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■論　文■

Neutron Personal Dose Equivalent Evaluation Using Panasonic UD-809P Type TLD Albedo Dosimeters

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Panasonic UD-809P 알비도 열형광선량계를 이용한 중성자 개인선량당량 평가

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Abstract - Panasonic UD-809P type albedo neutron TL dosimeters mounted on a water phantom were used to measure neutron personal dose equivalent in a Korean nuclear power plant. From the measured TL readings, personal dose equivalents from thermal, epithermal and fast neutrons were evaluated by using a method adopted in a neutron dose calculation algorithm for Panasonic UD-809P type albedo neutron TL dosimeters, which was suggested in a Panasonic TLD System User's Manual. The results showed that personal dose equivalent from fast neutrons could not be adequately evaluated in a field with high thermal neutron fraction to be encountered in a nuclear power plant. This seems to be related to the incomplete incidence of albedo thermal neutrons to the TL dosimeters. In order to evaluate appropriately the personal dose equivalent from fast neutrons in the field condition, new method for the neutron dose calculation algorithm was suggested. In this new method, neutrons are grouped into thermal neutrons and fast neutrons. For each neutron component, equations for TL response, sensitivity factor, calibration factor and personal dose equivalent were derived.

Key words : albedo neutron TL dosimeters, personal dose equivalent, calibration factor.

요약 - Panasonic UD-809P 알비도 중성자 열형광선량계를 팬텀에 장착시켜 원자력발전소에서 중성자 개인선량당량을 측정하였다. 측정된 판독값으로부터 Panasonic 사의 사용자 매뉴얼에 제시되어 있는 방법을 이용하여 열중성자와 초열중성자 및 속중성자로 인한 개인선량당량을 평가하였다. 그 결과 열중성자 성분의 비율이 높은 원자력발전소에서는 속중성자로 인한 개인선량당량을 적절하게 평가할 수 없는 것으로 확인되었는데, 이는 열중성자로 인한 알비도 성분이 열형광선량계로 재입사되는 양이 이론적인 값과 상당한 차이가 나기 때문인 것으로 추정되었다. 따라서 원자력발전소와 같이 열중성자 성분의 비율이 높은 조건에서 속중성자로 인한 중성자 개인선량당량을 평가하기 위하여 중성자 성분을 열중성자와 속중성자로 구분한 새로운 중성자 선량계산 알고리즘을 제안하였으며, 각각의 성분에 대한 개인선량당량과 교정인자, 민감도 인자 평가공식을 유도하였다.

중심어 : 알비도 중성자 열형광선량계, 개인선량당량, 교정인자

INTRODUCTION

Much attention has been paid to the improvement of measurement accuracy in the individual monitoring of neutrons at nuclear power plants since 1980[1]. Since the International Commission on Radiological Protection (ICRP) revised her recommendations on the annual dose limits and the radiation weighting factors in 1990[2], there has been a growing interest in albedo neutron TL dosimeters. Albedo neutron TL dosimeters can detect albedo thermal and epithermal neutrons diffusing back out of the body by incident fast neutrons. Therefore, personal dose equivalent can be separated for thermal neutrons, epithermal neutrons and fast neutrons by using an appropriate dose calculation algorithm.

In order to calculate neutron personal dose equivalent, TL response for a neutron with energy of *E* should be known. However, there is no data available on the TL response function. So the direct calibration of TLDs in the every working field characterized by a Bonner multisphere spectrometer has been attracting an interest from health physicists[3-5]. In-situ calibration method can provide high accuracy in the calibration of albedo TLDs. In addition, it is possible to compare effectivenesses for different monitoring methods by using the in-situ calibration method.

The purposes of this paper are (1) to carry out in-situ calibration of Panasonic UD-809P type albedo neutron TL dosimeters inside containment building of a PWR where the neutron energy spectrum was measured with a Bonner multisphere spectrometer; (2) to check the effectiveness of neutron dose calculation method recommended by Panasonic TLD System User's Manual; and (3) to develop a new method applicable to the neutron fields anticipated to be encountered inside the reactor containment building.

Panasonic UD-809P type albedo neutron TLD is one of albedo neutron personnel dosimeters used at Korean nuclear power plants. In-situ calibration of the Panasonic UD-809P type and Harshaw 8806 type albedo neutron TL dosimeters were simultaneously carried out inside the reactor containment building of Younggwang unit 4.

In order to check the effectiveness of old neutron dose calculation method recommended by Panasonic TLD System User's Manual, neutron personal dose equivalents were calculated from TL responses measured at American Arizona nuclear power plant and Korean Younggwang unit 4, a 1,000 MWe PWR. The results show that the old neutron dose calculation method has limitation on its application for the assessment of personal neutron dose in the nuclear power plants. In order to overcome this limitation, a new method will be introduced in this paper.

