To the Air Crew Exposure to Cosmic Radiation

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INTRODUCTION

The cosmic radiation is one of the contributor to the natural radiation environment. The level of exposure to it increases with the altitude. At the sea level the annual exposure level is about 0.3 mSv, at the air transport altitudes it can reach 10 µSv per hour. In 1990, the International Commission on Radiological Protection recommended that the radiation exposure due to the cosmic rays at high altitudes be taken into account where appropriate as part of occupational exposure to radiation (1). Air crew members have become in such a way another group of workers for whom exposure to ionising radiation is one of occupational hazard (2-6). Preliminary estimation shows that the level of this exposure is in average higher than for the most of other occupationally exposed groups of persons. It should be also mentioned that there are significant differences in exposure conditions of aircraft crew and occupational exposures generally (6):

- the fraction of absorbed dose deposited at high LET is much greater for air crew, about 50 % as compared to few percents only for others; and, as was noted, there are no useful human data for high LET radiation effects; and
- there is a little more than one half of females in air crew, while they represent only few percents for other occupationally exposed persons.

Both these two factors increase the importance of correct estimation of air crew exposure.
The contribution analyses the level of exposure to cosmic radiation on the board of subsonic aircraft and its variation both from the general point of view as far as on the concrete case of a small air company.

The results of some recent on board experimental measurements are also presented and discussed, they are compared with the results of theoretical calculations used for the general estimation of the exposure level.

COSMIC RADIATION AT SUBSONIC AIRCRAFT ALTITUDE - AIR CREW EXPOSURE ESTIMATION

Cosmic radiation on the aircraft board is composed mostly of secondary particles created during the transport of primary cosmic rays in the Earth's atmosphere. These particles originate mostly (more than 90 %) from the galactic cosmic radiation. The exposure level is predictable, with the exception of very rare giant solar flares. When such event would occur it had to be treated independently. Necessary approaches are not discussed in this contribution.

At the altitudes of subsonic air transport (11-14 km), the radiation field can be divided into (2):

- the component with the low linear energy transfer (LET), mostly the electrons and the high energy (~ 100 MeV) protons; and
- the component with high LET, mostly the neutrons with energies up to about 100 MeV.

These components contribute to the exposure level close to magnetic poles roughly by one half, the importance of high LET component relatively decreases when going to equatorial regions.. The exposure level depends on several parameters, there is a little variability of it within an aircraft.

One can estimate the exposure level on aircraft board experimentally or by calculation. The experimental measurement are rather difficult to organise when a large scale series have to be realised. The calculation can give an estimation of the influence of different parameters much more completely and easily, within reasonable time. The values presented in this chapter were obtained with the code CARI-3N, developed at the Civil Aeromedical Research Institute of the US Federal Aviation Administration in Oklahoma (3). It is at present widely used for this purpose (2,4-6). The exposure level is expressed in the ambient dose equivalent $\boldsymbol{H^*(10)}$.

As the first example, the variations of the dose equivalent rate with the geographic latitude and longitude at the flight altitude 41000 feet and the solar activity close to the minimum during the period 1958-1998 are shown in the Fig. 1. One can see that calculated dose equivalent rate vary at these conditions from about 2.5 close to the equator, to more than 7.5 µSv per hour close to poles.
The combined influence of the solar activity and geomagnetic parameters is demonstrated in the Fig. 2, where the relative values of $\boldsymbol{H^*(10)}$ on some flight routes are presented for the solar activity variations during the period 1958-1998 (heliocentric potential (HCP) between 400 and 1800 MV). One can see there that the exposure levels are at solar minimum for the routes close to magnetic poles (New York, Montreal) up to twice higher than at a solar maximum. For the routes situated close to the equator these variations are much lower, for the route between Abu Dhabi and Bangkok they do not exceed 10 %.

