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Space radiation dosimetry to evaluate the effect of polyethylene shielding in the Russian segment of the International Space Station

Aiko Nagamatsu[a],*, Marco Casolino[b,c], Oscar Larsson[c], Tsuyoshi Ito[a], Nakahiro Yasuda[a,d], Keiichi Kitajo[e], Ken Shimada[e], Kazuo Takeda[f], Shuichi Tsuda[g] and Tatsuhiko Sato[g]

[a] Japan Aerospace Exploration Agency (JAXA), Tsukuba Space Center, 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan
[b] The National Institute of Nuclear Physics (INFN) Roma2 & University of Roma Tor Vergata, Dept. Of Physics, Via della Ricerca Scientifica 1, 00133 Rome, Italy
[c] RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan,
[d] Fukui University Research Institute of Nuclear Engineering (RINE), 1-2-4 Kanawa-cho, Tsuruga, Fukui, 914-0055, Japan, [e] Advanced Engineering Services (AES), Co. Ltd., 1-6-1 Takezono, Tsukuba, Ibaraki 305-0032, Japan,
[f] Research Organization for Information Science and Technology (RIST), 4-49 Muramatsu, Tokai-mura, Naka-gun, Ibaraki 319-1184, Japan
[g] Japan Atomic Energy Agency (JAEA), 2-4 Shirakata-Shirane, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan

Abstract

As a part of the Alteino Long Term Cosmic Ray measurements on board the International Space Station (ALTCRISS) project, the shielding effect of polyethylene (PE) were evaluated in the Russian segment of the ISS, using active and passive dosimeter systems covered with or without PE shielding. For the passive dosimeter system, PADLES (Passive Dosimeter for Life-Science and Experiments in Space) was used in the project, which consists of a Thermo-Luminescent Dosimeters (TLD) and CR-39 Plastic Nuclear Track Detectors (PNTDs) attached to a radiator. Not only CR-39 PNTD itself but also a tissue equivalent material, NAN-JAERI, were employed as the radiator in order to investigate whether CR-39 PNTD can be used as a surrogate of tissue equivalent material in space dosimetry or not. The agreements between the doses measured by PADLES with CR-39 PNTD and NAN-JAERI radiators were quite satisfactorily, indicating the tissue-equivalent dose can be measured by conventional PADLES even though CR-39 PNTD is not perfect tissue-equivalent material. It was found that the shielding effect of PE varies with location inside the spacecraft: it became less significant with an increase of the mean thickness of the wall. This tendency was also verified by Monte Carlo simulation using the PHITS code. Throughout the flight experiments, in a series of four phases in the ALTCRISS project from December 2005 to October 2007, we assessed the ability of PE to decrease radiation doses in Low Earth Orbit(LEO).

 * Corresponding author. Aiko Nagamatsu, Tel.: +81-50-3362-2040; fax: +81-298-68-3954.
 E-mail address: nagamatsu.aiko@jaxa.jp

1. Introduction

Important ionizing radiation sources in International Space Station (ISS) orbits (altitude: 300 to 400 km; orbital inclination: 51.6°) are galactic cosmic rays (GCRs), electrons and protons trapped in the Earth's magnetic field, and solar particle events (SPEs). Primary GCRs comprise protons and heavier charged particles with energy spectra forming a broad peak around 1 GeV/n (Benton, 2001). Fluxes of less than about 10 GeV/n are inversely related to solar activity (Badhwar, 1997). The GCR fluxes heavily depend on ISS altitude, but they are difficult to shield against using a realistic shielding mass for the ISS structure (down to several tenths of grams per square centimeter) because of the high energy. In addition, primary GCRs produce many secondary particles through projectile and target fragmentation in the ISS shielding materials and in the astronauts' bodies.

Trapped protons (TPs) play an important role in increasing or decreasing an astronaut's radiation exposure in LEO. Energies of TPs are generally lower than those of GCRs, and their maximum energy is approximately several hundred megaelectron volts. The fluxes of primary TPs increase substantially as ISS altitude increases (Badhwar, 1997; Spuuny, 2001; Benton et al., 2001; Nagamatsu et al., 2015). Although the fluxes of primary TPs could be effectively reduced by thin shielding (a few g/cm^2), secondary particles produced by nuclear reactions increase in number as shielding mass increases and become dominant in fluxes under thick shielding conditions (Kolıskova et al., 2012).

Current career limits on radiation dose for crew members aboard the ISS are standardized by reference to estimated equivalent doses, based on the actual doses obtained from crew personal dosimeters (NCRP, 2000; NCRP, 2002). Each ISS partner has determined their own career dose limits (short-term or lifetime for each organ, age, and gender) for their crew members following ICRP advice and some specific recommendations of each country (McKenna-Lawlora et al., 2014). Expedition duration for each astronaut is strongly restricted by these career dose limits. For example, lifetime dose limits for first flights at ages of 46 and over are 1000 mSv for male Japanese astronauts and 800 mSv for female Japanese astronauts.

