Radiation Protection Dosimetry (2011), Vol. 144, No. 1–4, pp. 605–610
Advance Access publication 19 October 2010
doi:10.1093/rpd/ncq305

MONITORING ON BOARD SPACECRAFT BY MEANS OF PASSIVE DETECTORS

I. Ambrožová[1,*], K. Brabcová[1], F. Spurný[1], V. A. Shurshakov[2], I. S. Kartsev[2] and R. V. Tolochek[2]
[1]Nuclear Physics Institute, Academy of Sciences of Czech Republic, Prague, Czech Republic
[2]Institute for Biomedical Problems, Moscow, Russia

*Corresponding author: ambrozova@ujf.cas.cz

To estimate the radiation risk of astronauts during space missions, it is necessary to measure dose characteristics in various compartments of the spacecraft; this knowledge can be further used for estimating the health hazard in planned missions. This contribution presents results obtained during several missions on board the International Space Station (ISS) during 2005–09. A combination of thermoluminescent and plastic nuclear track detectors was used to measure the absorbed dose and dose equivalent. These passive detectors have several advantages, especially small dimensions, which enabled their placement at various locations in different compartments inside the ISS or inside the phantom. Variation of dosimetric quantities with the phase of the solar cycle and the position inside the ISS is discussed.

INTRODUCTION

During spaceflights the astronauts are exposed to cosmic radiation, which represents an important health risk for them, especially during long-term missions. The exposure level on board spacecraft is several hundred times higher than that on the Earth's surface, several times higher than on board aircraft. According to NCRP 132 recommendation[(1)], 10-y career limits for stochastic effects (based on 3 % excess lifetime risk of cancer mortality) range from 0.4 to 3.0 Sv, depending on the gender and age. To secure the safety of the astronauts and minimise their risks, it is important to determine the exposure level as accurately as possible.

Basically, there are two principal possibilities how to acquire information on the exposure level on board spacecrafts: experimental measurements and theoretical simulations usually based on the Monte Carlo approach. Such codes are able to simulate transport of various particles in complex geometries; however, the reliability of the predictions of the code depends on the environment and transport models used. Further, the complex composition of space radiation and the dynamical nature of energy and angular spectra do not permit to obtain accurate data on radiation conditions based only on calculations. There is still need to validate and benchmark the codes through direct comparison with the experimental results obtained in real spaceflight conditions.

The radiation field at low-Earth orbit is completely different from those on the Earth. The radiation field on board spacecraft is very complex; it is composed of primary high-energy galactic and solar particles, particles trapped in the Earth's radiation belts, and also by secondary and further generation particles produced in fragmentation and nuclear interactions of primary cosmic radiation with the walls of the spacecraft and the surrounding materials including astronauts' bodies[(2, 3)]. Moreover, dose characteristics depend on many parameters, such as the phase of the solar cycle, shielding of the spacecraft, orbit parameters, etc.

Because of this complexity, there is no simple detector efficient enough to collect all dose characteristics [the spectra of linear energy transfer (LET), total absorbed dose, dose equivalent and quality factor]. Usually, it is necessary to combine several types of detectors. For the measurements of dose characteristics on board spacecraft, a combination of thermoluminescent detectors (TLD) and plastic nuclear track detectors (PNTD) is very suitable and often used. Due to their several advantages, such as small weight and dimensions, easy manipulation and no need of power supply, they can be easily used to measure spatial distribution of dose characteristics in the phantoms simulating human bodies or they can be placed at various locations inside the spacecraft.

The object of this contribution is to summarise the results obtained during 2005–9 on board the International Space Station (ISS). All the experiments were performed in the frame of the MATROSHKA-R space experiment; its purpose is to study the radiation environment inside various compartments of the ISS and the dose distribution inside and on the surface of the spherical phantom, in order to improve the methods of space dosimetry and radiation hazard assessment[(4)].

METHODS

In these studies, packages composed of TLD and PNTD were used. TLDs are used to measure the absorbed dose, particularly from low-LET particles (photons, high-energy protons, etc.); for particles with higher values of LET (about >10 keV μm^{-1},

Table 1. Overview of experiments.

