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A COMPARISON OF THE RESPONSE OF PADC NEUTRON DOSEMETERS IN HIGH-ENERGY NEUTRON FIELDS

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Within the framework of the EURADOS Working Group 11, a comparison of passive neutron dosemeters in high-energy neutron fields was organised in 2011. The aim of the exercise was to evaluate the response of poly-allyl-glycol-carbonate neutron dosemeters from various European dosimetry laboratories to high-energy neutron fields. Irradiations were performed at the iThemba LABS facility in South Africa with neutrons having energies up to 66 and 100 MeV.

INTRODUCTION

Within the framework of the EURADOS Working Group 11, a comparison of passive neutron dosemeters in high-energy neutron fields was organised in 2011 at the iThemba Laboratory for Accelerator-Based Sciences (iThemba LABS) to evaluate the response of passive neutron dosemeters from various European dosimetry laboratories to different high-energy neutron fields. High-energy neutrons have been a subject of investigation for dosimetry for many years due to human space activities and changes in regulations for individual monitoring of aircrew in recent years. The development of new applications with high-energy particle beams for research or cancer treatment (hadrontherapy) with secondary high-energy neutrons, which is a matter of concern for both exposed workers and patients, has driven the need for adapted passive neutron dosimetry. Passive dosemeters used for routine monitoring such as track-etched poly-allyl-glycol-carbonate (PADC) detectors can be used for such applications, if properly calibrated. From the experimental data obtained in this work, participants could derive calibration factors for high-energy neutron dosimetry or validate track analysis methods developed for this purpose. The second step of WG11 activities will be to organise dosimetry benchmark tests to evaluate the performances of these neutron dosimetry systems in high-energy neutron fields.

MATERIALS AND METHODS

Layout of beam delivery system

A separated-sector cyclotron accelerates protons in the energy range from 25 to 200 MeV(1). The $^{7}Li(p, n)^{7}Be$ reaction is employed to produce neutrons up to 200 MeV. A 2-m-thick steel collimator with openings at 0° and 16° acts as a collimator resulting in 10×10 cm^2 shape squared beams at a distance of 8 m from the target.

Methods for beam characterisation

The characterisation of the spectral fluence distribution was performed by combining data from a NE213 scintillator and parallel-plate ^{238}U fission chamber(1). The relative neutron energy spectra were determined using the NE213 detector via time-of-flight measurements, and the fluence using the fission chamber. These reference detectors were calibrated by Physikalisch-Technische Bundesanstalt (PTB) in terms of neutron energy, energy threshold and efficiency.

Beam characteristics

As shown for the 100-MeV configuration in Figure 1, the neutron spectral fluence distribution at 0° consists of a high-energy peak and a continuum for lower neutron energy. At 16°, the continuum is similar but the 100-MeV peak is much reduced.

The transition to the ground state and first excited state of ^{7}Be produces quasi-monoenergetic neutron emission. In addition, break-up reactions in lithium cause a low-energy tail below the monoenergetic peak. Reactions (p, xn) with the higher Z nuclei from the target holder also generate neutrons of lower energies.

PADC description and chemical procedure

Table 1 summarises the type of PADC used by each participant, as well as the associated procedure used for the etching step. Pre-etching with a mixture of sodium hydroxide and methanol prior to irradiation was performed only by IRSN.

Track analysis

The track analyses were performed using different approaches and software. Paul Scherrer Institute (PSI) used the full system provided by TASL (microscope and software analysis)[(2)]. This system analyses and characterises each individual track based on 31 different track parameters in order to discriminate etched tracks from background features. At Polimi, the PADC dosemeters were analysed using a commercial reader called Politrack[(3)], developed at Polimi and marketed by MiAms.r.l. (Italy). Politrack permits two kinds of analysis to be performed: a simple one that just consists of measuring the track density (TD) and a second one based on estimation of the average LET of each track. UAB and IRSN used home developed systems to count the tracks. UAB imposed a threshold on track size to discriminate etched tracks from background. The routine procedure with such discrimination was not used for IRSN to analyse the raw data. PHE used a system developed for them, which has a minimum track size and applies corrections to eliminate irregular tracks and for linearity[(4)]. Because UAB and PHE use electrochemical etch systems, the tracks are large and easily counted. The other three systems have smaller tracks of different sizes, so the resolution and track size threshold of the read system will be a critical factor.

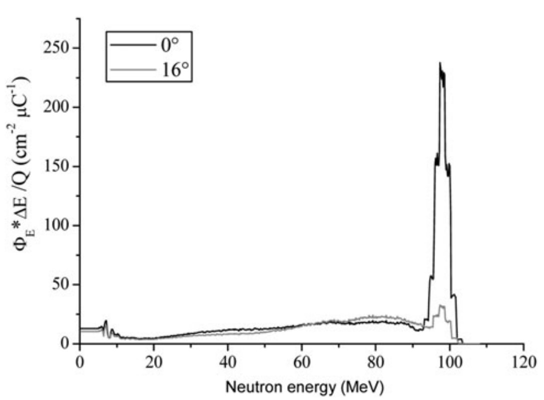

Figure 1. The measured neutron fluence distribution at 0° and 16° for 100 MeV protons.

