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Analysis of Microdosimetric Quantities of Mixed Radiation Fields in the Reactor Building at the Wolsong Nuclear Power Plant

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A commercially available tissue equivalent proportional counter (TEPC), model FW-AD1, was used as microdosimetric detector to measure the dose equivalent rates at several workplaces in the reactor building of a pressurized heavy water reactor, the Wolsong Nuclear Power Plant unit 3 in Korea. The microdosimetric quantities including the lineal-energy distributions and the dose-mean lineal energy were determined by unfolding the measured data, and then the mean quality factors and the dose equivalent rates were evaluated. The mean quality factors at places where neutron dose rates were significant were in the range of 2.2 to 7.1, while those values were near unity at the places where gamma-ray dose rates dominated. The lineal energy spectra of the reference radiation fields at the Korea Atomic Energy Research Institute (KAERI) were also measured for comparisons. Particularly in the vicinity of the primary heat transport pump, the dose-mean lineal energy and the mean quality factor appeared similar to those values of the D_2O moderated ^{252}Cf reference field. The tool and the analysis method can be applied to characterization of other mixed radiation fields.

KEYWORDS: ***tissue equivalent proportional counter, lineal energy, microdosimetric quantity***

I. Introduction

Today low pressure proportional counters are used as a versatile tool in radiation physics, radiation protection and radiation biology.[1)] Low pressure proportional counters which are made of tissue-equivalent (TE) plastic material and operated with TE gas mixtures are standard instruments in microdosimetry.[2)] Furthermore, TEPCs utilizing microdosimetric principles have unique diagnostic properties concerning radiation quality in unknown mixed neutron-photon fields, such as those found in space, commercial airlines and many nuclear reactors.[3)] A particular advantage of TEPCs is their potential ability to separate dose fractions due to neutrons and photons in mixed neutron-photon fields.[4)]

One of the principal quantities in radiation protection is the dose equivalent, which is the product of absorbed dose and the quality factor. Application of TEPCs provides absorbed doses and a spectral information in terms of the dose distribution in lineal energy d(y). Under the assumption that the lineal energy, y, is a good approximation for the unrestricted linear energy transfer L_∞, quality factor $Q(L_\infty)$ may be approximated by the quality factor distribution in lineal energy Q(y).

In this paper, measurements of the radiation environment inside the reactor building of a pressurized heavy water reactor (PHWR) were performed with a TEPC. The lineal-energy distributions, absorbed doses, dose equivalents and the mean-quality factors were determined and the lineal energy distributions were compared with those measured at the reference radiation fields operated by the KAERI.

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II. Material and Methods

1. Tissue Equivalent Proportional Counter

The detector used in this measurement was a TEPC, model FW-AD1 Environmental Radiation Monitor, commercially available from the Far West Technology, USA. This instrument is specially constructed to allow accurate measurement of absorbed dose and dose equivalent. It is sensitive to ionizing particles (ions, electrons and gamma rays) as well as to neutrons via the secondary charged particles created by them in the walls of the counter.

The counter consists of a 12.7 cm diameter sphere made of A-150 conducting TE plastic of 2.1 mm thickness and an outer cylindrical stainless steel container of 0.635 mm wall thickness. The collection anode wire of 0.051 mm diameter is positioned in the center of the sphere. This instrument was filled with a propane-based tissue-equivalent (PTE) gas mixture (C_3H_8: 55 %, CO_2: 39.6 %, N_2: 5.4 %) at 7 torr pressure that simulates an effective diameter of 2 μm of unit density tissue (ρ=1.0 g/cm^3).[5)]

This instrument relies on the use of an internal 33.3 kBq ^{244}Cm calibration source that provides a collimated beam of 5.8 MeV alpha particles crossing a diameter of the counter.[5)] The curium source calibration establishes the event size distribution scale in terms of lineal energy y. The proton edge occurs at a lineal energy near 150 keV/μm in spherical counter.[6)] From this information, it was decided that the lineal energy scale for the counter is approximately 1 keV/μm per channel in a 1024 multi-channel analyzer (MCA).

