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■ 論 文 ■

Determination of Microdosimetric Quantities of Several Neutron Calibration Fields at KAERI

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Abstract - The commercially available neutron survey meter, the REM500, which uses a tissue equivalent proportional counter (TEPC) and the self-constructed TEPC were used to determine the microdosimetric quantities of several neutron calibration fields at Korea Atomic Energy Research Institute (KAERI). Microdosimetric spectra, absorbed dose, dose equivalent as well as quality factor were derived and compared with several neutron fields which were produced by using the shadow objects to make neutron scattered and being used as a kind of realistic neutron calibration fields at KAERI. The response of REM500 as a function of mean energy was evaluated with these neutron fields using the counts measured and the predetermined reference value. The response of the self-made TEPC and the REM500 was compared using one of the neutron calibration filelds of a ^{252}Cf source. The reference quantities of scattered neutron calibration fields were determined using a Bonner Sphere (BS). The value of frequency-mean lineal energy, dose-mean lineal energy and quality factor of two ^{252}Cf sources (unmoderated and D_2O moderated) were determined to check the differences in the reference neutron fields between KAERI and Pacific Northwest National Laboratory (PNNL, USA) and the results were in good agreement within 1%. It means that there is no big difference in dosimetric quantities of neutron calibration fields of two laboratories.

Key words : microdosimetric quantity, tissue equivalent proportional counter, neutron calibration fields

INTRODUCTION

Characterization of neutron calibration fields is not easy and too complicate to perform in a routine base using an instrument commercially available. Even though it was made by a radioisotopic neutron source not by using an accelerator or a nuclear reactor, a dosimetric quantity which is needed for calibration does not be derived simply when neutron fields consist of considerable amounts of scattered neutron or not direct neutron only from source itself. It has been almost the only way to determine the neutron fluence or energy spectra which is getting from calculation or spectral measurement by the neutron spectrometer like a Bonner Sphere (BS)[1] at the reference point for the calibration of neutron measuring devices used in radiation protection dosimetry.

In case of intercomparison measurement of the reference neutron fields between laboratories, it is often to use a specific instrument according to its purpose and quantities to be measured such as neutron fluence, energy spectra or lineal energy spectra. Among the active monitoring instruments, typical neutron survey meters operating on the principle of neutron moderation are bulky and heavy because of using the massive hydrogenous plastic material to make neutron slowing down for easy detection and provide only an integral quantity such as dose equivalent or dose equivalent rate. But portable survey instruments employing a tissue equivalent proportional counter (TEPC) are not heavy and additionally provide the microdosimetric data, the lineal energy spectra of neutron fields as well as an integral quantity.

KAERI constructed the scattered neutron calibration fields (SNCF) using a means similar to the new draft of the ISO (PTB's method)[2] including fast neutron calibration fields of bare and D_2O moderated ^{252}Cf and $^{241}AmBe$ sources. A portable TEPC (the REM500) commercially available from the Health Physics Instrument (Far West Technology, USA) was used to measure the microdosimetric data of SNCF of KAERI and specially to intercompare the reference neutron fields of bare and D_2O moderated ^{252}Cf source between KAERI and PNNL. The dose equivalent response and some characteristic data to a ^{252}Cf source were compared for two TEPCs, the REM500 and the self-constructed TEPC of KAERI.

MATERIALS AND METHOD

Irradiation Facility and Neutron Fields of KAERI

The neutron irradiation room of KAERI is a bunker room whose dimensions are 8 m long, 6 m wide and 6 m high, and it is enclosed with 60 cm thick concrete walls and ceiling. Two kinds of neutron sources, ^{252}Cf and $^{241}AmBe$ can be used for calibration. ^{252}Cf source is placed at the center of the room and moved from storage to an irradiation position of a height of 2.9 m at the time of irradiation and this source is mainly used for routine calibration. In using ^{252}Cf, bare and D_2O moderated neutron spectra are available. D_2O moderator assembly is a 0.53 mm thick Cd-covered sphere with diameter of 32.3 cm to cut thermal neutrons off, so there are few thermal components in the reference calibration spectrum.

