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Response calculations for silicon-based direct-reading dosimeters for use at the international space station (ISS)

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A B S T R A C T

In 2007, the European Space Agency (ESA) initiated the development of European Crew Personal Active Dosimeters. The hardware development objective is to produce an active personal dosimeter which shows absorbed dose and dose equivalent spectra similar to a Tissue Equivalent Proportional Counter (TEPC), but which is based on more robust silicon detector devices. Several detector/dosimeter components have been investigated – by computer simulations – for their performance in the radiation field at the ISS position.

1. Introduction

Exposure monitoring for Astronauts by active personal dosimeters has not yet been performed onboard of the ISS despite a vast field of radiation measurements having been conducted. The present concept is the first attempt to equip crew members in the near future with an active personal dosimeter.

The passive radiation personal dosimeter packages currently used at ISS consist of TLDs (Thermoluminescence Dosimeters) and NTDs (Nuclear Track Detectors). The combination of these two passive systems enables the determination of the absorbed dose, the measurement of LET (Linear Energy Transfer) spectra, and – by applying the Q (Quality factor) versus LET relationship as based on ICRP 60 recommendations (ICRP, 1991) – the evaluation of dose equivalent (Straube et al., 2010). However, these detectors are evaluated on Earth; this evaluation is usually performed several weeks or even months after the exposure. The only active dosimeter at the ISS providing a warning in case of high dose rates is a TEPC (Tissue Equivalent Proportional Counter) operated by NASA which can be transported to different positions inside the ISS. Measurements with the dosimetry telescope (DOSTEL) show that the dose equivalent rate strongly increases up to about two orders of magnitude (Reitz et al., 2005), when the ISS passes through the SAA (South Atlantic Anomaly). During such a pass a similar integrated dose as originating from GCR (Galactic Cosmic Ray) radiation during the whole day is obtained within a few minutes from protons trapped by the Earth's magnetic field (inner Van Allen radiation belts). Astronauts wearing an active personal dosimeter can choose a better shielded position inside the ISS for this short time and can avoid part of the exposure. Passive TLD/CR-39 devices distributed at different positions inside the ISS showed a variation of dose equivalent by about 50% (Reitz et al., 2005; Zhou et al., 2007). In addition, active personal dosimeters are highly desirable to directly determine the dose equivalent in case of EVAs (Extra Vehicular Activities) and manned missions (e.g. to the Moon or Mars).

In 2007, the European Space Agency (ESA) initiated the development of European Crew Personal Active Dosimeters with a consortium consisting of Physikalisch-Technische Bundesanstalt (PTB), Mirion Technologies (RADOS) Oy, Austrian Institute of

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Technology (AIT), Tyndall National Institute and the German Aerospace Center (DLR) as lead. The first phase of the project dedicates to:

(1) An overview of existing devices and a selection of preferable ones
(2) Computer simulations of responses of the preferred detectors in the complex mixed radiation fields at ISS
(3) A preliminary design of a possible dosimetry system at the ISS.

Fig. 1 gives a rough idea of the proposed system. The system consists of a rack unit which has slots to store, readout and reload a few active personal dosimeters (on the left in Fig. 1) and contains a TEPC (shown as a sphere in Fig. 1).

It has been proposed that the active personal dosimeter should contain two silicon diodes:

– one detector, about 300 μm thick, similar to that which is already in use at the ISS in the LIULIN device (Dachev et al.) and DOSTEL (Reitz et al., 2005)
– one detector with about 5.6 μm effective thickness, as used in the DOS-2005 PTB prototype dosimeter (Luszik-Bhadra, 2007 and Luszik-Bhadra et al., 2008), which has shown a good response to high-energy neutrons.

These diodes should allow direct measurement of dose equivalent and give an indication of the radiation quality by accumulating LET spectra similar to those of the TEPC.

In addition, the dosimeter is equipped with an integrating type passive device – consisting of a DIS (Direct Ion Storage, Wernli and Kahilainen, 2001) chamber and a RadFET (Radiation Sensing Field Effect Transistor, Tyndall, 2008) – with direct readout capability in the instrument and inside the rack unit.