Experimental run	Duration (d)	ISS altitude (km)	Location
Phantom 2006	273 (December 2005–September 2006)	351 (344–361)	SM
SPD 2007	163 (May–October 2007)	346 (338–353)	SM, Piers-1
Phantom 2008	206 (May–December 2008)	356 (345–366)	Piers-1
SPD 2009	158 (May–October 2009)	356 (350–361)	SM, Piers-1

Table 2. Positions of SPD boxes.

SPD box #	Panel #; position
1	102; Piers-1, floor
2	401; Piers-1, star board
3	325; SM, cone, ceiling
4	462; SM, star board
5	323; SM, cone, ceiling
6	305; SM, ceiling

depending on the type of the TLD), their relative response decreases[5]. TLD do not provide any information about the differential LET spectra, therefore the dose equivalent and the quality factor cannot be easily determined.

On the other hand, track detectors register only particles with LET above the detection threshold; the detection threshold depends on the material used and evaluation conditions—the most sensitive PNTD are able to register particles from ~5 keV μm^{-1} (considered in water)[6].

The combination of both detectors (TLD and PNTD) can provide total values of absorbed doses, dose equivalents and quality factors[7].

Three different types of TLD were used—Al_2O_3:C[8], $CaSO_4$:Dy[9] and aluminophospate glasses Al-P[10]; the use of a concrete type of TLD in each experimental run depended on the experimental conditions and the availability of TLD. In all cases, presented values are expressed as the dose in water. Dependencies of their relative response (relative to ^{60}Co) on the LET of the particles were obtained using irradiation with several heavy ion beams[5]; the relative response decreases more rapidly for Al_2O_3:C than for other two TLD.

The detectors from two production companies were used as PNTD: Page (Page Mouldings, UK) and HARZLAS TD-1 (Nagase Landauer Ltd, Japan); both are polyallyldiglycolcarbonate. The irradiated detectors were treated under the same etching conditions—5N NaOH at 70°C for 18 h (bulk etch ~15–17 μm)[11]. The detectors were analysed by means of an optical microscope and image analysing software LUCIA-NIS[11] or HSP-1000[12]. The range of LET (considered in water) that can be determined using these detectors and conditions is ~7–450 keV μm^{-1}[13]. All detectors were calibrated in several heavy charged particle beams and also at some neutron sources[14, 15].

EXPERIMENTS

The detectors were exposed on board the ISS during several experiments since 2005; the overview of the experimental runs (period and duration, average altitude of the ISS as well as its variation, and location of the detectors) is summarised in Table 1. The passive detectors were placed in so-called sborka passivnych detektorov (SPD) boxes (SPD in Russian means an assemblage of passive detectors) in different compartments of the ISS, or on the surface and inside the tissue-equivalent spherical phantom MATROSHKA-R[16]. In total, six SPD boxes can be placed at various locations inside the Russian Service Module (SM) and Piers-1 Module; each box contains various packages of passive detectors. The boxes are always located at the same position; four boxes (labelled 3–6) are in the Russian SM and two boxes (1–2) in the Piers-1 Module[17] (Table 2).

The spherical phantom MATROSHKA-R is a multi-user unit for studies of the depth dose distribution at different sites of the organs; its dimension is 35 cm in diameter and it is made of tissue-equivalent plastic. The detectors can be placed in 32 pockets on the surface and in 20 containers inserted inside the phantom[16]. These detectors were put into some pockets evenly distributed on the phantom's surface; some detectors were also inserted inside the phantom. The detailed description about the positions of the detectors can be found in another paper[18]. The spherical phantom was located in the starboard crew cabin in the SM in 2006 or in the Piers-1 Module in 2008, in both cases close to the outer wall of the spacecraft.

RESULTS AND DISCUSSION

By means of track detectors, the spectra of LET can be determined. The spectra differ for various locations inside the ISS. Generally, one can say that in the Piers-1 Module, there is higher contribution of particles with lower values of LET; in the high-LET region there are practically no differences within the uncertainties. An example of differential fluency

