Performance Test of the Electronic Personal Neutron Dosemeter in Neutron Fields Simulating Workplaces of MOX Fuel Fabrication Facilities

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Abstract. Recently, several electronic personal dosemeters (EPDs) capable of measuring neutron dose equivalents were developed and have appeared on the market. The authors initiated the present study to assess performance of neutron EPDs. The EPD selected for this study was NRY21, manufactured by Fuji Electric Systems Co., Ltd. This dosemeter uses two silicon semiconductor detectors (a fast neutron sensor and a thermal neutron sensor) to provide wide measurable energy ranges from thermal to several tens of MeV. In the test, we focused on the energy and angular dependences of dose equivalent responses because they were of great importance in neutron dosimetry in work environments. Measurements of dose equivalent responses were performed in a moderated neutron field simulating neutron spectra likely to be encountered in workplaces at MOX fuel facilities. As a result, the dose equivalent responses of this EPD were evaluated to be 0.7 to 1.1 for a normal incidence of neutron irradiation. This is a satisfactory performance for neutron monitoring.

KEYWORDS: electronic personal dosemeter (EPD); neutron; thermoluminescence albedo dosemeter; performance tests; moderated neutron field; MOX fuel facility

1. Introduction

Recently, several electronic personal dosemeters (EPDs) capable of measuring neutrons dose equivalents were developed and have become available on the market. EPDs offer a number of advantages such as simultaneous measurements of photon, beta and neutron doses, the ability to set dose rate/dose alarms, computer interfacing with radiological control systems, etc. They appear to be promising devices which can replace or supplement the passive personal dosemeters; however, they also pose problems to some extent in terms of the accuracy of their measurements of neutron dose equivalents [1-2]. Although it is generally required for active personal neutron dosemeters to respond to dose equivalents to within a factor of two (although the latest IEC criteria [3] are actually more complicated than this) over a wide (or rated) energy and angle range, the overall performances observed in tests at monoenergetic neutron fields were less satisfactory than those for photon dosemeters. Among most of currently available EPDs for neutrons, the best dosemeter still depends on the neutron spectrum in which the measurement of the neutron dose equivalent is made. In other words, it is more practically important to establish the relationship between the neutron dose equivalent and the response of the dosemeter in the neutron field in which it is used. This idea is partly supported by the IEC’s recommendation to test the responses of dosemeters to simulated workplace neutron fields as an optional test in addition to their responses to monoenergetic neutron or radioisotopic neutron irradiation [3], and also by the recent comprehensive studies performed under the framework of the EVIDOS project [4-5].

The Nuclear Fuel Cycle Engineering Laboratories (NCL) of the Japan Atomic Energy Agency (formerly, Japan Nuclear Cycle Development Institute) operates the pilot plants for spent fuel reprocessing and MOX fuel fabrication. In personal monitoring, thermoluminescent dosemeters (TLDs) have been utilized as the dose-of-record dosemeters since the 1970s. TLDs have been well characterized and understood, and hence have also functioned successfully in routine monitoring programs. Moreover, in the reprocessing plant, EPDs for photons have been used as supplemental dosimeters and have become firmly entrenched as the preferred method for achieving ALARA goals,

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while in the MOX fuel fabrication facilities no EPDs capable of measuring neutrons and photons are employed yet, mainly due to the inadequacies in their neutron dose measurement capability. For this reason, the authors initiated the present study to assess the performances of neutron EPDs to determine their capacity to be used as dosemeters supplemental to TLDs. From a practical point of view, we focused on their dose measurement accuracy and suitability for use in work environments in MOX fuel facilities. The neutron EPD assessed in this study is the NRY21 electronic neutron/gamma personal dosemeter manufactured by Fuji Electric Systems Co., Ltd. This dosemeter uses two silicon semiconductor detectors to cover a wide measurable neutron energy range from thermal to several dozen of MeV. This paper presents the test results for the NRY21 dosemeters in moderated neutron fields simulating the fields likely to be encountered at workplaces in MOX fuel facilities.

2. Dosemeter description

2.1 NRY21 Electronic Personal Neutron/Gamma Dosemeter

The model NRY21 electronic personal neutron/gamma dosemeter is shown in Fig. 1. The history of this dosemeter can be traced back to the late 1980s; since then, a great deal of research and progress reports on its basic characteristics and field-test results at various nuclear installations have been published [6-11].

