Dosimetry of cosmic radiation in the troposphere based on the measurements at the summit of Mt. Fuji

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Summary. Dose rate of cosmic-ray origin neutrons (abbreviated to “cosmic neutrons”) at aviation altitude was estimated based on the measurements at Mt. Fuji. Cosmic neutrons were measured in a facility of the Mt. Fuji Weather Station located at the summit of Mt. Fuji, the highest mountain in Japan (3776 m in altitude), in the summer of 2008 and 2009. The average of 1 cm ambient dose equivalent $H^*(10)$ for two measurements was verified by numerical model simulation and then used to empirically estimate the solar force field potential (FFP). The $H^*(10)$ rates at aviation altitude estimated from the measurements at Mt. Fuji were compared to those obtained in in-flight measurements onboard a civilian aircraft flying near Mt. Fuji at the time between the two measurements at the mountain. According to the results obtained, we expect that the empirical estimation based on the measurements at Mt. Fuji will work effectively for dosimetry of cosmic radiation in troposphere.

1. Introduction

Earth is constantly bombarded by high-energy cosmic-ray particles. These particles hit atmospheric nuclei and produce numerous secondary radiation in troposphere. Such cosmic-ray origin radiation (abbreviated hereafter to “cosmic radiation”) in the troposphere is in great concern of airlines, since aircraft crew are exposed to the enhanced level of cosmic radiation at aviation altitude. Their exposure is considered to be a part of occupational exposure [1] for which some protective action is recommended. In Japan, succeeding European countries and Canada, the government issued a guideline in 2006 to manage radiation exposure of aircraft crew onboard international flights. The guideline has stated that cosmic radiation doses of aircraft crew should be assessed by numerical model simulation and the accuracy of calculation should be verified by measurements. We thus try to construct a practical and reliable method to determine cosmic radiation dose rates in troposphere (~ 13 km) based on measurements at the highest mountain, that is, the thinnest atmosphere place in Japan.

2. Materials and methods

2.1 Detector

Employed herein is an extended-energy neutron rem meter (WENDI-II, Ludlum Measurements Inc., Texas, USA; now available Thermo Fisher Scientific Inc., MA, USA) coupled with an exclusive data logger (Model 2350-1, Ludlum Measurements Inc.). A photo of the instruments is shown in Fig. 1. The physical and dosimetric properties including the responses to monoenergetic and quasi-monoenergetic neutrons are well introduced by Ohsher *et al.* [2, 3].

The WENDI-II measures 1 cm ambient dose equivalent $H^*(10)$ of neutrons by multiplying a constant conversion coefficient to the pulse counts generated from $^3\text{He}(n, p)^3\text{H}$ reactions with moderated thermal neutrons. The coefficient was determined in advance using a traceable standard $^{241}\text{Am-Be}$ source at a secondary radiation standard facility (Institute of Radiation Measurements, Ibaraki, Japan). Although the principle for neutron detection using ^3He gas is conventional, WENDI-II is modified to be sensitive to high-energy neutrons up to GeV by addition of a tungsten powder shell. The data logger records the pulse counts of the proportional counter, calculates $H^*(10)$ rates and displays those values on a LCD panel with flexible time intervals, while working also as a high-voltage power supply. The electro-

Fig. 1. A photo of the extended energy neutron rem meter WENDI-II connected to an exclusive data logger.

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magnetic interference of the instruments was checked at a standard test field (EMC Japan Corporation, Kanagawa, Japan) and confirmed low enough to be safe for use onboard a civilian aircraft.

2.2 Measurements

Cosmic-ray origin neutrons (abbreviated hereafter to “cosmic neutrons”) were measured at two places: in a building at the summit of Mt. Fuji, the highest mountain in Japan (altitude: 3776 m; location: N 35.36°, E 138.73°) and the second is onboard a civilian aircraft flying near Mt. Fuji.

