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CHARACTERISTICS OF THE KAERI NEUTRON REFERENCE FIELDS FOR THE CALIBRATION OF NEUTRON MONITORING INSTRUMENTS

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ABSTRACT - Neutron reference fields of Korea Atomic Energy Research Institute (KAERI) for calibrating neutron measuring devices to be used in radiation workplace monitoring consist of two kinds of neutron spectra, the direct and the scattered neutron fields, which are produced by using radionuclide neutron sources, 252Cf and 241AmBe sources. Necessary parameters for calibration such as the anisotropy factor of each neutron source and the room-scattered fraction of some neutron surveymeters in the KAERI calibration facility were determined by calculation or measurement. Spectral measurement of scattered neutron fields were performed at each reference calibration point using a Bonner Multi-sphere Spectrometer (BMS) and the dosimetric quantities for calibration also estimated from the neutron energy spectra which were unfolded using the BUNKI code.

INTRODUCTION

Normal calibrations using the radionuclide neutron sources, bare and D_2O moderated ^{252}Cf, ^{241}AmB, and ^{241}AmBe, which are recommended by the International Organization for Standardization (ISO) are performed using the direct component of incident neutron to the devices to be calibrated at the scatter-free or low scatter facility[1,2]. Major properties of a calibration source which are required to be known for characterizing neutron fields at a reference point are the neutron emission rate, the energy spectrum and the anisotropy of neutron emission due to an encapsulation type of source. In any sense, the configuration of calibration facility especially for the small-sized room can be more important than a source itself because the presence of scattered neutron from the ceiling and the wall or the structural material for holding the instruments results in the change of neutron energy spectrum at the reference point and consequently there might be a little difference in the response of instrument when it is compared with the case performed under the scatter-free or low-scatter condition. Because the response or calibration factor of instrument is a unique property and not dependent on the characteristics of calibration facility or experimental technique employed, the effects of scattered neutron in the reference point were corrected or subtracted in determining the response of neutron measuring devices.

Calibration laboratories should be able to characterize their reference fields according to the appropriate procedures, which can be adopted from ISO or some standardization bodies, before doing actual calibration services. Neutron calibration laboratories in particular have much work related with the characterization of the reference field even though it would be not necessary to get the highest accuracy of 5 to 10 % usually being considered in calibration. Sometimes they should do intercomparison study between different laboratories to assure the quality of their calibration works. In this case all data should be analyzed on the basis of the characteristics of the reference field and instrument used.

At KAERI neutron calibration facility, the characterization of reference field for calibration was performed : the determination of the anisotropy factors and the room-scatter fractions for several neutron monitors and the production of scattered neutron calibration fields.

MATERIALS AND METHODS

1. Calibration Facility

The neutron calibration facility 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 is placed at the center of the room and moved from storage to 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. Moderator assembly is a D_2O-filled sphere being a diameter of 32.3 cm with a 0.53 mm thick Cd-cover to cut-off thermal neutron, so there are few thermal components in the reference calibration spectrum. Reference point is variable from 0.5 m to 2 m for unmoderated and D_2O moderated ^{252}Cf sources because only one source is used for calibration.

2. Determination of Anisotropy Factors

The Monte Carlo Neutron Photon transport code(MCNP Ver.4A)[3] was employed to calculate the anisotropy factor of the commercially manufactured radionuclide neutron sources. The energy spectra and binning structure of ^{241}AmBe and ^{252}Cf were those of the reference spectra of ISO-8529, and source neutrons were generated randomly in the source volume. Doubly-encapsulated ^{241}AmBe (Type X.4 of Amersham) source was simulated for calculation and ^{252}Cf (Type SR-Cf-100) source was modeled for both doubly encapsulated capsule and transport capsule. The neutron fluence was averaged at a distance of 50 cm from the center of the source capsule over 11 equal surface area intervals (the same angular bin) on a spherical surface, using the F2 tally of MCNP, to determine the anisotropy factors. The ring detector tally (F5) was also considered to calculate the anisotropy factor at 15 angles to the vertical axis of capsule, including at 90 degree. In addition to calculation, measurements of the anisotropy factor were also carried out using a Precision Long Counter(PLC)[4].

$$H=\frac{H_0}{d^2}+H_s,\qquad H\cdot d^2=H_0\cdot(1+S\cdot d^2),\quad S=\frac{H_S}{H_0} \tag{1}$$

3. Determination of Room-scattered Fraction

Room-scattered fractions for several monitoring instruments were determined using a semi-empirical method which is based on the assumption that the contribution of scattered neutron to the reading of instrument being calibrated can be explained using the amount of deviation from the inverse-square law at calibration distance. The analogy for determining the room-scatter correction is as following equation (1), where H is the detector response which was corrected for air-scatter and geometrical effect between source and detector, H0 is calculated detector response due to direct neutron only, Hs is the response to room-scattered neutron, d is the calibration distance and S is the fractional room scatter contribution at unit calibration distance. The method is useful and generally accepted for a medium-sized irradiation facility like a bunker of PTB or KAERI. All measured data were corrected for air-scatter using the calculated values of the ISO-10647 and geometrical correction due to the effect of finite size of source or detector was applied only for spherical detector using the Axton's formula[5] but this correction would be below 0.1% over the distance of 1 m from the source and negligible. Room scatter fraction values for several neutron monitoring instrument in the KAERI calibration facility were shown in Table 1.

