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ARTICLE

Development of a Neutron Energy Monitoring System

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The neutron energy measurement is important to evaluate the neutron ambient dose-equivalent. A Bonner sphere spectrometer is a very powerful tool for the measurement of the large dynamic range of neutron energy. However, online monitoring of the neutron energy with Bonner spheres is hard to achieve because of the complex unfolding procedure. For this purpose, the neutron energy monitoring system consisted of a few ^{3}He proportional counters with cylindrical moderators were developed and their responses were evaluated using MCNPX transport calculations. The range of neutron energy from thermal to 5 GeV was divided into four intervals and six neutron energy spectra were studied to get the weighted average of the response. Spectral neutron fluences of ^{252}Cf source and D_2O-moderated ^{252}Cf source were measured in the neutron irradiation room at the Korea Research Institute of Standards and Science. The measured spectra were compared to those by the Bonner sphere spectrometer. The result showed that the neutron energy spectra using the weighted average response of cosmic-ray induced neutron distribution agreed with that obtained by offline analysis of the Bonner sphere spectrometer within 20 %. The system will be used to monitor the environmental neutrons in the near future.

KEYWORDS: neutron energy monitoring, response matrix, diagonalization, weighted response

I. Introduction

The measurement of the spectral fluence of neutrons is important for evaluating the neutron ambient dose equivalent and widely used to determine a neutron dose. Because of the large dynamic range of neutron energy from meV to a few GeV, there is no practical way to measure the full dynamic range with only a single detector. Many detectors and techniques have been developed to measure the neutron energy. Most common methods are based on the techniques with time-of-flight, multi-moderator detectors like Bonner sphere spectrometers, and threshold detectors like activation foil sets. Among them, a Bonner sphere spectrometer is a very powerful tool for the measurement of the large dynamic range of neutron energy. It consists of a thermal neutron detector and several polyethylene moderators called Bonner spheres. It could measure neutron energy up to a few GeV with an inlet metal moderator[1).

Conventional neutron ambient dosimeters differ greatly from the conventional true value in the unknown fields. Therefore, online monitoring of the neutron energy is also getting important to supplement the neutron ambient dosimeter. The Bonner sphere spectrometer could be used to monitor neutron energy. However, online monitoring of the neutron energy with Bonner spheres is hard to achieve because of the complex procedure like unfolding. The number of the spheres is usually less than 20 which is much smaller than the typical neutron energy bin size. Prior information such as an initial guess of neutron spectrum is required to do unfolding procedure which is quite dependent on experiences.

If the neutron energy bin size is small and the response of a Bonner sphere is negligible except for a typical energy bin like delta function, the neutron energy could be analytically determined without unfolding procedure. This method is rather difficult for the nominal Bonner sphere spectrometer because every sphere has responses in the whole neutron energy range. However, there is possibility to make the response function into delta function by a linear combination of the responses. Then, the response matrix will be diagonalized. Furthermore, if the neutron energy bin size is equal to the number of detectors, the neutron fluence rates could be evaluated directly from the count rates. For this purpose, the linear combinations of the responses were carefully studied for the Bonner sphere spectrometer of the Korea Research Institute of Standards and Science (KRISS). The spectrometer composed of 10 polyethylene spheres from 7.62 cm (3”) to 30.48 cm (12”) with a ^{3}He-filled spherical proportional counter (type SP9, Centronic Ltd., UK). Their response functions were calibrated and confirmed with a well-specified ^{252}Cf neutron source[2).

In this paper, the new technique of the response matrix diagonalization was studied and the responses of the newly developed neutron energy monitoring system were evaluated by detailed Monte Carlo calculations. The system and the validity of the diagonalization was tested in the neutron irradiation room at KRISS with ^{252}Cf source and D_2O-moderated ^{252}Cf source.

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II. General Instruction

1. Matrix diagonalization

Neutron count rate of Bonner spheres can be written as the product of the spectral fluence and the response,

$$\dot{C}_i = \sum_{i=1}^{n} R_{ij}(E)\dot{\Phi}_j(E), \tag{1}$$

where $\dot{C}$, R, and $\dot{\Phi}$ are, respectively, the neutron count rate, the neutron response, and the neutron fluence rate. This is the product of the response matrix R and the spectral fluence matrix $\dot{\Phi}$. If R is the square matrix, there will be a square matrix A which can diagonalize R such as $\dot{C}' = A\dot{C} = AR\dot{\Phi} = R'\dot{\Phi}$, where R' is a diagonal matrix whose entries above and below the main diagonal are all zero.

