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Dose Rate Effects on Mixed Field Neutron-Gamma Dosimetry Using a Tissue Equivalent Proportional Counter

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ABSTRACT

Tissue equivalent proportional counters (TEPCs) are commonly used for radiation monitoring in areas where a mixture of neutron and photon radiations may be present, such as those commonly encountered in nuclear power plants. In such radiation fields, the dose rate of each component can vary drastically from extremely low to very high. Among these possible combinations of radiation fields with very different dose rates, a mixed field of an intense photon and a weak neutron dose component is more commonly encountered.

This study describes the measurement of lineal energy spectra carried out with a 5.1 cm (2 inch) diameter spherical TEPC simulating a 2 μm diameter tissue site in low energy (33 – 330 keV neutrons) mixed photon-neutron fields with varying dose rates generated by the McMaster University 1.25 MV double stage Tandetron accelerator. The Tandetron accelerator facility was employed to produce neutrons using thick ^{7}Li targets via the ^{7}Li(p, n)^{7}Be reaction. A continuous spectrum of neutrons is generated at any selected proton beam energy which is very narrow at beam energies very close to the threshold of the reaction 1.88 MeV and becomes wider as the proton beam energy moves further away from the threshold energy of the reaction. Dose rates which resulted in dead times as high as 75% for the data acquisition system were employed to study the effect of dose rate on the measured quality factors, microdosimetric averages ($\bar{y}_f$ and $\bar{y}_D$), absorbed dose and dose equivalent. The dose rate at a given beam energy was varied by changing the accelerator beam current.

We have observed that high dose rates due to both photons and neutrons in a mixed field of radiation result in pile up of pulses and distort the lineal energy spectrum measured under these conditions. The pile up effect and hence the distortion in the lineal energy spectrum becomes prominent with dose rates which result in dead times larger than 25% for the high LET radiation component.

SUMMARY

A. INTRODUCTION

As knowledge of biological effects of radiation has improved, definitions and concepts have been developed for radiation protection purposes to assist the health physicist, the formulation of a system of units based upon the concepts of absorbed dose and dose equivalent have been found to work well for simple radiation fields, however, operational health physicists working in nuclear power plants or near particle accelerators are often faced with the complex problem of mixed fields of neutron and gamma radiations. It is difficult in these situations to evaluate absorbed dose and dose equivalent using a single measurement with sufficient accuracy for the purposes of radiation protection (Nguyen 1985).

One instrument providing simultaneous information on the photon and neutron dose equivalent is the tissue equivalent proportional counter, (TEPCs), which can be used for radiation monitoring in areas where a mixture of neutron and photon radiations may be present, such as those commonly encountered in nuclear power plants (Waker 1997).

For the work reported in this research, microdosimetric measurements were made with a 5.1 cm (2 inch) diameter TEPC using the Tandetron accelerator at the McMaster Accelerator Laboratory, which was used to produce extreme dose rates of mixed neutron-gamma fields, in order to investigate more thoroughly the influence of count rate on measurements with TEPC.

B. Material and Methods

I. Microdosimetric system calibration

A commercially spherical TEPC of diameter 5.1 cm (available from Far West Technology, Goleta, USA) filled with propane tissue equivalent (TE) gas to simulate radiation interactions and energy deposition in microscope tissue volumes was used for the determination of absorbed dose and the radiation quality of photons, neutrons and charged particles in a variety of radiation fields.

The experimental techniques generally followed those described in literature (Waker 1995). Analogue pulses from the preamplifier, which was connected directly to the anode of the counter, were shaped and amplified through two PC based amplifiers with a gain ratio of 40. A schematic diagram related to the experimental set-up for microdosimetric procedures is shown in figure 1.

The lineal energy distribution, yd(y), was obtained from the measured pulse height spectra by applying the appropriate calibration factors. The system was calibrated by irradiating the counter with a finely collimated internal ^{244}Cm alpha source which deposits 170 keV in a 2 μm diameter TE gas corresponding to a lineal energy of y_α = 127 keV μm^{-1}. Taking the mean chord length of the TEPC to be 2/3 diameter i.e. 1.337 μm. The mean pulse height, h_α corresponding to the mean energy imparted in the cavity, was evaluated by fitting a Gaussian curve to the measured peak. using y_α and h_α, the calibration factors (CF) were calculated to convert the pulse height measurements conducted with two overlapping blocks of amplifier settings into a single spectrum of lineal energy as $CF_2 = y_\alpha/h_\alpha$ for low gain amplifier and $CF_1 = CF_2/40$ for high gain amplifier (Waker 1995)

The gas gain was selected to measure lineal energy energies between 1.5 and 350 keV/µm, which is sufficient to register events generated due to low energy neutrons and the events caused by photons. Events generated by photons are less than 10 keV/µm and events triggered by low energy neutrons are mainly concentrated in the region between 10 and 200 keV/µm. The γ-ray contribution was eliminated from the n-γ overlapping region between 1 and 10 keV/µm by subtracting a measured and scaled 478 keV γ spectrum using the same simulated tissue size site. The 478 keV γ-ray spectrum was obtained at a proton beam energy below the threshold of the (p, n) reaction.

