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Estimates of cosmic radiation dose received by aircrew of DCTA's flight test special group

Abstract: *Aircraft crews are subjected to radiation doses of cosmic origin in the regular exercise of their functions. The present paper gives an estimate of typical doses received by crews of the Flight Test Special Group of DCTA (GEEV) from July 2007 to November 2009. The dose estimates were performed using the CARI-6 and PCAIRE codes and were compared with each other and with values obtained by other authors in other regions of the globe, being analyzed from the standpoint of estimating radiobiological risk.*

Keywords: *Cosmic radiation, Aircrew, Dosimetry.*

INTRODUCTION

Cosmic radiation (CR) is formed by several types of ionizing radiation from external sources to our planet, which interact with the Earth's magnetic field, as well as with the components of the atmosphere. The composition of the CR primary field of galactic origin is very heterogeneous, including nuclei (about 98% in total, of which 87% consists of hydrogen, 12% of helium and 1% of heavy nuclei), with a small contribution of electrons and positrons (2%) (Bartlet, 2004). In addition, the contribution of the solar radiation, which is composed of protons, electrons, helium nuclei and electromagnetic radiation, is also presented.

CR penetration depends on several factors, including the Earth's magnetic field and the attenuation caused by the atmosphere, such that only a part of the incident CR reaches the earth's surface, irradiating all living things continuously, including human beings. The particles of cosmic radiation collide with atoms in the atmosphere, causing ionization and losing their energy gradually. The process of energy loss occurs through elastic and inelastic collisions with atomic nuclei, generating a cascade of secondary radiation, as shown in Fig. 1. This secondary radiation includes neutral and charged pi mesons (π^o and $\pi^{+/-}$), and anti-protons and anti-neutrons ($\overline{p}$ and $\overline{n}$), heavy mesons (K) and hyperons (Y) (Hartmann, 2005; Oliveira, 2000; Brum, 2004).

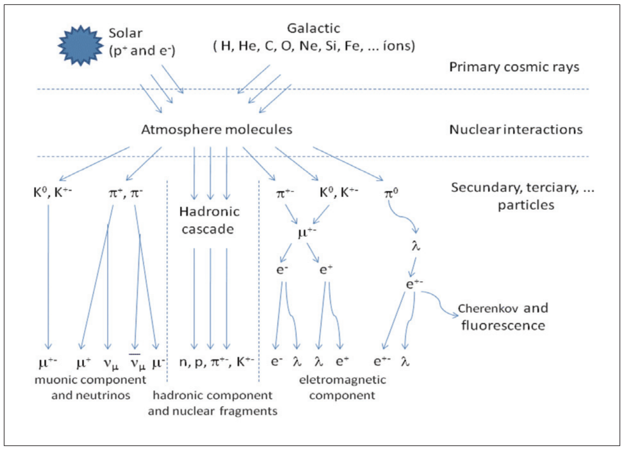

Figure 1: Representation of the reactions involved in the interaction of particles of primary cosmic rays with the atmosphere, giving rise to secondary cosmic rays.

The intensity of cosmic radiation, as well as its composition and co-products, depend on the altitude, and, at higher altitudes, the level of dose received due to cosmic radiation is greater than that at lower altitudes, as can be seen in Fig. 2.

This altitude effect causes the dose to be much higher than that in other groups of workers due to cosmic radiation

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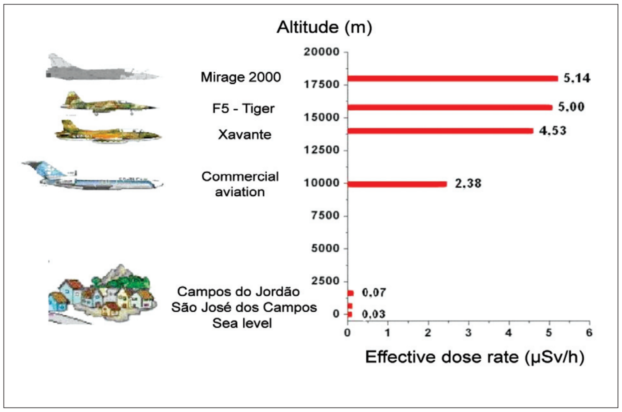

Figure 2: Rates of effective dose due to cosmic radiation as a function of altitude (calculated by CARI-6 code for the region of São José dos Campos, SP, for January 2008).

incident on aircraft crew members, justifying studies and preventive measures that have multiplied around the world (Noll *et al.*, 1999; Hajek, Berger and Vana, 2004; Spurný *et al.*, 2007).