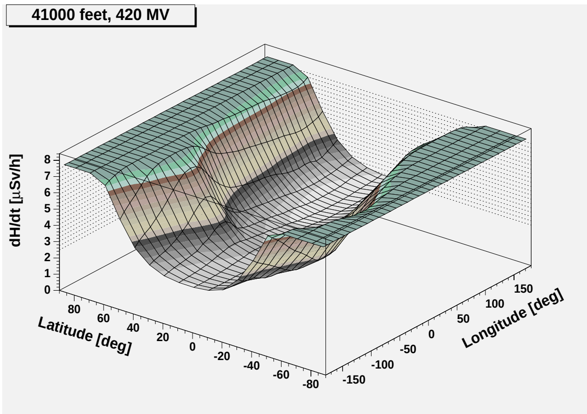


Fig. 1: Geographic variations of the dose equivalent rate at the altitude 41000 feet, at HCP 420 MV

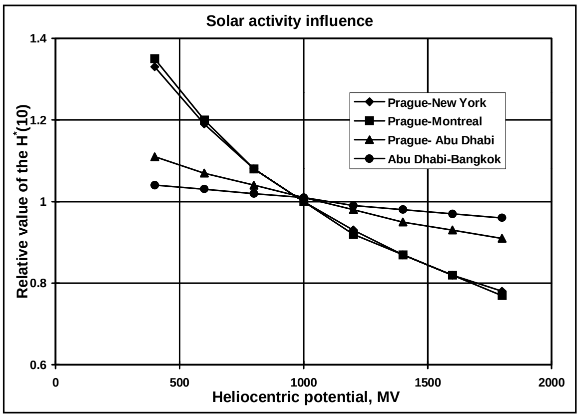


Fig. 2: The influence of solar activity on the exposure level during some flight

As far as the flight altitude influence is concerned, the exposure level increases between 9 and 12 km more than twice, the increase is a little higher in the period of low solar activity

Integral values of the dose equivalent for a route depend also on the duration of a flight. The working engagement of air crew is expressed in so called « block-time », i.e. the time which begin when the aircraft leaves the blocks before takeoff and end when it reaches the blocks after landing. The difference between the « air-time » (the time from takeoff to landing) and the « block-time » is lower for long haul flightsthe aircrafts at these flights are generally flying higher. Based on these factors, it was estimated that the exposure rate levels are, at the HCP about 500 MV, for short haul flights typically around the 2-3 µSv per block-hour, while for long haul flights roughly twice higher.

Annual exposure for an air crew member depends also on the total time of his engagement during a year. They exist a limits, they can differ in different countries. Generally, total number of block-hours per year is limited to less than 1000. For some concrete cases it was estimated that:

- for 700 block hours per year (typical value for the US air companies) the annual exposure would be between 0.14 and 4.1 mSv at HCP = 457 MV (7), or
- 60 % of total UK aircraft crew flying mostly short haul routes would receive annually in average about 2 mSv, 40 % of them flying mostly long haul routes about 4 mSv (6).

Such values are higher than average values for the most of other occupationally exposed group of workers. For example, the average annual dose in the UK was 0.8 mSv in 1996 (6), the average values for Czech Republic over 1975 - 1989 years were between 0.58 and 0.94 mSv for medical occupational exposures, between 1.10 and 1.51 mSv for industrial application of ionizing radiation, with descending tendency (8).

1998 EXPOSURE OF AIRCRAFT CREW OF AN AIR COMPANY

We estimated the exposure of aircraft crew in 1998 for a relatively small air company by calculation, using the code CARI in its version 5E. The complete data on the flights effected have been submitted by the company. The version CARI 5E calculates already the exposure level in the quantity ***effective dose, E,*** used in radiation protection to express the dose limits (1). The calculation was performed on the base of month average values of HCP (all 1998 average value of HCP was 551 MV). As far as the flight altitude's are concerned, the model values has been adopted for each aircraft type (see further). The results obtained can be characterised as follows:

As far as ***the routes*** realised are concerned, they were generally rather short, the average air time was 1.89 hours. As far as the distribution of route effective dose rate is concerned, three maxima were distinguished following the aircraft type and its typical flight altitude. The average value of effective dose rate was 2.59 µSv per hour, when flights with propeller aircraft are omitted, it increases to 3.27 µSv per hour.

