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Radiation exposure of space and aircrew

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Abstract

Cosmic radiation and its secondaries created in interactions with planetary atmospheres, shielding structures and the human body constitute one of the most important hazards associated with space and air travel. Crew members are facing exposures to radiation levels that may easily exceed those routinely received by terrestrial radiation workers. To assess the significance of potential biological implications on the health of space and aircrew, it is necessary to discuss the characteristics of the cosmic-ray environment and its dependencies on altitude and geomagnetic latitude. Exposure of space and aircrew to cosmic radiation will be reviewed, and recommended dose limits for astronauts working in low-Earth orbit will be dealt with in comparison with radiation protection guidelines of aircrew personnel.

Introduction

Accomplishments in engineering over the past century have provided unprecedented opportunities for people to become mobile and travel rapidly on or near the surface of the Earth (White and Averner, 2001). Now that new technologies are at our hands to enable us to travel away from our home planet, we are about to become citizens of the universe. For this to happen requires the development of both a new understanding of the risks imposed by the potentially dangerous levels of cosmic radiation, extended weightlessness and psychological stressors, and a more effective means of coping with these hazards to the human organism. Ions of high charge and energy encountered in cosmic radiation have been shown to produce distinct biological damage compared with radiation on ground, leading to large uncertainties in the projection of cancer and other health risks, and obscuring evaluation of the effectiveness of possible countermeasures (Cucinotta and Durante, 2006). On a microscopic scale, it becomes apparent that these particles are likely to deposit their energy in a rather heterogeneous way. Although absorbed doses—averaged over a sufficiently large macroscopic mass element—might be small, there will be microscopic regions of extremely high local doses in close vicinity to the ion path.

Cosmic radiation environment

The radiation environment in space is characterized by a high degree of complexity and dynamics. It is mainly fed by solar and galactic sources (Fig. 1), with additional particles created in interactions with planetary atmospheres, shielding structures and the human body. Among these secondary radiations, neutrons are of foremost importance.