The earth's magnetic field also acts as a shield, deflecting the incident particles on the earth. However, there is a strong dependence of deflection on the latitude of incidence. For instance, near the poles, the dose rate, caused by cosmic rays, is two to three times higher than that in equatorial regions (Lewis *et al.*, 2005). This deflection capacity of the particles is determined by a local characteristic of the geomagnetic field called rigidity cut-off.

An important difference in the case of Brazil is that most of its area, mainly the east coast, is subjected to the effects of a magnetic anomaly whose geological origin is not fully known yet, called South Atlantic Magnetic Anomaly (SAMA) (Lauriente, Vampola and Gosier, 1995; Costa and Mendes Junior, 2004). According to Fig. 3, one can see the SAMA at an altitude of 10 km, where a large part of Brazil, mainly the east coast, is located near the center of this anomaly.

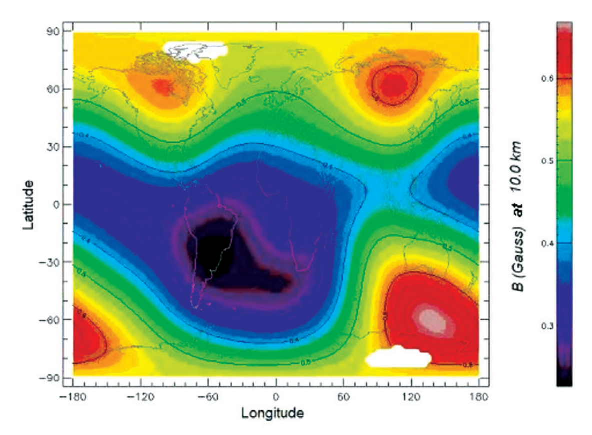

Figure 3: Earth's magnetic field map at 10 km altitude, taken from SPENVIS (2008).

This anomaly modifies the way that cosmic radiation interacts with the geomagnetic field and atmosphere. Many studies have been carried out in this region since 1968 using stratospheric balloons with instruments like scintillation counters and others (Martin, 1972; Costa, 1981; Pinto Junior, 1985). Most of these studies focused on geophysics purposes and mainly X-rays, gamma rays and charged particles fluxes were measured in the energy range from a few keV to hundred of keV's for the former one's and more than 7 MeV for the last one. These studies indicate that the SAMA modifies the radiation incidence in higher altitudes, but no modifications are detected in the aviation flight altitudes or lower.

For dosimetry studies, it is known that the main dose components in aircrews at flight altitudes are the neutrons generated by the interaction of the cosmic radiation in the atmosphere, followed by the electrons, positrons and proton components (Bartlett, 2004). The energy range of these radiations in flight altitudes varies from 0.023 eV to more than 400 MeV (Federico *et al.*, 2009) for neutrons, from tens of KeV to hundreds of MeV for the electromagnetic cascade and from ten's of MeV to hundreds of GeV for the proton component. Also, the flux-to-dose radiation conversion coefficients are highly energy-dependent, varying more than two decades over the range of energy presented at these altitudes, leaving the dose determination highly dependent on the energy spectra of all particles. This wide energy range and dependence increases the importance of complementary studies with dosimetry approach, as it has been done in other countries.

Besides the effects of cosmic radiation dose accumulated in the crew, another important effect, which has led to several recent studies, refers to the induction of failures in avionics by cosmic radiation interaction, a matter that will be addressed in a future work.

DETERMINATION OF COSMIC RADIATION DOSE IN AIRCRAFT CREWS

The complexity of the radiation field to aircrafts flight altitude makes the direct measurement of this field a difficult and expensive work, and few groups dominate this technique in the world. Equipment used for monitoring this type of radiation field must have special characteristics and be well characterized in terms of response to the various types of radiation and of the wide range of energies involved. This equipment characterization should be done in fields that reproduce in whole or in part the fields present in the cosmic radiation at flight altitudes. In addition, in case of lack of access to that type of field, it must be characterized in conventional fields, and the equipment answer should be verified and extrapolated to the fields of cosmic radiation at flight by means of computer simulations.