PANASONIC UD-809P TYPE TLDS

A Panasonic UD-809P type albedo neutron personnel dosimeter[7] consists of one $^{7}Li_2{}^{11}B_4O_7(Cu)$ and three $^{6}Li_2{}^{10}B_4O_7(Cu)$ phosphor elements in a cadmium housing filled with ABS resin. $^{7}Li_2{}^{11}B_4O_7(Cu)$ element is used for the measurement of gamma dose, and three $^{6}Li_2{}^{10}B_4O_7(Cu)$ phosphor elements are used for the measurement of neutron doses from thermal, epithermal and fast neutrons, respectively. In order to prevent neutrons from coming through the other area, the badge is entirely shielded by a 0.7 mm thick Cd layer except the element windows. With the differences of the measured components, the front and rear of each element have different shields. The elements and shield compositions of UD-809P type dosimeters are shown in Table 1.

NEUTRON DOSE CALCULATION METHOD

Table 1. Elements and Shield Compositions of UD-809P Type TL Dosimeters

Element	Phosphor	Front Shield		Back Shield	
		Material	Thickness	Material	Thickness
E1	$^{7}Li_2{}^{11}B_4O_7(Cu)$	Cadmium	0.7 cm	Cadmium	0.7 cm
E2	$^{6}Li_2{}^{10}B_4O_7(Cu)$	Tin	0.7 cm	Cadmium	0.7 cm
E3	$^{6}Li_2{}^{10}B_4O_7(Cu)$	Cadmium	0.7 cm	Cadmium	0.7 cm
E4	$^{6}Li_2{}^{10}B_4O_7(Cu)$	cadmium	0.7 cm	Tin	0.7 cm

Old Method Used in Neutron Dose Calculation Algorithm

A method, so called an old method in this paper, for the evaluation of neutron dose from TL responses of UD-809P type albedo neutron dosimeter was recommended in the Panasonic TLD System User's Manual. The basic methodology was developed by H. Ishiguro and S. Takeda in 1982[8]. From the measured TL readings, equations for personal dose equivalent from thermal, epithermal and fast neutrons have been provided in the manual for several neutron spectra used for the calibration of neutron dosimeters. For example, the equations for ^{252}Cf source were given by

$$H_{PNth} = 0.033(L2 - L3) \quad (1)$$

$$H_{PNep} = 0.011((L3 - L1) - 0.16(L2 - L3) - 0.20(L4 - L3)) \quad (2)$$

$$H_{PNf} = 2.4((L4 - L3) - 0.8(L2 - L3) - 0.19(L3 - L1)) \quad (3)$$

where H_{PNth}, H_{PNep} and H_{PNf} are personal dose equivalent from thermal, epithermal and fast neutrons in mrem, respectively. And L1, L2, L3 and L4 are measured TL responses from element 1, 2, 3 and 4.

Table 2. TLD Readings Measured at American Arizona Nuclear Power Plant[10]

Location*	Element 1 (mR)	Element 2 (mR)	Element 3 (mR)	Element 4 (mR)
1	331	2733	1979	3962
2	46	362	235	465
3	574	5762	4509	8615
4	67	452	265	474
5	106	1199	627	1037
6	163	1414	790	1400
7	116	961	497	855
8	5	53	30	50
9	9	51	29	55
10	17	45	45	79

* Locations were not shown in the original paper.

The above method may provide quite reliable results for the similar neutron spectra used for the calibration of neutron TLDs. However, there are big differences between the calibration spectra and neutron spectra found in the nuclear power plant. Therefore, the appropriateness of the above method should be carefully examined for the neutron spectra measured in the nuclear power plants. For the examination of the above method, neutron personal dose equivalent were calculated from TL readings measured at nuclear power plants using the above equations. Table 2 shows the TL readings of Panasonic UD-809A type TLDs measured at American Arizona nuclear power plant by R. M. Thurlow[10], and neutron personal dose equivalents calculated from the measured TL readings are given in Table 3. Table 4 gives neutron personal dose equivalents evaluated from TL readings and neutron energy spectrum measured at Younggwang unit 4[9].

As shown in Table 3, there is a big difference between the neutron personal dose equivalent calculated using the method given in the Panasonic TLD System User's Manual and the delivered dose. The difference found in Table 3 may be resulted from uncertainty related to the sensitivity factor. However, there is no reasonable way to explain negative personal dose equivalent found in several cases. If fast neutrons are present, L4 should be higher than 0.8×L2 in any case from Eq. (3). In the field condition, however, L4 often seems to be lower than 0.8×L2 as shown in Table 2. This tendency was also found in Younggwang unit 4. As shown in Table 4, personal dose equivalents calculated from the measured TL readings at 144D and 144E locations are very close to the personal dose

Table 3. Neutron Personal Dose Equivalent at American Arizona Nuclear Power Plant