$$\begin{pmatrix} \dot{C'}_1 \\ \dot{C'}_2 \\ \cdot \\ \dot{C'}_n \end{pmatrix} = \begin{pmatrix} R'_{11} & 0 & \cdot & 0 \\ 0 & R'_{22} & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ 0 & \cdot & \cdot & R'_{nn} \end{pmatrix} \begin{pmatrix} \dot{\Phi}_1 \\ \dot{\Phi}_2 \\ \cdot \\ \dot{\Phi}_n \end{pmatrix} \tag{2}$$

Then, the neutron fluence rate is determined by $\dot{\Phi}_k = \dot{C'}_k / R'_{kk}$ with a transformed count rate and a transformed response. Even though this is an ideal case, there could be possible to find a square matrix A which transforms the response matrix to the diagonal matrix whose off-diagonal components are near zero within 1 %. At first, diagonal components of A were set to be 1. Other components of A were varied from -1 to 1 until R' was near to a diagonal matrix. This was a naïve method but worked well.

2. Detector configuration

Four detectors were selected to cover the interesting neutron energy ranges from thermal neutrons to high energy neutrons. **Figure 1** shows the newly developed moderators for the neutron energy monitoring system. ^{3}He proportional counter SP9 was used for the thermal neutron detector. Because spherical shape is hard to make and deal with, cylindrical polyethylene was chosen for the moderator. Cylindrical shell of copper was inserted as an inlet metal moderator to the largest moderator to cover the neutron energy response up to 5 GeV. The density, diameters of the cylinders, and metal material are summarized in **Table 1**.

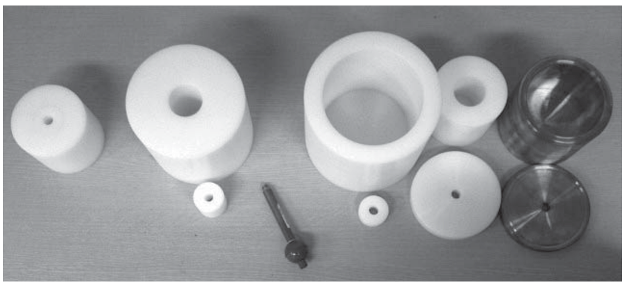

Fig. 1 Cylindrical moderators for the neutron energy monitoring system.

Table 1 Diameter, height, and density of the moderators.

Name	Polyethylene			Copper shell		
	φ (cm)	h (cm)	ρ (g/cm^3)	$φ_{in}$ (cm)	$φ_{out}$ (cm)	ρ (g/cm^3)
d100	10	8.8	0.95	-	-	-
d150	15	13.5	0.95	-	-	-
d170(Cu)	17	15.2	0.95	10	12	1.2

3. Response Calculations

Responses of newly developed moderators were calculated by using the MCNPX[3)] transport code. The neutron cross-sections were taken from the ENDF/B-VI.6[4)] and the LA150 library[5)]. The S(α,β) cross sections were used to take account of the binding effects in polyethylene. Above 150 MeV, the physical models of Bertini[6)] and ISABEL[7)] were used, because no tabular data for neutron cross sections were available. The directional dependence of the neutron ambient dosimeters was also studied. In order to study the directional dependence of the response functions, MCNPX transport calculations were carried out for two parallel incidences and one isotropic incidence. The two parallel incidences were in the directions of normal and parallel to the axis of the thermal neutron detector. Mono-energy neutrons were generated to be uniform on a log scale from 0.001 eV to 5 GeV. The responses of the three directions were calculated and compared to each other by changing the cylinder height. The diameter and the height of the cylindrical moderators shown in **Table 1** were finally determined to minimize the deviations of the responses less than 5 %. The response functions of the final detector configuration for the isotropic incidence are shown in **Figure 2**. As expected, responses of "d170(Cu)" increase above 20 MeV owing to large (n,xn) cross-sections of copper in high energy region.

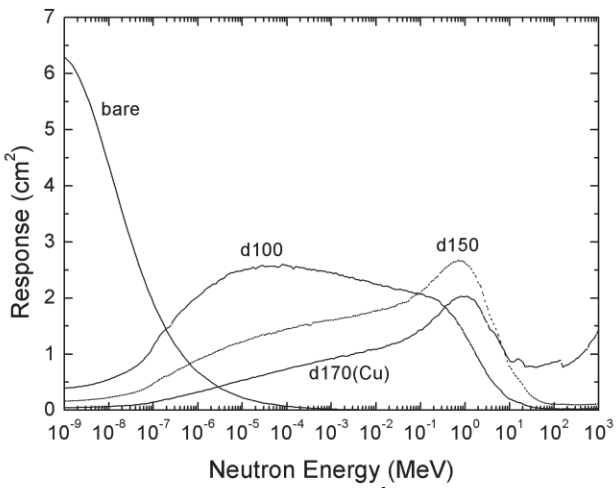

Fig. 2 Response functions of the bare ^{3}He proportional counter and that with the the moderators.