The selection of the detector systems is chosen based on the results of computer simulations which are shown and discussed in order to understand the main principles.

2. Computer codes used

Three different computer codes have been used to simulate detector responses. The codes FLUKA (Ferrari et al., 2005) and GEANT4 (Agostinelli et al., 2003 and Allison et al., 2006) were used at AIT and the PHITS code (Iwase et al., 2002 and Niita et al., 2006) was used at PTB. All codes can handle the transport and interactions of different types of particles (leptons, bosons, mesons, baryons, etc.) with energies up to TeV, and they have already been used for cosmic radiation (Roesler et al., 1998; Beck et al., 2005) and for space applications (Sato et al., 2006a, 2006b).

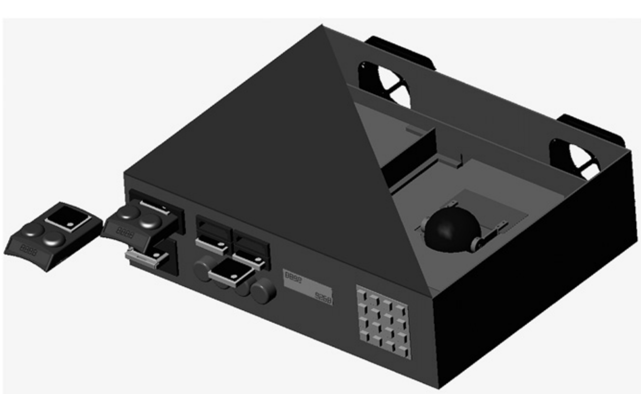

Fig. 1. Active dosimeter system concept (see text).

3. Radiation fields investigated at ISS

As a starting point for the simulations, only particles which give the main contribution to the dose equivalent are considered. The spectra selected correspond to a position outside the ISS during a maximum of solar activity (Solar MAX).

Neutron and proton spectra outside the ISS were taken from calculations by Armstrong (Armstrong and Colborn, 1998). These calculations were performed for a maximum of solar activity at a height of 500 km and an inclination of 51.6°. Scaling factors to convert the flux values to a height of 400 km were published in the same paper and were used to get the distributions presented in Fig. 2.

The spectra of He and Fe cosmic radiation during a maximum of solar activity at a height of 380 km and an inclination of 51.6° were taken from CREME96 (Tylka et al., 1997). The differential spectra were normalized to the flux in the solid angle 4π sr, reduced by 31% in order to account for the Earth's shadow. The Earth's shadow correction comes from simple geometry and the value was taken from Armstrong (Armstrong and Colborn, 1998). The spectral fluence distributions of He ions and Fe ions are plotted in Fig. 2, together with the neutron and proton distributions.

4. Irradiation geometries used in the calculations

The devices have been irradiated "free in air" and on a phantom with normally incident particles and also "free in air" with isotropic incidence. The phantom is a slab phantom as usually used for calibration measurements of personal dosimeters, having outer dimensions of 30 cm × 30 cm × 15 cm, walls made of PMMA (front wall: 2.5 mm thick, other walls: 10 mm thick), filled with water (ISO, 1998). Irradiations were simulated with normally incident particles and a detector placed on the front and another one on the backside of the phantom. In principle, the whole phantom should be irradiated in order to get the full information on particles scattered and secondary particles produced. Because of the long CPU time needed, the calculations on the phantom were restricted to normal incidence covering a few cm^2 surrounding the detectors.

5. Simulated devices

The LIULIN device contains a diode with a 2 cm × 1 cm sensitive area and 300 μm thickness, a ceramic holder, electronic boards and a housing.