Descriptions of the scattered neutron fields of KAERI constructed in the irradiation room are shown in Table 1. Two kinds of ordinary phantoms, a Poly-Methyl Meta-Acrylate (PMMA) and the ISO water filled phantom and a shadow-cone made of iron were placed to produce the scattered neutron fields between the source and the calibration point. The front end of a shadow-cone was 20 cm long iron with a diameter of 30 cm and the back end of it was 30 cm long air gap with a diameter of 35 cm. All reference positions were fixed at a center-to-center distance of 100 cm between the source and the detectors except for place E, where it is behind the wall in the irradiation room. The thickness of the concrete wall is 21 cm.

The dosimetric quantities including the neutron fluence rate at the test point were determined by neutron spectrometer, a BS. The calibration of a BS was performed in the KAERI neutron irradiation room by using the ^{252}Cf source with the same technique as done by Liu et al.[3] Integral properties such as the spectral mean neutron energy, E_{ave}, the neutron flux and dose rate on the reference date of June 9, 2002, the fractional contribution of thermal neutrons to the total fluence, φ_{th}/φ, and the fluence to ambient and personal dose equivalent conversion factors averaged over the neutron energy spectra, $h^*(10)$ and $h_p(10)$, with its dose equivalent averaged energy, $E^*_{ave.}$ and $E_{p,ave.}$ are summarized in Table 2 for ten scattered neutron fields.[4] The mean neutron energies and the conversion factors for the ambient and personal dose equivalents were calculated using the values obtained from the interpolation method of cubic spline for the conversion factors for mono-energetic neutron given by ICRP 74.[5]

Table 1. Description of KAERI scattered neutron fields.

Notation	Description
^{252}Cf (bare)	[A] Direct and scattered; unmoderated source only
	[B] Scattered; using the PMMA phantom (40 x 40 x 15 cm^3, contacted to the source guide holder)
	[C] Scattered; using the shadow cone (distance from the source to the front end : 32 cm)
	[D] Scattered; using the PMMA phantom (same as B) and polyethylene sheet with 5 % boron (61 x 61 x 5 cm^3, distance from the source to the surface : 40 cm)
	[E] Behind the concrete wall in the irradiation room (distance from the source : 385 cm)
^{252}Cf (D_2O)	[F] Direct and scattered; moderated source only
	[G] Scattered; using the PMMA phantom(same as B, distance from the source : 32 cm)
	[H] Scattered; using the shadow cone (distance from the source to the front end : 32 cm)
	[I] Scattered; using the water filled phantom (30 x 30 x 15 cm^3, 32 cm from the source)
$^{241}AmBe$	[J] Direct and scattered; unmoderated source only

Table 2. Integral properties of several scattered neutron fields in the neutron irradiation room of KAERI.

Field	Eave.[1)] (MeV)	Flux ($n.cm^{-2}sec^{-1}$)	φ_{th}/φ (%)	Dose rate[2)] ($mSvhr^{-1}$)	$h^*(10)/E^*ave$[3)] ($pSvcm^2/MeV$)	$h_p(10)/Ep,ave$[3)] ($pSvcm^2/MeV$)
[A]	1.282	1594	10.2	1.878	327/1.63	339/1.64
[B]	0.444	765	51.2	0.355	129/1.42	133/1.42
[C]	0.532	665	24.8	0.496	207/1.03	214/1.03
[D]	0.692	402	36.4	0.233	161/1.76	167/1.78
[E]	0.282	171	53.1	0.058	93/1.20	96/1.22
[F]	0.416	1444	9.4	0.578	111/1.46	115/1.47
[G]	0.205	533	48.6	0.138	69/1.18	72/1.19
[H]	0.171	560	38.9	0.184	91/0.70	94/0.70
[I]	0.184	543	44.9	0.147	75/0.95	78/0.98
[J]	2.765	95	6.4	0.109	347/3.29	362/3.30

1) spectral mean energy.
2) ambient dose equivalent rate, $H^*(10)$.
3) fluence to ambient (and personal) dose equivalent conversion factor and dose equivalent averaged mean energy reffered to the conversion factors given by ICRP-74.[5]

