Письма в ЭЧАЯ. 2009. Т. 6, № 1(150). С. 113–123

SPECTROMETRY OF LINEAR ENERGY TRANSFER AND DOSIMETRY MEASUREMENTS ON BOARD SPACE- AND AIRCRAFTS

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There are only few methods of dosimetry which could estimate the contribution of different particles to the exposure on board space- and/or aircraft. We describe an attempt to estimate the contribution of different components to the exposure level using:

— MDU-Liulin energy deposition spectrometer;

— thermoluminescent detectors (TLDs) in combination with the spectrometer of linear energy transfer (LET) based on track etch detectors.

This equipment has been exposed on board:

— the international Space Station during one long period and two shorter shuttle missions;

— a commercial subsonic aircraft during several long-term monitoring periods from 2001 to 2006.

The data obtained have been treated from several points of view.

Существует только несколько методов дозиметрии, которые позволяют оценить вклад разных частиц в уровень облучения на бортах космических кораблей и самолетов. Работа описывает попытку определить этот вклад при помощи:

— спектрометра выделенной энергии в Si, MDU-Liulin;

— термолюминесцентных детекторов (ТЛД) в комбинации со спектрометром ЛПЭ, на основе трековых детекторов.

Эти приборы были облучены на бортах:

— Международной космической станции во время одного длинного и двух коротких полетов;

— коммерческого самолета во время нескольких долгосрочных периодов мониторирования в течение 2001–2006 гг.

Полученные данные анализируются с нескольких точек зрения.

PACS: 07.81.+a; 07.87.tv; 94.05.HK

INTRODUCTION

On board space vehicle, radiation fields are composed of primary cosmic rays, as well as of secondary particles created during the nuclear interactions of primary radiation. Such fields cover very large spectra of particle types, of theirs energies, and also of theirs linear energy transfer (LET). A similar situation is encountered also on board aircraft at subsonic or supersonic flight altitudes. Among particle types one should mention primary cosmic rays, whose contribution is important on board spacecraft mainly. Secondary particles are represented mainly by neutrons, photons, and mesons.

There are only few methods of dosimetry which would estimate the contribution of all these particles to the on-board exposure. The contribution describes an attempt to estimate it using:

- MDU-Liulin energy deposition spectrometer;
- thermoluminescent detectors (TLDs) in combination with the spectrometer of linear energy transfer (LET) based on track etch detectors.

The contribution presents the results obtained during a few recent years on board the International Space Station (ISS) and/or FOTON satellite, resp. on board a commercial subsonic aircraft.

1. MATERIALS AND METHODS

1.1. MDU-Liulin Energy Deposition Spectrometer Based on a Si Diode. This equipment (see Fig. 1) was developed in the Bulgarian Academy of Sciences [1]. It is based on a Si-semiconductor diode. The diode is situated at the head of the unit; it has dimensions 10×20 mm, the thickness 0.3 mm. It is covered by 0.4 mm of Al and about 0.3 mm of epoxy resin. The equipment monitors simultaneously the doses and numbers of energy deposition events in Si diode. The amplitude of the pulses is proportional to a factor of 240 mV/MeV of the energy loss (deposited) in Si. Final adjustment of the energy scale is made through the 60 keV photons of ^{241}Am. The amplitudes are digitized and organized in a 256-channel spectrum. The dose D, in Gy in Si, is calculated from the spectrum as

$$D = K \sum (E_i A_i)/M_d, \tag{1}$$

where M_d is the mass of the detector, in kg; E_i is the energy loss, in J, in the channel i; A_i is the number of events in this channel; and K is a coefficient.

