HIGH-ENERGY NEUTRON RESPONSE OF ELECTRONIC PERSONNEL DOSIMETERS

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Electronic personnel dosimeters (EPD) are routinely used to monitor worker dose at neutron energies < 20 MeV. Second generation designs consist of both thermal and fast neutron detectors, whereby the combined data is used to determine neutron dose equivalent.

Though not specifically designed for use at high-energy accelerators, they nevertheless offer an attractive method of monitoring personnel in real time. However, a proper interpretation of displayed dose requires that the energy response of the device be known. To this end, measurements were conducted using several EPDs in common use (Siemens N2, Fuji Electric NY2001 and Saphydose-n) in quasi-monoenergetic fields at the Université Catholique de Louvain (33 and 60 MeV) and the T. Svedberg Laboratory (46, 95, 143 and 173 MeV). In addition, measurements have been made at the Los Alamos Neutron Science Center in broad energy fields at an average energy of 345 MeV.

In general, it has been found that these dosimeters over respond significantly in all of the above fields. It is postulated, that this is due to charged particle spallation production within the fast neutron detector – beyond recoil proton production in the proton converter. This theory has been substantiated using Monte Carlo simulations of dosimeter response.

I. INTRODUCTION

Neutron-sensitive electronic personal dosimeters (EPD) are now routinely used to monitor worker dose in mixed neutron-photon fields where neutron energies are less than 20 MeV. An overview of the current technology and its capabilities was provided by Luszik-Bhadra[1] and d'Errico[2] et al. The most sophisticated designs consist of both thermal and fast neutron detectors, whereby the combined data are used to determine neutron dose equivalent. All of the EPDs tested featured dual neutron channels. The thermal detector typically consists of a silicon diode in contact with a radiator impregnated with either ^{6}Li or ^{10}B, which acts as a source of alpha particles following thermal neutron capture. In the fast channel, a silicon diode in contact with a proton converter responds to fast proton recoils. Gamma rejection is provided either through subtraction of a gamma signal (requires a 3rd channel) or by making the silicon diode sufficiently thin and rejecting gamma pulses on the basis of pulse height.

Though not specifically designed for use in and around high-energy accelerators, such EPDs nevertheless offer an attractive method of monitoring personnel dose in real time. However, a proper interpretation of displayed dose requires that the energy response of the device be known. To this end, we have made measurements using several EPDs in common use (Siemens N2, Fuji Electric NY2001 and Saphymo company's Saphydose-n[3]) in quasi-monoenergetic fields at cyclotron facilities at the Université Catholique de Louvain (UCL) (33 and 60 MeV) and the T. Svedberg Laboratory (TSL), Uppsala, Sweden (46, 95, 143 and 173 MeV). All of the neutron fields were generated using the (p,Li) reaction at these facilities[(4,5)]. In addition, measurements were also conducted at the 90m flight path, Weapons neutron research (WNR) facility, Los Alamos Neutron Science Center (LANSCE)[6] in a broad energy neutron field extending to 800 MeV.

II. EXPERIMENTAL METHODS

For all measurements, the EPDs were positioned on a 40x40x15 (30x30x15 in Europe) cm PMMA (Lucite®) phantom. The dosimeters, phantom-mounted, are shown in Figure 1 where the Saphymo Saphydose-n is positioned on the left, the Siemens N2 is located on the upper right

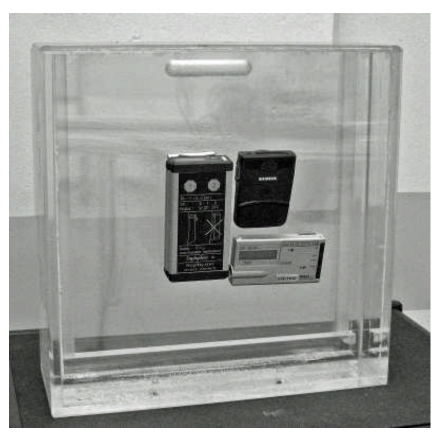

Fig.1. EPDs used in this study mounted on 40x40x15 cm Lucite phantom. See text for EPD identification.

hand side and the Fuji Electric is on the lower right hand side.