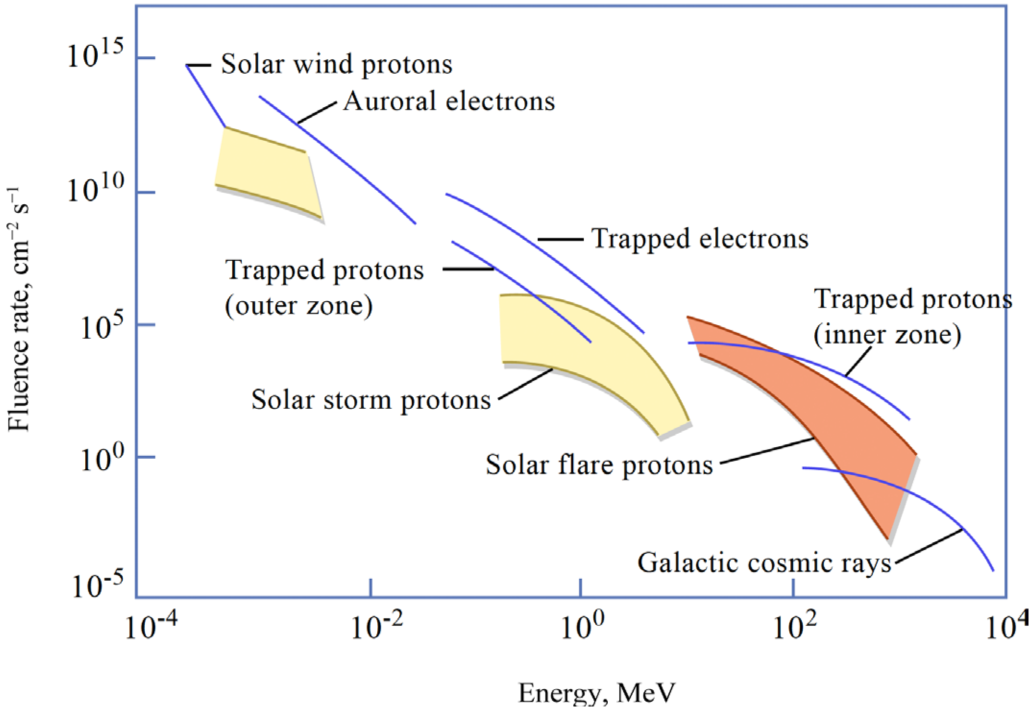

Fig. 1. Energy spectra of cosmic-ray contributors: energetic particles encountered in free space and low-Earth orbit cover a very broad range of energy and fluence rate (MIT OpenCourseWare).

Galactic cosmic radiation (GCR) originates from outside our solar system and is isotropic in distribution, *i.e.*, it arrives at any point in deep space with equal intensity from all directions. The GCR spectrum consists of all naturally occurring chemical elements with energies beyond 10^{20} eV (Lodders, 2003; Mewalt, 1988). Stellar flares, supernova explosions, pulsar spin-offs, or explosions of nascent galactic nuclei were believed to be the sources of GCR acceleration. However, there seems to be no credible mechanism, either inside or outside the galaxy, for accelerating particles to energies above 10^{20} eV (Schwarzschild, 1997). Astrophysicists developed plausible models for how ultra-high-energy cosmic rays might be produced, perhaps even involving new particle-physics phenomena or topological space-time defects left over from the Big Bang, but they still have no definite answers (Cronin *et al.*, 1997). The fluence rate of primary cosmic rays in the galaxy is ~1 $\text{cm}^{-2}\,\text{s}^{-1}$. Low-energy GCR particles consist of 92% protons and 6% helium nuclei, with the remainder being heavier ions with charges of $Z \leq 92$ (^{238}U). The incident fluence rate of cosmic rays with energies above 1 GeV is of the order of 10^{-2} $\text{cm}^{-2}\,\text{s}^{-1}$ at the edge of the exosphere.

Solar cosmic radiation (SCR) comprises the flood of low-energy electrons and protons called the solar wind, which increases by factors of the order of 10^6 during an active sun period to build into a torrential storm. This plasma, streaming out from the Sun's corona at velocities as high as 120 km s^{-1}, creates the interplanetary magnetic field (IMF), which varies according to the 11-year cycle of solar activity. GCR particles entering the heliosphere are scattered by IMF irregularities and undergo convection and adiabatic deceleration in the expanding solar wind (Heber *et al.*, 2009). The GCR intensity is thus anti-correlated with solar activity, which is usually determined from the number of sunspots (Lantos, 1993). Sporadically occurring solar particle events (SPEs) originate from impulsive solar flares, coronal mass ejections or shocks in the interplanetary medium. The emitted protons have energies up to several hundred MeV and, during strong flares, their flux at the Earth's orbit can increase for some hundred percent during hours or days. It is these events, which are of particular concern for the possible manifestation of acute radiation syndrome effects such as nausea, emesis, haemorrhaging or, possibly, even death, since SPEs are still impossible to forecast and might be accompanied by significant dose enhancement (Townsend, 2005).