The experimental time of use of the instrument depends on the power of the accumulators used and on the rate of the memory filling. Details of the use of that equipment for the exposure on board aircraft have been covered comprehensively in previous publications [2, 3]; they can be summarized as follows:

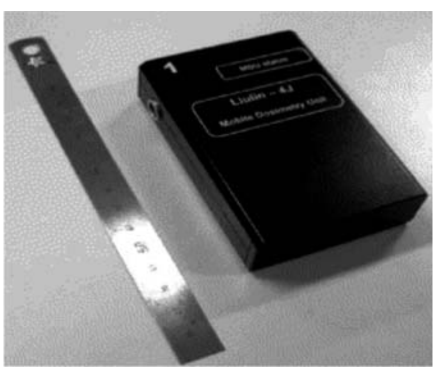

Fig. 1. Photo of the MDU-Liulin equipment

a) Energy deposition spectra in Si detectors are transformed to the dose in Si, D(Si).

b) This dose is, on the base of calibrations realized in several on-Earth reference radiation fields divided on the part corresponding mostly due the energy deposited due to non-neutron and/or neutron (and neutron-like) radiation field on board aircraft.

c) These partial values of D(Si) are converted to the ambient dose equivalent ($H^*(10)$) due to components mentioned using conversion factors determined in the CERF high-energy radiation fields [4] and during direct onboard-aircraft common measurements of MDU equipment with tissue equivalent proportional counters [5].

The procedure adopted to calculate the contribution of different components on board spacecraft is presented and discussed in the following chapters.

1.2. Thermoluminescent Detectors. Two types of thermoluminescent detectors have been used during our on-board studies:

• *Thermoluminescent detectors (TLD)* $CaSO_4$:Dy, the procedure of which preparation is described in [6, 7]. The detector is designed to determine dosimetric characteristics of the radiation with low LET, it can measure photon kerma in tissue from 1 μGy. We have been studying the properties of these materials for many years, including also their response to charged particles with higher LET values, and/or to neutrons [8, 9].

• *Thermoluminescent detectors (TLDs)* Al_2O_3:C [10] were used also to estimate mainly the contribution of on-board radiation component with low LET. They permit one to measure dose equivalent due to low LET radiation from about 1 μGy. They have been studied for several years, including the response to high LET radiation [11]. Their «light conversion factor» (thermoluminescence yield) decreases with the increase of LET above a few keV/μm more rapidly than for other «classical» TLDs, $CaSO_4$:Dy included.

1.3. LET Spectrometer Based on Chemically Etched PADC TED. *A spectrometer of the linear energy transfer (LET)* based on a chemically etched polyallyldiglycolcarbonate track-etch detector (PADC TED) can measure dose and dose equivalent distributions in LET between 10 and 700 keV per μm in tissue [12–15]. Two types of PADC were used: Page, 0.5 mm thick, and Tastrak, 0.5 and 1 mm thick. The etching time in 5N NaOH at 70°C is for all PADC used 18 h, removed layer is about 17 μm thick on each side of the detector. The spectrometer can measure dose equivalent from about 1 and 100 mSv. To determine LET value of a particle, the etch rate ratio $V\,(= V_T/V_B$, where V_B is bulk etching rate and V_T is track etching rate) is established through the measurement of track parameters by means of an automatic optical image analyzer LUCIA G. The V spectra obtained are corrected for the critical angle of the registration and transformed to LET spectra of registered particle tracks on the basis of the heavy charged particle calibration. Recently, an upgrading of the TED-based LET spectrometer calibration curves was achieved using the calibration by means of heavier charged particles with LET between about 8 and 200 keV/μm. Dose characteristics (D, H) due to particles registered by the spectrometer can be calculated from the LET spectra as

$$D = \int \left(\frac{dN}{dL}\right) L dL; \tag{1}$$

$$H = \int \left(\frac{dN}{dL}\right) L Q(L) dL; \tag{2}$$

where dN/dL is number of tracks per unit area in a LET interval; L is the value of LET; $Q(L)$ is the ICRP 60 quality factor [16].

It was found that the integral values obtained for neutrons agree with data measured at CERN, an AmBe source and/or onboard Concorde with tissue equivalent proportional counter [13, 14].

2. RESULTS AND DISCUSSION

2.1. Measurements with Passive Detectors on Board Spacecraft. General characteristics of long-term exposures on board ISS station with passive detectors discussed in this contribution are presented in Table 1. It should be mentioned that the solar activity has decreased

Table 1. **Time schedules of long-term exposures on board space stations***

Operation	ISS exposure	MESSAGE	BASE A
Junction to station	30.11.01	17.10.03	18.09.06
Positioning for exposure	03.11.02	19.10.03	20.09.06
Exposure time, days	328	11**	11**
Landing	05.11.02	28.10.03	29.09.06
Altitude, km	380–420	360–400	340–360

*Inclination always about 52°.
**From that two days at about 100 km lower.

since 2002–2003, it follows that the exposure level would be at constant conditions during 2006 higher. This effect could be partially compensated because the flight altitude was for 2006 exposure lower.

