NUKLEONIKA 2004;49(2):77–83

ORIGINAL PAPER

Air-crew exposure to cosmic radiation on board of Polish passenger aircraft

Paweł Bilski,
Paweł Olko,
Tomasz Horwacik

Abstract To establish the need for individual monitoring of air crew, exposure of air-crew members of Polish airlines – LOT to cosmic radiation has been determined and several dosimetry methods tested in flight. Passive radiation dosimetry (using thermoluminescent LiF and chemically etched CR-39 track detectors) was supported by calculations with the CARI computer code. We found that the air crew of most of the LOT aircraft studied (with the exception of those flying ATR propeller aircraft) may somewhat exceed or, in certain conditions (depending on solar activity), may considerably exceed the effective dose level of 1 mSv per year. For crew members flying regularly on B-767 aircraft, the estimated yearly effective dose ranged between 2 mSv and 5 mSv, depending mainly on flying frequency and solar activity. During periods of enhanced intensity of cosmic radiation (i.e. during minimum solar activity) the effective doses could be close to the level of 6 mSv per year.

Key words dosimetry • cosmic radiation • radiation protection

P. Bilski[✉], P. Olko, T. Horwacik
Health Physics Laboratory,
The Henryk Niewodniczański Institute of Nuclear Physics,
152 Radzikowskiego Str., 31-342 Kraków, Poland,
Tel.: +48 12/ 662 84 14, Fax: +48 12/ 662 80 66,
e-mail: pawel.bilski@ifj.edu.pl

Received: 17 July 2003, Accepted: 30 March 2004

Introduction

In 1991, the International Commission on Radiological Protection (ICRP) recommended that exposure of air crew to cosmic radiation be considered as occupational exposure [10]. This was followed by the European Directive 96/29 and recommendations [5, 6] which, among other considerations, state that for air-crew members whose annual effective doses may exceed 1 mSv, dose estimates should be procured. During the following years these recommendations became gradually incorporated into national regulations, which, in Poland, occurred in the year 2000 [1]. For these reasons, and also due to the growing apprehension concerning their radiation safety by crew members themselves, a number of studies on cosmic-radiation exposure of crews of local airlines and on the development of appropriate dosimetry methods, have been undertaken in many countries in recent years [4, 15, 16]. In concert with these studies, a user-friendly computer software has been developed to calculate effective dose. The CARI [7] or EPCARD [14] codes calculate the expected effective dose rate as a function of altitude, geomagnetic latitude and longitude or cut-off, and phase of solar cycle, combined with flight profiles. In several European countries, such as the Czech Republic, France or the Netherlands, these codes have been applied to calculate the radiation exposure of all flying personnel on a regular basis by specialised dosimetry services. EU regulations also suggest that, in addition to calculations, control measurements be performed on board of aircraft to verify code calculations and to identify rare but intensive solar flares which may lead to additional exposure which may occasionally be much higher than that estimated for normal solar-weather conditions. The choice of methods for on-board dosimetry is still under debate since the Tissue Equivalent Proportional Counter (TEPC), considered as a reference instrument for air-crew dosimetry, being sensitive to environmental conditions (such as vibrations, noise, change of pressure, etc.) and requiring specialised service and maintenance, is not applicable as a routine monitoring instrument.

While a broad range of measurements and calculations of air-crew radiation exposure exist, it is difficult to apply them in general, as various national airlines perform their regular flights along specific routes, at various destinations, frequency patterns, different altitude profiles, etc. So far, flight exposures have not been estimated for Polish air crews. The aim of this study was to estimate the in-flight radiation exposure of the air crews of the Polish national airlines – LOT and to field-test the available methods of measuring radiation exposure on board of Polish passenger planes, in view of likely need to establish means of permanent monitoring of radiation exposures of LOT air crews.

The radiation field at flight altitudes

Galactic cosmic ray particles arise from sources outside the Solar System. Their energy extends up to 10^{20} eV. Their composition, by fluence, is 85% protons, 12% helions, 1% heavier nuclei and 2% electrons and positrons. Entering Earth's atmosphere, these particles collide with atoms of air components, producing cascades of secondaries, including neutrons, pions, muons and gamma radiation. At typical commercial flight altitudes (10–13 km) most of the radiation dose originates from secondary particles. Figure 1 illustrates the calculated dependence on altitude of effective dose rate and of its components.