The former experiments were carried out during the summer of 2008 and 2009 in a facility of the Mt. Fuji Weather Station located at the summit of Mt. Fuji (Fig. 2). Radiation instruments were transported using a bulldozer and placed in a room at the 2nd floor of the 1st building of the facility.

The latter in-flight measurement was performed onboard a civilian aircraft (Boeing 747 of Nippon Cargo Airlines) on

5 February 2009, just in the middle between the two measurements at Mt. Fuji. The aircraft flew from Tokyo/Narita airport (IATA code: NRT; location: N 35.8°, E 140.4°) to Osaka/Kansai airport (KIX; N 34.4°, E 135.2°), passing near Mt. Fuji as shown in Fig. 3. Cosmic neutrons were measured with the same instruments on a passenger seat just behind the cockpit.

The measured data were compared to numerically predicted values with the PHITS-based Analytical Radiation Model in the Atmosphere (PARMA) [4] which was developed through comprehensive analysis of the calculation results obtained with the Monte Carlo simulation code PHITS. In calculation, it was assumed that the overall shielding effects of the facility building is equivalent to air thickness of 20 g cm⁻². The geomagnetic cutoff rigidities (r_c) of the Earth were calculated with the newest version (available up to 2010) of MAGNETOCOSMICS code [5] which was developed in the University of Bern, and a data set of r_c values with 1-degree resolution was incorporated. The accuracy of the model was partly checked in previous measurements onboard a chartered jet aircraft [6].

Fig. 2. A photo of Mt. Fuji and the Mt. Fuji Weather Station (left above); cosmic neutrons were measured at the 2nd floor in a facility building in the summer of 2008 and 2009.

Fig. 3. The route of the flight on 5 February 2009 from Tokyo/Narita to Osaka/Kansai. The location of Mt. Fuji is indicated.

3. Results and discussion

The time-lapse changes of neutron $H^*(10)$ rates measured at the summit of Mt. Fuji during the summer of 2008 and that of 2009 are plotted in Fig. 4. The average dose rates of cosmic neutrons were nearly the same for the two measurements, which indicates that solar magnetic condition had been relatively stable for the period of the experiments. Although we observed some fluctuations (about 8% as C.V.) partly due to air pressure changes, the measured data agreed well to the results of numerical model simulation using the PARMA code.

Intensity of cosmic radiation in troposphere is affected by solar magnetic condition which can be evaluated as the

Fig. 4. Time plots of the $H^*(10)$ rates measured with WENDI-II at the summit of Mt. Fuji during the summer of 2008 (above) and 2009 (below).

Fig. 5. Relationship between predicted values of solar force field potential (FFP) and $H^*(10)$ values of cosmic neutrons at the summit of Mt. Fuji. The shielding effect of the facility building is considered in calculation of $H^*(10)$.

force field potential (FFP). The FFP values are generally determined in an empirical way from neutron monitor data on the ground at high latitude or high mountain.

We therefore tried to predict the radiation exposure at aviation altitude by evaluating the force field potential (FFP) based on the measurements at Mt. Fuji. The predicted relationship between FFP and neutron $H^*(10)$ rate at the summit of Mt. Fuji is shown in Fig. 5. The detail of FFP determination process employed here is well introduced by Sato *et al.* [4]. Since FFP and $H^*(10)$ are in a one-to-one ratio as seen in the figure, it is expected that FFP can be determined from the measurements at Mt. Fuji in a simple, empirical way. For practical use, three order regression function is indicated in Fig. 5.

Precision of this method at aviation altitude was examined onboard a commercial jet aircraft flying from Tokyo to Osaka on 5 February 2009, just in the middle of the two measurements at Mt. Fuji (August 2008 and August 2009). The FFP value was evaluated using the empirical equation

Fig. 6. Plots of the $H^*(10)$ rates measured with WENDI-II in a civilian aircraft from Tokyo/Narita to Osaka/Kansai on 5 February 2009, compared to the estimated values based on the measurements at the summit of Mt. Fuji.