Space crews for interplanetary missions are expected to receive much higher doses than those in LEO. In addition, the duration of interplanetary cruising to Mars is longer (~500 days) than ISS expeditions (~1 year). From radiation dosimetric results for Mars (Zeitlin et al., 2013), equivalent doses of 1100 to 1533 mSv are estimated for a 2-year-mission. These doses already exceed the current ISS lifetime dose limit. Therefore, dose-reduction technology is a requirement for interplanetary missions.

In the ISS module structure itself, there are no positive shielding and countermeasures. However, inside the crew quarters of the Russian 'Zvezda Service Module' and the U.S. segment of the ISS, some shielding experiments have been conducted. These have used various shapes and masses of PE as part of TeSS PE "Radiation Bricks" (Broyan et al., 2008), Kevlar (Fino et al., 2014) and water towels (Ploc et al., 2013; Kodaira et al., 2014; Durante et al., 2015). The shielding effects of various materials used in virtual spacecraft and moon bases have been simulated using many different simulation codes (Wilson et al., 1997, 2001; Cucinotta et al., 2006, 2013; Singleterry, 2013; Emmanuel et al., 2014). Since shielding effects increase with decreasing atomic number for most of the particles in the GCR spectrum (Guetersloh, 2006), hydrogen-rich material PE has been applied experimentally to ISS crew sleeping quarters and in some ground performance tests (Ambrozová, 2014).

The ALTCRISS (Alteino Long Term Monitoring of Cosmic Rays on the International Space Station) project is a long-term survey of the radiation and cosmic ray environment on board the ISS. Five aims have been set for this project: 1) monitoring of long- and short-term solar modulation of cosmic rays; 2) observations of solar particle events; 3) survey of doses at different locations in the ISS modules; 4) study of the effectiveness of shielding materials; and 5) comparisons with other detectors. During the later phase (2005–2007) of this project, several types of passive dosimeters based on TLDs and CR-39 PNTDs supplied by JAXA, DLR, and Napoli Federico II University were launched to evaluate the radiation shielding effect of PE pads and to compare the LET spectra from the Sileye-3/Alteino detector and passive dosimeters. Detailed descriptions of these missions together with the configurations and performances of the main cosmic-ray detector (Sileye-3/Alteino) have been given elsewhere (Casolino et al., 2007; Larsson et al., 2015). This paper describes the results obtained from the JAXA passive dosimeters placed in the ISS Russian segment (PIRS and Zvezda), and focuses on the analysis of the shielding effects of PE. To support the experimental results, Monte Carlo simulations were performed using PHITS (Particle

and Heavy Ion Transport Code System; Sato et al., 2013) version 2.64, and the results of these simulations are also presented in this paper.

2. The shielding effect of PE pads inside the ISS Russian segment

PADLES (PAssive Dosimeters for Lifescience Experiments in Space) is a passive dosimeter package developed by JAXA. Each package consists of three CR-39 PNTD plates (HARTZLAS TD-1 PNTD: Fukuvi Chemical Industry, 0.9 mm thick) and seven TLDs (TLD-MSO-S: Kasei Optonics, LTD., 12 mm × 2 mm ∅) (Doke et al., 1995; Nagamatsu et al., 2013). The outer dimensions of the package are 2.5 × 2.5 × 0.6 cm. Figure 1 shows a photo (a) and the configuration (b) of PADLES.

The PADLES packages included CR-39 PNTD reference plates pre-exposed to heavy ions (390 MeV/n ^{12}C and 427 MeV/n ^{56}Fe) in order to check the sensitivity stability of the CR-39 PNTDs during the experiment. A second radiator, composed of tissue-equivalent material NAN-JAERI (Tsuda et al., 2005), was enclosed in each package to measure personal exposed doses. The reason for attaching two types of radiators will be given in the next section.

PADLES provides the absorbed dose in the lower LET region (LET $\leq$10 keV/μm) from the TLDs and, in the higher LET region (LET >10 keV/μm), the LET spectrum from the CR-39 PNTDs. The sets of TLD elements selected for each experiment ensured a response deviation of less than 5.7% for 160 MeV/n protons. Using the information from PADLES, we can determine the total absorbed dose (D_{TOTAL}), the total dose equivalent (H_{TOTAL}), and the mean quality factor (Q_{MEAN}).

Four sets of PADLES were used in each experimental phase; one set was kept at the ground as the "ground control," and the others were put into thin storage bags and attached to the wall of the ISS Russian segment (PIRS and Zvezda). Two sets of PADLES (PADLES #1 and #2) in the ISS were installed into PE tiles with a thickness of approximately 5 g/cm^2, while the other (PADLES #3) was left unshielded as the "space control," as shown in Figure 2. Data from both shielded and unshielded PADLES were corrected by taking the difference from the ground control data. Detector location was frequently changed, as shown in Figure 3 and Table 1. The average altitude of the ISS during the experimental span was approximately 350 km.