Energetic particles trapped in the geomagnetic field are confined via magnetic mirroring in two radiation belts, which surround the Earth. The inner belt, which extends from ~1–3 Earth radii in the equatorial plane, was discovered by J. A. Van Allen and co-workers[1] using data taken from Geiger-Müller counters flown on early U.S. satellites. It is mostly populated by protons with energies exceeding 10 MeV. The origin of these protons is thought to be the decay of albedo neutrons from the Earth's atmosphere. The inner belt is fairly quiescent. Particles eventually escape due to collisions with neutral atoms in the upper atmosphere above the Earth's poles. However, such collisions are sufficiently uncommon that the lifetime of particles in the belt range from a few hours to 10 years. Clearly, with such long trapping times only a small input rate of energetic particles is required to produce a region of intense radiation. The outer belt, which extends from ~3–9 Earth radii in the equatorial plane, consists mostly of electrons with energies below 10 MeV. The origin of these electrons is via injection from the outer magnetosphere. Unlike the inner belt, the outer belt is very dynamic, changing on time scales of a few hours in response to perturbations emanating from the outer magnetosphere. In regions not too far distant (*i.e.*, less than 10 Earth radii) from the Earth, the geomagnetic field can be approximated as a dipole field, which is tilted with respect to the Earth's rotational axis by an angle of ~11°. The intersection between the magnetic and rotational axis is located ~500 km more to the North, above the centre of the Earth. Because of this tilt and translation, the radiation belts are closest to the Earth's surface over the South Atlantic Ocean. This region is called the South Atlantic Anomaly (SAA) and is of great significance to space vehicles that orbit the Earth at several hundred kilometres altitude. These orbits take them through the anomaly periodically, each time exposing them for several minutes to increased radiation levels. The high SAA proton fluxes were explained to give rise to light flash phenomena in the eyes of astronauts (Casolino *et al.*, 2003).

Galactic cosmic rays and energetic particles generated in large solar flares finally interact with the Earth's atmosphere to produce in cascade-like reactions hadron, lepton and photon fields at aircraft altitude. The energy spectra of these secondary particles extend from the lowest possible energy to more than 10^{18} eV (O'Brien *et al.*, 1996). The total flux of ionizing particles in the upper atmosphere is fairly constant from 150–50 km altitude. Below 50 km the flux increases due to build-up of cascades and reaches the so-called Pfotzer maximum at about 15–20 km above sea level where absorption starts to dominate. The geomagnetic field deflects the incoming cosmic rays, depending on their rigidity, *i.e.*, momentum per unit charge, and angle of incidence. The vertical critical rigidity is zero at the magentic poles and at its maximum near the magnetic

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[1] Van Allen was actually trying to measure the GCR flux in deep space, to see if it was similar to that measured on Earth. However, the flux of energetic particles detected by his instruments so greatly exceeded the expected value that it prompted one of his co-workers to exclaim, "My God, space is radioactive!"

equator. As a consequence, the primary (and secondary) cosmic-ray flux shows a distinct latitude effect. With respect to dose equivalent, atmospheric neutrons are the most important particles at aircraft altitude. They are produced as evaporation products of highly excited nuclei to form a peak around 1 MeV, and in peripheral collisions or charge exchange reactions of high-energy protons with a maximum flux around 100 MeV (Hajek *et al.*, 2004a). The dependence of neutron production on solar activity is most pronounced in polar regions, while the variation around the equator is just about 5%, since low-energy primaries are shielded by the Earth's magnetic field and high-energy particles undergo only slight solar modulation. The higher energy of primary cosmic rays entering the atmosphere around the equator causes the created neutrons to be able to penetrate deeper into the atmosphere, compared with pole-near latitudes. The maximum of the neutron flux is thus found at about 120 g cm^{-2} at the equator and at about 75 g cm^{-2} in polar regions. Considerable fluxes of neutrons are also produced when a strong solar flare hits the Earth.

Space crew exposure and radiation protection

Space travellers are facing exposures to radiation levels that may easily exceed those routinely received by terrestrial radiation workers. Missions in low-Earth orbit (LEO) are not exposed to the full intensities of the GCR and SPE spectra because of the protection afforded by the Earth's atmosphere and magnetic field. Hence, particle fluence rates are much lower than will be encountered in interplanetary missions—about a factor of three from the International Space Station (ISS) to deep space, where no protection from the magnetosphere or planetary bulk exists. The degree of protection is a function of spacecraft orbital inclination and altitude. For the 51.6° orbit of the ISS, typical dose equivalent rates are between 0.5 and 1.2 mSv d^{-1} (Berger, 2008; Hajek *et al.*, 2008), with ~75% coming from GCR and 25% coming from protons encountered in passages through the SAA region of the radiation belts (NCRP, 2006). For high-inclination space missions in LEO, only 25–30% of SPE protons are intercepted due to geomagnetic shielding, while the contribution of SPEs to the radiation load of astronauts is mostly negligible for low-inclination orbits (Benton and Benton, 2001). Outside the protection offered by the geomagnetic field, doses received from a major SPE in less shielded modules might reach lethal levels within a couple of hours. Hence, radiation shelters have to be provided to minimize the health risks for astronauts.