The contributions of different routes to the collective effective dose of aircraft crew of the company increases also with the route air time, with the occupancy of an aircraft and with the frequency of a route. For the 1998, about 30 % of the collective effective dose was received on the North Atlantic routes, at the effective dose rates about 6 µSv per hour.

As far as the ***aircraft crew*** exposure in 1998 is concerned, their characteristics can be characterised as follows. The total air time for a member of air crew varied from less than 10 hours up to about 700 hours. The most frequent were times between 500 and 600 hours, the average personnel air time in 1998 was 459,6 hours.

The personal effective dose rate distributions in 1998 showed also several maxims following the most frequent routes and/or aircraft occupied, from less than 1.0 µSv/h up to about 4.5µSv/h.

The annual effective dose distribution of the company aircraft crew in 1998 is shown in Fig. 3.

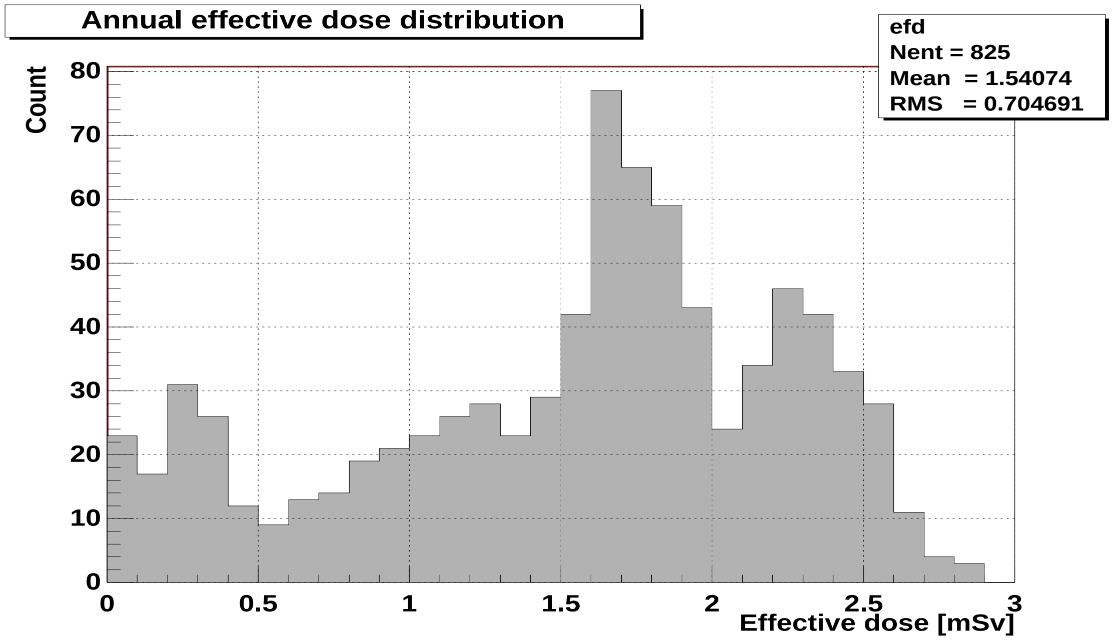


Figure 3: Annual effective dose distribution in 1998

One can see there that the three maxima and a shoulder are observed in this frequency distribution:

- the lowest one, around 0.3 mSv corresponds to cockpit crew of propeller aircraft (9) and to the crew members flying only a little in 1998 (below ~200 hours);
- the shoulder around 1 mSv corresponds to cabin crew flying frequently on board of propeller aircraft;
- the maximum around 1.7 mSv corresponds to air crew flying mostly on board European routes; while
- the highest maximum, at 2.3 mSv to air crew flying mostly North Atlantic routes and these on aircraft flying high.

The average annual effective dose of the aircraft crew of the company was in 1998 1.54 mSv. When only the contributions above 1 mSv are taken into account, the average value increases to 1.85 mSv.

It should be discussed to what extent the values of the annual effective doses obtained and their distribution reflect the real situation. There are mainly two aspects which should be analysed: the relevance of flight route altitudes chosen; and the reliability of values calculated as compared to existing experimental data.

