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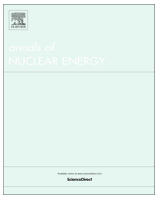

Monte Carlo based investigation of a universal two-component albedo neutron dosimeter in a deep geological disposal system for high-level nuclear waste

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ABSTRACT

Albedo neutron dosimeter utilizes the property of the human body to moderate incident high energy neutrons, which are scattered and reflected as thermal and low energy neutrons that can be measured by thermoluminescence detector (TLD) with high sensitivity. The current study is devoted to the assessment of possible utilization of the albedo neutron dosimeter as a personal monitoring device in a deep geological disposal system for high-level nuclear waste. When a nuclear waste package is transported to its final disposal position in a deep geological repository, such as in a horizontal emplacement drift in a rock salt mine, the question about the appropriate calibration factor of the albedo neutron dosimeter arises. Neutrons backscattered by the surrounding host rock layers might contribute significantly to the composition of the radiation field and in turn influence the response of the neutron detector. To account for different radiation field compositions, a field calibration technique providing field-specific calibration factors was applied in the current study. The field calibration of an albedo neutron dosimeter in a deep geological repository was performed with Monte Carlo method. The radiation field was simulated by a shielding cask loaded with a ^{252}Cf neutron source that is placed in a horizontal drift of a rock salt mine. Calibration factors were calculated at various distances to the shielding cask. In the investigated case, the neutron radiation field in a geological repository can be assigned to the calibration factor N1, which is recommended for reactors and accelerators with heavy shielding.

1. Introduction

Incident neutrons on a human body will be moderated and reflected mainly due to elastic scattering on hydrogen nuclei in the human body. Consequently, a flux of thermal and low energy neutrons will leave the front surface of the body. These neutrons are called albedo neutrons (Piesch and Burgkhardt, 1985). By making appropriate measurements of these neutrons, using a detector worn close to the surface of the body, it is possible to estimate the dose equivalent in the body due to the original incident neutrons. This process is called albedo neutron dosimetry (Piesch and Burgkhardt, 1985).

In mixed radiation fields where neutrons can contribute lager than 20% of the personal dose equivalent or where the risk of an accidental exposure with neutrons exists, individual monitoring of workers in such fields with neutron personal dosimeter must be carried out (Luszik-Bhadra, 2014). As agreed by the national committee “Nuclear energy-radiation protection” (see Luszik-Bhadra, 2014), the official personal neutron dosimeter system used in Germany is based on the universal two-component albedo neutron dosimeter developed by Piesch and Burgkhardt (1988) in the former Karlsruhe Nuclear Research Centre (KfK). Henceforth this dosimeter is named in short as the “KAL” (**K**fK **AL**bedo) neutron dosimeter. Fig. 1 shows the principle structure of the KAL neutron dosimeter. The dosimeter case is made of boron loaded plastic (shielding for thermal neutrons) with two boron-free windows. The field window at position (a) allows to register the field neutrons (i.e. direct incident radiation), while at the albedo window at position (i), the neutrons scattered back by the phantom (human body) can be measured. At both positions a TLD-pair is located, with a TLD sensitive to photons (G) and a TLD sensitive to both neutrons and photons (NG).

When ionizing radiation hits a TLD, energy is stored in the detector crystal. By heating the TLD, part of the stored energy can be released in form of light. The light intensity can be measured, which is used as a measure unit for the absorbed energy and in turn for the absorbed dose. The KAL neutron dosimeter uses

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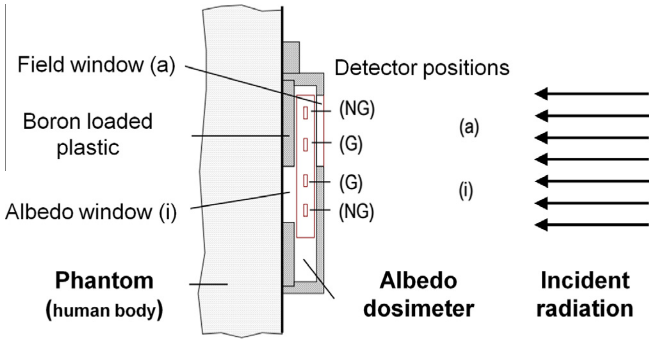

Fig. 1. Schematic illustration of the KAL neutron dosimeter with two TLD-pairs at position (a) facing the field window and position (i) facing the albedo window. Each TLD-pair consists of a gamma sensitive (G) and a neutron gamma sensitive detector (NG) TLD.

lithium fluoride based TLDs doped with Mg and Ti (LiF:Mg,Ti) that has a linear dose response up to several *Gy* (Bilski, 2002). A LiF:Mg, Ti TLD (size 0.09 cm × 0.3 cm × 0.3 cm) enriched (more than 95 mol-%) with ^6Li (TLD-600) is used as the (NG) detector, while another TLD of the same size but enriched (more than 99.9 mol-%) with ^7Li (TLD-700) is used as the (G) detector. Essential for neutron detection is the $^6Li(n,\alpha)^3H$ reaction, which produces heavy charged α particles and tritium nuclei that depose their kinetic energy inside the TLD. Since TLD-600 and TLD-700 have essentially the same response to gamma radiation, the neutron reading of the TLD-pair M_n is given simply by subtraction of the TLD-700 reading from that of the TLD-600:

$$M_n = M_{TLD-600} - M_{TLD-700} \tag{1}$$

where $M_{TLD-600}$ and $M_{TLD-700}$ are the readings of the TLD-600 and TLD-700, respectively.

