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# Sequential measurements of cosmic-ray neutron energy spectrum and ambient dose equivalent on the ground

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The cosmic-ray neutron energy spectrum and dose rate were measured sequentially by using a $^3$He-loaded multi-moderator detector (Bonner ball) and rem counter, respectively. The Bonner ball is composed of a 5.08-cm diameter spherical $^3$He counter filled with 5 or 10 atm $^3$He gas, which is placed at the center of a set of polyethylene spheres of different diameters of 8.1, 11.0, 15.0, 23.0 cm. Neutron energy spectra were obtained by an unfolding technique using the SAND-II code. The rem counter consists of a 12.9-cm diameter 5 atm $^3$He gas filled spherical proportional counter. The measuring interval is every 12 hours for Bonner ball, and every 30 minutes for rem counter. This measurement was carried out at the Kawauchi-campus of Tohoku University in Japan.

The neutron energy spectra and the neutron ambient dose equivalent rate were obtained on the ground level with an atmospheric pressure correction. The ambient neutron dose equivalent rate measured by the rem counter keeps an almost constant values of 4.1 [nSv/h], after atmospheric pressure correction, and it often decreased about 30% after a large Solar Flare, that is called as the Forbush decrease. The total neutron flux was also obtained by the Bonner ball measurements to be 7.5 x $10^{-3}$ [n cm$^{-2}$ sec$^{-1}$].

***KEY WORDS: Neutron energy spectrum, neutron ambient dose equivalent, rem counter, Bonner ball***

## I. Introduction

The Sun has an 11-year solar cycle, and the solar activity becomes a maximum in the period of 2000-2002. During the solar maximum, big solar flares sometimes happen and give large effects on our earth environment. Proton is the main element among the solar event particles that reach the earth. When the proton comes into and interacts with the atmosphere, high-energy secondary neutrons and another electromagnetic waves are generated. About 90% of the secondary particles which are able to reach the ground is photons and muons, and the rest is neutrons.

Recently, an accumulation of the semiconductor device greatly increases and the soft-errors of SRAM and DRAM on the ground level caused by high-energy cosmic-ray neutrons become serious problem in the world. In this study, a sequential measurement has been carried out from October 2000 to March 2003 in order to investigate the long-term changes of cosmic-ray neutron flux and dose rate on the ground using the Bonner ball and rem counter. In this paper, we present the results of measurement from April 2001 to March 2003.

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## II. Experiment

### 1. Neutron detectors

The rem counter was used to measure the time variation of cosmic-ray neutron dose equivalent rate. This rem counter, as shown in **Fig.1**, consists of a 12.9-cm (5-inch) diameter spherical $^3$He counter filled with 5 atm $^3$He gas, made by LND Inc., surrounded with the polyethylene moderator and the inner absorber of 50 wt% boron carbide and 50 wt% silicon [1]. The high-voltage of this detector was +1700V. The neutron flux-to-dose conversion factor is 18.5 cps/(μSv/h), which was recalibrated at JAERI (Japan Atomic Energy Research Institute) using a $^{252}$Cf neutron source [2] for this measurement. The measuring interval is every 30 minutes in this study.

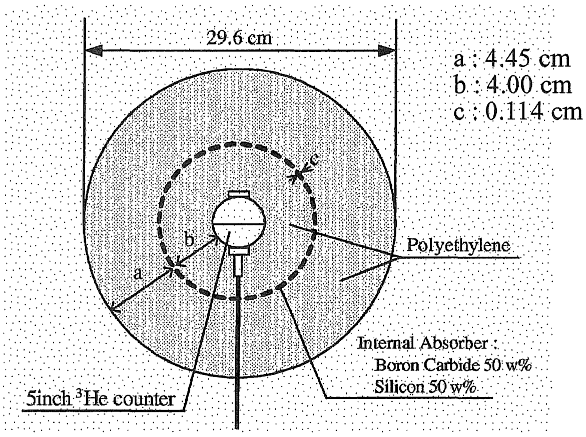


**Fig. 1** Cross-sectional view of the rem counter

The Bonner ball is composed of a 5.08-cm (2 inch) diameter spherical $^3$He counter filled with 5 or 10 atm $^3$He gas, made by LND Inc., which is placed at the center of a set of polyethylene spheres of different diameters of 5.1(bare), 8.1, 11.0, 15.0, 23.0 cm, as shown in **Fig.2** [3]. The high-voltages of these detectors were from +1300V to +1500V. Neutron energy spectra were obtained by an unfolding technique using the SAND-II code [4]. The measuring interval is every 12 hours from 6:00 AM.