Tissue Equivalent Proportional Counter (TEPC)

The REM500 employs a nominal 5.72 cm diameter TEPC that is filled with the propane-based tissue equivalent gas[6] to a low pressure that simulates an effective diameter of 2 μm of unit density tissue. This instrument relies on the use of an internal ^{244}Cm calibration source that provides a collimated beam of 5.8 MeV alpha particles that cross a diameter of the counter. The curium source calibration establishes the event size distribution scale in terms of lineal energy, *y*. It was determined that with the peak of the curium source alpha particle peak in channel 91, the lineal energy scale for the counter was approximately 1 keV㎛$^{-1}$ per a channel in multichannel analyzer.

Cylindrical TEPC was manufactured by KAERI for measurement of neutron dose in mixed fields. It was filled with the methane-based TE gas (CH_4 : 65.6 %, CO_2 : 31.6 %, N_2 : 2.84 % by volume percent) and also was to be simulated for 2 ㎛ of unit density tissue. An internal calibration source, ^{241}Am, source was installed inside the sealing aluminum can (outside the chamber wall of TE plastic, A150, at the middle part of chamber wall in the left side of Figure 1) and the SPAR program[7] was used for calculating the stopping power of alpha particle from ^{241}Am and ^{244}Cm sources. Calculated stopping power which was 85 keV㎛$^{-1}$ and 91 keV㎛$^{-1}$ for ^{241}Am and ^{244}Cm sources respectively was used for channel calibration of multichannel analyzer employed. An inside and a completely assembled feature of the self-constructed TEPC are shown in Figure 1.

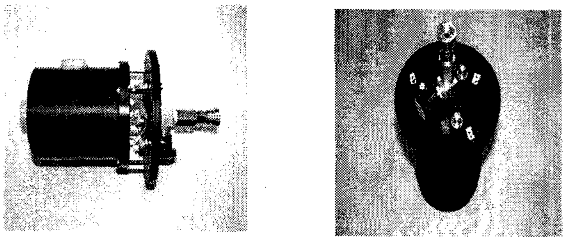

Fig. 1. Photographs of the self-constructed TEPC (left : TEPC chamber with connectors and valve for TE gas filling, right : assembled with aluminum sealing can)

Intercomparison of micro dosimetric properties of ^{252}Cf source between KAERI and PNNL

At the time of measurement in two laboratories, the REM500 was placed on an aluminum cart at a distance of 100 cm from the ^{252}Cf source. This same distance was used for both the unmoderated and D_2O moderated irradiation conditions. The neutron dose equivalent rate at this position for unmoderated ^{252}Cf neutrons was approximately 2.0 mSvh^{-1} and 8.3 mSvh^{-1} for KAERI and PNNL respectively. The instrument was allowed to count enough time to achieve reasonably good counting statistics and total counts in all channel of internal multichannel analyzer ranged from 38,000 to 145,000. The neutron irradiation room of PNNL is a low-scatter room with concrete walls whose dimensions are approximately 10 m x 9 m x 15 m and the source is situated in the geometrical center during irradiation.

After finishing the measurement first in Jan. and second in March 2001 at PNNL, the same REM500 instrument that was used at PNNL was transported to KAERI and used for similar measurements at the same distance, 100 cm from source to detector in May 2001.

Determination of absorbed dose and dose equivalent

All data measured were processed to determine the absorbed dose or dose equivalent after the contribution of gamma radiation was subtracted. The gamma response of TEPC, shown in Figure 2, was obtained using ^{137}Cs source according to the gamma dose rate of each SNCF and the gamma dose rate ranged from 3.3 μSvh^{-1} to 72.3 μSvh^{-1} at the time of measurement.

Neutron absorbed dose in tissue can be calculated using the measured channel data of multichannel analyzer as follows :

$$D = \frac{c}{\rho \cdot V} \cdot \sum N(I) \cdot \varepsilon(I),$$

where, C : conversion factor = 1.6 x 10^{-13} (Gy.gkeV^{-1}), : density of TE gas, V : effective volume of TEPC, N(I) : counts in channel number I, and ε(I) : energy equivalent to channel number I.

