Experimental Study on the Response of Electronic Personal Dosimeters in Simulated Workplace Neutron Fields

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Abstract

Neutron dose measurement faces accuracy challenges due to the wide neutron energy range and the complexity of energy response; electronic neutron personal dosimeters (n-EPDs) exhibit significant response differences under different energy spectra, and calibration using common isotopic neutron sources may lead to deviations in field dose measurements. To investigate the influence of neutron energy spectrum distribution on the response of n-EPDs, four neutron radiation fields with different energy spectrum distributions were established using a 252Cf isotopic neutron source, a D-T accelerator neutron source, and materials such as heavy water, tungsten, iron, graphite, and polyethylene. Combined with the measured energy spectra from a Bonner sphere neutron spectrometer and incident angular distributions calculated by Monte Carlo methods, the response differences of two commercial electronic neutron personal dosimeters (n-EPDs) were tested. The results show that: in the bare 252Cf source reference radiation field, the relative deviation between the measured spectrum from the Bonner spheres and the standard spectrum in the main energy region is within \$±10^{2}\$; the maximum response differences of the two commercial n-EPDs to the four neutron fields are 5.7 and 6.7 times, respectively. The study indicates that when calibrated using isotopic neutron sources, n-EPD readings typically overestimate the actual personal dose equivalent in the field, and special attention must be paid to the effects of energy response, field energy spectrum distribution, and incident direction on measurement accuracy.

Full Text

Experimental Study on Response of Electronic Personal Neutron Dosimeters Based on Simulated Workplace Neutron Fields

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Abstract

Neutron dose measurement faces significant accuracy challenges due to the wide energy range of neutrons and the complexity of energy-dependent responses. Electronic neutron personal dosimeters (n-EPDs) exhibit substantial response variations under different energy spectra, and calibration using conventional isotopic neutron sources may introduce biases in workplace dose measurements. To investigate the influence of neutron energy spectrum distribution on n-EPD response, we established four neutron radiation fields with distinct spectral distributions using a ^{252}Cf isotopic source, a D-T accelerator source, and various moderating materials including heavy water, tungsten, iron, graphite, and polyethylene. By combining measured energy spectra from a Bonner sphere spectrometer with Monte Carlo calculations of incident angular distributions, we tested the response differences of two commercial electronic neutron personal dosimeters (n-EPDs).

The results demonstrate that in the ^{252}Cf bare source reference field, the relative deviation between the measured spectrum and the standard spectrum remains within $±10^{2}$. The maximum response differences for the two commercial n-EPDs across the four fields are 5.7-fold and 6.7-fold, respectively. These findings indicate that when calibrated with isotopic neutron sources, n-EPDs typically overestimate actual workplace personal dose equivalent values. Therefore, special attention must be paid to the effects of energy response, workplace energy spectrum distribution, and incident direction on measurement accuracy.

Keywords: simulated workplace neutron field; neutron personal dosimeter; energy response; neutron dosimetry

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1. Introduction

Neutron dose measurement presents unique challenges due to the strong energy dependence of neutron fluence-to-dose conversion coefficients and the broad energy range encountered in workplace environments (typically from thermal neutrons to 20 MeV). Consequently, the impact of energy response variations on measurement accuracy must be carefully considered. Since monoenergetic neutron reference fields are generally unavailable, calibration of neutron dosimeters primarily relies on isotopic sources with relatively hard spectra, such as ^{241}Am-Be and ^{252}Cf (with fluence-averaged energies of 4.16 MeV and 2.13 MeV, respectively). This practice often leads to significant discrepancies between field measurements and actual values, sometimes by factors or orders of magnitude. For example, the European EVIDOS project evaluated personal dosimetry in mixed neutron-photon fields across 14 workplace environments including boiling water reactors, pressurized water reactors, research reactors, nuclear fuel cycle facilities, and spent fuel storage areas. The study found that workplace area dosimeters yielded measurement-to-reference ratios of 0.5–1.5, while neutron personal dosimeters showed a much broader distribution of 0.1–10, with some individual cases exceeding even this range.