Table 2 shows the absorbed doses and the dose equivalents for all the experimental phases (total absorbed dose (D_{Total}), dose absorbed by TLD (D_{TLD} $\leq$10 keV/μm), dose absorbed by CR-39 PNTD D_{CR-39} >10 keV/μm, and dose equivalent (H_{CR-39} >10 keV/μm)). For each experimental phase, #1 and #2 are the shielded PADLES, and #3 is the unshielded one. Here, the shielding effect is defined as

$$\text{Shielding effect} = \frac{D(\#3) - \frac{D(\#1) + D(\#2)}{2}}{D(\#3)},$$

where D(#n) is the absorbed dose from PADLES #n. Certain differences in the shielding effect of doses were observed throughout experimental phases 1–4. The shielding effect due to PE was within 0.6–7.8% for D_{TLD} $\leq$10 keV/μm, 9.5–24.4% for D_{CR-39} >10 keV/μm, and 0.1–19.6% for H_{CR-39} >10 keV/μm. The shielding effect of space radiation for D_{Total} and total dose equivalent (H_{Total}) in phases 1–4 is shown in Figure 4.
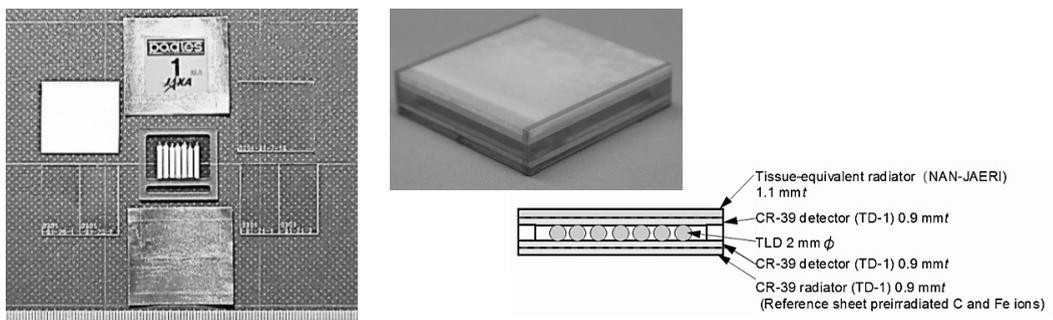