Radiation transport codes, which model the atomic and nuclear interactions of the cosmic-ray particles, are usually applied to describing how the external radiation fields are altered by passage through the spacecraft structure (Sihver, 2008). However, the high degree of complexity of both the shielding distribution and the generation of secondary charged and uncharged radiation makes it virtually impossible to simulate in detail the variation of the resulting particle fluence and energy spectra of the radiation field constituents within a space vessel. Unlike the situation for terrestrial exposures, the high costs of launching materials into space place limitations on spacecraft size and mass and preclude the purely engineering solution of providing as much additional shielding as needed to reduce radiation exposure to some desired level. Some model predictions indicate that some types of shielding materials may even give rise to secondary radiation environments that are more damaging than the unattenuated primary fields, which produced them.

Table 1. 10-year career limits for stochastic radiation effects applicable to missions in low-Earth orbit. Limits are expressed in effective dose (*E*). Recommendations by NASA and JAXA are age and gender specific (male/female).

NASA		Roscosmos	JAXA		CSA
Age, yrs	*E*, Sv	*E*, Sv	Age, yrs	*E*, Sv	*E*, Sv
25	0.7 / 0.4	1.0	25−29	0.6 / 0.6	1.0
35	1.0 / 0.6		30−35	0.9 / 0.8	
45	1.5 / 0.9		36−39	1.0 / 0.9	
55	2.9 / 1.6		≥ 40	1.2 / 1.1	

The development of radiation protection recommendations for astronauts reflects the current knowledge about radiation risks, which is based to a large extent on cancer incidence and cancer mortality in the atomic-bomb survivors of Hiroshima and Nagasaki. Since until now only few experimentally verified data on the biological effectiveness of heavy ions and the dose distribution within the human body exist, the concepts of terrestrial radiation protection are of limited applicability to human spaceflight, except for the principles of justification and optimization (ALARA). Radiation protection limits for astronauts are designed to prevent deterministic or non-cancer hazards and reduce the risk of stochastic effects to an acceptable level. Instead of applying the annual dose limits for workers on ground also to astronauts, whose careers are of comparatively short duration, the overall lifetime risk is used as a measure. The selection of dose limits for stochastic effects are related to the risk for fatal cancers (solid tumours and leukaemia) as well as for genetic effects. While radiation protection in the pre-Apollo era was concerned primarily with the avoidance of exposures, which might deteriorate the operational performance of astronauts, the first genuine radiation protection guidelines of the U.S. Space Science Board (NAS/NRC, 1970) allowed doubling of the spontaneous incidence of malignant tumours[2]. In 1989, the National Council on Radiation Protection and Measurements (NCRP) proposed age and gender specific dose limits for a 10-year career on the basis that a lifetime excess risk of cancer mortality of 3% was acceptable (NCRP, 1989). This risk was comparable with the risk in less safe but ordinary occupations, such as agriculture and construction. However, it is lower than the 5% lifetime risk that a radiation worker on ground would incur if the present annual protection limits were exhausted (20 mSv per year over 50 years). The increase of risk factors for fatal cancers per unit dose by UNSCEAR and BEIR V required reappraisal of the effective dose limits (Table 1), which were published in NCRP Report 132 (NCRP, 2000).

The Russian Federal Space Agency Roscosmos allows an annual limit of 500 mSv, and—in agreement with the Canadian Space Agency (CSA)—a career limit of 1 Sv, both independent of age and gender, since Russian studies yielded an increasing probability of non-cancer radiation effects with age that compensates the decreasing cancer risk (Roscosmos, 2004). The Russian career limit corresponds to an excess risk between 4.6% (at 30 years of age) and 2.4% (at 50 years of age). Like their U.S. analogue, the dose limits defined by the Japan Aerospace Exploration Agency

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[2] In industrialized countries, the spontaneous cancer incidence is on average 20–25%.