Another factor influencing the dose rate of cosmic rays in the atmosphere is geomagnetic shielding: Lorentz force deflects charged particles moving through the Earth's magnetic field. Only particles with sufficiently high energy are capable of entering the atmosphere. The effect of

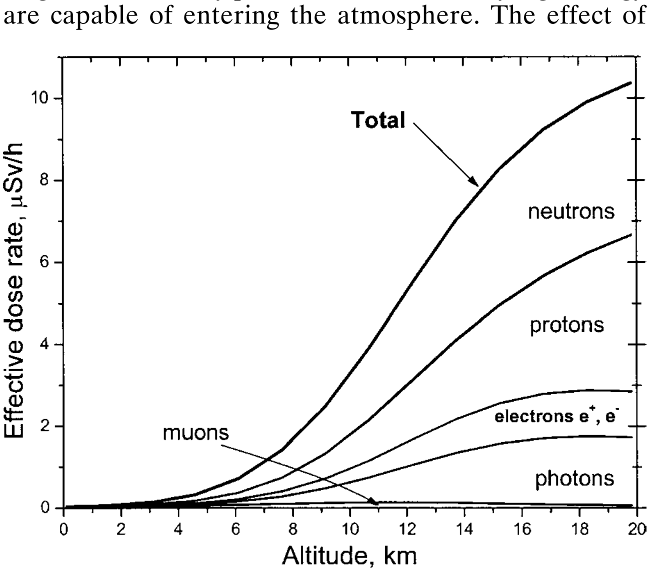

Fig. 1. Dependence of effective dose rate and composition of radiation field on altitude above sea level, calculated with the CARI-LF code, for co-ordinates of Warszawa-Okęcie airport and solar activity typical for the year 2002.

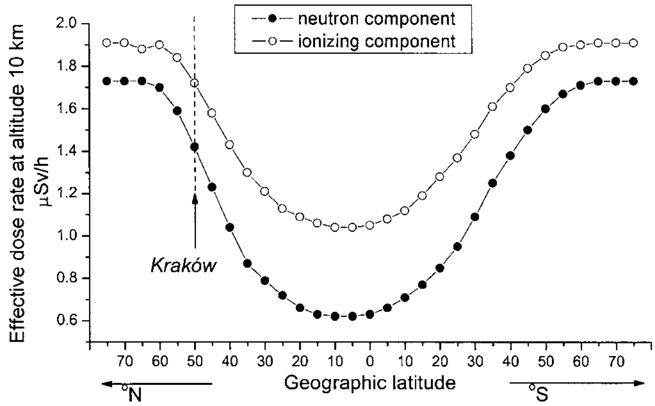

Fig. 2. Dependence of effective dose rate on geographic altitude, calculated with the CARI-LF code for geographic longitude 20° N at 10 km altitude and April 2002 solar activity.

shielding is strongest near the equator (e.g., to reach the region south of India, protons must enter the atmosphere with an energy of 16.7 GeV [9]) and the weakest near the poles. This is illustrated in Fig. 2. Due to this shielding effect, higher dose rates may be expected over northern flight routes (such as those between Poland and North America).

The Sun also affects the intensity of galactic cosmic rays: the more intensive proton flux (solar wind) during the maximum of Sun's 11-year activity cycle modifies the Earth's magnetic field in such a way that GCR particles are more likely to be deflected outside the atmosphere. The intensity of the solar wind, therefore, varies with the 11-year cycle of solar activity. Over periods of high solar activity the solar wind is stronger, thus decreasing the cosmic ray flux (intensity of cosmic radiation anti-correlates with solar activity). The influence of the solar activity on flight dose is illustrated in Fig. 5.

Apart from galactic cosmic rays, the Sun also emits some radiation, consisting mainly of protons with energies too low to enter the Earth's magnetic field. However, during relatively rare (on the average 1 per year) eruptions on the surface of the Sun (solar flares) protons may be emitted with energies exceeding hundreds of MeV or even more. The highest dose rate at flight altitudes so far, was connected with the solar flare of February 1956: the maximum estimate is 10 mSv/h at 10 km [13]. However, all other events have contributed dose rates some ten times lower than this value. As large solar flares occur infrequently and irregularly, their contribution to the total air-crew dose is low and is usually neglected.