Examples of differential LET distributions of the dose and dose equivalent are for TED LET spectrometer samples exposed during BASE A mission presented in Fig. 2.

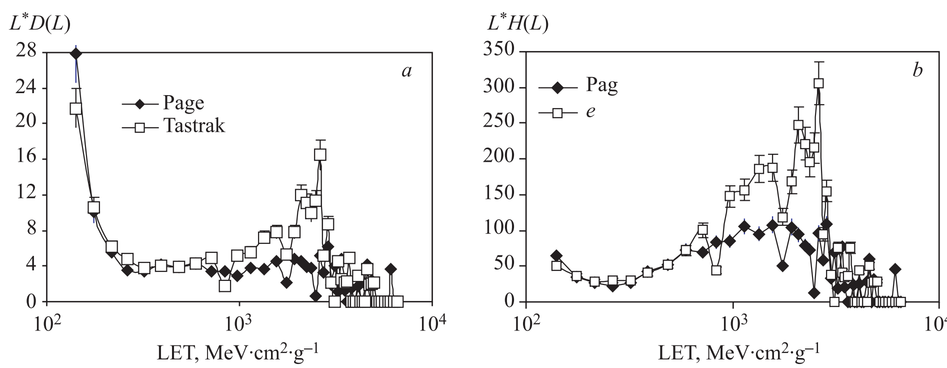

Fig. 2. Differential spectra $L^*D(L)$ (*a*) and $L * H(L)$ (*b*), experiment BASE A (ISS, September 2006)

One can see there that the LET distributions of both dose quantities are rather similar, absolute values being a little higher in the case of Tastrak PADC material. Integral dose quantity values have been calculated from these spectra using equations (1) and (2), it should be reminded that these values correspond only to particles with LET higher than about 10 keV/μm.

These integral values obtained from the TED LET spectrometer data, averaged for both PADC materials used, are presented in Table 2, together with the integral values obtained on the base of TLDs evaluation. One can see there that the results obtained, recalculated to 1 day of exposure, are rather close to each other. Three factors have to be further considered:

1. Decreases of solar activity from 2002 to 2006.
2. Higher flight altitude for the first two exposures when compared to the last one.
3. Two days of lower altitude exposure for MESSAGE and BASE A missions.

Table 2. **Results of TLDs and TED LET spectrometer evaluation during several space missions**

Mission	TLDs,	TED LET spectrometer*	
	H, μSv/d	D, μSv/d	H, μSv/d
ISS	212 ± 15	22 ± 2	202 ± 22
MESSAGE	166 ± 17	16 ± 2	223 ± 27
BASE A	187 ± 15	32 ± 6	236 ± 38

*Corresponding to the particles with LET above 10 keV/μm.

The last factor would increase the values measured roughly by not more than 10%. The similarity of all values determined would mean that, actually, the increase due to decrease of solar activity compensates expected decrease due to lower flight altitude during shorter missions.

2.2. Estimation of Neutron Contribution on Board Spacecraft with MDU-Liulin Equipment. Due to long-term monitoring on board aircraft (2001–2005) and simultaneous measurements on board spacecrafts (ISS — 2001; FOTON capsule — 2005), we were able to compare energy deposition spectra at all the three cases. The results of this comparison are presented in Fig. 3.