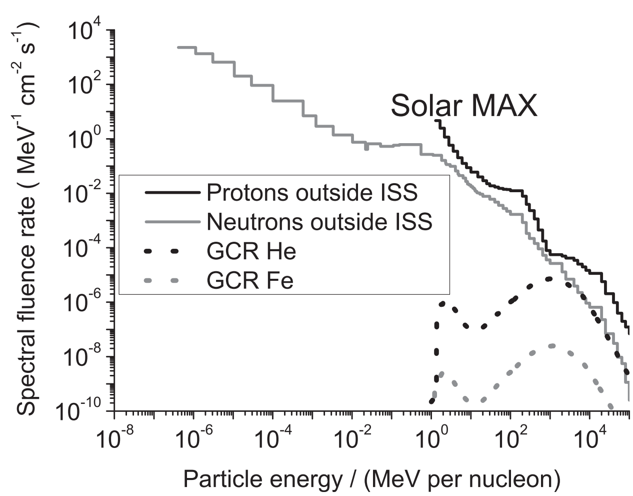

Fig. 2. Spectral distributions of protons, neutrons, He ions and Fe ions as used in the calculations.

In the case of the DOS-2005 device, the sensitive part containing the diode with a nominal sensitive area of 0.25 cm^2 and an effective sensitive thickness of 5.6 μm, the diode holder and neutron converters and absorbers (^{6}LiF, polyethylene and boron plastics, for details see Luszik-Bhadra et al., 2008) has been simulated.

The TEPC is of the type developed by NASA and installed on the ISS. The sensor part and the required electronics are arranged in a cylinder made of stainless steel and aluminium. The counter is of cylindrical shape (radius: 2.73 cm, height: 8.08 cm), made of tissue-equivalent material (A150) and filled with pure propane gas (C_3H_8) at 1.86 kPa (14 Torr) pressure. This configuration corresponds to 1.4 μm thickness of tissue.

6. Results of response calculations

The results as obtained by the computer simulations are deposited energies in silicon and in tissue, respectively. Folding the number of counts obtained in a deposited energy interval by the mean deposited energy of this interval and dividing by the detector mass yields absorbed dose spectra.

Figs. 3 to 5 show absorbed dose (upper part) and dose equivalent spectra (lower part) as obtained for the devices as a function of lineal energy y (deposited energy divided by mean chord length). The lineal energy can be approximated to the LET and contains information on the radiation quality (ICRU, 1983). Folding the absorbed dose spectra with Q(LET) values (ICRP, 1991) yielded dose equivalent spectra. The absorbed dose and dose equivalent values as shown in Figs. 3–5 on the right axes are calculated for one day outside ISS. By using a lethargy presentation, equal doses are presented by equal areas below the curves.

Fig. 3 shows results for the TEPC for protons, neutrons, He ions and Fe ions with isotropic incidence. Fig. 3a shows that chiefly protons and low-LET radiation (y < 10 keV/μm) contribute to absorbed dose. After folding with Q(LET) values, the high-LET contribution of proton-induced dose increases significantly; and also neutrons and Fe ions contribute significantly to dose equivalent (see Fig. 3b).

Fig. 4 shows absorbed dose and dose equivalent distributions for the LIULIN and DOS-2005 devices, irradiated by ISS protons with perpendicular incidence free in air. The absorbed dose and dose equivalent distributions were obtained by calculating deposited energies in silicon and using – as a first approximation – mean

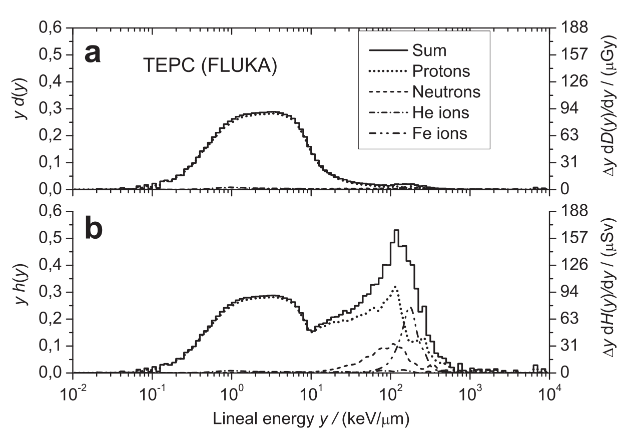

Fig. 3. Microdosimetric spectra of lineal energy y (a) and microdosimetric spectra of lineal energy y folded with the radiation quality factor Q(L), where L is approximated by y (b) as calculated for the TEPC for the sum of protons, neutrons, He ions and Fe ions and the corresponding relative contributions of these particles. The right axis shows the corresponding absorbed dose and dose equivalent values as calculated for one day at a position outside the ISS. Δy is the bin-width of the logarithmic y scale.