Microdosimetric parameters such as the event size distribution with lineal energy, f(y), the probability density of dose, D(y), the frequency-mean lineal energy, y_F, and the dose-mean lineal energy, y_D were calculated using equations described in ICRU 36.[8]

The relationships between radiation quality factor and y_D or data as a function of y were also adopted from ICRU 36 and ICRP 26[9] respectively. Using these quality factors, dose equivalents were calculated and compared with the data determined by a BS to each SNCF.

RESULTS AND DISCUSSION

The gamma radiation response of the REM500 was measured and used to correct the data of TEPC and shown in Figure 2 and 3. Because the gamma radiation response depended on dose rate as seen in Figure 3, each dose rate of SNCF was measured and corrected one by one. But the response change due to the gamma radiation sources, e.g. ^{137}Cs or ^{60}Co, was reported to be negligible by Liu.[10]

The event size distribution, f(y), lineal energy spectra, yf(y), and neutron dose spectra, yD(y), with lineal energy of the ten kinds of SNCF are shown in Figure 4, 5, and 6 respectively. Main trend in these spectra of lineal energy is that the lineal energy spectra of neutron field of higher average energy is shift to the part of lower lineal energy and the lineal energy of all SNCF spans from 7 keV μm^{-1} to 150 keVμm^{-1}.

Figure 7 shows the gamma and neutron dose distribution determined by the KAERI TEPC for the neutron calibration field of an moderated ^{252}Cf source and the area under each spectra means the absorbed dose in simulated tissue. The lineal energy spectrum in this figure was extended to about 15 keVμm^{-1}.

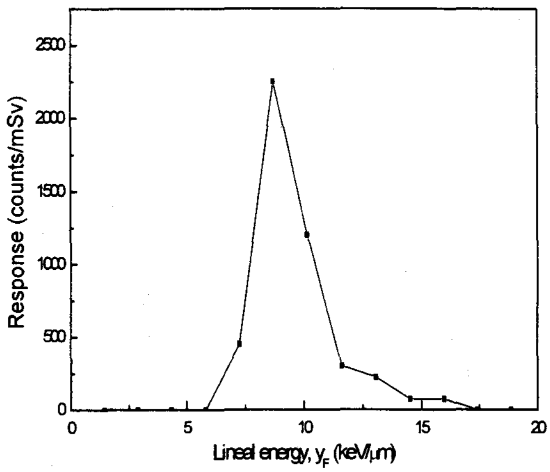

Fig. 2. Gamma radiation response of the REM500 to ^{137}Cs. (response was processed to counts/mSv)