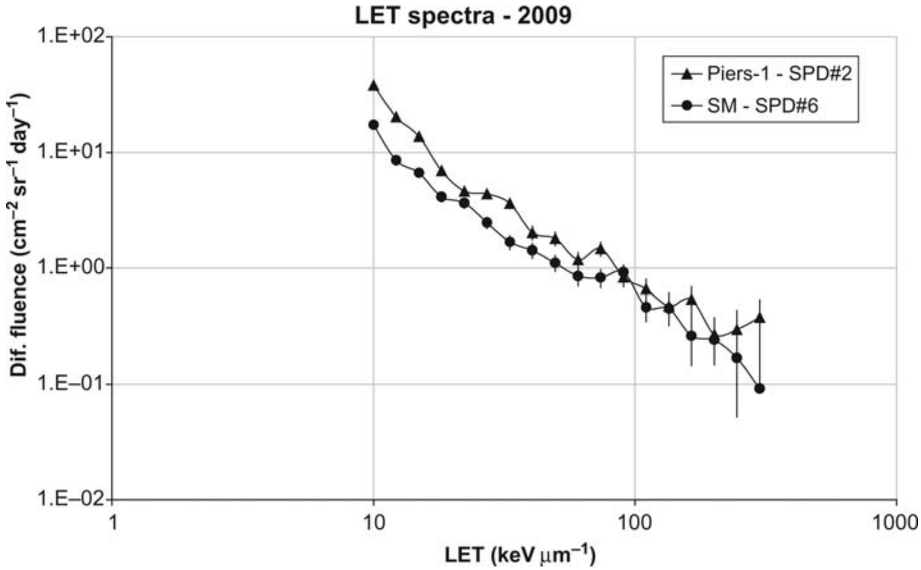

Figure 1. LET spectra in Piers-1 Module and SM (year 2009); TD-1 was used as PNTD.

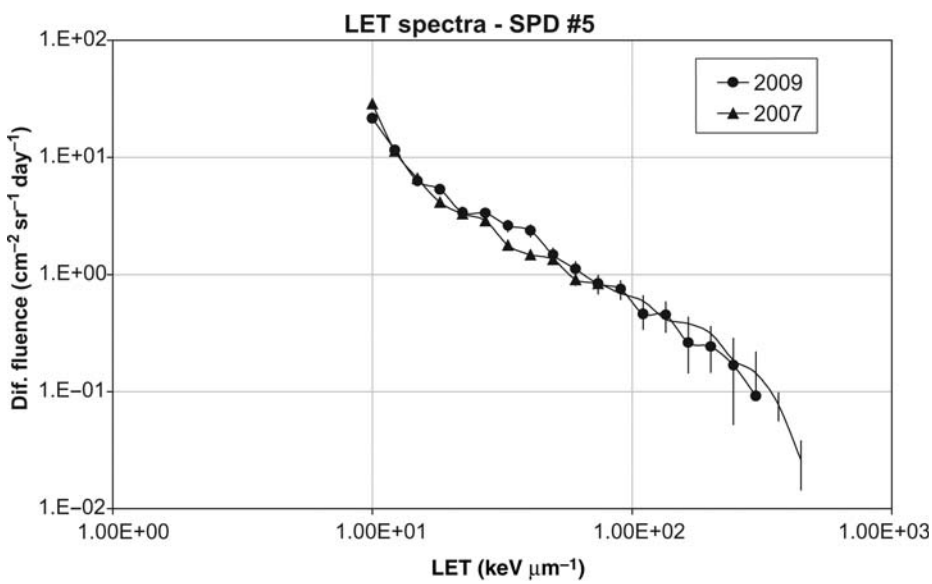

Figure 2. LET spectra in SM SPD #5 in 2007 and 2009; in 2007, Page was used as a PNTD and in 2009 TD-1.

spectra measured in 2009 in the Piers-1 and in the SM is presented in Figure 1. In Figure 2, there are compared spectra measured at the same location (in SM) during different experiments (in 2007 and 2009). It should be mentioned that in 2007 a type of PNTD was used different from that in 2009; however, from experience in other experiments, both the materials (TD-1 and Page) give similar results.

From the LET spectra, the absorbed dose and the dose equivalent can then be calculated[19]. Using the LET spectra and the function of the relative response of TLD on LET of the particle, the high-LET contribution to the signal measured with the TLD was subtracted[7]. The remaining absorbed dose corresponding to low-LET particles was combined together with the data from PNTD to obtain

Table 3. Absorbed doses, dose equivalents and quality factors measured in SPD boxes in 2007 and 2009.

