radiator. Hence, in this report, the deviation in the energy dependence was tried to be reduced within a colored band. For energetic neutrons higher than about 20 MeV, prevailing techniques will have little effect, and one of countermeasures using deuterized hydro-carbon material was discussed in another opportunity.[4]

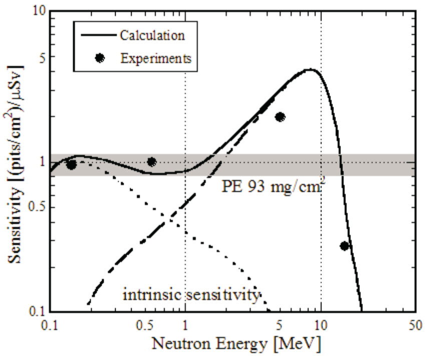

Fig. 2 Experimental and theoretical results of the sensitivity of PADC-based dosemeter

IV. Proposal of Multi-layer Structured Radiator

1. Thickness Dependence of Radiator Effect

PE is the most effective radiator material for fast neutron detection owing to its high concentration of hydrogen atoms. A determination of the radiator thickness is an important process for designing a personal neutron dosemeter in energy region of interest. The enhancement in the sensitivity of PADC-based dosemeter was calculated as a function of the radiator thickness, and is shown in **Fig. 3** for three neutron energies. The sensitivity increases with the thickness and reaches its maximum. The thickness at which the sensitivity saturates would correspond to that of the maximum range of proton recoils. It is found that PE sheet of 96 mg/cm^2 thick used in the previous experiment was insufficient for neutrons higher than 10 MeV.[7]

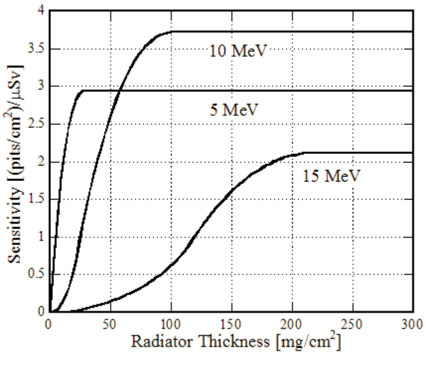

Fig. 3 Dependence of calculated sensitivity on the radiator thickness

2. Multi-layer Structure

There have been many attempts for adjusting the neutron detection efficiency by several authors[2-4, 7-9]. Matiullah *et al.*[8] suggested that the efficiency could be reduced arbitrarily by inserting intentionally a thin degrader of lead (Pb) between PADC and PE radiator. One of the present authors have succeeded in designing different energy dependence by determining carefully the thickness of both aluminum degrader and PE radiator.[9] If such a technique of degrader-radiator structure is applied to our dosemeter, the response to lower energy neutrons between 0.5 and 1 MeV is eventually lost, because an insensitive layer attached directly to the detector element would block the protons recoiled in outer PE region. Referring to these works, the following new idea has been obtained in which the radiator is divided into plural segments and insensitive layers are inserted between radiator segments.

In the case of plural radiator segments, the contribution of each segment is obtained by calculating Eq. (1) with a given set of lower and upper limits in z-integral. It is more comprehensive to see **Fig. 4,** which is derived by differentiating the ordinate of Fig. 3 with respect to the thickness. The increment in the sensitivity means how efficiently the enhancement effect works at the depth in the radiator. There are three regions colored in gray, corresponding to three typical radiator segments of 0-2, 10-20 and 100-200 mg/cm^2, respectively.

