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Radiological Protection from Cosmic Radiation in Aviation

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EDITORIAL

To be drafted

ABSTRACT

Radiological protection from cosmic radiation in aviation

ICRP Publication 1XX

Approved by the Commission in Month 201X

Abstract–In this report, the Commission provides updated guidance on the radiological protection from cosmic radiation in aviation taking into account the current ICRP system of radiological protection, the latest available data on exposures in aviation and the experience gained worldwide in their management. The report describes the origins of cosmic radiation, how it exposes passengers and aircraft crew, the basic radiological protection principles that apply to this existing exposure situation, and the available protective actions. For the implementation of the optimisation principle, the Commission recommends a graded approach proportionate with the level of exposure that may be received by individuals. The objective is to keep the exposure of the most exposed individuals to reasonable levels. The Commission also recommends that information be disseminated to raise awareness about cosmic radiation, and to support informed decisions among concerned stakeholders.

Keywords: Cosmic radiation; Aviation; Aircraft crew; Frequent flyers; Graded approach

PREFACE

"*Well, I made it*!" were the first words of aviator Charles Lindbergh after the *Spirit of St. Louis* touched down on Le Bourget airport after flying 5,800 kilometres from Long Island (*The New York Times*, 21 May 1924). The observers of the time emphasised the courage of the pioneer against the cold, the weather conditions and the tiredness – but no one talked about radiation exposure! And for good reason. Only a handful of scientists were aware of the phenomenon at that time. This pioneering performance opened the way for transcontinental flights. Since the flight of Charles Lindbergh, the increase in an airplane's performance and capacity, low-cost companies and expansion of tourism, have led to large increases in the number of air passengers: in 2013, around 3.1 billion flight tickets were sold, and this figure is expected to double by 2030 (International Civil Aviation Organization Air Navigation Report, 2014). Furthermore, the business jet market continues to grow at about 4 % per year, and this fleet is expected to double by 2032. This raises the potential for a significant increase in individual and collective exposure from cosmic radiation of aircraft crew and passengers keeping in mind that the opportunities and mechanisms to control exposure in aircraft are very limited.

Given this context, the Main Commission of ICRP approved at its meeting in Cape Town, South Africa, in October 2010, the formation of a Task Group, reporting to Committee 4, to develop guidance on radiological protection against cosmic radiation exposure in aviation.

The terms of reference of the Task Group was to prepare a publication that describes and clarifies the application of the 2007 Recommendations (*Publication 103*) for the protection of aircraft crew, and also passengers, against cosmic radiation exposure and particularly frequent flyers. The publication should discuss the type of exposure situation relevant to the control of exposures in aviation and the appropriate radiological protection principles to be implemented. Particular attention should be given to the implementation of the optimisation principle, which is the cornerstone of the system of radiological protection recommended by the Commission.

The membership of the Task Group was as follows:

J. Lochard (Chair)	J-F. Bottollier-Depois	W. Rühm
D.T. Bartlett	R. Hunter	H. Yasuda

Corresponding member was:

S. Mundigl

Committee 4 Critical Reviewers were:

M. Kai D.A. Cool

Main commission Critical Reviewers were:

H. Liu S. Romanov

Acting as Secretary of the Task Group, Sylvain Andresz provided a welcomed scientific assistance during the preparation of this report. Numerous helpful comments were also received from Gerhard Frasch, Gérard Desmaris and Frank Bonnotte. The Task Group would like to thank all of these persons as well as Le Centre d'étude sur l'Evaluation de la Protection dans le domaine Nucléaire (CEPN, Fontenay-aux-Roses) for their valuable support.

The Task Group met on 1-2 February 2011 at CEPN premises at Fontenay-aux-Roses, France and then worked by correspondence.

The membership of Committee 4 during the period of preparation of this report was:

(*2009-2013*)

J. Lochard (Chair)	W. Weiss (Vice-chair)	J-F. Lecomte (Secretary)
P. Burns	P. Carboneras	D.A. Cool
T. Homma	M. Kai	H. Liu
S. Liu	A. Mc-Garry	S. Magnusson
G. Massera	K. Mrabit	S. Shinkarev J
J. Simmonds	A. Tsela	W. Zeller

(*2013-2017*)

D.A. Cool (Chair)	K-W. Cho (Vice-chair)	J-F. Lecomte (Secretary)
F. Bochud	M. Boyd	A. Canoba
M. Doruff	E. Gallego	T. Homma
M. Kai	S. Liu	A. McGarry
A. Nisbet	D. Oughton	T. Pather
S. Shinkarev	J. Takala	

MAIN POINTS

- **Cosmic radiation is composed of high-energy particles originating from space and from the Sun. Basically, the higher the altitude and the latitude, the higher the dose rate. Solar eruptions can also affect dose rate of cosmic radiation. As a result, flying in aircraft increases exposure to cosmic radiation.**
- **Considering that the number of passengers will continue to increase, and aircraft technology will enable planes to fly for longer duration and at higher altitudes, cumulative exposures of aircraft crew and passengers to cosmic radiation are likely to increase. The Commission therefore considers that the development and implementation of a protection strategy is justified.**
- **Exposure to cosmic radiation, including solar eruptions, is considered by the Commission as an existing exposure situation.**
- **The Commission continues to consider that the exposure of all aircraft passengers, mainly occasional flyers, but also frequent flyers - for personal needs or for professional duties - should be regarded as public exposure, and that the exposure of aircraft crew should be treated as occupational exposure.**
- **The Commission also considers that exposure should be maintained as low as reasonably achievable (ALARA) with a dose reference level selected in the 5–10 mSv/year range. Selection of the dose reference level should be done taking into account the level of exposure of the most exposed individuals who warrant specific attention.**
- **For the practical implementation of the protection strategy, the Commission recommends a graded approach based on the flight frequency of the individuals.**
    - **Most passengers in aircraft are occasional flyers and their exposure to cosmic radiation is considered negligible in the context of their total radiation exposure. However, the Commission recommends that general information about cosmic radiation should be made available to all passengers.**
    - **For frequent flyers for personal reasons and personal duties, in addition to the recommendation to provide general information, the Commission encourages the self-assessment of their doses in order, if desired, to adjust their flight frequency.**
    - **For the small fraction of frequent flyers for professional duties of which exposures are comparable to those of aircraft crew, the Commission recommends that the requirements for aircraft crew could be utilised on a case-by-case basis through interactions between the individual and their organisation, according to the prevailing circumstances.**
    - **For aircraft crew, the Commission recommends that the operating management:**

(i) Individually inform the aircraft crew about cosmic radiation through an educational programme;

(ii) Assess the dose of aircraft crew using dedicated calculation programmes;

(iii) Record the individual and cumulative dose of aircraft crew. These data should be made available to the individuals and kept for sufficient time; and

(iv) When appropriate, to respect the selected dose reference level and after consultation with the concerned aircraft crew, operating management may adjust the flight schedule.

- **Pregnant frequent flyers for personal reasons or professional duties may adjust their flight frequency to limit the cosmic radiation exposure to their embryo/fetus. For pregnant aircraft crew, airline management should have provisions in place to adjust duties during the remainder of the pregnancy after its notification.**
- **The Commission also recommends that national agencies or airline companies disseminate information to raise awareness about cosmic radiation and support informed decisions among all concerned stakeholders, and foster a radiological protection culture for occupationally exposed individuals.**

GLOSSARY

Categories of exposure

The Commission distinguishes between three categories of radiation exposure: occupational, public, and medical exposures of patients.

Cosmic radiation

Cosmic radiation is the ionising radiation consisting of high-energy particles, primarily atomic nuclei, of extra-terrestrial origin, and the particles generated by interaction with the atmosphere and other matter.

Primary cosmic radiation is cosmic radiation incident from space and the Sun at the Earth's orbit.

Secondary cosmic radiation comprises particles that are created directly or in a cascade of reactions by primary cosmic radiation interacting with the atmosphere or other matter. Important particles with respect to radiological protection and radiation measurements in aircraft are: neutrons, protons, photons, electrons, positrons, muons, and to a lesser extent, pions and nuclear ions heavier than protons.

Galactic cosmic radiation (GCR) is cosmic radiation originating outside the solar system.

Solar cosmic radiation (SCR) is cosmic radiation from the Sun.

Detriment

Detriment reflects the total harm to health experienced by an exposed group and its descendants as a result of the group's exposure to a radiation source. It is a multi-dimensional concept. Its principal components are the stochastic quantities: probability of attributable fatal cancer, weighted probability of attributable non-fatal cancer, weighted probability of severe heritable effects, and length of life lost if the harm occurs.

Embryo

The human product of conception up to approximately the end of the second month of pregnancy.

Emergency exposure situation

Emergency exposure situations are exposure situations resulting from a loss of control of a planned source, or from any unexpected event involving an uncontrolled source (e.g. a malevolent event). These situations require urgent and timely actions in order to avoid exposure to occur or to mitigate it.

Employer

An organisation, corporation, partnership, firm, association, trust, estate, public or private institution, group, political or administrative entity, or other persons designated in accordance with national legislation, with recognised responsibility, commitment, and duties towards a worker in her or his employment by virtue of a mutually agreed relationship.