Fig. 1 Photograph and cross-sectional view of PADLES for the ALTCRISS project. The length, width, and thickness are 2.5, 2.5, and 0.6 cm, respectively.
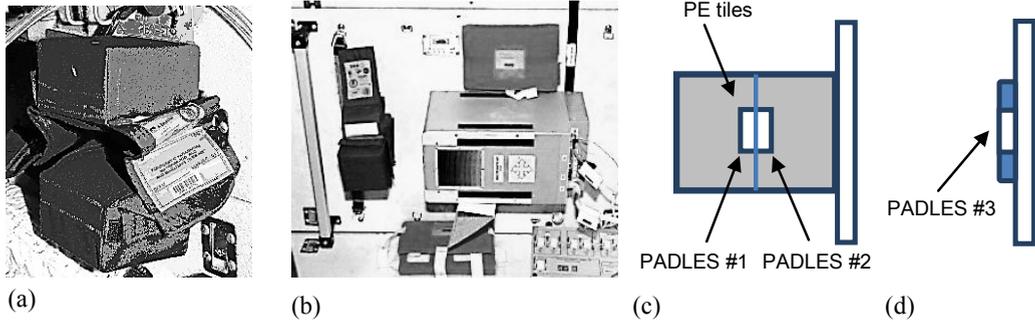
Fig. 2 Flight condition of three sets of PADLES insulation in the ISS Russian segment. (a) PE pads (thickness of $5g/cm^2$ per pad); (b)Example installation condition in Phase 1 experiment; (c) Cross-sectional view of PADLES #1 and #2 placed between two PE pads ($11 \times 11 \times 9$ cm per pad); (d) Cross-sectional view of unshielded (without PE pads) PADLES #3 forming a "space control," which was placed in a thin storage bag attached to the surface of the wall.
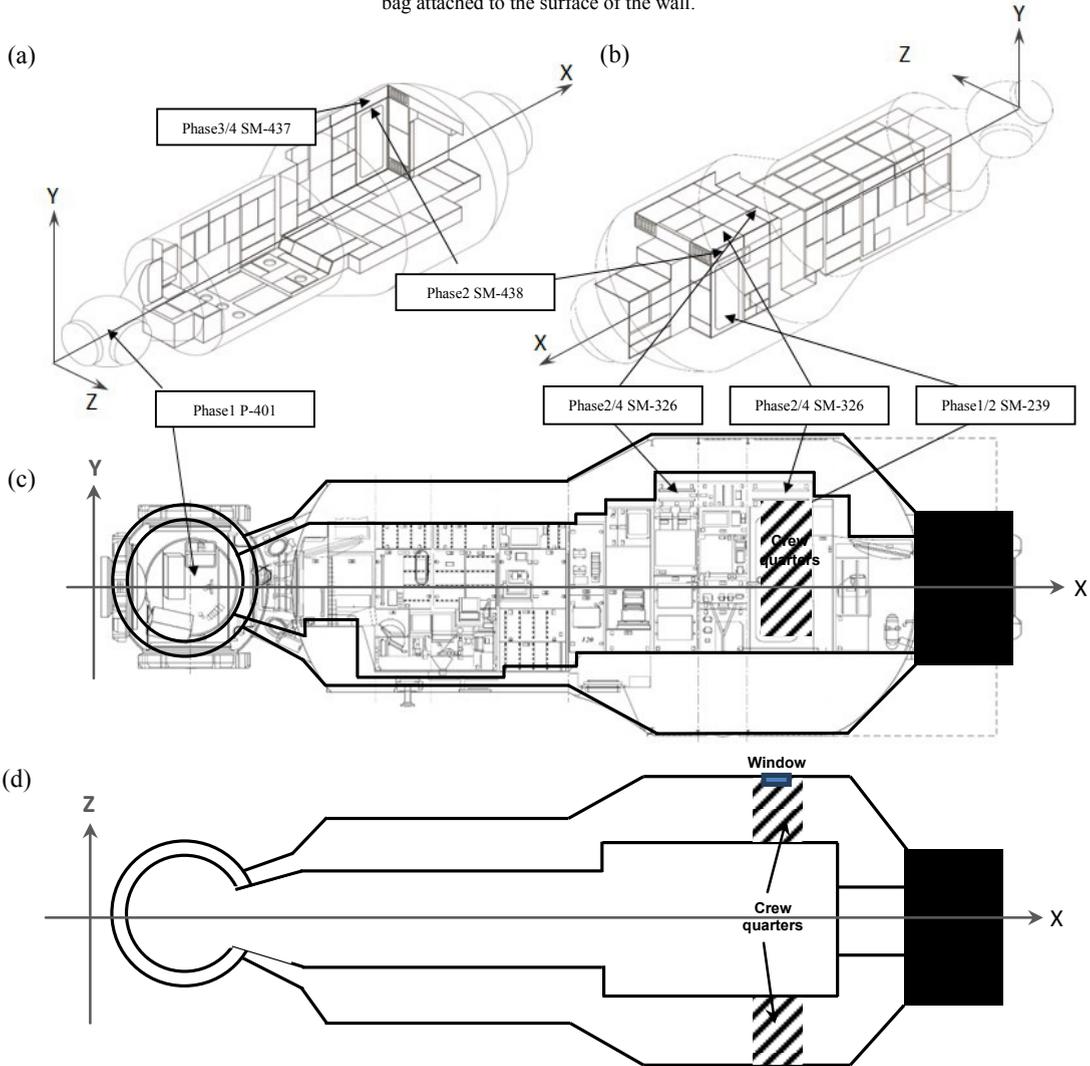

Fig. 3 Flight condition of PADLES insulation in the Russian segment. Projective figures (a) from starboard deck and (b) from port overhead; (c) Cross-sectional view of the XY-plane of the Russian segment. (d) Cross-sectional view of the XZ-plane of the Russian segment.

Table 1.Timeline and location of phase 1–4 experiments as part of the ALTCRISS project

Experiment	Launch and return vehicle (mission)[*1]	Date	Total flight time[days][*2]	PADLES location[*3] (Panel No.)	Duration [days]
Phase 1[*4]	Launch / 20P Progress (M-55) Return / 11S Soyuz (TMA-7)	22 Dec., 2005 6 Apr., 2006	107	PIRS (P-401)	30
				Zvezda crew cabin (SM-239)	67
				Zvezda (SM-333)	5
Phase 2[*4]	Launch / 21P Progress (M-56) Return / 12S Soyuz (TMA-8)	24 Apr., 2006 29 Sep., 2006	158	Zvezda (SM-333 and 438)	144
				Zvezda crew cabin (SM-239)	7
Phase 3[*4]	Launch / 13S Soyuz (TMA-9) Return / 13S Soyuz (TMA-9)	18 Sep., 2006 21 Apr., 2007	215	Zvezda (SM-333)	52
				Zvezda crew cabin (SM-437)	163
Phase 4[*4]	Launch / 25P Progress (M-60) Return / 14S Soyuz (TMA-10)	12 May, 2007 21 Oct., 2007	162	Zvezda crew cabin (SM-437)	9
				Zvezda (SM-326)	153

[*1] Phase 1 docking occurred at an altitude at 350 km, Phase 2 at 344 km, Phase 3 at 342 km, and Phase 4 at 335 km.
[*2] Total flight time includes the storage duration before and after the experiment.
[*3] This is the location for a set of PADLES including PE-shielded packages and an unshielded package in a thin storage bag on the surface of the wall.
[*4] ISS orbital inclination was 51.6°.