SPD	D_{TLD} (μGy d^{-1})	D_{PNTD} (μGy d^{-1})	H_{PNTD} (μSv d^{-1})	Q_{PNTD}	D_{total} (μGy d^{-1})	H_{total} (μSv d^{-1})	Q
2007, #1	284 ± 20[a]	42 ± 4	428 ± 68	10.2	298 ± 18	684 ± 69	2.3
2007, #2	216 ± 15	28 ± 3	275 ± 44	9.8	223 ± 13	470 ± 44	2.1
2007, #3	190 ± 13	40 ± 4	376 ± 60	9.4	211 ± 12	547 ± 59	2.6
2007, #4	218 ± 15	39 ± 4	197 ± 31	9.2	222 ± 14	393 ± 57	1.8
2007, #5	187 ± 13	26 ± 3	357 ± 57	7.6	206 ± 11	524 ± 32	2.5
2007, #6	152 ± 11	35 ± 4	390 ± 62	11.1	172 ± 10	527 ± 61	3.1
2009, #1	445 ± 31	43 ± 5	446 ± 52	10.4	452 ± 41	854 ± 66	1.9
2009, #2	417 ± 29	51 ± 5	537 ± 61	10.6	425 ± 38	911 ± 71	2.2
2009, #3	368 ± 26	41 ± 4	550 ± 62	13.5	376 ± 34	885 ± 70	2.4
2009, #4	387 ± 27	41 ± 4	437 ± 49	10.8	394 ± 36	790 ± 60	2.0
2009, #5	321 ± 22	34 ± 4	396 ± 46	11.5	327 ± 29	689 ± 55	2.1
2009, #6	301 ± 21	28 ± 3	348 ± 42	12.3	306 ± 28	626 ± 50	2.0

As TLD Al-P was used in both experiments; as PNTD Page was used in 2007 and TD-1 was used in 2009.
[a]Uncertainties are combinations of statistical and systematical uncertainties.

Table 4. Average absorbed doses, dose equivalents and quality factors measured on the surface and inside the phantom.

Phantom	D_{TLD} (μGy d^{-1})	D_{PNTD} (μGy d^{-1})	H_{PNTD} (μSv d^{-1})	Q_{PNTD}	D_{total} (μGy d^{-1})	H_{total} (μSv d^{-1})	Q
2006 inside	129 ± 10	—	—	—	—	—	—
2006 pockets—in	178 ± 23	22 ± 3	173 ± 20	7.7 ± 0.3	183 ± 18	333 ± 9	2.0 ± 0.2
2006 pockets—wall	227 ± 26	31 ± 5	226 ± 29	7.3 ± 0.2	235 ± 26	430 ± 45	2.0 ± 0.2
2008 inside	163 ± 6	—	—	—	—	—	—
2008 pockets—in	231 ± 36	55 ± 15	479 ± 114	8.8 ± 1.2	235 ± 37	658 ± 124	2.8 ± 04
2008 pockets—wall	264 ± 31	72 ± 13	635 ± 89	8.9 ± 1.1	270 ± 31	832 ± 101	3.1 ± 0.3

Inside the phantom, CaSO4:Dy was used. On the surface of the phantom, Al-P was used as the TLD in both experiments; as PNTD Page was used in 2006 and TD-1 in 2008.

total values of the absorbed dose and the dose equivalent. Absorbed doses and dose equivalents measured with TLD and PNTD in various SPD boxes in 2007 and 2009, as well as total values and quality factors, are summarised in Table 3.

The dosimetric characteristics depend on the location inside the ISS. In the Piers-1 Module, which is less shielded, the absorbed doses are in general higher than in the SM. When averaged values (averaged from all detectors placed in the given compartment) are considered, the total absorbed dose in the Piers-1 is ~30 % higher than in the SM, and the dose equivalent is ~20 % higher. A similar trend was also observed in previous experiments[17].