The flight altitudes chosen are very close to the reality for propeller aircraft. For other types the actual average values based on the analysis of data concerning about 1 thousand real flights are probably a little, about 2000 feet, lower (4,6,10). It could decrease the general exposure level by about 15 %, the characteristic features of the distribution would rest unchanged, with the maxims mentioned shifted roughly in the same extent.

However, it was stated several times, that the values of ***H^*(10)*** calculated by means of the CARI code are lower than measured ones , by about at least 30 % (2,6,11). The version used in this work calculates the effective dose ***E***, the quantity which is not directly measurable. Nevertheless, it is known from the model calculation that ***E*** should be for the radiation field on board higher than ***H^*(10)*** (6)**.** We have found out that, actually, the values of ***E*** obtained with the version CARI-5E are for the flights to New York or Montreal about 20 % higher than the values of ***H^*(10)*** obtained for the same flight parameters with the version CARI-3N (10). Nevertheless, the values of ***E*** calculated using of CARI 5E were still about 15 % lower than the values obtained by the linear regression of our experimental data on ***H^*(10),*** obtained between 1991 and 1995. That's why we have realised at 1999 another series of measurements on board of the air company aircraft.

RESULTS OF MEASUREMENTS ON BOARD AIRCRAFT – 1999

Measuring facilities used.

For the low LET component we used mainly (12):

- Reuter Stokes argon filled high pressure steel ionisation chamber RSS 112, reference instrument for environmental gamma radiation;
- NB 3201 scintillation counter, also used for the measurements of environmental gamma radiation; and

- Two types of individual electronic dosemeters, both based on a Si-diode.
- To characterise the contribution of high LET (neutron) component we used following equipment:
- Bubble damage neutron detectors (BDND's) (13) were used to determine the dose equivalent doses from the neutron component. The samples available, with a 100 keV neutron energy threshold, presented a nominal sensitivity of 1 bubble per 1 µSv of AmBe neutrons.
- Superheated drop detectors (SDD), available from Apfel, New Haven, USA, were also used to determine the dose equivalent from the neutron component (14). The samples used, with three energy thresholds (0.1; 1.0; and 6.0 MeV) presented a nominal sensitivity of 3 bubbles per 1 µSv of AmBe neutrons.
- Bubble damage spectrometer, available as well as BDND from the Bubble Technology Industries, Chalk River (15), was used to determine the dose equivalent on the base of an estimation of neutron spectra. It is composed of 6 sets of detectors with 6 "thresholds" in neutron energy: 0.01; 0.10; 0.60; 1.0; 2.5; and 10 MeV. It should be mentioned that these thresholds as well as response functions vary with the temperature of exposure.

Low LET radiation measuring instruments were calibrated with ^{60}Co photons, high LET radiation measuring equipment's with an AmBe neutron source. For both components, the response has been primarily expressed in terms of the ambient dose equivalent of reference radiation. These responses were finally corrected for their response in high energy reference field at SPS facility at CERN (16,17) to obtain ***H*(10)*** values corresponding to the radiation field on board..

Flight routes.

Several types of routes have been chosen to perform the measurements with the goal to characterise the most of possible exposure types for air crew members of the considered air company: intraeuropean flights, mostly to Northern Europe; flights to holiday's region of Spain and/or Greece; northatlantic routes (from Prague to New York and Toronto); and a flight to South-East Asia (Bangkok). Measurements have been performed between March and November 1999; on 11 round trip flights. For each flight, all necessary parameters registered by means of the board computer have been received and the exposure for a flight has been calculated by means of CARI 5E code and compared with the measured data. Some of results obtained with active instruments characterising low LET component and their comparison with calculated data for total effective dose are shown in Figs 4 to 9.