Table 2.Results from PADLES for phase 1–4 experiments. Indicated errors are one standard deviation.

Experiment	Shielding condition	D_{TLD} rate (mGy/day)			D_{CR-39} rate > 10 keV/μm (mGy/day)			H_{CR-39} rate > 10 keV/μm (mSv/day)			D_{TOTAL} rate (mGy/day)			H_{TOTAL} rate (mSv/day)		
Phase 1	Shielded[1]	0.223	±	0.018	0.0415	±	0.0035	0.370	±	0.040	0.265	±	0.018	0.594	±	0.044
	Unshielded[2]	0.225	±	0.018	0.0549	±	0.0045	0.461	±	0.050	0.279	±	0.017	0.686	±	0.053
Phase 2	Shielded[1]	0.169	±	0.013	0.0331	±	0.0026	0.374	±	0.034	0.202	±	0.012	0.543	±	0.036
	Unshielded[2]	0.179	±	0.008	0.0367	±	0.0031	0.461	±	0.041	0.216	±	0.007	0.640	±	0.042
Phase 3	Shielded[1]	0.206	±	0.027	0.0218	±	0.0022	0.259	±	0.030	0.228	±	0.026	0.465	±	0.043
	Unshielded[2]	0.223	±	0.011	0.0249	±	0.0027	0.298	±	0.034	0.248	±	0.010	0.521	±	0.036
Phase 4	Shielded[1]	0.175	±	0.008	0.0181	±	0.0019	0.190	±	0.023	0.193	±	0.008	0.365	±	0.025
	Unshielded[2]	0.187	±	0.003	0.0165	±	0.0017	0.190	±	0.025	0.203	±	0.002	0.377	±	0.025

[*1] Shielded doses are averaged doses obtained from PADLES #1 and #2, as described in Section 2.
[*2] Shielded doses were obtained from PADLES #3, as described in Section 2.
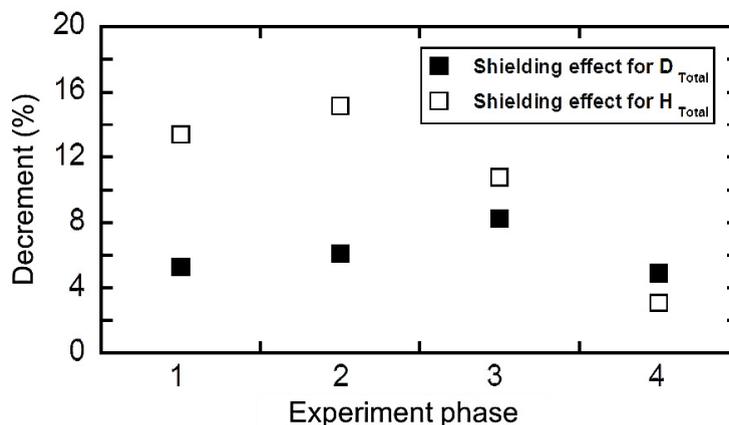
Fig. 4 Shielding effect for doses D$_{total}$, and H$_{total}$ obtained from phase 1–4 experiments.

The results using the PADLES in phase 1-4 experiments as part of the ALTCRISS project were obtained on the surface of thick inside walls in the ISS Russian segment. When we added the PE shielding in this environment, absorbed doses ≤ 10 keV/μm showed a slight change. The shielding effect of 5 g/cm^2 PE was estimated to be 6.1%

for total absorbed doses and 10.6% for total dose equivalents over the four experiments. A detailed discussion based on Monte Carlo simulation will be given in Section 4.

Since the ALTCRISS project aims to measure the radiation environment with active in many different locations, the set of the shielded/unshielded PADLES dosimeters was relocated when the active detector was moved. This relocation changed the shielding condition. A clearer shielding effect can be obtained by conducting fixed location measurements because the shielding effect depends on the measurement position, surrounding shielding condition, orientation, and so on.