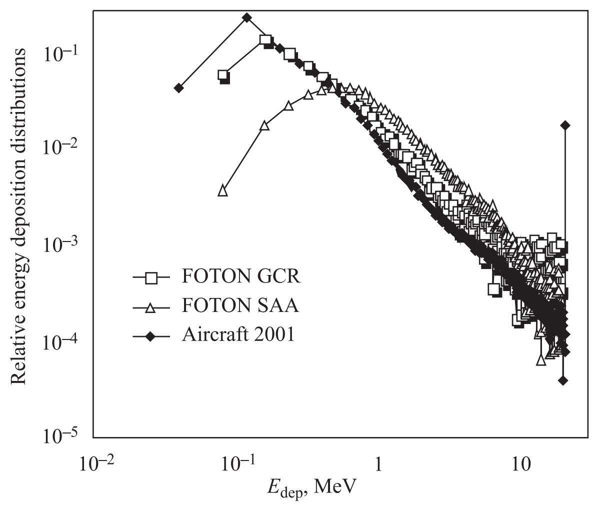

Fig. 3. Comparison of relative energy deposition spectra on board aircraft and FOTON capsule (inside SAA, outside SAA = GCR)

One can see that:

a) Relative energy distributions for $E_{\rm dep} < 1$ MeV are rather similar for aircraft and spacecraft when flying out of South Atlantic anomaly (SAA), i.e., for galactic cosmic rays (GCR);

b) For $E_{\rm dep} < 1$ MeV, the energy deposition spectra on board spacecraft represent a sum of two components, that of neutrons and that of primary galactic cosmic radiation, while on board aircraft only neutrons contribute;

c) $E_{\rm dep}$ spectra inside SAA are quite different from both other cases, being the results of radiation belts protons energy deposition.

We have tried to interpret these data supporting that:

• Events with $E_{\rm dep} < 1$ MeV correspond to low LET radiation;

• Events with $E_{\rm dep} > 1$ MeV correspond to the sum of neutron and heavier charged particles of GCR (HECP).

Based on these assumptions, we have treated these data in the following way:

a) For low LET component $D(\mathrm{Si}) \to D(\mathrm{tissue}) \to H^*(10)$;

b) For neutron contribution in the region of $E_{\rm dep} > 1$ MeV we have adopted the same procedure as on board aircraft [2], considering that the neutron spectra are in both cases similar (see Fig. 4 [17]);

c) For HECP we obtained $H^*(10)$ as: $D(\mathrm{Si}) \Rightarrow D(\mathrm{tissue})$; $5 \times D(\mathrm{tissue}) = H^*(10)$; i.e., supposing that the average quality factor for this component of galactic cosmic radiation is equal to about 5;

d) For flight inside SAA we supposed that all events are due to protons with average QF ~ 1.3, calculated from the energy deposition spectra in Si detector of MDU-Liulin.

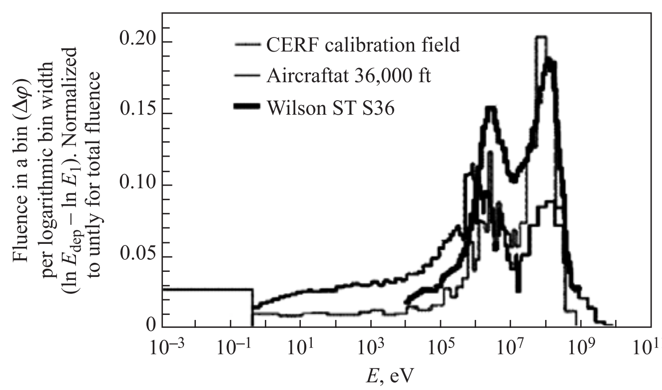

Fig. 4. Neutron spectra on board aircraft, spacecraft, and at CERF

The critical point for the exposure to galactic cosmic radiation is to distinguish as correct as possible the contribution of neutrons in the region of $E_{\rm dep}$ above 1 MeV. For that we have taken profit of the fact that our database concerning exposure on board aircraft is very large (more than 5000 flight hours at altitude, more than 40000 spectra, total D(Si) about 10 mGy). To improve the statistical reliability we have integrated all available data on board aircraft and regressed their energy deposition spectra in the region of $E_{\rm dep}$ above 1 MeV. The results obtained in this way are compared in Fig. 5 with integrated energy deposition spectra on board ISS (D(Si) total $\sim$ 3 mGy), and/or FOTON capsule (D(Si) total $\sim$ 1 mGy). One can see there that, actually, the contribution of energy deposition events in the region of $E_{\rm dep}$ above 1 MeV is clearly higher on board ISS and/or FOTON capsule than on board aircraft.