Table 1. Characteristics of PADC and chemical procedures.

Laboratory	Supplier (dimension (mm^3))	Chemical procedure
PSI	TASL[a] (20×25×1.5)	6.25 N NaOH for 2.5 h at 80°C
PHE	Instrument Plastics Ltd (27×39×0.5)	5 N NaOH for 11.5 h at 40°C+8 h with an electric field of 23.5 kV cm^{-1}
Polimi	Intercast[b] (25×25×1.5)	6.25 N NaOH for 1.5 h at 98°C
UAB	Intercast (20×20×1)	3-step ECE[c]: 20 kV cm^{-1} at 50 kHz for 5 h+2 kHz for 1 h+15-min chemical post-etching
IRSN	TASL[a] Technol[d] (20×25×1.5)	6.25 N NaOH for 15 h at 70°C

[a]Track Analysis System Ltd, Bristol.
[b]Intercast Europe S.r.l., Parma.
[c]Electro-chemical etching.
[d]Chiyoda Technol Corporation.

Experimental set-up

The dosemeters were irradiated at 8 metres from the target. Irradiations were performed at emission angles of 0° and 16° simultaneously. For a given configuration, a minimum of four dosemeters were irradiated. For the Polimi PADC, 1 cm of PMMA was used in front of the PADC as a converter and to ensure the full charged particle equilibrium. The UAB system used 3-mm polyethylene+300-μm Makrofol®+100-μm Nylon® as a converter, and a 5-mm lead sheet was added to the dosemeter housing to investigate the increase of sensitivity expected for high-energy neutrons. PADC from PSI, PHE and IRSN were irradiated in the personal dosemeter holder use routinely. Irradiations were performed in air or on slab PMMA phantom. The integrated doses on PADC ranged between 2 and 7 mSv in terms of $H_p(10)$ or $H^*(10)$, depending on irradiation configurations (air or phantom). It should be noted that dosemeters that did not use additional material in front of the detector may have a component of response from the charged particles generated in air.

Reference dosimetry

For each irradiation, the fluence was determined from monitors calibrated by PTB. For each irradiation configuration, a conversion factor from fluence to operational quantities was derived from the combination of measured neutron spectra and the monoenergetic conversion factors from ICRU report 57[5]. For $H_p(10)$ of >20 MeV, as no conversion factor is available in ICRU57, conversion factors for $H^*(10)$ were used: this should be acceptable because the irradiations were for normal incidence and $H^*(10)$ and $H_p(10, 0°)$ then only differ because of the shape of the phantom. Table 2 summarises the mean neutron energy and the conversion coefficients for each irradiation configuration. The total uncertainty on the fluence measurements has been estimated at ~10 %.

RESULTS

Irradiation on phantom

The results of the irradiations performed on phantom for the four configurations are presented in Figure 2. Each point represents the average of the TD per mSv for the different detectors exposed in that configuration. The uncertainty is the combination of the standard deviation on TD and the total uncertainty on reference dose. The TD reported by PSI is found to be on average about a factor of 2.6 lower than the 4 other PADC types. The 4 other types have close TD ranging between 120 and 160 tracks cm^{-2} mSv^{-1}. The difference between IRSN (TASL) and UAB is ~10 % and ~6 % between UAB and PHE.

Whilst the readings on the IRSN (TASL) and PSI dosemeters are very different, they do exhibit similar behaviour: the variation for the three configurations with the lowest mean neutron energies is lower than uncertainties whereas a slight decrease is observed for the highest mean energy configuration (15 and 28 % for IRSN-TASL and PSI). Although IRSN and PSI have used the same PADC, i.e. both TASL, it is difficult to identify a specific cause for the observed difference in TD values. The etching procedures, the track analysis methods and the housings of the dosemeter are different and may have some influence. For the UAB and PHE detectors, the variations observed between the configurations are of the same magnitude as the uncertainties. For UAB PADC, the addition of 5 mm of lead does not lead to an increase in the sensitivity. Obviously, a thicker layer might be effective but that can hardly be envisaged for a personal dosemeter.

Table 2. Ambient and personal dose equivalents per unit neutron fluence delivered for each irradiation configuration.