Thus, the use of monitoring as a routine for aircrews, as done in the nuclear industry workers, would be impractical and difficult to be implemented. Although the International Commission on Radiological Protection (ICRP) in its document number 60 (ICRP, 1991) recognizes and recommends the exposure control for the flight professionals critical group, such as pilots and crews, the same is recommended that this may be done through the use of codes that perform a calculation of the estimates based on interaction of cosmic radiation in space environment and atmospheric data. Moreover, the direct measurements should be taken periodically, as recommended by ICRP (1991), to assess and monitor the accuracy and applicability of computational estimates. This same recommendation was maintained and improved in details in the publications of ICRP numbers 75 (ICRP, 1998) and 103 (ICRP, 2008). Moreover, the European Union and Canada have already recognized aircrews as personnel occupationally exposed to ionizing radiation, as explained by Courades (1999), Transport Canada (2001) and Lim and Bagshaw (2009).

Brazilian regulatory authorities in the nuclear area (*Comissão Nacional de Energia Nuclear* – CNEN) and in the aeronautical area (*Agência Nacional de Aviação Civil* – ANAC) have not issued recommendations or standards in this respect yet, although, in both cases, they normally follow the international recommendations. In both cases, contacts of these authors with those authorities indicate a growing interest and concern on this issue.

COMPUTATIONAL TOOLS

There are several types of computer codes to estimate the dose received by aircrews, which may be based on computer simulations using the Monte Carlo method, the analytical solutions of the transport equation of particles in a material, or solutions provided by empirical function that fits to experimental data.

In this study, CARI-6 and PCAIRE codes were used in order to perform dose estimate calculations, and both codes provide the results in terms of the effective dose quantity, which is a limiting quantity, that is, an appropriate quantity to estimate human health risk due to ionizing radiation and can be directly related to the dose limits set by regulatory authorities.

The computer code CARI-6 (EURADOS, 2004), prepared by the Federal Aviation Administration (FAA), is based on the LUIN code (O'Brien, 1978), which is based on an analytical solution of the general radiation transport equation for the cosmic radiation field, and it calculates the total dose on the shortest path, considering the geodesic curve between the origin and destination airports. The code is DOS-based and require the user to input the date of the flight, the origin and destination airports, the altitudes and duration of flight at those altitudes and the ascend and descend times. The knowledge about heliocentric potential is necessary as an input for the code, so that the doses are weighted by the solar activity. The heliocentric potential values tabulated by the FAA, which represent the monthly averages, were used in this work. The calculation results are recorded in a text file for further analysis.

The PCAIRE code (Lewis *et al.*, 2005) uses a hybrid method composed of a set of fits to experimental ambient dose equivalent measured data, taken with a tissue equivalent proportional counter (TEPC) in a wide range of geomagnetic latitudes and solar cycles. The user is required to input the date of the flight, the origin and destination airports, the altitudes and duration of flight at those altitudes. A great circle route is produced between the two airports and the coordinates and the radiation dose are calculated at every minute of flight by means of an interpolation from an extensive set of data. The conversion of these results in the effective dose is done by the PCAIRE code through a relationship based on FLUKA and LUIN codes calculations. The PCAIRE code is web-based and the results are recorded in a dosimetry report for further analysis.

At the time of this study, none of the codes used allowed dose calculations from solar particle events. Such events consist of sporadic emissions of particles due to large solar flares, which, in some cases, may reach the low atmosphere and significantly increase the doses, especially at higher altitudes and low geomagnetic latitudes. As an example, the greatest event of this type occurred on February 23rd 1956, increasing the dose from a normal level of about 10 μSv/h to about 4.5 mSv/h at an altitude of 9 km (Lewis, Green and Bennett, 2009). The sporadic occurrence of such event is one of the factors that highlights the importance of the experimental measurement ability of this type of radiation field.

