Radiation Measurements 50 (2013) 67–70

Contents lists available at SciVerse ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Experimental study for improving the angle dependence of the response of PADC-based personal neutron dosemeters

R. Bedogni*, A. Esposito

INFN – LNF (Laboratori Nazionali di Frascati), Via E. Fermi n. 40, 00044 Frascati, Italy

HIGHLIGHTS

► The response of a two-orthogonal-element PADC personal neutron dosemeter have been studied.
► The angle response is greatly improved with respect to a single element planar configuration.
► The new configuration is suitable for ready implementation in dosimetry services.

ARTICLE INFO

Article history:
Received 19 December 2011
Received in revised form
30 September 2012
Accepted 15 October 2012

Keywords:
PADC
Neutron dosemeter
Angle response

ABSTRACT

The large angle dependence of the $H_p(10)$ response in PADC-based personal neutron dosemeters constitutes a serious concern in operational radiation protection dosimetry. For planar dosemeters, the typical $H_p(10)$ response falls by half or more when the incidence angle changes from 0° to 60°. To reduce this source of systematic uncertainty, configurations based on multiple detectors at different angles have been developed, but their complex geometries constitute an important obstacle to the implementation in routine services.

This works proposes a simplified configuration, based on two orthogonal PADC detectors, which is suitable for the implementation in the routine service of INFN-LNF (Frascati).

This system was tested, using a ISO slab standard phantom, in the following reference neutron fields: ^{241}Am–Be and 252Cf(D2O) available at ENEA-Bologna, and 1.2 MeV, 5 MeV and 14.8 MeV mono-chromatic beams available at PTB Braunschweig. Incidence angles of 0°, ±15°, ±30°, ±45° and ±60° were chosen. The sum of the track density in the PADC parallel to the phantom and that in the detector normal to the phantom face, was regarded as "dosemeter reading". On this basis the Hp(10) response was calculated for different energies and incidence angles. As expected, the angular response of the two-orthogonal-element dosemeter is highly improved with respect to that of a single planar PADC.

1. Introduction

At INFN—LNF (Frascati, Rome) a chemically etched PADC based fast neutron dosimetry service has been established for the needs of the radiological surveillance around the DAΦNE high energy e+/e− collider (Bedogni et al., 2008). Whilst the area dosimetry system relies on a four-element planar configuration (Bedogni et al., 2008a), an individual monitoring system for neutrons is not implemented yet. The large energy and angular dependence of the response in terms of $H_p(10)$ are the main concerns in PADC based personal dosimetry. Because the energy distribution of the workplace neutron fields in DAΦNE is known, workplace-specific factors to correct for the energy dependence of the PADC dosemeters have been derived (Esposito et al., 2008). Consequently, the remaining problem to investigate is the angle dependence of the $H_p(10)$ response.

Most of the PADC-based personal neutron dosemeters rely on planar configurations. Because of the planar geometry, an increase in the angle between the incident neutrons and the normal to the detector surface (termed "incidence angle") results in an increase in the fraction of secondary particles having incidence angles higher than the critical angle, thus decreasing the number of readable tracks. As a result, the $H_p(10)$ response falls by half or more when the incidence angle changes from 0° to 60° (Morelli et al., 2006; Tanner et al., 2005). To reduce this source of systematic uncertainty, configurations based on multiple detectors at different angles have been developed. An example is the pyramid-shaped dosemeter (Harvey, 1992; Devine et al., 1996; Gopalani et al., 2003).

* Corresponding author. . Tel.: +39 (0) 694032608; fax: +39 (0) 694032364.
E-mail address: roberto.bedogni@lnf.infn.it (R. Bedogni).