3. Evaluation of tissue-equivalent doses obtained from PADLES

In the ALTCRISS experiments, dose reduction for an astronaut must be evaluated. Therefore, prior to analyzing the shielding effect from PE, we examined the dosimetry to determine whether the CR-39 PNTD/TLD combination in PADLES could measure tissue-equivalent doses, including of neutrons produced by interaction with the bodies of the crew. For this purpose, we employed two types of radiators, CR-39 PNTD and NAN-JAERI (see Fig. 1), and compared the results obtained from the two radiators. The elemental compositions of a soft-tissue substitute (NAN-JAERI) is shown in Table 3 as atomic weight ratios, together with the corresponding data for CR-39 PNTDs and the soft tissue used for a typical CT phantom in ICRU Report 44 (1989). NAN-JAERI has tissue-equivalent characteristics optimized for neutron personal dosimetry, and the absorbed dose distributions in NAN-JAERI agree to within 10% with those in soft tissue in the energy range from 1 to 100 MeV (Tsuda et al., 2004).

Figure 5 shows the LET distributions using radiator CR-39 PNTDs and NAN-JAERI averaged over all phase 1–4 experiments. No significant difference between the radiators was observed: the differences are well within errors over the whole LET region. The slight differences that can be seen are probably attributable to the unfixed location of the measurements and the change in shielding condition between the ZVEZDA and PIRS module. From the data for doses ≤10 keV/μm and comparison of LET distributions, we conclude that tissue-equivalent doses obtained from PADLES adequately reproduce those aboard the ISS, even though CR-39 PNTD is not a perfect tissue-equivalent material. Thus, the results concerning PE shielding in Section 2 are relevant.

Table 3. Compositions of soft tissue, a soft tissue substitute (NAN-JAERI), and CR-39 PNTDs

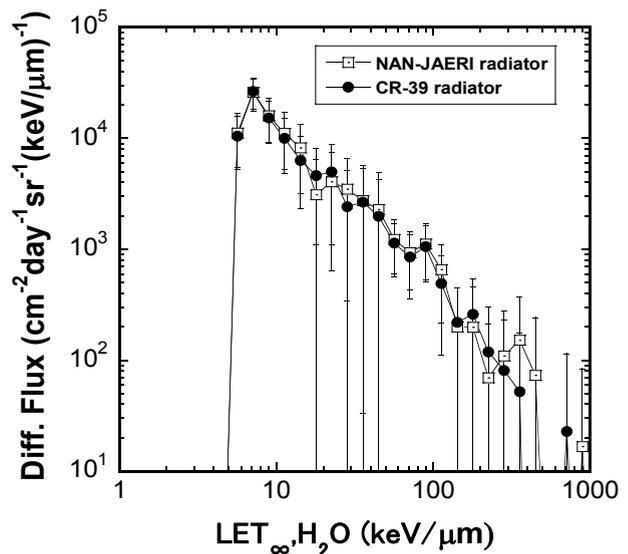| Material	Ion	Atom %
CR-39 PNTD	H	48.6
	C	32.4
	O	18.9
NAN-JAERI	H	60.9
	C	30.7
	N	0.8
	O	7.7
Soft tissue	H	63.2
	C	7.4
	N	1.5
	O	27.7
	other	0.2

Fig. 5 The LET distributions using radiator CR-39 PNTDs and NAN-JAERI averaged over all phase 1–4 experiments.

The tissue-equivalent characteristics of CR-39 PNTD for neutrons were investigated using PHITS because the selection of the radiator material is important in neutron dosimetry. The absorbed doses and the dose equivalents were calculated for CR-39 PNTDs using a 1.1 mm thick radiator made of the soft tissue, NAN-JAERI, and a CR-39

PNTD in the parallel beam irradiation geometry, as shown in Figure 6. The neutron fluence inside location in a spherical spacecraft with a wall thickness of 27 g/cm^2 was employed as the source spectrum, which was calculated by Monte Carlo simulation described in the next section.

Table 4 shows the calculated ratios between the doses in the soft tissue and those in NAN-JAERI or CR-39 PNTD. The statistical uncertainties of the absorbed dose calculation were less than 1%. The absorbed doses in NAN-JAERI agree closely with those in the soft tissue. The dose equivalent in CR-39 PNTD is in satisfactory agreement with that in the soft tissue, while the absorbed dose in CR-39 PNTD is 2.7% higher than that in the soft tissue, mainly due to the difference in the hydrogen compositions. These results indicate the tissue-equivalent characteristics of CR-39 PNTD for neutron dosimetry. If the actual incident direction of neutrons in space and the dose contribution of charged particles, such as protons, were considered, the material difference between the soft tissue and CR-39 PNTD would be less significant than was estimated in this simulation.
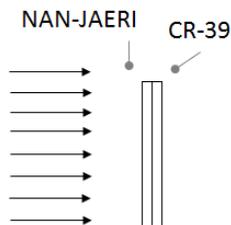

Fig. 6 Geometry of CR-39 PNTDs and NAN-JAERI for PHITS simulation

Table 4. The calculated ratios of doses in soft tissue to those in NAN-JAERI or CR-39 PNTD