RESULTS

This work was performed collecting flight data over a period of two years with the pilots and crews of the Flight Test Special Group (GEEV) of DCTA totalizing 218 flights evaluated. Data were collected through a statement delivered to the crew, which consisted of the following information needed for the evaluation of the estimated doses: origin and destination airports, flight levels, flight duration at each level, ascending and descending time as well as information on the aircraft used.

Averages of evaluated flight altitudes are presented in the histogram in Fig. 4. According to this figure, most of the GEEV flights are performed in low altitudes, which imply lower cosmic radiation dose rates. Only a few cases of flights were at higher altitudes, with pressurized aircraft. In the case of flights made up of more than one level of altitude, the averages were calculated by weighting the time spent at each level. As the flight level, in most cases, is strongly dependent on the used aircraft, this will ultimately bring great influence on the dose rate received by the crew.

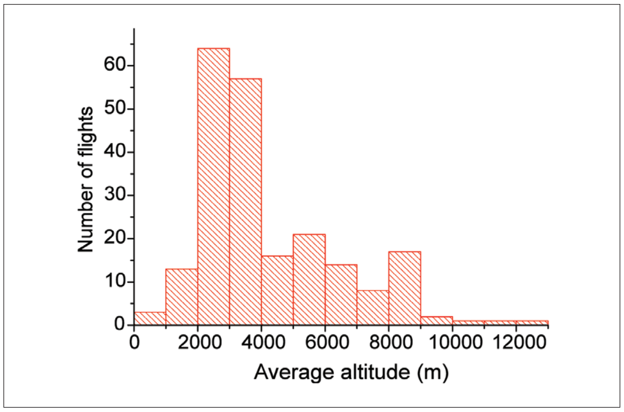

Figure 4: Frequency distribution of the average altitudes of 218 flights evaluated.

The flight data were processed through the CARI-6 and PCAIRE codes, and the effective dose results obtained for each one by the code CARI-6 are presented as a histogram in Fig. 5.

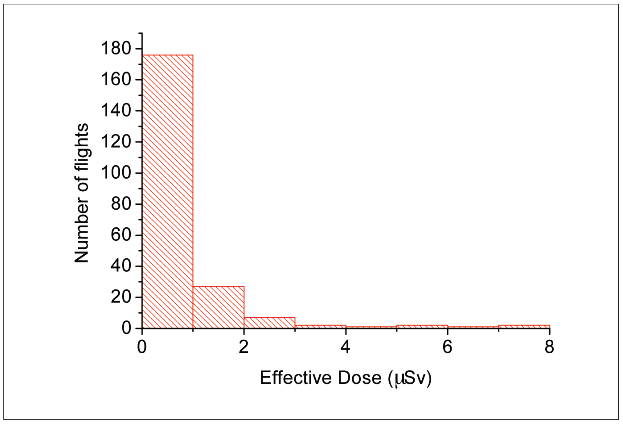

Figure 5: Effective dose histogram for the 218 flights evaluated by the CARI-6 code.

Figure 5 shows that most of the flights received low doses, with the average standing at 0.61 μSv and the mode at 0.13 μSv. The highest value, 7.46 μSv, occurred on a flight from high altitude (12,192 m) and longer duration (2h30min).

DISCUSSION

Altitude dependence

Referring to Fig. 6, it is observed that, as expected, there is a strong dependence of the effective dose rate on the average flight altitude. It is important to mention that the approximated effective dose rate was calculated through the quotient of the effective dose by the total flight time duration, including ascending and descending time intervals.

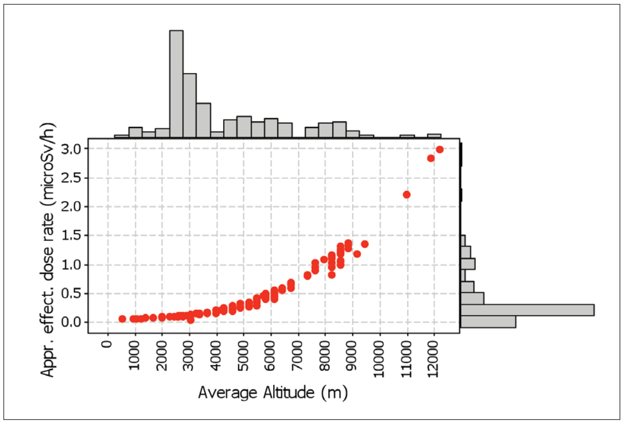

Figure 6: Scatterplot with histograms in the margins showing the relationship between the approximated effective dose rate and the average altitude.