(Fig. 5) from the observed $H^*(10)$ rates of cosmic neutrons over the summer seasons. The average value of measured $H^*(10)$ and numerically predicted one are shown in Table 1. Both values agreed very well.

The $H^*(10)$ rates measured with the same instruments at 10.4 km in altitude were nearly 10 times higher than those at the summit of Mt. Fuji (Fig. 6). This level is reasonable as seen in the result of numerical model simulation as shown in Table 1. As to the result obtained with the proposed empirical method based on the measurements at Mt. Fuji, we found about 12% underestimation from the predicted value regarding the $H^*(10)$ rate of cosmic neutrons. Although the range of this error is acceptable for radiological protection purpose, it is desirable to make clear how large deviation could appear in other flight conditions. We also hope to establish a radiation monitoring system which can work continuously throughout the year at the summit of Mt. Fuji for more reliable dosimetry.

Table 1. The 1 cm ambient dose equivalent $H^*(10)$ rate measured with an extended energy neutron monitor WENDI-II at the summit of Mt. Fuji and that in an aircraft flying from Tokyo/Narita to Osaka/Kansai in comparison with numerical model simulations and empirical estimation based on the measurements at Mt. Fuji.

Average $H^*(10)$ rate at the summit of Mt. Fuji (3.78 km) measured for the summer of 2008 and 2009 ($\mu\text{Sv h}^{-1}$)		Average $H^*(10)$ rate at the cruising altitude (10.4 km) of a flight from Tokyo/Narita to Osaka/Kansai on 5 February 2009 ($\mu\text{Sv h}^{-1}$)		
Measured with WENDI-II	Numerically predicted ^a	Measured with WENDI-II	Numerically predicted ^a	Empirically estimated ^b
0.098 ± 0.008	0.099	1.088 ± 0.120	1.018	0.967 ± 0.079

a: Predicted using an analytical model based on the PHITS Monte-Carlo code [4]; in this model, the FFP values have been derived from selected neutron monitors located at high latitude;

b: Calculated using the FFP value determined from the measurements at the summit of Mt. Fuji.

In conclusion, the method proposed here for the evaluation of solar modulation intensity based on the measurements at Mt. Fuji is expected to work effectively so far. This method will improve the reliability of dosimetry of cosmic radiation exposure in troposphere, particularly onboard aircraft flying near Japan. The validity of this method, however, is to be further investigated for other flight conditions at low geomagnetic cutoff rigidity and in solar maximum. We will continue such efforts to expand the applicability of this method.

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References

1. International Commission on Radiological Protection (ICRP): The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publ. **103**, Ann. ICRP 37(2–4) (2007).
2. Olsher, R. H., Hsu, H.-H., Beverding, A., Kleck, J. H., Casson, W. H., Vasilik, D. G., Devine, R. T.: WENDI – an improved neutron rem meter. *Health Phys.* **79**, 170–181 (2000).
3. Olsher, R. H., McLean, T. D.: High-energy response of the PRESCILA and WENDI-II neutron rem meters. *Radiat. Prot. Dosim.* **130**, 510–513 (2008).
4. Sato, T., Yasuda, H., Niita, K., Endo, A., Sihver, L.: Development of PARMA: PHITS based analytical radiation model in the atmosphere. *Radiat. Res.* **170**, 244–259 (2008).
5. Desorgher, L.: MAGNETOCOSMICS – Geant 4 Application for Simulating the Propagation of Cosmic Rays Through the Earth's Magnetosphere. University of Bern (2006), <http://cosray.unibe.ch/laurent/magnetocosmics/>, accessed on October 2009.
6. Yasuda, H., Yajima, K., Sato, T., Takada, M., Nakamura, T.: Responses of selected neutron monitors to cosmic radiation at aviation altitude. *Health Phys.* **96**, 655–660 (2009).