The spectrum analyzer system electronics are housed in a partially sealed 15 x 15 cm cylindrical aluminum canister attached directly to the stainless steel detector base. The spectrum analyzer consists of three 12.7 cm diameter circuit board: power conversion board; computer processor board; and 256 and 1024 MCA board. The processor software and electronics provide a complete data acquisition system, including high voltage power supply, battery power, test pulsars, LCD display and data recording compact-flash memory card.[5)]

For determination of dose equivalent, a simple interpolation method was applied in FW-AD1 for neutron-photon discrimination which divides the pulse height spectrum at lineal energy around 10 keV/μm and attributes the doses associated with the lower part to photons and the upper part to neutrons.

2. Calibration

Calibration factors in terms of ambient dose equivalent were determined at the reference radiation fields established in the KAERI. The irradiation facility equips with various radiation sources including ^{137}Cs, bare and D_2O moderated ^{252}Cf and ^{241}Am-Be sources.

3. Data Analysis

The lineal energy y is the quotient of ε by $\bar{l}$:

$$y = \frac{\varepsilon}{\bar{l}} \quad [\text{keV}/\mu\text{m}] \tag{1}$$

where ε is the energy imparted to the matter in a volume by a single energy-deposition event and $\bar{l}$ is the mean chord length in that volume.[2)]

Practically, the lineal energy was obtained as follows [7)]:

$$y = \frac{h\delta_\alpha}{h_\alpha} G \tag{2}$$

where h is the channel number of the measured spectrum, δ_α and h_α are the energy deposition and the channel number of alpha particles from a built-in ^{244}Cm alpha source to calibrate the channel in keV/μm, respectively, and G is the gain ratio of two different MCAs.

The absorbed dose in tissue can be calculated using the measured data of TEPC as follows [8)]:

$$D = \frac{C}{\rho V} \sum N(h)\varepsilon(h) \tag{3}$$

$$\varepsilon(h) = y \times \frac{2}{3} d \tag{4}$$

where C is a conversion factor, 1.6×10^{-13} [Gy g/keV], ρ is a density of TE gas, V is an effective volume of TEPC, N(h) is counts in channel number h, ε(h) is an energy equivalent to channel number h and d is an effective diameter of unit density tissue.

A mean quality factor is defined by ICRU [2)] as follows:

$$\bar{Q} = \frac{1}{D} \int_0^\infty Q(y)D(y)dy \tag{5}$$

where Q(y) is the quality factor distribution and D(y) is the absorbed dose distribution. Q(y) can be derived from the $Q(L_\infty)$ function to approximate that the lineal energy is equal to the linear energy transfer L_∞ introduced by ICRP 60.[9)]

Table 1 Measurement locations in the reactor building.

Notation	Description
A	R-201[a)] lounge
B	R-405[b)] the side of lead shielding
C	R-405 the back side of water shielding
D	R-405 the front side of water shielding
E	R-009[c)] the side of moderator collection tank
F	R-501[d)] lounge
G	R-501 the side of primary heat transport pump
H	R-501 the top of detectors
I	R-405 motor valve room
J	R-406[e)] motor valve room

a) R-201: Liquid injection shutdown system
b) R-405: Heater transport system auxiliaries "C"
c) R-009: Moderator D_2O collection region
d) R-501: Boiler room
e) R-406: Heater transport system auxiliaries "A"

4. Measurement

The measurements were performed at 10 selected locations in the reactor building of Wolsong Nuclear Power Plant unit 3 in Korea. The locations were the places where the dose rate was expected to be high and the contribution of neutron component was expected. The descriptions about the selected locations in the reactor building are given in **Table 1**.

Ⅲ. Results and Discussion

The lineal energy distributions obtained by unfolding the data measured with the TEPC at the locations in the reactor building are shown in **Fig. 1**. The ordinate is multiplied by y and in this semi-log representation the area under the curve delimited by any two values of y is proportional to the fraction of dose delivered by events with lineal energies in this range. This yd(y) vs. y plot is the standard representation of a microdosimetric spectrum.[6)]

In **Fig. 1a)**, the absorbed dose distributions in lineal energy, except for location D, are significant in the range of lineal energies less than 10 keV/μm, which means that the dose rates at those locations are dominated by low LET radiation. On the other hand, at locations F to J shown in **Fig. 1b)**, significant contributions from higher lineal energies are observed. This implies that at these locations including location D there exist contributions from neutrons to absorbed doses.