Location	Personal Dose Equivalent (mrem)				Delivered Dose* (mrem)	Ratio (Total/D. Dose)
	Thermal	Epithermal	Fast	Total		
1	24.88	12.44	2560.03	2597	286	9.08
2	4.19	1.35	221.98	228	37	6.16
3	41.35	32.05	5654.28	5728	650	8.81
4	6.17	1.39	52.27	60	43	1.39
5	18.88	3.82	-351.82	-329	110	-2.99
6	20.59	4.46	-19.99	5	136	0.04
7	15.31	2.59	-205.42	-188	85	-2.21
8	0.76	0.19	-7.56	-70	5	-14.0
9	0.73	0.12	11.04	12	5	2.40
10	0.92	0.18	15.07	16	6.5	2.46

* Delivered dose was evaluated based on containment characterization by Battelle Northwest Laboratories

Table 4. Neutron Personal Dose Equivalent at Korean Younggwang Nuclear Power Plant

Location*	Personal Dose Equivalent (mSv/s)				BMS Dose** (mSv/s)	Ratio (Total/BMS)
	Thermal	Epithermal	Fast	Total		
144C	3.66E-06	4.18E-07	-1.02E-04	-9.83E-05	6.97E-05	-1.41
144D	4.65E-09	1.18E-08	3.83E-07	3.99E-07	3.47E-07	1.15
144E	2.84E-06	4.74E-07	8.14E-05	8.47E-05	8.53E-05	0.99
122D	5.24E-08	2.32E-09	-2.32E-06	-2.26E-06	1.45E-07	-15.6

* 144C, 144D and 144E are three locations in the 144ft level inside the containment building of Younggwang unit 4 where the spectrum and the TL responses were measured. 122C is located in the 122ft level.

** BMS dose means personal dose equivalent evaluated from the neutron spectrum measured with a BMS.

equivalents evaluated from the measured neutron spectrum with the BMS. However, personal dose equivalents calculated from the measured TL readings become negative at 122D and 144C locations. Negative personal dose equivalents shown in Table 3 and 4 resulted from underestimation of fast neutron dose.

For fast neutrons, if (L4 - L3) is less than [0.8 (L2 - L3) - 0.19 (L3 -L1)] in Eq. (3), the personal dose equivalent contributed by the fast neutrons cannot be evaluated. This seems to be mainly because of lower contribution of albedo thermal neutrons to L4 than that expected. E4 element measures albedo thermal neutrons, and has high sensitivity to thermal neutrons. Therefore, any loss in the albedo thermal flux may cause significant decrease in the L4 response. This decrease in the L4 response directly affects the calculated personal dose equivalent from fast neutrons in the method used in the dose calculation algorithm of Panasonic TLD System. Such a situation is suspected to happen in a field condition with high fractional thermal neutron fluence. For example, fractional thermal neutron fluence at 122D was about three times higher than those found in the other locations[9]. Because of the limited data, it was impossible to find any reasonable cause for the negative personal dose equivalent. However, it is certain that fractional neutron fluence has a great effect on the L4 response.

New Method for the Neutron Dose Calculation Algorithm

As discussed above, the old method may raise an intrinsic problem when evaluating personal dose equivalent from fast neutrons in the neutron field with high thermal fraction.

Therefore, it is desirable to use a new method which can compensate any possible lose of albedo thermal neutrons. One way is to apply a new value of a_{tt}, which is the albedo thermal neutron fraction for thermal neutrons. In the old model, albedo fraction of 0.8 is used in the dose calculation algorithm. However, it is suspected that the albedo fraction is slightly less than 0.8 because of the geometry of wearing the TLD. If it is possible to obtain the real value of a_{tt} for the geometry of wearing a UD-809P type TL dosimeter, the possibility of negative personal dose equivalent may be reduced.

Another method is to treat fast neutrons and epithermal neutrons together as fast neutrons. Then TL reading registered by fast neutrons cannot be lost totally unless any loss of albedo thermal neutrons by thermal neutrons is greater than total albedo thermal neutrons by fast neutrons. Even though there might be some decrease in the measured reading of E4 element because of the loss of albedo thermal neutrons, it can be compensated by adjusting the sensitivity for fast neutrons from the delivered personal dose equivalent. In this paper, the latter method is adopted.

3.2.1 Energy Ranges Measured with $^{6}Li_2{}^{10}B_4O_7(Cu)$ Elements

In order to compensate possible loss of fast neutron component, incident neutrons are divided into thermal neutron component (N_{th}) and fast neutron component (N_f) according to their energies. Since the cadmium shield absorbs low energy neutrons very effectively, cadmium cutoff energy (0.5 eV) was used as a boundary between thermal neutron component and fast neutron component. That is to say, the thermal neutrons include thermal and epithermal (> 0.1 eV - < 0.5 eV Cadmium) neutrons, and the fast neutrons include epicadmium (> 0.5 eV), slow (< 10 eV), intermediate (10 eV ~ 0.5 MeV) and fast (> 0.5 MeV) neutrons. Energy ranges for thermal neutrons and fast neutrons measured with the Panasonic UD-809P type albedo neutron dosimeter was defined as follows.

