Altitude Variation of cosmic-ray neutron energy spectrum and ambient dose equivalent at Mt.Fuji in Japan

M. Kowatari¹, K. Nagaoka¹, S Satoh¹, Y Ohta¹, J.Abuaka²
¹Division of Radioactivity Analysis, Japan Chemical Analysis Center, 295-3,Sanno-cho, Inage-ku, Chiba-shi, Chiba, Japan
E-mail: m-kowatari@jcac.or.jp

Abstract. The experimental studies on the cosmic-ray neutron energy spectrum and the neutron dose rate were performed in the Mt.Fuji area (altitude: 40m – 2400m) by using a Multi-sphere neutron Spectrometer (Bonner Sphere: BS) with the 5.07-cm diam. spherical He-3 proportional counter to assess the natural background neutron dose rate in Japan with good accuracy. The spectra measured at each altitude were compared with each other and with other environmental neutron spectra and the neutron energy spectra measured at each altitude are confirmed to be almost the same in their shapes. The total neutron fluence rate, the ambient dose equivalent H*(10) were estimated to be about 0.0073 cm⁻²·s⁻¹, and the neutron dose rate (ambient dose rate H*(10)) at sea level is estimated to be about 6.0 nSvh⁻¹. The altitude variations of neutron fluence rate and neutron dose rate were also evaluated and they vary according to an exponential law with the altitude, -α exp(αZ), where α = 0.00070 m⁻¹. This α-value is smaller than those of other researches obtained at high geomagnetic latitude.

1.Introduction
The experimental studies on the cosmic-ray neutron energy spectrum and the neutron dose rate in low geographical latitude area are quite few [1] , although many researches in high geographical latitude area have been performed [2-5] . According to the recommendation of ICRP Publication 60, the contribution of neutrons to public dose should be more emphasized. The more detailed knowledge about the cosmic-ray induced neutrons in the environment is therefore essential to estimate the natural background dose. The neutron dose rate in the environment varies with the altitude. In this study, the altitude variation of cosmic-ray neutron energy spectrum and the ambient dose equivalent has been measured in the Mt.Fuji area (altitude: 40m – 2400m) by using a Multi-sphere neutron Spectrometer (Bonner Sphere: BS) to assess the natural background neutron dose rate in Japan with good accuracy. The cosmic-ray neutron energy spectrum and the ambient dose equivalent obtained in this study were then compared with those of other researches obtained at high geomagnetic latitude area.

2.Experimental Setup and Measurement
The energy spectrum of the cosmic-ray induced neutrons was determined by using a Multi-sphere neutron Spectrometer (BS). The BS consists of five 5.07-cm diam. spherical He-3 proportional counters filled with 5 atom He-3 gas. Spherical polyethylene moderators with different thickness are attached to each counter. The diameters of the polyethylene moderators are 0cm(bare), 8.0cm, 11cm, 15cm, and 23cm, respectively. As the response of the BS to neutron in the energy range from thermal to 400MeV, the set of response functions determined by Uwamino et al. [6] was used except for the bare He-3 counter. The response function of bare He-3 counter was given by Nunomiya [7]. Figure 1 shows the response functions used in this study. Calibration of the BS was performed using monoenergetic neutrons with the energy range of 250keV to 15MeV at Dynamitron facility of Tohoku University [8]. The BS was also calibrated using thermal neutrons and a Cf-252 neutrons source at Facility of Radiation Standard of JAERI (Japan Atomic Energy Research Institute). Throughout the series of these calibrations, the mean errors between the measured and calculated response was within the range of 20%. The cosmic-ray neutron energy spectra were obtained by unfolding with the SAND2 code. The SAND2 code calculates the neutron energy spectrum from the counting rate obtained in each He-3 counter. In this study, the cosmic-ray neutron spectrum at sea level obtained by Goldhagen et al. [5] was employed as an
initial guess spectrum. The energy range selected for the unfolding calculation was 0.01 eV to 400 MeV.

Fig. 1 Measured and calculated response functions of the Multi-sphere neutron spectrometer

The BS was installed in a air-conditioned freight car. The temperature in the cargo container was kept within 23 ±2°C. The BS was placed so that the centers of each counter locate on the horizontal plane, which is about 2.0 m height above the ground level. A series of measurement of the cosmic-ray neutron around Mt. Fuji area (40m, 620m, 1020m, 1660m, and 2400m altitude: about 26°N geomagnetic latitude) were performed until the counting errors of each He-3 proportional counter become lower than 3%. In parallel with the cosmic-ray neutron measurement, temperature, atmospheric pressure and geographical position were also measured. The conversion of geographical position into geomagnetic coordinate was carried out according to IGRF 2000. After obtaining neutron spectra, the ambient dose equivalent rate $H^*(10)$ and the effective dose rate of the cosmic-ray at each altitude were estimated based on ICRP Publication 74. To estimate the ambient dose equivalent rate $H^*(10)$, we used neutron fluence to ambient dose equivalent conversion factor calculated by Sannikov and Savitskaya [9] in the energy range of 200 MeV to 400 MeV. The fluence to effective dose (AP and ISO geometries) conversion factors calculated by Ferrari et al. [10] were used for the estimation of the effective dose in the energy range of 200 MeV to 400 MeV.