The gamma-ray and neutron ambient dose equivalent rates, $H^*(10)$, were obtained using the TEPC at the measurement locations in the reactor building. The dose-mean lineal energy $\bar{y}_D$, dose equivalent-mean lineal energy $\bar{y}_H$ and mean quality factor $\bar{Q}$ were determined by using

Table 2 Ambient dose equivalent rates and microdosimetric quantities evaluated at the measurement locations in the reactor building.

Location	Ambient dose equivalent rate		$\bar{y}_D$	$\bar{y}_H$	$\bar{Q}$
	Gamma-ray	Neutron			
	μSv/hr	μSv/hr	keV/μm	keV/μm	
A	3.940±0.21	0.310±0.82	3.35	13.17	1.07
B	106.8±2.67	3.830±2.25	2.18	4.92	1.03
C	39.79±0.84	3.371±1.96	2.46	8.80	1.09
D	27.74±0.80	31.13±7.45	7.04	50.29	2.21
E	26.97±0.45	0.364±0.06	2.29	3.74	1.01
F	8.500±0.17	9.757±2.30	7.21	50.78	2.23
G	92.03±1.03	789.9±22.7	26.84	76.67	7.11
H	31.49±0.36	49.05±1.54	7.11	49.65	2.23
I	943.0±14.0	3536±163	15.98	68.91	4.40
J	1079±3.00	3232±68.0	13.67	65.84	3.84

the equations (5) to (7) and the values are in **Table 2**.

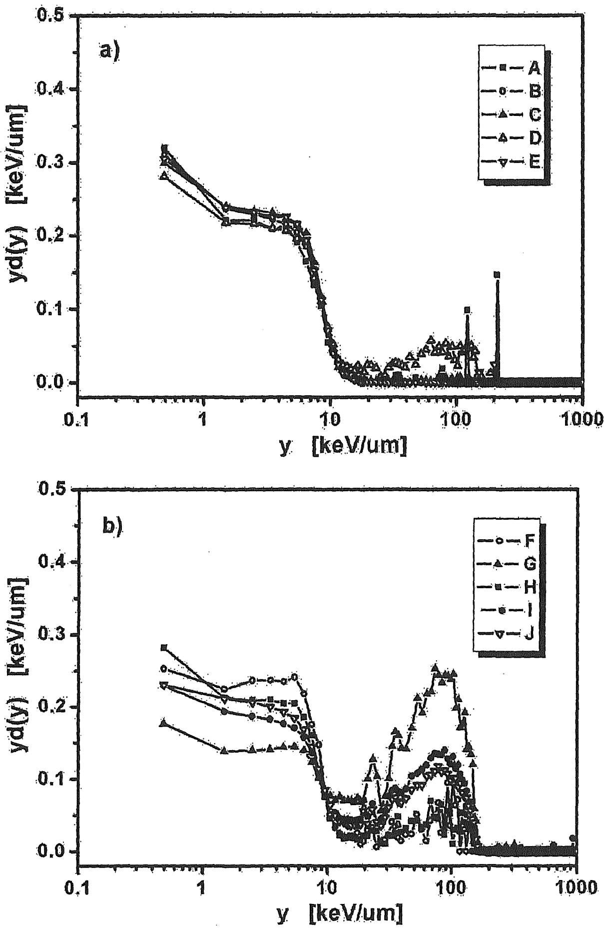

Fig. 1 Absorbed dose distributions in y at the measurement locations in the reactor building. a) Locations A~E. b) Locations F~J.

$$\bar{y}_D = \int_0^\infty y d(y) dy \quad (6)$$

$$\bar{y}_H = \int_0^\infty y h(y) dy \quad (7)$$

As shown in **Table 2**, at locations A~C and E where dose rates are dominated by gamma-ray component, the absorbed dose-mean lineal energies are in the range of 2~3 keV/μm and it means that approximately a half of the absorbed dose is delivered by events with lineal energy y values below 2~3 keV/μm. However, those values at locations D and F~J, where neutron contributions are significant, are in the range of 7~27 keV/μm. Similarly, the dose equivalent mean-lineal energies for the gamma-ray dominant fields are roughly less than 10 keV/μm and over 50 keV/μm for the latter. The mean quality factors are in the range of 1.01 to 1.09 for the gamma-ray dominated radiation fields and of 2.2 to 7.1 for the fields with significant neutron contributions. It is also noted that at location G neutron dose component is particularly high.