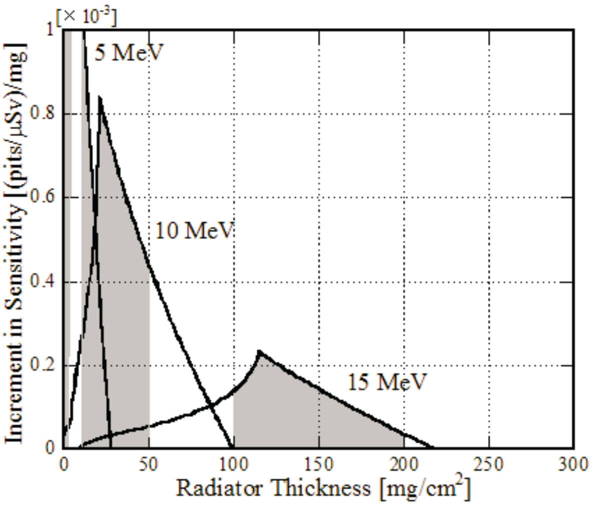

Fig. 4 Contribution of radiator effect as a function of the radiator thickness, which is derived by differentiating the curves in Fig. 3**.**

The area of the leftmost thin region represents the enhancement effect caused by a thin PE layer with a thickness of 2 mg/cm^2. As is shown in this figure, little effect is found for energetic neutrons of 10 MeV or higher. It can also be recognized with careful attention to Fig. 4 that the enhancement effect in a given segment in the radiator may be dependent largely on the neutron energy. The results of numerical calculations are shown in **Fig. 5** for three radiator segments; 0-2, 10-20 and 100-200 mg/cm^2, corresponding to the area of colored region in Fig. 4. The total effect by sufficiently thick radiator shown by a chain line in Fig. 2 could be divided by the segmentation technique, and each response curve is narrower than that in Fig. 2. It is easily found that much better energy dependence may be constructed by combining these different response curves. This is the principle of the radiator segment technique.

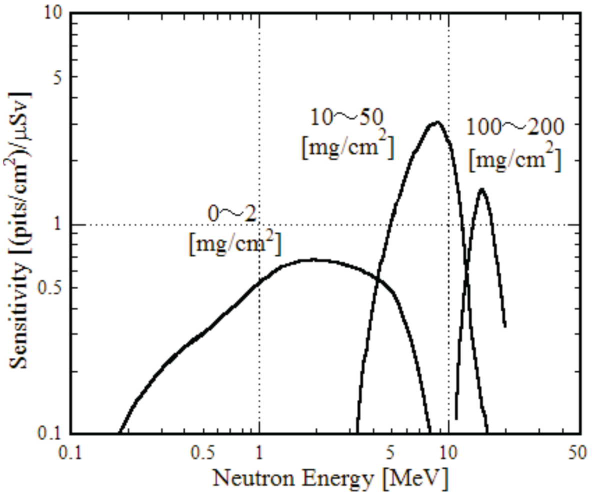

Fig. 5 Energy dependence of the sensitivity on proper radiator thickness

3. Design of Multi-layer Radiator

It is the purpose of the sensitivity control, as stated above, to keep its deviation within 15% indicated by a grayed band shown in **Figs.** 2 and **6.** The intrinsic sensitivity for a bare PADC track detector, without PE radiator, is represented by a dotted line in Fig. 6. By introducing a radiator on PADC, the sensitivity increases for neutrons of 0.5 MeV or higher, as is expected from the curve for 0-2 mg/cm^2 in Fig. 5. Its peak point of about 0.7 (pits/cm^2)/μSv near 2 MeV would become large and shift to higher energy side, with increasing the thickness of the single PE layer. However, it is not necessary to exceed the upper line of grayed band; which means the thickness of 2.8 mg/cm^2 is enough as the first PE layer as shown in Fig. 6.