3. Results and Discussion

3.1 Neutron energy spectra

Figure 2 shows the neutron energy spectra measured by BS (Sea level and 2400m height) around Mt. Fuji area and those of other researchers for comparison. At sea level, neutron energy spectra obtained in this study is in good agreement with that of obtained by Nakamura et al. [1], except in the high energy region (above 10 MeV). The neutron spectrum obtained at 2400m altitude is in quite good agreement with that of obtained by Florek et al. [3], especially in the range up to 1 MeV. In contrast, in the lower energy region (below several hundred keV) the spectrum obtained by Florek et al. [3] is higher than our result. This discrepancy might be caused by the differences of the measuring location (differences of geomagnetic latitude and altitude) and the number of energy bin for spectrum unfolding process. Taking
these differences into consideration, both spectra are in good agreement each other.

Figure 3 shows the neutron fluence rate per lethargy obtained at each altitude around Mt.Fuji area. As mentioned in UNSCEAR 1993 [11] and other articles [4,5], three major peaks (thermal neutron region, evaporation peak around 1MeV and peak around 100MeV caused by nuclear spallation reaction) are clearly confirmed. Figure 4 depicts the normalized neutron spectra using the highest fluence rate around evaporation peak. At the 2400m-altitude measurement, relative fluence rate of peak around 100MeV is slightly lower than those of at other altitude. Except for the high-energy region of spectrum at 2400m-altitude, the neutron energy spectra measured at each altitude are almost the same in their shapes.
3.2 Neutron fluence rate and the estimated neutron dose rate

Total fluence rate, ambient dose equivalent rate H*(10) and effective dose rate have been determined from the measured spectra at each altitude. The results of these values are shown in Table I.

Table I. Measured neutron fluence rate and dose rate at various altitude around Mt.Fuji area

<table>
<thead>
<tr>
<th>Altitude (m)</th>
<th>Atmospheric Depth (g·cm⁻²)</th>
<th>Neutron Fluence Rate (#·cm⁻²·s⁻¹)</th>
<th>Effective Dose Rate (AP geometry) (nSv·h⁻¹)</th>
<th>Effective Dose Rate (ISO geometry) (nSv·h⁻¹)</th>
<th>Ambient Dose Equivalent Rate (H*(10)) (nSv·h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1025</td>
<td>0.0073</td>
<td>6.3</td>
<td>4.5</td>
<td>6.0</td>
</tr>
<tr>
<td>620</td>
<td>965</td>
<td>0.0099</td>
<td>8.9</td>
<td>6.4</td>
<td>8.5</td>
</tr>
<tr>
<td>1020</td>
<td>923</td>
<td>0.0130</td>
<td>11</td>
<td>8.1</td>
<td>11</td>
</tr>
<tr>
<td>1660</td>
<td>856</td>
<td>0.0190</td>
<td>17</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>2400</td>
<td>785</td>
<td>0.0400</td>
<td>33</td>
<td>23</td>
<td>32</td>
</tr>
</tbody>
</table>

All values vary with measuring altitude. The cosmic-ray neutron fluence rate obtained at sea level is estimated to be about 0.0073 cm⁻²·s⁻¹, and the neutron dose rate (ambient dose equivalent rate H*(10)) at sea level is about 6.0 nSv·h⁻¹. These values are both lower than those of other researches. It is pointed out by some references that cosmic-ray neutron intensity decreases against geomagnetic latitude of the measuring location [3,11-12]. Taking it into consideration that a series of measurement in this study was carried out in the lower geomagnetic latitude area, these results are quite reliable. As shown in Table I, ambient dose equivalent rate H*(10) and effective dose rate (AP geometry) obtained at each altitude indicate values of almost the same level, although ambient dose equivalent rate H*(10) are slightly lower than effective dose rate (AP geometry). In contrast, effective dose rate (ISO geometry) at each altitude is estimated to be lower than those of AP geometry and ambient dose equivalent rate. The similar tendency is pointed out by reference [5]. It might be caused by the fact that the fluence to dose conversion factors
of ISO geometry is especially lower in the energy region (below 1MeV) than those of AP geometry and ambient dose equivalent H*(10).