The absorbed dose and dose equivalent distribution in y at G are shown in **Fig. 2** comparing with those value at B, where gamma-ray doses are dominant. As shown in **Fig. 2**, the fraction of high LET dose equivalent is significantly greater than the low LET component at G, however, the radiation field at B is dominated by the low LET component below 10 keV/μm.

For the purpose of comparison, similar measurements and analysis were made at the reference radiation fields in the KAERI. **Figure 3** shows the absorbed dose and dose equivalent distributions for the D_2O moderated ^{252}Cf and the ^{241}Am-Be sources. By comparing with **Fig. 2**, it is

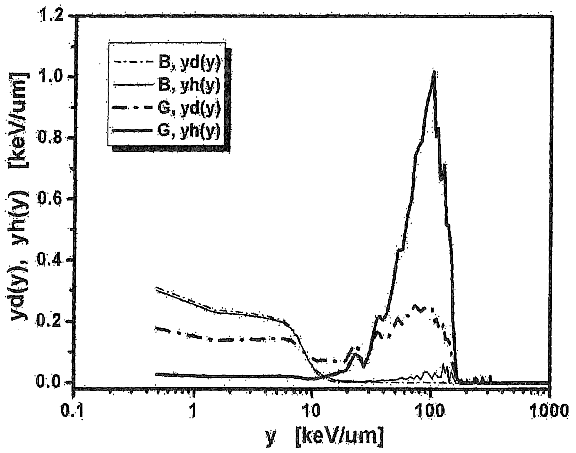

Fig. 2 Absorbed dose and dose equivalent distributions in y at locations G and B.

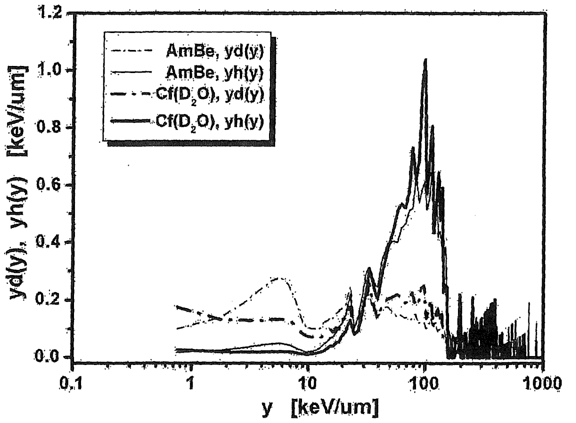

Fig. 3 Absorbed dose and dose equivalent distributions in y at the KAERI neutron reference fields.

found that the shape of dose distribution in y at location G is similar to that of the D_2O moderated ^{252}Cf source.

The dose-mean lineal energies and the mean quality factors at the KAERI reference radiation fields are given in **Table 3**. In comparison with **Tables 2** and **3**, it is also found that the microdosimetric quantities of the field of point G and D_2O moderated Cf source have practically the same values. It means that the characteristics of both radiation fields are similar without regard to the dose equivalent rate.

IV. Conclusion

A TEPC was successfully applied to characterization of unknown mixed radiation fields. Microdosimetric quantities including the dose distribution in lineal energy and the mean quality factors were determined at several locations of interest in the reactor building of Wolsong Nuclear Power Plant unit 3 in operation. For comparisons, measurements were also made at the reference radiation fields established in the KAERI. At locations in the reactor building where neutron component in dose equivalents are significant, the evaluated mean quality factors were in the range of 2.2 to 7.1, while those values at gamma-ray dominant locations were essentially close to 1.0.

The tool and the analysis techniques used in this study can be applied to characterization of other mixed radiation fields which appear in space or at the flight altitudes and in the accelerator environment.

Table 3 The microdosimetric quantities of reference sources.

source	$\bar{y}_D$	$\bar{y}_H$	$\bar{Q}$
	keV/μm	keV/μm	
^{137}Cs	2.30	2.50	1.01
$^{252}Cf\ (D_2O)$	30.32	81.39	7.00
^{252}Cf (bare)	49.20	85.98	11.32
$^{241}AmBe$	32.53	90.09	5.77

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