Materials and methods

Thermoluminescent detectors

Measurements of photon and ionizing components of the radiation field were carried out using lithium fluoride thermoluminescent (TL) detectors, in the form of sintered pellets of dimensions ∅ 4.5 × 0.9 mm thickness. Two types of TL detectors were used: ^{7}LiF:Mg,Ti (MTS-7) and ^{7}LiF:Mg,Cu,P (MCP-7), which are about 25 times more sensitive than MTS-7 to ^{137}Cs γ-ray doses, but show a significantly lower efficiency after doses of densely ionizing radiation. As the final result, the average of dose values measured with both types of detectors was taken. Prior to their exposure, detectors were prepared by annealing, performed at 240°C/10 min (MCP-7) and 400°C/1 h + 100°C/2 h (MTS-7). Detectors were exposed encapsulated in PMMA holders. Readout was performed using a RA'94 manual reader (produced by Mikrolab Kraków). Detectors were calibrated in terms of air kerma using a ^{137}Cs gamma-ray source of the INP irradiation facility.

CR-39 track detectors

PADC (Polyallyl Diglycol Carbonate) track detectors produced by Track Analysis Systems, TASTRAK® Bristol were applied to measure the fluence of high energy neutrons at aircraft altitudes. This material, known as CR-39, is widely used for nuclear measurements, heavy ion detection, neutron and radon dosimetry. Charged particles passing through the CR-39 damage the detector material along their path. The detector is sensitive to charged particles of LET exceeding roughly 10 keV/mm. Using chemical treatment (etching) it is possible to convert this damage into tracks visible under standard optical microscope magnification. CR-39 panels of size 20 mm × 20 mm × 1 mm were placed together with TL detectors in holders covered with a hydrogen – rich plastic. These radiators, made of 10, 20 and 30 mm thick high density polyethylene (HDPE) and polystyrene (PS) were a source of recoil protons and heavy charged particles from nuclear reactions. After exposure, detectors were etched as follows: step 1 – 40 vol.% ethanol + 60 vol.% 6.25 N NaOH, 45 min, 70°C; step 2 – 6.25 N NaOH, 6 h, 70°C. Track density was determined at the German Aerospace Center (DLR) in Cologne using a Leitz optical microscope with a mechanical stage and different magnification for fast (200x) and accurate (781.25x) measurements.

The advantage of CR-39 detectors is their relatively flat energy response to neutrons in the energy range between 0.5 MeV and 100 MeV [2]. Only tracks of relatively slow (E < 2–3 MeV) recoil protons can be identified and scored. For neutrons of higher energies, tracks produced by alpha particles from the (n,C) reaction are registered.

Albedo dosimeters

As an additional tool, ALBEDO neutron cassettes were applied as personal dosimeters, worn by pilots on their body (trunk). Vinteen ALBEDO dosimeters use ^{7}LiF:Mg,Ti (MTS-7) and ^{6}LiF:Mg,Ti (MTS-6) TL detectors manufactured using lithium highly enriched in respective isotopes. MTS-7 detectors respond only to the ionizing component of the radiation field, while MTS-6 – to neutrons and ionizing components. The difference between the signals measured by these detectors represents the signal produced by neutrons. The ALBEDO dosimeter exploits the effects of moderation and reflection of neutrons by the human body. LiF detectors are sensitive to thermal neutrons through the nuclear reaction ^{6}Li(n,α)^{3}H. In this way, the response of dosimeters is enhanced and less dependent on neutron energy. The ALBEDO cassette, made of boron plastic, shields the TL detectors from ambient thermal neutrons, with a window facing the body in the plastic cassette of the dosimeter, permitting only the back-scattered (albedo) neutrons to reach the TL detectors. The obvious implication of the described technique is that ALBEDO dosimeters may be used only as personal dosimeters, worn on the body.

A serious disadvantage of ALBEDO dosimeters for air-crew dosimetry is their poor neutron energy response above 1 MeV. Therefore, if the measured neutron energy spectrum differs from that used for calibration, the uncertainty of dose measurement is difficult to estimate. However, the results of calculations and measurements of neutron energy distributions at flying attitudes tend to show that the structure of the neutron spectrum does not change significantly, showing two characteristic peaks (at 1–2 MeV and 70 MeV). Therefore, in reproducible flying conditions, the ALBEDO neutron dosimeter can still be applied to indicate the variation of the neutron component and to estimate the effective dose from that component.