(JAXA) depend on age and gender, but differ in the tolerated dose values and the age structure (Table 1). The associated excess risk is ~3%, but never exceeds 5%. The European Space Agency (ESA) based its radiation protection concept on the recommendations of the International Commission on Radiological Protection (ICRP, 1991) and the European Council Directive 96/29/Euratom (European Commission, 1996), both of which do not explicitly classify astronauts as radiation workers[3]. The limits applied to European astronauts are thus based on thresholds for deterministic radiation effects in dedicated organs and tissues (Straube *et al.*, 2010).

Dose limits for acute deterministic effects in the bone marrow, lens of the eye and the skin (Table 2) are expressed in gray equivalents (Gy-Eq), in which the organ absorbed dose is weighted by multiplication with the appropriate relative biological effectiveness (RBE) for a specific radiation quality and endpoint. The concept of Gy-Eq became necessary, since the radiation weighting factors used for stochastic effects do not apply to deterministic detriments. Considering the significant uncertainties in assessing RBE at low dose and dose rate, the values on which the dose limit recommendations are based have been determined at the threshold doses for the regarded deterministic effect (ICRP, 1989; Urano *et al.*, 1984).

For long-term missions outside Earth's magnetic field, the acceptable level of risk has not yet been defined, since there is not enough information available to estimate the risk of effects to the central nervous system and of potential non-cancer radiation health hazards (cataracts, cardiovascular diseases, etc.). Available data and pending questions have been compiled in NCRP Report 153 (NCRP, 2006), which will form the basis for developing radiation protection guidelines for missions into deep space.

Table 2. Recommended organ dose limits in Gy-Eq applicable to missions in low-Earth orbit. All limits are independent of age and gender.

Organ		NASA	Roscosmos	JAXA	ESA	CSA
Bone marrow, Gy-Eq	Acute	0.25	0.15	–	–	–
	30 d	0.25	0.25	–	0.25	–
	1 yr	0.5	0.5	0.5	0.5	–
	Career	–	–	–	–	–
Eye, Gy-Eq	Acute	–	–	0.5	–	–
	30 d	1.0	0.5	–	0.5	–
	1 yr	2.0	1.0	1.0	1.0	–
	Career	4.0	2.0	5.0	–	4.0
Skin, Gy-Eq	Acute	–	–	2.0	–	–
	30 d	1.5	1.5	–	1.5	–
	1 yr	3.0	3.0	4.0	3.0	–
	Career	6.0	6.0	20.0	–	6.0

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[3] A task group appointed by the ICRP in 2006 shall develop recommendations for human space missions in low-Earth orbit and beyond.

Aircrew exposure and radiation protection

Aircraft passengers and crew are subject to elevated levels of secondary cosmic radiation produced in the atmosphere, the aircraft structure and its contents. From the beginning of the first commercial supersonic Concorde operations, measurements on board passenger aircraft became attractive and contributed to the vast pool of data available today. Total exposure on a given flight depends on the particular air route in terms of altitude (pressure rather than radar altitude) and geomagnetic latitude, as well as on solar activity and the duration of the flight. The dose rate increases with altitude and geomagnetic latitude, reaching a maximum at 15–20 km and a constant level above ~55°, respectively. As a rule of thumb, the effective dose from neutrons in polar regions is enhanced by a factor of ~6 compared with the equator, while the dose delivered by the directly ionizing component increases only by a factor of ~2. Commercial subsonic aircraft generally have cruising altitudes of 7–12 km. The effective dose rate at an altitude of 8 km in temperate latitudes is typically up to ~3 μSv h^{-1}, but decreases to only ~1–1.5 μSv h^{-1} near the equator (Fig. 2). At 12 km, the values are greater by about a factor of two. The dose for a return trans-Atlantic flight is typically 60–70 μSv (Hajek *et al.*, 2004b). The annual hours flown by crew members varies from individual to individual and from airline to airline, depending on policy. The average appears to be 300–900 hours per year. The annual effective doses received by aircraft crew usually lie within 2–4 mSv, with only few crew members receiving higher doses. At aircraft altitude and temperate latitudes, representative values of the main components of effective dose are neutrons 55%, electrons and positrons 20%, protons 15%, photons 5% and muons 5% (Bartlett, 2004). At sea level, the dominant component of effective dose is the muon component.