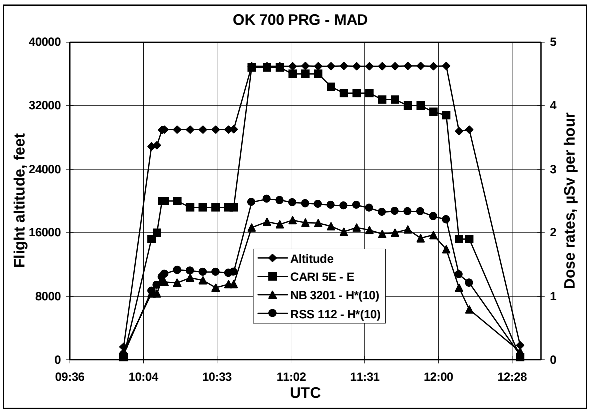


Figure 4: Flight and doses profiles for the flight Prague- Madrid

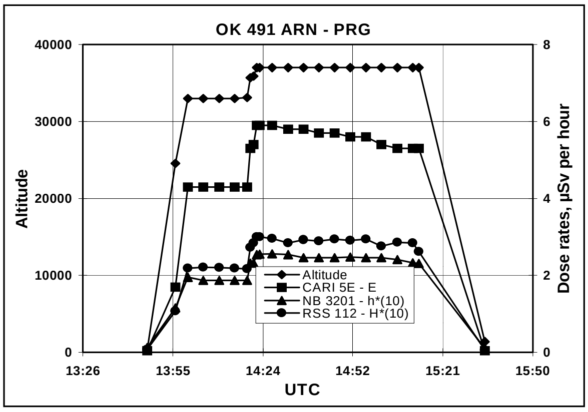


Figure 5: Flight and doses profiles for the flight Stockholm- Prague

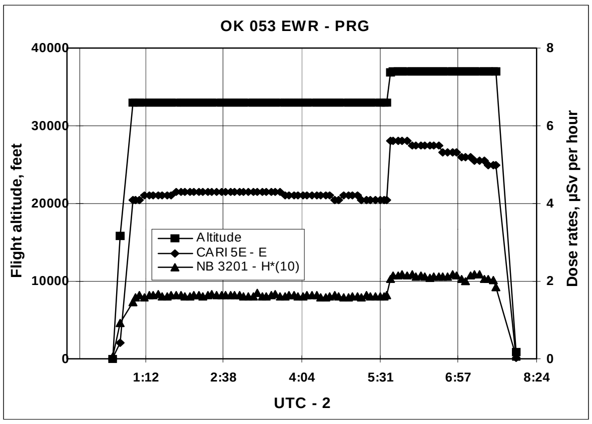


Figure 6: Flight and dose profiles for a flight New York - Prague

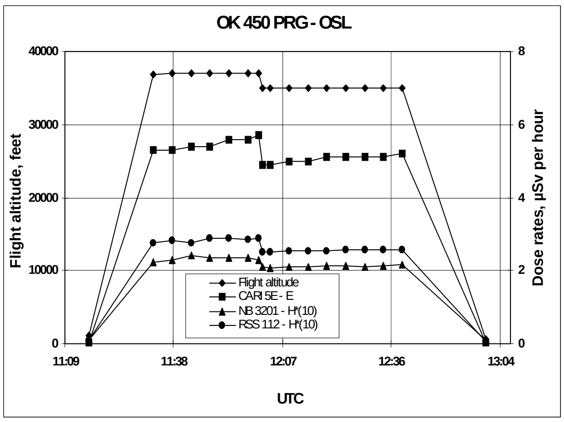
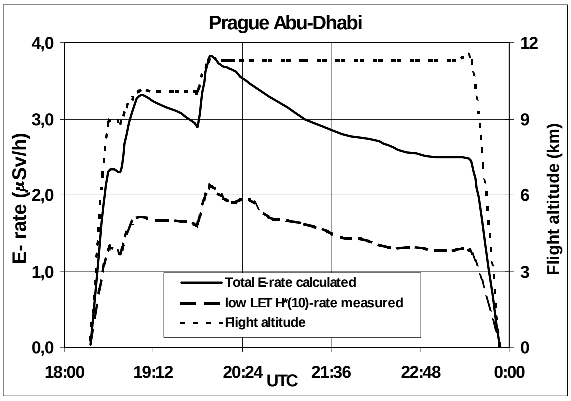


Figure 7: Flight and dose profiles for a flight Prague - Oslo

It is evident from these figures that the values obtained by means of all methods used follow the same tendency, depending on the flight altitude and geomagnetic parameters of a route. For example:

- the influence of geomagnetic position is sensible even for intraeuropean flights like these to/from Madrid, Stockholm and/or Oslo, as well as during the flight from New York to Prague; it is much more evident when flying from Prague to the south-east (Abu-Dhabi) where the influence of geomagnetic position is the most important;
- the exposure level changes substantially with the flight altitude for all routes studied.