Existing exposure situations

Existing exposure situations are exposure situations resulting from sources that already exist when a decision to control the resulting exposure is taken. This includes natural sources [cosmic radiation, radon and other naturally occurring radioactive material (NORM)] and man-made sources (long-term exposure from past practices, accident or radiological events). Characterisation of exposures is a prerequisite to their control.

Exposure situation

A situation where a natural or man-made radiation source is transferred through various pathways, and the radiation results in exposure of human or biota.

Exposure pathway

A route by which radiation or radionuclides can reach humans and cause exposure.

Fetus

The prenatal development stage of a mammal in the later stages of development, when it shows all the main recognisable features of the mature animal, especially a human fetus from the end of the second month of pregnancy until birth.

Fluence

Fluence is the number of particles incident on a sphere of cross-sectional area (e.g. a number of protons per cm^{-2}).

Frequent flyer

A person who regularly travels by aircraft, for personal reasons or for professional duties and who might be registered in a frequent flyer programme. Some frequent flyers may fly at a frequency that is of the order of magnitude of a typical aircraft crew (e.g. 500 h a year).

Graded approach

A graded approach aims to ensure that the recommendations or requisites formulated for a group of individuals are commensurate and proportionate with their level of exposure, considering also the prevailing circumstances.

Justification

The process of determining whether: (1) a planned activity involving radiation is overall beneficial [i.e. whether the benefits to individuals and to society from introducing or continuing the activity outweigh the harm (including radiation detriment) resulting from the activity]; or (2) the decision to control exposure in an emergency or an existing exposure situation is likely overall to be beneficial (i.e. whether the benefits to individuals and to society (including the reduction in radiation detriment) outweigh its cost and any harm or damage it causes).

Occasional flyer

A person who travels by air from time to time, generally for personal purposes or professional duties.

Occupational exposure

This refers to all exposure of workers incurred as a result of their work; however, because of the ubiquity of radiation, the Commission limits its use of 'occupational exposure' to radiation exposures incurred at work as a result of situations that can reasonably be regarded as being the responsibility of the operating management.

Operating management

The person or group of persons that directs, controls, and assesses an organisation at the highest level. Many different terms are used, including, e.g. chief executive officer, director general, managing director, and executive group.

Optimisation of protection

The principle of optimisation of radiological protection is a source-related process aiming to keep the magnitude of individual doses, the number of people exposed and the likelihood of potential exposure as low as reasonably achievable (ALARA) below the appropriate dose criteria (constraints or reference level), economic and societal factors being taken into account.

Planned exposure situations

Planned exposure situations are exposure situations resulting from the deliberately introduction and operation of sources. Exposures can be anticipated and fully controlled.

Principles of protection

The three basic principles that structure the system of radiological protection: the principle of justification and the principle of optimisation of protection that apply to all controllable exposure situations, and the principle of application of dose limit that applies only to the planned exposure situations.

Protection action

Action set to protect people from the harm of radiation. Protection actions are generally those that influence the distance to the source, time of exposure, or the shielding.

Reference level

In emergency and existing exposure situations, this represents the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimisation of protection should be implemented. The chosen value for a reference level will depend upon the prevailing circumstances of the exposures under consideration.

Risk

Risk relates to the probability that an outcome (e.g. cancer) will occur. Terms relating to risk are grouped together here:

Excess relative risk (ERR) is the difference between a risk factor and a specific outcome. For example, ERR could be the difference between the proportion of subjects in a population with a particular disease who were exposed to a specified risk factor and the proportion of subjects with that same disease who were not exposed.

Relative risk is the ratio of the incidence rate or the mortality rate from the disease of interest (e.g. cancer) in an exposed population compared to the same ratio in an unexposed population.

Solar particle event or solar proton event (SPE)

An unusually large fluence of energetic solar particles ejected into space by a solar eruption.

Sun's solar wind

The solar wind is a plasma of electrons and protons that boils off the solar corona and propagates – due to the Sun's magnetic field – radially from the Sun at a velocity on average of 400 $km.s^{-1}$. The solar wind carries with it a relatively strong and convoluted magnetic field. The Sun's solar wind is responsible for the aurora in the Arctic (*aurora borealis*) and the Antarctic (*aurora australis*).

1. INTRODUCTION

(1) Reaching one's seat in an aircraft can sometimes be a long journey. After check-in and police control, one has to undergo airport security control. Radiation may play a role in this process, being used to screen carry-on luggage, and in some cases, screen individuals themselves. The Commission has recently published recommendations on radiological protection on security screening (ICRP, 2014).

(2) After take-off, as the aircraft climbs to cruising altitude, exposure to cosmic radiation increases. At typical cruise altitude (>10,000 metres), the dose rate can reach 7 $\mu Sv.h^{-1}$ (more than 150 times the cosmic radiation exposure at sea level). The future use of new ultra long-range jets that fly at higher altitudes, and for longer durations, is estimated to increase the dose by 30–50% compared to current flight practices.

(3) So far, the Commission has developed a set of recommendations regarding specifically the radiological protection of aircraft crew and notably pregnant aircraft crew (ICRP, 1984, 1991). The report intends to review these recommendations but also consider the exposure of passengers and notably the exposure of the so-called frequent flyers travelling for personal reasons or as part of their job.

1.1. Background

(4) The Commission first mentioned exposure resulting from flying at high altitude in *Publication 9* (ICRP, 1965). The Commission also noted in paragraph 88 of *Publication 26* that "*flight at high altitude*" can increase the normal exposure to natural radiation (ICRP, 1977). In paragraph 10 of *Publication 39*, "*flying in the present manner*" was presented as an example of an existing exposure situation (ICRP, 1984).

(5) The Commission then published its first recommendations on protection against cosmic radiation exposure in *Publication 60* (ICRP, 1991). The Commission recommended that the personnel involved in the operation of commercial jet aircraft should be treated as occupationally exposed. As doses are not likely to exceed a pre-defined value because of the limitations of flight duration, individual monitoring using dosimeters was not considered necessary. Furthermore, the Commission pointed out that attention should also be paid to groups such as frequent flyers and couriers who fly more often than other passengers. There was no mention of protection of the remaining passengers.

(6) The Commission subsequently clarified its recommendation in *Publication 75* (ICRP, 1997), indicating that because a business traveller could only receive an annual effective dose in the range of 1 mSv (considering about 200 h of flying at about 5-6 $\mu Sv.h^{-1}$), the Commission considered that the only group occupationally exposed to elevated levels of cosmic radiation was aircraft crew. The Commission also reiterated that there is no need to consider that the use of designated areas in aircraft and the annual effective doses to aircraft crew should be derived from the flying time and typical effective dose rates for the relevant routes, and the control of exposure mainly ensured by restrictions on the flying time and route selection. Recently, the International Commission on Radiation Units and Measurements (ICRU) jointly with ICRP published reference and data for the validation of doses from cosmic radiation to aircraft crew to facilitate international harmonization of dose assessments for aircraft crew by airlines and their regulators (ICRU, 2010).

(7) The report supersedes the previous ICRP recommendations in this area.

1.2. Scope

(8) The Commission has recently published recommendations on controlling exposure from cosmic radiation in space in *Publication 123* (ICRP, 2013). The purpose of the present report is to update and clarify the recommendations of the Commission on controlling exposure from cosmic radiation in aviation. This report takes into account the evolution of the general recommendation in *Publication 103* (ICRP, 2007) for the protection of aircraft crew. The report is intended to enlarge the scope of discussion beyond aircraft crew by considering the exposure of passengers, notably frequent flyers for personal reasons or professional duties. Given the high proportion of female cabin crew, the report also addresses the topic of the exposure of pregnant women.

1.3. Structure of the report

(9) Chapter 2 presents the characteristics of exposure in aviation from cosmic radiation. It provides a brief description of the source and pathways of exposure as well as an insight on solar eruptions, routine assessment of levels of exposure and individual and collective dose data. Chapter 3 describes the Commission's system of radiological protection in the context of cosmic radiation exposure in aviation, including the type of exposure situation, the category of exposure concerned and the basic principles to be applied. Chapter 4 provides guidance on the implementation of the system of radiological protection using a graded approach for the various exposed individuals: occasional flyers, frequent flyers and aircraft crew. A section addresses the particular situation of the exposure of pregnant passengers and aircraft crew.

2. CHARACTERISTICS OF EXPOSURE FROM COSMIC RADIATION IN AVIATION

2.1. Historical background

(10) In September 1859, R.C. Carrington, an English amateur astronomer, observed a solar eruption with a major mass ejection that travelled towards the Earth. Telegraph systems failed all over Europe and America, and auroras filled the sky as far south as the Caribbean. Today, it is known that solar particle or proton events (SPEs), such as this 1859 event, release relatively high-energy particles.

(11) In 1912, V. Hess took a historic balloon ride with three ionisation chambers to an altitude of 5,300 metres. He found higher levels of radiation as he rose that he attributed to ionising radiation: four times that on the ground at the flight peak. Hess ruled out the Sun as the source of radiation by making several balloon ascents at night and one during a total eclipse. He concluded "the results of my observation are best explained by the assumption that a radiation of very great penetrating power enters our atmosphere from above" (*Physikalische Zeitschrift*, November 1912).

(12) In 1925, R.A. Millikan proved the extra-terrestrial origin of these radiations and introduced the terms “cosmic rays” and “cosmic radiations”. In the same year, A. Compton had the idea that cosmic rays were primarily charged particles.