Other experiments were performed using the spherical phantom MATROSHKA-R to study the dose distribution. In this case, packages with TLD and PNTD were placed in several pockets evenly distributed on the surface of the phantom; some TLD were also inserted inside the phantom, up to a depth 10 cm from the surface[18]. Higher values of the absorbed dose and the dose equivalent were observed at the site closer to the outer wall of the ISS, lower values at the site oriented towards the inside of the spacecraft; dose characteristics on the surface of the phantom can differ up to a factor of 1.9. The average absorbed dose inside the phantom is ~30 % lower than the averaged absorbed dose on the surface. In Table 4, there are summarised results from the detectors inside the phantom (10 cm from the phantom's surface), as well as from the detectors placed in the pockets on the surface. The values from the phantom's surface are divided into two groups—'pocket in' corresponds to the detectors located at the site oriented towards the inside of the ISS and 'pocket wall' to the detectors close to the outer wall of the ISS. When the results obtained in the two experimental phases (2006 and 2008) are compared, the absorbed dose increased by ~20–30 % and the dose equivalent almost doubled. The results measured with TLD are in a good agreement with the results obtained by Shurshakov *et al.*[16], who also measured the absorbed dose on the surface of the phantom in various experimental sessions.

CONCLUSIONS

Results obtained in several experimental runs on board the ISS during recent years are presented. The absorbed dose and the dose equivalent were obtained using the combination of TLD and PNTD. Dose characteristics depend on the position inside the spacecraft and period of the mission. In the Piers-1 Module, the absorbed dose and the dose equivalent are generally higher (by ~20–30 %) than in the SM, which is more shielded.

From 2005 to 2009, dose characteristics on board ISS increased; for example, the absorbed dose measured at the same locations inside the ISS increased from 2007 to 2009 by 40–70 %. The growth anticorrelates with the decreasing phase of the solar cycle; the year 2009 is close to the solar minimum of the 23rd solar cycle. However, also other parameters influence the dosimetric characteristics. The average altitude of the ISS during the experimental phase in 2009 was ~10 km higher than in 2007, which also could have caused the increase of the absorbed dose and the dose equivalent (especially due to the higher contribution of trapped protons). In the preliminary simulations[20], it was found that the increase of the height of the ISS by ~10 km can cause an increase in the absorbed dose by ~11 %.

Another factor which should be taken into account during the analysis of the results is the surrounding material and shielding distribution at the specific location inside the spacecraft. Unfortunately, this is usually not exactly known. The dose characteristics obtained with the tissue-equivalent phantom showed that there can be significant differences depending on the position inside or on the surface of the phantom; similar trends were also observed by other authors[16, 21, 22].

The major part (~90 %) of the absorbed dose comes from the low-LET (<10 keV μm^{-1}) particles, probably from high-energy protons. To the dose equivalent, the particles with high LET (mostly secondary particles from neutron and proton interactions or target fragments) contribute significantly—about 60 % from the total dose equivalent comes from the particles with LET higher than 10 keV μm^{-1}, more than 30 % from the particles with LET above 100 keV μm^{-1}.

The data accumulated in these studies could bring additional information on individual monitoring of the spacecraft crew members and help to estimate their radiation risk.

FUNDING

This work was supported through GACR 205/09/0171, GAAV KJB100480901 and bilateral scientific cooperation of the Academy of Sciences of the Czech Republic and the Russian Academy of Sciences. The authors are much obliged to the organisers of ICCHIBAN experiments and the staff of HIMAC (NIRS, Japan), NSRL (BNL, USA) and Nuclotron (Dubna, Russia) for their help and assistance.