The dosemeter uses two silicon semiconductor detectors (a fast neutron sensor and a slow neutron sensor) for neutron measurements. Each sensor is a $10 \times 10 \text{ mm}^2$ p-type silicon crystal on which an amorphous silicon is deposited. The fast neutron sensor detects recoil protons produced from a polyethylene radiator of ~0.08 mm (~80 µm) in thickness by neutron-hydrogen nuclei interactions. The slow neutron sensor detects alpha- and Li-particles produced from a natural boron layer formed on the crystal. The fast neutron sensor is sensitive to neutrons > ~1 MeV, which corresponds to neutrons with energies above the threshold level (set at ~0.9 MeV) for neutron- and gamma-pulses discrimination. In contrast, the slow neutron sensor, categorized as a typical albedo detector, is sensitive to neutrons < ~1 MeV, specifically from thermal to ~10 keV. The personal dose equivalent ($H_p(10)$) is derived by adding the dose equivalents for two neutron energy intervals, namely a fast component $H_f (> 1 \text{ MeV})$ and a slow component $H_s (< 1 \text{ MeV})$, which are separately measured by the fast and slow neutron sensors, respectively. This relatively simple dose evaluation is advantageous for highly reliable operation and good maintainability. In the factory setting, the fast and slow neutron sensors are calibrated using a bare $^{252}\text{Cf}$ neutron source and a graphite pile-moderated thermal neutron field, respectively [11].

![Figure 1: External view of the NRY21 dosemeter.](Size: 103 × 55 × 15 mm³, weight: 110 g with battery)

The energy dependence of the combined dose equivalent response (dosemeter-indicated $H_p(10)$ per reference $H_p(10)$) of this dosemeter at normal incidence is shown in Fig. 2, which is reproduced from Fig. 4 of Nunomiya [11]. Although this dosemeter has two discrete neutron-measurable ranges, showing unity at two energy points calibrated by $^{252}\text{Cf}$ (~2 MeV) and thermal neutrons, it exhibits a significant response dip around several hundred keV. This is attributed to the low counting efficiencies for both recoil protons (compatible with good signal discrimination) and albedo neutrons in such
incident neutron energy regions. The energy dependence of the combination response over the energy region from thermal to MeV is similar to that of a nuclear track emulsion dosemeter (NTED) and thermoluminescent albedo dosemeter (TLAD). It is well known [12] that NTEDs are essentially insensitive to neutrons below ~800 keV, and therefore are suitable only for occupational environments in which the majority of dose equivalents comes from neutrons with energies above 1 MeV or in which the fraction of neutrons below 1 MeV is known. It is anticipated that the principal weakness of the NTEDs plus TLADs combination dosimetry system will consequently apply to that of the NRY21 dosimeters. d’Errico [13] suggested that the NRY21 dosemeter can seriously underestimate the neutron dose equivalent in the energy region from 10 keV to 1 MeV, which is important for some nuclear power plants.

Figure 2: Personal dose equivalent response of the NRY21 dosemeter as a function of neutron energy in angles of normal incidence. This graph is reproduced from Fig. 4 of Nunomiya [11].

2.2 Panasonic UD-809 Thermoluminescence Albedo Dosemeter

For comparison with the NRY21 dosemeters, we also tested the Panasonic UD-809 thermoluminescence albedo neutron dosemeter. This dosemeter has been used as the dose-of-record neutron dosemeter for a long time at nuclear facilities of the NCL.

The UD-809 TLAD has four elements of Li$_2$B$_4$O$_7$(Cu) phosphor. Element 1 is enriched in $^7$Li and $^{11}$B, and is insensitive to neutrons. Elements 2, 3, and 4 are enriched in $^6$Li and $^{10}$B and are very sensitive to neutrons. The reading to incident neutrons can be derived from readings of four elements with different filtration by cadmium and tin in front and behind the elements.