(13) Commercial supersonic planes were developed during the 1960’s: the Tupolev-144 prototype first flight in 1968 and the Concord prototype in 1969. The high altitude at which supersonic planes cruised (around 19,000 meters) increased concerns on the exposure of aircraft crew and passengers to cosmic radiation. To ensure the monitoring of doses, some aircraft crew carried personal dosimeters and a radiometer was installed in the Concord. A special dosimeter was also developed for the Tupolev-144’s aircraft crew. In the case of a significant increase in radiation level (e.g. 300 µSv/h in Tupolev 144), the plane would descend to lower altitude. This marked the beginning of the routine monitoring of exposure to cosmic radiation in aircraft. Nowadays, the dose from cosmic radiation in aviation is monitored using computer codes.

2.2. Source and pathways

(14) The Earth is exposed continuously to high-energy particles that come from outside the solar system – galactic cosmic radiation (GCR) – and from the Sun – solar cosmic radiation (SCR). In addition, the Earth is exposed occasionally to bursts of energetic particles from the Sun (SPEs). GCR is mostly protons (85 %) with an energy fluence distribution that extends from 10^6 electron volts (eV) to more than 10^{20} eV. These high-energy particles are a particular characteristic of cosmic radiation, and contribute greatly to the dose. Protons with energies generally below 10^6 eV constitute 99% of SCR. GCR and SCR are commonly referred to as primary cosmic radiation (UNSCEAR, 2008; ICRU 2010).

(15) GCR interacts with the atomic constituents of the atmosphere, producing a cascade of interactions and secondary reaction products that contribute to cosmic radiation exposure (Fig. 1). These decrease in intensity with depth in the atmosphere, from aircraft altitudes to ground level. The decrease is almost linear between 16 and 8 kilometres of altitude: – 1.5 $\mu Sv\ h^{-1}\ km^{-1}$ (EC, 2004).

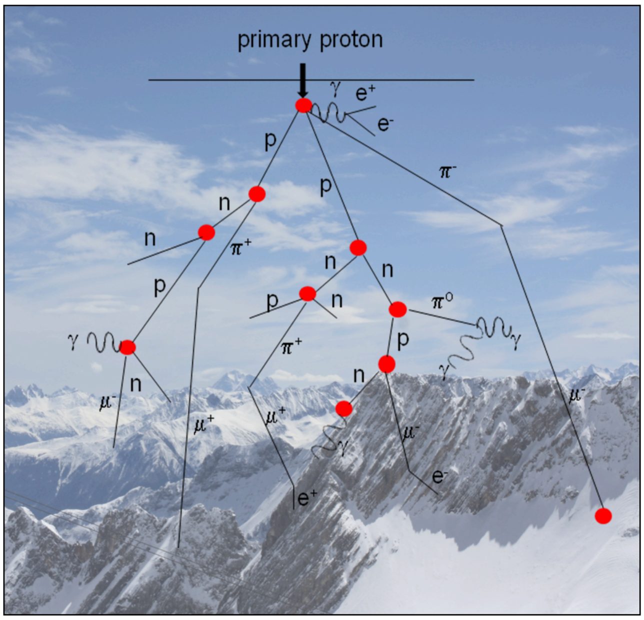

Fig. 1. Cascade of secondary cosmic radiation, μ: muon, e^{-}: electron, e^{+}: positron, γ: photon, n: neutron, p: proton, π: pion (Rühm, 2012).

(16) Since the particles making up GCR are electrically charged, they can be affected by the magnetic field of the Sun's solar wind – the plasma of protons and electrons from the solar corona that generate a magnetic field throughout the solar system. The magnetic fields deflect the low-energy GCR that would otherwise enter the Earth's atmosphere. The solar wind varies with the Sun's 11-year solar cycle, and causes variations in the magnetic field. Close to the Earth's orbit, GCR is at a maximum during solar minimum activity, and GCR is at a minimum when the Sun's activity is greatest with sunspots, flares and coronal mass ejections (Fig. 2).

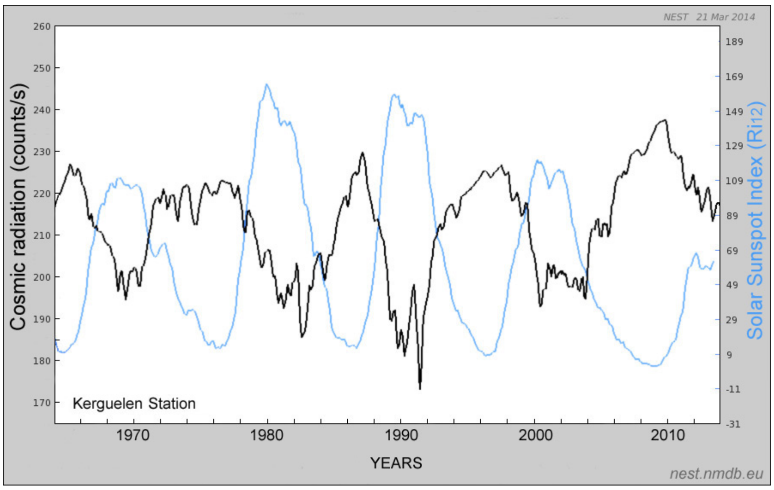

Fig. 2. The anti-correlation between the activity of the Sun (expressed as the number of sunspots– blue curve) and the cosmic radiation exposure (expressed as the monthly average neutron counts– black curve) from 1964 to 2014 (Paris-Meudon Observatory data).

(17) Paths of cosmic radiation particles are also bent as they cross the magnetic field of the Earth, which acts as a partial shield against charged particles. Near the

equator, where the geomagnetic field is nearly parallel to the ground, fewer particles reach lower altitudes: the magnetic shielding effect is greater. Near the magnetic poles, where the geomagnetic field is nearly vertical to the ground, the maximum number of primary cosmic radiation particles can reach the atmosphere and generate secondary radiation that penetrates to aviation altitudes. Thus, rates of cosmic radiation exposure are higher in polar regions, and lower near the equator (Fig. 3).

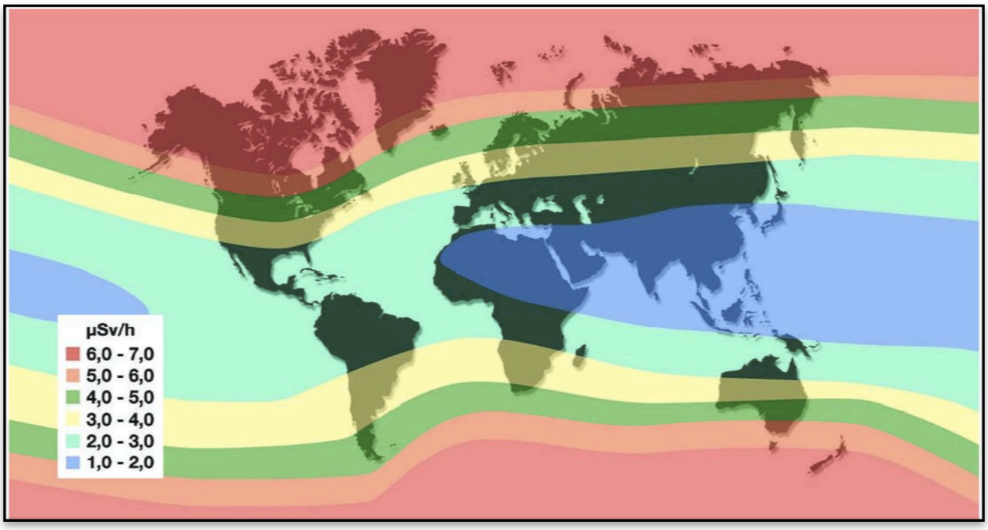

Fig. 3. Geomagnetic shielding of cosmic radiation: Ambient dose rate by latitude and longitude at 11 km altitude in December 2002 (Frasch, 2012).

(18) In summary, the cosmic radiation field in aircraft is modulated by altitude, geomagnetic latitude, and solar cycle. At normal aircraft altitudes and at the equator, the electrons/positrons and neutrons are the larger components in dose, followed by protons. In contrast, at higher latitudes, the dose comes mostly from neutrons (Table 1). Additionally, at higher altitudes, nuclei heavier than protons (e.g. Fe) start to contribute.

Table1. Contributions to cosmic radiation by its ambient dose equivalent component according to latitude (at the altitude of 12,000 metres and at solar minimum) (EC, 2004).

Component	Equator	High latitude
Muons	5 %	3 %
Electrons/positrons	38 %	14 %
Neutrons *	37 %	64 %
Protons	12 %	14 %
Photons	8 %	5 %

* The radiation weighting factors for neutrons used in the computation of dose vary as a continuous function of neutron energy (ICRP, 2007).

2.3. Solar eruptions

(19) Exceptional high levels of radiation can occur from SPEs. The mean energy of the particles of SPEs – mainly protons – is generally below 100 MeV. Neutrons and γ rays may also be associated with these events (Bramlitt, 2014). Only a small number of SPEs, about one per year, have significantly higher proton energies and

can be observed by neutron monitors on the ground. These SPEs can cause increases in dose rates at aviation altitudes. Fig. 4 gives the daily proton fluence observed by a satellite in April 1989; the solar eruption of the 10 April is easily observable.