Neutron component	Energy range	Evaluated value
Thermal neutron (N_{th})	E_n < 0.5 eV	H_{PNth}
Fast neutron (N_f)	0.5 eV ≤ E_n	H_{PNf}

In the above classification, E_n is the energy of incident neutrons, and H_{PNth} and H_{PNf} are neutron personal dose equivalents evaluated for two neutron components.

3.2.2 Neutron Interaction Model with Elements

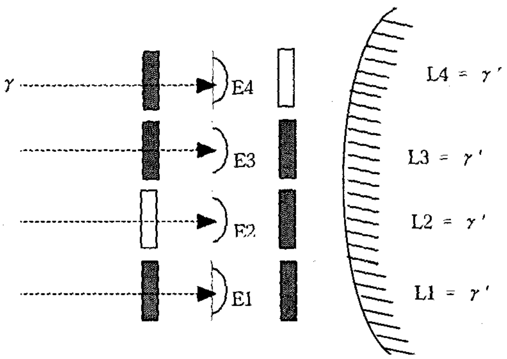
From the design characteristics of Panasonic UD-809P type albedo neutron personnel dosimeter, neutron interaction model with each element can be defined as follows.

E1, being made of $^{7}Li_2{}^{11}B_4O_7(Cu)$ phosphor, has sensitivity to gamma ray only;
E2 has sensitivity to incoming thermal and epithermal neutrons, and albedo epithermal neutrons reflected back from a body by the incoming fast neutrons;
E3 has sensitivity to incoming epithermal neutrons, and albedo epithermal neutrons reflected back from a body by the incoming fast neutrons;
E4 has sensitivity to all type of neutrons originated by incoming fast neutrons and albedo thermal neutrons reflected back from a body by the incoming thermal neutrons.

Thermal neutrons cannot be detected by E3 and E4 elements, since they are absorbed by Cd shields covered in the front of E3 and E4 elements. And albedo thermal neutrons cannot be detected by E2 and E3 elements because they are absorbed by Cd shields covered in the rear of E2 and E3 elements. Detection efficiency of fast neutrons by $^{6}Li_2{}^{10}B_4O_7(Cu)$ elements is very low, since the enriched isotopes ^{6}Li and ^{10}B have high sensitivity to low energy neutrons only. The incident fast neutrons are moderated and scattered inside the body, and the reflected albedo (thermal and epithermal) neutrons will be detected by E4 element. Fig. 1 to 3 show the neutron interaction model with each element including reflection of incoming thermal and fast neutrons inside the body.

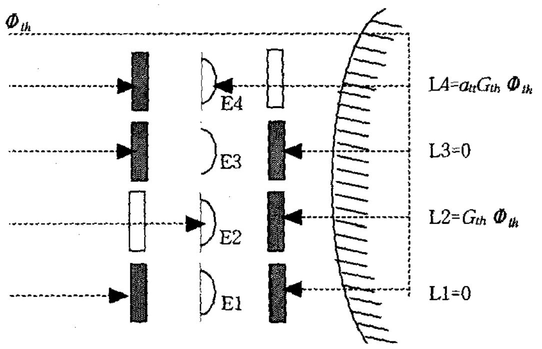
3.2.3 Dose Calculation Method

From the models shown in Fig. 1 to 3, a series of equations for element responses, calibration factors and personal dose equivalents can be derived. Total element response for each element can be expressed as follows from Fig. 1 to 3.



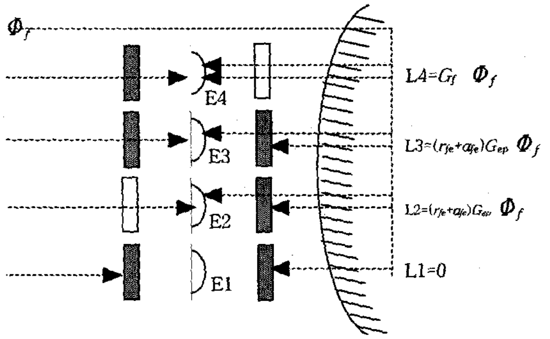
γ' is the component of ray passing through Cd or Sn shield.