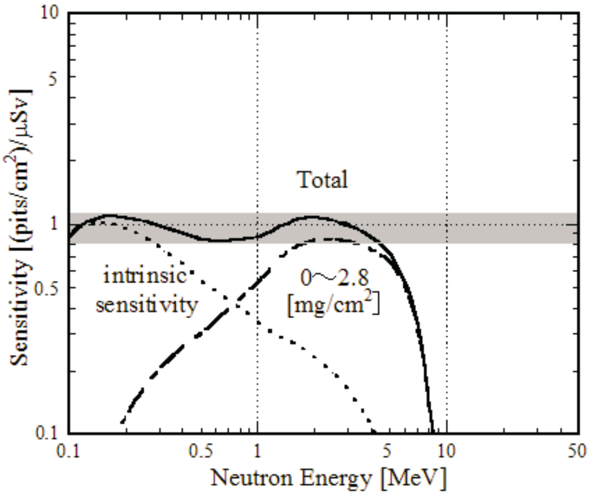

Fig. 6 Enhancement by the single-layer of PE radiator

It is found that the sensitivity stays in the band in the energy region from 0.1 to about 4.5 MeV. In the next step, the second PE segment, for which the sensitivity starts to increase at 4.5 MeV, was chosen from such response curves as are shown in Fig.5. After several calculations, the edge of the second PE was found to be 24.3 mg/cm^2, which means that there should be an insensitive layer between the first and second PE layers, namely from 2.8 to 24.3 mg/cm^2. The thickness of the second PE layer could be determined so that the peal value does not exceed the upper line of the grayed band, and found to be 15 mg/cm^2. This three-layer structure, 1st PE of 2.8 mg/cm^2, insensitive layer of 21.5 mg/cm^2 and 2nd PE of 14 mg/cm^2, will satisfies the given condition up to about 11 MeV. After repeating the same procedure, PE segments of 103-155 and 202-300 mg/cm^2 are designed as the third and fourth PE layer, respectively. **Figure 7** shows the final result, where the deviation is kept within 14%.

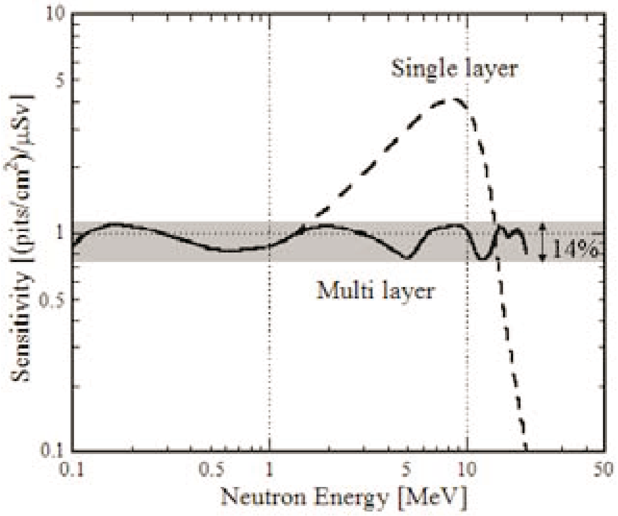

Fig. 7 Comparison of neutron sensitivity between single layer and multi-layer structure

The normal incidence was assumed in this report. It is necessary to optimize the number of layers and each thickness with a consideration of angular dependence. A preliminary result of numerical calculation shows that the average sensitivity for isotropic exposure would be reduced by about 50 % compared with that for normal incident. More detail calculations are now in progress.

V. Conclusion

In this report, we tried to establish a technique for controlling the energy dependence of personal neutron dosemeter based on PADC track detector.

The following results were obtained:

(1) The response of a personal dosemeter composed of PADC plastic and a polyethylene sheet was experimentally checked in a reference neutron field. The relative sensitivity to 5 MeV neutrons was much higher than that to lower-energy neutrons. Then, the goal of flat energy response was set in a region between 0.1 and 20 MeV.

(2) A mathematical model was introduced to calculate the dosemeter sensitivity, and its effectiveness was confirmed from a comparison between theoretical and experimental values.

(3) Thickness dependence of the radiator effect was calculated by using the model. Differentiating this curve, a contribution of PE radiator at a depth could be understood.

(4) The sensitivity of an arbitrary chosen segment of PE radiator could be found to have a different dependence on the neutron energy.

(5) The multi-layer structure was proposed to control the energy dependence, and a procedure was actually demonstrated to keep the variation within 15%, in the case of normal incidence on the detector.

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