Calibration of TLDs in terms of effective dose and ambient dose equivalent

The limits on radiation exposure for workers are expressed in terms of effective dose, a non-measurable quantity which is calculated as a sum of radiation quality-weighted dose contributions from the exposed organs. Ambient dose equivalent $H^*(10)$ and personal dose equivalent $H_p(10)$ are the respective operational quantities, because for most radiation fields they overestimate the value of effective dose. It is recommended that instruments for dose measurements at flying attitudes determine the ambient dose equivalent [8]. These instruments, such as Tissue Equivalent Proportional Counters, recombination chambers or silicon semiconductor spectrometers, are capable of measuring both high and low radiation LET components and of estimating the radiation quality factor, Q. Another possibility is to determine the non-neutron and neutron field components separately, as performed in this study.

There is no established dosimetry protocol to convert the measured TL signal at flying altitudes into effective dose. Bartlett *et al.* [2] proposed a method of calibrating the response of ^{7}LiF:Mg,Ti detectors at flying attitudes in terms of effective dose. Their analysis of photon interaction coefficients and of electron, proton and muon stopping powers in LiF has shown that ^{7}LiF:Mg,Ti TLD calibrated using ^{137}Cs calibration in terms of tissue kerma will estimate the value of absorbed dose to a small mass of tissue for all non-neutron components to within 5%. The contribution of fast neutrons to the signal of ^{7}LiF:Mg,Ti was estimated at the level of 5–10%. About 20% of proton dose, that is 5–6% of the total non-neutron dose component, is deposited by secondary particles from neutron-like interactions.

Taking all this into account, Bartlett *et al.* proposed a factor of 0.92 to the equivalent ^{137}Cs tissue dose to account for the contribution to the TLD signal from both neutron and neutron-like energy deposition. They also concluded that tissue dose may be equated with the average absorbed dose in the human body, with a systematic error of no more than 10%. Finally, the corrected value of tissue dose (D_T) can approximate the value of ambient dose equivalent from non-neutron or neutron-like interactions, i.e. $H^* = D_T \times 0.92$. Applying a proton weighting factor of 5 for energy deposition by protons of energy exceeding 2 MeV [10], the respective component of the effective dose may be also estimated as $E = D_T \times 0.92\,[(1 - X) + 5X]$, where X is the proportion of tissue dose due to protons to the total non-neutron and non-neutron like tissue dose. Lewis [11] estimated the fraction of proton tissue dose at typical flying altitudes to be 18%, which, after deducting 20% of neutron-like interactions (to avoid "double counting" of the protons by TLDs and track detectors), leads to $X = 0.144$. To summarise, the measured equivalent ^{137}Cs tissue dose is multiplied by the factor $0.92[(1 - 0.144) + 5 \times 0.144 \approx 1.45$ to determine the component of effective dose excluding neutron and neutron-like interactions.

Calibration of neutron dosimeters

Neutron dosimeters typically show a significant dependence of their response on neutron energy. It is, therefore, important to calibrate them in a radiation field similar to that measured. The only available laboratory-produced radiation field designed to mimic the cosmic ray field at aircraft altitude is the high-energy radiation CERN reference field (CERF) [12]. In this facility, secondary radiation induced by a hadron beam of momentum 120 GeV/c impinging a copper target and filtered by 80 cm of concrete is used for calibration of dosimetric instruments. The surface mass of the concrete layer is close to that of the layer of atmospheric air above typical flying altitudes. The spectrum of neutrons extends to a few hundred MeV, with a maximum around 70 MeV (and another smaller maximum around 1–2 MeV). CERF usually operates 1–2 times a year. Our ALBEDO dosimeters were exposed to a phantom at CERF and calibrated in terms of the neutron ambient dose equivalent. The results described in this work are based on a calibration exposure performed during the October 2001 run of CERF. Table 1 shows the calibration coefficients for each detector system. To calculate the neutron effective dose, the following average conversion factors for the neutron spectrum at flight altitudes were applied: $H^*(10)/F$ = 242 pSv·cm^2 and E/F = 207 pSv·cm^2 [14], resulting in $H^*(10)/E = 1.17$.

Computer calculations of effective dose

The CARI-6 computer program [7], developed by the US Federal Aviation Administration, is based on the LUIN cosmic radiation transport code and calculates the effective dose of galactic cosmic radiation received during flight. The program requires the following information: time-altitude profile of a flight, geographic locations of starting and landing airports, and solar activity during flight. The basic and most commonly used version of the CARI code assumes a great circle route between airports. Another version, the CARI-6M, calculates dose according to a user-entered route plan consisting of geographic co-ordinates and altitudes. Another version, CARI-LF, calculates not only the total dose but also dose contributions due to particular particles of the cosmic radiation spectrum. For this study, flight dose was calculated with the basic version of the CARI-6 code.