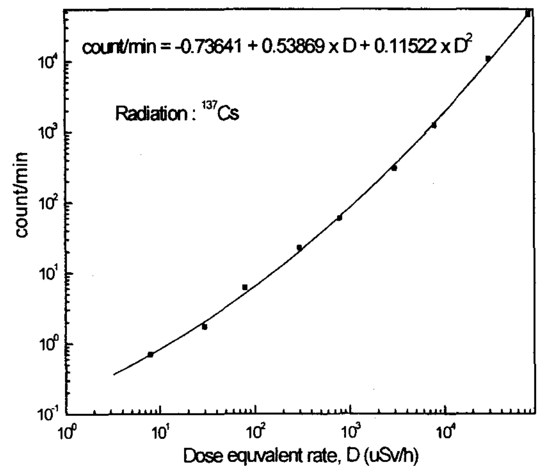

Fig. 3. Gamma dose rate dependence of the REM-500

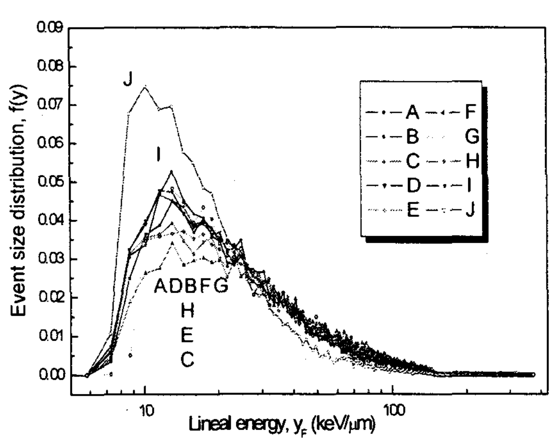

Fig. 4. Event size distribution with lineal energy for the ten kinds of SNCF

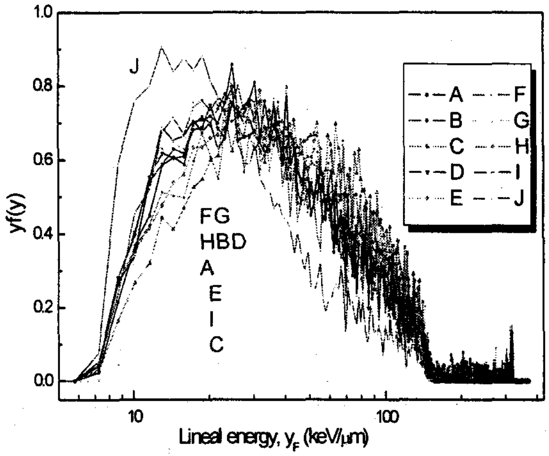

Fig. 5. Lineal energy spectra for the ten kinds of SNCF (Notation is the same as listed in Table 1.)

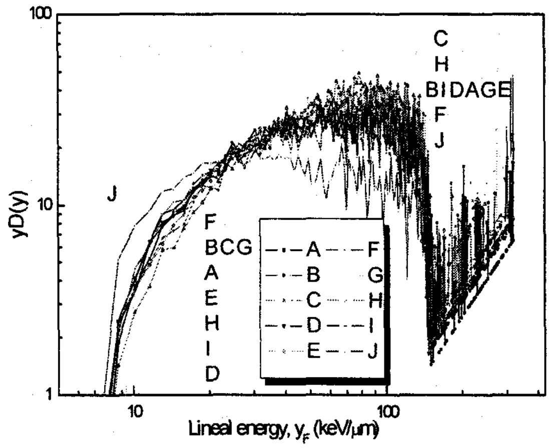

Fig. 6. Neutron dose spectra for the ten kinds of SNCF (Notation is the same as listed in Table 1.)

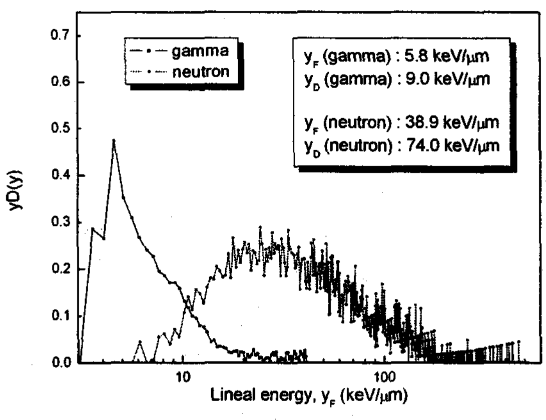

Fig. 7. Gamma and neutron dose distribution with the lineal energy for the neutron field of [A] measured by KAERI TEPC

In case of using the REM500, it is impossible to extract the gamma dose portion from the measured spectra perfectly because the discriminator level was set to about 8 keV.μm^{-1} to exclude the contribution of gamma radiation by the manufacturer. The fraction of gamma (2.02 μGy) to neutron absorbed dose (5.20 μGy) in case of Figure 7 was estimated to 38.8 % by KAERI TEPC.

Microdosimetric parameters by the REM500 and dosimetric quantities by a BS are summarized in Table 3. It is clearly that the response or neutron sensitivity of the REM500 increases with the average energy of SNCF. It has been known for general feature of TEPC and was also reported that the REM500 has the relatively low response to low energy neutron.[11] According to Table 3, the frequency mean lineal energy, y_F, shows the neutron field characteristics and can be used as a spectral index at least to show that neutron field has soft or hard spectrum.