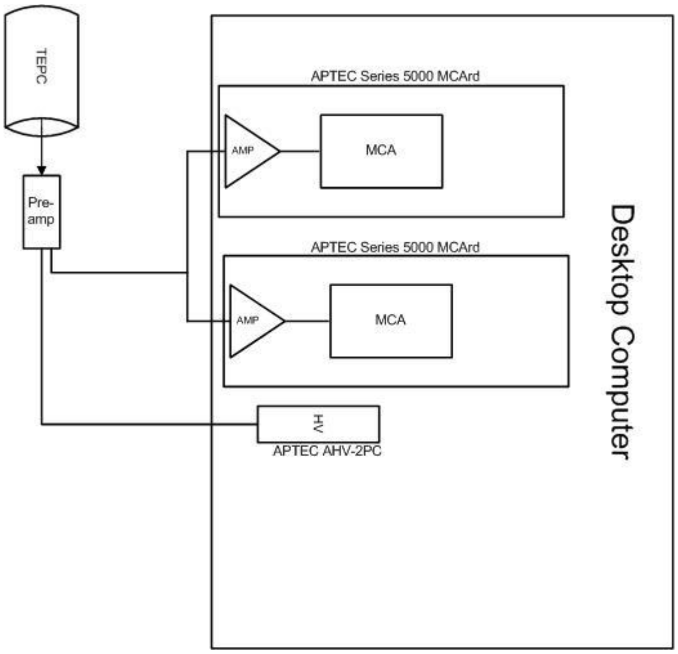

Figure 1: Overall arrangement for the measurement of the lineal energy spectrum with a TEPC in various neutron beams at the McMaster University Accelerator Laboratory.

II. Characteristics of irradiation field

Accelerator based neutron sources provide an opportunity to change the dose rate without changing the neutron spectrum by varying the projectile beam current at a given beam energy. The Tandetron accelerator at McMaster University can be safely operated under stable conditions to provide a proton beam current as high as 400 µA and low as 10 µA at a given beam energy. Therefore, at any given beam energy dose rates can safely be changed by a factor of 40 without changing the neutron spectrum. In addition, neutron dose rates with a thick ^{7}Li target via ^{7}Li(*p*, *n*)^{7}Be reaction can vary approximately by a factor of 400 when the proton beam energy is changed from the threshold (1.88 MeV) of the reaction to the Tandetron maximum beam energy of 2.5 MeV. Inelastic scattering interactions of protons with the target produce 478 keV γ rays. The ratio of photon to neutron dose depends on the beam energy and is highest at the threshold of the neutron production reaction and decreases with an increase in proton beam energy.

III. Data Analysis

The dose mean lineal energy, $\bar{y}_D$, of a lineal energy dose distribution d(y), is defined as (Aslam and Waker, 2010):

$$\bar{y}_D = \frac{\sum_{i=1}^{N} y_i^2 d(y_i)}{\sum_{i=1}^{N} y_i d(y_i)} \qquad (1)$$

In this work the lineal energy scale of y is subdivided into 50 equal logarithmic intervals per decade (N). Similarly, the frequency-mean lineal energy, $\bar{y}_F$, was determined for semi-logarithmically distributed lineal energy distribution as:

$$\bar{y}_F = \frac{\sum_{i=1}^{N} y_i d(y_i)}{\sum_{i=1}^{N} d(y_i)} \tag{2}$$

The mean quality factor, $\bar{Q}$, of each component radiation in a mixed photon-neutron field using a TEPC, $\bar{Q}$ is given by (ICRP 1991).

$$\bar{Q} = \frac{\sum_{i=1}^{N} Q(y_i) y_i d(y_i)}{\sum_{i=1}^{N} y_i d(y_i)} \tag{3}$$

This relationship for $\bar{Q}$ assumes that the linear energy transfer, L, equals lineal energy y, and the definition of Q(L=y) was adopted from ICRP 60 (ICRP, 1991).

C. Results and Analysis

Direct neutron beam energy from the Tandetron accelerator laboratory at McMaster University was employed to generate extreme dose rates of mixed fields by varying the beam current from 400 µA to as low as 10 µA at a selected beam energy which gave rise to dead times as high as 75% and as low as 5%. The highest dead time resulted from the highest dose rate achieved at a given beam energy with 400 µA proton current and the lowest dose rate achieved at 10 µA which had the smallest dead times of less than 10%. The proton energies investigated for these measurements range from 2.0 to 2.5 MeV. The measurements were conducted with a two inch diameter single wire TEPC which was placed 17cm from the lithium target. In this set of measurements the gas gain was set to measure the lineal energy spectrum in the range above 6 keV/µm which have contributions from both photons and neutrons in the spectrum.