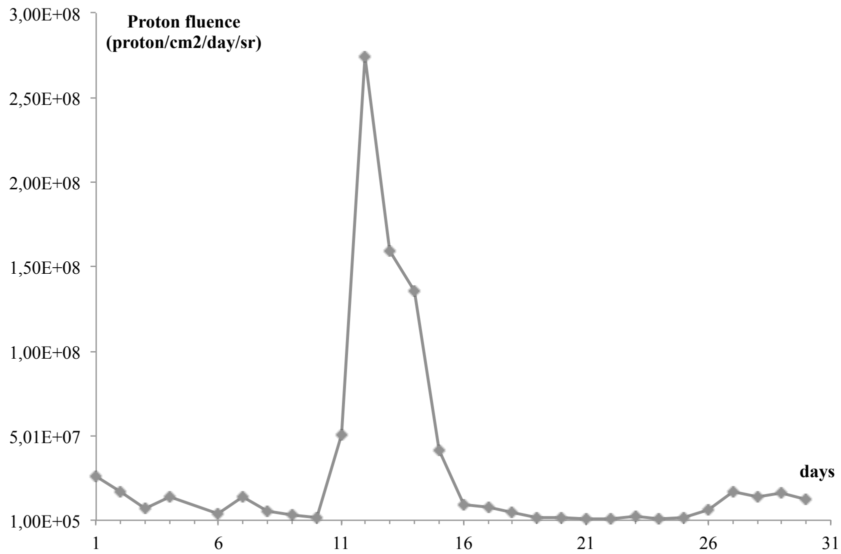

Figure 4. Daily proton fluence between 1 and 30 April 1989 (data from GOES-7 satellite, National Atmospheric and Astronautics Administration).

(20) At present, it is almost impossible to estimate in advance the dose of an SPE with any precision. The calculation of the doses to aircraft crew for the elevated effective dose rates in the event of an SPE is usually made retrospectively using results from ground-level neutron monitors, or in exceptional cases, with on-board measurements. The calculated dose rate can be quite substantial, but is characterised with associated large uncertainties of the order of factor 5 or more according to results obtained by EURADOS Working Group 11 (EC, 2004). According to Lantos and Fuller (2003), 64 SPEs were observed from 1942, and only 18 of them were associated with a significant likelihood of an increase in the effective dose rate of aircraft crew of more than 30 μSv.h^{-1}at 12,000 metres (like the SPE in April 1989) and only 4 by more than 1 mSv.h^{-1} at 12,000 metres. Given their low frequency and the level of individual dose involved, the contribution of SPEs to the total lifetime exposure of aircraft crew to cosmic radiation is therefore marginal.

(21) The Commission is also aware that some concerns have recently been raised about the potential exposure of aircraft crew and passengers to flashes of γ rays produced in the atmosphere on the occasion of thunderstorms. This phenomenon, which is not related to cosmic radiation, was first observed by the National Aeronautics and Space Administration in 1991. These flashes named "Terrestrial Gamma Flashes" (TGF) appear to occur at flight altitude and last a few milliseconds with energy up to 20 MeV. The details of their mechanism of production are uncertain, but the γ rays are presumably produced by electrons accelerated by lighting and travelling close to the speed of light and colliding with atoms in the atmosphere (Dwyer, 2012). There is currently no element to assess the potential exposure of aircraft crew and passengers associated with TGF. It should also be noted that pilots systematically avoid thunderstorms for reasons of flight safety.

2.4. Assessment of individual exposure in aircraft

(22) Individual exposure in aircraft can be estimated relatively easily with computer programmes. Indeed, the cosmic radiation field in an airplane is to a large extent uniform: for a given flight, the exposure of different individuals is similar (Battistoni et al., 2005). For most of the computer programmes, the atmosphere is divided into cubes through which the aircraft flies; the mean effective dose rate in a cube depends on altitude, geomagnetic latitude and solar modulation. The dose when crossing a cube is the product of the dose rate with the time needed by the plane to cross the cube (Fig. 5), which depends on the standard flight profile. The standard flight profile between two airports can differ from the actual flight profile, mainly because of weather conditions, but the impact on the dose is not considered significant (Van Dijk, 2003).

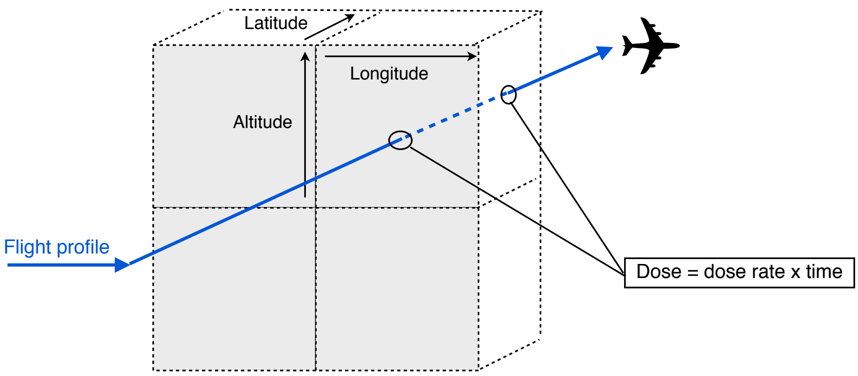

Fig. 5. Typical mode of calculation of dose from cosmic radiation used by computer codes (Bottollier Depois, 2007).

(23) Computer codes that evaluate dose rates in airplanes can be validated and consolidated by measurements of ambient dose rates in the aircraft. For example, in Germany, two passenger aircrafts were equipped with ambient dose rate meters for a period of 4 years in order to validate the calculation programmes used for official dose calculation (Frasch, 2014). Details of the determination of ambient dose rate are discussed in various consensus standards, for example in European Commission (EC, 2004) and the International Organization for Standardization (ISO) standards ISO 20785 parts 1 to 3 (ISO, 2012).

(24) The EC has published a compilation of measured and calculated ambient dose equivalent rates covering the time period from 1993 to 2003 (EC, 2004). These data are the major basis for the analysis leading to the specification of reference values of ambient dose equivalent given in a joint ICRP and ICRU Report (ICRU, 2010). These reference values can be used to check the conformity of the routine procedure for the assessment of aircraft crew doses.

(25) Monitoring of occupationally exposed individuals in aircraft has been recommended by ICRP in various previous publications (ICRP, 1997, 2007). Because individual doses can be properly estimated retrospectively, the Commission continues to recommend the use of validated computer codes, instead of using measurement devices (dosimeters and other instruments) to monitor individual exposure in aviation.

(26) As an example, the effective doses for three flight routes estimated with the software SIEVERT[1] (based on the EPCARD code, Mares, 2009; Schraube 2002– and available at http://www.sievert-system.org) can be found in Table 2. One can notice that the value of the dose rate for the trans-equatorial route is the lowest. Other examples of doses can be found in Appendix A.

Table 2. Example of effective dose calculated for different flight routes (for flights during 15 March 2013).

Type of flight	Total effective dose (µSv)	Dose rate (µSv/h)
Transatlantic flight: Paris – New York	60	6.8
Trans-equatorial flight: Colombo – Jakarta	9.7	2
Transpolar flight: Beijing – Chicago	82	6.8

2.5. Exposure of aircraft crew

(27) Data presented in the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2008 report (UNSCEAR, 2008) indicate that the range of average annual effective dose for aircraft crew is of the order of a few mSv (from 1.2 to 5 depending on country) with a maximum value of about 6-7 mSv. The average annual effective dose is highly dependent of the average annual flight time: of the order of 600 h in European countries and 900 h in the USA.

(28) A review of the exposure of aircraft crew in Europe (Andresz, 2015) indicates that the average annual effective dose varies from 1 mSv for the airline of the Czech Republic to 2.5 mSv for airlines from both Finland and Sweden. The highest maximum annual effective dose is about 6-7 mSv for airlines from Denmark, Germany and Finland (Fig. 6). Apart from exceptional circumstances, aircraft crew receive exposures of less than 10 mSv per year.

[1]Reference to a particular software programme is for illustrative purposes, and does not constitute an ICRP endorsement of this, or any similar codes.