When using the procedure mentioned above, the contributions of different radiation components estimated for both ISS and FOTON spacecraft are presented in Table 3. For comparison, the values of these contributions established on the base of passive detectors data treatment are also presented in Table 3.

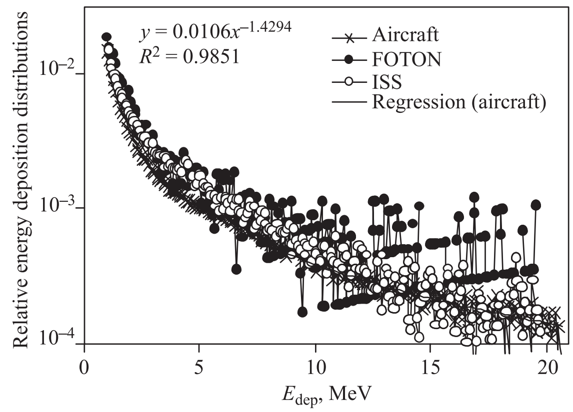

Fig. 5. Comparison of relative energy deposition spectra on board aircraft, ISS, and FOTON in the region above 1 MeV

Table 3. **Total daily values of dose quantities on board space vehicles**

Quantity	ISS-MDU	ISS –TLD + TED	FOTON
D(Si), μGy	237 ± 20	—	87 ± 9
H^*(10) high, μSv	284 ± 50	316 ± 46	115 ± 23
H^*(10) total, μSv	622 ± 88	518 ± 72	316 ± 45
Neutrons, %	20.5 ± 4.5	27.0 ± 5.7	14.5 ± 3.2

One can see there that the results obtained on board ISS with MDU-Liulin agree reasonably well with those obtained with passive detectors. The results obtained on board FOTON are naturally lower, considering its 100 km lower flight altitude.

2.3. Recent Results Concerning the Exposure on Board Aircraft. In this part of the contribution we would like to present recent data concerning:

1. The analysis of the results of long-term measurements performed on board a commercial aircraft in the period 2001–2006.

2. The results of long-term measurements with MDU equipment and passive detectors on board the same aircraft during 2005.

Long-term measurements on board aircraft were performed with MDU-Liulin Si-diode-based spectrodosimeter (MDU) placed on board aircraft (A 310-300) several times in 2001 to 2006. The general characteristics of database collected are given in Table 4. Dosimetric characteristics are based on measurements with MDU and calculated by codes CARI-6 [18] and EPCARD v3.2 [19].

Table 4. **Statistics of database parameters**

Parameter	Minimum	Maximum	Most frequent value (frequency, %)
Altitude, ft	20,000	41,000	35,000 (25)
Vertical cut-off rigidity, GV	0	17	1–3 (70)
Apatity NM, counts/s	1020	1340	1130–1190 (50)

Presently, the database mentioned contains more than 41,000 records. Each record consists of dosimetric characteristics rates identified as H_{app}(MDU), H^*(10)EPCARD, E(EPCARD) and E(CARI-6), and spectrum of pulses recorded in each of 256 channels of spectrometer. They can be treated following:

a) date and time;

b) direction of flight (e.g., Prague–New York);

c) geographic coordinates;

d) altitude in feet (1 foot = 30.48 cm);

e) vertical cut-off rigidity in GV (based on data in 1990 at 20 km);

f) Apatity and Oulu neutron monitors (NM) records (to estimate influence of actual solar activity).

An advantage of the database is that we can choose rates of dosimetry characteristics values measured and calculated for the same conditions taken from the long period. Thus, the average values are mostly statistically significant and easily comparable. We have studied their dependences on the parameters of altitude and rigidity. The results are shown in Fig. 6 as a function of altitude and in Fig. 7 as a function of rigidity. The ratio of non-neutron and neutron components of ambient dose equivalent rates are compared in Fig. 8 (as a function of altitude) and in Fig. 9 (as a function of rigidity). Vertical bars indicate the uncertainty including systematical (15% for both measurements and calculations [20] and statistical (relative standard deviation for an individual value) uncertainties.