Table 1. Calibration factors (in terms of neutron ambient dose equivalent, H^* and effective dose, E) obtained after irradiation at the CERF facility (CERN, Geneva). The signal of TL detectors was normalised to the signal after exposure with 1 mGy air kerma of ^{137}Cs photons. The uncertainties reflect only statistical fluctuations of counting and not the uncertainty of CERF calibration.

Dosimeter type	Calibration factor H^*	Calibration factor E
ALBEDO	5.12 ± 0.70 mSv/mGy	4.38 ± 0.60 mSv/mGy
CR-39	75 ± 2.2 tracks/cm^2/mSv	64 ± 1.9 tracks/cm^2/mSv

Results and discussion

Personal dosimeters

The first phase of this study consisted of measurements using personal dosimeters, i.e. dosimeters assigned to individual crew members. Thirty selected flight crew members participated in the first measurement run. All the 30 received TL dosimeters for measuring the ionizing component and 15 persons also received ALBEDO cassettes. Each person was requested to fill in individual forms to record their flight data, necessary for CARI calculations.

Most of the air-crew members participating in this stage flew B-767 aircraft on long-distance flights (Poland–North America) and a few flew B-737, EMB-145 and ATR aircraft on European routes. Measurements began in July 2000 and in most cases ended in the second half of September 2000, resulting in an average exposure period of about 2.5 months. Not all dosimeters were returned at the same time, so in a few instances these exposures ranged between 1 and 4 months. A total of 693 flight altitude profiles were recorded. Because the total number of flight hours was much smaller than the total time between annealing of TL detectors and their readout, it was necessary to include the ground level natural radiation dose rate in evaluating the detector readout. We did this by subtracting dose values calculated

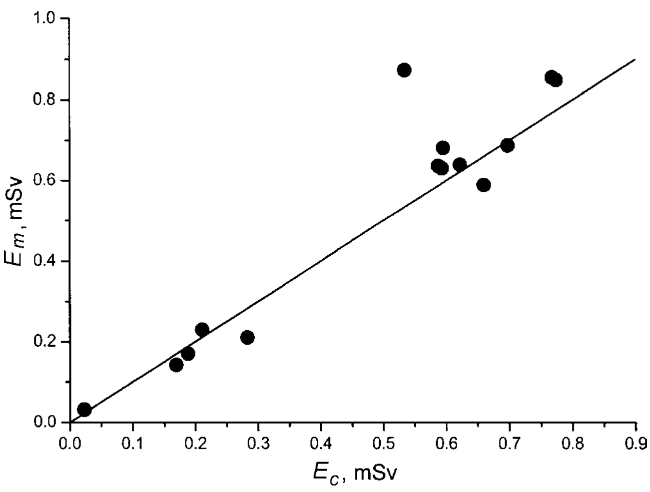

Fig. 3. Values of effective dose calculated basing on measurements with ALBEDO dosimeters (E_m) *vs.* values of effective dose calculated with the CARI-6 code (E_c). The statistical uncertainties (not shown) are within 10%.

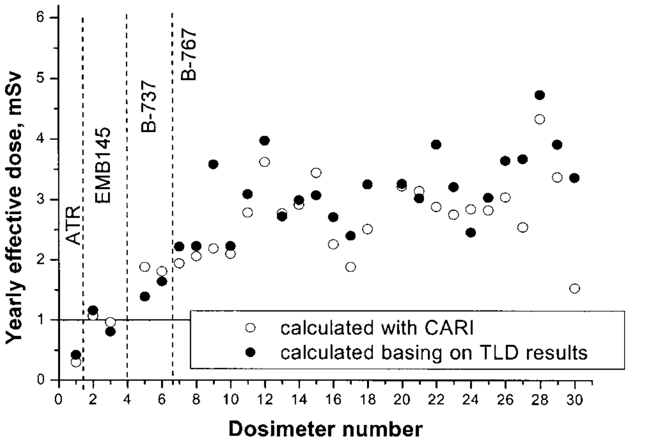

Fig. 4. Values of effective dose calculated basing on measurements and effective dose calculated with the CARI-6 code for all persons taking part in the study. To obtain some rough estimates of total dose for persons not wearing ALBEDO cassettes, the measured value of dose of the ionizing component was multiplied by ratio of total/ionizing dose evaluated for persons flying B-767 and equipped with ALBEDO dosimeters (the value of this ratio was 2.0).

assuming the average value of natural dose rate in Poland as 69 nGy/h. Obviously, the actual natural background radiation could differ from this value, increasing the uncertainty of the obtained results.