A $1/r^2$ correction was applied to the beam monitor measurements to obtain the fluence at the measurement location. Time-of-flight measurements were performed at WNR/LANSCE using a ^{238}U fission chamber for a stop signal. In-line beam filters were employed at WNR/LANSCE to harden the beam and reduce the incident gamma and neutron fluence rate. The data of interest to this work was obtained using 10 cm of copper followed by 20 cm of polyethylene and 10 cm of lead to generate a filtered spectrum, shown in Fig.2, with an average energy of approximately 345 MeV.

No filters were used for the irradiations at UCL. Staff of the German Bureau of Standards (PTB) measured the neutron spectra, which are shown in Fig. 3. However, all of the irradiations at TSL used polyethylene filters to preferentially attenuate the fluence below 20 MeV since the contribution from neutrons below the full peak energy to the dose measurement can be disproportionately large due to the relatively high response of the EPDs at low energies. As a result, the filters also had the effect of

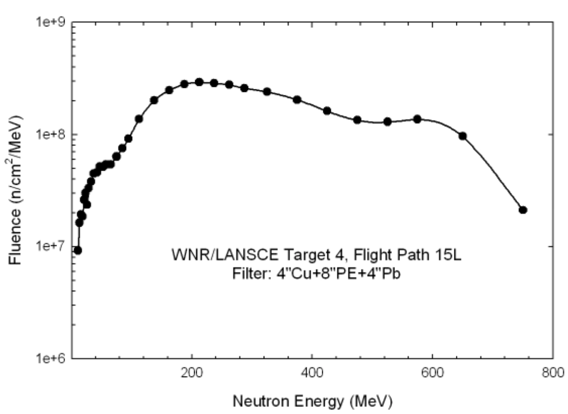

Fig. 2. Neutron spectrum: LANSCE/WNR, Target 4, Flight path 15L

increasing the fluence fraction in the full-energy peak from typical unfiltered values of roughly 40% to about 60%. The optimum filter thickness for each full-energy peak, ranging from 30 cm at 46 MeV to 50 cm at 173 MeV, was determined using the Los Alamos MCNPX[7] Monte Carlo code. A semi-classical approach[8,9] was used to calculate the source term spectra for these calculations. Later, the calculations were repeated using empirically determined spectra[5], the agreement in the transmitted fluence was within 15%, and generally improved with increasing peak energy. The filtered spectra are shown in Fig. 4.

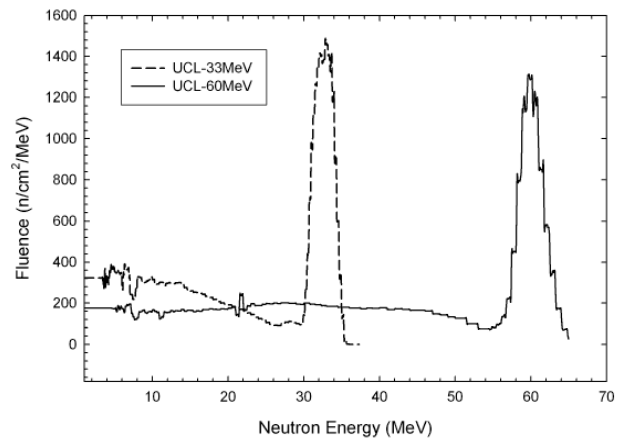

Fig. 3. Neutron spectra: UCL Cyclotron Facility

Due to the highly collimated nature of the beam, the room return contribution at the measurement location was expected to be relatively small. This assumption was confirmed at TSL by comparing on and off-axis count rates with a neutron spectrometer[(10)].