Fig. 1. Case of only γ ray incoming.



a_{tt} is the ratio of albedo thermal neutron flux to the incident thermal neutron flux

Fig. 2. Case of only thermal neutron incoming.



a_{fe} is the ratio of albedo epithermal neutron flux to incoming fast neutron flux

r_{fe} is the ratio of incoming epithermal neutron flux to incoming fast neutron flux

Fig. 3. Case of only fast neutron incoming

$$L1 = \gamma' \tag{4}$$

$$L2 = G_{th}\,\Phi_{th} + G_{ep}\,(r_{fe}+a_{fe})\,\Phi_f + \gamma' \tag{5}$$

$$L3 = G_{ep}\,(r_{fe}+a_{fe})\,\Phi_f + \gamma' \tag{6}$$

$$L4 = a_{tt}\,G_{th}\,\Phi_{th} + G_f\,\Phi_f + \gamma' \tag{7}$$

where γ' : component of gamma ray passing through Cd or Sn shield

Φ_{th} : incident thermal neutron fluence in n/cm^2

Φ_f : incident fast neutron fluence in n/cm^2

G_{th} : sensitivity of $^6Li_2{}^{10}B_4O_7(Cu)$ phosphor to thermal neutrons in mR-cm^2

G_f : average sensitivity of $^6Li_2{}^{10}B_4O_7(Cu)$ phosphor to all type of neutrons originated by incident fast neutrons in mR-cm^2

G_{ep} : sensitivity of $^6Li_2{}^{10}B_4O_7(Cu)$ phosphor to epithermal neutrons in mR-cm^2

r_{fe} : ratio of incoming epithermal neutron flux to incident fast neutron flux

a_{fe} : ratio of albedo epithermal neutron flux to incident fast neutron flux

a_{tt} : ratio of albedo thermal neutron flux to incident thermal neutron flux

It should be noted that G_f does not mean the sensitivity to fast neutrons. It means the average sensitivity to incident epithermal neutrons and albedo thermal and epithermal neutrons reflected by the incident fast neutrons. Therefore, it should be determined from the measured TL responses for each neutron spectrum.

From the above equations, TL response for each neutron component can be obtained as follows.

$$G_{th}\,\Phi_{th} = L2 - L3 \tag{8}$$

$$G_f\,\Phi_f = (L4 - L1) - a_{tt}\,(L2 - L3) \tag{9}$$

In the above equations, the sensitivities of $^6Li_2{}^{10}B_4O_7(Cu)$ phosphor to thermal and fast neutrons are defined as the TL readings registered by unit neutron fluence. They can be easily derived from Eq. (8) and (9).

$$G_{th} = \frac{L2 - L3}{\Phi_{th}} \tag{10}$$

$$G_f = \frac{(L4 - L1) - a_{tt}\,(L2 - L3)}{\Phi_f} \tag{11}$$

Let's define sensitivity factors for thermal neutrons and fast neutrons, which are indicated by TL reading per unit personal dose equivalent. Then, they are

$$H_{Nth} = \frac{L2 - L3}{CF_{th}\ \Phi_{th}} = \frac{L2 - L3}{H_{PNth}} \text{ ------------------- } (12)$$

$$H_{Nf} = \frac{(L4 - L1) - a_{tt}(L2 - L3)}{CF_f\ \Phi_f} = \frac{(L4 - L1) - a_{tt}(L2 - L3)}{H_{PNf}} \text{ -----} (13)$$

where H_{Nth} : sensitivity factor of $^6Li_2{}^{10}B_4O_7(Cu)$ phosphor to thermal neutrons in mR/mSv

H_{Nf} : sensitivity factor of $^6Li_2{}^{10}B_4O_7(Cu)$ phosphor to fast neutrons in mR/mSv

CF_{th} : conversion factor of personal dose equivalent per unit fluence in mSv cm^2 for thermal neutrons

CF_f : conversion factor of personal dose equivalent per unit fluence in mSv cm^2 for fast neutrons

Calibration factors for thermal neutrons and fast neutrons, which are defined as personal dose equivalents per unit TL reading, can be expressed as the reciprocal of the sensitivity factors obtained from Eq. (12) and (13), respectively. Therefore,

$$C_{HNth} = \frac{1}{H_{Nth}} = \frac{H_{PNth}}{L2 - L3} \text{ ---------------------- } (14)$$

$$C_{HNf} = \frac{1}{H_{Nf}} = \frac{H_{PNf}}{(L4 - L1) - a_{tt}(L2 - L3)} \text{ ----- } (15)$$

where C_{HNth} : calibration factor for thermal neutrons in mSv/mR

C_{HNf} : calibration factor for fast neutrons in mSv/mR

If we can determine calibration factors from the measured TL readings in a field condition, then neutron personal dose equivalents for thermal neutrons and fast neutrons can be determined from the following equations.

$$H_{PNth} = C_{HNth}\,(L2 - L3) \text{ ------------------------------- } (16)$$

$$H_{PNf} = C_{HNf}\,[(L4 - L1) - a_{tt}\,(L2 - L3)] \text{ ------ } (17)$$

$$H_{PNwd} = H_{PNth} + H_{PNf} \text{ --------------------------------- } (18)$$

where $H_{PNth},$ H_{PNf} and H_{PNwb} are personal dose equivalent for thermal and fast neutrons, and total neutron personal dose equivalent to external whole body in mSv, respectively.