Among the quality factors calculated with three different ways, values which use the linear relation of ICRU 36 are seemed to be more appropriate that others. Quality factor of [A] was estimated lower than that of reference neutron fields of ISO 8529[12], but it was not for [B]. Quality factors were 11 for ^{252}Cf and 8 for ^{241}AmBe sources in ISO 8529 respectively.

For the application of TEPC in neutron field of energy between 0.2 MeV and 5 MeV and in case of simulating tissue diameter as 1 or 2 μm, some authors reported that quality factor calculated using the linear relationship between Q and dose mean lineal energy, y_D, : $Q = 0.8 + 0.14 \cdot y_D$, agreed with the quality factor of maximum dose equivalent. Delivered dose equivalent in this paper was determined using a BS and its value was estimated conservatively 18 % higher (532 μSv for [A]) than dose equivalent (450 μSv for [A]) calculated using the dose conversion factor given in ISO 8529-3[13], because there was some dose contribution due to the scattered neutrons being incident to the calibration position of the irradiation room.

Table 3. Summary of dosimetric parameter determined by the REM500 for the scattered neutron calibration fields : spectral average energy, ambient dose equivalent, response, the frequency mean (y_F) and dose mean (y_D) lineal energy and quality factors determined using different relationships.

Item \ Field	[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]
Average energy (MeV)	1.282	0.444	0.532	0.692	0.282	0.461	0.205	0.171	0.184	3.436
Dose equivalent (Sv)[1]	532	462	562	540	595	424	476	650	483	263
Fluence (x 10^2)	16259	35802	27132	33527	63099	38122	66199	71232	64183	8256
Counts	15509	12660	11978	12981	11797	10150	9179	10473	9675	10753
Response (counts/Sv)	29.15	27.43	21.31	24.05	19.84	23.95	19.28	16.11	20.05	40.82
Sensitivity (10^{-3}) (counts/neutron)	9.54	3.54	4.41	3.87	1.87	2.66	1.39	1.47	1.51	13.0
y_F (keV/m)	39.0	38.0	45.1	38.4	40.6	36.8	39.7	41.9	37.9	29.4
y_D (keV/m)	65.3	64.2	69.1	64.3	65.0	63.9	65.3	65.6	63.0	61.6
Absorbed dose (Gy)[2]	37.7	29.9	33.6	31.0	29.8	23.3	22.7	27.3	22.9	19.7
Q (0.8 + 0.14 y_D)	9.9	9.8	10.5	9.8	9.9	9.7	9.9	10.0	9.6	9.4
Q (y = L)	8.0	7.9	8.5	7.9	8.1	7.8	8.0	8.2	7.8	7.1
Q (y = 9L/8)	7.2	7.1	7.7	7.2	7.3	7.1	7.2	7.4	7.1	6.6
DE ratio [3] (REM500/BS)	0.702	0.634	0.630	0.563	0.496	0.533	0.472	0.420	0.455	0.704

[1] Dose equivalent determined by a BS.
[2] Absorbed dose determined by the REM500.
[3] Ratio of dose equivalent determined by the REM500 and a BS.

Table 4 shows the response and some specifications of the KAERI TEPC and the REM500. The response of the KAERI TEPC was six times higher than that of the REM500 and it was simply the effect of the chamber size. Even though the y_F was in good agreement, the y_D and quality factor determined by the KAERI TEPC were bigger than the values of the REM500. It was thought that there were differences in TE gas and in the chamber geometry. KAERI TEPC is being under modification such as the change of a central wire from platinum to stainless steel and TE gas, and even the geometry of chamber to the spherical type.

The intercomparison result for a bare and a D_2O moderated ^{252}Cf sources using the REM500 between KAERI and PNNL agreed within 1 % except for the y_F of an unmoderated ^{252}Cf as shown in Table 5. It means that there was no big difference in the neutron calibration fields between two laboratories and this kind of instrument also can be used for intercomparison measurement.