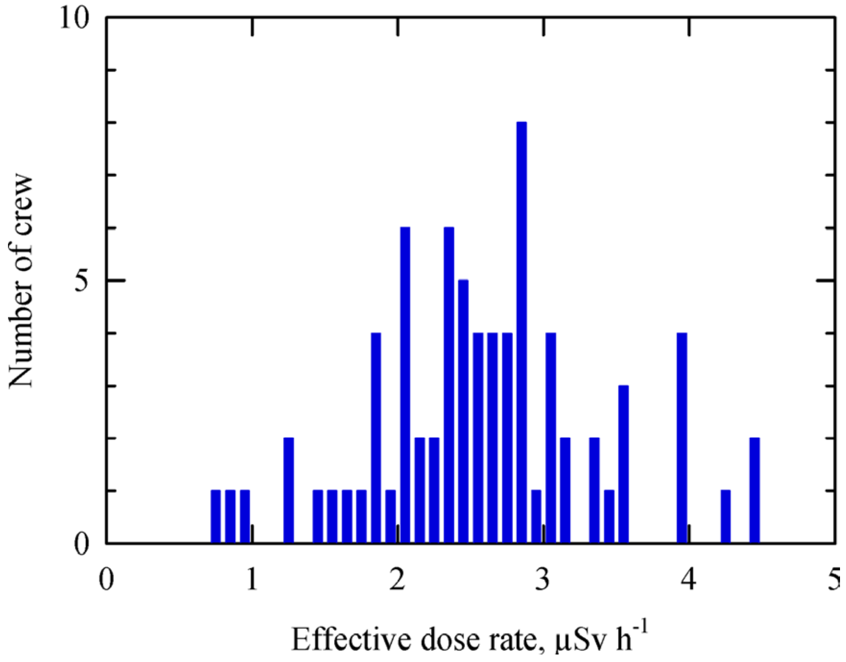

Fig. 2. Histogram of Tyrolean Airways crew radiation exposure on short- and medium-haul flights. The distribution of measured effective dose rates peaks between 2 and 3.5 μSv h^{-1}. For an average of 750 flight hours per year, effective dose can be estimated to result in 1.5–2.6 mSv.