The concept of simulated workplace neutron fields was first proposed by Chartier et al. in the 1990s and subsequently incorporated into international standards for neutron reference radiation fields (ISO 12789). These fields are produced by strategically placing neutron moderating, absorbing, and multiplying materials around isotopic or accelerator sources. For instance, the UK's National Physical Laboratory simulated gas-cooled reactor neutron fields using a p-Li source with heavy water moderation, while the China Institute of Atomic Energy simulated pressurized water reactor fields using a D-T source with depleted uranium, iron, water, and polyethylene. Due to limited universality, laboratories continue developing simulated workplace neutron fields tailored to specific target spectra while exploring modular construction methods and expandability.

To improve neutron dose measurement accuracy, two primary technical approaches exist: (1) optimizing the intrinsic energy response of neutron dosimeters through multi-detector designs or spectrometric methods, and (2) establishing laboratory neutron fields that closely approximate workplace spectra to directly provide calibration factors, or alternatively, measuring workplace spectra to calculate correction factors. For area monitoring, the current trend involves developing spectrometric dosimeters with single-moderator, multi-detector configurations to achieve consistent intrinsic energy response across broad energy ranges. However, for the increasingly popular electronic (active) personal dosimeters, achieving consistent response across wide neutron energy ranges remains challenging. Typical commercial n-EPDs show response variations up to 20–60 times across different energy regions from 0.025 eV to 15 MeV. This study combines ^{252}Cf and D-T sources with heavy water, tungsten, iron, graphite, polyethylene, and cadmium to create four distinct neutron fields, then experimentally evaluates the response differences of two commercial n-EPDs using measured spectra and calculated angular distributions to provide guidance for field measurements.

2. Experimental Setup

2.1 Neutron Sources and Field Configurations

The neutron sources used in this study include ^{241}Am-Be and ^{252}Cf sources at the China Institute for Radiation Protection metrology station, and a D-T neutron source at the Ruichang Institute of Nuclear Physics Application. The ^{241}Am-Be source has a neutron emission rate of 2.43$\times10^{7}$ $n \cdot s^{-1}$ (reference date: December 27, 2018). The ^{252}Cf source emission rate is on the order of 1.65$\times10^{8}$ $n \cdot s^{-1}$. The D-T source emission rate is on the order of 10^8 $n \cdot s^{-1}$, determined through measurements with an associated alpha-particle silicon surface barrier detector and solid angle calculations.

Two isotopic neutron fields with different spectra were created using a bare ^{252}Cf source and a ^{252}Cf source moderated by a 30 cm diameter heavy water sphere (wrapped externally with 1 mm thick cadmium). To simulate workplace fields, target spectra from two actual workplace measurements in IAEA Report 403—one from a pressurized water reactor containment and one from a main pump room—were used to design simulated workplace neutron field assemblies. These assemblies consist of fast neutron moderators, intermediate neutron adjustment layers, and thermal neutron reflector components, as shown in [Figure 1: see original paper]. The main pump room simulation uses an 8 cm tungsten/30 cm iron moderator with a 30 cm polyethylene reflector, while the reactor containment simulation employs an 8 cm tungsten/10 cm iron moderator with a 5 cm graphite adjustment layer.

2.2 Measurement Equipment and Dosimeters

Neutron energy spectra were measured using a Bonner sphere spectrometer consisting of an SP9 spherical ^{3}He tube (33 mm diameter, 0.5 mm stainless steel wall) filled with 4 atm ^{3}He and 1.2 atm Kr. The ^{3}He tube output signals were amplified, shaped, and fed into an Ortec 923MCB multi-channel analyzer for pulse height spectrum acquisition. The moderating spheres consist of ten polyethylene spheres with diameters ranging from 3 to 12 inches.