Figure 2 illustrates lineal energy spectra measured in mixed photon and neutron fields with a 2 inch spherical TEPC at proton beam energies of 2.4 MeV which correspond to mean neutron energies of 285 keV. The pile up effect is clearly visible at the highest dose rate which amounts to approximately 70% dead-time on both MCAs. This pile up results in extending the event size towards higher lineal energy and as a result the proton peak position and proton edge are shifted towards higher lineal energies, i.e., we expect to observe an increase in the values for quality factor, and $\bar{y}_f$ and $\bar{y}_D$. This effect becomes less obvious as the dead time is reduced to the order of 25% on MCA_2 and the effect is almost negligible below 25%.

Table 1 presents the analysis of the lineal energy spectra presented in Figure 2. Statistical uncertainty was estimated using error propagation formula and is included in this table for quantities of interest. The table demonstrates that the quality factor increased by almost 30% when the dead time was changed from less than 10% to the highest value we have in this set of measurements.

Table 1: Effect of high dose rate on lineal energy spectrum of neutrons measured with 2 inch TEPC at a proton beam energy of 2.4 MeV.

I_P	Dead time (%)		Dose rate per unit 100 μA	$\bar{Q}_n$	Dose eq. rate per unit 100 μA	$\bar{y}_F$	$\bar{y}_D$
(μA)	MCA_1	MCA_2	(mGy/min)		(mSv/min)	(keV/μm)	(keV/μm)
400	76.40	65.77	7.44±0.0011	19.39±0.137	144.20±0.137	54.49±0.113	81.49±0.152
300	76.14	57.42	7.23±0.0012	18.47±0.139	133.57±0.139	49.39±0.112	74.51±0.152
200	74.42	46.07	7.95±0.0019	17.38±0.207	138.22±0.207	44.44±0.163	67.77±0.222
75	39.74	19.10	7.49±0.0019	15.55±0.192	116.41±0.192	37.90±0.145	57.99±0.197
25	14.81	7.87	7.67±0.0024	15.04±0.231	115.44±0.231	36.64±0.174	55.20±0.232
10	6.74	3.37	7.86±0.0041	15.13±0.382	118.98±0.382	36.86±0.288	55.20±0.380

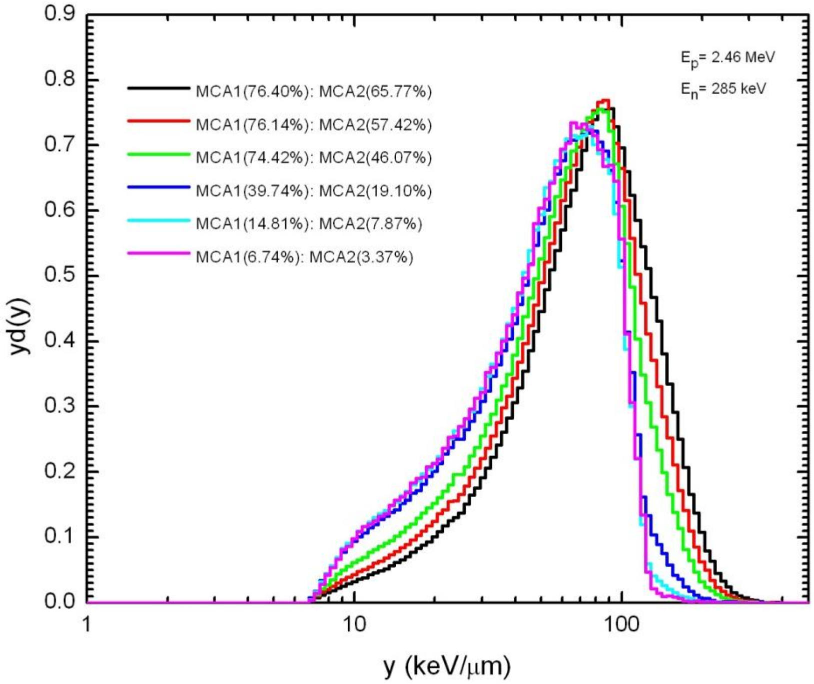

Figure 2**:** Effect of high dose rate on TEPC lineal energy spectra measurements at E_p = 2.46 MeV\

D. CONCLUSIONS

This study demonstrated that moderate dose rates which do not result in dead times more than 20-25%, due to either of the component radiation or due to both components of mixed field radiation can generate results which are acceptable for most of operational health physics radiation monitoring purposes.

E. References

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received his bachelor degree (BSc) in Nuclear Engineering from the Ben-Gurion University of Israel. He has been involved in many different duties. He worked as a research assistant at the Soroka medical centre in Israel, his main research work was an investigation and measurement of absorbed dose in the build up region for photon beams from linear accelerators. In 2008, he joind the Faculty of Energy Systems and Nuclear Science at the University of Ontario Institute of Technology in Canada. He has recently completed his MASc degree in Nuclesar Engineering. His main research work was in the field of radiation protection and neutron-gamma dosimetry. His Master work at UOIT was primarily experimental using tissue equivalent proportional counters for mixed field neutron-gamma dosimetry, his reasearch work was carried out at the Tandetron accelerator laboratory at McMaster University. He is currently employed as research assistant with the faculty of Energy Systems and Nuclear Scinece at UOIT.