Ratio of doses	Absorbed dose (mGy/day)	Dose equivalent (mSv/day)
Soft tissue / NAN-JAERI	0.996 ± 0.013	0.994 ± 0.016
Soft tissue / CR-39	1.027 ± 0.014	1.008 ± 0.016

4. PHITS simulation to verify the dependence of PE shielding on hull wall thickness

As described in Section 2, we conducted space radiation dosimetry for the ALTCRISS project to evaluate the shielding effect of PE pads in the Russian segment of the ISS. From measurements with PADLES dosimeters, we concluded that adding PE shielding inside the wall in the ISS Russian segment changed the total absorbed doses only slightly (an average change of 6.1% for total absorbed dose and 10.6% for dose equivalent).

In contrast, a similar shielding experiment in the ISS Russian segment in 2010 (Kodaira et al., 2014) concluded that water towels could drastically reduce doses, by up to 37% on the surface of the outside wall and window (see Fig. 3). Note that the shielding thicknesses of the PE (5 g/cm^2) in ALTCRSISS and the water towel (6.3 g/cm^2) in the past experiment are similar, but only one side of the detector was covered in the case of the water towel experiment.

In order to clarify the PE shielding mechanism, a detailed analysis based on Monte Carlo simulation was performed using PHITS. Figure 7 shows the simulation setup for the analysis. In the simulation, the Zvezda module was represented as a simple spherical shell made of aluminum. The inner radius of the shell was fixed at 220 cm, and the wall thickness was changed from 1 cm to 10 cm, which corresponds to a change of shielding thickness from 2.7 to 27 g/cm^2. Three PADLES were placed 10 cm away from the wall, and two of them were covered by 5 g/cm^2 PE blocks on one or both (two) sides of the detectors. Depending on the type (or lack) of PE covering, the detectors are called "bare PADLES," "one-sided PE covering PADLES," and "two-sided PE covering PADLES" hereinafter.

The shielding thickness averaged over 12 typical locations for area monitoring experiments with SPD boxes in the ISS Zvezda module was estimated to be approximately 40 g/cm^2 (private communication with IBMP-JAXA, 2008 and NIRS-R-62, 2009). This value is equal to the mean shielding thickness of the detector location in our simulation for a 23 g/cm^2 wall thickness. This is much thicker than the corresponding data for the water towel experiments, which is 1.5 g/cm^2 (Kodaira et al., 2014) on the surface of the window wall in the crew quarters (see Fig. 3 (d)).

In the PHITS simulation, the virtual spacecraft was irradiated by trapped protons and GCRs with charges up to +28 in the isotropic irradiation geometry. The procedure for determining the energy spectra of these incident particles is described elsewhere (Sato et al., 2011). The details of ISS altitudes over the ALTCRISS phase 1–4 experiments were taken into account in this source term calculation. Doses and dose equivalents in the three PADLES were deduced from the PHITS simulation. The neutron fluxes in the bare PADLES were also estimated in

order to utilize them in the PHITS simulation for investigating the radiator effects as described in the previous section.

Figure 8 shows the ratios of absorbed dose and dose equivalents in the PE covered PADLES relative to those in the bare PADLES as a function of wall thickness. The statistical uncertainties are roughly 20%. As can be seen from Figure 8, the additional PE shielding dramatically reduces the doses and dose equivalents for thin walls, whereas the shielding effect becomes less significant with an increase of wall thickness. The reduction of dose equivalents measured by the water towel experiment were $37 \pm 7\%$ for 1.5 g/cm^2 wall thicknesses, which agrees with the calculated data for the one-sided PE covering PADLES fairly well, even though the thicknesses of the water towel and the PE shielding were slightly different. However, the decrements due to two-sided PE shielding for 23 g/cm^2 wall thickness are approximately 21% and 29% for absorbed dose and dose equivalent, respectively; these are higher than those obtained from the ALTCRISS experiment. This discrepancy may be attributable to the difference between the shielding distributions at the locations of the bare and PE-covered PADLES in the experiments: the bare PADLES was directly attached to the wall, while the PE-covered PADLES were located away from the wall due to the PE shielding. This difference in position is important because the mean shielding distribution decreases by approximately 15% when a detector is placed 5 cm away from the wall rather than being directly attached.