The test subjects were two commercial electronic personal dosimeters capable of measuring mixed neutron-photon fields, designated EPD1 and EPD2. EPD1 uses a combination of polyethylene and ^{6}LiF fast/thermal neutron conversion layers covering a single diode, with a sensitivity of approximately 0.5 counts per Sv. EPD2 employs two diodes for neutron measurement: one covered with a plastic converter for fast neutrons (sensitivity 0.1 counts per Sv) and another covered with a ^{6}LiF converter for thermal, epithermal, and intermediate neutrons (sensitivity 0.5 counts per Sv).

3. Methods and Results

3.1 Spectrum Measurement and Validation

The response matrix of the Bonner sphere spectrometer for neutrons from thermal energies to 20 MeV was calculated using Monte Carlo methods. After measuring the ^{3}He tube count rates under different moderating spheres, the measured spectra were unfolded using the UMG 3.1 code with the GRAVEL algorithm from the German Physikalisch-Technische Bundesanstalt (PTB).

The spectrometer was validated using ^{241}Am-Be and bare ^{252}Cf sources. At 1.5 m from the source, count rates were measured for the bare ^{3}He tube and ten different moderating spheres. Scattered neutron contributions were measured using a shadow cone and subtracted. The unfolded spectra were compared with ISO 8529-1 reference spectra. As shown in [Figure 2: see original paper], the measured and standard spectra show good agreement, with relative deviations in neutron fluence within $±$10% in the main energy regions. Although the Bonner sphere spectrometer cannot determine neutron incident direction, its isotropic response allows characterization of spectral dose properties using the weighted sum of the fluence spectrum and ambient dose equivalent conversion coefficient h*(10). The relative deviations in h*(10) between measured and standard spectra are -1.35% for ^{241}Am-Be and -1.55% for ^{252}Cf.

[Figure 3: see original paper] shows the measured spectrum of the heavy-water-moderated ^{252}Cf source at 1.5 m, with a -8.18% deviation in h*(10) from the standard spectrum.

3.2 Simulated Workplace Field Measurements

Using the target spectra from IAEA Report 403, design spectra were calculated for the simulated workplace field assemblies based on the D-T source and structural information. Actual neutron spectra were then measured in the two constructed fields. During measurement, both the associated alpha-particle counts and ^{3}He tube counts were acquired simultaneously, with alpha counts used to correct for accelerator beam intensity fluctuations.

Due to space constraints between the effective measurement region and the assembly, shadow cones could not be installed to subtract scattered neutrons from the experimental hall. Therefore, a computational model of the hall, simulated field assembly, Bonner sphere spectrometer, and support structures was developed to correct for scattered neutron contributions using Monte Carlo methods. Using the design spectrum as the initial guess, the corrected count rates were unfolded to obtain the simulated workplace neutron spectra.

The target, design, and measured spectra for the reactor containment and main pump room simulations are shown in [Figure 4: see original paper] and [Figure 5: see original paper], respectively. Since design spectra cannot match target spectra in all energy regions, the measured spectra should serve as the reference for practical applications. The relative deviation in h*(10) between measured and design spectra is -7.78% for the reactor containment simulation and 3.09% for the main pump room simulation. The large difference in neutron fluence at 14 MeV between measured and design spectra for the reactor containment field arises primarily from insufficient moderation, thin structures, and assembly gaps that allow fast neutron leakage.

Monte Carlo simulations of the incident neutron direction distribution at the measurement position were performed following ISO 12789 recommendations. For the main pump room simulation with thick moderator and reflector, neutrons in the 30–45° cone contribute up to 30.6% of the total. For the reactor containment simulation with thinner moderator and no reflector, the 15–30° cone contributes the most at 32.8%.

3.3 Dosimeter Response Testing

The response factor is defined as the ratio of the personal dose equivalent rate measured by the dosimeter to the reference value. presents the average energies, spectrum-averaged fluence-to-dose conversion coefficients, and normalized response factors (relative to the ^{252}Cf bare source) for both EPDs across the four neutron fields.

Dosimeters were placed in front of a standard 30 cm × 30 cm × 15 cm water phantom to measure their response to the four neutron spectra, as shown in [Figure 6: see original paper]. For the isotopic fields, scattered neutrons were subtracted using the shadow cone method. For the simulated workplace fields, space limitations prevented shadow cone measurements, so dosimeter responses include scattered neutron contributions.