3. Test Methods

3.1 Test Facility Description

The neutron irradiation tests were performed at the Instrument Calibration Facility (ICF) of the NCL. The ICF was specifically constructed to provide in-house calibration of the radiation-measuring devices being used for radiological monitoring in the reprocessing plant, MOX fuel fabrication facilities and other related research laboratories of NCL. The calibration facility is a one-story building made up of two irradiation rooms. The low-scatter neutron irradiation room is 13.0 m × 12.5 m × 5.3 m (height from the ground level) equipped with an open pit of 2.0 m in depth. The roof and walls which face the outside of the facility are made of an autoclaved aerated concrete with a thickness of 10 cm for reducing room-scattered neutrons. The floor is made of a steel grating which acts as a pseudo ceiling for the pit room (basement), which has an 8 m × 12 m concrete floor and four concrete walls of 2-m in height. Although the radio-isotopic neutron sources of $^{252}$Cf (nominal activity of ~1 GBq) and $^{241}$Am-Be (~111 GBq) are generally used for routine calibration of the neutron-measuring devices, the moderated neutron calibration field – what we call the ‘simulated workplace neutron field’ – consisting of a $^{252}$Cf source plus moderators was also established for determining the calibration factors specific to workplaces and for the performance testing of neutron dosemeters [15]. Moderators
and a $^{252}$Cf source were arranged to mimic the neutron spectral and dosimetric conditions of workplaces, based on the neutron spectral measurements at the representative workplaces of ~70 points.

**Figure 3** schematically shows a vertical cross-sectional view of the irradiation room and an experimental set-up. The $^{252}$Cf source of known neutron emission rate is remotely moved to the irradiation positions of A and B on a guide tube from a storage vault using a pneumatic or mechanical source transfer system. Annular cylinders or slabs made of steel, graphite and acrylic plastic can be placed surrounding the source in order to alter the initial fission neutron spectrum. The source position A is at a height of 126 cm from the steel grating floor of a large low-scatter room and can produce neutron fields simulating the spectrum of neutrons transmitted through MOX-handling glove boxes and their shielding windows. Position B is at a height of 126 cm from the concrete floor of a concrete-walled basement, and produces a neutron field simulating the high-scatter neutron spectrum typical of work environments where large glove boxes containing MOX fuels are installed in a concrete wall-enclosed room. One major difference between positions A and B is the directionality of the fields. Due to the greater scattering in the small rooms, the fields of position B are more multidirectional than those of position A.

**Figure 4** shows reference neutron spectra measured with the Bonner multisphere spectrometer at the point of the test. The neutron emission rate is normalized to 1. Each spectrum is assigned by abbreviated moderator identification code. In the graphical presentation, ordinates are multiplied by the indicated factors to avoid overlaps. The effects of acrylic plastic shielding are apparent in these figures; the peaks in the $^{252}$Cf spectrum shift to slightly lower energies as the amount of shielding increases, and the number of low-energy neutrons is significantly increased. The fission neutron spectrum is markedly degraded to the lower energies due to inelastic scattering with steel. Thermal and epithermal neutrons are fairly dominant components, especially at position B. **Table 1** lists moderator arrangements and neutron field parameters, $\bar{E}$ (fluence average energy, MeV), $\bar{h}$ (spectrum average dose equivalent conversion coefficients, pSv cm$^{-2}$), and $\bar{\theta}$ (average angle of neutron incidence, degree), showing neutron spectral and dosimetric characteristics. These parameters were determined by the angle-integrated neutron energy distribution measured with the Bonner multispheres spectrometer and the energy and angular distributions obtained from Monte-Carlo calculations. In column 7 of Table 1, the dosimetric parameters obtained from BS measurements at representative locations are also presented for comparison. The shapes of the neutron spectra and dosimetric parameters of the calibration field entirely reproduce and cover those likely to be found in workplaces. The field meets the ISO 12789 guidelines [16].

**Figure 3:** Vertical cross-sectional view of the irradiation room and experimental set-up. The $^{252}$Cf neutron sources can be placed at the two positions of A and B.
**Figure 4:** Neutron spectral fluence per unit lethargy interval for the $^{252}$Cf source positions of A and B. The spectra were measured with a Bonner multi-sphere spectrometer at a distance of 100 cm. The neutron emission rate is normalized to 1. Each spectrum is assigned by abbreviated moderator identification code (see Table 1), and ordinates are multiplied by the indicated factors to avoid overlap. The vertical broken lines correspond to the peaks of the uncollided fission spectrum.

