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Abstract

We developed a real time personal neutron dosimeter by using two types of silicon p-n junction detectors, thermal neutron sensor and fast neutron sensor. The thermal neutron sensor which is $^{10}$B doped n-type silicon with a polyethylene radiator mainly counts neutrons of energy from thermal to 1 MeV, and the fast neutron sensor which is p-type silicon with a polyethylene radiator is sensitive to neutrons above 1 MeV. The neutron sensitivity measurements revealed that the dosimeter has a rather flat response for dose equivalent from thermal to 15 MeV, excluding a drop from 50 keV to 1 MeV. In order to get the conversion factor from counts to dose equivalent as accurately as possible, we performed the field test of the dosimeter calibration in several neutron-generating fields. By introducing the two-group dose estimation method, this dosimeter can give the neutron dose equivalent within about 50 \% errors.

Introduction

The development of personal neutron dosimeters that indicate the dose equivalent in real time becomes important with the increased number of people working in high intensity, high energy accelerator facilities and nuclear fuel reprocessing plants. To produce an instrument that is small and light, and has enough sensitivity to neutrons is a difficult task.

Recently, two types of direct-reading personal neutron dosimeters have newly been developed. One is a bubble-damage polymer detector which uses tiny, superheated droplets of a detector liquid uniformly dispersed in a firm elastic polymer developed separately by Ing et al.\textsuperscript{1)} and Apfel et al.\textsuperscript{2,3)} The other is a silicon dosimeter developed by Nakamura et al.\textsuperscript{4)} which uses two types of silicon p-n junction detectors fabricated by Fuji Electric Co. Ltd. This dosimeter had low neutron sensitivity and we further realized the dosimeter of higher sensitivity by using larger silicon detector of 1 cm x 1 cm. One type, thermal neutron sensor, is an n-type silicon crystal on which a p\textsuperscript{+} layer of elementary boron enriched 94\% $^{10}$B is deposited in about 1 mm thickness and the other type, fast neutron sensor, is an p-type silicon crystal without boron coating. Both crystals are contacted with 0.08 mm thick polyethylene
radiators and in some cases only the thermal neutron sensor is covered with a polyethylene moderator of 10 mm thickness. Figure 1 shows a schematic cross sectional view of the dosimeter.

Neutron Sensitivity Measurement

A. Experimental

The neutron detection efficiencies of these two sensors were measured in the monoenergetic fast neutron field at the Fast Neutron Laboratory of Tohoku University. Monoenergetic neutrons of five discrete energies of 200 keV and 550 keV by the Li(p, n) reaction, 1 MeV by the T(p, n) reaction, 5 MeV by the D(d, n) reaction and 15 MeV by the T(d, n) reaction were produced using the Dynamitron accelerator. The dosimeter was placed in the forward direction to the beam axis. The neutron fluence incident on the dosimeter was measured with a $^{235}$U fission chamber placed in front of the dosimeter. Since the $^{235}$U fission chamber is sensitive to low energy neutrons scattered from the surrounding objects, a hydrogen proportional counter which was adjusted to count neutrons above several tens of keV was also placed at about 45 deg to the beam axis as a subsidiary neutron fluence monitor. The efficiency measurement of the thermal neutron sensor to thermal neutrons was done in the experimental hole of the TRIGA-II type reactor of Rikkyo University and in the thermal neutron field leaked from a graphite pile of Institute of Radiation Measurements. Thermal neutron fluence incident on the dosimeter was measured with a gold activation foil. The dosimeter encapsulated two silicon sensors was placed in front of a commercially available ellipsoidal water phantom, 45 cm high and 30 cm wide. The output pulses due to alpha particles produced by the $^{10}$B(n, α) reaction and protons recoiled from the elastic collision in the polyethylene radiator were measured with a multichannel analyzer.

B. Results

Figure 2 shows the neutron detection efficiency of the dosimeter as a function of neutron energy. The measured results are the sum of the integrated counts given by the thermal neutron sensor and the integrated counts of the fast neutron sensor multiplied by a factor of 40, in order to get the detection efficiency as close as possible to the fluence-to-dose-equivalent conversion factor given by ICRP-51 which is drawn in a dotted line. In Fig. 2, the results calculated with the MORSE-CG code are also shown to compare with the results measured by the thermal sensor. Since the recoil proton pulses from the radiator were not included in the MORSE calculation, this comparison is valid only in the energy range below 1 MeV, where it shows good agreement between experiment and calculation.

This dosimeter which combines two silicon sensors has neutron sensitivity over a wide energy range from thermal to 15 MeV and also has good energy response, excluding a large deviation from the ICRP-51 response curve in the energy range from 50 keV to 1 MeV, as seen in Fig. 2.
Field Test of Dosimeter Response

Because of the deviation of the dosimeter energy response from ICRP-51, it is necessary to determine the conversion factor from counts to dose equivalent values to be fitted in various spectral fields necessary for neutron monitoring. For getting this conversion factor, we have been doing the field test of the dosimeter calibration in the following typical neutron fields having known neutron energy spectra; 1) moderated $^{252}$Cf neutron source calibration field, 2) a beam extraction hole of the fast neutron source reactor of University of Tokyo, 3) labyrinth from the 40 MeV cyclotron room of Tohoku University, 4) MOX (Mixed Oxide) fuel handling room of Power Reactor and Nuclear Fuel Development Corporation and so on.