Fluence was converted to personal dose equivalent, $H_p(10,0)$, using a composite function based on ICRP-74 published values below 20 MeV, extended to 1 GeV using recent MCNPX simulations at Los Alamos (to be published). These simulations tracked all charged particle secondaries in a tissue slab phantom to determine absorbed dose from first principles - without recourse to the kerma approximation. Appropriate quality factor functions were folded in to determine dose equivalent.

EPD readings were taken as personal dose equivalent and were divided by the delivered Hp(10,0) to obtain relative response ratios. Original Factory calibrations were used for the Fuji Electric and Saphymo EPDs, while the Siemens N2 was re-calibrated to bare ^{252}Cf in the Los Alamos Central Health Physics Calibration Facility.

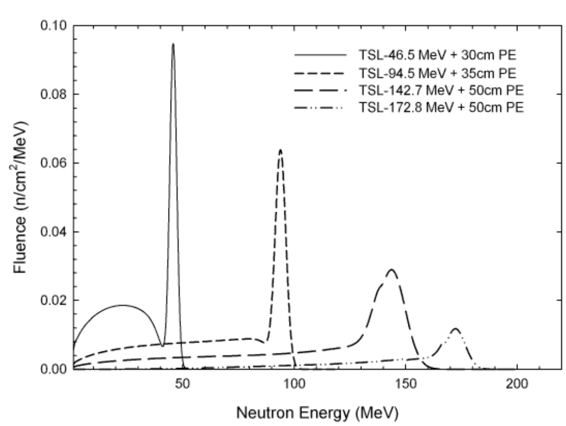

Fig. 4. Neutron spectra: TSL Cyclotron Facility

III. RESULTS AND ANALYSIS

Since the fast neutron channel in the all of the EPDs under evaluation was designed to respond to proton recoils, it seems reasonable to assume that the high-energy response would decrease monotonically, in concert with the elastic scattering cross section. To a first approximation, the n-p scattering cross section is inversely proportional to the square root of neutron energy in MeV. Based on this information, one might expect that the EPD response would drop by a factor of two between 20 and 80 MeV. In fact, the opposite happens. The response is actually observed to increase by up to a factor of about four – relative to a standard reference field calibration due to the onset of charged particle spallation production directly in the diode, its casing, and surrounding material.

A summary of all the EPD measurements is presented in Fig. 5. Whenever two EPD samples of the same model were irradiated, the average value is given. The Fuji electric EPD was only evaluated at 33 and 60 MeV. The Siemens N2 ranged in response from 3.45 to 5.79, with the highest response obtained at WNR. The Saphymo Saphydose-n gave the lowest over response in the cyclotron produced fields (1.03 -2.38), but exhibited a factor of 20 over response at WNR. The response linearity of the Siemens N2 was also measured at WNR as a function of integrated dose. The results are presented in Fig. 6.