REFERENCES

1. National Council on Radiation Protection and Measurements, *Radiation protection guidance for activities in low Earth orbit*, NCRP Report No. 132, Bethesda, MD (2000).
2. Benton, E. R. and Benton, E.V. *Space radiation dosimetry in low-Earth orbit and beyond*. Nucl. Instrum. Methods Phys. Res. B **184**, 255–294 (2001).
3. National Council on Radiation Protection and Measurements, *Operational radiation safety program for astronauts in low Earth orbit: a basic framework*, NCRP Report No. 142, Bethesda, MD (2002).
4. Akatov, Yu. A., Arkhangelsy, V. V., Benghin, V. V., Bondarenko, V. A., Mitrikas, V. G., Petrov, V. M., Tsetlin, V. V., Shurshakov, V. A., Lyagushin, V. I. and Kartsev, I. S. *Study of regularities in radiation fields in human body and in space station compartments in spaceflight*. Cosmonautics and Rocket building **4**(49), 71–84 (2007) (in Russian).
5. Spurny, F. *Response of thermoluminescent detectors to high-energy charged particles and to neutrons*. Radiat. Meas. **38**, 407–412 (2004).
6. Benton, E. V., Frank, A. L., Csige, I., Frigo, L. A. and Benton, E. R. *LET spectra measurements on LDEF: variations with shielding and location*. Radiat. Meas. **26**, 783–791 (1996).
7. Doke, T., Hayashi, T., Nagaoka, S., Ogura, K. and Takeuchi, R. *Estimation of dose equivalent in STS-47 by a combination of TLDs and CR-39*. Radiat. Meas. **24**, 75–82 (1995).
8. Akselrod, M. S., Kortov, V. S., Kravetsky, D. J. and Gottlib, V. I. *Highly sensitive TL anion-defect α-Al2O3:C single crystal detectors*. Radiat. Prot. Dosim. **33**, 119–122 (1990).
9. Yamashita, Y., Nada, N., Onishi, H. and Kitamura, S. *Preparation and properties of new CaSO4:Dy [Tm] thermoluminescent detectors*. Health Phys. **21**, 295–299 (1971).
10. Trousil, J., Plichta, J., Prouza, Z. and Studena, J. *Basic dosimetric characteristics of the Czechoslovak thermoluminescent and neutron dosimetry*. Kernenergie **27**, 246–254 (1984).
11. Jadrnickova, I. *Spectrometry of linear energy transfer and its use in radiotherapy and radiation protection in high-energy particle fields*, Ph.D. thesis, Czech Technical University (2006).
12. Yasuda, N., Namiki, K., Honma, Y., Umeshima, Y., Marumo, Y., Ishii, H. and Benton, E. R. *Development of a high speed imaging microscope and new software for nuclear track detector analysis*. Radiat. Meas. **40**, 311–315 (2005).

13. Brabcova, K., Jadrnickova, I. and Spurny, F. *Comparison study of polylallyl-diglycolcarbonate PADC variations as spectrometers of linear energy transfer*. Safety Nucl. Energy **516**, 173–175 (2010) (in Czech).
14. Spurny, F. and Jadrnickova, I. *Track etch and thermo luminescent detectors response to high energy charged particles*. Radiat. Meas. **43**, S169–S173 (2008).
15. Brabcova, K., Spurny, F. and Jadrnickova, I. *Track etch based LET spectrometry in beams of neutrons with energies from 0.2 to 200 MeV*. Radiat. Meas. **44**, 969–971 (2009).
16. Shurshakov, V. A., Akatov, Yu. A., Kartsev, I. S., Petrov, V. M., Tolochek, R. V., Petrov, V. I., Polenov, B. V. and Lyagushin, V. I. *Study of dose distribution in a human body in space station compartments with the spherical tissue-equivalent phantom*. In: Fundamental Space Research, Conference Proceedings. Sunny Beach, Bulgaria, 21–28 September 2008, pp. 234–237 (2008).
17. Jadrnickova, I. *et al*. *Variation of absorbed doses onboard of ISS Russian Service Module as measured with passive detectors*. Radiat. Meas. **44**, 901–904 (2009).
18. Jadrnickova, I., Brabcova, K., Mrazova, Z., Spurny, F., Shurshakov, V. A., Kartsev, I. S. and Tolochek, R. V. *Dose characteristics and LET spectra on and inside the spherical phantom onboard of ISS*. Radiat. Meas. (2010), doi:10.1016/j.radmeas.2010.07.002.
19. Spurny, F., Jadrnickova, I., Bamblevski, V. P. and Molokanov, A. G. *Upgrading of LET track-etch spectrometer calibration: calibration and uncertainty analysis*. Radiat. Meas. **40**, 343–346 (2005).
20. Mrazova, Z., Sihver, L., Ambrozova, I., Spurny, F., Sato, T. and Shurshakov, V. A. *Simulations of Matroshka-R experiments at ISS using PHITS*. In: Presented at 38th COSPAR Scientific Assembly, Bremen, July (2010).
21. Semkova, J. *et al*. *Radiation measurements inside a human phantom aboard the International Space Station using Liulin-5 charged particle telescope*. Adv. Space Res. **45**, 858–865 (2010).
22. Hallil, A. *et al*. *MOSFET dosimetry mission inside the ISS as part of the Matroshka-R experiment*. Radiat. Prot. Dosim. **138**, 295–309 (2010).