1350-4487/$ – see front matter
http://dx.doi.org/10.1016/j.radmeas.2012.10.005

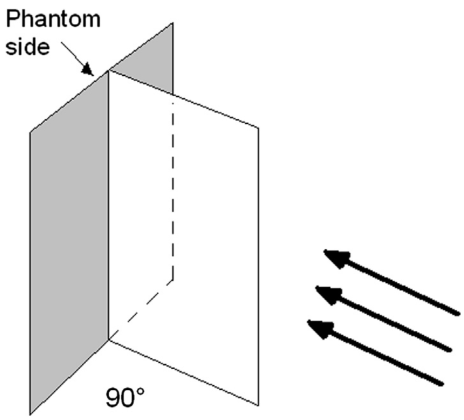

Fig. 1. Schematic diagram of the double dosemeter.

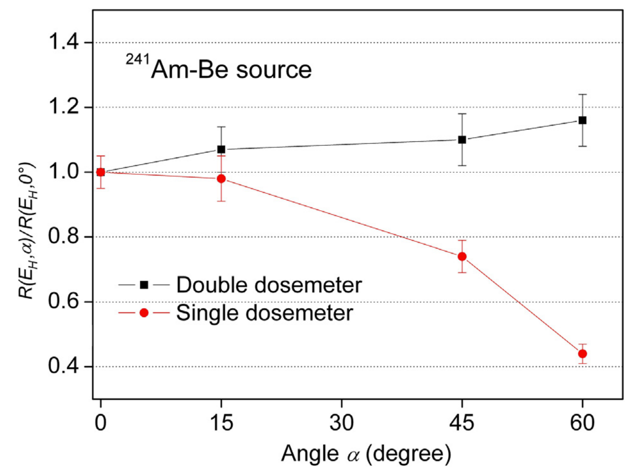

Fig. 2. Angle dependence of the $H_p(10)$ response for the single and the double dosemeters. The neutron field is the ^{241}Am–Be. The data are normalized to the normal incidence.

This works proposes a simplified configuration, based on two orthogonal PADC detectors (also termed "double dosemeter"), which is suitable for a ready implementation in the routine service of INFN-LNF. The response of this dosemeter was determined as a function of the energy (from 1.2 to 14.8 MeV) and of the incidence angle. As a term of comparison, the energy and angle responses of a single-element planar dosemeter (termed "single dosemeter") were also determined. The dosemeters were compared using numerical indexes that quantify the variability of the response as a function of the energy and/or the incidence angle.

2. Materials and methods

The PADC (with 0.1% dioctyl-phthalate) is produced by the Italian company Intercast Europe S.p.A. A single detector has dimension 2.5 cm × 3.5 cm × 0. 14 cm. Because the detector acts also as n-p converter, only one side is counted. In the single dosemeter configuration this side is facing the phantom. The double dosemeter (see Fig. 1) is composed by a detector parallel to the phantom face, plus another that is normal to the phantom face. The normal dosemeter may be exposed, especially for high-energy neutrons, in non-equilibrium condition. However, if a symmetrical distribution of incidence angles is supposed as in this work, this effect does not significantly affect the results.

The PADC detectors are stored at low temperature (−30 °C), to limit the ageing effects. After irradiation, the detectors are processed through a pre-etching of 1 h in a 60% ethanol + 40% 6.25N KOH solution at 70 °C, followed by a 10 h etching in 6.25N KOH solution at 70 °C (Morelli et al., 1999). The read out is performed at the INFN-LNF with an automated reader (Bedogni et al., 2008) equipped with an epi-illuminated microscope and an 8 Mpixel USB camera (3272 × 2469 pixels, 256 grey levels). For each detector, four fields of view are analysed for a total scanned area of 2.224 cm^2. The final resolution is 2.5 μm/pixel. A Labview program controls the motion, acquisition and counting processes.

Irradiations of the double dosemeter in terms of $H_p(10)$ have been performed using a ISO slab phantom and incidence angles of 0°, ±15°, ±30°, ±45° and ±60°. The following reference fields have been used:

- ^{241}Am–Be and ^{252}Cf(D_2O) available at ENEA-Bologna.
- 1.2 MeV, 5 MeV and 14.8 MeV mono-chromatic beams available at PTB Braunschweig.