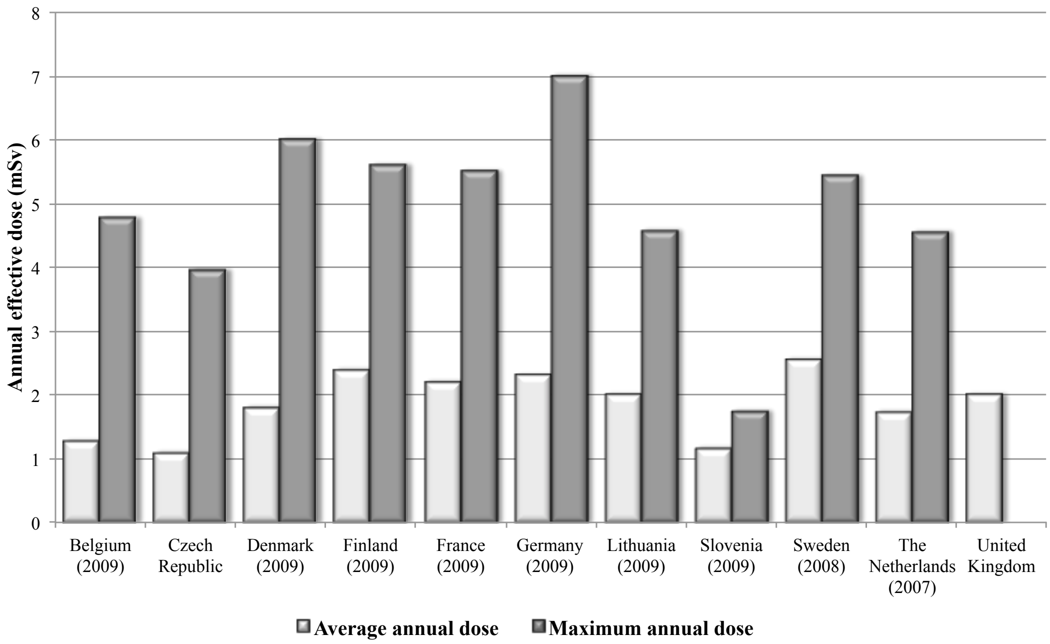

Fig. 6. Average and maximum annual effective dose for crew members in European countries (EAN, 2012).

(29) Aircraft crew exposure is also an important component of annual collective effective dose. According to UNSCEAR (2008), the total collective annual effective dose of aircraft crew in the world is of the order of 800 man Sv. The collective effective dose per country is largely dependent on the size of the national airline companies and the annual flying time. The collective effective dose can reach more than 50 man Sv per year for certain countries (for example, 78.5 man Sv for Germany in 2012). Such collective doses are by far the main contributor to the collective occupational exposure. Table 3 represents the occupational collective exposure for aircraft crew in some countries.

Table 3. Collective dose for aircraft crew (UNSCEAR, 2008)

Country	Monitored individuals	Collective dose (man Sv)
Denmark	3,990	6.8
Finland	2,520	4.2
Germany	31,000	60.0
Lithuania	160	0.2
The Netherland	12,500	17.0
United Kingdom	40,000	80.0
United States of America	150,000	*Not available*

(30) The distribution of doses received by aircraft crew results from the combination of two Gaussian distributions: one for cockpit crew and the other for cabin crew (Fig. 7). Such exposure profiles are typical of a population that has a relatively uniform exposure at levels sufficiently low that has not warranted the application of controls. By comparison, the underlying exposure conditions in the nuclear industry are typically much more variable than those in aviation. This fact and the application of the optimisation of protection typically result in a much more skewed distribution of doses (e.g. approaching a lognormal distribution).

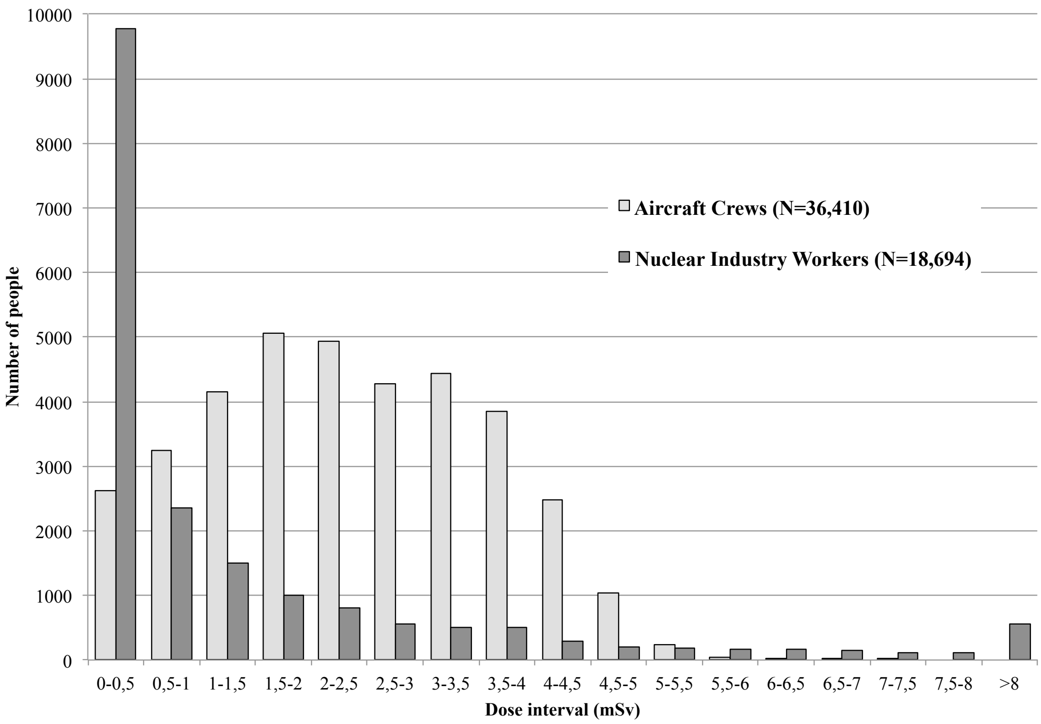

Fig. 7. Distribution of dose for aircraft crew and nuclear industry workers in Germany in 2009 (Frasch, 2012).

2.6. Epidemiological studies of aircraft crew

(31) Epidemiological studies of aircraft crew have been conducted over the last 20 years (for example, as reviewed in Zeeb, 2012). The early studies were investigations of pilots from Canada, the United Kingdom and Japan. With regards to cancer, pilots, almost completely composed of males, showed reduced cancer mortality when compared with the general population – this reduction is often observed in occupational cohorts as a healthy worker effect. But, certain specific types of cancers, namely melanoma and brain cancer, seem elevated in the aircraft crew population (Zeeb, 2012).

(32) A second generation of investigations in the 1990s included a larger set of European and American studies. As was observed previously, cancer mortality of pilots was lower than that of the general population and some cancers (melanoma and brain cancer) showed "*a very moderate excess risk*". A study also showed a slightly increased risk of cataracts for female cabin crew (80 % of the cabin crew, essentially represented by women before pregnancy) and "*a very moderate elevation*" of breast cancer mortality compared with the general population (Rafnsson, 2005).

(33) UNSCEAR (2006) stated that evidence has been found for consistent excess risk of melanoma, non-melanoma skin cancer and breast cancer. But, no relation with the duration of employment was found, and without the information on individual radiation dose, it is difficult to correlate the observed excess risks to ionising radiation, or to solar ultraviolet light (UV) exposure. A recent paper shows that breast cancer incidence is not associated with cosmic radiation exposure, which might be explained by lower parity and older age at first birth (Schubauer-Berigan, 2015).

(34) A study on the mortality of commercial aircraft crew members followed 94,000 Europeans and Americans for an average of 22 years (Hammer et al., 2014). This study showed an overall reduction of cancer and cardiovascular mortality compared to the general population. An elevated mortality from skin melanoma was observed for cockpit crew, but apparently not directly related to occupational exposure and attributable to light skin and sunbathing. Contrary to other studies, no elevation of breast cancer for female aircraft crew was found, but an increased mortality from prostate cancer in male aircraft crew was observed. Generally, the mortality from radiation-related cancers was lower than expected for aircraft crew. The authors recommend further analysis as aircraft crew are exposed to a number of potential risk factors besides ionising radiation: stress, disruption of the circadian rhythm, exposure to jet fuel, etc.

(35) In conclusion, the available epidemiological data show no clear relation between the duration of work of aircraft crew and their corresponding doses from cosmic radiation, with an excess risk of radiation-related cancers.

3. THE COMMISSION'S SYSTEM OF PROTECTION FOR PASSENGERS AND AIRCRAFT CREW

(36) The Commission's system of radiological protection of humans is described in *Publication 103*[2] (ICRP, 2007). According to its paragraph 44, it "*applies to all radiation exposures from any source, regardless of its size and origin*." In particular, according to paragraph 45, the Commission's Recommendations cover exposures to both natural and man-made sources.

(37) The philosophy of *Publication 103* is to recommend a consistent approach for all type of exposure situations, with the central consideration being optimisation process below appropriate dose restrictions.

3.1. Type of exposure situations and categories of exposure

3.1.1. Type of exposure situations

(38) The Commission defines an exposure situation as a network that begins with a natural or man-made radiation source, the transfer of the radiation or radioactive materials through various pathways, and the resulting exposure of individuals (paragraph 169 of *Publication 103*). Protection can be achieved by taking action at the source, or at points in the exposure pathways, and occasionally by modifying the location, the time of exposure and the protection of the exposed individuals. For convenience, the environmental pathway is usually taken to include the link between the source of exposure and the individuals receiving doses.

(39) According to paragraph 176 of *Publication 103* (ICRP, 2007), the Commission intends its Recommendations to be applied to all controllable sources in the following three types of exposure situations, which address all conceivable circumstances:

- *Existing exposure situations* are exposure situations resulting from sources that already exist when a decision to control the resulting exposure is taken. Characterisation of exposures is a prerequisite for their control;
- *Planned exposure situations* are situations resulting from the deliberate introduction and operation of sources. Exposures can be anticipated and fully controlled; and
- *Emergency exposure situations* are situations that may occur during the operation of a planned situation in case of loss of control of the source, or from any unexpected event involving an uncontrolled source. Urgent action is necessary in order to avoid or reduce undesirable exposures.