CONCLUSION

The microdosimetric parameter, especially the frequency-mean lineal energy, yF, also can be

Table 4. Result of intercomparison between KAERI an (Jan. 2001. ~ May. 2001)

Source	Lab.	y_F (keV/m)	Ratio (KAERI/PNNL)	y_D (keV/m)	Ratio (KAERI/PNNL)	Quality factor	Ratio (KAERI/PNNL)
^{252}Cf	KAERI	39.4	0.968	63.6	0.992	9.7	0.990
	PNNL	40.7		64.1		9.8	
D_2O mod. ^{252}Cf	KAERI	39.4	1.005	63.3	1.014	9.6	1.011
	PNNL	39.2		62.4		9.5	

Table 5. Comparison of response to the neutron calibration field, [A], and specifications for the KAERI TEPC and the REM500.

Item / TEPC	KAERI TEPC (self-constructed)	REM-500 (FWT, USA)
Delivered dose equivalent (μSv)[1)]	57.8	532
Counts measured	10468	15509
Response (counts/μSv)	181.11	29.15
y_F (keV/μm)	38.9	39.0
y_D (keV/μm)	74.0	65.3
Quality factor	11.2	9.9
Effective volume (cm^3)	785.4	111.4
Mass of TE gas (mg)	16.66	3.54
Geometry	Cylindrical (diameter : 10 cm, length : 10 cm)	Spherical (diameter : 5.72 cm)
Tissue equivalent gas (base material)	Methane	Propane
Simulated tissue diameter (μm)	2	2

1) Delivered dose equivalent was calculated using the dose conversion factor given in the ISO 8529-3[13]

used for the characterization of neutron filed like as a fluence (spectrum) averaged energy or dose-mean energy. It may be used for a spectral index to estimate the property of neutron field such as the dose equivalent or the quality factor. The self-made KAERI TEPC showed the possibility of use for radiation protection monitoring in mixed field and need to be modified for the improvement of measurement performance in future and the REM500 can be used effectively to intercompare the neutron calibration field.

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REFERENCES

1. R.L.Bramlett, R.J. Ewing, and T. Bonner, A New Type of Neutron Spectrometer, *Nucl. Inst. Meth.*, (9), 1-12 (1960)
2. International Organization for Standardization, *Reference Neutron Radiations : Characteristics and Methods of Production of Simulated Workplace Neutron Fields*, ISO

12789 (2000)

3. J.C. Liu, F. Hajnal, C.S. Sims and J. Kuiper, Neutron Spectral Measurements at ORNL, *Radiat. Prot. Dosim.*30(3), 169-178 (1990)
4. B.H. Kim, J.L. Kim, S.Y. Chang and G. Cho, Scattered Neutron Calibration Fields of KAERI, *J. Nucl. Sci.Technol. Supplement 1*, 781-784 (2000)
5. ICRP and ICRU, *Conversion Coefficients for Use in Radiological Protection Against External* Radiation, Report of the Joint Task Group, ICRP 74(1997), ICRU 57 (1998)
6. Health Physics Instrument, *Operation and Repair Manual : Model REM 500 Neutron Survey Meter* (1993)
7. T.W. Armstrong, *Stopping Power and Range*, ORNL-4869 (1996)
8. International Commission on Radiation Units Measurement, *Microdosimetry*, ICRU 36 (1983)
9. ICRP, *Recommendations of the ICRP,* ICRP Publication 26, Ann. ICRP 1(3), Oxford: Pergamon Press (1977)
10. J.C. Liu, Evaluation of a Microdosimetric-based Neutron Instrument, *Radiat. Prot. Dosim.* 88(4), 323-328 (2000)
11. D.J. Thomas and G.C. Taylor, Response Function Measurements for the REM 500: a Microdosimetric Counter Based Area Survey Instrument, in: *Proc. Int'l Conf. on Radiat. Dosim. and Safety*, Mar. 31-Apr. 2, Taipei, Taiwan, 285-289 (1997)
12. International Organization for Standardization, *Neutron Reference Radiations for Calibrating Neutron Measuring Devices used for Radiation Protection Purposes and for Determining their Response As a Function of Neutron Energy*, International Standard ISO 8529 (1989)
13. International Organization for Standardization, *Reference Neutron Radiations - Part 3 : Calibration of Area and Personal Dosimeters and Determination of their Response as a Function of Neutron Energy and Angle of Incidence,* ISO 8529-3 (1998)