In Fig. 3, we compare dose values measured with TL dosimeters with those calculated using the CARI code. Agreement between measurement and calculation typically is better than 15%. For one data point, the measured value is significantly higher than that calculated, perhaps due to incomplete flight data.

Figure 4 presents the values of effective dose for all persons, represented as values extrapolated to the full year from the period of actual monitoring. This approach will obviously increase the uncertainty, as the number of flights per person over the analysed period may not be fully representative and may lead to under- or over-estimation of individual dose values. Values of yearly effective dose were found to exceed 1 mSv for most of the persons monitored. The effective dose obtained for persons flying B-767 was considerably higher than that for crew flying other types of aircraft, with an average value of about 3 mSv. Analysing the dose levels, one should also remember that measurements took place during maximum solar activity, i.e. when the level of cosmic-ray exposure in the atmosphere was the lowest. If the same flights were to have taken place, e.g., three years earlier – in 1997, some 40% higher dose values would result. Multiplying the measured results by this factor would lead to one case where the level of 6 mSv (6.6 mSv for dosimeter #28) would be exceeded. The influence of the solar cycle on the dose received during a flight is illustrated in Fig. 5.

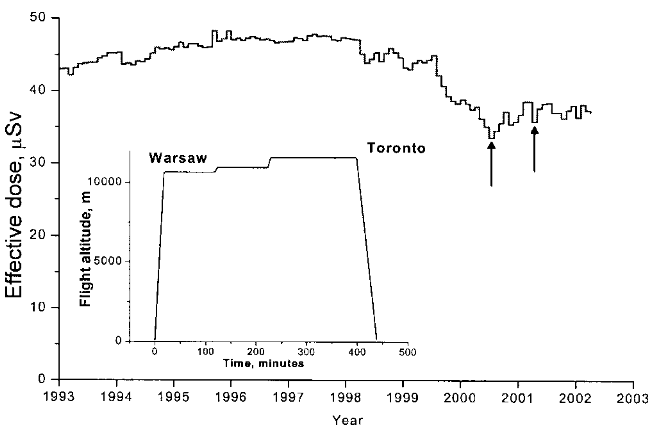

Fig. 5. Effective dose calculated with the CARI-6 code for an exemplary flight from Warsaw to Toronto, over different periods of the recent solar cycle. Arrows indicate approximate dates at which two cycles of measurements were performed in this study. Inset: a time-altitude flight profile.

In Table 2, the lowest and the highest values of effective dose for selected routes, as calculated with the CARI code, are presented. It can be seen that even over the same route and the same solar activity the dose values may differ even by a factor of two, due to the differences in time-altitude profiles.

Environmental dosimeters

The second phase of the study consisted of measurements performed with dosimeters not attributed to any person, but fixed to the aircraft. In this way, the so-called environmental doses (i.e. representing the environment of a workplace), instead of personal doses, were estimated. Detectors (TLDs and CR-39 track detectors) were placed inside cylindrical dosimetric holders made of 2 mm thick polystyrene. Dosimeter assemblies were mounted in the cockpits of seven LOT aircraft: five Boeing-767 and two Boeing-737. The exposure period was about 2.5 months: from the end of February 2001 to around May 10, 2001. The B-767 aircraft flew mostly between Poland and North America, while B-737 – over European and Mediterranean routes.

In the case of these exposures only the lists of performed flights, without detailed altitude profiles, were available.

Table 2. Maximum and minimum values of effective dose, as calculated with the CARI-6 code for selected routes.

Route	Minimum effective dose (μSv)	Maximum effective dose (μSv)
Chicago–Kraków	30.4	50.4
Chicago–Warsaw	27.4	69.2
New York–Kraków	26.3	55.2
New York–Warsaw	26.0	52.6
Toronto–Warsaw	22.6	46.1
Bangkok–Warsaw	26.7	36.9
Hurghada–Warsaw	9.5	12.5
London–Warsaw	5.2	10.5
Paris–Warsaw	6.6	10.4
Kraków–Warsaw	0.16	0.80

Table 3. Values of effective dose (E_m) and ambient dose equivalent (H^*) calculated basing on measurements compared with effective doses calculated with the CARI code (E_c) for the seven aircraft studied.