In applications of the albedo neutron dosimeter, the personal dose equivalent $H_p(10)$ is given as:

$$H_p(10) = H_n + H_\gamma \tag{2}$$

where H_n and H_γ refer to the personal dose equivalent induced by incident neutrons and gammas, respectively. The current study focuses on the neutron personal dose equivalent H_n. According to Eq. (1), the TLD-pair at position (i) yields the albedo neutron reading $M_n(i)$, which is further used to determine H_n according to the following equation:

$$H_n = N_n(i) \cdot M_n(i) \tag{3}$$

where $N_n(i)$ is the calibration factor of the albedo neutron dosimeter. The TLD-pair at position (a) behind the field window measures neutrons from the incident neutron field and produces the field neutron reading $M_n(a)$. The reading ratio $M_n(a)/M_n(i)$ will be used to characterize the different application areas of the albedo neutron dosimeter (Piesch and Burgkhardt, 1988).

Due to the enhanced cross section of the neutron detectors to thermal and low energy neutrons, a standard calibration performed with a radionuclide source such as ^{252}Cf in a backscatter-free, reference neutron field (DIN ISO 29661, 2013) cannot account for all the components of a real, stray neutron field in working places. Field-specific moderation and scattering of neutrons can contribute significantly to the albedo neutron readings. Therefore, the calibration factor of the albedo neutron dosimeter $N_n(i)$ must be determined specifically to its application areas. As proposed by Burgkhardt and Piesch (1988), $N_n(i)$ can be determined by a field calibration technique using a polyethylene (PE) sphere of 30 cm diameter, which serves as phantom for the albedo neutron dosimeter. An identical TLD-600 and TLD-700 pair as that used in the albedo neutron dosimeter is placed at the center of the PE sphere with its neutron reading termed as $M_n(c)$. The field calibration can be summarized into two steps (the following description is based on the references Burgkhardt and Piesch, 1988 and Luszik-Bhadra, 2014):

(a) Step 1: the PE sphere with the TLD-pair at its center will be calibrated in a reference neutron field as defined in the German standard (DIN ISO 29661, 2013). The calibration factor of the center TLD-pair N_c is determined in terms of the ambient dose equivalent $H^*(10)$ in the reference neutron field.

$$N_c = \frac{H^*(10)}{M_n(c)} \tag{4}$$

N_c will be further used in step 2 in a real, stray neutron field.

(b) Step 2: in a real, stray neutron field, two additional albedo neutron dosimeters (termed as dosimeter 1 and 2) will be placed on the surface of the PE sphere in the diametrically opposed positions. The reading of the center TLD-pair in the real, stray neutron field $M_n(c)$ is now used to determine the reference dose equivalent of the real, stray neutron field H_R with the calibration factor N_c obtained in step 1:

$$H_R = N_c \cdot M_n(c) \tag{5}$$

The field calibration is based on the basic assumption, that the ambient dose equivalent in the real, stray neuron field $H^*(10)$ can be approximated with the reference dose equivalent H_R as:

$$H^*(10) = H_R = N_c \cdot M_n(c) \tag{6}$$

The sum of the albedo neutron readings of the two dosimeters (1 and 2) $M_n^1(i) + M_n^2(i)$ will then be used to determine the calibration factor $N_n(i)$ as:

$$N_n(i) = \frac{H^*(10)}{M_n^1(i) + M_n^2(i)} = \frac{M_n(c) \cdot N_c}{M_n^1(i) + M_n^2(i)} \tag{7}$$

With the calibration factor $N_n(i)$, the neutron personal dose equivalent, taken dosimeter 1 as example, is finally given as:

$$H_n^1 = N_n(i) \cdot M_n^1(i) \tag{8}$$

The inverse value of $N_n(i)$ is termed as the neutron response of the albedo neutron dosimeter $R_n(i)$:

$$R_n(i) = \frac{1}{N_n(i)} = \frac{M_n^1(i) + M_n^2(i)}{M_n(c) \cdot N_c} \tag{9}$$

Furthermore, the neutron response in the reference neutron field is termed as $R_{nr}(i)$, which is determined in the same way as $R_n(i)$ but in the reference neutron field. As shown by Piesch and Burgkhardt (1988), the variety of workplace fields can be categorized into four different application areas, if the normalized neutron response $[R_n(i)/R_{nr}(i)]$ is plotted against the reading ratio of the field neutrons to the albedo neutrons $\left[M_n^1(a) + M_n^2(a)\right] / \left[M_n^1(i) + M_n^2(i)\right]$.

In the current investigation, the KAL neutron dosimeter will be studied regarding its applicability in a deep geological disposal repository for high-level nuclear waste. When a nuclear waste package is transported to its final disposal position in a geological repository, for instance in a horizontal emplacement drift in a rock salt mine as investigated in a previous study (Saurí Suárez et al., 2015), neutrons backscattered by the surrounding host rock layers might contribute significantly to the neutron field. Therefore, a field calibration of the albedo neutron dosimeter in such a facility is of interest. Since geological disposal repositories are not yet