To compare the results obtained with mono-chromatic or continuous calibration spectra, the calibration fields have been identified through their value of *dose equivalent average energy*, E_H, as defined and tabulated in ISO Standard 8529-1 (ISO, 2001). Whilst for mono-chromatic spectra this energy coincides with the nominal beam energy, for ^{241}Am–Be and ^{252}Cf(D_2O) its value is 4.4 MeV and 2.1 MeV, respectively.

For every energy and incidence angle, nine double-dosemeters were exposed. The dosemeter reading is defined as the sum of the track density of the PADC parallel to the phantom face (N_{par}) and that of the detector normal to the phantom face (N_{norm}). This value normalized to the delivered $H_p(10,\alpha)$ value provides the dosemeter response, as shown in Eq. (1):

$$R(E_H,\alpha) = (N_{par} + N_{sum})/H_P(10,\alpha) \tag{1}$$

In addition to the double dosemeters, lots of nine single-element planar dosemeters have been exposed in the same conditions. This allowed appreciating the improvement, in terms of

Table 1
$H_p(10)$ responses of the double and the single dosemeters, as a function of the incidence angle and of the neutron energy. The data are normalized to the Am–Be source (4.4 MeV) and normal incidence ($\alpha = 0°$). The variability index v_α is reported for each energy and dosemeter type.

E_H (MeV)		Energy- and angle- dependent $H_p(10)$ response normalized to Am–Be									
		Double dosemeter					Single dosemeter				
		1.2	2.1	4.4	5.0	14.8	1.2	2.1	4.4	5.0	14.8
Angle α (deg)	0°	0.80	0.88	1.00	0.88	0.64	0.84	0.88	1.00	0.92	0.43
	15°		0.98	1.07				0.91	0.98		
	30°				0.84	0.69				0.69	0.48
	45°		0.94	1.10				0.78	0.74		
	60°	0.76	0.90	1.16		0.70	0.25	0.62	0.44		0.33
v_α		±2%	±5%	±8%	±2%	±4%	±54%	±19%	±39%	±15%	±18%

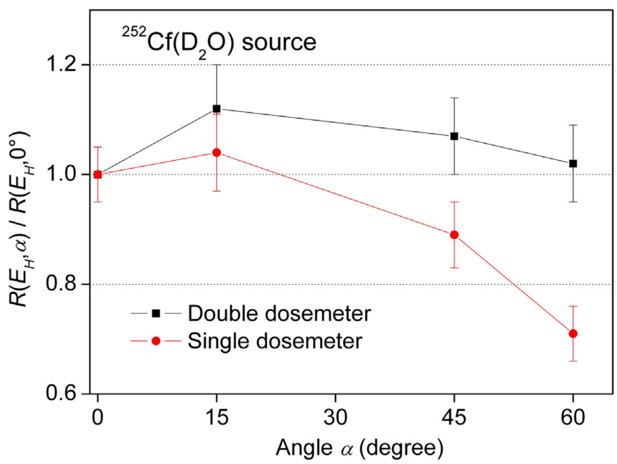

Fig. 3. Angle dependence of the $H_p(10)$ response for the single and the double dosemeters. The neutron field is the ^{252}Cf(D_2O). The data are normalized to the normal incidence.

angle response, of the double dosemeter with respect to the traditional planar configuration.

3. Results

The $H_p(10)$ responses of the double and the single dosemeters, as a function of the incidence angle and of the neutron energy, are reported in Table 1. The data are normalized to the Am–Be source (for each dosemeter, separately) and normal incidence ($\alpha = 0°$).