![Graph showing neutron spectral fluence for different positions and moderators.](image)

**Table 1:** Neutron dosimetric parameters showing characteristics of neutron spectra at a distance of 75 cm

<table>
<thead>
<tr>
<th>Moderator ID Code</th>
<th>Source Position</th>
<th>Moderator (a)</th>
<th>$E$ (MeV)</th>
<th>$h$ (b) (pSv cm$^2$)</th>
<th>$\theta$ (c) (deg.)</th>
<th>Remarks (d) (Workplaces)</th>
</tr>
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<tbody>
<tr>
<td>Cf A</td>
<td>None</td>
<td>2.0$^{(e)}$</td>
<td>380$^{(e)}$</td>
<td></td>
<td>~6</td>
<td>MOX powder can (source term)</td>
</tr>
<tr>
<td>F A</td>
<td>Steel 40 mm</td>
<td>1.5</td>
<td>362</td>
<td>~7</td>
<td></td>
<td>Glove box area (source term)</td>
</tr>
<tr>
<td>P15 A</td>
<td>PMMA 15mm</td>
<td>1.7</td>
<td>332</td>
<td>~8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P35 A</td>
<td>PMMA 35mm</td>
<td>1.4</td>
<td>271</td>
<td>~8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P60 A</td>
<td>PMMA 60mm</td>
<td>1.2</td>
<td>225</td>
<td>~8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P100 A</td>
<td>PMMA 100mm</td>
<td>0.97</td>
<td>183</td>
<td>~8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FP A</td>
<td>Steel 40 mm + PMMA 60mm</td>
<td>0.86</td>
<td>191</td>
<td>~9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-Cf B</td>
<td>None</td>
<td>1.6</td>
<td>336</td>
<td>~25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-P B</td>
<td>PMMA 100mm</td>
<td>0.80</td>
<td>157</td>
<td>~30</td>
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<td></td>
</tr>
<tr>
<td>B-G B</td>
<td>Graphite 100mm</td>
<td>0.90</td>
<td>182</td>
<td>~27</td>
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<td>B-F B</td>
<td>Steel 100mm</td>
<td>0.72</td>
<td>185</td>
<td>~29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-GP B</td>
<td>Graphite 100mm + PMMA 100mm</td>
<td>0.72</td>
<td>136</td>
<td>~43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-FP B</td>
<td>Steel 100mm + PMMA 100mm</td>
<td>0.50</td>
<td>118</td>
<td>~45</td>
<td></td>
<td></td>
</tr>
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</table>

(a) Moderator materials and thickness of moderators placed between a $^{252}$Cf source and the dosemeters.
(b) Spectrum-averaged conversion coefficients from neutron fluence to ambient dose equivalent.
(c) Average angle of neutron incidence to the plane of which the normal vector points toward the source. These values were derived from the ratio of neutron spectral current to spectral fluence for neutrons incident from the frontal half space, based on the Monte Carlo computations.
(d) Derived from the Bonner multisphere spectrometer measurements at the workplaces.
(e) Minor differences of values from the ISO are ascribed to the neutron scattering with a source holder and source support structures.
3.2 Experimental set-up

The experiments were performed using both the bare and moderated $^{252}$Cf neutron source. An experimental set-up was already presented in Fig. 3. The response of the dosemeters was determined by exposing them at locations where the reference personal dose equivalent has been determined. All irradiations were made with EPDs and TLADs mounted on an ISO water-filled parallelepiped phantom with an outer size of 30 cm $\times$ 30 cm $\times$ 15 cm. The distance from the source center to the face of the phantom was 75 cm. Two EPDs, serial numbers 000001 and 000002, were simultaneously irradiated, while three TLADs were irradiated as a group. The effective center of the grouped dosemeters was positioned at a height of 126 cm above the floor, which is a typical height for a personal dosemeter worn at the chest.

For irradiations at position A in the low-scatter condition, the phantom was set at 0º and 60º. Since experience showed that the room-scatter corrections are almost negligible for a distance of 75 cm [17], no corrections were made. For irradiations at position B in the high-scatter condition, the phantom was fixed facing the source (0º), and room-scattered neutrons were included in the measurements.

4. Results and Discussion

4.1 Test Results

We summarize the response data from the viewpoint of the variation in relation to spectral transition from a fission spectrum, i.e., an initial neutron spectrum. Figure 5 presents the neutron spectral-dependence of dose equivalent responses of both NRY21 and TLADs, namely the relationship between the spectrum-weighted dose equivalent responses of both dosemeters (NRY21 and TLADs) and the spectrum-weighted neutron energy. Note that the figure is for broad neutron spectra, not for monoenergetic neutrons. In this figure, the responses of both dosemeters are normalized to unity at a $^{252}$Cf (~2.0 MeV) since it corresponds to the starting point in the neutron spectral variation. A decrease in neutron energy represents a significant increase of the relative magnitude of thermal and epithermal neutron components.