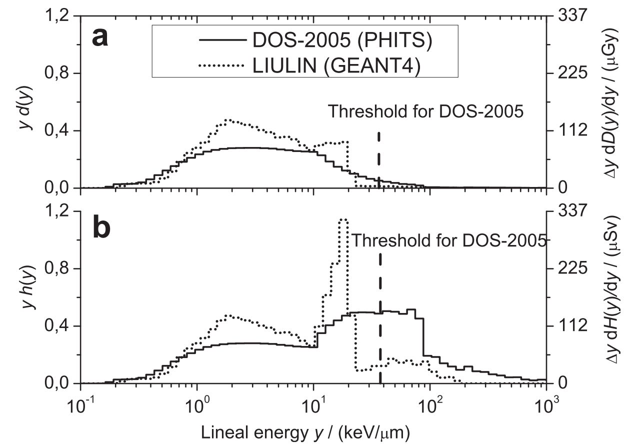

Fig. 4. Microdosimetric spectra of lineal energy y (a) and microdosimetric spectra of lineal energy y folded with the radiation quality factor Q(L), where L is approximated by y (b) as calculated for the DOS-2005 and relative contributions as calculated for the LIULIN for protons. The right axis shows the corresponding absorbed dose and dose equivalent values as calculated for one day at a position outside the ISS. Δy is the bin-width of the logarithmic y scale.

chord lengths as given by the thickness of the diodes, e.g. 300 μm in the case of the LIULIN device and 5.6 μm in the case of the DOS-2005 device.

The absorbed dose distributions look quite similar to those for the TEPC, both in shape and in absolute height. However, for measurements the electronic thresholds of the devices have to be taken into account. This threshold is 83 keV for the LIULIN device (0.3 keV/μm in terms of lineal energy), whereas the thinner diode showed greater electronic noise and the threshold had to be set at 200 keV (indicated at 35 keV/μm in Fig. 4). Hence, the absorbed dose is rather accurately measurable by the LIULIN device, whereas the DOS-2005 measures only a small percentage of absorbed dose which is indicated above the threshold (see Fig. 4a).

In terms of dose equivalent, however, a considerable part of the high-LET contribution is measurable by the DOS-2005 device (see Fig. 4b) and should be used for estimating the dose equivalent for higher LET values. Since the diode of the DOS-2005 device is much thinner than that of the LIULIN device (5.6 μm as compared to

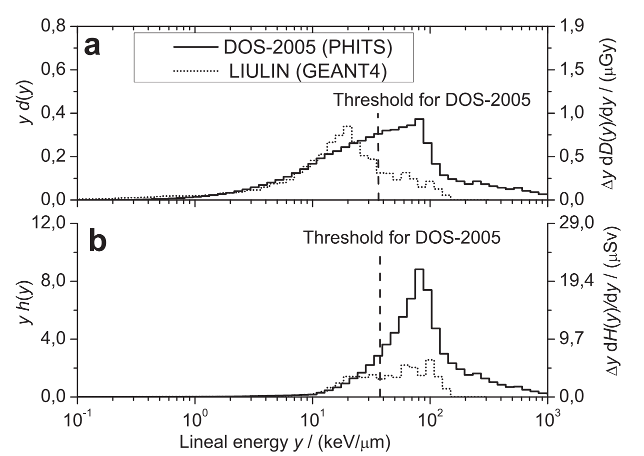

Fig. 5. Microdosimetric spectra of lineal energy y (a) and microdosimetric spectra of lineal energy y folded with the radiation quality factor Q(L), where L is approximated by y (b) as calculated for the DOS-2005 and relative contributions as calculated for the LIULIN for neutrons. The right axis shows the corresponding absorbed dose and dose equivalent values as calculated for one day at a position outside the ISS. Δy is the bin-width of the logarithmic y scale.