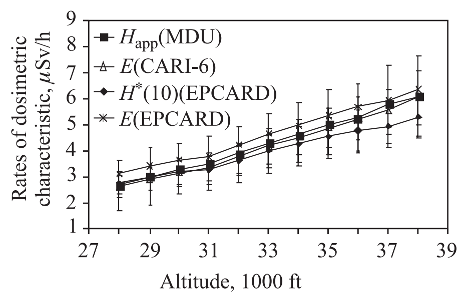

Fig. 6. Rates of dosimetric characteristics measured with MDU and calculated with codes CARI-6 and EPCARD v3.2 as a function of altitude (rigidity is from interval 1–3 GV)

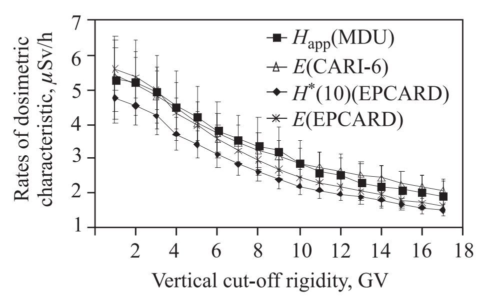

Fig. 7. Rates of dosimetric characteristics measured with MDU and calculated with codes CARI-6 and EPCARD v3.2 as a function of rigidity (for altitude at flight level 35,000 ft)

One can see there that:

• Rates of dosimetric characteristics increase closely proportionally to ascending altitude and decrease with ascending rigidity;

• H_{app}(MDU) and E(CARI) values correlate well;

• H^*(10)EPCARD values are systematically lower than measured; difference rises as a function of altitude (at 30,000 ft is 3%, at 38,000 ft is 13%) and does not depend on the rigidity; E(EPCARD) values are higher than measured between 1 and 3 GV of rigidity for all flight altitudes and are lower from 5 to 17 GV;

• Ratio of non-neutron and neutron components does not depend on the altitude (see Fig. 8), but is high dependent on the rigidity (see Fig. 9); neutron contribution is dominant

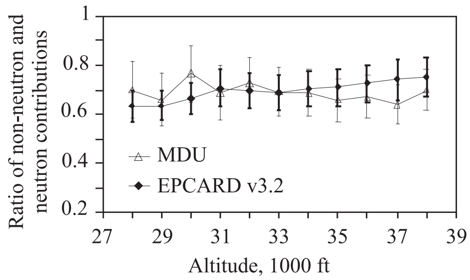

Fig. 8. Ratio of non-neutron and neutron components of $H^*(10)$ measured with MDU and calculated with EPCARD v3.2 as a function of altitude (rigidity is from interval 1–3 GV)

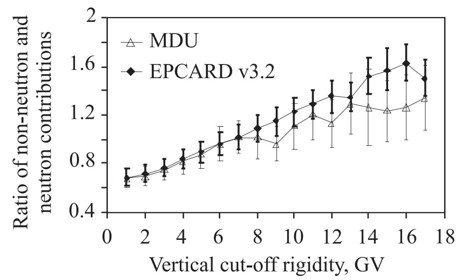

Fig. 9. Ratio of non-neutron and neutron components of $H_{\rm app}$(MDU) and $H^*(10)$(EPCARD) as a function of rigidity (altitude 35,000 ft)

above 7 GV; as far as the influence of rigidity is concerned, the fluctuations above 4 GV are probably caused by lower statistics.

Database enables us to analyse relative D(Si) spectra. Figure 10 shows comparison of relative energy deposition distributions at the same flight level 35,000 ft, at similar solar activity (1130–1190 counts/s of Apatity NM) and three different vertical cut-off rigidities. One can see that contribution of events with $E_{\rm dep}$ between 0.2 and 0.6 MeV with ascending rigidity increases, is constant between 0.6 and 0.9 MeV, and decreases between 0.9 and 7.0 MeV. More measurements with MDU on aircraft flights in areas with rigidity from 4 up to 17 GV should be carried out to accumulate more data to reach better statistics of integral and spectral values.