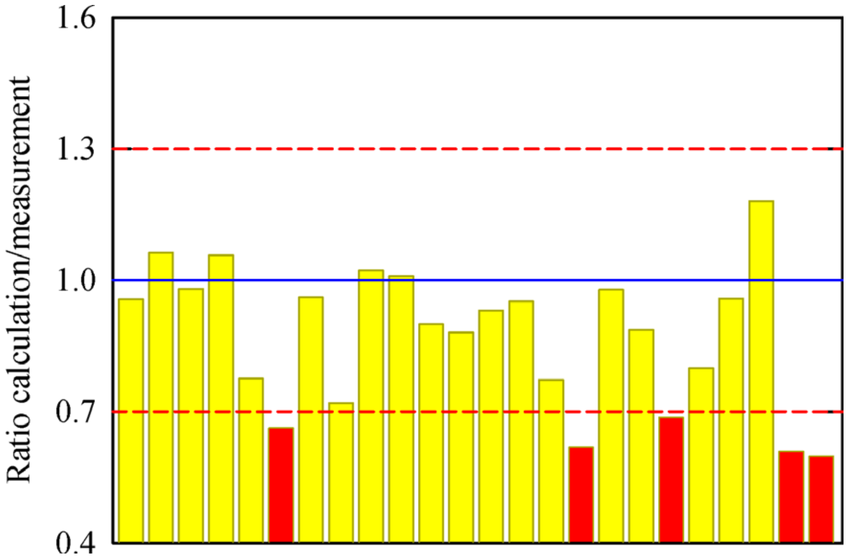

Fig. 3. Comparison of computed and measured route doses for 24 Tyrolean Airways flights. Agreement within ±30% is indicated, as required by Austrian regulations. There is generally good agreement between the results of calculations using CARI-6M and experimental determinations, except for very short-haul flights operated by propellant aircraft at low altitude.

There are a number of radiation transport codes and programmes to calculate dose rates and route doses in current use. The radiation transport codes take as input the cosmic radiation field at the top of the atmosphere and solve, either analytically or by Monte Carlo simulation, the radiation transport equations, which describe the interactions of each particle with the constituents of the atmosphere, in order to calculate the field at a given aircraft altitude and geographic location. The effect on particle trajectories of the Earth's magnetic field is included in approximations using tables of rigidity cut-offs. The programmes take account of the effects of IMF variation by applying an equivalent heliocentric electrostatic field. Generally, there is good agreement (Fig. 3) between the results of calculations and experimental determinations (Lindborg *et al.*, 2004).

Following ICRP recommendations (ICRP, 1991), the European Union (EU) introduced a revised Basic Safety Standards Directive (European Commission, 1996), which, *inter alia*, included the exposure to enhanced levels of cosmic radiation. The Directive requires account to be taken of the exposure of aircrew personnel liable to receive effective doses of more than 1 mSv per year. It further identifies the following protection measures (Bartlett, 2004): (i) to assess the exposure of the crew concerned; (ii) to take into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed crew; (iii) to inform the workers concerned of the health risks their work involves; and (iv) to apply the same special protection during pregnancy to female crew irrespective of the 'child to be born' as to other female workers. The EU Directive has already been incorporated into laws and regulations of the majority of the EU Member States and has been included in the aviation safety standards and procedures of the Joint Aviation Authorities (JAA). The preferred approach, supported by guidance from the European Commission and ICRP Publication 75 (ICRP, 1997), is that where the assessment of the exposure of aircraft crew to cosmic radiation is necessary, doses can be computed from staff roster information, flight profiles and calculations of cosmic radiation dose rates as a function of altitude, geomagnetic latitude and solar modulation. The calculations are to be verified by measurements.

References

Bartlett DT. Radiation protection aspects of the cosmic radiation exposure of aircraft crew. Radiat. Prot. Dosim. 2004; 109 (4): 349–355.

Benton ER, Benton EV. Radiation dosimetry in low-Earth orbit and beyond. Nucl. Instrum. Methods Phys. Res. B 2001; 184 (1–2): 255–294.

Berger T. Radiation dosimetry onboard the International Space Station ISS. Z. Med. Phys. 2008; 18 (4): 265–275.

Casolino M, Bidoli V, Morselli A, Narici L, De Pascale MP, Picozza P *et al*. Space travel: dual origins of light flashes seen in space. Nature 2003; 422 (6933): 680.

Cronin JW, Gaisser TK, Swordy SP. Cosmic rays at the energy frontier. Sci. Am. 1997; 276 (1): 44–49.

Cucinotta FA, Durante M. Cancer risk from exposures to galactic cosmic rays: implications for space exploration by human beings. Lancet Oncol. 2006; 7 (5): 431–435.

European Commission. Council Directive 96/29/Euratom of 13 May 1996 laying down the basic saftey standards for protection of the health of workers and the general public against the dangers arising from ionising radiation. Off. J. Eur. Commun. 1996; 39 (L159).

Hajek M, Berger T, Vana N. Passive in-flight neutron spectrometry by means of bonner spheres. Radiat. Prot. Dosim. 2004a; 110 (1–4): 343–346.