4. Weighted Average of Responses

In order to diagonalize the response matrix, the responses have the same number of the detectors. Because the dynamic ranges of responses are broad and only four detectors are

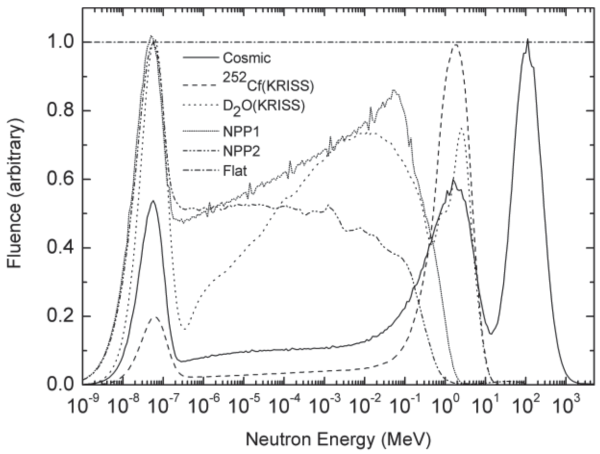

Fig. 3 Neutron energy distributions for the weighted average of responses. All distributions are normalized so as to the peak heights to be unity.

used, the responses could be varied rapidly in some energy region. Thus, the responses should be averaged with the proper weighting for the improvement of the results. Real neutron energy distributions could be used. Six distributions of neutron energy were considered for the weighting. They are flat distribution, ^{252}Cf distribution in KRISS neutron irradiation room, D_2O-moderated ^{252}Cf distribution in KRISS neutron irradiation room[2], nuclear power plant distribution 1, nuclear power plant distribution 2, and cosmic-ray induced neutron distribution at ground level (altitute 142 m, latitute 36.3916, longitude 127.3690). They are abbreviated “Flat”, “^{252}Cf(KRISS)”, “D_2O(KRISS)”, “NPP1”, “NPP2”, and “Cosmic”, respectively. The energy distribution of “NPP1” and “NPP2” were measured at Youngkwang and Uljin nuclear power plants in Korea and “Cosmic” was measured at KRISS with the KRISS Bonner sphere spectrometer. The spectral fluences of them were extracted with the MAXED[8] code of the UMG[9] package developed for the unfolding process at PTB. **Figure 3** shows the neutron energy distributions. All distributions are normalized so as to the peak heights to be unity.

III. Results

Figure 4 shows the response diagonalization for “Flat” case. In the figure, plot (A) is the response R before diagonalization and plot (B) is the response R' after diagonalization. The responses of plot (A) show just average values of Fig. 2 but the responses in the plot (B) become delta-function like. The neutron count rates were also transformed by multiplying the same square matrix A. The range of neutron energy from thermal region to 5 GeV was divided into four intervals; 1 meV - 0.5 eV, 0.5 eV - 100 keV, 100 keV - 20 MeV, and 20 MeV - 5 GeV. These intervals were chosen to represent for thermal neutrons, epithermal neutrons, fast neutrons, and high energy neutrons. Division of the energy range is not unique and can be determined by other ways.

The evaluated responses and the methods of matrix diagonalization were tested for the ^{252}Cf distribution and the D_2O-moderated ^{252}Cf distribution in the neutron

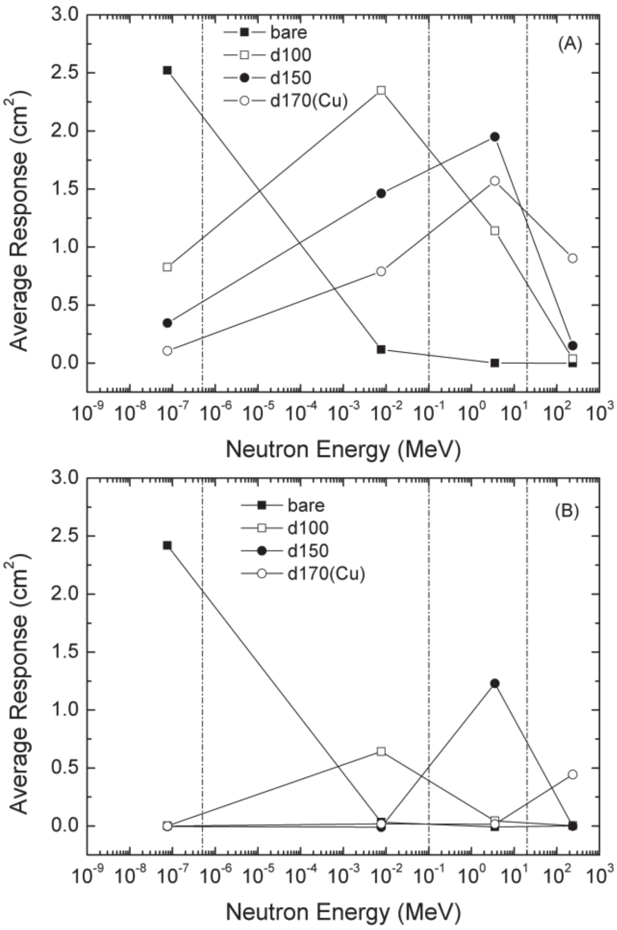

Fig. 4 Diagonalization of the responses. (A) and (B) denote the average responses before and after diagonalization for the flat distribution.