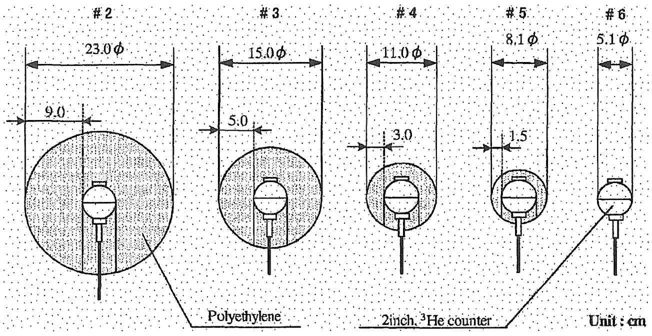


**Fig. 2** Cross-sectional view of $^3$He-loaded multi-moderator detectors

## 2. Experimental arrangement

This measurement was carried out at the Kawauchi-campus of Tohoku University in Japan, which is located at N 38.25, E 140.87 (geomagnetic latitude of about 8 to 9) and about 70 m in altitude. Each detector was set up in the hutch as shown in **Fig.3** with the distance of about 40 cm, and the air conditioner was equipped to keep the temperature constant. Signals from the rem counter were fed into a pre-amplifier (ORTEC 142PC), a linear amplifier (ORTEC 571, 572), a timing single channel analyzer and multi-channel scaler (MCS). For Bonner ball, signals were fed into a pre-amplifier, linear amplifier and multi-channel analyzer (MCA), respectively.

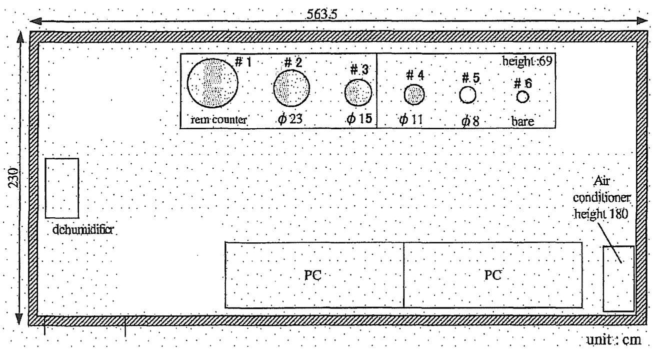


**Fig. 3** Experimental arrangement in the hutch at the Kawauchi-campus of Tohoku University

## III. Analysis

A example of pulse height distributions of the rem counter and Bonner ball is shown in **Fig.4**. The pulse height components lower than about 100 channel in **Fig.4** are the signals of muons and gamma rays, and above this channel are neutron components from the $^3$He(n,p)$^3$T reaction and recoil $^3$He events. The total counts of neutron components of the rem counter and Bonner ball were used to obtain the neutron ambient dose and neutron energy spectrum, respectively, after atmospheric pressure correction, which obeys an exponential attenuation as given in Eq.(1). The correction factor, μ, in Eq.(1) is obtained by the least mean square method as

$$y = A \exp(-\mu x) \quad (1)$$

where y is the measured total counts, x is the atmospheric pressure in hPa. The measured total counts, y, at any atmospheric pressure are extrapolated to the value, y', at 1013 hPa as

$$y' = y \exp[-\mu(1013 - x)]. \quad (2)$$

The μ values are tabulated in **Table 1**. The neutron flux-to-dose conversion factor of the rem counter is 18.5 cps/(μSv/h) [2]. The neutron energy spectrum was obtained by using the SAND-II code [4]. The response functions of the Bonner ball with polyethylene moderator are calculated using the ANISN code [5] by Uwamino et al. [3] and that of the bare $^3$He counter without moderator, is calculated using the MCNPX code [6], which are shown is **Fig.5**. The initial guess spectrum, as shown in **Fig.6**, used in this study is obtained by Goldhagen et al.[7].

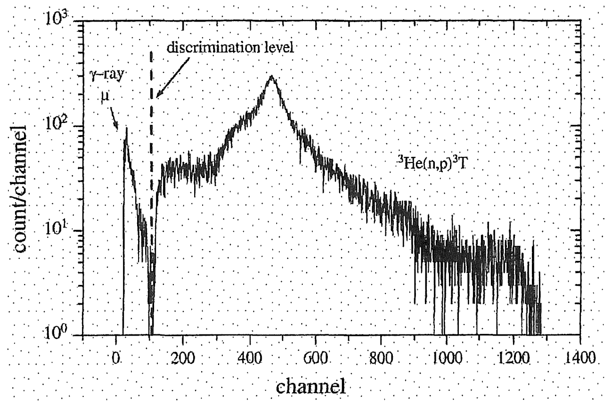


**Fig. 4** Pulse-height discrimination of rem-counter and Bonner ball

**Table 1** Atmospheric pressure correction factor, μ.

| | year | Rem counter x 10$^{-4}$ | Bonner ball x 10$^{-4}$ | | | | |
|---|---|---|---|---|---|---|---|
| diam. | | 29.6 | 23 | 15 | 11 | 8.1 | 5.1 |
| μ | [1]2001 | 45 | 30 | 55 | 46 | 45 | 48 |
| | [2]2002 | 47 | 46 | 46 | 43 | 47 | 67 |