For the purposes of this work it is convenient to define the quantity $v_\alpha(E_H)$ as follows:

$v_\alpha(E_H)$: maximum relative variability of the response as a function of the incidence angle, derived at the energy E_H. $v_\alpha(E_H)$ is calculated with Eq. (2):

$$v_\alpha(E_H) = \frac{1}{2}\cdot\frac{\max\limits_\alpha[R(E_H,\alpha)] - \min\limits_\alpha[R(E_H,\alpha)]}{R_{central}} = \frac{\max\limits_\alpha[R(E_H,\alpha)] - \min\limits_\alpha[R(E_H,\alpha)]}{\max\limits_\alpha[R(E_H,\alpha)] + \min\limits_\alpha[R(E_H,\alpha)]} \quad (2)$$

where the maximum and minimum of the response are obtained, at fixed energy E_H, by varying the incidence angle α.

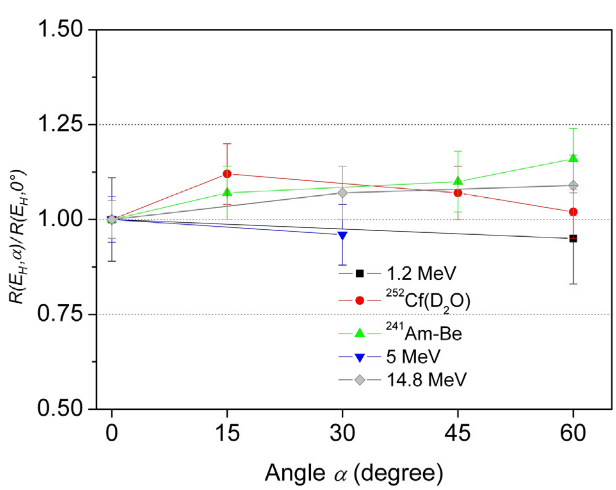

Fig. 4. Angle dependence of the $H_p(10)$ response for the double dosemeter. All neutron energies are studied. The data are normalized to the normal incidence for each energy.

Table 2
Values of the response variability indexes v_{max}, v_{E_H} and v_{α,E_H} for the single dosemeter and the double dosemeter. The indexes are defined in Section 3.

Index	Single dosemeter	Double dosemeter
v_{max}	±54%	±8%
v_{E_H}	±40%	±22%
v_{α,E_H}	±60%	±29%

$R_{central}$ is the central value of the response, i.e. the half sum of the maximum and the minimum response.

Figs. 2 and 3 compare the angle dependence of the $H_p(10)$ response for the double dosemeter with that of the single-element planar dosemeter for the ^{241}Am–Be and ^{252}Cf(D_2O) sources. The data are normalized to the 0° response for every energy. Uncertainty bars (one sigma) are always higher than ±10%. The improvement in the angle response, from the single dosemeter to the double dosemeter, is evident from both Figures.

According to the data of Table 1 and to Figs. 2 and 3, v_α(^{241}Am–Be, E_H = 4.4 MeV) changes from ±39% to ±8% when passing from the single dosemeter to the double dosemeter. In analogy, v_α(^{252}Cf(D_2O), E_H = 2.1 MeV) passes from ±19% to ±5%.

The angle dependence of the response is considered for all studied energy in Fig. 4. For a given energy the data are normalized to the normal incidence response at that energy. The maximum value of $v_\alpha(E_H)$, termed v_{max}, is ±8% for the double dosemeter. This corresponds to E_H = 4.4 MeV (^{241}Am–Be). For the single dosemeter this is ±54% and corresponds to E_H = 1.2 MeV. This data are shown in Tables 1 and 2.

The maximum relative variability of the response as a function of the neutron energy, in normal incidence condition ($\alpha = 0°$), is symbolized with v_{E_H} and is calculated as follows:

$$v_{E_H} = \frac{\max\limits_{E_H}[R(E_H,0°)] - \min\limits_{E_H}[R(E_H,0°)]}{\max\limits_{E_H}[R(E_H,0°)] + \min\limits_{E_H}[R(E_H,0°)]}$$

The energy dependence of the response for the single and the double dosemeter is shown in Fig. 5. Here the data are reported for normal incidence ($\alpha = 0°$) and are normalized to the Am–Be. Also data for the bare ^{252}Cf source were included. The single and the double dosemeters show comparable energy dependence, excepted for E_H = 14.8 MeV. The quantity v_{E_H} is ±40% for the single dosemeter and ±22% for the double dosemeter (see Table 2).