irradiation room of KRISS. One bare SP9 detector and three moderators were installed at 150 cm from the source and the count rates of the detectors were measured. The spectral fluence at the same position was measured with the Bonner sphere spectrometer by unfolding the count rates and the response function. The spectral fluences of the ^{252}Cf distribution and the D_2O-moderated ^{252}Cf distribution were added in each four energy division. The fluence rates of the sources obtained by the diagonalization method and those from the Bonner sphere spectrometer are summarized in **Table 2**. The term “BS” in the table denotes the results from the Bonner sphere spectrometer measurement. Negative fluence rates in the table were caused by the fact that the diagonalized response matrix R' is not a perfect diagonal matrix. In other words, the contribution of the non-zero off-diagonal components is not negligible and gives rise to the negative fluence rates. These negative fluence rates could be considered as zero, which will be discussed later.

The results shown in Table 2 indicate that a fluence rate of ^{252}Cf (or D_2O-moderated ^{252}Cf) source with an averaged response of ^{252}Cf (or D_2O-moderated ^{252}Cf) distribution shows the good result except for the 20 MeV - 5 GeV region compared to the results of “BS”. This is quite reasonable because the diagonalized response matrix R' was optimized to the measured neutron spectrum. On the

Table 2 Fluence rates of ^{252}Cf and D_2O-moderated ^{252}Cf. BS denotes the Bonner sphere spectrometer result and the others are written in the text.

Energy range	Source	Fluence rate ($cm^{-2}s^{-1}$)						
		BS	Flat	^{252}Cf(KRISS)	D_2O(KRISS)	NPP1	NPP2	Cosmic
1 meV - 0.5 eV	^{252}Cf	28	28	27	28	30	34	28
	D_2O	42	40	40	41	38	38	37
0.5 eV - 100 keV	^{252}Cf	34	22	41	11	-56	-82	30
	D_2O	132	136	146	135	117	103	143
100 keV - 20 MeV	^{252}Cf	175	233	188	209	234	258	205
	D_2O	47	66	44	53	63	78	50
20 MeV - 5 GeV	^{252}Cf	0	-24	46	47	22	5	-10
	D_2O	0	-13	-1	2	-3	-8	-9

other hand, "NPP1" and "NPP2" show the large deviations for the ^{252}Cf distribution because their distribution have large components in epithermal region while ^{252}Cf distribution has small compoents.

Because there is no neutron energy distribution above 20 MeV for the ^{252}Cf distribution and the D_2O-moderated ^{252}Cf distribution, the large values in that region should be zero in principle. In that respect, only flat distribution and cosmic-ray induced neutron distribution will be accepted for the weighting distribution because they only have the high-energy components in the energy distribution. If the negative values are considered to be zero, the results of "Cosmic" is better than those of "Flat" as shown in the **Table 2**. Cosmic-ray induced neutron distribution shows distinct components in each energy region thus could be applied to any unknown field. The result showed that the spectral fluence obtained by the responses of "Cosmic" agreed with those by offline analysis of the Bonner sphere spectrometer within 20 %.

IV. Conclusion

One ^{3}He proportional counter and three cylindrical moderators coupled with ^{3}He proportional counters were developed to monitor neutron energy distribution on online. Their responses were evaluated using the MCNPX transport calculation and averaged in four energy region. For online monitoring of the neutron energy, the response matrix was diagonalized by multiplying an appropriate square matrix, which made it possible to get the neutron fluence rate from the count rate without the complicated unfolding procedure. The evaluated responses and the method of the matrix diagonalization were tested in the neutron irratiation room at KRISS for ^{252}Cf distribution and D_2O-moderated ^{252}Cf distribution. The obtained neutron fluence rates were compared to those from the unfolding results using the Bonner sphere spectrometry.

Present results show that the spectral fluence with the weighted average response of cosmic-ray induced neutron distribution gives the better result to that of the flat distribution and agrees within 20 % for both ^{252}Cf distribution and D_2O-moderated ^{252}Cf distribution. This study indicates that simple configuration of moderators and thermal neutron detectors could be used to monitor neutron energy in thermal, epithermal, fast, and high energy neutron region. The system together with a graphical user interface will be used to monitor the environmental neutrons in the near future.

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