Still referring to Fig. 6, it is clearly noticed that only three flight data greatly differ from the other ones, with values of approximate effective dose rates well above the others. This fact occurs because such flights were held at medium altitudes higher than 10,000 m and were long-term, so that the ascending and descending times do not contribute significantly to total path.

Latitude dependence

In order to analyze the behavior of the effective dose rate as a function of the latitude, a mean latitude point was calculated between the origin and the final destination for each flight. The effective dose rate in this mean latitudes and respective altitudes was plotted in Fig. 7, where only a slightly effect of latitude can be observed in the range of flights. It is clear that most of the flight data is grouped, thus not contributing so much for this type of evaluation.

In the range of the latitude covered by the Brazilian territory (from about 5° N to 30° S), the effect of latitude is more relevant only for high altitudes, as can be seen in Fig. 8, where some calculations are presented for the 45.5 W longitude and latitudes varying from 0° S to 90° S.

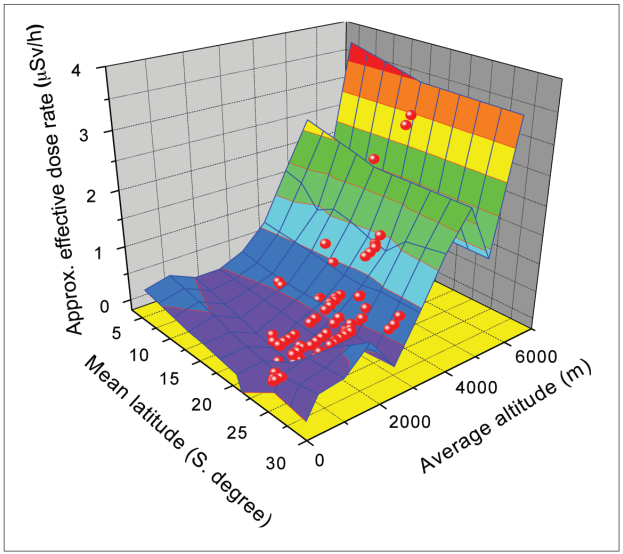

Figure 7: 3-D view of the calculated effective dose rates as a function of the mean latitude and altitude, where the surface plane was a mean approximation for behavior viewing purposes.

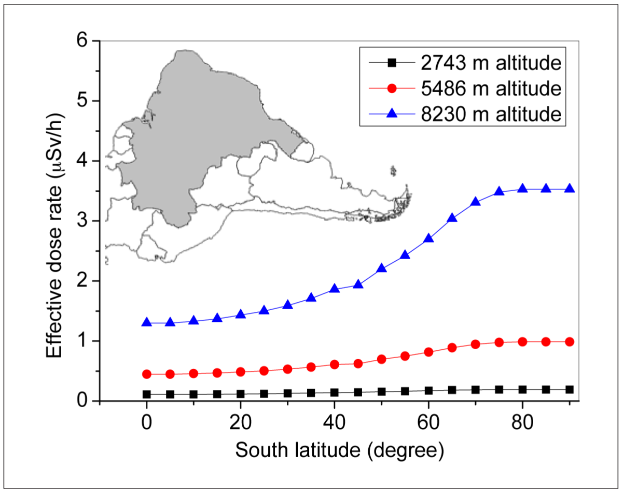

Figure 8: Effect of latitude in dose rates from 0° to 90°, for several altitudes. The map is only present for comparison with the latitude range in Brazilian territory.

In Fig. 8, it can be observed that the flights over the pole are subjected to higher dose rates. This is of special interest for crews that make frequent flights over this region, *e.g.* the crew from FAB traveling to the Brazilian scientific station in Antarctica.