Based on both actual measurement and PHITS simulation, we have shown that a remarkable shielding effect for space radiation in LEO can be found only under very limited conditions with thin shielding thickness. Basically, we have to pay attention not only to the shielding effect of the material but also location and wall thickness effects. In addition, any shielding materials are effective under thin shielding conditions of up to a wall thickness of a few tens g/cm^2 (Cucinotta et al., 2006, 2013).
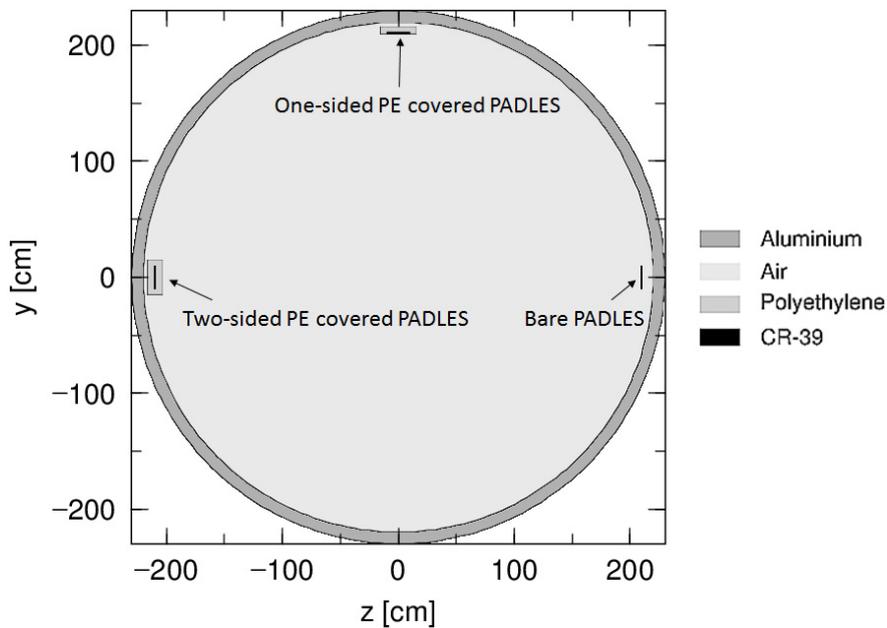

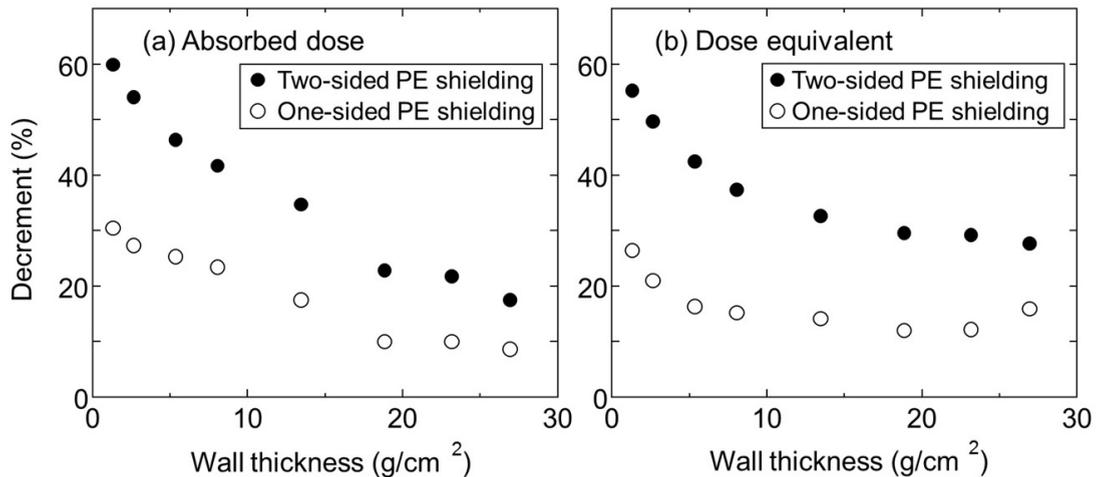Fig. 7 Geometry of the PHITS simulation for analyzing the shielding effect of PE

Fig. 8 Decrements of the absorbed dose (a) and dose equivalent (b) due to two-sided and one-sided PE shielding estimated from the PHITS simulation

5. Conclusion

As a part of the ALTCRISS project from December 2005 to October 2007, we have evaluated the shielding effect of PE in the ISS Russian segment, using PADLES dosimeter systems with or without PE shielding. The shielding effect of 5 g/cm^2 PE was estimated to be 6.1% for total absorbed doses and 10.6% for total dose equivalents averaged over four experiments.

The shielding effect of PE was also verified by Monte Carlo simulation using PHITS. It was found that the shielding effect of PE varies with location inside the spacecraft, becoming less significant with an increase of the mean thickness of the wall. We can conclude that the shielding material is more effective under thinner shielding conditions in LEO.

The space radiation environment differs in and beyond LEO (Angelis et al., 2007; Hayatsu et al., 2008; O'Neill et al., 2010), so we must try to determine effective materials, effective locations, and appropriate thicknesses or combinations on the basis of a benchmark evaluations of actual measurements in space experiments similar to the one reported here. This information will be useful for interplanetary space flight and travel expected in the near future.

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