ASSESSMENT OF CALIBRATION FACTORS

In order to calculate personal dose equivalent from the above derived equations, calibration factors for each field should be evaluated. The calibration factors can be obtained from albedo factors (a_{tt}), neutron fluences measured with a Bonner multisphere spectrometer in the field (Φ), conversion factors of personal dose equivalent per unit neutron fluence (CF), and the readings measured with Panasonic UD-809P type TLDs at the same position as the Bonner multisphere spectrometer was placed. Albedo factors for thermal neutrons was taken from reference 8.

Neutron energy spectra were measured at four locations(144C, 144D, 144E and 122D) inside the reactor containment building of Younggwang unit 4 using a Bonner multisphere spectrometer. 144C, 144D and 144E are three locations chosen in the 144 ft level inside the

Table 5. The conversion factors calculated by the neutron spectra in the fields

Neutron Component	Location	Energy	Conversion Factor (10^{-9} mSv-cm^2)
Thermal Neutrons	144D	0.025 - 0.5 eV	13.78
	122D	0.025 - 0.5 eV	13.78
	144E	0.025 - 0.5 eV	13.78
	144C	0.025 - 0.5 eV	13.78
Fast Neutrons	144D	130.5 keV	47.94
	122D	137.5 keV	43.28
	144E	192.9 keV	111.42
	144C	215.2 keV	118.02

Note) Energy of fast neutrons means the average energy of fast neutron spectrum.

containment building, and 122D is a place in the 122 ft level. The results are summarized in Ref. 9. Based on the measured spectra, average conversion factors for thermal neutrons and fast neutrons were calculated. Then, the calibration factors for thermal and fast neutrons were evaluated from Eq. (14) and (15).

Albedo Factor for Thermal Neutrons

Albedo factor for the incident thermal neutrons, a_{tt}, was taken as 0.8 from Ref. 8.

Measured TL Readings

In order to evaluate calibration factors in the field conditions, TL readings of Panasonic UD-809P type TLDs were measured at the four positions where the energy spectra were measured with the Bonner multisphere spectrometer. Panasonic TLDs were mounted on the water slab phantom ($40 \times 40 \times 15$ cm^3) at perpendicular (0°) irradiation. Table 6 shows the readings measured in the containment building of Younggwang unit 4. The measured TL readings were given in the unit of mR/sec by dividing the readings by the measured time.

Table 6. The readings measured by Panasonic UD-809P type TLDs in the fields

Location	E1 (mR/s)	E2 (mR/s)	E3 (mR/s)	E4 (mR/s)
144D	(5.810±0.000)E-05	(1.921±0.131)E-04	(1.782±0.016)E-04	(2.280±0.295)E-04
122D	(3.901±2.697)E-05	(2.899±0.336)E-04	(1.310±0.292)E-04	(1.788±0.189)E-04
144E	(1.956±0.196)E-03	(1.860±0.196)E-02	(1.000±0.080)E-02	(2.180±0.180)E-02
144C	(1.840±0.196)E-03	(1.970±0.205)E-02	(8.599±0.535)E-03	(1.450±0.082)E-02

Conversion Factors

Conversion factors of personal dose equivalent per unit neutron fluence were taken from ICRP report 74[11]. From the measured neutron energy spectra inside the containment building of Younggwang unit 4 using Bonner multisphere spectrometer[9], the average conversion factors were evaluated for thermal and fast neutrons. The results are shown in Table 5.

As shown in Table 5, the same conversion factor is used for thermal neutrons in any field condition. However, conversion factor for fast neutrons depends on the characteristics of neutron energy spectrum. In general, the higher the average energy of fast neutrons is, the higher the conversion factor is.

Calibration Factors

Calibration factors for thermal and fast neutrons can be calculated from Eq. (14) and (15). From the measured TL readings given in Table 6, neutron fluence rates measured with Bonner multisphere spectrometer, personal dose equivalent obtained by multiplying neutron fluence rates with the averaged conversion factor given in Table 5, the calibration factors were evaluated. The results are listed in Table 7.

Thermal neutron cross section with ^{6}Li and ^{10}B also varies with neutron energy. Because thermal neutrons were considered as neutrons

Table 7. TL Readings, Neutron Fluence Rates, Personal Dose Equivalent Rates and the Calculated Calibration Factors in the Field Conditions

Location	TL Readings (mR/s)		Fluence Rates (n/cm^2-s)		Hp(10) (mSv/s)		Calibration Factors (mSv/mR)	
	L2-L3	L4-L1	Thermal	Fast	Thermal	Fast	Thermal	Fast
144D	1.39E-05	1.699E-04	1.06	7.234	1.46E-08	3.47E-07	1.05E-03	2.18E-03
122D	1.59E-05	1.398E-04	2.88	3.493	3.97E-08	1.45E-07	2.50E-04	1.14E-03
144E	8.59E-03	1.984E-02	126.65	765.25	1.75E-06	8.53E-05	2.03E-04	6.58E-03
144C	1.11E-02	1.266E-02	101.74	590.36	1.40E-06	6.97E-05	1.26E-04	1.84E-02