Influence of the solar cycle

The influence of the solar cycle is of great importance in the effective dose rate at flight altitudes. Figure 9 shows a simulation of a hypothetical flight from São José dos Campos (SP) towards Itaituba (PA) for the same month between the years 1995 to 2009, based on the mean heliocentric potential for each year. The anomaly observed in 2000 corresponds to an abnormally high solar activity over the same period in the estimative, which means that the radiation of cosmic origin is expected to decrease due to momentary interaction with the solar field. For the year 2009 and, more recently, in 2010, there was a significant increase in the incidence of radiation resulting from a period of solar minimum that persists with the lowest values of the last century (NASA, 2009).

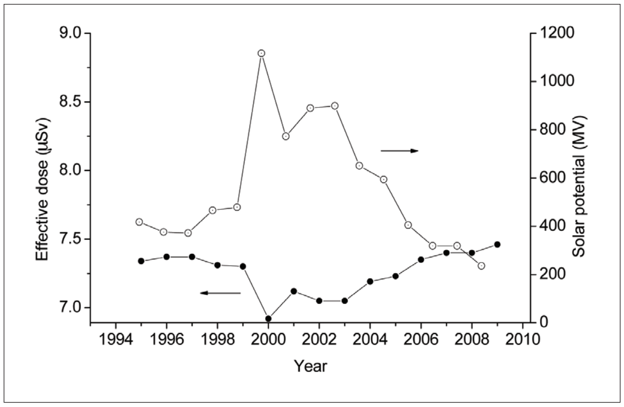

Figure 9: Estimates of effective dose for flights in July from 1995 to 2009, using the CARI-6 code (lower curve) and mean solar potential (uper curve), showing its anticorrelation.

Comparison between the codes

The methodological differences between the used codes cause differences between their results, as can be seen in Fig. 10. In most cases, the CARI-6 code underestimates the dose in comparison to that calculated by the PCAIRE code, as reported by other references (EURADOS, 2004). Part of these differences may be due to a fewer resolution

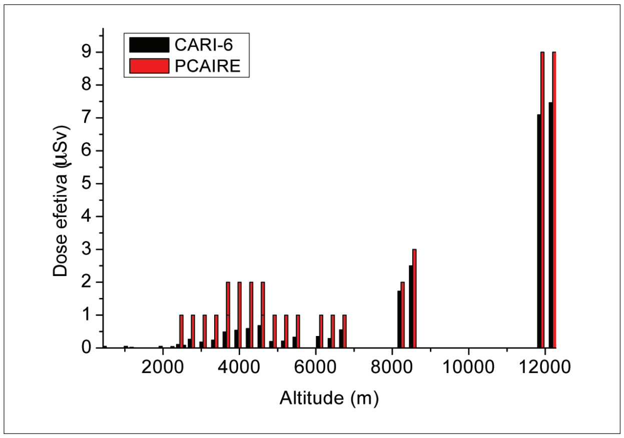

Figure 10: Comparison between results from CARI-6 and PCAIRE codes.

of the PCAIRE code, which is in units of microsieverts while the CARI-6 code has resolution of decimal of microsieverts leading to high differences as up to one microsievert region, as can be seen in Fig. 11.

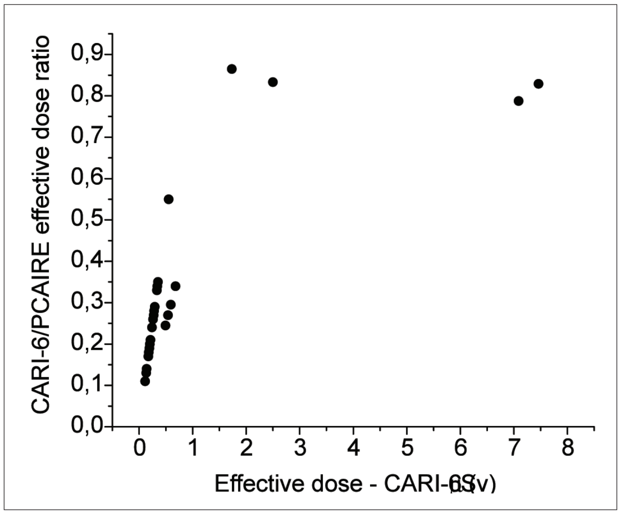

Figure 11: CARI-6/PCAIRE code dose ratio as a function of the CARI-6 code dose.