In these field tests, the dosimeter was fixed on the water phantom faced to the neutron beam direction. The measured counts were compared with the dose equivalent values obtained from the dose equivalent counters (rem counters) of Studsvik 2202D and Fuji Electric NSN1 which were used as neutron dose monitors. Considering the energy response of the dosimeter shown in Fig. 2, we propose the following two-group dose estimation method which divides neutrons into two energy groups of thermal to 1 MeV and above 1 MeV. The total neutron dose equivalent $H$ is given by adding the neutron dose equivalent of energy higher than 1 MeV, $H_1$ and that of energy lower than 1 MeV, $H_2$. $H_1$ and $H_2$ are given by

$$H_1 = K_1 C_1$$
$$H_2 = K_2 (C_2 - R C_1)$$

for $E_n \geq 1 \text{ MeV},$

for $E_n \leq 1 \text{ MeV},$

where $C_1, C_2$ are the respective counts measured with fast sensor and thermal sensor, $K_1, K_2$ are the respective conversion factor in units of $\mu\text{Sv}/\text{count}$, $R$ is the correction factor which subtracts the contribution of fast neutrons above 1 MeV counted in thermal sensor. From the results of these field tests, the $K_1$ and $R$ values were found to be fixed as 2.0 and 0.5, while on the other hand, $K_2$ had to be three different values corresponding to the neutron energy spectra.

Table 1 summarizes typical examples. The $K_2$ value becomes smaller with decreasing the mean neutron energy in the test neutron fields. Figures 3 to 5 show the neutron energy spectra in lethargy units. The $K_2$ value of 2.0 in Table 1 corresponds to the field close to fission neutron spectrum which is appeared in bare $^{252}$Cf neutron source field in Fig. 3 5), and in PuO$_2$ -UO$_2$ mixed fuel field in Fig. 4 6). The $K_2$ value of 0.075 corresponds to the field close to $1/E$ slowing-down neutron spectra which is seen in polyethylene-moderated $^{252}$Cf neutron source field in Fig. 3 and at the point 2 in the entrance of the labyrinth connected to the accelerator room in Fig. 5 7), and that of 0.015 to the well-thermalized neutron field at the point 7 near the exit of labyrinth in Fig. 5. Table 1 also gives the ratio of dose equivalent values given by this dosimeter and those by the rem counters. By using the
conversion factors of $K_1$, $K_2$ and $R$ shown in Table 1, it was revealed that this dosimeter can give the neutron dose equivalent within about 50 % difference at maximum.

Conclusion

The characteristics of our newly-developed real-time personal neutron dosimeter based on the present study can be summarized as follows:

1) From these field experiments, this dosimeter will be possible to give the neutron dose equivalent within about 50 % errors in the energy range from thermal to 15 MeV.
2) The dosimeter is insensitive to gamma rays up to about 100 mSv/h.
3) The size and weight of the dosimeter is about 100 mm x 60 mm x 20 mm and about 150 g, respectively, which is small and light enough for personal dosimeter.

References

6) unpublished

Table 1. Summary of field test of dosimeter calibration.

<table>
<thead>
<tr>
<th>Field</th>
<th>Mean Neutron Energy (MeV)</th>
<th>K1 (µSv/count)</th>
<th>K2 (µSv/count)</th>
<th>Ratio ¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{252}$Cf(bare)</td>
<td>2.11</td>
<td>2.0</td>
<td>2.0</td>
<td>1.11</td>
</tr>
<tr>
<td>PuO2</td>
<td>1.8</td>
<td>2.0</td>
<td>2.0</td>
<td>1.09</td>
</tr>
<tr>
<td>$^{252}$Cf(polyethylene)</td>
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<td>2.0</td>
<td>0.075</td>
<td>1.40</td>
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<tr>
<td>Labyrinth No. 2</td>
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<td>2.0</td>
<td>0.075</td>
<td>0.71</td>
</tr>
<tr>
<td>Labyrinth No. 7</td>
<td>0.012</td>
<td>2.0</td>
<td>0.075</td>
<td>1.32</td>
</tr>
</tbody>
</table>

¹) Ratio of equivalent values given by this dosimeter to those by rem counter.
Fig. 1. Schematic cross sectional view of two silicon sensors.

Fig. 2. Comparison of measured and calculated neutron detection efficiencies of the dosimeter, together with the ICRP-51 fluence-to-dose-equivalent conversion factor.
Fig. 3. Neutron energy spectra of bare, iron-moderated and polyethylene-moderated $^{252}$Cf neutron source fields [ref. 5].

Fig. 4. Neutron energy spectrum of PuO$_2$-UO$_2$ mixed oxide nuclear fuel field [ref. 6].
Fig. 5. Neutron energy spectra at several points in the labyrinth connected to the 40 MeV cyclotron room [ref. 7].