Table 8. Differences Between the Calibration Factors and the Fitted Values

Average Energy (MeV)	Calibration Factor (C) (mSv/mR)	Fitted Values (F) (mSv/mR)	C/F
0.1322	1.85E-3	1.82E-3	1.016
0.1929	6.58E-3	6.60E-3	0.997
0.2152	1.84E-2	1.83E-2	1.005

with energy less than 0.5 eV in this paper, thermal neutron spectrum also affect the calibration factor. This effect may cause the difference found in the calculated calibration factors for thermal neutrons. However, it is impossible to obtain thermal neutron spectrum in the field condition. Therefore, constant calibration factor for thermal neutrons was assumed here.

Calibration factors for thermal neutrons show large deviation from 1.26×10^{-4} to 1.05×10^{-3} mSv/mR possibly due to difference in the thermal neutron spectrum. The calibration factor for thermal neutrons given in Table 7 must be used for the measured neutron spectrum. However, the calibration factor calculated at 144D, where the thermal neutron fluence rate is relatively small, may carry high uncertainties in the measured TL readings and the measured neutron spectrum. In addition, relative importance of the low neutron flux area is very low compared to the high neutron flux area when evaluating neutron personal dose equivalent of a radiation worker. Therefore, calibration factor for thermal neutrons was obtained by averaging the calibration factors except the value at 144D location. The averaged calibration factor for thermal neutrons was 1.93×10^{-4} (mSv/mR).

Calibration factors for fast neutrons show a tendency to increase with the average energy of fast neutrons. The calibration factors for fast neutrons at 144E, 144C locations and the interpolated calibration factor for fast neutrons at 144D and 122D locations may be fitted by the following equation:

$$C_{HNf}(Ei) = A\exp(B\,E_i^{C}) \text{ ---------------------------- } (19)$$

where $C_{HNf}(E_i)$ is the calibration factor for a fast neutron spectrum with the average energy of E_i in mSv/mR, E_i is the average energy for fast neutron spectrum (from 0.5 eV to 20 MeV) in MeV, and A, B and C are the fit constants. From the regression analysis, the fit constants were evaluated as 1.343×10^{-3} for A, and 2747 for B, and 4.529 for C. The regression coefficient of the fit equation was 0.9999. The calibration factors and the fitted values and their differences are shown in Table 8.

New method suggested here can be used in the neutron dose calculation algorithm for Panasonic UD-809P type albedo neutron TL dosimeters. The use of generalized formula for the calibration factor may be limited to a certain range of average energies, because the exponential relationship assumed in the formula will cause dramatic increase in the calibration factor at a high energy range. However, the average energies for the fast neutron spectra measured with the Bonner multisphere spectrometer inside the reactor containment building of Younggwang unit 4[10] fell into the range from 61.8 keV to 578 keV except one of 16 locations where the spectrum was measured. Therefore, no significant error is anticipated when using this method to estimate the calibration factor for a neutron spectrum to be usually encountered in the nuclear power plants.

It should be noted that the calibration factor obtained here must be restricted its use on the field condition with considerable fraction of thermal neutron component. For a calibration spectrum without thermal neutron component, the calibration factor for fast neutrons becomes much lower than the calibration factor obtained

Table 9. Comparison of Personal Dose Equivalents Calculated from the Measured TL Readings Using Generalized Equations for Calibration Factors with Those Estimated from Neutron Energy Spectrum Measured with a BMS

Location	Hp(10) from Neutron Spectrum			Hp(10) from TL Readings			B/A
	Thermal	Fast	Total (A)	Thermal	Fast	Total (B)	
144D	1.46E-08	3.47E-07	3.62E-07	2.68E-09	2.80E-07	2.82E-07	0.78
122D	3.97E-08	1.45E-07	1.85E-07	3.07E-08	2.41E-07	2.71E-07	1.46
144E	1.75E-06	8.53E-05	8.71E-05	1.66E-06	8.54E-05	8.70E-05	1.00
144C	1.40E-06	6.97E-07	7.11E-05	2.14E-06	6.93E-05	7.14E-05	1.00

here.

The comparison between the neutron personal dose equivalent calculated by the generalized expressions for Panasonic UD-809P type albedo neutron TL dosimeters and that estimated from the measured neutron energy spectrum is given in Table 9. Personal dose equivalents were calculated for the exposed time of TLDs in the fields. As shown in Table 9, difference between the neutron personal dose equivalent calculated from the measured TL readings and that calculated from the measured neutron spectrum was less than 22 % except the 122D location where the measured neutron flux with a BMS was relatively small compared to the other areas.