(40) The Commission views human exposures in aviation resulting from cosmic radiation as an existing exposure situation. The source already exists, and any protection decisions are made in that context to control the exposure. The pathway from the radiation source is outer space, the atmosphere and the aircraft structure, and the exposed individuals are the aircraft crew and passengers. Action to control exposures can only be implemented by changing the exposure conditions of the exposed individuals. The Commission considers that SPEs, even major ones, are part of existing exposure situations given their infrequent presence in the flight

[2]At the time of the publication of the present report, the Commission was revising the glossary enclosed in the *Publication 103* because of some imperfections and inconsistencies with the text so that the report is referring to the text of *Publication 103* rather than to its glossary.

environment, and the resulting contribution to the exposure of aircraft crew and passengers (see paragraphs19 and 20).

3.1.2. Categories of exposure

(41) The Commission distinguishes between three categories of exposure: occupational, medical and public exposures. Occupational exposure is radiation exposure of workers incurred as a result of their work. However, because of the ubiquity of radiation, the Commission traditionally limits the definition of 'occupational exposures' to radiation exposures incurred at work as a result of situations that can reasonably be regarded as being the responsibility of the operating management. Medical exposure is the exposure of patients in the course of medical diagnosis and treatment. Public exposure encompasses all exposures other than occupational exposures and medical exposures.

(42) In aviation, the exposed population to cosmic radiation includes occasional flyers, frequent flyers - for personal reasons and for professional duties - and aircraft crew. The Commission maintains its view that the exposures of occasional and frequent flyers are public exposure, and the exposure of the particular group of aircraft crew is occupational exposure (ICRP, 1991, 1997, 2007). However, the Commission is now proposing a graded approach for the protection of these three groups, taking into account the level of exposure expected for each of them and the responsibilities that need to be considered (Section 4.2).

3.2. Justification of protection strategies

(43) The principle of justification is one of the two fundamental source related principles that apply to all exposure situations. The recommendation in *Publication 103*, paragraph 203, requires, through the principle of justification, that any decision that alters the radiation exposure situation should do more good than harm. The Commission goes on to emphasise that for existing exposure situations, the justification principle is applied in making the decision as to whether to take action to reduce exposure and avert further additional ones. Any decision will always have some disadvantages and should be justified in the sense that it should do more good than harm. In these circumstances, as stated in paragraph 207 of *Publication 103*, the principle of justification is applied in aviation in making the decision as to whether or not to implement a protection strategy against cosmic radiation exposure.

(44) After characterising the situation, the responsibility for judging the justification usually falls on governments or other national authorities to ensure that an overall benefit results, in the broadest sense to society, and thus not necessarily to each individual. However, input to the justification decision may include many aspects that could be informed by users or other organisations or persons outside of the government or national authority. In this context, radiological protection considerations will serve as input to the broader decision process.

(45) Although possibilities to control exposures in aircraft are limited (Section 4.1), the Commission considers that the implementation of a protection strategy is justified, especially for aircraft crew, given that this is one of the most occupationally exposed population both in terms of mean individual and collective effective doses (Section 2.5).

3.3. Optimisation of protection

(46) When decisions have been made regarding the justification of implementing a protection strategy, then the optimisation of protection becomes the driving principle to select the most effective actions for protecting the exposed individuals.

(47) Optimisation is the second source-related principle that applies to all exposure situations and is central to the system of radiological protection. It is defined by the Commission as the process to keep the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures, as low as reasonably achievable (ALARA) below appropriate individual dose criteria, taking into account economic and societal factors. This means that the level of protection should be the best under the prevailing circumstances. In order to avoid serious inequity in the individual dose distribution, the Commission recommends using individual dose criteria (reference levels and dose constraints) in the optimisation process (paragraph 226 of *Publication 103*).

3.3.1. Reference levels

(48) In existing exposure situations, the reference level represents the dose above which it is judged to be inappropriate to allow exposures to occur, for which protective actions should therefore be implemented. Reference levels are guides for selecting protective actions in the optimisation process in order to maintain individual doses as low as reasonably achievable taking into account economic and societal factors, and thus prevent and reduce inequities in the dose distribution. As such, reference levels are also a benchmark against which protective actions can be judged retrospectively.

(49) For existing exposure situations, the Commission recommends setting reference levels within the 1 to 20 mSv/year band as presented in Table 5 of *Publication 103*. In this band, the sources or the pathways can generally be controlled, and individuals receive direct benefits from the activities associated with the exposure situation, but not necessarily from the exposure itself. In aviation, passengers receive direct benefits from flying; travelling rapidly with comfort and security. Like for other situations of occupational exposure to ionising radiation, aircraft crew receive direct benefit from their employment.

(50) For a particular exposure situation, the Commission recommends that the selection of the value of the reference level should be made based upon the prevailing circumstances (paragraph 234 of *Publication 103*). This selection should be made considering the individual dose distribution with the objective to identify those exposures that warrant specific attention. For the protection against cosmic radiation in aviation, the Commission recommends that a reference level can generally be selected in the 5 to 10 mSv/year range.

(51) The selected reference value is not a dose limit, but represents the level of dose below which exposure should be maintained and reduced as low as reasonably achievable taking into account economic and societal factors. The principle of application of individual dose limits only applies in planned exposure situations (paragraph 203 of *Publication 103*). Nevertheless, some regulatory bodies may decide to introduce occupational dose limits to aircraft crew as a procedure to impose legally binding values.

3.3.2. The optimisation process

(52) In practice, optimisation of protection in existing exposure situations is implemented through a process that involves (a) the assessment of the exposure situation taking into account economic and societal factors; (b) identification of the possible protective options to maintain or reduce the exposure to as low as reasonably achievable; (c) the selection and implementation of the most appropriate protective options under the prevailing circumstances; and (d) the regular review of the exposure situation to evaluate if there is a need for corrective actions, or if new opportunities for improving protection have emerged. In this iterative process, the Commission considers that the search for equity in the distribution of individual exposures (i.e. the objective to limit the possibility that some individuals may be subject to much more exposure than the average in a group exposed under similar circumstances), and the improvement of radiological protection culture are important aspects (ICRP, 2006). When optimising protection, the Commission also recommends "*the need to account for the views and concerns of stakeholders*" (ICRP, 2007).

(53) Detailed advice of the Commission on how to apply the optimisation principle in practice has been provided earlier (ICRP, 1983, 1989, 1991b, 2006a), and remains valid.

4. IMPLEMENTATION OF THE SYSTEM OF PROTECTION

4.1. Protective actions

(54) The review of potential protective actions to control exposure in aviation shows that there is little room to manoeuvre. In *Publication 75* (ICRP, 1977), the Commission noted that "*the control of* [cosmic radiation] *exposure is mainly ensured by restrictions on the flying time and route selection*". Indeed, shielding of aircraft (fuselage) is not a feasible option. For example, a 30 g cm^{-2} shielding is necessary to achieve a reduction in the dose rate at 12,000 metres by only 20%. Even flying time limitation and route selection are difficult actions to implement.

- Flying time limitation. Since the dose depends on flight time, work planning of aircraft crew is a means to limit time in air. However, limiting flight time of aircraft crew increases the number of people exposed, and its implementation at large scale may raise societal and economic problems.
- Route selection. It is conceivable to limit exposure by choosing the flight route and acting on altitude and latitude.
    - Altitude. As described in Section 2.2, the Earth's atmospheric layer provides significant shielding from cosmic radiation. Optimisation by flight level is a matter of fine-tuning taking into account factors such as weather condition and air traffic but also costs. For example, it is estimated that a reduction of flight altitude by 1,300 metres can reduce dose by 30%. However, this change in altitude increases the risk of incident, and also fuel consumption and cost by 2% (Hammer and Blettner, 2014).
    - Latitude. As also described in Section 2.2, the Earth's magnetic field deflects many cosmic radiation particles that would otherwise reach ground level, and this effect is most effective at the equator and decreases at higher latitudes. However, optimisation by latitude, in particular re-routing polar flights, increases flight distance, time, and also cost.

(55) Regarding the exposure during an SPE, it could be envisaged to reduce the altitude of flying aircrafts and delay flights that have yet to take off. The implementation of these actions requires the use of sophisticated information systems, which currently remain difficult to develop given technical and organisational considerations. It can also disrupt air traffic, which is already tightly scheduled, and increase the potential for incidents.

(56) In view of the current options for the control of exposure during flights, the Commission continues to emphasise that the main action to control exposures in aviation is to adapt the flight schedules of the most exposed individuals by combining flight time and route selection. For the protection in aviation, the Commission is now recommending a graded approach according to the level of exposure that individuals are likely to receive depending on the frequency of their flights.

4.2. Graded approach

(57) Important consideration for the protection from cosmic radiation in aviation are the circumstances requiring air travel, the frequency with which an individual

may be exposed and the responsibilities at stake. In this regard, it is important to distinguish between people flying on their own initiative or in the context of their work at the request of their operating management. Because of these considerations, the Commission is now adopting a graded approach for the various categories of persons exposed in aviation.