### 3.3 Altitude variation of neutron fluence rate and neutron dose rate

As shown in Figs. 5 and 6, the total neutron fluence rate and the ambient dose equivalent rate H*(10) indicate exponential dependence on the altitude of measuring location Z (m), as pointed out by some references [3,12]. The variations of the total neutron fluence rate and the ambient dose equivalent rate could be fitted by exponential function in the form of ~exp(aZ). In this study, the α-values are consequently determined to be about 0.00070 m⁻¹ using least squares method. The α-values for the total neutron fluence rate and the ambient dose equivalent rate are almost the same.

![Fig.5 Altitude dependence of the total neutron fluence rate](image1)

![Fig.6 Altitude dependence of the ambient dose equivalent (H*(10)) rate](image2)

Table II indicates the comparison of the α-values obtained for various geomagnetic latitudes. The value introduced in UNSCEAR 2000 [12] is derived by converting the attenuation factor per atmospheric depth into attenuation factor per altitude in unit of m⁻¹ assuming the standard air. The α-value obtained in this study is smaller than those of other researches. It is confirmed that the α-value decreases according
to geomagnetic latitude and that the magnitude of the attenuation of cosmic-ray neutron is influenced on the geomagnetic intensity.

**Table II. Comparison of α-value obtained by various geomagnetic latitudes**

<table>
<thead>
<tr>
<th>Geomagnetic latitude (degrees)</th>
<th>α-value $\times 10^{-3} \cdot m^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.0</td>
<td>0.7</td>
</tr>
<tr>
<td>48.0</td>
<td>$0.78^* \ [12]$</td>
</tr>
<tr>
<td>49.0</td>
<td>0.85 $\ [3]$</td>
</tr>
<tr>
<td>50.0</td>
<td>1.04 $\ [13]$</td>
</tr>
</tbody>
</table>

*1 converted value of attenuation factor per atmospheric depth assuming the standard air

UNSCEAR 2000 $\ [12]$  
Florek et al. $\ [3]$  
Bouville et al. $\ [13]$  

Figure 7 shows the comparison of the altitude variation of the relative neutron dose rate using various α-values. In Fig.7, neutron dose rate is normalized by dividing the values by the dose rate at the altitude of 0m.

In estimation of the neutron dose rate at a certain altitude, the use of larger α-value will result in higher dose values. Since the α-values obtained by other researchers $\ [3,12-13]$ were determined for higher geomagnetic latitudes, the use of these α-values will possibly lead to an overestimation of the natural neutron dose rate in lower geomagnetic latitude including Japan. In order to assess the cosmic-ray neutron component of the natural background dose in Japan more accurately, it is therefore indispensable to adopt reliable α-values obtained in lower geomagnetic region in the evaluation of the altitude variation.
4.Conclusions
Measurement of the cosmic-ray neutron energy spectra and estimation of the ambient dose equivalent and effective dose around Mt. Fuji (altitude: 40m – 2400m) area were performed. From the results of the measurement, we compared the shape of cosmic-ray neutron spectra obtained at various altitudes with each other, and with those of other researches. In this study, the following facts were clarified:
1) The neutron energy spectra measured at each altitude are almost the same in their shapes.
2) The cosmic-ray neutron fluence rate obtained at sea level is about 0.0073 cm$^{-2}$·s$^{-1}$, and the neutron dose rate (ambient dose equivalent rate $H^\bullet(10)$) at sea level in Japan is estimated to be about 6.0 nSv·h$^{-1}$ at the geomagnetic altitude of around 26°N. These values are both smaller than those of other articles reflecting the difference of the geomagnetic latitude of the measuring location.
3) The cosmic-ray neutron fluence rate varies according to an exponential law with the altitude, $\sim \exp(\alpha Z)$, where $\alpha = 0.00070$ m$^{-1}$. The value $\alpha$ for neutron dose rate is almost the same as that for neutron fluence rate. This $\alpha$-value is smaller than those of other researches obtained in high geomagnetic latitudes. The $\alpha$-value decreases according to geomagnetic latitude.

Acknowledgement
The authors thank to Dr. Uwamino and Dr. Nunomiya for having provided them with the response function of BS. And we also wish to thank Prof. T. Nakamura for the suitable advise about the evaluation of the data and about English expression and also for his continuous encouragement of this study.

This work was performed under the commission of Ministry of Education, Culture, Sports, Science and Technology in Japan.

References
10. Ferrari, A., Pelliccioni, M., Pillon, M., *Fluence to effective dose conversion coefficients for neutrons