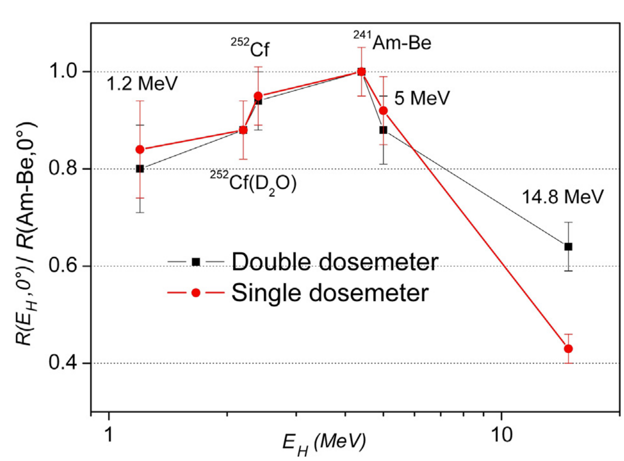

Fig. 5. Energy dependence of the $H_p(10,0°)$ response for the single and the double dosemeters. The data are normalized to the ^{241}Am–Be source.

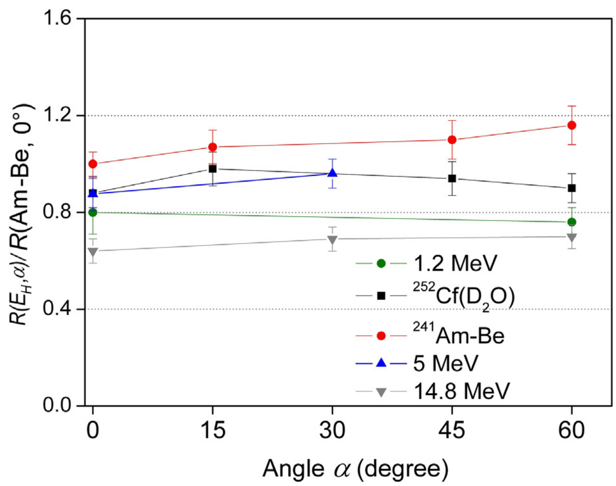

Fig. 6. Combined energy and angle dependence of the double dosemeter response. The data are normalized to the Am–Be in normal incidence condition ($\alpha = 0°$).

If the energy and angle dependence of the response are considered together, the maximum relative variability v_{α,E_H} can be defined:

$$v_{\alpha,E_H} = \frac{\max_{\alpha,E_H}[R(E_H,\alpha)] - \min_{\alpha,E_H}[R(E_H,\alpha)]}{\max_{\alpha,E_H}[R(E_H,\alpha)] + \min_{\alpha,E_H}[R(E_H,\alpha)]} \quad (4)$$

It should be noted that if a normal distribution is assumed to describe the occurrence of the $R(E_H,\alpha)$ in practical measurements, the relative standard uncertainty of $R(E_H,\alpha)$ can be estimated as v_{α,E_H} /3 (EC, 2009).

Fig. 6 shows the combined energy and angle dependence of the double dosemeter response. The data are normalized to the Am–Be and normal incidence condition ($\alpha = 0°$). The index v_{α,E_H} is ±29% for the double dosemeter and ±60% for the single dosemeter (see Table 2).

The ISO performance requirements (ISO, 2005) can be used to further compare the double and the single dosemeters. This Standard treats the energy and angle dependence independently. For energy dependence it requires $v_{E_H} < \pm 50\%$. This is fulfilled by both dosemeters.