For the two isotopic fields where scattering could be subtracted, most neutrons are incident from the front. The dose reference value was calculated as the weighted sum of the measured neutron spectrum and the 0° incident fluence-to-dose conversion coefficient hp(10,0°).

For the two D-T simulated fields where scattering could not be subtracted, the incident direction distribution was calculated as described above. The dose reference value hp(10) was obtained by weighting the measured spectrum with hp(10,α) for different incident angles α. As shown in [Figure 7: see original paper], incident directions are concentrated within a 15–60° cone, contributing approximately 80% of hp(10). The spectrum-averaged fluence-to-dose conversion coefficients assuming 0° incidence would be 40.2% and 16.3% higher than those calculated with the actual angular distributions, consistent with the decreasing trend of hp(10,α) with increasing incident angle.

4. Analysis and Discussion

As shown in , the four neutron fields exhibit fluence-averaged energies of 0.12–2.00 MeV, dose-averaged energies of 0.75–3.65 MeV, and spectrum-averaged fluence-to-dose conversion coefficients of 51.17–390.3 pSv · cm^2. The average energies and conversion coefficients for the bare and moderated ^{252}Cf sources are slightly lower than recommended values in neutron reference field standards.

The neutron fluence-to-personal-dose-equivalent conversion coefficient increases dramatically by approximately 40 times between 0.01–1 MeV, with more gradual changes in other energy regions. Consequently, the spectrum-averaged conversion coefficient does not vary monotonically with average energy. For example, despite having a higher fluence-averaged energy than the bare ^{252}Cf field, the reactor containment simulation field has a smaller conversion coefficient due to its significant high-energy neutron component above 14.8 MeV.

Normalized to the ^{252}Cf bare source, EPD1 and EPD2 show response factors of 3.0–5.7 and 3.4–6.7, respectively, in the other three fields. Calibrating personal neutron dosimeters with a ^{252}Cf bare source could therefore overestimate personal dose equivalent in field applications, consistent with EVIDOS project findings of overestimation by more than threefold in reactor environments. The primary causes are the energy response characteristics of n-EPDs and workplace spectral distributions. Silicon diode-converter combinations typically exhibit high response below 1 keV and under-response in the 0.1–several MeV region (with peak under-response near 1 MeV), while ^{252}Cf spectra predominantly fall in this under-response region. Additionally, unlike area monitoring, personal dosimetry must account for incident direction. For the two simulated fields, assuming pure 0° incidence yields conversion coefficients 40.2% and 16.3% higher than those calculated with actual angular distributions, consistent with the angular dependence of hp(10,α).

5. Conclusion

This study established four neutron radiation fields with different spectral distributions using ^{252}Cf and D-T sources, combined with Bonner sphere spectrometry and Monte Carlo calculations of incident angular distributions to determine spectrum-averaged fluence-to-dose conversion coefficients and reference personal dose equivalent rates. Testing two commercial n-EPDs revealed maximum response differences of 5.7-fold and 6.7-fold across the four fields. Calibration using the ^{252}Cf bare source would overestimate personal dose equivalent for the other three spectral distributions.

Accurate neutron dose measurement with n-EPDs requires knowledge of the dosimeter' s energy response, workplace energy spectrum, and incident direction distribution. When such information is unavailable, comparative measurements using multiple dosimeter types are essential. This work represents the first published study in China investigating active neutron personal dosimeter response using simulated workplace neutron fields. Given the ongoing challenges in optimizing n-EPD intrinsic energy response, establishing simulated workplace neutron fields remains a necessary and viable approach for improving workplace dose measurement accuracy. To elevate simulated workplace neutron fields to reference fields for personal dosimeter calibration, further research is needed, including: measuring intermediate-energy neutron spectra (above 50 keV) using hydrogen proportional counters or scintillation detectors to compensate for the limited energy resolution of Bonner spheres; measuring neutron incident directions with directional spectrometers combined with simulation; and analyzing contributions from secondary photons to dose equivalent.

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