[1] 10 June to 31 December in 2001
[2] 1 January to 31 March in 2003

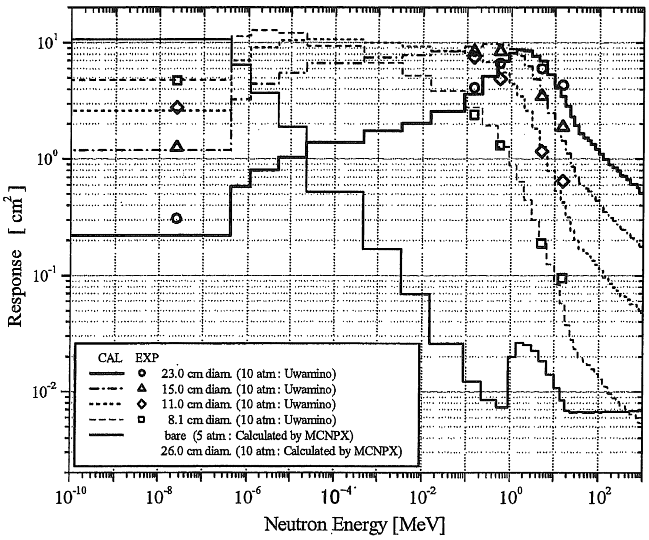


**Fig. 5** Response functions of $^3$He-loaded multi-moderator detectors calculated with the ANISN code [5] by Uwamino et al. [3] and the MCNPX code [6]

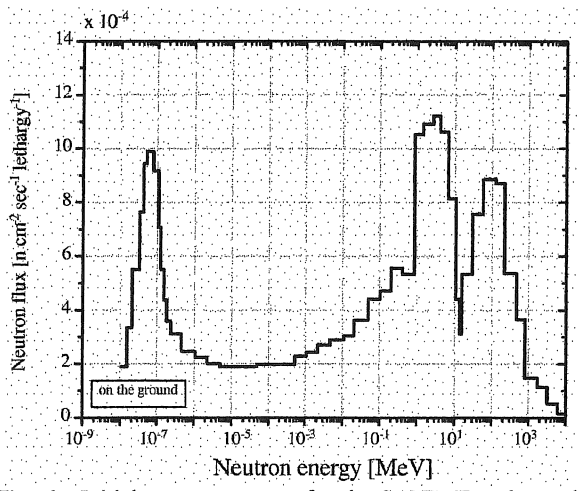


**Fig. 6** Initial guess spectrum for the SAND-II code used in this study obtained by Goldhagen et al.[7].

## IV. Results and discussions

### 1. Neutron ambient dose equivalent

**Fig. 7** shows the variation of neutron ambient dose equivalent rate obtained by the rem counter. The dose rate keeps almost constant of about 4.1 nSv/h with a variation of about 5% over the entire time period of April, 2001 to March 2003, although there are some remarkable variations at A and B points. At the A point, the neutron ambient dose equivalent rate was steeply decreased about 10% and this phenomenon was kept in a few days. In these days, it was snowing in Kawauchi campus and about 20-cm-thick snow was piled up on the hutch. Neutrons were attenuated with the hydrogen in the snow to decrease the neutron dose rate. The total counts of the Bonner ball, on the other hand, without polyethylene moderator, i.e. bare, increased about 20%. At the B points, large solar flares were observed by the ACE satellite [8)] and the neutron dose rates decreased in about 30%. This phenomenon is called as the Forbush decrease.