Table 1. Room scatter fraction of several neutron monitoring instrument in KAERI calibration facility

Area monitor (%/m^2)			Personal dosimeter (%/m^2)	
Instrument	^{252}Cf	D$_2$O mod. ^{252}Cf	Dosimeter	D2O mod. ^{252}Cf
9" remmeter	9.2	11	Teledyne PB-3	12.3
NP-2	~8.0	~9.5	Teledyne P-300-DS	45.8
REM-500(TEPC)	7.9	8.5	Panasonic UD809	33.4
LB6411	8.1	9.5	Panasonic UD802	22.3
NNV470As	>100	>100	Harshaw	19.7

4. Scattered Neutron Calibration Fields

One of the scattered neutron calibration field is the D_2O moderated $^{252}C_f$ source which was already well characterized and the useful data available from the ISO standards[1,6]. But it is necessary to get some correction for use of D_2O moderated neutron field of KAERI because the size of moderator sphere of KAERI (a diameter of 32.3 cm and a 0.53 mm thick Cd cover) is bigger than that of ISO specification (a diameter of 30 cm and a 1 mm thick Cd cover). From the fluence measurement using a BMS, neutron loss fraction due to the use of Cd-covered D_2O moderator sphere was determined to be 0.137 by comparing the total fluence between the free field spectra of the unmoderated and that of the D_2O moderated $^{252}C_f$ source. The calibration of BMS[7] was performed in the KAERI neutron irradiation room by using the $^{252}C_f$ source with the same technique as done by Liu et al [8].

In order to produce the scattered neutron calibration field according to the new ISO recommendations[9], KAERI used the shadow objects to produce wall-scattered neutron in the irradiation room without a big change of the structural configuration of facility. Descriptions on the scattered neutron fields of KAERI constructed in the irradiation room are shown in Table 2. Two kinds of ordinary phantoms, a Poly-Methyl Meta-Acrylate (PMMA) and the ISO water filled phantom, used for irradiation of personal dosemeter and the shadow cone were placed to produce the scattered neutron fields between the source and the calibration point. The shadow cone was made of iron with a length of 50 cm. The front end was 20 cm iron with a diameter of 30 cm and the back end 30 cm air with a diameter of 35 cm. All reference points 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 was 21 cm.

Table 2. *Description of KAERI scattered neutron fields.*

Notation		Description
^{252}C$_f$ (bare)	[A]	Direct and scattered; unmoderated source only
	[B]	Scattered; using the PMMA phantom (40 x 40 x 15 cm3, 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 (61x 61 x 5 cm3, 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}C$_f$ (D$_2$O)	[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

RESULTS AND DISCUSSION

Neutron reference fields of KAERI which are being used for normal calibration are summarized in Table 3 and a comparison of fluence-to-dose equivalent conversion coefficient determined by BMS measurement with other recommended values were shown in Table 4. Conversion coefficient, $h^*(10)$ and $h_p(10)$, of free field spectra for unmoderated source was nearly same with the values of ISO or NIST, but was not for D_2O moderated $^{252}C_f$ field. This is one of the problems in using a BMS. Due to poor resolution of BMS, it was difficult to resolve the peaks in measured spectrum and h*(10) and hp(10) were found to be about 40% high because of the dramatic changes of conversion coefficients in neutron energy of 0.1 to 1 MeV.

Anisotropy factors of $^{252}C_f$ and ^{241}AmBe were found to be 1.057 and 1.036 respectively and these were in good agreement with the values founded in the open literature. The neutron loss fraction obtained by comparing the neutron fluence at the position of irradiation with and without the D_2O moderator sphere was determined to be 0.137, and thus the neutron escape fraction from the D_2O moderator sphere was 0.863. Calculation using a MCMP code also showed the same value (0.138). The value of neutron loss (0.137) was a little greater than 0.115 obtained by Eisenhauer[12] for the US NIST D_2O moderator sphere but when considering that the KAERI D_2O moderator sphere is bigger than that of NIST, it could be explained that more neutrons were attenuated and absorbed in the moderator sphere. The value, 0.863, was applied to calculate dose equivalent rate for D_2O moderated ^{252}Cf field.

Table 3. Neutron reference fields of KAERI used for normal calibration

Field	$^{252}C_f$ 1)	D_2O mod. $^{252}C_f$	^{241}AmBe 2)
Emission rate (n/sec)	2.03×10^9	1.75×10^9	7.01×10^6
Uncertainty (%, 2σ)	4	>4	3.34
DE 3) average energy(MeV)	2.4	2.2	4.4
Reference date	2/16/1992	2/16/1992	7/15/1997
Anisotropy factor	1.06	1	1.04
DE rate @1/1/2001	2.31 mSv/h	0.53 mSv/h	0.14mSv/h
distance (cm)	100	100	75
Uncertainty (%, 2σ) 4)	4.65	8.98	8.76

1) $^{252}C_f$ source was calibrated at NIST, U.S.A
2) ^{241}AmBe source was calibrated at KRISS, Korea
3) DE : Dose Equivalent
4) Uncertainty was estimated for FFDE.