Hajek M, Berger T, Vana N. A TLD-based personal dosemeter system for aircrew monitoring. Radiat. Prot. Dosim. 2004b; 110 (1–4): 337–341.

Hajek M, Berger T, Vana N, Fugger M, Pálfalvi JK, Szabó J *et al*. Convolution of TLD and SSNTD measurements during the BRADOS-1 experiment onboard ISS (2001). Radiat. Meas. 2008a; 43 (7): 1231–1236.

Heber B, Kopp A, Gieseler J, Müller-Mellin R, Fichtner H, Scherer K *et al*. Modulation of galactic cosmic ray protons and electrons during an unusual solar minimum. Astrophys. J. 2009; 699 (2): 1956–1963.

ICRP. RBE for deterministic effects. ICRP Publication 58. Ann. ICRP 1989; 20 (4): 1–57.

ICRP. 1990 recommendations of the International Commission of Radiological Protection. ICRP Publication 60. Ann. ICRP 1991; 21 (1–3): 1–201.

ICRP. General principles for the radiation protection of workers. ICRP Publication 75. Ann. ICRP 1997; 27 (1): 1–61.

Lantos P. The sun and its effects on the terrestrial environment. Radiat. Prot. Dosim. 1993; 48 (1): 27–32.

Lindborg L, Bartlett DT, Beck P, Schraube H, Spurný F (eds). Cosmic radiation exposure of aircraft crew: compilation of measured and calculated data. 2004; Radiat. Prot. 140. European Commission, Luxembourg.

Lodders K. Solar system abundances and condensation temperatures of the elements. Astrophys. J. 2003; 591 (2): 1220–1247.

Mewalt RA. Elemental composition and energy spectra of galactic cosmic rays. 1988; Publication 88-28. Jet Propulsion Laboratory, Pasadena.

NAS/NRC. Radiation protection guides and constraints for space-mission and vehicle-design studies involving nuclear systems. 1970; National Academy of Sciences /National Research Council, Washington.

NCRP. Guidance on radiation received in space activities. 1989; Report 98. National Council on Radiation Protection and Measurements, Bethesda.

NCRP. Radiation protection guidance for activities in low-Earth orbit. 2000; Report 132. National Council on Radiation Protection and Measurements, Bethesda.

NCRP. Information needed to make radiation protection recommendations for space missions beyond low-Earth orbit. 2006; Report 153. National Council on Radiation Protection and Measurements, Bethesda.

O'Brien K, Friedberg W, Sauer HH, Smart DF. Atmospheric cosmic rays and solar energetic particles at aircraft altitude. Environ. Int. 1996; 22 (Suppl. 1): S9–S44.

Roscosmos. Limitation of cosmonaut exposure in near-Earth spaceflights [in Russian]. 2004; MR 2.6.1. 44-03-2004. Ministry of Public Health, Moscow.

Schwarzschild B. Auger project seeks to study highest energy cosmic rays. Phys. Today 1997; 50 (2): 19–21.

Sihver L. Transport calculations and accelerator experiments needed for radiation risk assessment in space. Z. Med. Phys. 2008; 18 (4): 253–264.

Straube U, Berger T, Reitz G, Facius R, Fuglesang C, Reiter T *et al*. Operational radiation protection for astronauts and cosmonauts and correlated activities of ESA Medical Operations. Acta Astronaut. 2010; 66 (7–8): 963–973.

Townsend LW. Implications of the space radiation environment for human exploration in deep space. Radiat. Prot. Dosim. 2005; 115 (1–4): 44–50.

Urano AC, Verhey LJ, Goitein M, Tepper JE, Suit HD, Mendiondo O *et al*. Relative biological effectiveness of modulated proton beams in various murine tissues. Int. J. Radiat. Oncol. Biol. Phys. 1984; 10 (4): 509–514.

White RJ, Averner M. Humans in space. Nature 2001; 409 (6823): 1115–1118.

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