Aircraft type and number	Flight hours	H^* non-neutron (TLD) mSv	H^* neutron (CR-39) mSv	E_m non-neutron (TLD) mSv	E_m neutron (CR-39) mSv	Total H^* (measured) mSv	Total E_m (measured) mSv	Total E_c (calculated with CARI-6) mSv
B-767 SP-LPA	961	1.41	1.57	2.22	1.34	2.98	3.57	3.79
B-767 SP-LPB	577	0.95	1.19	1.50	1.02	2.14	2.52	2.30
B-767 SP-LPC	1044	1.47	1.77	2.32	1.51	3.24	3.83	4.15
B-767 SP-LOA	1054	1.74	1.94	2.74	1.66	3.68	4.40	4.46
B-767 SP-LOB	1090	1.68	2.47	2.64	2.11	4.15	4.76	4.55
B-737 SP-LLG	376	0.43	0.62	0.67	0.53	1.05	1.20	1.16
B-737 SP-LMC	612	0.67	0.86	1.06	0.74	1.53	1.79	1.72

Therefore, average effective dose values for particular routes, obtained in the previous phase of the study, recalculated for the current solar activity, were used in further calculations.

The results of measurements and calculations are presented in Table 3 and Fig. 6. For the dose values measured with TLDs, results obtained using MCP-7 and MTS-7 detectors, agreed to within 1%. This is a somewhat surprising result, in view of the very different response of these two detector types to different radiation modalities (this issue is discussed elsewhere [3]). The achieved agreement between effective doses calculated basing on CARI-6 results and measurement results was better than 10%. This agreement may be somewhat accidental because measurements of the neutron component were performed at dose levels close to the lower detection limit (LDL) of the track detectors. The value of LDL = 0.32 mSv (in terms of H^*) was established as the double value of the standard deviation of the response of background detectors ($1\sigma_B$ = 12 track/cm^2) and the detector response factor (75 tracks/(cm^{2}mSv)). This relatively high value clearly indicates the need to use high-quality, freshly produced CR-39 for neutron measurements. The largest uncertainty of determining the non-neutron component of E using TLDs appears to result from the applied conversion coefficient from air kerma E/K_{air} = 1.45, and may be as high as 20–30%. However, the measured TL signal was at least one order of magnitude higher than the LDL for LiF:Mg,Ti (MTS-7) and two orders of magnitude higher than that of LiF:Mg,Cu,P (MCP-7) detectors, i.e. 50 μSv and 0.15 μSv, respectively.

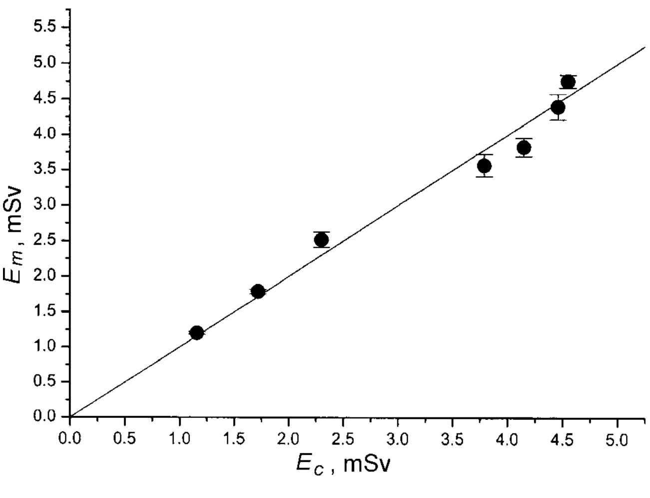

Fig. 6. Values of effective dose (E_m) calculated basing on measurements with environmental dosimeters (TL + CR-39) and calculated with the CARI-6 code (E_c). Error bars represent only statistical uncertainties of measurements. The full line represents $E_c = E_m$.