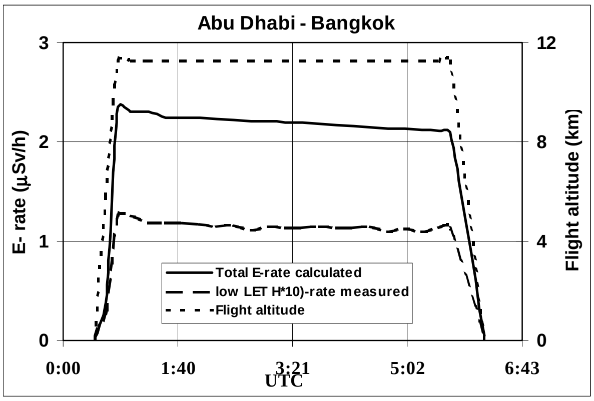


Figure 8: Flight and dose profiles for a flight Prague - Abu Dhabí	Figure 9: Flight and dose profiles for a flight Abu Dhabí - Bangkok

The results obtained with all methods characterising low and/or high LET component on the board have been combined together and corrected taking into account the response in CERN high energy reference field (concrete shielding). For low LET component, mostly the difference between depth dose characteristics of on-board and reference radiation was taken into account, the underestimation of high energy neutrons by bubble detectors was mainly considered in the case of high LET (neutron) component. The experimental integral dosimetric characteristics obtained in this way were expressed in ***H*(10)*** and were compared with the values calculated by means of CARI 5E code, obtained directly in the effective dose ***E.*** As already mentioned, the calculation has been performed in all cases for actual flight altitude profile and geomagnetic parameters of the route, taking into account the actual value of heliocentric potential (solar activity) in a month. First, we have analysed, to what extent our experimental results reflect some of general tendencies.

As we mentioned above, the contribution of both components to total dose equivalent should be for the routes situated not oo far from geomagnetic poles roughly the same, that of high LET component should relatively decrease when going to equatorial region. From that point of view it was interesting to confront our experimental results with this expectation. The results of such confrontation are presented in Table 1.

Table 1: Relative contributions of low and high LETcomponents to the total dose equivalent.

Destination from Prague	Ratio of values high to low LET component	Contribution of high LET component to the total
Northern America	1.15 [1]	0.535 [1]
Northern Europe	1.09	0.521
Southern Europe	0.86	0.462
Abu Dhabi	0.514	0.338
Abu Dhabi - Bangkok	0.439	0.291

[1] Relative uncertainty of values is estimated to about ± 15 %.

One can see in the Table 1 that the tendencies expected are well confirmed by our experimental results:

- the relative importance of both component of radiation field at northern parts is close to be the same, the importance of high LET component clearly diminishes when going to the south,
- the contribution of high LET component diminishes by the same way from about 50 % for northern routes to less than 30 %in the case of the most south route studied.

Experimentaly determined values of dose equivalent ***H*(10)*** for both components were summed up and compared our with the theoretical values of the effective dose ***E*** calculated by means of the CARI 5E code. The results of such comparison are compared in Table 2.

Table 2: Comparison of experimental and calculated total exposure levels on board of aircraft

Flight route	H*(10) measured, µSv	E, calculated by CARI 5E, µSv
Prague-Oslo-Prague	14.8	12.1
Prague-Helsinki-Prague	21.2	17.7
Prague-Madrid-Prague	18.5	16.2
Prague Stockholm-Prague	15.0	15.8
Prague-New York (Newark)	42.4	38.0
New York (Newark)-Prague	33.6	32.2
Prague-St.Petersburg-Prague	20.7	18.2
Prague-Moscow-Prague	17.7	17.5
Prague-Montreal-Toronto	42.6	37.4
Toronto-Prague	45.0	36.9
Prague-Preveza-Prague	15.5	14.6
Prague-Valencia-Prague	17.6	17.9
Prague-Abu Dhabi-Bangkok	26.8	26.9
Bangkok-Abu Dhabi-Prague	29.5	28.2