Comparison with other results

The doses calculated in this work are within the range of 0.02 μSv to 7.46 μSv for all flights, and the majority of them (93%) is in the range from 0.02 μSv to 2.00 μSv. These values are consistent with those obtained by Tommasino (1999) in routes between Rome and Rio de Janeiro (from 2.0 μSv to 2.4 μSv) which, otherwise, had been subjected to SAMA in only a part of this route and in a lower intensity radiation period also. The majority of the doses obtained in the present study lay bellow the values estimated by FAA for the US flight crew (FAA, 1990) for commercial routes, which varies from 0.2 μSv to 9.5 μSv, but the entire range of our calculated doses is consistent with FAA's range. Furthermore, the majority of the results obtained in this work lay bellow those calculated by Alves and Mairos (2007) for similar military flight crews, which varies from 1.0 μSv to 16.5 μSv. The lower altitudes and geomagnetic location of the flights of GEEV make it difficult to compare with results from other studies that were mostly made in commercial altitudes in North American or European routes.

CORRELATION WITH BIOLOGICAL EFFECTS AND DOSE LIMITS

Biological effects of ionizing radiation can be divided into two types: deterministic effects and stochastic effects. Deterministic effects are those caused by high doses over short periods of exposure, resulting in the so-called acute radiation syndrome, a set of characteristic symptoms and effects of exposure to high doses of radiation. These types of effects are not observable in case of exposure of aircrews to cosmic radiation, which are several orders of magnitude lower than those needed for the occurrence of such effects.

In the case of stochastic effects, they are linked to the likelihood of deleterious damage arising from molecular ionization that, in the event of molecules into the cellular DNA, can cause neoplasic changes leading to the occurrence of cancer and hereditary effects, in the case of germ cells. Such effects are typical of exposures at low doses and long exposure periods, such as exposure of aircrews to cosmic radiation.

The limitation to the likelihood of deleterious effects is accomplished through effective dose limits established by regulatory agencies based on biostatistics observed in irradiated large populations (such as Hiroshima and Nagasaki) and experiments with animals extrapolated to effects of long exposure in low doses.

This limitation is reflected in the primary limits on annual effective dose, which are established for individuals who usually work with ionizing radiation and have their health and doses monitored, and also for individuals who are not normally exposed, referred to as the public. The primary limits of effective dose, established in Brazil by CNEN and consistent with international recommendations (ICRP, 1991) is 20 mSv per year (averaged on 5 consecutive years) for individuals occupationally exposed and 1 mSv per year for the general public.

Epidemiological studies have been conducted since 1990 with the objective of evaluating health risks of aircraft crew members (Blettner and Zeeb, 1999). Although there have been noticeable increases in the incidence of breast cancer in female crews, as well as slightly increased incidence of brain tumors and melanomas in crews of both gender, it is difficult to assess the real origin of those risks since many factors such as variation in the circadian rhythm and UV incidence work together with the incidence of cosmic radiation as possible causes.

Special care has to be taken in relation to pregnant female aircrew, since the total dose of the fetus must be kept as low as possible and always below 1 mSv in the whole gestation period. This limitation must be considered in the case of frequent flyer aircrew.

CONCLUSIONS

The collected data show that the dose varies from 0.02 μSv up to 7.46 μSv per flight. Due to the low frequency of flights, crews which were evaluated are located in a range of annual cumulative dose well below the 1mSv annual limit for public individuals. For this work condition, additional controls are not justified for the GEEV aircrew.

Likewise, it is possible to see that flights of longer duration and altitude, approaching the condition of commercial flights, can reach and probably exceed cumulative doses of about 8 μSv per flight. This condition implies the possibility of exceeding the annual primary limits for individuals of the public if these crews, for example, carry out more than 125 flights of this type. This frequency is easily exceeded in the case of commercial flight crews.

Another aspect to be highlighted concerns the importance of the ability to measure this type of radiation during flights in order to verify and monitor the computer estimates, in accordance to the provisions in the guidelines of the ICRP. This training is being developed within the Institute for Advanced Studies (Federico *et al.*, 2009), and has special importance due to the fact that the codes to estimate doses crews were rarely used and evaluated in confrontation with experimental measurements in the South America region. An evaluation of the codes in this region is particularly important and interesting, mainly due to the existence of the SAMA.

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