Uncertainty estimation in the routine calibration of neutron monitoring instrument was performed using a concept recommended by ISO guide[13] and ISO10647[2]. Each item of uncertainty in calibrating a typical 9″ remmeter was listed in Table 5 except for a reading of instrument and all was expressed using a relative uncertainty.

Table 4. Comparison of fluence-to-dose equivalent conversion coefficient determined by BMS measurement with other recommended values

Field	distance (cm)	H/φ [pSv.cm²] 2)	h*(10) [pSv.cm²] 2)	$h_p(10)$ [pSv.cm²] 2)	Eave. [MeV] 3)	Remarks
$^{252}C_f$	50	321.2	379.2	393.3	1.77	scattered
	100	293.7	354.1	366.7	1.46	scattered
	200	216.9	266.7	276.2	1.09	scattered
	KAERI	330.8	384.1	399.2	2.15	FFDE 4)
	ISO,NIST	333~340	385	400	2.07~2.13	FFDE
D_2O mod. $^{252}C_f$	50	111.4	143.5	157	0.42	scattered
	100	99.6	132.2	136.8	0.34	scattered
	KAERI	123	151	148.5	0.51	FFDE
	ISO,NIST	93	105	110	0.51	FFDE
AmBe	50	354.9	374.1	390.8	3.48	scattered
	ISO,NIST	380	391	411	4.3	FFDE

1) Fluence to dose equivalent conversion factor based on the concept of Maximum Absorbed Dose Equivalent in the ICRP-21[10]
2) Fluence to ambient (and personal) dose equivalent conversion factor and dose equivalent averaged mean energy reffered to the conversion factors given by ICRP-74[11]
3) spectral mean energy　4) FFDE : Free Field Dose Equivalent

Table 5. Uncertainty table for routine calibration using three kinds of KAERI neutron reference fields

Item	Type	Remarks	Uncertainty (%, 1σ)		
			252Cf	D2O mod. 252Cf	AmBe
Emission rate, B	B	from KRISS or NIST	2	2	1.67
Anisotropy factor, FI(θ)	B	ISO	0.5		0.5
Distance, d	B	$[2u(d)/d]^2$	0.4	0.4	0.4
Decay correction (9 years elapsed for ^{252}Cf)	B	$t\ln 2u((T_{1/2})/(T_{1/2})$	0.36	0.36	0
Geometrical correction, F_g	B	$1+\delta(r/2d)^2$	0.1	0.23	0.1
Air scatter fraction, AS	B	0.15P%	0.35	0.74	0.27
Room scatter fraction, RS	B	0.10P%	2.65	3.06	2.65
Timing for irradiation	B	Accumulated dose	0.1	0.1	0.1
DE comversion coefficient	B	ISO	1	4	4
Reading of instrument	A	statistical uncertainty	-	-	-
Combined uncertainty(%)			3.55	5.49	5.13
Expanded uncertainty(k=2)			7.1	11.0	10.3

The dosimetric quantities for the scattered neutron calibration fields at the reference point were determined by means of a BMS. Integral properties such as the spectral mean neutron energy, Eave. and the fractional contribution of thermal neutrons to the total fluence, φ_{th}/φ, and the fluence to ambient/personal dose equivalent conversion factors averaged over the neutron energy spectra, h*(10) and hp(10), with its mean neutron energy, E*ave. and Ep,ave. are summarized in Table 6 for ten scattered neutron fields. 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[11]. The dose rate for each scattered neutron field is fixed to one kind because of the limitation of the number of neutron sources available. Nevertheless these scattered neutron fields would be useful for the calibration of personal dosemeters and survey meters used for radiation protection purpose if the energy spectra of workplace is not so different from KAERI's.

Table 6. Integral properties of several scattered neutron fields in the neutron irradiation room of KAERI

Fields	Eave. [1] (MeV)	φ_{th}/φ (%)	$h^*(10)/E^*ava$ [2] (pSvcm²/MeV)	$H_p(10)$/Ep,ave [2] (pSvcm²/MeV)	H_{MADE} [3]/E_{MADE} (pSv.cm²/MeV)
A	1.282	10.2	327/1.63	339/1.64	278/1.70
B	0.444	51.2	129/1.42	133/1.42	107/1.50
C	0.532	24.8	207/1.03	214/1.03	157/1.09
D	0.692	36.4	161/1.76	167/1.78	127/1.99
E	0.282	53.1	93/1.20	96/1.22	70/1.35
F	0.461	9.4	111/1.46	115/1.47	88/1.66
G	0.205	48.6	69/1.18	72/1.19	56/1.28
H	0.171	38.9	91/0.70	94/0.70	66/0.72
I	0.184	44.9	75/0.95	78/0.98	59/1.02
J	3.436	6.4	347/3.29	362/3.30	320/3.44

[1] spectral mean energy [2],[3] same notations as in Table 4

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