(58) For the vast majority of people, using air transport is an occasional event, and exposure to cosmic radiation is very low (occasional flyers). The exposure becomes higher for a minority of passengers using aircraft frequently, either privately or in the course of their work (frequent flyers). For this minority of passengers, simple ways can be used by these individuals to assess their exposures and give them the opportunity to understand their exposure. For aircraft crew who generally receive more significant doses, an appropriate management of protection is required, based on a regular monitoring of all individual doses and the adaptation of the flight schedules for those individuals with doses approaching the reference level adopted by the operating management.

4.2.1. Occasional flyers

(59) The Commission is of the view that exposure received by occasional flyers is negligible and does not warrant the introduction of protection measures.

(60) However, for the sake of transparency and applying the right to know principle, the Commission recommends that general information about cosmic radiation should be made available for all passengers. For example, this information could be posted on airlines' websites. These websites could make the people aware of the free and validated calculators that estimate flight doses, such as with EPCARD, SIEVERT, etc. Annex A gives estimated effective doses for some typical international flight routes.

4.2.2. Frequent flyers for personal preference and for professional duties

(61) Groups of individuals may use aircrafts frequently for their personal needs or convenience. Other individuals fly frequently at the request of their operating management. Most frequent flyers are not exposed to cosmic radiation under the same circumstances as aircraft crew (e.g. in terms of exposure, frequency of flights, and degree of choice). Therefore, the Commission recommends that the exposure of frequent flyers be considered as public exposure (see paragraph 43), and that individuals exposed be treated in the same way as occasional flyers. The Commission recommends that general information about cosmic radiation be made available to these individuals.

(62) In addition, the Commission encourages frequent flyers who may be concerned by their cosmic radiation exposure to assess their personal exposure using freely available dose calculators, in order to be aware of their exposure and adapt their flight frequency as they feel the need.

(63) Among the frequent flyers for professional duties, a very small fraction is exposed under circumstances, which result in exposures comparable to aircraft crew. This may be the case, for example, for couriers transporting documents and materials, or air marshals. The Commission recommends that the exposure of these frequent flyers be managed in a manner similar to the requirements applying to aircraft crew. It is not the intention of the Commission to provide an exhaustive list of the professions at stake, and the decision to consider these frequent flyers as occupationally exposed should be taken on a case-by-case basis according to the

prevailing circumstances. This may result from an individual assessing their exposure, and using this information to engage their employer in a dialogue, if appropriate. A decision should result from a process involving all concerned stakeholders.

4.2.3. Aircraft crew

(64) The Commission recommends that the airlines management inform the concerned aircraft crew about radiation and cosmic exposure through educational programmes. Information could also be provided to crew at safety meetings, and should be given emphasis in line with other safety issues.

(65) Like for any occupationally exposed worker, the Commission recommends that annual effective dose of each aircraft crew be assessed. The annual effective dose can be derived from the staff-roster and typical effective dose rates using dedicated computer codes. The Commission recommends the occasional use of on-board ambient monitoring for verification and validation of dose calculations (ICRU, 2010). Because the contribution of SPEs to the total dose is marginal, the Commission does not recommend the use of specific monitoring systems such as real time alert systems.

(66) The Commission also recommends that aircraft crew doses should be recorded, and that annual and cumulative individual doses should be made available as per request from the individual. To facilitate potential epidemiological studies, this information should be kept for sufficient time.

(67) Aircraft crew routinely undergo medical examination. The Commission considers that exposure to cosmic radiation does not require specific additional medical examination. Generally, routine medical examination is an opportunity to engage a dialogue between a worker and a physician on the topic of cosmic radiation exposure.

(68) When judged appropriate and to respect the selected dose reference level, the operating management may adjust, in consultation with the concerned aircraft crew, their flight schedule (frequency and destination).

4.2.4. Summary

(69) Table 4 lists the recommendations of the Commission regarding the cosmic radiation exposure of the individuals.

Table 4. Recommendations of the Commission for the individuals exposed to cosmic radiation in aviation.

	Exposed individuals	**Recommendations**	**Categories of exposure**
Reference level to be selected in the 5–10 mSv/year band	Occasional flyers	• General information	Public*
	Frequent Flyers	• General information • Self-assessment of doses • Adjustment of flight frequency as	

		appropriate	
	Aircraft crew	• Individual information • Assessment of individual doses • Recording of individual doses • No specific additional medical surveillance • Adjustment of flight schedules as appropriate	Occupational

*Some groups of frequent flyers may be managed in a manner similar to those occupationally exposed on a case-by-case basis according to the prevailing circumstances.

4.3. Protection of embryo and fetus

(70) In *Publication 82* (ICRP, 1999), the Commission concluded that prenatal exposure in the case of an existing exposure situation does not require protective actions other than those aimed for the general population. The Commission does not therefore believe that actions to adjust flight schedules of pregnant women will be necessary. Women who fly frequently and may be or expect to be pregnant should be provided with sufficient information to make informed judgments regarding the flight schedule and any adjustment they may which to consider.

(71) Regarding the occupationally exposed aircraft crew, it is the Commission's policy that the methods of protection at work for pregnant women should provide a level of protection for the embryo/fetus broadly similar to that provided for members of the public. The Commission recommended in paragraph 186 of *Publication 103* (ICRP, 2007): "*Once an employer has been notified of a pregnancy, additional protection of the embryo/fetus should be considered. The working conditions of a pregnant worker, after declaration of pregnancy, should be such as to ensure that the additional dose to the embryo/fetus would not exceed about 1 mSv during the remainder of the pregnancy*".

(72) Generally, female workers have to declare their pregnancy to their employer after a few months of pregnancy. In some countries, the decision is a voluntary matter for the individuals. Irrespective of these differences, pregnant crew may receive more than a millisievert before declaring the pregnancy. To encourage the timely declaration of pregnancy, the Commission recommends that female aircraft crew and frequent flyers be informed about the risk for the embryo/fetus from exposure to cosmic radiation. After the declaration, the operating management for occupationally exposed individuals should have provision in place to adjust duties during the remainder of the pregnancy.

4.4. Information of the general public and stakeholder engagement

(73) Aside from experienced scientists, experts and professionals trained in radiological protection, citizens are usually not well informed about radiation and their potential health effects. On the matter of exposure to cosmic radiation, apart from most of the aircraft crew, few people among the general public are aware of this exposure, although they are constantly exposed to cosmic radiation in everyday

life on the ground and at an elevated level when travelling in aircraft. However, in recent years, there has been growing information on cosmic phenomena and particularly solar flares (SPE), disseminated by space and weather organisations, and relayed by media; occasionally giving rise to alerts of airlines. This information has awakened the attention of some passengers to cosmic radiation, but also raised questions and sometimes concerns among frequent flyers and aircraft crew about the risk associated with cosmic radiation exposure.

(74) In accordance with the right to know principle, which states that people have the right to be informed about the potential risks that they may be exposed in their daily life, the Commission encourages national authorities, airline companies, consumer unions and travel agencies to disseminate general information about cosmic radiation associated with aviation. This information must be easily accessible and present the origins of cosmic radiation as well as the influence of altitude, latitude and solar cycle, and indicate typical doses associated with a set of traditional flight routes and the potential of receiving significant exposures when flying frequently in case of a rare but intense SPE.

(75) As mentioned in Sections 2.4 and 4.2, several easy-to-use tools have been made available on the internet in recent years, which allow dose calculations associated with all possible flights.

(76) The Commission recommends that the general information on cosmic radiation should be such that the messages are accurate, informative, and responsive to the nature of the concerns and the challenges in terms of radiological protection according to the situation. It is not the Commission's intent to suggest that cosmic radiation be viewed out of proportion with other risks or considerations, but instead, to foster a more inclusive view of all risks so that individuals can make informed decisions.

(77) In this perspective, comparison with other exposure situations to natural and man-made radiation sources may be useful (e.g. a flight London – New York gives the same effective dose as spending 10 days on holiday in high mountain regions) and should be made accessible as part of the general information on cosmic radiation. However, such comparisons must be undertaken with care, because the perception and tolerability of risk depend largely on the characteristics of the situation, and in particular, the benefit for the individuals of the activities that lead to the exposures.

(78) The Commission considers that, as regards to the protection against cosmic radiation in aviation, passengers who are not occupationally exposed must remain accountable for their choices, but that these choices should be made knowingly based on relevant information without bias. The decision by individuals to reduce the frequency of their flights will be based on personal considerations for which the risk of exposure to cosmic radiation is only one element among many others. Finally, it is up to the people who take the risk to judge about its tolerability based on accurate information, and to make decisions for their own protection.

5. CONCLUSION

(79) The Earth is continuously bombarded from particles coming from deep space and the Sun. The atmosphere and the Earth's geomagnetic field provide a sufficient shielding to make exposure at ground level not of particular concern but exposure to cosmic radiation increases with altitude. This existing exposure situation is experienced by millions of travellers: passengers for personal reasons, or on request of their operating management, and aircraft crew who are one of the most highly exposed occupational populations.

(80) The Commission notes that flying occasionally only contributes to a very small increment of the dose received annually due to natural background radiation at ground level, and does not warrant the introduction of protection measures. It is recognised that some passengers may, for personal and very different reasons, be concerned about exposure to cosmic radiation. The Commission thus recommends the dissemination of relevant information to allow them to make informed decisions.