Conclusions

Almost every studied LOT air-crew member (except those flying propeller ATR aircraft) regularly exceeded or at least could very likely exceed (depending on solar activity) the effective dose level of 1 mSv per year. Values of yearly effective dose received by crew members regularly flying B-767 aircraft range between 2 mSv and 5 mSv, and depend mainly on their flying frequency and on solar activity. During periods of enhanced intensity of cosmic radiation (i.e. during minimum solar activity) it is possible to receive effective doses close to the level of 6 mSv per year, however such cases appear to be rare. Results of calculations performed with the CARI-6 code and measurements performed with TL and track detectors are consistent. The proposed dosimetry package with TLDs for measuring the ionizing component and CR-39 for measuring the neutron component is suitable for environmental dosimetry on board of commercial aircraft.

A system for routine monitoring of radiation exposure of air crew can be based on a simplified calculation of individual dose for each crew member and for each flight. The calculation can be performed using CARI-6 or EPCARD computer codes, taking into account only the solar activity and the position of take off and landing airports, without detailed knowledge of the route. The calculation procedure should be verified by on-board radiation monitoring using the appropriate detectors (e.g. such as those proposed in this study). The measured dose values should be compared with the sum of all dose values calculated for every flight performed during the monitoring period. The aim of such a comparison is not to verify the correctness of the calculation methods (because this would require active systems of dosimetry, such as TEPC or recombination chambers), but rather to identify cases where, over some monitoring period, for one or more aircraft, any significant discrepancy is observed between measurement and calculation. The most likely reason for such a discrepancy could be incomplete or erroneous flight data input to the computer code. However, another reason could be the occurrence, during flight, of a large solar event – an event which cannot be accounted for by CARI-6 or EPCARD calculations.

Acknowledgment This work was partly supported by the State Committee for Scientific Research Grant No. 4PO5D 016 18.

References

1. Atomic Law (2000) Act of the Parliament of Poland of 29 November 2000, http://www.paa.gov.pl (in Polish)
2. Bartlett DT, Hager LG, Irvine D, Bagshaw M (2000) Measurements on concorde of the cosmic radiation field at aviation altitudes. Radiat Prot Dosim 91:365–376
3. Bilski P, Budzanowski M, Marczewska B, Olko P (2002) Response of TL dosemeters to cosmic radiation on board passenger aircraft. Radiat Prot Dosim 100:549–552
4. Curzio G, Grillmaier R, O'Sullivan D, Pelliccioni M, Piermattei S, Tommasino L (2001) The Italian national survey of aircrew exposure: II. On-board measurement and results. Radiat Prot Dosim 93:125–133
5. EURATOM (1996) Basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation. Council Directive 96/29/EURATOM of the 13th May 1996. Official J of the European Communities 19;L159:1–114
6. European Commission (1997) Recommendations for the implementation of Title VII of the European Basic Safety Standards Directive (BSS) concerning significant increase in exposure due to natural radiation sources; DG Environment. Radiation Protection 88
7. Friedberg W, Copeland K, Duke FE, O'Brien III K, Darden EB (1999) Guidelines and technical information provided by the U S Federal Aviation Administration to promote radiation safety for air carrier crew member. Radiat Prot Dosim 86:323–327
8. Golnik N, Silari M, Otto T (1999) On the use of a recombination chamber for radiation measurements in CERN-EU high energy reference radiation fields. Radiat Prot Dosim 86:173–179
9. Heinrich W, Roesler S, Schraube H (1999) Physics of cosmic radiation fields. Radiat Prot Dosim 86:253–258
10. ICRP (1991) Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Annals of ICRP 21
11. Lewis BJ, Tume P, Bennet LGI *et al.* (1999) Cosmic radiation on Canadian-based commercial airline routes. Radiat Prot Dosim 86:7–24
12. Mitaroff A, Silari M (2002) The CERN-EU high-energy reference field (CERF) facility for dosimetry at commercial flight altitudes and in space. Radiat Prot Dosim 102:7–22
13. Reitz G (1993) Radiation environment in the stratosphere. Radiat Prot Dosim 48:5–20
14. Schraube H, Heinrich W, Leuthold G, Mares V, Roesler S (2000) Aviation route dose calculation and its numerical basis. In: Proc of the 10th Int Congress of the International Radiation Protection Association, 14–19 May 2000, Hiroshima, Japan, T-4-4, P-1a-45, pp 1–9
15. Schrewe U (1999) Radiation exposure monitoring in civil aircraft. Nucl Instrum Meth A 422:621–625
16. Verhaegen F, Poffijn A (2000) Air crew exposure on long-haul flights of the Belgian airlines. Radiat Prot Dosim 88:143–148