First, the test results for the TLADs are shown since they are easy to explain. The experimental data shown in Fig. 5 demonstrate the strong spectrum-dependent nature of the albedo-type dosemeter. As the neutron spectrum decreases in energy, TLADs tend to overly respond. The TLADs can overestimate the dose equivalent by a factor of up to 3 to 4 around the average neutron energy of ~0.5 MeV, which is typical around the MOX-handling glove boxes. In routine neutron monitoring with TLADs, a location-specific correction factor of 0.3 has been applied based on the field calibration method performed near the glove boxes in the 1990s. The value of this factor is reasonably consistent with a reciprocal of the experimental responses (3~4) shown in Fig. 5.

In contrast to the results of TLADs, the test results on the NRY21 dosemeters show a nearly spectrum-independent response. The dose equivalent response of the NRY21 dosemeter was evaluated to be 0.7 to 1.1 at angles of normal incidence at irradiation position A and with the dosemeter’s reference orientation facing the source at irradiation position B. A simple explanation of this neutron spectral dependence in response is that in the test neutron field, most neutrons that contribute significantly to the dose equivalent have energies above several hundred keV, and hence the fast neutron sensor can function well without missing large portions of neutrons with energy below the threshold, while the slow neutron sensor virtually does not work. The thickness of the moderators used in the test fields was less than 100 cm of acrylic plastic or steel; therefore, they did not alter the fission neutron spectrum sufficiently to introduce the large dose evaluation errors that are ascribed to the response inadequacies in Fig. 2. The energy response of the NRY21 dosemeter seems to be at least adequate for a bare and lightly-moderated fission sources.

The angular response was also tested using a $^{252}$Cf plus steel/PMMA combination moderator source (moderator code = FP). The conclusion of Sasaki’s work was that the NRY21 dosemeter has a cosine-like angular dependence for a bare $^{252}$Cf neutron source. Similar results were obtained for a moderated
$^{252}$Cf source. The dose equivalent response at $60^\circ$ relative to the $0^\circ$ response was 0.6, slightly mitigated relative to the expected value (~0.5) from the cosine curve, because of the angular dependence of $H_p(10)$ itself.

Figure 5: Personal dose equivalent response of the NRY21 dosemeter and TLAD as a function of neutron energy averaged over the incident neutron spectrum. The responses of both dosemeters are set to unity at uncollided $^{252}$Cf neutrons (~2 MeV).

4.2 Discussion

From the experimental results, we can draw the conclusion that for unmoderated or lightly moderated fission neutron fields likely to be found in the workplaces of the MOX fuel fabrication facilities, the NRY21 dosemeter functions satisfactorily in the factory calibration setting.

Conversely, it is anticipated that this dosemeter may only measure a small fraction of the neutron dose equivalent in highly-moderated or degraded neutron spectra typical in power reactors because of the threshold at ~1 MeV for the fast neutron sensor. For instance, for a $1/E$ spectrum extending from 100 keV to thermal, the NRY21 dosemeter behaves just like an albedo neutron dosemeter, since the fast neutron sensor does not work. In such cases, instead of applying the factory calibration setting at thermal neutrons, the appropriate calibration factor specific to the workplace should be applied for the slow neutron sensor so as to account for the correct neutron dose equivalents.

5. Conclusion

The authors investigated the neutron dose equivalent evaluation performance of the NRY21 electronic neutron personal dosemeter and discussed its suitability to work environments in MOX fuel fabrication facilities. All tests were conducted at the moderated $^{252}$Cf neutron fields having neutron spectral and dosimetric characteristics similar to those found in the workplaces of MOX fuel facilities. Experiments showed that the response of this dosemeter was evaluated to be 0.7 to 1.1 in angles of normal incidence. This is satisfactory, and also provides the expected data on how the dosemeters will respond to different neutron spectra in actual workplaces. From the experiments, it is concluded that for lightly-moderated fission neutron fields like MOX fuel facilities, this dosemeter functions well in factory calibration setting. If the dosemeters were used in unknown neutron spectrum or highly-moderated spectra such as those encountered at commercial power reactors, new calibration factors, not factory calibration settings, should be used to improve their dosimetry performances.
REFERENCES