(81) For frequent flyers for personal preference and professional duties, the Commission also recommends the dissemination of relevant information and moreover the self-assessment of their exposure in order to adjust flight frequency as appropriate. For particular groups of frequent flyer for professional duties who are exposed under flight durations similar to those of aircraft crew, the Commission recommends that they engage in discussions with their organisations in order to manage their exposure with requirements similar to those applying to aircraft crew.

(82) For the protection of aircraft crew, the Commission maintains its previous recommendations, and introduces the use of a reference level to be selected by operating managements in the 5 to 10 mSv/year range. The specific level selected should take into account the prevailing circumstances so that the value can meaningfully contribute to the optimisation process. The margins for manoeuvre to reduce exposures from cosmic radiation are very small, and the only effective option is to reduce flight time when doses are approaching the selected reference level.

(83) With the above recommendations, the Commission expects to keep doses of the most exposed individuals –aircraft crew and some frequent flyers– to reasonable levels. The Commission also anticipates that by raising the general awareness of exposure to cosmic radiation in aviation. All involved stakeholders – occasional flyers, frequent flyers and aircraft crew – are encouraged to make informed decisions with regard to the exposures associated with flying by considering at the same time all the benefits they receive from air travel.

APPENDIX A. COSMIC RADIATION EXPOSURE ASSOCIATED WITHSELECTED FLIGHT ROUTES

Effective doses are in mSv	Abu Dhabi (Emirates)	Johannes burg	Kuala Lumpur	Lima	London	Mexico (city)	Moscow	New York (city)	Rio de Janeiro (city)	Tokyo	San Francisco	Sydney
Abu Dhabi (Emirates)		0.015	0.013	0.037	0.025	0.107	0.016	0.077	0.029	0.024	0.109	0.039
Johannesburg	0.015		0.025	0.046	0.027	0.048	0.028	0.045	0.032	0.035	0.072	0.096
Kuala Lumpur	0.013	0.025		0.131	0.043	0.072	0.028	0.1	0.067	0.012	0.59	0.012
Lima	0.037	0.046	0.131		0.039	0.013	0.073	0.024	0.014	0.058	0.025	0.072
London	0.025	0.027	0.043	0.0385		0.079	0.019	0.049	0.028	0.08	0.08	0.075
Mexico (city)	0.107	0.048	0.072	0.013	0.079		0.091	0.017	0.023	0.062	0.009	0.036
Moscow	0.016	0.028	0.028	0.073	0.019	0.091		0.064	0.04	0.053	0.089	0.045
New York (city)	0.077	0.1	0.1	0.024	0.049	0.017	0.064		0.025	0.095	0.03	0.058
Rio de Janeiro (city)	0.029	0.067	0.067	0.014	0.028	0.023	0.04	0.025		0.126	0.038	0.102
Tokyo	0.024	0.012	0.012	0.058	0.08	0.062	0.053	0.095	0.126		0.042	0.02
San Francisco	0.109	0.59	0.59	0.025	0.08	0.009	0.089	0.03	0.038	0.042		0.033
Sydney	0.039	0.012	0.012	0.072	0.075	0.036	0.045	0.058	0.102	0.02	0.033	

Distance and flight-time were calculated with the HAVERSINE formula; effective doses are calculated for January 2012 using the software SIEVERT (http://www.sievert-system.org/index.html).

REFERENCES

Advisory Committee for Radiation Biology Aspects of the SST, 1975. Final Report. Cosmic radiation exposure in supersonic and subsonic flights. Aviat. Space Environ. Med. 46, 1170–1185.

Andresz, S., Croüail, P., Drouet, F., Michelet, M., 2015. Results of the EAN Request on the Radiological Protection of Aircrew, European ALARA Newsletter n°36, February 2015 (www.eu-alara.net).

Battistoni, G., Ferrari, M., Pelliccioni, M., Villari, R., 2005. Evaluation of the dose to aircrew members taking into consideration aircraft structure. Adv. Space Res. 36, 1645–1652.

Bottollier-Depois, J.-F., Blanchard, P., Clairand, I., et al., 2007. An operational approach for aircraft crew dosimetry: The SIEVERT system. Radiat. Prot. Dosimetry 125:421–424.

Bramlitt, E.T., Shonka, J.J., 2015. Radiation exposure of aviation crewmembers and cancer. Health Phys. 108, 76–86.

Desmaris, G., 2006. Does space weather forecast worthwhile for an airline in terms of radiation protection? Air France document.

Dwyer, J., Smith, D., Cummer, S., 2012. High energy atmospheric physics: Terrestrial gamma-ray flashes and related phenomena, Space Sci. Rev. 133, 133–196.

EC 2004, Radiation Protection 140, Cosmic Radiation Exposure of Aircraft Crew – Compilation of Measured and Calculated Data, European Radiation Dosimetry Group (EURADOS), 2004.

Frasch, G., 2012. Aircraft Crew Exposure in Germany from 2004 – 2009, 14th European ALARA Network Workshop, ALARA in existing exposure situations, Dublin, September 2012.

Frasch, G., et al., 2014 Radiation exposure of German aircraft crews under the impact of solar cycle 23 and airline business factors. Health Phys. 107, 542–554.

Hammer, G.-P., Blettner, M., 2014. Strahlenexpositionbeim Fliegen – Ein Fall für den Strahlenschutz, Strahlenschutz Praxis, Heft 2, 2014.

Hammer, G.-P., Auvinen, A., De Stravola, B.L., et al, 2014. Mortality from cancer and other causes in commercial airlines crews: a joint analysis of cohorts from 10 countries. Occup. Environ. Med. 71, 313–322.

IAEA 2009. Regulations for the Safe Transport of Radioactive Material. Safety Requirements No. TS-R-1, IAEA Safety Standards.

ICRP 1965. Recommendations of the International Commission on Radiological Protection. ICRP Publication 9.

ICRP, 1977. Recommendations of the ICRP. ICRP Publication 26. Ann. ICRP 1(3).

ICRP, 1984. Principles for limiting exposure of the public to natural sources of radiation. ICRP Publication 39. Ann. ICRP 14(1).

ICRP, 1991. Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Ann. ICRP 21(1–3).

ICRP, 1997. General principles for the radiation protection of workers. ICRP Publication 75. Ann. ICRP 27(1).

ICRP, 1999. Protection of the public in situations of prolonged radiation exposure. ICRP Publication 82. Ann. ICRP 29(1/2).

ICRP, 2006. Part 2: The optimisation of radiological protection: broadening the process. ICRP Publication 101. Ann. ICRP 36.

ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37(2–4).

ICRP, 2013. Assessment of radiation exposure of astronauts in Space. ICRP Publication 123. Ann. ICRP 42(4).

ICRP 2014. Radiological protection in security screening. ICRP Publication 125. Ann. ICRP 43(2).

ICRU, 2010. Report 84. Reference data for the validation of doses from cosmic-radiation exposure of aircraft crew, J. ICRU 10.

ISO 2012, ISO 20785:2012 Dosimetry for exposures to cosmic radiation in civilian aircraft.

Lantos, P., Fuller, N., 2003. History of the solar particle event radiation doses on-board aeroplanes using semi-empirical model and Concorde measurements. Radiat. Prot. Dosimetry 104, 199–210.

Mares, V., Maczka, T., Leuthold, G., Rühm, W., 2009. Air crew dosimetry with a new version of EPCARD. Radiat. Prot. Dosimetry 136, 262–266.

Rafnsson, V., 2005. Cosmic Radiation increases the risk of nuclear cataract in airline pilots. Arch. Ophthalmol. 123, 1102–1105.

Reynolds, P., Cone, J., Layefsky, M., et al., 2002. Cancer incidence in Californian flight attendants. Cancer Causes Control 13, 317–324.

Rühm, W., 2012. Application of ALARA to cosmic ray Exposures, 14th European ALARA Network Workshop, ALARA in existing exposure situations, Dublin, September 2012.

Schubauer-Berigan, M.K., Anderson, J.L., Hein, M.J., et al., 2015. Breast cancer incidence in a cohort of U.S. flight attendants. Am. J. Ind. Med. 58, 252–266.

Schraube, H., Leuthold, G., Heinrich, W., et al., EPCARD – European program package for the calculation of aviation route doses, User's manual. GSF-National Research Center, Neuherberg, Germany (2002). ISSN 0721 - 1694. GSF-Report 08/02.

UNSCEAR 2006, Effects of Ionizing Radiation, Report to the General Assembly, volume 1, annexe A: Epidemiological studies of radiation and cancer, United Nation publication, New York, 2008.

UNSCEAR, 2008, Sources and effects of ionizing radiation, Report to the General Assembly with Scientific Annexes, volume I, annexe B: Exposures from natural radiation source, United Nation publication, New York, 2010.

Van Dijk, J.W.E., 2003. Dose assessment of aircraft crew in the Netherlands. Radiat. Prot. Dosimetry 106, 25–31.

Yasuda, H., Sato, T., Yonehara, H., et al., 2011. Management of cosmic radiation exposure for aircrew in Japan. Radiat. Prot. Dosimetry 146, 123–125.

Zeeb, H., Hammer, G.P., Blettner, M., 2012. Epidemiological investigations of aircrew: an occupational group with low-level cosmic radiation exposure. J. Radiol. Prot. 32, 15–19, 2012.