One can see there, that both sets of values are not very different. Nevertheless, the experimentally obtained values of ***H*(10)*** are a little higher, in average by (9±6) %, than theoretically calculated values of ***E***. However, as it was mentioned, the values of ***E*** should be in the radiation fields on aircraft board higher than the values of ***H*(10) .*** As we have already mentioned the difference in favour of ***E*** should be about 20 % in the case of “northern routes”, a little lower for the routes close to the equator. It seems therefore, that the code CARI 5E still underestimate a little the actual exposure level.

CONCLUSIONS

They are two aspects of the air crew exposure problem which should be emphasised.

The first one concerns the individual dosimetry (or effective dose estimation) for an air crew member of an air company. The results of such “routine” procedure based on the calculation were obtained in this contribution on the base of the calculations by means of one of used procedures (code CARI 5E). Some model approaches were adopted, particularly as far as flight altitude were concerned. We stated, that the values obtained could be about 15 % higher as compared to real flight altitudes. On the other hand, experimentally obtained values of ***H*(10)*** are about 9 % higher than the values of ***E*** calculated on the base of real flight altitudes. When probable underestimation of ***E*** by ***H*(10)*** is considered, the model flight altitudes chosen could well compensate for the underestimation by calculation. Of course, some uncertainties will still exist as far as the absolute values of effective dosis to which air crew members are exposed. Nevertheless, it is believed, that within the limits of about ± 20 %, the values presented in this contribution represent a reliable estimation.

In any case, when requirements concerning the individual dosimetry formulated in international recommendations (± 50 % at the level of few mSv (18)) are taken into account, it seems to us that the accuracy of procedure adopted for individual dosimetry in this work is acceptable.

The second what should be discussed is what to do to improve our knowledge of the exposure level of air crew members. There are two principal ways how to improve it: through the improvement of calculation codes, and/or by means of still more complexe and complete experimental measurements on board, complemented by the calibration in on-Earth high energy reference fields.

It was stated during the last Workshop on the topic (14) that the code CARI is still being updated and improved, it is expected that it would lead to an additional increase of calculated values (20-22). It seems, that the increase would be rather uniform and, therefore, it would not change the distributions like these presented in Fig. 3. Independently, other codes are developed and tested, based or on Monte-Carlo calculation of cosmic ray particle transport through the atmosphere, or on a semiempirical approach (19). It would be very useful to organise an intercomparison of all these codes in larger extent, including the most typical flight routes. Such intercomparison could help in the decision whether and what code should be used.

New measurements on board are also in progress in several laboratories, particularly in the frame of EC projects supporting these studies (23). We would like also to continue the campaign of measurements on aircraft board similarly as that described in this contribution. Further measurements would be more concentrated to the equatorial regions. The calibration of instruments and dosimeters in high energy reference fields are also continuing regularly in the frame of CEC-CERN collaboration on the topic.

Finally, it should be much more deeply analysed, what would be the influence of the changes of solar activity on the exposure levels and their distribution. Let us remind that the values and the distribution presented in Figure 3 correspond to the heliocentric potential of about 555 MV, i.e. closer to the solar minimum of last forty years. The measurement during 1999 were realised in the period of increasing heliocentric potential, from about 600 to about 800 MV. The exposure level will decrease with the increasing solar activity and vice-versa, the distribution of effective dose would rest qualitatively similar. However, it could change quantitatively at still lower levels of solar activity. Due to more pronounced influence of solar activity for North Atlantic routes (see Fig. 2 - flights to New York and Montreal) the maximum at high values of ***E*** could become more pronounced and shifted to higher values during such period, i.e. for some air companies lead to annual exposures exceeding 6 mSv.

From all these reasons it would be very important to concentrate the measuring activities mainly to periods of next solar maximum (2001-2002) and, mainly next solar minimum (2006-2007), which should probably rather sharp.

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