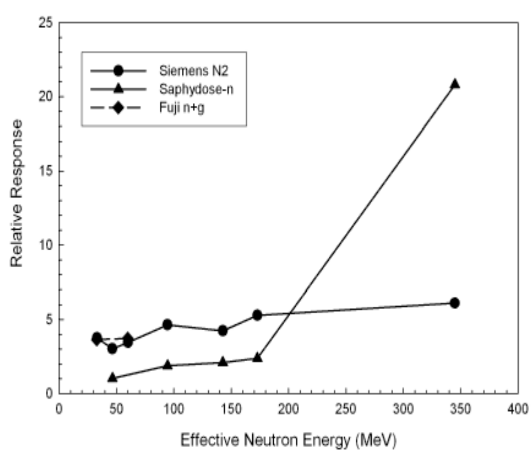

Fig. 5. Relative response ratios for the EPDS under test

To confirm that the observed over response was in fact due to spallation products, the MCNPX code was used to simulate the fast neutron channel response of the Siemens N2 EPD for all four irradiations at TSL. Basic information about the device was obtained from the vendor. The fast neutron channel detector, a silicon PIN photodiode, was modeled as a 525 µm thick wafer of silicon with a 4mm x 4mm active area. The wafer was segmented into a 14 µm p+ layer followed by a 70 µm intrinsic layer. The thickness of the intrinsic layer was not precisely known, and was adjusted in the model to give good agreement with the measured response of the fast channel in a bare ^{252}Cf reference field. A radiator was placed above the silicon wafer consisting of a 25 µm polyimide film layer followed by a 25 µm thick layer of epoxy glue resin. Additional details included in the model were the diode's ceramic case and aluminum window, and the EPD's plastic case. LA150[(11)] cross section tables were used for all materials of interest. Above 150 MeV, the CEM03.01[(12)] physics model was invoked.

A pulse height light tally was defined for the intrinsic layer of the diode to include contributions from all charged particle secondaries: protons, deuterons, tritons, He-3, alphas, and electrons. All secondaries were transported down to a cutoff energy of 1 keV within the diode. The fast neutron channel's discriminator setting was estimated by the vendor to be equivalent to about 0.6 MeV. Therefore, each neutron history giving rise to a cumulative deposited energy in excess of 0.6 MeV was considered to produce a count in the fast neutron channel. The main dose contributors were proton, alpha and deuteron tracks. The EPD model was placed on a PMMA phantom and irradiated to the spectra calculated for the filtered TSL neutron fields. The calculated fast neutron

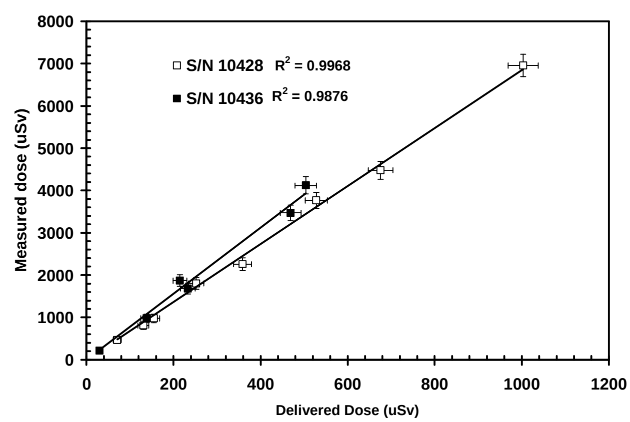

Fig. 6. Linearity of Siemens N2 EPD in WNR field

channel counts were normalized to the total delivered fluence for each irradiation. The results are presented in Table I. Considering the uncertainty inherent in the delivered fluence (±20% at the k=2 coverage level), the agreement between calculation and measurement is seen to be quite reasonable.

TABLE I. Siemens N2 fast neutron channel response. Neutron counts normalized to delivered fluence.

Neutron Energy (MeV)	Measured Counts	Calculated counts	Percent Difference
46.5	1913.5	1610.1	-15.9
94.5	2618.5	2053.0	-21.6
142.7	553.5	525.5	-5.06
172.8	368	244.7	-33.5

IV. DISCUSSION

A method is proposed for explicitly taking advantage of spallation products induced within a photodiode to measure neutron dose equivalent at >30 MeV neutron energies. Such a design would dedicate a pair of photodiodes to fast neutron detection. – one diode with a proton recoil radiator and one without. The signal in the diode without a radiator would be associated strictly with spallation products, while the other diode would give a combined signal to include proton recoils. Appropriate calibration factors applied to the difference signal and to the signal from the 'nude' diode should give a reasonable estimate of the dose equivalent over a wide energy range. This appears to be an especially promising approach in the case of the Siemens N2 EPD whose spallation induced signal is seen to vary slowly over a wide energy range.

V. CONCLUSIONS

EPDs with a proton-recoil fast neutron channel have been found to over respond significantly in >30 MeV neutron fields. The over response has been demonstrated using Monte Carlo simulations to be due to charged particle spallation production within the fast neutron detector. A method based on using a pair of photodiodes for fast neutron detection has been suggested as a means of explicitly taking advantage of this phenomenon.

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