For angle dependence, the Standard states "*the arithmetic mean of the response of a dosimeter at angles of incidence of 0°, 15°, 45° and 60° from normal shall not differ by more than 40% from the corresponding response at normal incidence*". This difference is 35% for the single dosemeter and 10% only for the double dosemeter.

Both dosemeters fulfil the ISO criteria. Nevertheless, the double dosemeter practically eliminates the angle dependence of the response, substantially improving the accuracy of the response when the irradiation geometry in not known a priori.

4. Conclusions

The energy and angle responses of a personal neutron dosemeter based on two orthogonal PADC detectors have been determined and compared with those of a single element planar dosemeter. The irradiations have been performed with monochromatic beams from 1.2 to 14.8 MeV and with radionuclide sources.

When passing from the single dosemeter to the double dosemeter, the maximum angle variability of the response changes from ±54% to ±8%. When energy and angle are considered together, the maximum response variability changes from ±60% to ±29%.

The proposed configuration certainly implies additional costs in terms of number of detectors and development of new holders, but the increased accuracy of the dosemeter response is a major achievement for a dosimetry service.

Acknowledgements

The irradiations with ^{241}Am–Be and ^{252}Cf(D_2O) sources have been performed at ENEA-Bologna Calibration Laboratory. The monochromatic beams have been provided by PTB-Braunschweig in the framework of the ERINDA (European Reasearch Infrasctructures for Nuclear data applications) project PAC 1/8 (2011).

References

Bedogni, R., Esposito, A., Lovestam, G., García, M.J., Virgolici, M., 2008. The new PADC based fast neutron dosimetry system of the INFN-LNF. Radiat. Meas. 43, S491–S494.
Bedogni, R., Esposito, A., Garcia, M.J., 2008a. Dosimetric performance of the new four elements PADC neutron dosemeter of the INFN-LNF. Radiat. Meas. 43, 1108–1112.
Devine, R.T., Walker, S., Staples, P., Duran, M., 1996. Track-etch dosemeter response to neutrons up to 300 MeV. Proceed. 9th international congress on radiation protection and general assembly of the International Radiation Protection Association (IRPA), Vienna (Austria), 14–19 April 1996.
EC, European Commission, 2009. Technical recommendations for monitoring individuals occupationally exposed to external radiation. Report Radiation Protection n. 160.
Esposito, A., Bedogni, R., Gentile, A., 2008. Monitoring the ambient neutron radiation around a high energy collider using PADC dosemeters. Radiat. Meas. 43, S487–S490.
Gopalani, D., Saravanan, S., Jodha, A.S., Kumar, S., 2003. Angular response characteristic of pyramid shape fast neutron dosimeter using CR-39 films. Radiat. Meas. 36 (1–6), 499–502.
Harvey, J.R., 1992. A three element etched track neutron dosemeter with good angular and energy response characteristics. Radiat. Prot. Dosimetry. 44 (1–4), 325–328.
ISO, International Standardization Organization, 2001. Reference Neutron Radiations: Characteristics and Methods of Production. International Standard ISO 8529-1:2001.
ISO, International Standardization Organization, 2005. Passive Personal Neutron Dosemeters - Performance and Test Requirements. International Standard ISO 21909:2005.
Morelli, B., Vilela, E., Fantuzzi, E., 1999. Dosimetric performance of the fast neuton dosemeter for ENEA personal dosimetry service. Radiat. Prot. Dosimetry. 85 (1–4), 105–108.
Morelli, B., Mariotti, F., Fantuzzi, E., 2006. The ENEA neutron personal dosimetry service. Radiat. Prot. Dosimetry. 120 (1–4), 312–315.
Tanner, R.J., Bartlett, D.T., Hager, L.G., 2005. Operational characteristics of etched-track neutron detectors in routine radiation protection dosimetry. Radiat. Meas. 40, 549–559.