300 μm), it can better estimate the lineal energy of shorter range protons and secondary reaction particles and hence gives a better estimate of the Q(LET) values which are used for folding absorbed dose spectra to obtain dose equivalent.

Fig. 5 shows dose and dose equivalent distributions for the LIULIN and DOS-2005 devices irradiated by ISS neutrons with perpendicular incidence free in air, using the same mean chord lengths as previously. For neutrons, only secondary charged particles are detected by the diodes. Most of these particles have chord lengths shorter than 300 μm, resulting in an underestimation of the dose equivalent by the LIULIN device. For the DOS-2005 device, calculated absorbed dose and dose equivalent spectra agree well with those of the TEPC, both in shape and in height. Most of the dose equivalent is also above the electronic threshold. A combination with pulses of the LIULIN at lower lineal energies can add the remaining part of dose equivalent.

7. Comparison with effective dose equivalent

Fig. 6 shows integral values of dose equivalent for protons, neutrons, He ions and Fe ions as calculated for the LIULIN and the DOS-2005 devices (electronic thresholds taken into account) for different irradiation geometries, compared to values of effective dose equivalent as defined in ICRU Report 51 (ICRU, 1993):

$$\frac{H_E}{\Phi} = \sum_T w_T \int_L \frac{D_{L,T}(L)}{\Phi} Q(L) \mathrm{d}L$$

H_E values have been obtained by folding the fluence spectra as given in Fig. 1 with conversion coefficients for effective dose equivalent and isotropic radiation distribution as calculated by Sato et al. (Sato et al., 2003a, 2003b, Sato et al., 2006a, 2006b and private communication). Reason for taking effective dose equivalent as defined above instead of using the effective dose is a statement given by ICRP in its newest recommendation (ICRP, 2007) telling that a single value of the radiation weighing factor w_R of 20 for all types and energies of heavy charged particles is a conservative estimate and that for applications in space where these particles contribute significantly to the total dose in the human body, a more *realistic* approach may have to be used.

The highest effective dose equivalent is obtained from protons (178 μSv d^{-1}), followed by Fe ions (44 μSv d^{-1}), neutrons (23 μSv d^{-1}) and He ions (13 μSv d^{-1}). The mean dose equivalent as

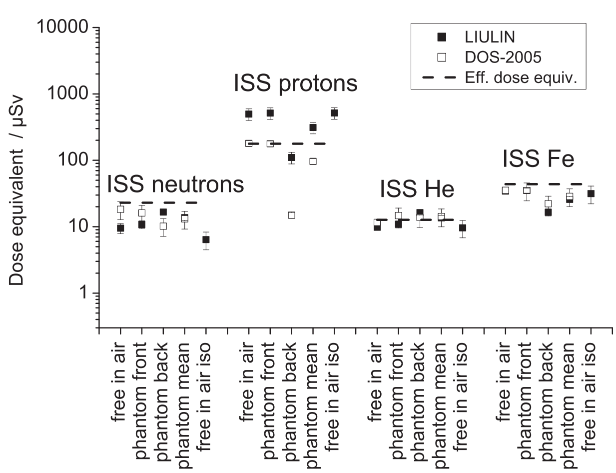

Fig. 6. Dose equivalent as calculated for the LIULIN and DOS-2005 devices for different irradiation geometries and compared to effective dose equivalent. The values correspond to one day outside the ISS (see text).

calculated for the DOS-2005 and the LIULIN devices agrees with calculated values of effective dose equivalent better than a factor of two. A combination of the two devices will improve the agreement.

8. Conclusion

The computer simulations demonstrate that a combination of a thick silicon detector (about 300 μm, e.g. LIULIN type) and a thin silicon detector (about 5.6 μm, e.g. DOS-2005 type) yields dose values for radiation fields at the ISS which agree reasonably well with effective dose equivalent and also indicates the radiation quality in a way similar to that accomplished by a TEPC. The calculations have to be extended to all galactic cosmic ray ions up to iron to obtain a complete picture.

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