It may not be enough to derive generalized equations for neutron personal dose equivalents from the confined number of data measured at a Younggwang nuclear power plant. However, there must be a strong relationship between TL responses and neutron energy. Therefore, generalized equations were derived as follows from the fitted equation and the average calibration factor for thermal neutrons. By using the following equations, it is possible to obtain calibration factors for the neutron spectrum measured with a BMS in a certain workplace or for the neutron spectrum averaged for several workplaces by considering relative work occurrence in each place

$$H_{PNth} = 1.93\times10^{-4}\ (L2 - L3) \quad \text{------------} \ (20)$$

$$H_{PNf} = 1.343\times10^{-3}\exp(2747\ E_i^{4.529})[(L4 - L1) - 0.8(L2 - L3)] \quad \text{------------} \ (21)$$

In order to evaluate the appropriateness of the above equations, neutron personal dose equivalents from TL readings measured at Arizona nuclear power plant were calculated using the above equations. As shown in Table 10, the differences between the delivered doses and the calculated doses range from 1.96 to 2.88 for the case of assuming 150 keV of average neutron energy, and from 1.38 to 2.05 for the case of assuming 100 keV of average neutron energy. Since the information on the neutron energy spectrum measured at Arizona nuclear power plant is not available, it was impossible to derive an exact calibration factor for fast neutrons. However, the differences shown in Table 10 can be considered quite negligible compared to uncertainties coming from the measurement of neutron spectrum and handling of TLD. We believe that the above methodology can be applied to evaluate neutron personal dose equivalent when using Panasonic UD-809P Type TLD albedo dosimeters.

CONCLUSION

The method used in the neutron dose calculation algorithm of Panasonic UD-809P type albedo neutron TL dosimeters suggested by Panasonic TLD System User's manual has been found to raise a serious problem when applied for the assessment of neutron personal dose equivalent in the nuclear power plants. In a certain neutron field with high fractional thermal component, personal dose equivalent calculated from the method becomes negative mainly because of underestimation of fast neutron component. It was suspected to be caused by the loss of thermal albedo neutrons in the element 4.

Table 10. Comparison of Personal Dose Equivalents Calculated from the Measured TL Readings at Arizona Nuclear Power Plant(Table 2) Using Generalized Equations for Calibration Factors with Delivered Doses

Location	Delivered Dose (mrem)	Calculated Dose Using Generalized Equations			
		Assumed E_i = 100 keV*		Assumed E_i = 150 keV*	
		Calculated (mrem)	Ratio (Cal./Del.)	Calculated (mrem)	Ratio (Cal./Del.)
1	286	588	2.05	824	2.88
2	37	71	1.92	96	2.59
3	650	1,269	1.95	1,818	2.80
4	43	74	1.72	94	2.19
5	110	180	1.64	216	1.96
6	136	228	1.68	286	2.10
7	85	143	1.68	172	2.02
8	5	8	1.60	10	2.0
9	5	8	1.60	11	2.2
10	6.5	9	1.38	14	2.15

* Since the information on the neutron energy spectrum is not available, the average neutron energy was assumed as 100 keV and 150 keV.

In order to compensate any possible loss of thermal albedo neutrons in the element 4, a new method was suggested in this paper. In the new method, neutrons are grouped into two components, thermal neutrons and fast neutrons. And the relevant energy for each component was determined from the cutoff energy by cadmium which is used as front and rear covers of Panasonic UD-809P type TLDs. From the design characteristics of the Panasonic UD-809P type TLDs, the element 4 responds to incident fast neutrons, albedo neutrons reflected by incident fast neutrons and albedo thermal neutrons reflected by incident thermal neutrons. Then, it is possible to discriminate fast neutron component by subtracting thermal albedo fraction from L4 response.

Calibration factors for thermal and fast neutrons were evaluated in the field conditions. At four selected locations inside the containment building of Younggwang unit 4, neutron spectra were measured with a Bonner multisphere spectrometer. And TL responses of Panasonic UD-809P type TLDs mounted on a water slab phantom were measured at the same positions. Neutron personal dose equivalents for thermal and fast neutrons were calculated from the measured neutron spectrum and conversion factors given in ICRP 74. Then calibration factors were estimated for each location.

The calibration factors were significantly different from location to location. It may suggest that the calibration factor depends on the neutron energy spectrum even for thermal neutrons. Unfortunately, information on the measured thermal neutron spectra were not so enough as to verify the correlation between the calibration factors and thermal neutron energy spectra. Therefore, the calibration factors for thermal neutrons were assumed to be constant. However, the calibration factors for fast neutrons showed a clear correlation with the average energy of fast neutron spectrum. A generalized formula for the calibration factor was derived by fitting the data in a equation. Regression coefficient was 0.9999.

However, it should be noted that the measurement of TL responses was made only at four locations. More measured data may be required for the generalization of a formula for the calibration factor.

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