Configuration	E_{mean} (MeV)	$H^*(10)$ per unit fluence (pSv cm^2)	$H_p(10)$ per unit fluence (pSv cm^2)
100 MeV, 0°	68.1	342.2	344.1
100 MeV, 16°	58.8	363.3	366.1
66 MeV, 0°	44.2	413.5	416.9
66 MeV, 16°	37.4	439.2	443.7

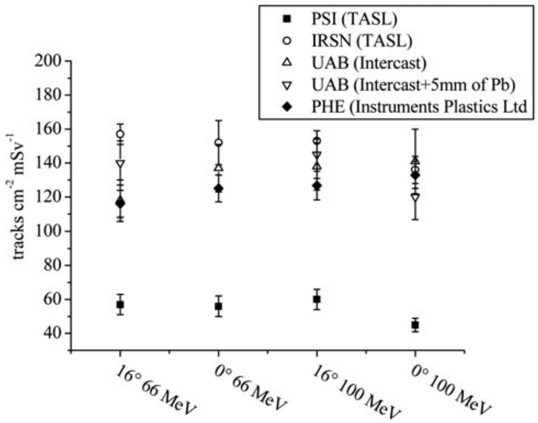

Figure 2. A comparison of TD per mSv for PADC irradiated on phantom for four different configurations.

Irradiation in air

The results of the irradiation performed in air for the four configurations are presented on Figure 3. As for irradiation on phantom, UAB and IRSN (TASL) PADC have a similar TD. The difference between the air and phantom configurations is of the same magnitude as the uncertainties. IRSN PADC (TASL) shows a similar behaviour as in air, with a slight decrease for the highest mean energy. Technol PADC is slightly more sensitive than the TASL ones by ~10 %. But these results are hardly interpretable as the procedure is not optimised at these levels of energy and no specific procedure adapted to the type of PADC was developed. For UAB PADC, the 5 mm of lead in front of the PADC has no influence on the TD, as for irradiation on phantom. The TD of Polimi PADC is about twice as high as those from other PADC. If Polimi and UAB have used the same PADC, it is difficult to explain the observed difference, as the etching procedure, the track analysis method and the housing of the dosemeter are different and may have some influence.

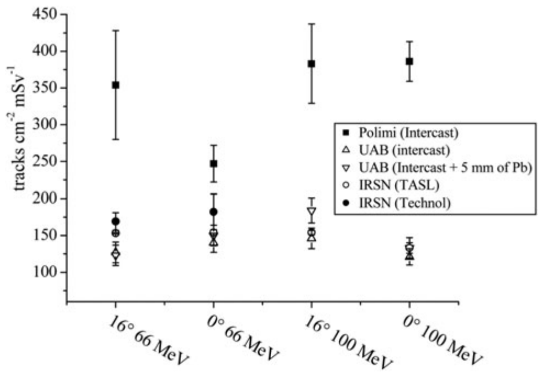

Figure 3. A comparison of TD per mSv for PADC irradiated in air for four different configurations.

For Polimi, except for the 0° and 66-MeV configuration, the TD variation is within the uncertainties. For the 0° and 66-MeV configuration, the TD decreases by a factor of 1.5 relatively to other configurations. Nevertheless, it is worth noting that the Politrack analysis software is designed to estimate dose through LET estimation of each track; the track counting mode not being used routinely[6]. In Figure 4, the relative TD and dose sensitivity are compared. The decrease for the 0° and 66-MeV configuration is not observed anymore in the dose mode.

CONCLUSION

For the different neutron spectra investigated in this work, the TD of each PADC type varies only weakly, compared with the energy dependence observed at lower energy (<20 MeV). For the PADC presenting the lowest uncertainties, a slight decrease of the TD has been observed for the highest mean energy (68.1 MeV). The difference of TD observed between the different detectors, which reaches a factor of 6 between the minimum and maximal values, cannot be explained without further investigations, but it is likely to be linked to track size: the ratio of the track diameters for PSI, IRSN and Polimi should be ~1:3:6 based on etch duration and temperature. With these experiments, participants had the possibility of calibrating their detectors to high-energy neutrons or to validate specific methods for dose estimation. Based on these data, the dosimetry performances of PADC of participants will be evaluated in future benchmarking experiments.

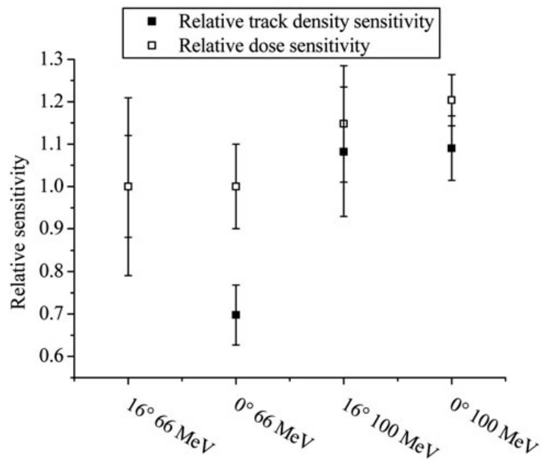

Figure 4. A comparison of relative sensitivity in terms of TD and $H^*(10)$ for POLIMI PADC irradiated in air for four different configurations.

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