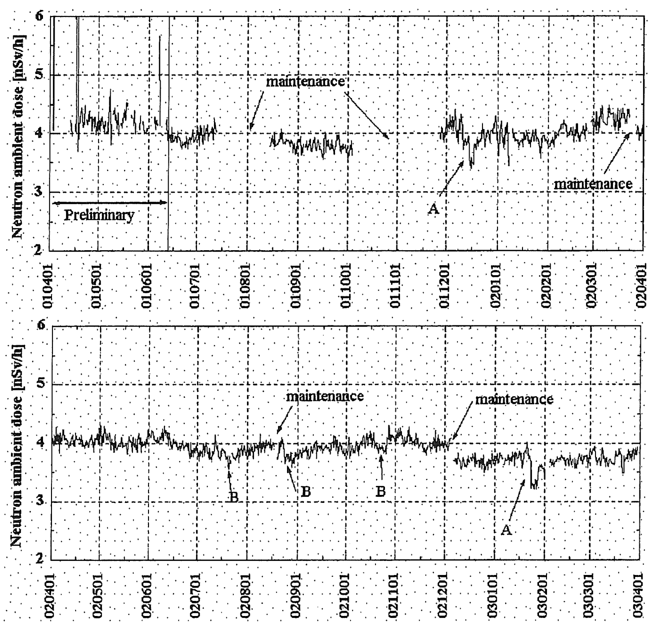


**Fig.7** Neutron ambient dose equivalent measured by the rem counter from April 2001 to March 2003.

### 2. Neutron energy spectra

The neutron energy spectra on the three different days, May 12, July 12, September 6 in 2002, obtained by the Bonner ball are shown in **Fig.8**. Three components can be seen in **Fig.8**, the first highest peak is a cascade peak component, which appears above 10 MeV, and this component fluctuates from day to day in about 30%. The second middle peak is an evaporation peak component, which appears around a few MeV. The third lowest peak is a thermal neutron peak component, which appears below about 1eV. The peak values of second and third components keep almost constant values of about 7.5 x $10^{-4}$ [n $cm^{-2}$ $sec^{-1}$ $lethargy^{-1}$] and about 1.8 x $10^{-4}$[n $cm^{-2}$ $sec^{-1}$ $lethargy^{-1}$], respectively.

The neutron ambient dose equivalent rate estimated from the flux-to-dose conversion factor, H*(10), of ICRP74 is about 6.5 nSv/h and this value is about 60% larger than 4.1 nSv/h given by the rem counter. This big difference mainly comes from the fact that the rem counter has a low sensitivity to neutrons above 20 MeV, which is largely deviated from the flux-to-ambient dose equivalent conversion factor, while on the other hand, the Bonner Ball can give the neutron spectra up to 1 GeV by using the initial guess spectrum extending to 1 GeV shown in **Fig. 6**, although the response function decrease for high-energy neutrons. The neutron dose obtained by the rem counter, therefore, gives a large underestimation to that by the Bonner ball. The neutron dose obtained by the rem counter, therefore, underestimate that of Bonner ball.

The total neutron flux and neutron flux above 20 MeV obtained by Bonner ball are about 7.5 x $10^{-3}$ [n $cm^{-2}$ $sec^{-1}$] and about 2.1 x $10^{-3}$ [n $cm^{-2}$ $sec^{-1}$], respectively.

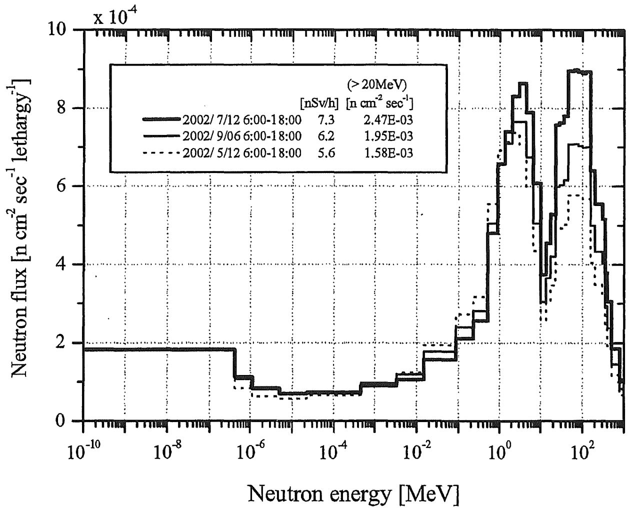


**Fig. 8** Comparison of neutron energy spectra on three different days obtained by the Bonner ball with the SAND-II unfolding.

## V. Conclusion

The neutron ambient dose equivalent rate and the neutron energy spectra were obtained on the ground level with an atmospheric pressure correction. The neutron ambient dose equivalent rate measured by the rem counter and Bonner ball keeps an almost constant values of 4.1 nSv/h and 6.5 nSv/h, respectively, after the atmospheric pressure correction, and it often decreased about 30% after a large Solar Flare, that is called as the Forbush decrease. The total neutron flux and neutron flux above 20 MeV were also obtained by the Bonner ball measurements to be 7.5 x $10^{-3}$ [n $cm^{-2}$ $sec^{-1}$] and 2.1 [n $cm^{-2}$ $sec^{-1}$], respectively.

## Acknowledgement

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