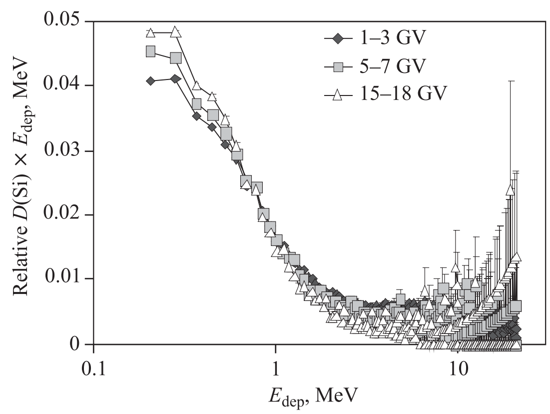

Fig. 10. Geomagnetic position dependence of $E_{\rm dep}$ distribution

To compare the results obtained with MDU equipment and with passive detectors (TLDs and TED-based LET spectrometer, the MDU was on board aircraft (A 310-300) screwed on the inner aircraft wall close to the entrance to cockpit. Si diode, oriented by the surface 10×20 mm of Si diode to sky. Passive detectors were scotched on its surface. The on-board exposure started on the 5th May 2005, the last flight was realized on the 2nd January 2006. In total, 494 individual flights have been monitored during this period. Integral values of dose quantities as obtained by means of different detectors and/or evaluation procedures are presented in Table 5.

One can see there that:

1) Generally, a good agreement can be stated when uncertainties of individually established values are considered in the case of non-neutron component.

Table 5. **Integral values of dose quantities established on board an aircraft during the whole period of monitoring**

Method	Quality	Integral exposure value, mSv		
		Non-neutrons	Neutrons	Total
CARI	E	—	—	11.9
EPCARD	E	—	4.90	11.7
	$H^*(10)$	4.31	5.72	10.0
MDU	$E \sim$	$5.04 \pm 0.50^*$	6.20 ± 0.92	11.2 ± 1.3
TLD – Al_2O_3:C	$H^*(10)$	4.21 ± 0.30	—	—
TLD – AlP glass	$H^*(10)$	4.40 ± 0.18	—	—
LET spectr. Page	$H_{\rm app}(10)$	—	3.6 ± 0.6	—
LET spectr. Tastrak	$H_{\rm app}$ (10)	—	4.3 ± 0.7	—

*Here and in all other cases, 1 s (reliability 67%) is given.

2) The values for neutron component are for MDU, when compared with calculation, a little higher, however within the limit of statistical reliability, lower in the case of both PADC-based LET spectrometer.

3) Lower values for LET spectrometer could be explained considering that it considers only the events with LET higher than about 10 keV/μm, while other methods estimate the neutron contribution independently of LET, PADC-based LET spectrometer.

Finally, it should be mentioned that $CaSO_4$:Dy TLDs have been exposed only from the 23rd August. Its reading corresponded to the value of $H^*(10)$ equal to (2.3 ± 0.2) mSv, in a good agreement with non-neutron component contribution measured for the same period by means of MDU equipment (2.6 ± 0.3) mSv.

CONCLUSIONS

It was proved that both approaches used to determine dosimetric characteristics, i.e. on board space- and aircraft, MDU-Liulin energy deposition spectrometer and thermoluminescent detectors (TLDs) in combination with the LET spectrometer based on track etch detectors, permit one to get independent and relevant data, comparable with those obtained by other methods. In some cases these methods bring new approaches how to treat that complex and important problem.

To get still more relevant appreciation of these methods, other experimental data, supplemented by properly chosen calculations, should be gathered. We are therefore continuing studies similar to those described in this contribution.

Acknowledgements. We acknowledge the colleagues from cosmic ray monitor stations, K. Kudela, M. Stovini and E. Mavromidralaki for providing the data, the colleagues from Czech Airlines V. Hlavatý, B. Kolář for submitting the navigation data and other support, and the colleagues helping us to participate at space missions, V. Shurshakov, and F. Vanhavere. The studies were also partially supported through Grant of the GA CR No. 202/04/0795, the project AS CR K2067107, EC Grant FIGM-00068, and ESA grant DOBIES No. 118401.

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Received on April 17, 2008.